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FLUVIAL SEDIMENTS OF CRETACEOUS AGE ALONG THE SOUTHERN BORDER OF THE CANTABRIAN MOUNTAINS, SPAIN

BY

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ABSTRACT

This study deals with a sedimentological description and interpretation of a strip of continental deposits of Cretaceous age along the southern border of the Cantabrian Mountains. In this work they are designated as Voznuevo Formation (Evers, 1967). They belong to the type of deposits which have commonly been referred to as 'sediments in Wealden facies'.

As regards stratigraphy, palynological analyses (apart from pollen, the Voznuevo Formation proved completely barren) made it clear that the transition between the Lower Cretaceous and the Upper Cretaceous runs obliquely through the formation. Hence, the Voznuevo sediments are diachronic deposits, decreasing in age in a westerly direction and forming the continental counterparts of successively younger shallow marine deposits towards the west.

In comparison with similar deposits in Wealden facies in other parts of Spain they represent one of the last vestiges of continental deposition in Upper Cretaceous times.

Sedimentological investigations made it clear that the Voznuevo sediments are of purely fluvial origin, derived from a granitic source area, probably now partly hidden, which must have been situated on the arc of granitic rocks which runs from Galicia via northern Portugal to the Sierra de Guadarrama, N of Madrid. Especially paleocurrent directions indicate a transport from southwesterly directions. Typical final products of weathering of granites – kaolinite and quartz – form the main share of the sediments.

The independence of the Voznuevo deposits of the Paleozoic rocks which they overlie is striking; only the very lower part of the formation testifies to a small contribution from the Cantabrian Mountains. In the extreme west of the area some supply could be ascertained from the Precambrian rocks present there. The transition into the overlying shallow marine deposits is very gradual; a very small amount of lagoonal deposits probably occurs in the upper part of the formation. Apart from these, no sediments transitional to a marine environment, such as beach deposits, could be observed.

The fluvial sediments can be subdivided into braided and meandering river deposits, the former much coarser-grained than the latter. The braided river deposits show characteristic features such as channelling, cut-and-fill structures, absence of distinct grading etc. The meandering river deposits exhibit fining-upward grading cycles in which cross-bedding of the planar type with backflow phenomena in their bottomsets is common, and sub-environments such as point bar, natural levee, crevasse-splay and backswamp deposits.

Towards the coastal side of the area of deposition (i. e. the eastern part of the area studied) meandering river deposits were found. They presumably represent sediments of a coastal plain in which meandering rivers, chiefly carrying sandy sediments, ran to the sea in the east. At the same time, much coarser-grained braided river deposits formed further westwards in a mountain foreland. In shifting towards the west in its entirety, this model has yielded the sediments as they can be observed today.

The Voznuevo Formation clearly stands out against the deposits which are to be found at its bottom and its top. First of all, there is the complete absence of limestone, the predominance of quartz over quartzite and the abundance of kaolinite. Secondly, heavy minerals not resistant to chemical weathering, such as hornblende, epidote and augite are completely lacking. Erosion of fresher rocks in the source area during the latter part of the sedimentation is reflected by the increased appearance of metamorphic minerals such as andalusite and kyanite.

The abundance of authigenic kaolinite favours the supposition that weathering took place after deposition. The high percentage of kaolinite, the ubiquity of organic matter, the flatness and roundness of the pebbles and the absence of any trace of laterization indicates weathering under temperate to warm, humid conditions with relatively strong leaching.

The Voznuevo sediments form a clearly foreign element in the depositional history of the sediments along the southern border of the Cantabrian Mountains. Tertiary and Quaternary sediments, all having the Cantabrian Mountains as source area, have been partially supplied from the Voznuevo sediments. But hitherto enigmatical occurrences of, for instance, staurolite and kaolinite in Tertiary deposits can also be explained by considering them as erosion products of the Voznuevo Formation.

SAMENVATTING

Dit onderzoek omvat een sedimentologische beschrijving en interpretatie van een strook continentale afzettingen van Krijt ouderdom, die gelegen zijn aan de zuidrand van het Cantabrisch gebergte. In dit proefschrift zullen zij Voznuevo Formatie (Evers, 1967) worden genoemd. Zij behoren tot het type afzettingen dat men gewoonlijk 'sedimenten in Wealden faciës' heeft genoemd.

Wat de stratigrafie betreft, bleek uit palynologische analyses (behalve pollen is de Voznuevo Formatie volkomen fossielloos) dat de overgang van Onder Krijt naar Boven Krijt zich scheef door de formatie beweegt. De Voznuevo sedimenten zijn dientengevolge diachrone afzettingen die naar het westen toe jonger worden en de continentale voortzetting vormen van geleidelijk naar het westen toe jonger wordende ondiep-mariene afzettingen.

Vergeleken met dergelijke afzettingen in Wealden faciës in andere delen van Spanje vertegenwoordigen zij één der laatste resten van continentale afzettingen in het Boven Krijt.

Uit een sedimentologisch onderzoek bleek dat de Voznuevo sedimenten van puur fluviatiele oorsprong zijn, afkomstig van granitische gesteenten die – wellicht heden gedeeltelijk bedekt – gelegen waren in de boog van granitische gesteenten die van Galicië via Noord-

Portugal naar de Sierra de Guadarrama, ten N van Madrid, loopt. In het bijzonder aanvoerrichtingen, gemeten in scheef gelaagde pakketten, wijzen op een aanvoer vanuit zuidwestelijke richtingen. Typische eindproducten van verwering van granieten, zoals kaoliniet en kwarts, vormen het leeuwendeel van het sediment.

De onafhankelijkheid der Voznuevo sedimenten van de Paleozoische gesteenten die zij bedekken is opvallend; slechts het onderste deel van de formatie getuigt van een geringe invloed van het Cantabrisch gebergte. In het uiterste westen van het gebied kon enige aanvoer van de daar aanwezige Praecambrische gesteenten worden aangetoond. De overgang naar de op de Voznuevo Formatie liggende ondiep mariene afzettingen is zeer geleidelijk; in het bovendeel van de formatie zijn vermoedelijk enige lagunaire afzettingen aanwezig. Afgezien hiervan werden nergens sedimenten, die de overgang vormen naar een marien milieu – zoals strand afzettingen – aangetroffen.

De fluviatiele afzettingen kunnen worden onderverdeeld in sedimenten van verwilderde en van meanderende rivieren; die van het eerstgenoemde type zijn beduidend grofkorreliger. De afzettingen van het verwilderde rivier type vertonen specifieke kenmerken zoals geulvorming, 'cut-and-fill' structuren, afwezigheid van gradering enz. De afzettingen van meanderende rivieren vertonen cycli met graderingen, die naar boven toe fijner van korrel worden. In deze cycli komen pakketten met scheve gelaagdheid van het type met vlakke grensvlakken voor. In de onderste delen der scheef gelaagde eenheden werden vaak 'backflow'-verschijnselen – veroorzaakt door tegengestelde circulatie aan de lijzijde van een ribbel – waargenomen. Gedetailleerd onderzoek in enkele goed ontsloten gedeelten van het gebied maakte een indeling in fluviatiele sub-milieus mogelijk, zoals bijvoorbeeld kronkelwaard-, oeverwal-, doorbraak- en komgrond-afzettingen.

Aan de kustzijde van het sedimentatiegebied (het oostelijke gedeelte van het onderzochte gebied) werden afzettingen van meanderende rivieren gevonden. Naar alle waarschijnlijkheid vertegenwoordigen zij de sedimenten van een kustvlakte, waarin kronkelende rivieren, die voornamelijk zand met zich mee voerden, zeewaarts stroomden. Tegelijkertijd werden veel grovere afzettingen verder westelijk, in het voorland van een gebergte, door verwilderde rivieren gevormd. Dit zich langzaam naar het westen verplaatsende model leverde de sedimenten zoals zij heden aangetroffen kunnen worden.

De Voznuevo Formatie steekt schril af tegen de boven- en onderliggende sedimenten. Ten eerste is er de totale afwezigheid van kalk, de overheersing van kwarts over kwartsiet en de overvloed aan kaoliniet. Ten tweede moet de samenstelling der zware mineralen genoemd worden, waarin mineralen die niet bestand zijn tegen chemische verwering, zoals hoornblende, epidoot en augiet, ontbreken. De erosie van steeds versere gesteenten in het brongebied gedurende de latere stadia van de sedimentatie van de Voznuevo Formatie wordt weerspiegeld in het in toenemende mate verschijnen van metamorfe mineralen zoals andalusiet en distheen.

De grote hoeveelheid authigene kaoliniet (die wijst op verwering na sedimentatie), het veelvuldig voorkomen van organisch materiaal, de afplatting en afronding der rolstenen en de afwezigheid van ieder spoor van lateritisatie wijst op verwering onder gematigde tot warme, vochtige omstandigheden met betrekkelijk sterke uitloging.

De Voznuevo afzettingen vormen een duidelijk vreemd element in de sedimentatie-geschiedenis langs de zuidrand van het Cantabrisch gebergte. De samenstelling van Tertiaire en Kwartaire sedimenten, allen met het Cantabrisch gebergte als herkomstgebied, werd gedeeltelijk beïnvloed door Voznuevo materiaal. Ook de tot op heden niet verklaarde aanwezigheid van bijvoorbeeld stauroliet en kaoliniet in Tertiaire afzettingen kan verklaard worden wanneer men ze beschouwt als erosie-producten van de Voznuevo Formatie.

RÉSUMÉ

Cette étude concerne une description et une interprétation sédimentologique d'une zône avec des sédiments continentaux du Crétacé le long de la bordure méridionale du Massif asturien. Dans cet ouvrage ils sont désignés par: Formation de Voznuevo (Evers, 1967). Ces dépôts appartiennent au groupe des sédiments habituellement nommés 'des sédiments à faciès Wealdien'.

Quant à la stratigraphie, des analyses palynologiques (on ne trouve dans la Formation de Voznuevo que des pollen) ont montré que la transition du Crétacé inférieur au Crétacé supérieur traverse obliquement la formation. Par conséquent, les sédiments du Voznuevo sont des dépôts diachroniques, rajeunissant vers l'Ouest et formant les pendants continentaux de dépôts marins peu profonds, qui rajeunissent successivement vers l'Ouest.

En comparaison avec des dépôts à faciès Wealdien semblables dans d'autres parties d'Espagne, ils représentent les derniers vestiges des dépôts continentaux du Crétacé supérieur.

Les recherches sédimentologiques ont montré que les dépôts du Voznuevo ont une origine strictement fluviale, et qu'ils sont dérivés d'une région granitique, qui est à présent probablement partiellement recouverte et qui a dû avoir été située dans un arc de roches granitiques, s'étendant de la Galice, par le Nord du Portugal, vers la Sierra de Guadarrama, située au Nord de Madrid. Particulièrement les directions de paleocourants indiquent un transport de directions sud-ouest. Des produits d'altération typique des granites – le kaolin et le quartz – représentent la majorité des sédiments.

Il est frappant qu'il n'y ait pas de relation entre les dépôts de Voznuevo et les roches Paléozoïques en dessous; seule la partie la plus basse de la formation montre qu'il y a eu une contribution, tant soit peu, de la part du Massif des Asturies. Dans la partie de la région située tout à l'Ouest, on a pu constater un influx peu important de roches Précambriennes. La transition aux dépôts marins qui les recouvrent est fort graduelle; probablement une quantité minimale de dépôts lagunairs est présente dans la partie supérieure de la formation. Hormis ceux-ci pas un seul des sédiments ne montre une transition à un milieu marin, comme par exemple des dépôts littoraux.

Les sédiments fluviaux peuvent être subdivisés en dépôts de rivières anastomosées et en dépôts de rivières serpentantes, les premiers étant plus grossiers que les derniers. Les dépôts de rivières anastomosées montrent des propriétés caractéristiques comme des rigoles (channelling), des chenaux d'érosion, l'absence de classement distinct etc. Les dépôts de rivières serpentantes montrent souvent des 'fining-upward grading cycles' dans lesquels on trouve une stratification entrecroisée à groupe planaire de laminae (planar cross-stratification), avec des phénomènes de circulation inverse (backflow) dans leur couches basales. Des recherches détaillées dans quelques parties bien exposées de la région ont montré des sous-milieux fluviaux comme par exemple des bourrelets arqués, des levées naturelles, des crevasses et des dépôts de dépressions latérales.

Dans la partie côtière de la région de déposition (c'est à dire la partie orientale de la région étudiée), des dépôts dérivés de rivières serpentantes ont été trouvés. Ils représentent probablement les sédiments d'une plaine littorale dans laquelle les rivières serpentantes, apportant principalement des sédiments sableux, descendaient vers la mer en direction orientale. En même temps, des dépôts de rivières anastomosées consistants de sédiments bien plus grossiers se sont formés dans un promontoire vers l'Ouest. En se déplaçant intégralement vers l'Ouest, ce modèle a donné les sédiments du type comme ils peuvent être observés aujourd'hui.

La Formation de Voznuevo contraste avec les dépôts sous-jacents et les dépôts sus-jacents. Premièrement il y a l'absence complète du calcaire, la prédominance du quartz sur le quartzite et l'abondance du kaolin. Secondement, il y a la composition des minéraux lourds dans laquelle des minéraux non-résistants aux actions météoriques chimiques, comme par exemple l'hornblende, l'epidote et l'augite manquent totalement. L'érosion de roches plus fraîches dans la région d'origine pendant les derniers stades de la sédimentation du Voznuevo, devient évidente par l'apparition plus fréquente de minéraux métamorphiques comme l'andalousite et le disthène.

L'abondance de kaolin authigène renforce la supposition que des actions météoriques ont pris place après la déposition. Le pourcentage élevé de kaolin authigène, la présence constante de matières organiques, l'aplatissement et l'émoussé des galets, et l'absence totale de toute trace de latéritisation indiquent que les actions météoriques ont pris place sous des conditions climatologiques tempérées à chaudes et humides avec un lessivage relativement fort.

Les sédiments du Voznuevo représentent un élément clairement étranger dans l'histoire de la sédimentation dans la bordure méridionale du Massif asturien. Les sédiments du Tertiaire et du Quartaire, originaires du Massif asturien, ont été fournis partiellement par les sédiments du Voznuevo. Egalement la présence énigmatique du staurolite et du kaolin dans les dépôts tertiaires peut maintenant être expliquée en considérant ces minéraux comme des produits d'érosion de la Formation de Voznuevo.

RESUMEN

Este trabajo trata la descripción e interpretación sedimentológica de una faja de depósitos continentales de edad Cretácea a lo largo del límite sur del macizo Cantábrico. En este trabajo han sido designados estos depósitos como la Formación de Voznuevo (Evers, 1967). Pertenecen a un tipo de depósitos comúnmente referidos como sedimentos en facies Wealdense.

En cuanto a la estratigrafía, el análisis palinológico (aparte de polen, la Formación de Voznuevo es completamente estéril) aclaró que la transición entre el Cretáceo inferior y superior corre oblicuamente atravez de la formación. De aquí que los sedimentos de Voznuevo son depósitos diacrónicos, aminorando de edad en dirección occidental, formando la parte continental complementaria de depósitos marinos aplacerados sucesivamente rejuveneciendo hacia el occidente.

En comparación a depósitos similares en facies Wealdense en otras regiones de España representan uno de los últimos vestigios de deposición continental del Cretáceo superior.

Investigaciones sedimentológicas aclararon que los sedimentos de Voznuevo son puramente de origen fluvial, derivados de un área de fuente granítica, probablemente ahora parcialmente cubierta, la cual debe haberse encontrado dentro del arco de rocas graníticas que se extende desde Galicia por el norte de Portugal hasta la Sierra de Guadarrama, al norte de Madrid. Especialmente las direcciones de las paleocorrientes indican un transporte de direcciones sudoccidentales. Productos típicos de meteorización de granitos – caolinita y cuarzo – forman la mayor parte de los sedimentos.

La independencia de los depósitos de Voznuevo de las rocas Paleozoicas que cubren es sorprendente; solo una parte muy inferior de la formación da testimonio de una pequeña contribución del macizo Cantábrico. En el extremo occidental del área se puede observar una contribución litológica de las rocas Precámbricas allí presentes. La transición a los depósitos marinos aplacerados suprayacentes es muy gradual; una pequeña cantidad de depósitos lacustres probablemente ocurre en la parte superior de la formación. Aparte de esta, ningún sedimento transitorio a una región marina, así como depósitos costales, pudo observarse.

Los sedimentos fluviales pueden subdividirse en depósitos de ríos anóstomos y ríos con meandros, los primeros de grano más grueso que los segundos. Los depósitos de ríos anóstomos muestran características tal como paleocanales, cauces de eroción rellenos, ausencia de distinta clasificación, etc. Los depósitos de un río que meandra, muestran ciclos de clasificación con refinación hacia arriba, en la cual estratificación entrecruzada basiplana con fenómenos de circulación inversa ('backflow') es común. Investigaciones detalladas en partes bien expuestas del área, revelaron sub-regiones fluviales así como depósitos 'point bar', 'natural levee', 'crevasse-splay' y 'backswamp' (Allen, 1965a).

Hacia el lado costal del área de deposición (es decir la parte oriental del área estudiada), se encontraron depósitos de ríos con meandros. Presumiblemente representan sedimentos de una llanura costal en la cual estos ríos, portando principalmente sedimentos arenosos, corrían hacia el mar en el oriente. Al mismo tiempo, depósitos de ríos anóstomos de granulación gruesa se formaron más hacia el occidente en un antepaís montañoso. En su migración total hacia el occidente, este modelo ha cedido los sedimentos como se pueden observar hoy en día.

La Formación de Voznuevo se destaca claramente contra los depósitos Paleozoicos y post-Mesozoicos. Primero existe una ausencia completa de caliza, una predominancia de cuarzo sobre cuarcita y una abundancia de caolinita. En segundo lugar hay una composición de minerales pesados en cual minerales no resistentes a la desagregación química, tal como la hornblenda, epidota y augita, carecen completamente. Erosión de rocas frescas en el área de origen durante la última fase de sedimentación es reflejada por un aumento de aparición de minerales metamórficos así como la andalucita y la distena.

La abundancia de caolinita autígena, favorece la suposición que la meteorización tuvo lugar despues de la deposición. El alto porcentaje de caolinita, la ubicuidad de materiaorgánica, el aplanamiento y la redondez de los guijarros y la ausencia de trazas de lateritización indican meteorización bajo condiciones temperadas a calientes húmedas con lixiviación relativamente fuerte.

Los sedimentos de Voznuevo forman claramente un elemento extranjero en la historia de deposición de los sedimentos a lo largo del límite sur del macizo Cantábrico. Sedimentos del Tertiario y Cuaternario, ambos con área de origen en el macizo Cantábrico, han sido abastecido parcialmente por los sedimentos de Voznuevo. Mas hasta ahora ocurrencias enigmáticas, por ejemplo estaurolita y caolinita en depósitos Tertiarios, pueden explicarse tambien considerandoles como productos de erosión de la Formación de Voznuevo.

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Drawing of text figures and enclosures by Mr. M. L. Brittijn

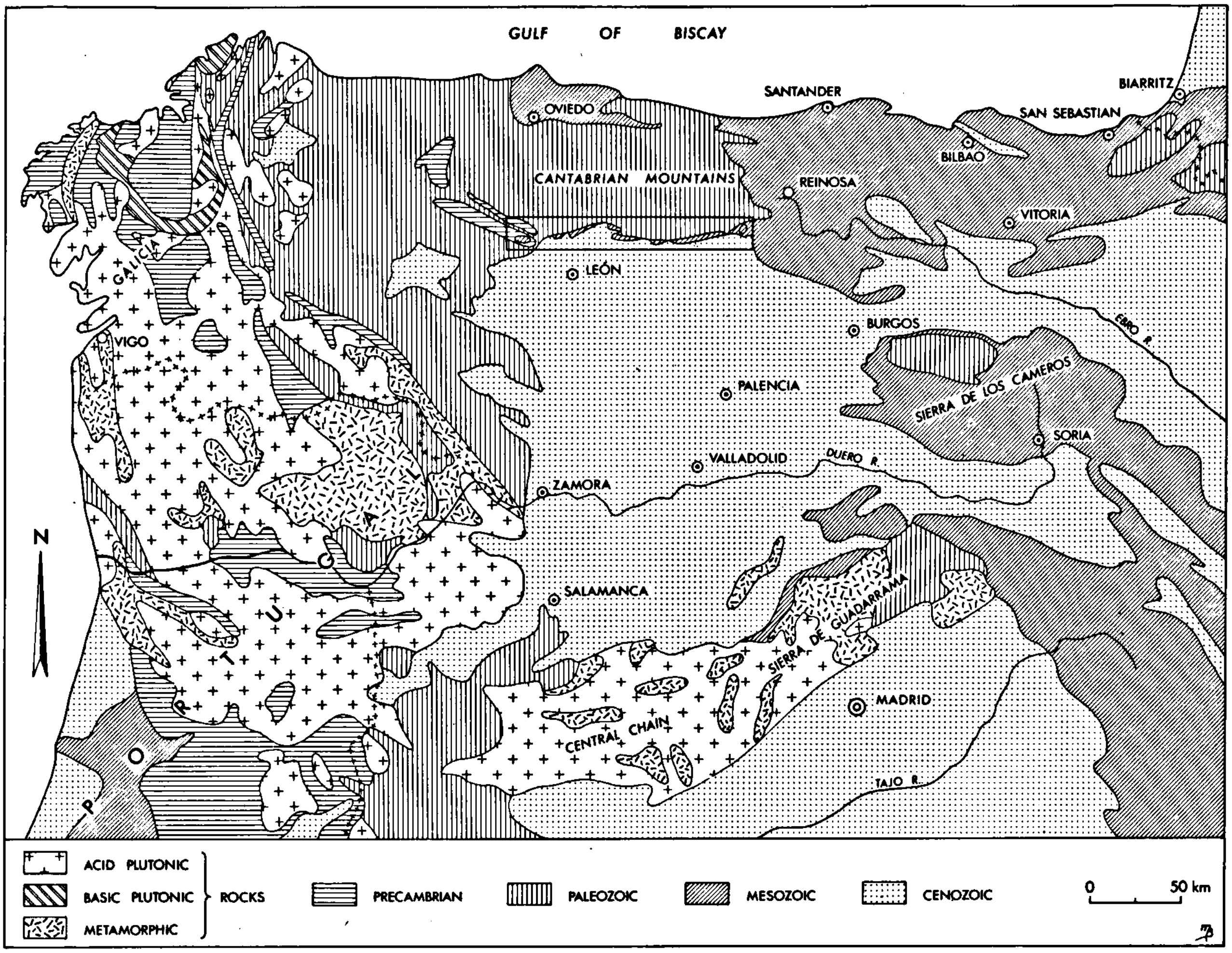

Fig. 1. Geological sketch map of NW Spain. Area studied within rectangle.

CHAPTER I

INTRODUCTION

GENERAL REMARKS

The Cretaceous of northern and central Spain contains continental, chiefly sandy deposits of considerable thickness, which have often been referred to, especially in older literature, as 'Wealden' or 'sediments in Wealden facies'. The sedimentology of these so-called Wealden beds occurring along the southern border of the Cantabrian Mountains is the subject of the present study.

Recently, Evers (1967) proposed the name Voznuevo* Formation for these deposits, which name will be used in the present work.

Since the southern border of the Cantabrian Mountains is structurally a steep flexure (locally passing into a fault), the Voznuevo deposits are exposed in a narrow S-dipping zone, over 130 km long and only a few kilometres wide (Fig. 1). The variations in area could therefore only be studied in an E–W direction.

The Voznuevo deposits directly overlie the Paleozoic (and locally the Precambrian) with an angular unconformity and are overlain by marine Cretaceous, followed – more to the south – by the continental Tertiary of the Duero Basin.

* Named after the village of Voznuevo, 2.5 km east of Boñar.

CHARACTERISTICS IN THE FIELD

In the field the deposits of the Voznuevo Formation show the following characteristics:

1. They have a white to yellow or buff colour, with occasional dark red and orange-red colours. The sediments are clearly lighter in colour than those of the Vegaquemada Formation (Evers, 1967; Kuyp, 1969) of

Lower Tertiary age in which orange colours predominate.
2. They show highly varying grain sizes, from gravel (rarely of cobble or boulder size) to clay.
3. There is an obvious absence of limestone pebbles and cobbles and limestone layers (another contrast to the Vegaquemada Formation).
4. In general the sediments are not – or only slightly – consolidated.

Natural exposures in the Voznuevo Formation are very rare and most information has been gathered in sand and clay pits. These pits, many of them now abandoned, are commonly situated beside villages. They are now used for dumping rubbish. Exposures other than in excavations can be found in brooklets, in river banks and in railway and road cuttings.

In contrast to the mountainous area to the north, summers are very dry near the meseta border. Very intensive precipitation takes place in spring and autumn; in May and June many excavations are inaccessible on account of the water accumulated in them. In summer occasional rain showers can obliterate in a matter of minutes the sedimentary structures which were minutely carved by sun and wind. This is one of the reasons why the degree of exposure in the Voznuevo Formation can vary from day to day. Even more far-reaching changes could be observed from year to year in recently excavated pits. Collapse of the pit walls, and rain wash and solifluction along them, followed by vegetation, completely obscure stratification and structures in the sediments and make their study impossible.

Vegetation along the southern border is in general very scanty, neither of the Mesozoic or Tertiary formations is very fertile and agriculture is almost exclusively restricted to the lowest parts of the valley. In many locations examples of badland erosion could be observed.

A weathering phenomenon which can be observed on the surface of the sediments is the discolouration of generally white or yellowish coloured sediments into purple to red coloured ones. This process must be ascribed to surface waters rich in iron, running downslope. The very superficial cementation of the sediment was probably also caused in this manner. Other discolourations, especially in sediments of silt-size, occur as purple mottles with a diameter of up to several decimetres. Although their appearance reminds one of a paleosol, they proved to have formed recently.

SCOPE OF THE PRESENT STUDY

Until recent years the sediments of the Voznuevo Formation have been little known. The only information given concerns the high content of kaolinite (the main reason for the white colour) and the megascopical monotony of the components. The circumstances in which, and the mechanism by which, the sediments were deposited have been the subject of various speculations. Many uncertainties also surround the question where the Voznuevo Formation has to be located stratigraphically in the Cretaceous. The only reliable information was given by van Amerom (1965) who, by means of pollen analyses, determined a Cenomanian to Turonian age for the formation near Boñar. It will be the subject of this study to contribute to the solution of various questions surrounding the Voznuevo Formation, the following of which are the most important:

a. What is the textural and mineralogical composition of the sediments, both megascopically and microscopically?
b. By which agent and in which sedimentary environment has the deposition taken place?
c. Can a direction of supply be reconstructed?
d. What is the possible source area of the sediments?
e. Are there any differences in the characteristics of the sediment from east to west or from bottom to top?
f. Of what nature are the stratigraphical relationships of the formation within the area studied and what is its stratigraphical position as compared with other deposits in a similar facies reported from other parts of Spain?
g. How much have the sediments been influenced by the underlying Paleozoic rocks?
h. What is the transition to the overlying deposits like, and to what extent has infiltration from these deposits taken place?

APPROACH OF THE STUDY

The description of the sediments of the Voznuevo Formation consists of four main parts.

First (Chapters II and IV) a survey is given of the investigations by previous authors in the present area as far as mapping, descriptional and stratigraphical work are concerned. The occurrences of similar deposits in other parts of Spain, especially those in the provinces of Santander, Burgos and Vizcaya and in the Sierra de los Cameros between Burgos and Soria, will be compared with the present sediments. New data on the age of the formation found by means of pollen analyses will be of great help in determining the stratigraphical position of the formation within the Cretaceous and will contribute to a better understanding of the paleogeographical development along the southern border zone.

The second part (Chapters III and V, also VI) contains the description of observations in the field with their conclusions. This part forms the core of the sedimentological approach of this investigation.

The third part (Chapters VII, VIII and to a lesser extent IX) deals with the petrological description and the interpretation of samples which have been submitted to special treatments.

Finally, as a general conclusion, a synthesis of new facts contributing to a better understanding of these so far enigmatic deposits is presented in Chapter X.

METHODS AND TECHNIQUES USED

Investigations in the field

The areal extension of the Voznuevo Formation can in fact only be mapped by delimiting the more resistant and better exposed rocks which limit the formation at its bottom and its top.

Of 34 sections of varying reliability and length, the best 24 sections have been selected to represent the Voznuevo Formation (Enclosures II to VIII). The sections have been logged by means of the conventional techniques.

As to sampling we have aimed at obtaining representative samples; no statistical methods were used. Since an introductory study by the present author had shown that the composition of the sediments does not show large differences over short horizontal or vertical distances, spacing of the samples has been adapted accordingly.

Paleocurrent directions have mainly been obtained from the positions of foreset plains in cross-stratified units and to a lesser extent from observations on imbrication and in channels. Since paleocurrent analyses can only be achieved in very well exposed, mainly recently excavated, pits, cross-stratified units were measured wherever possible. The slightly consolidated condition of the sediments makes it possible to cut intersecting planes in which the orientation of the foreset plane can exactly be determined.

Other determinations which had to be carried out in the field are those with regard to the composition of the pebble-sized sediments and to the geometrical properties of the pebbles.

Laboratory examination of the samples

About 75 samples, among which a certain percentage of Paleozoic age, proved to be sufficiently well cemented for preparing thin sections. A few voluminous samples with structures of macroscopical size could be studied after mounting them in plastic. Less well cemented samples of fine gravel-, silt- and clay-size were treated in the sedimentological laboratory of the University of Leiden for studying the grain-size distribution, the heavy- and light-mineral content of the sands and the composition of the clays. For the computation of grain-size distribution use was made of a PL/1 computer programme composed by Koldijk (1968b). The study of heavy and light minerals was carried out by means of the polarizing microscope with traversing light and by means of the binocular with reflected light, respectively. In both cases the percentages obtained were the result of line counts. The fractions from 37 to 2 microns and smaller than 2 microns were subjected to X-ray analysis; they were studied in diffractograms.

The following classifications were applied. For the description of grain size the Udden grade scale (Udden, 1914) with the Wentworth modifications of size limits (Wentworth, 1922) was used (see also Pettijohn, 1957). Morphometrical analysis of pebbles and cobbles was carried out according to Cailleux's method (summarized in 1959). Bed thickness was described according to McKee and Weir's nomenclature (1953). The classification and terminology of cross-stratified units largely follows that proposed by McKee and Weir (1953), but wherever possible use was made of the classification by Allen (Allen, 1963a). Grain-size distribution was calculated according to Friedman's moment measures (Friedman, 1962).

The sediments in the present area will be dealt with systematically from west to east, except in some instances. The area is arbitrarily subdivided into a western, a central and an eastern part, separated by the Río Bernesga and the Río Esla, respectively.

ECONOMIC USE OF THE SEDIMENTS

The Voznuevo deposits have been dug for many purposes. The sands have been, and are still, used for the manufacture of tiles and bricks; the clays – especially the black coloured clays – are used for the same purpose and for the manufacture of ceramics and pottery. Small brick works are found adjacent to the excavations. Most of the factories are now abandoned and reorganization led to concentration into a small number of large factories. The sand pit south of the village of Grandoso is the only excavation with a production of several dozens of tons a day in the area studied. The sand pits near Sorribos de Alba, Llanos de Alba, those 1.5 km E of Boñar and those N of La Ercina are only of local importance. Large excavations of black clay can be found 2 km E of Boñar, NE of Valmartino and S of Cervera de Pisuerga, along the road to Herrera del Pisuerga.

The fine-grained sands and silts are used as abrasives for household purposes but their economic importance can be neglected.

It should finally be mentioned that the cobble conglomerates which occur west of La Magdalena are used as materials for roads and especially for railway tracks.

REMARKS ON THE RELIEF

The drainage pattern

The main rivers which drain the area belong to the northern part of the Duero drainage basin. They all come from the Cantabrian Mountains and follow a N–S directed course; they cross the Voznuevo Formation more or less perpendicular to the strike. All these rivers have cut deep valleys into the Paleozoic rocks of the Cantabrian Mountains.

In the depression coinciding with the Voznuevo Formation, situated between the mountain range and the ridges of Cretaceous limestones, no rivers of any importance are encountered; it is drained by small subsequent brooklets – parallel to the mountain border – which run dry in summer.

The relief clearly reflects the geological structure as expressed in differences in resistance to weathering of the various rock units. From the massif to the south one finds, in order of decreasing age:

a. The Voznuevo Formation (Cretaceous).
b. A Mesozoic limestone complex, gradually decreasing in thickness and wedging out in a westerly direction (Cretaceous).
c. The Vegaquemada Formation (Paleogene) (Evers, 1967).
d. The Candanedo Formation (Paleogene) (Evers, 1967).
e. The red beds, beginning with the Vega de Riacos Formation (Neogene) (Evers, 1967).

Units a, c and e are only slightly cemented and weather easily. Especially the sediments of the Voznuevo Formation form depressions in topography. The Mesozoic limestones and the coarse conglomerates of the Candanedo Formation are much more resistant; their generally south-dipping strata provide clear examples of cuestas. The dip-slope of the Candanedo Formation gradually passes into the Spanish central table-land, the 'meseta'. In the eastern part of the area the transition from the Cantabrian Mountains to the central plateau is more gradual. There, the Mesozoic limestones are the only rocks which stand out in topography.

In several locations the Tertiary sediments are in direct contact with the Paleozoic rocks and prevent outcropping of Cretaceous sediments; there, erosion was less intensive so that topographically higher parts can be found.

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CHAPTER II

MAPPING OF THE AREA STUDIED

Most investigators, who had the Cretaceous sediments under consideration as part of the area studied by them, have dealt with them in a stepmotherly fashion. The reason for this is that the emphasis of their studies has always been laid on the Cantabrian Mountains themselves. The result is that mapping of the post-Paleozoic rocks has usually been carried out in a hasty manner. For Ciry (1939), the only one who concentrated on Cretaceous deposits, the present area only forms a western offshoot, besides, the part W of the Rio Curueño was beyond the scope of his study.

An excellent map of the part between the Río Bernesga and the Río Cea was prepared by Almela (1949), scale 1:50,000; the easternmost part of the area studied, south of Cervera de Pisuerga, was mapped on the same scale by Ciry.

More recent work was carried out by investigators working on the mapping programme of the Department of Structural Geology of the University of Leiden in the southern and central part of the Cantabrian Mountains. The following maps, each on a 1:50,000 scale and enumerated from W to E, were found useful:

1. Sheet Luna-Sil (van den Bosch, 1969).
2. Sheet Luna-Bernesga-Torío (van Staalduinen, 1967).
3. Sheet Bernesga-Torío-Curueño-Porma (Evers, 1967).
4. Sheet Cea-Esla-Porma (Helmig and Rupke, 1965).
5. The geological maps belonging to the theses by Koopmans (1962) and Kanis (1956) for the area between Guardo and Cervera de Pisuerga.

Apart from these, use was made of two sheets belonging to the Mapa Geológico de España.

As the preparation of a geological map is decidedly not the object of the present study, the general map (Enclosure I) is presented on a 1:100,000 scale. Differences with respect to the conceptions of previous workers will be discussed below.

COMPARISON WITH MAPPING BY PREVIOUS AUTHORS

The westernmost part of the area studied is situated in the south-eastern corner of the area investigated by van den Bosch. Strangely enough the sediments outcropping between Riello and Bobia were not recognized by him as being of Cretaceous age, but were thought to belong to the Vega de Riacos Formation (Miocene). This name was given to the red beds in the Duero basin by Mabesoone (1959). Van den Bosch provisionally included the sediments in the Riello area in the Vega de Riacos Formation since (p. 183): 'The outcrops ... closely resemble the Miocene deposits further to the south .... They also resemble the Upper Cretaceous Voznuevo Formation ... , but their flat-lying position on the ESE dipping peneplain or pediplain, similar to that of most of the Miocene deposits further to the south, suggests these deposits to be of a Miocene age.' It is abundantly clear that van den Bosch only considered these deposits to belong to the Tertiary on purely structural grounds. From the direction of cross-bedding and channels and from the terrestrial properties of the sediment a mechanism of deposition by a fast running river with a transport direction from WNW to ESE was proposed. The sediments between Riello and Bobia are supposed to have been deposited in a basin (Riello basin) and to consist of an asymmetric former river valley. The total thickness of the sediments in this basin is supposed to comprise 200 m. Southwest of Oterico, coarse quartzite cobbles mark the base of the formation, whilst 'the uppermost deposits contain rather coarse pebbles deposited in channels'.

Before discussing van den Bosch's findings we shall first consider the geological map, scale 1:50,000, issued by the Instituto Geológico y Minero de España, Sheet 128, Riello, prepared and commented upon by Pastor Gómez (1969). From the legend of this map we may conclude that Pastor Gómez attributes a Mesozoic age to the kaolinitic sands of the Riello area. In order to shed some light upon these contradictory statements, the western border of the area studied by us was drawn near Riello.

Apart from the lithological properties, both macroscopical and microscopical, and the sedimentological features of these deposits, which clearly show that they belong to the Voznuevo Formation further to the east, a cast-iron proof could be found in the field. It showed that a plain division could be made into two different formations with an east-west directed boundary, splitting the area into a northern and a southern strip. Only the northern part shows the properties characteristic of the sediments of the Voznuevo Formation. In the southern strip sands and gravels were found with the typical dark red to orange-red colours belonging to the Vegaquemada Formation, as described by Kuyp (1969) between the Río Bernesga and the Río Esla. The Mesozoic limestones, which separate the Voznuevo Formation from the Vegaquemada Formation further to the west, wedge out between Llanos de Alba and Carrocera, as is proved in an exposure SE of Carrocera (Chapter III). The sediments in the southern part of the Riello area should not only be classed among the Vegaquemada deposits on account of the colour, but also on account of the high content of quartzite pebbles and the presence of limestone pebbles. Pastor Gómez's conception of the age therefore only proves correct for the northern strip.

Since we are dealing with two gently south-dipping formations, we may not speak of a 'Riello basin'. Besides, it appears that the quartzite-cobble conglomerate SW of Oterico is not situated at the basal part of the formation but at the very top, whilst the coarse pebbles 'deposited in channels in the top of the basin' in fact lie in the upper part of the Voznuevo Formation! Apart from this, it was deduced from a section near Bobia, that the Voznuevo Formation alone has a thickness of more than 300 m.

Regarding the geological map, it should be mentioned that the Voznuevo Formation proved to be present as far as west of Riello.

Some objections have also to be made to the distribution of the Voznuevo Formation as mapped by van Staalduinen (1967):

1. The formation is mappable just N of the road from Otero de las Dueñas to La Robla between km 2.5 and 3.5 and does not form small 'islands' near the contact with the Paleozoic E of Santiago de las Valles. This triangle-shaped area is a continuation of the narrow strip which runs from Llanos de Alba to Olleros de Alba, separated by a topographically higher part, in which the overlying Vegaquemada Formation has not been eroded and is in direct contact with the Paleozoic (at the pass in the road). The contact between the Voznuevo Formation and the Vegaquemada Formation will be described separately in Chapter III.
2. About 400 m W of Olleros de Alba, the formation dips under the contact Paleozoic-Vegaquemada Formation and not about 1 km W of this village as proposed by van Staalduinen.
3. At the lower contact of the formation N of Sorribos de Alba, the Voznuevo deposits are clearly overturned and not S-dipping.
4. No Cretaceous was found N of the village of Rabanal de Fenar; the contact must be drawn through the village.
5. Mesozoic limestones were found along the path S of Robledo de Fenar, some tens of metres N of the railway; for this reason the boundary of the formation is shifted slightly to the N at this location.

To Almela's map, which covers only a very small part of van Staalduinen's area, only the last mentioned objection can be made.

Sheet 129, La Robla, issued by the Instituto Geológico y Minero de España, with description by Pastor Gómez (1963), suffers from the same imperfections as listed above with the exception of the structure N of Rabanal de Fenar. A conception in which these Spanish investigators differ is the traceability of the Voznuevo Formation between La Robla and Brugos de Fenar. We tend to believe that Almela's (and van Staalduinen's) proposition is much more likely.

East of the road from Otero de las Dueñas to León, near km 27 and opposite the path to Benllera, a small outcrop of Voznuevo sands and Vegaquemada sands was found between Precambrian schists and post-Mesozoic sediments. At the western side of the road, some 500 m W of km 25, the same situation is encountered. This exposure runs in the direction of Tapia de la Ribera (both outcrops are represented on the general map, Enclosure I). Both exposures are not recognized as Cretaceous with overlying Eocene on the map prepared by Pastor Gómez; he quotes Almela (1951) on page 48 of the explanation accompanying the map: 'En las inmediaciones de Tapia de la Ribera, la base de este terreno (the Miocene is meant, remark by the present author), que se apoya sobre el Precambriano, consiste en unas arcillas blancas y rosadas, muy micáferas, arenas arcillosas y arenas con gravilla. Sobre ellas van unas arenas arcillosas, de color salmón, con cantos bien rodados de tamaños muy variables, que llegan hasta lo mas alto del páramo'. Both Almela and Pastor Gómez attribute a Miocene age to these deposits. The resemblance in the field and the mineralogical composition (especially the heavy-mineral content) leave no doubt, however, that the sediments of these exposures belong to the Voznuevo Formation (white and pink sands and clays), overlain by sediments which apparently belong to the Vegaquemada Formation (salmon coloured clayey sands etc.).

Other isolated outcrops indicated as Cretaceous on both maps proved to consist of weathered Paleozoic rocks.

Some corrections of the map presented by Almela were made by Evers (1967) between the Río Torío and the Río Porma. Unfortunately these corrections proved to be wrong. They refer to the mention of 'Voznuevo islands' north of the thrust or fault-line between Valdepiélago and Boñar. Closer inspection showed that we are again dealing with weathering products of Paleozoic rocks. Besides, they are hardly explainable N of the flexure zone. Evers' alluvial fan conglomerate WNW of the village of Boñar, consisting of 'rounded limestone and sandstone cobbles', is also highly enigmatic. On his geological map a limestone conglomerate is drawn at this location but not a single limestone fragment could be encountered, either in the field or in thin sections of samples taken from this conglomerate; apparently a soil rich in limestone pebbles was the reason of this confusion. Finally we do not agree with the indication 'fossil-fauna' in the southernmost anticline 1 km S of La Mata de la Riba, on the right bank of the Río Porma. It became evident that in this location a huge block of several cubic metres dislodged itself from the overlying Mesozoic limestones, and is now situated in the core of the anticline.

A geological map of the Río Porma area was prepared by Helmig and Rupke (1965). According to this map, the sediments in the area between Boñar and Colle are cut out by a fault belonging to the Sabero–Gordon fault zone (Rupke, 1965, N–S sections 1–4). The area between the Sabero–Gordon fault zone and the southern border fault is the westward extension of the so-called Peña Corada Unit. The Cretaceous and the overlying pre-Miocene deposits have been draped anticlinally over the Peña Corada Unit.

Since the two S-dipping flanks have been preserved, a second strip of Voznuevo sediments is present, running continuously from the Río Porma to the Río Esla.

Minor corrections with regard to this map refer to the boundary with the Paleozoic near Oceja de Valdellorma, which runs through the village and not south of it and the boundary with the Mesozoic limestones E of Cistierna which runs mainly on the NE side of the road between Cistierna and Valmartino. It was finally found that the Voznuevo deposits already disappear midway between Quintana de la Peña and Valmartino.

The part of the area studied which is situated in the province of Palencia was mapped by Koopmans (1962). His ideas on the geographical distribution of the Voznuevo Formation cover those of the present author.

The formation is traceable to the east as far as Traspeña. Between Traspeña and Dehesa de Montejo no outcrops showing Voznuevo sediments were found. The Cretaceous between Villanueva de la Peña and Cubillo de Castrejón which Kanis (1956) believes to represent Wealden (= Voznuevo Formation) were not recognized as such in the present investigation. For the easternmost part of the area, SW of Vado de Cervera, Kanis made use of the previously published geological map of the Ligüerzana area (Ciry, 1939, Planche A). As a result of new exposures thanks to clay exploitation in this area, we propose to shift the western limit south of the railway some 100 m to the west.

CHAPTER III

STRUCTURE AND CONTACTS

STRUCTURE IN GENERAL

General remarks

Apparently Termier (1918) was the first to detect north-dipping strata of Cretaceous age below the Paleozoic along the southern border of the Cantabrian Mountains. Ciry (1928) remarked that the Paleozoic massif has compressed the Cretaceous deposits into a syncline which is opened to the south. West of the village of Aviñante this syncline was said to be visible in its entirety. Some years later, Ciry (1933c) returned to this subject and stated that: 'Le massif paléozoïque Asturien apparaît donc comme un pli de fond qui s'ennoie périclinalement vers l'Est en même temps qu'il montre une tendence générale de déversement vers le Sud'. Finally this author (Ciry, 1939) noted that the Voznuevo Formation and the Mesozoic limestones have formed the normal cover of the Asturian massif which has locally been pushed into an overturned position in a southward direction.

The structures of the southern border are dealt with in three parts: a. Between Cervera de Pisuerga and Guardo, b. between Guardo and Cistierna and c. between Cistierna and Valdepiélago.

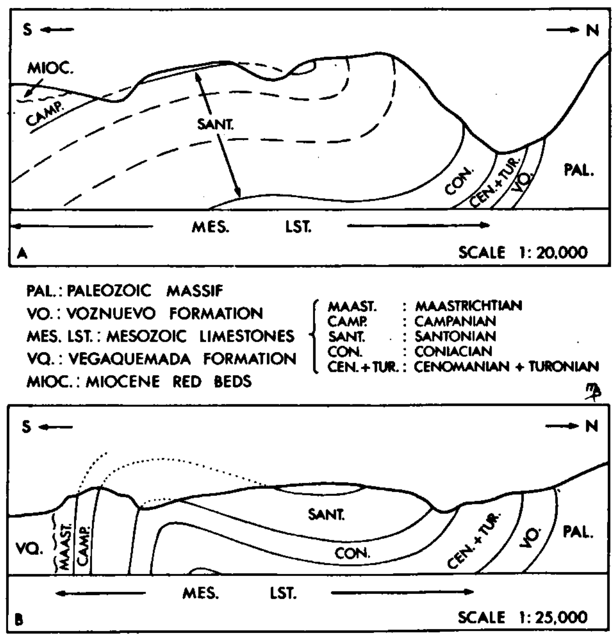


Fig. 2. A: Schematical section near Aviñante (modified after Ciry, 1939), showing asymmetrical syncline, open towards the south.
B: Schematical section along the Río de las Cuevas (modified after Ciry, 1939), showing asymmetrical syncline followed to the south by an asymmetrical anticline.

a. Along the border of part 'a' two sections were presented which are reproduced in a simplified form in Figs. 2A and 2B. The first figure shows a section near Aviñante, in which the asymmetrical syncline, opened to the south, shows an overturned northern flank and a nearly horizontal southern flank. In Fig. 2B a section 2 km W of Villanueva de la Peña is shown in which a more extensive deformation can be distinguished; the syncline is followed to the south by an equally asymmetrical anticline.

b. Part 'b' is a fragmentarily exposed area in which only the overturned position of the Cretaceous sediments can be observed.

c. From Cistierna to the W the influence of the pressure of the Paleozoic massif to the south seems gradually to decrease. The San Adrian anticline, which causes the duplication of exposed Cretaceous sediments, is, according to Ciry, a consequence of an oppositely directed tectonic force to the south. This supposition which would call for explanation by a very local process, will be discussed below. The supposed exposures on the northern flank of the San Adrian anticline are somewhat questionable.

West of the Río Porma, Ciry reported a structural situation comparable to that found between Guardo and Cistierna, with clearly overturned Cretaceous deposits.

Observations by Almela (1949) for the most part cover those by Ciry, although Almela's interest is mainly directed at the Mesozoic limestones. His finding that there has never been any indication of faulting between the Paleozoic and the Cretaceous is important.

In the area W of La Robla, Almela (1951) noted that the influence of pressure of the Paleozoic massif decreases W of Carrocera. The sediments of the Voznuevo Formation, which outcrop below the Miocene cover (red beds) near Tapia de la Ribera, were also supposed to be of Miocene age, which obliged Almela to assume intramiocene tectonic movements, since the red beds are known to show a very flat dip to the S (generally less than 5°), while the dips recorded at this location are 15° to the S (30° to 45° SE according to our measurements). Since these deposits proved to be of Cretaceous age, the intramiocene movements of Almela must be abandoned.

With respect to the contact between the Paleozoic and the Voznuevo Formation Pastor Gómez (1963), who likewise failed to notice a fault between them, proposed the existence of a deeper situated E–W directed fault, or a system of parallel faults. One of these faults was held responsible for the disappearance of the Mesozoic limestones between Candanedo de Fenar and Rabanal de Fenar.

A glance at van Staalduinen's map shows that the contact mentioned above is interpreted as an unconformity with a probable fault. The supposed fault between the Voznuevo Formation and the Mesozoic limestones is not shown on that map; both units dip below the Paleozoic-Vegaquemada Formation contact W of Brugos de Fenar.

Most information on the structural relationships between the Paleozoic core and the sediments on its southern border was given by Evers (1967). From his map with structural sections we learn that the structures S of Boñar (the San Adrian anticline, accompanied to the south by the Las Bodas syncline) need not be explained by compression from the south as previously proposed by Ciry (1939): they were probably formed by reactivation of the Sabero Fault zone and the Valdepiélago fault to the north and by an extension of the fold-thrust near Cistierna (Rupke, 1965, Fig. 32). Viewed in this light, the rocks of Cretaceous age near Boñar have simply been draped anticlinally over an extension of the Peña Corada Unit; the structure originated as a result of mainly vertical movements. Rupke's Fig. 32, a N–S section W of Cistierna, however, in which the Paleozoic to the Miocene is shown, is slightly misleading since the low-angle unconformity between the Paleozoic and the Cretaceous occurring in this section is certainly not representative of other contacts in the area. The absence of Mesozoic limestones in this section can hardly be explained by the unconformity between the Voznuevo Formation and the Tertiary conglomerates, since only a fraction of the total thickness of the Voznuevo Formation proved to be present in this location. Apart from this, indications of very strong compression could be found, so that one or more faults instead of an unconformity are, in our opinion, much more likely.

East of Guardo, the zone in which fault movements or flexuring took place is apparently situated further to the north than the zone of Cretaceous outcrops (Koopmans, 1962; Kanis, 1956). The Cretaceous sediments are reported to overlie the Carboniferous strata with a small angular unconformity in the area studied by Koopmans, whilst the angular unconformity still further east, along the road from Cervera de Pisuerga to Vado de Cervera (the base of the present section T), shows an angle of more than 30° (cf. Kanis, 1956, Fig. 14).

Strike-dip measurements in the Voznuevo Formation

As a consequence of a fold-thrust uplift (Berg, 1962; Evers, 1967), which will be explained below, the sediments of Cretaceous and Paleogene age have been affected by the upthrusting Paleozoic massif in such a manner that they were dragged into a vertical or overturned position. The deposits of the Voznuevo Formation, which represent the first sediments after those of the Stephanian in this area, have suffered most, due to their position close to the tectonically active region. The influence of this mountain flexuring on the Voznuevo Formation has, however, not been the same along the entire southern border. Table I, which gives a listing of some strike/dip values of the stratification planes from W to E, clearly shows the differences. Measurements have always been carried out in the finest-grained material present, generally in clays, in order to avoid misreadings in sediments which could have been deposited on an inclined surface.

In the western part of the area, W of the Río Bernesga, a clear uniformity is recognizable in the isolated area between Riello and Bobia. The formation dips to the S with a gentle slope between 26° and 36°, except for Section C 2 where a slightly steeper position could be observed. Apparently this area has not been influenced very much by the fold-thrust, which is not surprising since the sediments are bounded, also on their southern flank, by a Precambrian block.

Between Carrocera and La Vecilla the Voznuevo Formation has been influenced very strongly by the southward pushing Paleozoic massif: the strata dip more than 80° to the south (SSE), except at Solana de Fenar. At three locations (Carrocera, Sorribos de Alba and Brugos de Fenar) a clearly overturned position was observed. Between Boñar and Colle a very constant dip occurs of 22° to 27° to the SW. As for the southern strip, it could be observed that the Voznuevo Formation

Section A :	180/36	173/32	175/26	
Section B :	178/26	178/33		
Section C1 :	175/35			
Section C2 :	175/50			
Section C3 :	175/36			
Carrocera :	10/65	178/80		
Section D :	174/83			
Section E :	345/70	347/85		
Section F :	0/65			
Section G :	160/87			
Section H :	154/55			
Section I :	155/81			
E of Boñar :	207/22	220/26		
La Devesa :	185/45			
S of Oceja :	175/80			
Section O :	20/60			
Section P :	45° overturned			
Cistierna :	50/40	35/60		
Prado :	55/90?			
Cerezal :	80°-90° overturned			
W of Guardo:	315/80?			
E of Guardo:	20/75			
Muñeca :	355/26!			
Section Q :	355/75			
Section R :	307/42			
Aviñante :	346/80	0/70		
Section S :	350/55			
Villaverde :	355/85			
Section T :	116/39	125/30	115/30	35/45 ...
	... 65/21	100/30	130/30	

When more than one reading is given, the first is situated most to the north (i.e. contact with the Paleozoic)

Table I. Direction of dip and angle of dip of the stratification plane from W to E (top to bottom) and N to S (left to right).

again turns into a more and more overturned position in the direction of Cistierna. From here on to Villaverde de la Peña the steep, overturned northward dip remains, with excessive overturns near Muñeca and Santibañez de la Peña (dips less than 45° N). Near Cervera de Pisuerga the influence of the fold-thrust uplift has obviously decreased; a situation is found comparable to that E of Boñar.

Faults and folds within the formation and their consequences

Tectonic disturbances within the sediment, especially faults, can only be observed with great difficulty, on account of the unconsolidated state of the deposits. In Section F near Brugos de Fenar, some normal faults could be observed with a stratigraphic throw of one or two metres. Larger faults of unknown dimensions were seen in Sections P (Cistierna) and R (Santibañez de la Peña), both causing a sudden change in dip. For the rest most fault movements have taken place along planes parallel to the plane of stratification. This was deduced from the presence of slickensides which proved to be rather frequent in the section near Cistierna and in all sections E of Guardo, including Section T. It appears that the formation of faults within the Voznuevo Formation has only taken place in locations where the Cretaceous has been dragged into an overturned position.

A much more drastic result of the pressure to which the Voznuevo Formation has been exposed is the intensive pulverization of the sediments in places where compression must have been very strong. This was above all encountered in Section O and Section P (Yugueros and Cistierna, respectively), and could frequently be observed east of Cistierna. In such locations it proved hardly possible (or even impossible) to obtain unbroken pebble specimens from the sediment. The tectonic influence is not only limited to mega-components, but proved present in the thin sections as well (Chapter VII).

Near Solana de Fenar it was noticed that the formation turns into a flatter S-dipping position towards the top of Section H, (within 50 m). The Mesozoic limestones which constitute the southern limit have a much steeper position than the strata in Section H, so that a structure may be assumed comparable to the one described by Ciry (1939) near Aviñante (Fig. 2A). Such a structure would easily explain the apparent thickness of the Voznuevo Formation in this location on the geological map.

In Section T near Vado de Cervera a syncline was found, flanked to the south by an anticline. Both structures have an E-plunging fold axis. Their consequence for the thickness of the formation will be dealt with in Chapter V.

The thickness of the Voznuevo Formation

Thicknesses reported by previous authors vary considerably. Ciry (1939) remarked that the thickness is variable, but generally exceeds 100 m. Almela (1949) mentioned a thickness of 125 m in his description of the Cretaceous but the sections accompanying his work show an average thickness of 250 m, with an excessive value near Solana de Fenar: 1000 m. As we have stated previously, folding within the formation probably plays an important part in the area between Naredo de Fenar and Rabanal de Fenar. Two exploratory drill-holes (Zaloña and Sampelayo, 1943; Almela, 1949) near La Mata de la Riba and Las Bodas, carried out in search of the continuation of the Carboniferous strata below the Mesozoic and Tertiary cover, not only gave negative results as to their original purpose: according to Zaloña and Sampelayo, 352 m of Cretaceous sand have been penetrated near La Mata. Below this depth Paleozoic rocks were hit. According to Almela, the greater part of these sands belongs to what is now called the Vegaquemada Formation while only the last 87 m are supposed to be Cretaceous. It has been assumed that a fault-zone was penetrated, since the Mesozoic limestones, which were to be expected in a complete section, did not show up. Unfortunately drilling near Las Bodas was not continued as far as the Paleozoic and was stopped in sediments of the Voznuevo Formation. For this reason only a minimum value can be given: 208 m.

Koopmans (1962) did not give an explicit thickness, but it may be deduced from his sections that a thickness of 200–350 m was assumed.

Rupke (1965) proposed a thickness of 70–350 m, while Helmig (1965) assumed a thickness of 600 m between Boñar and Colle and a 'normal' thickness of 250 m.

Evers (1967) reported values fluctuating between 150 and 550 m.

The thickness of the sediments near Riello was estimated to be approximately 200 m (van den Bosch, 1969) but the proposed sedimentary explanation (i. e. a river valley), proved to be wrong (cf. Chapter II).

Incomplete outcropping as a result of which a continuous section is nowhere present causes that thicknesses can only be measured with some reserve. Most valuable are those measurements which were carried out in locations where tectonic activity has been fairly weak. Notwithstanding these impediments, thicknesses could be measured accurately in various locations, giving surprisingly constant results. A maximum thickness of the Voznuevo Formation is found W of La Robla, where values exceeding 350 m – with a maximum of 380 m near Llanos de Alba – were encountered. There appears to be a gradual decrease in thickness towards the east, to approximately 250 m between Aviñante and Villaverde (Section S) and S of Cervera de Pisuerga (Section T). This trend is clearly visible in the correlation chart (Encl. XI). It should be mentioned that the 250 m reported near Cervera is a minimum value since a hiatus of unknown extent is present due to folding, but we certainly do not share the view of other workers (i. e. van de Graaff-Trouwborst, 1970) who estimated a thickness of more than 600 m.

The fold-thrust

The relationship between the Paleozoic massif and the post-Paleozoic (i. e. post-Jurassic) deposits, as found at the southern border of the Cantabrian Mountains, has been compared by Evers (1967) with the situation in the Rocky Mountain foreland as described by Berg (1962). There, the border structures are thought to have originated from a combination of folding and thrusting; a process which has been referred to as 'fold-thrust uplift'. According to Berg, a fold-thrust uplift can explain a strongly overturned sequence beneath a fault plane, whereas uplift by thrusting alone cannot. Fig. 3 shows a hypothesis of such a fold-thrust uplift as proposed by Berg. In the Rocky Mountains several fault planes may occur, the most predominant ones, however, are those between the Precambrian and the Paleozoic rocks and between the Paleozoic and the post-Paleozoic sediments. Berg's observation that: 'The inverted section may be relatively undisturbed, somewhat folded and faulted, or highly deformed and jumbled' is important for the situation in the present area.

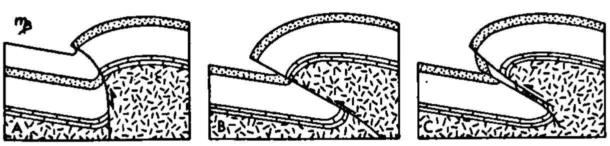


Fig. 3. Diagram illustrating mountain flank deformation according to Berg (1962). A: Block uplift; B: Thrust uplift; C: Fold thrust uplift.

Geophysical examination of the southern border fault zone

New light was shed upon the structures near the contact of the Paleozoic with younger sediments by means of a gravity survey, carried out by the Geophysical Department of the University of Leiden in the years 1964 and 1965. This survey covered the area between the Río Luna and the Río Cea. The results of this investigation, presented in unpublished reports, were summarized and reinterpreted by de Bruyn and Evers (in prep.). As mentioned in Chapter I, the Mesozoic and Paleogene sediments along the southern border in fact constitute the transition from the Paleozoic core, which forms the Cantabrian Mountains, to the Tertiary basin in the south. This transition has been the main object of interest for the geophysicists. Gravity measurements were carried out along the valleys of the main rivers (from W to E: Río Bernesga, Río Torío, Río Curueño, Río Porma and Río Esla), and the gravity profiles consequently show a N–S orientation. In this manner, the structures of the border zone are intersected at a favourable angle. The interpreted gravity curves which were constructed from a steep gradient in gravity contours show that strong gravity changes are present at the transition from Paleozoic to younger rocks. The hypothetical plane which separates rocks with different densities is expected to have the following orientation:

Bernesga valley	: 35° N-dipping (overturned)
Torío valley	: 60° N-dipping (overturned)
Curueño valley	: 75° N-dipping (overturned)
Porma valley	: 40° S-dipping
Esla valley	: 20° N-dipping (overturned)

Considering the Porma valley as a relatively stable centre, a torsion of the contact plane in a western and eastern direction is noticeable; towards the west the overturn gradually increases.

Taking two different values for the density contrast between the Paleozoic and the younger rocks a throw along a probable fault line of 1.75 or 2.1 km, respectively, was reconstructed. For further information on the reconstruction of the southward extension of the Tertiary basin the reader is referred to the abovementioned publication.

The age of the deformation

Investigations by Evers (1967) and Helmig (1965) proved that the Stephanian strata, being the last deposits in this area before the deposition of the Cretaceous, has been considerably folded before being covered. The Paleozoic massif must have been in an advanced state of peneplanization when Cretaceous sedimentation took place. In this respect it is very questionable whether the whole massif was covered at all; it seems much more logical to assume that only a part of the southern border ever received post-Paleozoic sediments. The uplift of the Paleozoic massif probably began after the deposition of the Mesozoic limestones, at the beginning of the Paleogene. It presumably lasted until the end of the Paleogene or the beginning of the Miocene. The maximum influence of the uplift was probably reached towards the later part of the Paleogene when very coarse alluvial fan deposits of the Candanedo Formation (Evers, 1967; Kuyp, 1969) spread out from the Hercynian mountain chain towards the south. The red beds of Miocene age have hardly been influenced at all by tectonic movements, since they are always less than 5° south-dipping. The main uplift can be correlated to Stille's Savian phase (Stille, 1924). Moreover, the uplift seems to have been very gradual, since angular unconformities have a small angle which often could not be determined in the field. Besides, the phenomenon of 'inversed sedimentation' (Evers, 1967; Fig. 74), the participation of increasingly old material derived from the mountain chain in increasingly young deposits, is in favour of gradual tectonic movements.

THE CONTACTS WITH THE UNDERLYING ROCKS

In spite of the scarcity of well exposed contacts along the whole southern border, a systematic survey from east to west will be presented of a number of phenomena which could be observed at the contacts in the field.

In the Riello area, the contact between the Voznuevo Formation and the Precambrian is never exposed.

E of Carrocera, the Cretaceous is found in contact with the Stephanian but the contact itself is not exposed. A gravitational sliding along the hill which occurs in this location, probably causes a duplication of the contact in this exposure. Both the Paleozoic and Mesozoic rocks seem to have been folded into an overturned position. It is a striking feature that the Stephanian in this location shows an abundance of quartzites (as conglomerates), while the quartz/quartzite/lydite ratio in the Voznuevo Formation within 10 metres from the contact (cf. Chapter VI, Table II) shows that over 80% of the pebbles consist of quartz. Between these ten metres only clays and silts were found exposed, so that a lithological connection between the Voznuevo Formation and the underlying rocks does not seem very likely. We must assume that at least slight fault movements took place in this location.

The contact W of Sorribos de Alba (Section E) is much better exposed (Fig. 23). Again Stephanian conglomerates outcrop at the contact. The situation is as follows:

c. 3.50 m of red clay
b. 3.50 m of white silt — with closely packed quartzite cobbles and boulders, over 45 cm in diameter.

a. Stephanian conglomerates with quartzite cobbles and boulders.

The quartzite cobbles and boulders, floating in a Voznuevo matrix, probably derived directly from the underlying Carboniferous conglomerate. Since no evidence of a fault could be found, it must be assumed that we are dealing with an unconformable contact in this location. This presumption is strengthened by the fact that the thickness of the formation has the expected value and does not seem to be influenced by faults.

The next contact which deserves our attention is situated at the bottom of Section F, north of Brugos de Fenar. A few metres between the folded Carboniferous (Cuevas Formation) and the steeply N-dipping Voznuevo strata are not exposed. Digging in the arroyo brought a transition in the Paleozoic rocks to light: from fresh via weathered rocks to greyish silts and clays with purple and red-brown discolourations. The latter might represent a Paleozoic soil. Unfortunately, the material was found to be in such a state of weathering that thin sections could not be prepared. It is very well possible that the contact near Brugos de Fenar is unconformable and has not been influenced by any faulting.

Near Solana de Fenar (Section H) an impressive angular unconformity between the Paleozoic and the Cretaceous was encountered: Paleozoic strata dipping 35° to the northwest, while the Voznuevo Formation dips 55° to the south. The direct contact is covered everywhere, but the first silts which are reckoned among the Voznuevo sediments show light yellow spots, over 10 cm in diameter, that might be weathered Paleozoic material: the contact is assumed to be again unconformable.

The unconformity north of Naredo de Fenar (Section I) on the northern side of the road, W of the Río Torío, is very clear. From bottom to top we distinguished:

80 cm of Paleozoic quartzites, intensively cut by joints; steeply N-dipping.
170 cm of angular quartzite cobbles and boulders with between them the joint pattern of the underlying rocks.
? cm of silts and clays belonging to the Voznuevo Formation.

The 170 cm thick unit with cobbles and boulders may have originated:

1. during a period of non-deposition between the Carboniferous and the Cretaceous.
2. after deposition of the Cretaceous, at the contact between consolidated and hardly consolidated sediments.
3. as a result of a combination of 1 and 2.

The best exposed contact W of Boñar is the one in the arroyo N of La Valcueva which is presented in Fig. 24. From left to right the following units could be distinguished:

f. consolidated Voznuevo sand.
e. 40 cm of quartzite boulders, maximum diameter 40 cm.
d. 60 cm of partly consolidated Voznuevo sand.

c. 20 cm of quartzite cobbles, poorly rounded, with a maximum diameter of 25 cm.
b. 20 cm of red clay.
a. Paleozoic quartzites in beds of 12 cm thickness, with a dip of approximately 50° to the north.
Units b to f are vertical to steeply N-dipping.

The quartzite cobbles and boulders cannot have derived directly from the underlying thinly bedded quartzites; yet the source area of the poorly rounded cobbles and boulders could have been very nearby, presumably the area which nowadays forms the Cantabrian Mountains (cf. Chapter V, A; Section A). The 20 cm red clay can be seen as a weathering product of underlying Paleozoic deposits; it has been completely homogenized and does not show any stratification. The red clay can be seen as a post-Carboniferous soil which originated before the deposition of the Cretaceous. Also in this location a plain unconformity is found without any sign of a fault contact.

By far the best exposed contact was encountered N of the village of Voznuevo (Figs. 25 to 28), at both sides of the Arroyo de Voznuevo. Here orthoquartzites of the Barrios Formation (Ordovician), which have been folded into an overturned position and dip 35° to the NW, are covered by sediments of the Voznuevo Formation which dip 27° to the SW. The latter, as could frequently be observed between Boñar and Colle, are more or less consolidated. The unconformity is beautifully exposed W of the Arroyo de Voznuevo (Fig. 25, looking W). In this location no soil formation has been preserved between the Paleozoic and the Cretaceous; the loosely consolidated gravels and sands of the Voznuevo Formation immediately overlie the quartzites. The contact can even be studied in hand specimens: in Fig. 26 the rare situation is shown in which cross-stratified coarse sand is deposited on the unconformity surface. The paleocurrent direction indicates a supply from the SW, which coincides with the paleocurrent directions found in channels in this area (Chapter V, B). Imbrication in conglomerates within one metre from the contact also indicates a supply from the SW. The unconformity surface itself, which is magnificently exposed in some locations, has a slightly undulating surface; locally remainders of consolidated Voznuevo material have been preserved on it (Fig. 27). It is strange to realize that the old erosion plane today reappears in this form for the second time. Another phenomenon which could be observed on the unconformity surface can be seen in Fig. 28: a crack or fissure in the Barrios Formation has been filled with sand and gravel from the Voznuevo Formation.

The composition of the pebbles in the conglomerates strongly depends upon grain size: 62% of the pebbles coarser than 3 cm in diameter proved to be quartzite; in the sediment finer than 3 cm in diameter 90% consist of quartz.

The unconformity as encountered N of Voznuevo continues along the entire border between Boñar and Colle, although it has never been found so conspicuously as in the exposure described above.

In the southern strip no exposures occur between La Devesa de Boñar and La Ercina. Strike and dip measurements in an excavation in the village of La Ercina proved to be highly diverging within a short distance. They suggest that tectonic movements have been active in this location.

The reduced thickness of the Voznuevo Formation N of Yugueros (Section O) makes faulting very probable. It could not be established whether this fault runs along the contact or elsewhere in the formation, or both. At least five metres between the Paleozoic and the Voznuevo Formation are not exposed.

In the excavation on the southeastern side of the village of Cistierna clear indications are found of one or more faults; less than 60 metres are all that is left at the surface of the total thickness of the formation. At some hundreds of metres SE of this excavation, between Cistierna and the brick factory NW of Valmartino, twenty centimetres of very distorted black and grey clays and sands form the transition from Paleozoic limestones to the Voznuevo Formation. Fault movements have apparently taken place along this clayey horizon which must have acted as a sliding plane. Opposite the village of Valmartino the Paleozoic probably participated in the faulting, since a 40 cm thick limestone breccia overlain by 70 cm of white to light brown clay, with a considerable quantity of limestone fragments, together with quartz pebbles, was found near the contact.

About 200 m E of the border between the provinces of León and Palencia, 30 m E of km 35 of the recently constructed road from Puente Almuhey to Guardo, a small exposure on the northern side of the road was found which showed (from top to bottom):
c. 400 cm of grading from pebbles to clay via coarse sand, fine sand and silt, yellow and white coloured.
b. 80 cm of originally grey silt and clay, for the most part showing a purple to red discolouration. The top is lighter coloured and contains quartz pebbles and crushed quartzites.
a. ? cm of white silt and black clay with coal fragments and yellowish sand layers.

Units a and b possibly belong to the Carboniferous, while unit c might represent the first Cretaceous deposits. In this case unit b can be considered as a paleosol with an eluvial zone at the top. There are no indications of faulting near this contact.

The contact is not exposed until Santibañez de la Peña where, at the bottom of Section R, the following could be observed (top to bottom):
c. 300 cm of yellow and pink sands belonging to the Voznuevo Formation.
b. approximately 10 cm of clayey shales with purple to red weathering colours. Frequent slickensides.
a. dark grey sandy and silty shales (Carboniferous).

The contact between b and c seems somewhat undulating. Although indications are present of small fault movements (slickensides), their influence probably was not very great. The clayey red shales of unit b could – as in the preceding case – be the remnant of a fossil soil. The reduction in thickness of the Voznuevo Formation near Santibañez de la Peña need not be explained by faulting along the contact, since clear indications could be observed of faulting within the section.

North of the village of Aviñante, along the road to Villafria, a plain unconformity is exposed. The following units can be distinguished:

d. silts and clays.
c. 14 m of fine-grained sand, partly consolidated by iron oxides.
b. about 80 cm of quartzite conglomerate; maximum diameters of the cobbles 16 cm, nearly all broken. The matrix consists of broken quartzite.
a. Paleozoic graywackes and black shales.

The conglomerate mentioned under b seems to be a basal conglomerate of the Voznuevo Formation. The same situation is encountered N of the village of Villaverde where the conglomerate, which again consists entirely of quartzite components, has reached a thickness of 300 cm (maximum diameter of the boulders 23 cm).

The basal conglomerate also proved to occur at the base of Section S between Aviñante and Villaverde, but exposure was rather poor.

The angular unconformity is best seen along the road from Cervera de Pisuerga to Vado de Cervera where the conglomerate immediately overlies alternating sandstones and shales of Paleozoic age (cf. Kanis, 1956; Fig. 14). In this location the conglomerate has reached a thickness of 10 m. In contrast to the conglomerate further to the W, thin intercalations of fine-grained material do occur (see Section T).

It is surprising to find that, in spite of strong movements along the border zone which have been able in many locations to push the Cretaceous sediments into vertical and overturned positions, and in spite of a considerable throw along a deep-seated fault as assumed by geophysical survey, the unconformity between the Paleozoic and the Cretaceous has been preserved at so many contacts. The only area where a fault contact could be ascertained lies between Yugueros and Quintana de la Peña; slight fault movements probably took place near Carrocera and Santibañez de la Peña.

THE CONTACTS WITH THE OVERLYING ROCKS

Except for one location, all contacts between the Voznuevo Formation and the overlying deposits suffer from a very bad degree of exposure. The only contact which could be studied in greater detail is situated at km 3 on the northern side of the road Otero de las Dueñas – La Robla. In this location a proof was found of the disappearance (by wedging out) of the Mesozoic limestones (Chapter IV), the Voznuevo Formation being directly overlain by sediments of the Vegaquemada Formation (Fig. 29). Although the Cretaceous deposits proved to be considerably weathered and have been disturbed by recent vegetation, one can distinguish, from top to bottom:

h. coarse-grained sand, brick-red with white speckles (quartz grains).
g. 2 cm as in h, colour: lilac to purple.
f. 7 cm of bluish-grey fine sand, very rich in muscovite, with mm-thick red to purple clay stringers, especially at the top.
e. 4 cm of white silt with dark yellow weathering colour.
d. 2 cm of white silt.
c. 12 cm as in b.
b. 15 cm of silt, pink to brick-red, with clay at the top, dark purple and grey. Lower part: fine-grained sand.
a. more than 150 cm of sand and clay, strongly weathered. The coarser the grain size, the lighter the colour.

Unit h shows the typical colour, peculiar of the Vegaquemada Formation, while unit f can be compared with the sediments of the Voznuevo Formation. Unit g, the very thin transition zone, belonging lithologically to the Vegaquemada Formation, has been discoloured due to its position near the boundary. The contact is straight (as far as could be determined in this exposure) and gradual, no signs of a hiatus in the sedimentary history being present.

Very gradual transitions from the Voznuevo Formation to the Mesozoic limestones could be observed NW of Brugos de Fenar, E of Boñar, S of La Devesa de Boñar, W of Muñeca and in Section T.

In the field the first appearance of lime in the sands was taken as a criterion of separation. Observations in thin sections from the transitional zone will be described in Chapter VII.

SUMMARY

Retaining some main points of this chapter, we may say that the sediments of the Voznuevo Formation have been strongly influenced by a tectonic uplift, at the end of the Paleogene (Savian phase), of the Hercynian massif which now forms the Cantabrian Mountains.

In many locations the Voznuevo Formation has been dragged into an overturned position. Where strong compression has been active, the formation may be folded or faulted; in extreme cases pulverization of the sediments took place.

During a geophysical survey differences in density were found which led to the assumption of a deep-seated fault with a throw of about 2 km between the Paleozoic and the Cretaceous. With the exception of results obtained in the Porma valley, the fault plane was found to be dipping to the north.

Although fault movements near the contact are almost certainly to be expected in the subsurface, examination

of the contacts in the field showed that by far the most contacts are unconformable and have not been influenced by strong faulting. Only between Yugueros and Puente Almuhey, especially near Cistierna, has intensive faulting along the contact taken place.

The contact with the overlying Mesozoic limestones proved to be very gradual everywhere, with the exception of the contact south of Carrocera, where the Voznuevo Formation is in direct contact with the Vegaquemada Formation. No fault between these two formations could be observed, so that the idea of a fault which might be the reason for the disappearance of the Mesozoic limestones in a westerly direction must be abandoned.

CHAPTER IV

STRATIGRAPHY

THE LOWER CRETACEOUS IN THE BASCO-CANTABRIAN AREA

The very comprehensive work by Ciry (1939) is of great value to anyone studying Jurassic or Cretaceous sediments in the Basco-Cantabrian area. The reader is referred to him for a complete list of previous work carried out by investigators of these sediments. We shall confine ourselves here to a few remarks on the history of the investigations in the area between Riello and Cervera de Pisuerga. This area has been separately dealt with by Ciry, who referred to it as 'the southern border' (bordure méridionale) of the Asturian Massif.

As early as the middle of the nineteenth century, the sediments between Boñar and Colle had been recognized as belonging to the Cretaceous (Casiano de Prado, 1850; Pratt, 1850). These authors distinguished kaolinitic sands and more or less consolidated conglomerates, overlain by limestones and sands, both fossiliferous.

Oriol (1876a and b), who investigated the Río Carrión Basin, assigned the kaolinitic sands to the Cenomanian and the overlying limestones to the Turonian.

Some years later (Mallada, 1891), both the kaolinitic sands and the limestones were considered to be Turonian. Except for some short remarks by Mallada (1900) and by Termier (1918), the southern border was not a subject of interest until 1933, when Ciry published some preliminary notes (Ciry, 1933a, b and c) on the area which is roughly bounded by the triangle Santander-Burgos-Boñar.

In 1934 Karrenberg reported on an area between Bilbao, Burgos and Oviedo, covering the whole of Ciry's area except for the southern border west of Aviñante. As for the Upper Cretaceous, the Upper Cenomanian is found to be transgressive over the older deposits. The kaolinitic sands of the southern border zone were thought to belong to it.

Ciry (1936) remarked that the Upper Cretaceous is transgressive over the old Asturian Massif. The transgression starts in the E in the Cenomanian and continues to the W in an uninterrupted manner during the following stages. The maximum extension, as far as his study is concerned, is reached in the Santonian.

The Lower Cretaceous, as investigated by Ciry (1939) in parts of the provinces of Santander, Burgos and León, can be divided into three zones:

1. A northern zone, with sandy and marly lagoonal or limnic and marine deposits.
2. A southern zone, exclusively laguno-lacustrine and continental (the southern border of the Cantabrian Mountains is an extension of this zone).
3. A zone in which a transition from 1 to 2 is found.

Sections through the Cretaceous of the northern zone near the boundary of the provinces of Burgos and Santander give the following general picture:

Cenomanian	
'Sus-Aptien'	sandy complex, barren
Bedoulian, Gargasian	{ sands with Orbitolinas marls with Cephalopods
Neocomian, Barremian = Wealden	sandy complex in Wealden facies

By way of simplification, we may say that the Lower Cretaceous of the northern zone consists of marine deposits flanked by two mainly sandy deposits in Wealden facies.

In the southern zone the situation is different, and two sequences can be distinguished (according to Ciry): a lower sequence, of moderate thickness with lacustrine limestones and 'bright red' deposits, and an upper sequence, with a maximum thickness of more than 1000 metres, consisting of exclusively detrital sediments, mainly sands and conglomerates. Studying the contact with the underlying sediments it became clear that the two sequences are not present everywhere; locally the upper sequence may be in direct contact with pre-Cretaceous deposits. According to Ciry, the absence of the lower sequence is not the result of differences in sedimentation, but is due to abrasion between the deposition of the two sequences. These sediments of the upper group have also been referred to as 'Wealden', with the restriction that the entire Lower Cretaceous may be meant by this name, and not only the Neocomian and Barremian. The name 'Wealden' therefore has no timestratigraphical value and is only usable for the description of a facies type. Apart from some wood remains, the upper sequence never yielded any fossils. Columns 3 to 7 in Fig. 5 show a simplification of Ciry's schematic picture of the variations in facies in the

Lower Cretaceous, from NE to SW with corrections by Rat (1962).

Summarizing Ciry's comments on the paleogeographical development of the Lower Cretaceous, we retain that after deposition of Callovian sediments a long period of stability set in during which no sediments appear to have formed on the continent. Influence by subdesert-like climatic conditions led to the generation of hamada*-like red sediments. These are found again in the first Cretaceous deposits as red clays and polygenetic pudding stones.** With the beginning of the Lower Cretaceous, a transgression set in and a basin was formed in the northern zone in which sandy detrital sediments were deposited. This situation lasted until the Aptian. In the meantime, the subsidence of the basin was less important in the southern zone, where first red clays and later lacustrine limestones were deposited. With the ingression of the Bedoulian sea, which entered the area from the north, marine sedimentation took place in the north, while a continental basin originated in the south.

Ríos, Almela and Garrido (1945) gave a description of the Cretaceous in the area between Bilbao and Miranda de Ebro, consisting of parts of the provinces of Burgos and Alava, and to the north of small parts of the provinces of Santander and Vizcaya. The Lower Cretaceous deposits attain extraordinary thicknesses, from 5000 m in the north to 1000 m in the south. There are no indications of an exaggeration of these values due to faulting or folding. The character is mainly continental, detrital with carbonaceous intercalations. In the central part of the area these deposits were found to cover Jurassic rocks. The upper limit was defined, as in many other areas, by Orbitolinas. As a consequence of the thickness of the deposits, the authors believe all stages of the Lower Cretaceous to be present (Wealden s. s. to Albian). On the basis of investigations by Ciry in the provinces of Santander on fossils of the marine intercalations, this hypothesis seems correct. In the southern part exclusively detrital sediments are found, changing into more clayey counterparts towards the north; we see that the situation is highly comparable to that in the region studied by Ciry. One of the most important remarks of the authors concerns the origin of the continental sediments (p. 110): 'Hacia el Norte (read: Sur) nos acercamos al área elevada de denudación que suministraba el material provinente probablemente de la masa granítica castellana (cuarzo blanco, abundancia de mica)'. The discussions by these authors on the stratigraphical conceptions by Schriel (1930), Sáenz (1933), Karrenberg (1934) and Ciry (1939) does not shed any new light upon problems concerning our area.

* Schieferdecker (1959): hamada = rocky desert, rocky uplands of a desert, which have been swept clear of sand and dust by wind; the rocky surface is usually covered by coarse rock fragments.

** Pudding stone is a term sometimes used for conglomerates in which the matrix is preponderant (French: poudingue; Spanish: pudinga).

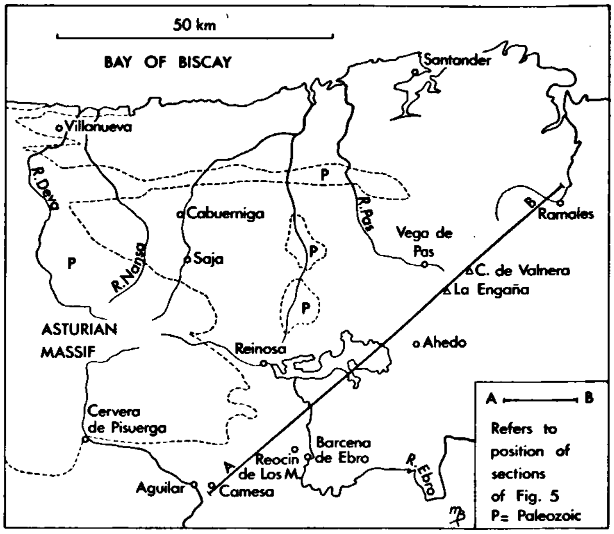


Fig. 4. Schematic geographical map of the area S of Santander, showing the position of the section in Fig. 5 (simplified after Rat, 1962).

Neither does Ríos (1956), in another summarizing article on the Cretaceous of the Pyrenees (= Pyrenees s. s. + Basco-Cantabrian Pyrenees), contribute many new facts to the comprehension of our Voznuevo Formation. The sediments of the southern border are indicated as being of the Iberian type, which is equivalent to Ciry's southern zone. On a schematic map, on which the Cretaceous along the northern and the southern borders of the Asturian Massif is shown, the deposits of the area between Riello and Cervera de Pisuerga are included in the Upper Cretaceous. In the accompanying text, Ríos notes that they may belong to the uppermost Lower Cretaceous or to the lowermost Upper Cretaceous.

A very comprehensive work on Cretaceous sediments in the Basco-Cantabrian area, comparable to that by Ciry, was published by Rat (1959). The area studied by him lies between San Sebastian and Santander and is limited in the north by the Bay of Biscay and in the south by the town of Vitoria. The essence of his investigation is the marine Aptian – Lower Albian, the Urgonian Complex. This Urgonian Complex can be seen as a marine wedge which separates the red clayey and sandy complex in Wealden facies into two (Fig. 5). The overlying deposits, of which the sediments of the southern border zone of the Cantabrian Mountains form part, have been referred to as: 'sus-Aptien' or super-Aptian sands, (Ciry, 1939) or supra-Urgonian Complex (Rat, 1959).

In the time between Callovian and Aptian, three areas with a clearly different sedimentological development can be distinguished:

1. A western region, formed by the eastern part of the province of Santander, where calcareous, sandy beds of Berriasian age have been deposited on top of marine

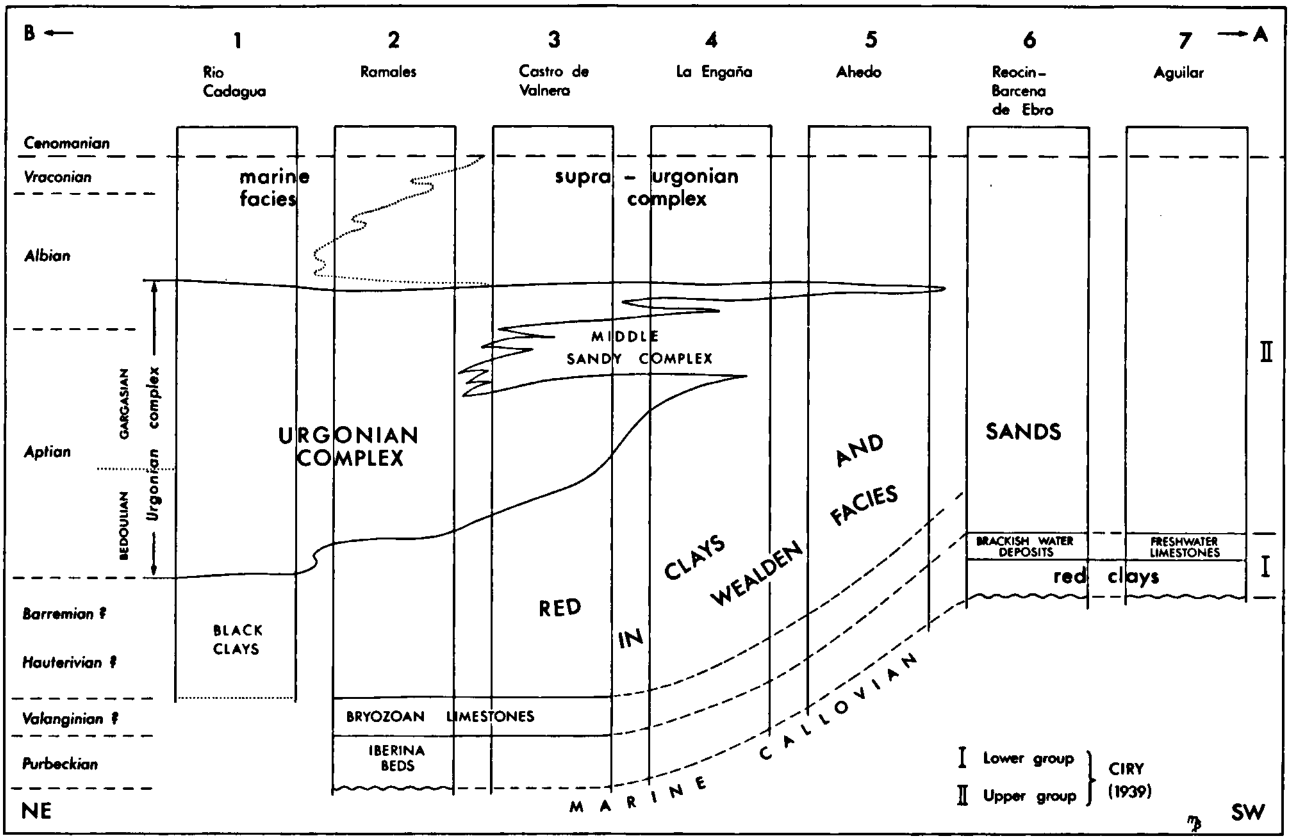


Fig. 5. Correlations in the Lower Cretaceous S of Santander (simplified after Ciry, 1939 and Rat, 1962). For location of the section see Fig. 4.

Callovian. They are overlain by Valanginian limestones which are in their turn covered by vividly coloured, mainly red fresh water sediments in Wealden facies.

2. A central part, near Bilbao, from where black clays with brackish water features have been reported. Evaporites occur locally.

3. An eastern part, formed by the province of Guipuzcoa, in which exclusively limestones have been formed (e. g. near Tolosa).

The correlation between these three areas as proposed by Rat (1959) is presented in Fig. 6, columns j, k and l.

The paleogeographical history in Rat's region is well comparable to the history further to the west as given by Ciry. In Jurassic times fine-grained marly to calcareous sediments, associated with a stable flattened continent (the Hercynian Massifs and the Meseta), were deposited in the Basco-Cantabrian area. The Callovian uplifts caused an increase in erosion and a reduction of the marine territory; continental sedimentation took place. Until the return of marine conditions Rat distinguished three periods:

1. Emersion phase or brackish regimen (post-Callovian-Purbeckian) with the uplift of a land mass related to the Asturian Massif and the Meseta together with the generation of the Basco-Cantabrian gulf. In the meantime vividly coloured erosion products originated on the land which were later to be carried away and form the sediments of the Wealden facies.

2. Return of the marine influence (Valanginian?) with neritic marine conditions and deposition of sandy limestones and oolites.

3. Active terrigenous sedimentation (Wealden s. s.) of material derived from the Asturian and the Castilian continents. The sea has withdrawn towards the zone of Bilbao and Tolosa.

In this connection it is worth noting that Rat proposed changes in climatic conditions (apart from tectonic events) as the main reason for the differences during these three periods. This process, which is dealt with in a separate publication (Rat, 1963) is called 'climatic marine transgressions and regressions'.

In the Urgonian (Aptian – Lower Albian) the coastline shifted towards the continent (still formed by the Asturian and the Pyrenean Massifs and the Meseta). In the north of Old Castile the sedimentation in Wealden facies continued; the transition zone between the terrigenous sediments and those of the marine Basco-Cantabrian gulf lies, as we have seen from the description by Ciry, in the province of Santander.

The sandy supra-Urgonian Complex, comprising sediments deposited before the Cenomanian transgres-

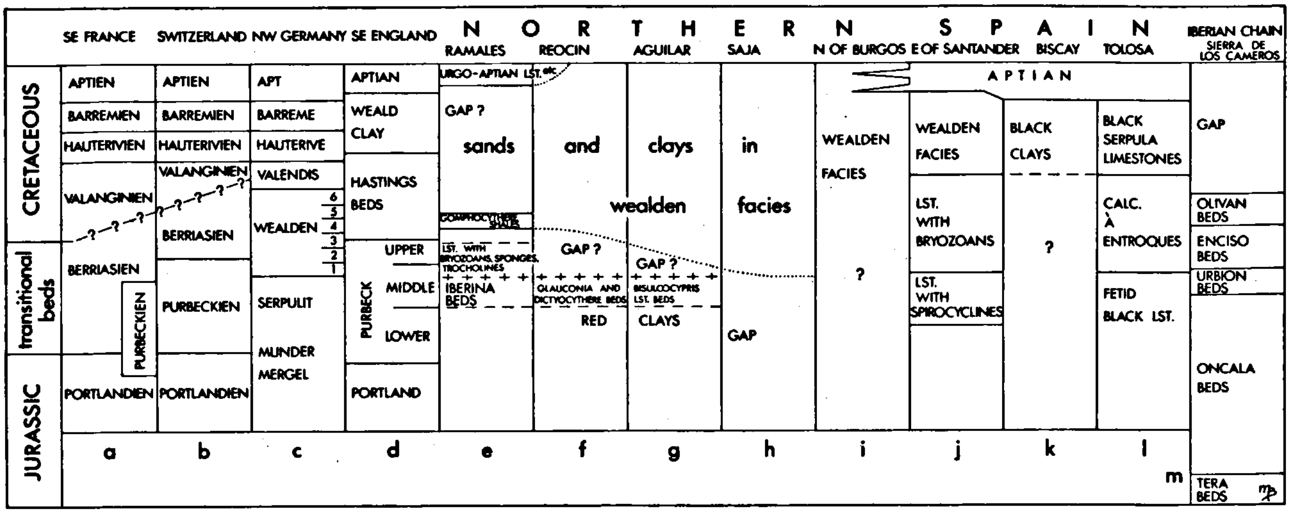


Fig. 6. Approximate correlation between the Lower Cretaceous deposits in northern Spain and the Lower Cretaceous in other parts of Europe (composed after data by Rat, 1959 (a, c, d, i, j, k, l); Rat, 1962 (a, c, d, e, f, g, h); Bartenstein, 1962 (a, b, c); Kneuper-Haack, 1966 (b, c, d, m) and Rat & Salomon, 1969 (e).

sion (Upper Albian – Cenomanian), is an extension of the Wealden facies sedimentation which still took place in the southwestern part of Rat's area. The sandy and clayey material was provided from southwesterly directions, since it clearly decreases in grain size in a northeasterly direction.

Three years later, Rat (1962) returned to the problems connected with the Lower Cretaceous in the eastern part of the province of Santander. In order to facilitate orientation, a strongly simplified outline of the geographical situation is given in Fig. 4. In the southwestern corner of the sketch the easternmost location can be seen of the area studied at present, Cervera de Pisuerga. The locations near the line A–B correspond to the sections of Fig. 5, simplified after Rat (1962). Sections 3 to 7 of Fig. 5 are almost identical to the correlations proposed by Ciry (1939; Fig. 73). The correlations introduced by Rat form the main part of his publication: they concern the correlation of Ciry's lower sequence (bottom of sections 7 and 8) with section 3. Ciry had provisionally connected his lower sequence to the Urgonian complex (Bedoulian).

The ostracods (*Iberina*) in the beds directly overlying the Jurassic limestones and marls near Ramales (section 2, Fig. 5) could be correlated to the Serpulit of NW Germany and the Middle Purbeck of SE England (cf. Fig. 6). New paleontological and stratigraphical investigations near Barcena de Ebro and Reocin de los Molinos brought to light that the beds of the lower sequence must be correlated to the Iberina beds of Ramales.

Considering the situation near the border of the Asturian Massif, it was found that some 12 m of lacustrine limestones occur between Jurassic and sands and clays in Wealden facies near Cabuerniga; S of Saja (cf. Fig. 4) the latter directly overlie the marine Callovian. In a section in the valley of the Río Deva the Urgonian complex rests directly upon Carboniferous rocks; a 2 to 3 m thick, probably reworked, wine-red, sandy and clayey unit is the only witness of the Wealden facies complex.

New facts on the position of Ciry's lower and upper sequence are brought forward in a recent paper by Rat and Salomon (1969) in connection with new finds near Vega de la Pas. Already in 1962, Rat noted the presence of limestones with Trocholinae and Bryozoans between the two sequences (Fig. 5; sections 2 and 3). A study of new exposures of this limestone N of Vega de la Pas showed that the transition from the lower sequence to the limestones is due to rapid lateral changes. It could not be established whether these changes are caused by a difference in distribution of the marine sediments or by differential erosion before deposition of the upper sequence. The discovery of a horizon of black shales near the base of the upper sequence is more important. These shales supplied Ostracods (Gomphocythere) which could be correlated to Wealden 4 of Germany (cf. Fig. 6). As for the stratigraphical position of the boundary between Ciry's two sequences, the following can be said: The fresh water and brackish water sediments of the lower sequence can be correlated to the Serpula zone of Germany and the Middle Purbeck of England (Rat, 1962). The sedimentation of the sandy upper sequence began as early as the Berriasian, i.e. at the very base of the Cretaceous. The question whether the upper sequence is continuous up to the Urgonian complex or not is still open.

THE SEDIMENTS IN WEALDEN FACIES IN OTHER PARTS OF SPAIN

In anticipation of an assumption by Ciry (1939) that the sediments of the Voznuevo Formation do not have a diachronic character due to their homogeneous appearance, it is the object of the following part of this chapter to show that sediments in Wealden facies, reported from other regions in Spain, are distributed over a considerable time interval, during the entire Lower Cretaceous and even during the early Upper Cretaceous.

Almela (1956) made a study of Cretaceous deposits in an area south of the Ebro Basin, bounded in the east by the Mediterranean coast near Barcelona and in the west by the meridian of Teruel. In the north of this area lignitic layers in deposits of Albian age have been the object of mining activities, near Utrillas amongst other places. These deposits are also reported from other areas and have been referred to as 'Utrillas Beds' (Utrillas Schichten, Capas de Utrillas). For the most part the Cretaceous unconformably overlies slightly folded rocks of Jurassic age; where the Jurassic is absent (in the northern and the western parts) the Cretaceous rests upon Triassic. The following depositional history was presented by Almela: towards the end of the Jurassic period, after the Kimmeridgian folding phase, a continental basin, bounded by the Ebro Massif in the north and by a spur of the Cordillera Catalana in the east, came into existence. Continental deposits originated with a thickness of 200 m in the north and 50 m in the east. These sediments were deposited in what is called a 'Wealden facies'. The moment of cessation of this sedimentation is hard to determine, since paleontological evidence is lacking, but according to Almela a marine transgression took place towards the end of the Neocomian (=Valanginian + Hauterivian) or the beginning of the Barremian (=Urgonian), and the Urgo-Aptian sea began to rule over this area. Its neritic deposits attain a thickness of between 400 m and 1000 m. With the first Austrian phase a regression took place, and a new continental basin was formed in which mainly sandy deposits of Albian age (Utrillas Beds) were deposited with a maximum thickness of 600 m. The second Austrian phase finally was followed by the Cenomanian transgression in this area, which definitely ended continental Cretaceous sedimentation.

Martínez Peña (1956) carried out investigations in an area little of which was as yet known, viz. a part of the provinces of Guadalajara, Ciudad Real and Cuenca. A well exposed road section between Mota del Cuervo and Belmonte shows (p. 168):

c. Arenas blancas y amarillas, areniscas blancas silíceas, duras, con esquistos de areniscas blancas y duras. Arenas cuarzosas blancas y vinosas con granos de cuarzo. Arcillas rojas y violadas con grano suelto y rodado de cuarzo.

b. Calizas rojovinosas con lentejones de areniscas silíceas. Calizas y carniolas irregulares, rojas, grises y violadas, con grano de cuarzo.

a. Caliza gris, grisvioladas, cristalinas, finas, con Pentacrinus e Isocrinus.

According to Martínez Peña, unit a belongs to the Liassic, while units b and c belong to the Eocretacéo (Lower Cretaceous), because of their position and their undeniable facies; unit b represents the 'Wealden–Aptian facies', unit c the typical Albian. In the western part of the area the combined thickness of units b and c is very constant, 30–40 m, consisting mainly of unit c. In the eastern part the thickness varies from 40 to 100 m. Unit c proved to be easily traceable, since 'el Albiense es siempre un grupo arenisco y silíceo, de tonos vivos y alegres'. The overlying Cenomanian and younger deposits all consist of an alternation of limestones and marls.

Dupuy de Lôme and Sánchez Lozano (1956) described Cretaceous sediments in the 'Levante Español', a 100 km broad strip between Valencia and Alicante. Only in the northern part of this area have typical Wealden facies deposits developed. They are not entirely continental and several marine intercalations occur. The lower boundary of these sediments could not be studied in detail with respect to its age; only the following observation could be made:

Where the Cretaceous overlies Jurassic ròcks, deposition began in early Cretaceous times (Neocomian); where the substratum is formed by Triassic rocks ('Suprakeuper') the sedimentation is believed to have commenced much later, probably towards the beginning of the Aptian.

From the northern part of the area two sections through pre-Aptian sediments are described, deposited in Wealden facies some units of which show a strong resemblance to the lithological properties of our Voznuevo Formation as for instance near Ahillas where '50 m de arenas caoliníferas sueltas, rojizas y blancas, con cantos en la base de cuarzo lechoso y cuarcita' are exposed (p. 222). The other beds described are less well comparable, since they show many limestone and marl intercalations. One remark by the investigators concerning the above mentioned unit merits our special attention (p. 222).

The facies of these 50 m is identical to that of the Utrillas Beds of Upper Albian age, yet according to their position they must be older than Aptian. As no distinction can be made between these sediments and the Utrillas Beds, the stratigraphical position of the latter (of which we know that they normally directly underlie the Cenomanian) becomes uncertain, when the age of the beds surrounding them cannot be fixed with certainty.

As a résumé, the authors mention that the Wealden facies represents conditions of fluviomarine or lacustrine sedimentation with times of non-deposition or littoral-marine sedimentation. During the Aptian exclusively marine sedimentation took place, showing a uniformity which lasted until the Albian. In Albian times deposits consisting of loose sand in Utrillas facies were formed in isolated areas, apart from bathyal, neritic and littoral sediments. This sandy Utrillas facies is best developed and reaches its largest extension in the northern part of the area. Where both marine and continental Albian sediments are present, the latter will always be at a higher stratigraphical position since they precede the Cenomanian transgression.

Llopis Lladó (1956) investigated the Cretaceous in the surroundings of Oviedo, which are the westernmost sediments of this age north of the Cantabrian mountain chain. From well-exposed contacts with the Paleozoic it could be deduced that a peneplanation had taken place before deposition of the Cretaceous. The Cretaceous does not always overlie Paleozoic rocks, however; in several places a contact with Triassic or Jurassic rocks could be observed. The area has been subdivided into three parts:

1. Oviedo zone.
2. Pola de Siero zone, E of Oviedo.
3. Avilés zone, NNW of Oviedo.

From the Oviedo zone several sections through the Cretaceous are presented by the author. In most of these sections a 15–20 m thick unit was found showing: 'yellowish sand in Wealden facies with cross-stratification' (so far cross-stratification has seldom been reported by any other Spanish author). According to Llopis Lladó the Oviedo zone can be subdivided into three units (from top to bottom):

Unit I: 145–150 m of alternations of sandstones, marls and sands, predominantly detrital, with a marked continental character. Only in the lower part do limestones occur with a small vertical extension and a marine character.

Unit II: 45–50 m of alternations of sands, marls and limestones, mainly marine, with frequent detrital, continental intercalations.

Unit III: 25–30 m of molasses and sandy marls with a littoral character.

It is clear that a progressive increase in limestone components takes place from I to II. In unit I quartzite conglomerates occur with median diameters of the components between 10 and 60 cm (much coarser than the coarsest sediments found in the area studied by the present author!). These conglomerates grade into coarse-grained and fine-grained sands. They contain lenses of kaolinite and of clays sometimes rich in lignite. Llopis Lladó also realizes that the name 'Wealden' is not to be used here in a chronostratigraphical sense, but as a description of a certain type of facies. On account of frequent cross-stratification, the rapid changes in the size of quartz elements, and the clay lenses, especially those containing ligniferous beds, it is almost certain that we are dealing with continental deposits.

Unit II forms a transition zone to the littoral sediments of unit

III, which belong to the Upper Cretaceous as is shown by its fossil content. As to the stratigraphical positions, indications were only found in unit III, in which an abundant Turonian fauna proved to occur. According to a correlation with stratigraphical determinations by Karrenberg (1934), the upper part of unit II must belong to the Upper Bedoulian; a Lower Bedoulian age is probable for the lower part of unit II, while the sands and pudding stones in Wealden facies have not been dated, and may therefore occupy a stratigraphical position from the Valanginian to the Aptian.

In the second zone (E of Oviedo), unit I proved to be entirely continental while unit II, on the contrary, is more marine; which indicates differences in sedimentary conditions between E and W.

In the third zone, near Avilés, the quartzose pudding stones in Wealden facies attain considerable thicknesses (the conglomerate at the base measures more than 80 m). A division into two units can be made here, the lowermost sediments having mainly a detrital character (176 m thick), comparable to units I and II in the area near Oviedo, and stratigraphically to be located in the Aptian (or lower), and the uppermost sediments (90 m thick), belonging to the Cenomanian-Turonian (comparable with unit III).

In exposures near the coast between Luanco and Candás, at least 20 m of yellowish sand and dark clays overlie the limestones of Gargasian age. It is clear that the marine Aptian layers of Luanco are situated between two detrital layers, both developed into a Wealden facies. As was shown before, the 'Wealden' (facies) may have developed in a much higher stratigraphical position than in the 'Wealden s. s.' as used in Spain (=Valanginian + Hauterivian + Barremian).

Summarizing we may say that there is an increase in thickness from W to E, together with a change in facies from mainly continental to mainly marine. In the eastern part of the area studied by Llopis Lladó we see that a complete sedimentary cycle takes place between the basal sediments in Wealden facies and the sediments on top of the Gargasian (also developed in a Wealden facies). Llopis Lladó summarizes the paleogeographical events as follows:

1. Aptian transgression with marine sediments near Luanco and continental or paracontinental sedimentation near Oviedo and Siero.
2. Limit (of the greatest extension) of the Aptian transgression in the Upper Bedoulian – Gargasian; marine limestones near Luanco, marls near Siero and limestones near Oviedo.
3. Gargasian – Albian regression, deposition of the 'upper' sands near Luanco.
4. Continental Albian, maximum extension of the regression.
5. Cenomanian – Turonian transgression.

Alastrué (1956) reports on the Cretaceous of the Andalusian Cordillera Bética. Both Lower and Upper Cretaceous are entirely marine in this part of Spain, so that a comparison with our Voznuevo sediments cannot be made.

Investigations by German geologists in the northwestern Iberian Chain north of Soria – the so-called Sierra de los Cameros – which began in 1953, were summarized in 1966 (Der Jura und Wealden in Nordost Spanien – Beuther, Dahm, Kneuper-Haack, Mensink, Tischer).

The western part of the Sierra was investigated by Beuther. The sediments between marine Jurassic and marine Upper Cretaceous deposits have been subdivided into:

Upper Cretaceous
Utrillas Beds

	3. Urbión Beds
Wealden	2. Oncala Beds
	1. Tera Beds

Jurassic

Beds 1 and 2 are both limnic-fluvial sediments in which limestone intercalations such as lagoonal deposits are very common. The Urbión Beds and the Utrillas Beds have so many features in common with the sediments of our Voznuevo Formation that they deserve some special attention:

The Urbión Beds resemble the two older beds, apart from the absence of limestone intercalations. As in beds 1 and 2, sediment transport as deduced from measurements on cross-stratification and decrease in grain size must have been from S to SW. The complex begins with conglomerates which clearly separate this unit from the Oncala Beds. The components are well-rounded and have a very uniform composition: 73% quartz, 25% quartzite and 2% lydite. The quartz is glass-like and milky; the quartzites grey and brownish. Deviations from this pattern only occur in locations where very coarse gravel has been deposited; in that case they consist mainly of quartzite. On top of these conglomerates 'quartz sandstones containing feldspars' occur, sometimes with pebbly intercalations. Towards the northeast of the area the feldspar content decreases. Coal layers rich in pyrite, accompanied by dark coloured clays are reported from several locations. As no seatearths could be observed, these were probably formed by floating plant remains. According to Beuther these Urbión Beds must be considered as exclusively fluvial deposits in view of their characteristics.

The Utrillas Beds, formerly regarded as belonging to the Cenomanian, proved to be of Upper Albian age in view of their paleontological and stratigraphical characteristics. They unconformably overlie the Wealden sediments. The lithological description of the Utrillas Beds strongly resembles that of the Urbión Beds. The composition of the conglomerates with 65–68% quartz, 30–35% quartzites and 5% lydite, consisting of well-rounded components, is almost identical, as is the presence of coal rich in pyrite, carbonized wood and chopped plant remains. The paleocurrent direction from S to SW is also identical. The higher Utrillas Beds consist of alternations of fine to coarse-grained, sometimes rather angular micaceous quartz sands with clays. The maximum diameter of the pebbles in these sands is 16 cm. The quartz sands have white-grey to purplish-red colours. The clays can be greyish-purple, dark red or grey with dark brown iron concretions. Grey coloured, leafy claystones occur locally. In the upper part of the beds, lignite layers of moderate lateral extension and a maximum thickness of 1 m may be present. Near the village of Fuentetoba, oil impregnations cause the formation of asphaltic layers; this occurrence is, however, very local. The top of the Utrillas Beds is formed by greenish-brown sandy to pebbly calcareous oyster-beds with a maximum thickness of 3 metres; they are often thinner or altogether absent. These beds mark the beginning of the marine Upper Cretaceous. The author finally notes that the total thickness of the Utrillas Beds ranges between 300 and 350 m, with a maximum of 380 m W of Soria.

In view of a comparison with the Voznuevo Formation sediments we shall now consider the source area and the mechanism of deposition, applicable to the Urbión Beds and the Utrillas Beds. Following Beuther's train of thought we note:

1. The composition of the gravel and the sand indicate a derivation from Paleozoic and crystalline rocks.
2. A paleocurrent direction from S to SW.
3. A short distance of transport, concluded from the material involved.

The source area of the Urbión Beds, as for the two other Wealden Beds, is thought to be situated NW and N of the present Sierra de Guadarrama, N of Madrid. A source area further to the E can be left out of account, since Jurassic sediments covered the Paleozoic. In the southern part of the Sierra de los Cameros, indications are found of a nearby border of the basin, while the sediments probably continue below the Tertiary cover of the Ebro Basin to the N.

For the Utrillas Beds the same source area must have been active. The extension towards the south, however, covers a larger area than do the Wealden sediments; the Utrillas Beds extend as far as the northern border of the Sierra de Guadarrama. The size of the feldspar fragments and their good state of preservation would indicate the presence of crystalline rocks over a broader surface and at a closer distance than during Wealden times.

In combination with findings by Tischer in the eastern part of the Sierra de los Cameros, Beuther thinks that the clastic units of the Wealden and the Utrillas Beds show characteristics of a deltaic environment. In the part of the area studied by Beuther, especially in the south, the coarse clastic sediments are believed to represent the root of this delta.

The Cretaceous succession in the eastern part of the Sierra, as studied by Tischer, has been subdivided into five lithological units, the lowest three of which are already known to us from the western part:

5. Oliván Beds (top clastic deposit)
4. Enciso Beds (upper calcareous deposit)
3. Urbión Beds (middle clastic deposit)
2. Oncala Beds (lowest calcareous deposit)
1. Tera Beds (basal clastic deposit)

This purely lithostratigraphical subdivision roughly represents a time-stratigraphical subdivision. The description of the five beds will not be repeated in detail here; the three clastic units resemble those described by Beuther. Red colours prove to be most intensive in the lowest beds. Paleocurrent directions in this area predominantly indicate transport from SW or S, sometimes from NW. The top of the Oliván Beds is absent, as are the Utrillas Beds in this area.

In the part studied by Beuther we find one complete and one incomplete deltaic cycle, while in the area described by Tischer two complete and one incomplete cycle have developed. This difference is caused by a gradual displacement of the deltaic system in a northerly direction.

One of the strongest 'proofs' of a deltaic mechanism is the presence of fresh-water and brackish water fossils. A paleontological study on the ostracod fauna of the Wealden sediments was carried out by Kneuper-Haack. Among the ostracods only brackish water types do occur. In the right column (m) of Fig. 6 the stratigraphical results of this paleontological investigation are shown. In contrast to the sedimentation after the transition from the Oxfordian to the Kimmeridgian in the remainder of Europe, no marine intercalations are found in this area. Compared with the age of Wealden type sediments in other parts of Spain, the continental deposition in the Sierra de los Cameros set in at a very early time and ceased just after the transition from the Jurassic to the Cretaceous.

Quintero Amador and Trigueros Molina (1956), who previously reported on the Cretaceous of an area of which the Sierra de los Cameros forms the northwestern half, also remarked that the Utrillas Beds strongly resemble those of the Wealden facies with the exception of the degree of cementation which is clearly less intensive, resulting in beds which are very little consolidated. This difference was also observed by Beuther (1966), as he reports *sandstones* in the description of the Urbión Beds and *sands* in the description of the Utrillas Beds.

THE STRATIGRAPHICAL POSITION OF THE VOZNUEVO FORMATION

As we have seen from the foregoing, the Voznuevo Formation is a constituent part of Ciry's 'upper sequence' of the Lower Cretaceous, which is developed in Wealden facies in the southern border zone of the Cantabrian Mountains. From the general description of the upper sequence, we may already notice a strong resemblance to the sediments along the southern border. The most striking fact is the scarcity and in this case even complete absence of limestones and marls in comparison with the lower sequence, although a fairly extensive lithological spectrum is present. According to Ciry (1939) there is (p. 78) 'a domination of coarse sands and gravel, showing cross-stratification; they consist of well-rounded quartz pebbles with a median size of a pill, drowned in finer siliceous sands' (translation by the present author). Apart from lignitic layers, which are not uncommon in our sediments, Ciry mentions, in the general description of the upper sequence, the appearance of azurite and malachite and impregnations of asphalt. Ciry's observation that in the upper part of the upper sequence exclusively fine-grained clayey sands are exposed, with a reddish or white colour, accompanied by micaceous clay layers, often ligniferous or with plant imprints, which are overlain by analogous deposits which contain a marine Cenomanian fauna is very important, as it is also a characteristic of the sediments studied at present.

Apart from these general properties of the upper part of the upper sequence, the sediments along the southern border of the Asturian Massif (Cantabrian Mountains) have been dealt with separately from other deposits of the southern border zone in Ciry's work. The richness in kaolinite appears to be the main reason for this special treatment. It is these sediments, to which the name 'Voznuevo Formation' has been given, that form the object of this dissertation.

We shall not deprive the reader of the description of part of the Voznuevo Formation, as given by Ciry. The easternmost location where these kaolinitic sediments appear is Cervera de Pisuerga (also the easternmost part of the area studied) where (p. 86): 'Below the marine Cenomanian a sandy to gravelly complex, more or less kaolinitic, can be observed, directly overlying the Paleozoic. We are dealing with coarse detrital deposits, cross-bedded, consisting of more or less consolidated gravel and coarse sand composed of siliceous, mainly quartzose, elements which are perfectly rounded. They are associated with kaolinitic sands and clays. The terms 'destroyed granite' or 'arkose' which have been used by Casiano de Prado (1850) and by d'Archiac (1853), respectively, to describe these deposits, are only locally applicable. Their colour is predominantly white because of the high content of kaolinite, but red and yellow colours were also found. The deposits have never yielded any fossils' (translated).

One of the most striking observations by Ciry concerns the geographical distribution of the formation. Not only does he recognize these deposits as far as La Robla, he even mentions the existence of these sediments, surrounded by Paleozoic (and older) rocks, near the village of Soto (=Soto y Amío) where 'they occupy the bottom of a valley'. As we have seen in Chapter II, this observation is absolutely correct.

Since 1852 most investigators have attributed a Cenomanian age to the deposits of the Voznuevo Formation. Karrenberg (1934) was the first to compare these sediments with the Utrillas Beds of the Celtiberian Chain. The former were not considered to be of Albian age, however, but were located at the base of the transgressive Cenomanian, as was done by other investigators. The conclusions with respect to the age of the Voznuevo Formation have been mainly based on investigations near Cervera de Pisuerga, where a section through the formation is indeed more complete than anywhere else. Investigations on the contact with the overlying limestones further to the west, however, showed that the Voznuevo sands are covered by successively younger stages transgressive to each other. As no lateral passages or interfingerings exist between them, the most obvious conclusion would be that the Voznuevo sediments are i n d e p e n d e n t of the sediments by which they are covered.

An interesting problem now arises, which was not solved by Ciry:

If the Voznuevo deposits are considered as transgressive, onlapping upon the basement, we may regard them as:

a. Belonging to the base of the Cenomanian along the whole border.
b. Not only belonging to the Cenomanian, but connectible to the overlying transgressive stages (Cenomanian, Turonian etc.).

Ciry lists the following objections against these two alternatives:

In case a the main transgression would begin in the Turonian, which seems in contradiction with the generally accepted history of the Cenomanian transgression.

In case b one will have to explain:

1. The remarkable equality in composition of the Voznuevo Formation in all outcrops.
2. The independence in lithology of the overlying stages (Cenomanian, Turonian etc.).
3. The absence in the overlying marine beds of pebbles derived from the Voznuevo Formation.

Possibilities a and b are shown in Figs. 7 A and 7 B, respectively; 'A' is for the most part a sketch of the Upper Cretaceous transgression over the Asturian Massif as originally proposed by Ciry, and referred to by many other investigators on this subject. The sketch presented here was extended to the west as far as Brugos de Fenar by Evers (1967). The second possibility is represented in 'B', which shows the diachronic character of the Voznuevo Formation.

Before giving our opinion on this problem, let us first consider some remarks by investigators in this area after the time of Ciry's publication.

Almela (1949), in his study on the possible extension of Carboniferous coal seams below younger deposits, accurately mapped the lines of outcrop of the lowest level of the Cretaceous deposits ('el Caolín') between La Espina and the Río Bernesga. One of his observations in this area should not remain unmentioned (p. 424):

'En el camino de Boñar a Adrados, en el contacto con el Paleozoico, se encuentra una curiosa formación cretácea muy localizada, ... integrada por areniscas bastas y duras, de color oscuro o rojo, de las que existen muchos bloques grandes y pequeños diseminados por el suelo'.

This is the same location where Evers (1967) erroneously mapped his limestone conglomerate. In part B of Chapter V more attention will be paid to the phenomena in this outcrop. Other facts on the Voznuevo Formation as given by Almela are the disappearance of the overlying limestones between Rabanal de Fenar and Candanedo de Fenar, and the thickness of the formation in the area between La Devesa de Boñar and La Ercina: 125 m. The age of the formation is still the main pro-

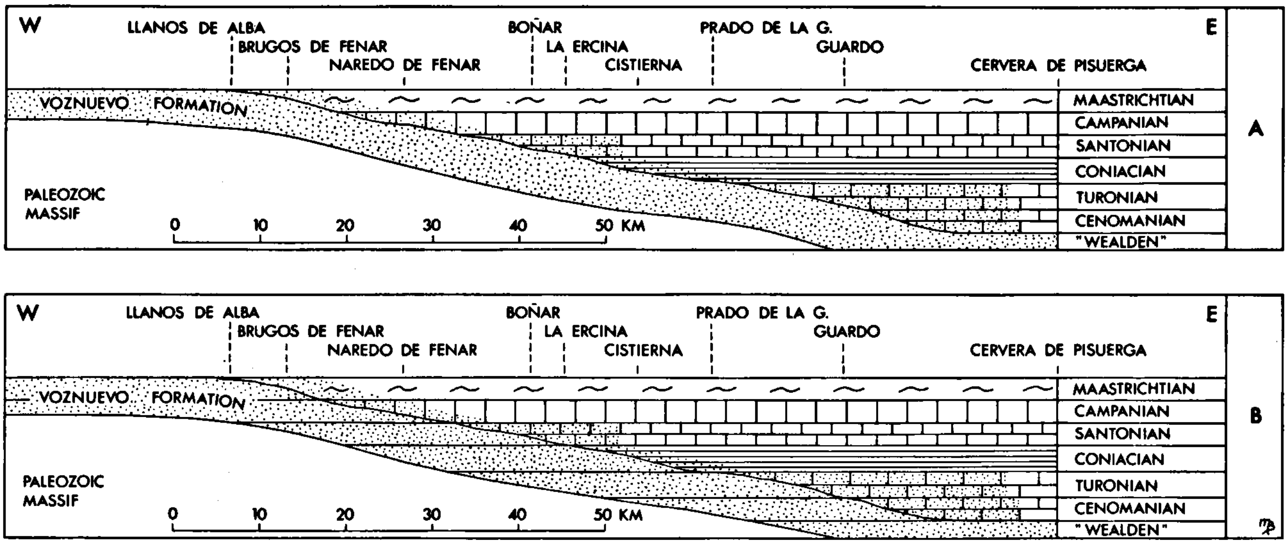


Fig. 7. Diagram of the Upper Cretaceous transgression along the southern border of the Cantabrian Mountains (modified after Ciry, 1939 and Evers, 1967).
A: Voznuevo Formation as synchronous deposits.
B: Voznuevo Formation as diachronous deposits.

blem; Almela observed 'analogous aspects' (=facies!) to the Albian deposits in the provinces of Burgos, Soria and Teruel. He is an advocate of Ciry's version of the Cenomanian transgression, i. e. with a slight unconformity between the Voznuevo Formation and the overlying stages, although this unconformity could not be seen in the field.

Two years later (Almela, 1951), a study with a purpose similar to that mentioned above appeared for the area W of La Robla. Again the sediments near Riello were recognized as Cretaceous; according to the author 'they form the westernmost outcrop of Cretaceous sediments in the province of León and in Old Castile'. Strangely enough Almela did not succeed in measuring the position of the stratification plane of the Cretaceous near Riello. The deposits near Tapia de Ribera were not regarded as Cretaceous (cf. Chapter III).

Pastor Gómez (1963) largely followed Almela with respect to the Cretaceous between the Río Luna and the Río Torío. The Mesozoic limestones still disappear between Rabanal de Fenar and Candanedo de Fenar, but they are limited at the top by a fault, which would be the cause of their disappearance. In accordance with Ciry and Almela, the age was considered to be Albian.

By far the most important contribution to the stratigraphy of the Voznuevo Formation was made by van Amerom (1965), whose pollen analysis proved a Cenomanian to Turonian age in deposits near Boñar and Cistierna.

Evers (1967), who introduced the name 'Voznuevo Formation', made a number of brief remarks on the formation, the quintessence of which is a bipartition into a lower complex with deltaic properties and an upper complex with lagoonal properties. He reported (p. 120): 'approximately 200 m downstream from the Puente Romano over the Porma River, poorly sorted gravel and sandstone lenses are accumulated in typical deltaic fore-set beds showing inclined cross-stratification. In the deltaic lower part (200 m), several allochthonous lignitic streaks (10 cm) occur. ... The upper part (200–400 m) of the Voznuevo Formation is composed of finer-grained, micaceous sandstones with carbonaceous clay lenses, but gravel streaks still occur.'

Unfortunately we could not recover the evidence on which these observations were based.

Apart from these workers, all others refer to the investigations by Ciry (1939), and do not present any new facts.

Continuing our discussion on the reconstruction of the Cenomanian transgression, we shall first summarize the evidence from which the schematic picture of Fig. 7 A has been obtained. As is to be expected, the determination of the age of the overlying complex has always been carried out by determining the fossil content of the limestones. Since the 'Wealden' of Fig. 7 proved to be unfossiliferous, its age could not be determined. Ciry's study of the distribution (i. e. the lateral extent) of the Upper Cretaceous stages along the southern border of the Cantabrian Mountains results in the picture presented in Fig. 7 A. For the locations mentioned below the reader is referred to the topographical map (Enclosure I).

The Cenomanian

As we have seen, the entire Voznuevo Formation has been considered as Cenomanian by various authors since 1853. This is in any case true of the deposits near Cervera de Pisuerga. Here the Upper Cenomanian consists of calcareous sands, alternating with sandy limestones, both rich in iron concretions, lignitic clays and sandy lignitic layers. Only in the very upper part of the Cenomanian are pure marly sediments found. As we could ascertain in the field, the contact between the Voznuevo Formation and the Upper Cenomanian (which was established in the field on account of the absence or presence of calcite) proved to be very gradational. Probably the marine transgression took place via a long period of brackish water conditions. Ciry found that only a few metres of this brackish-marine complex are left near Villaverde de la Peña.

The Turonian

The Turonian limestones, with a thickness of 12–15 m near Vado de Cervera, grow very detrital W of this location; their thickness also diminishes in this direction. Only sands and sandy limestones are found, intermingling with those of the Cenomanian. Thanks to the (scarce) presence of fossils, the Turonian is traceable as far as Guardo and possibly extends as far as Prado de la Guzpeña. Further to the west it is certainly not developed.

The Coniacian

The Coniacian is clearly traceable from Vado de Cervera to Prado de la Guzpeña, and is mainly deposited as white marls. From Valmartino, in the Esla valley, to La Ercina sands, conglomerates and sandy marls represent a littoral facies. West of La Ercina the Coniacian is no longer present. The Coniacian is plainly a regressive stage, as compared with the Turonian and the Santonian.

The Santonian

The Santonian consists at its base of white compact limestones, overlain by yellowish to reddish limestones and again white limestones. Changes in this pattern occur W of the Esla valley; the reddish limestones grow more and more sandy towards the west. Near La Ercina a more or less clayey, micaceous sandy complex with a rust-red colour has developed. The white limestones of the lower part have considerably diminished in thickness in this location, and directly overlie the Voznuevo Formation. Further to the west they only consist of limestone debris – rich in quartz – gradually passing into sandy limestones and even into sands. The white limestones die out before reaching La Devesa de Boñar. The mainly sandy complex which was studied in detail by Ciry E of Boñar is still present near Valdepiélago, the western limit of the area studied by him. According to Evers (1967), the Santonian disappears E of Naredo de Fenar.

Campanian and Maastrichtian

As far west as Guardo the Campanian and Maastrichtian are developed in the same facies as that east of Cervera de Pisuerga. West of the Esla valley, a considerable change in facies takes place: the lower part of the complex becomes sandy, while the upper part shows a marly development. In the very top of the Maastrichtian, sandy, green or variegated marls, deposited under lagoonal conditions (the so-called Garumnian facies), constitute the end of the Cretaceous sedimentation. The Campanian–Maastrichtian complex which, according to Almela (1949) and Pastor Gómez (1963), disappears between Candanedo de Fenar and Rabanal de Fenar, according to Evers (1967) and Kuyp (1969) NW of Brugos de Fenar, was found to be traceable as far as Llanos de Alba, west of the Bernesga valley.

Reviewing the lateral variations in these Upper Cretaceous stages, one important fact should be retained: all deposits of the various stages conspicuously pass into more sandy equivalents in the direction in which they wedge out. In the southern border zone this direction is always to the west.

If Ciry's first assumption (cf. 'a', p. 298) concerning the relation of the Voznuevo Formation to the overlying limestones is correct, we would be dealing with a Voznuevo deposit of, say, 300 m thickness deposited during the upper part of the Albian and the lower part of the Cenomanian, just before the transgression set in from the east. During the following stages, up to the Maastrichtian, the marine influence moved a little further to the west during each stage. This would mean that between the Upper Cenomanian and the Maastrichtian, the sediments of the Voznuevo Formation in the westernmost part of the area must have been exposed to erosion all this time, without being influenced. Of course the sediments can have been partially eroded and incorporated into the sandy facies of the overlying stages. In that case one should expect a coarse-grained residue and a diminished thickness of the formation in the western part of the area. Neither of these features could be observed, however. Apart from this, we should expect to find an unconformity between the Voznuevo Formation and the transgressive stages. The poor degree of exposure near the contacts does not shed any light on this problem either, no indications of a break in the sedimentary history have ever been found.

Regarding the second possibility (cf. 'b', p. 298) in which it was assumed that the Voznuevo Formation is the direct continuation of each transgressive stage, we shall have to refute the objections made by Ciry ('1', '2' and '3' of p. 298).

1. The following must be remarked with respect to the first objection, which questions the equality of the sediment during the whole of the Upper Cretaceous: As we have seen in the first parts of this chapter, sediments deposited in a Wealden facies have been reported from many locations in Spain, and from most diverging ages. They are found to have been formed during the entire Lower Cretaceous, while in one location deposition in Upper Jurassic times could be proved. The sediments can reach enormous thicknesses; even when marine intercalations occur during a considerable span of time, the continental deposits still reappear in the same Wealden facies (cf. Ciry's Northern Zone). A source area must have existed with an enormous capability of producing incredible quantities of clastic material of a fairly

constant composition. There is no reason whatsoever to assume that this state of affairs ceased during the Upper Cretaceous in areas which had not been invaded by the sea.

2. An independence of the Voznuevo Formation of the overlying stages does not show up at all. On the contrary, in the very few locations where a contact, however poorly exposed, could be seen, there are more indications of a very gradual transition: nowhere could a sign of a break in the stratigraphical continuity be observed. As Ciry noticed himself, all marine deposits grow shallow marine or lagoonal on approaching the contact with the underlying Voznuevo Formation, and sandy counterparts develop. As could be observed in thin sections of samples taken near the contact, there is a close textural and mineralogical resemblance between samples from the top of the Voznuevo Formation and the lower parts of the overlying stages.

3. The absence of pebbles derived from the Voznuevo Formation in the overlying marine beds is of course related to the gradational change-over mentioned under 2. Moreover, the solution of this problem is again given by Ciry himself, when he mentions in the description of his upper sequence (p. 78): 'A la partie supérieure cependant, et d'une façon très constante se montrent exclusivement des grès argileux fins, roux ou blancs, qu'accompagnent des lits d'argiles micacées, feuilletées, souvent lignitifères ou à empreintes végétales, et auxquels succèdent des dépôts tout à fait *analogues*, mais à faune marine cénomanienne'. From the sections through the Voznuevo Formation we shall see that the sediments are generally much finer-grained near the top of the formation. A possible cause for this fining upwards will be presented at the end of the next chapter. Probably a very small quantity of the sediments in the top was reworked and incorporated in the shallow marine deposits.

For these reasons, obtained from observations in the field and in thin sections, it becomes most likely that the Voznuevo Formation is indeed a diachronic deposit, and hence corresponding to successively younger marine deposits belonging to various stages in a westerly direction, representing their continental continuation. An irrefutable proof of this hypothesis, however, was found by pollen analysis.

POLLEN ANALYSIS

Part of the stratigraphical problems related to the Voznuevo Formation could be solved by palynological investigations. It was van Amerom (1965) who examined pollen and spores of three black clay samples from the locations Campohermoso (our Section J), S of La Mata de la Riba (Chapter V, B), and Soto de Valderrueda. Van Amerom found that in this part of the southern border zone the Voznuevo Formation must be placed in the lower part of the Upper Cretaceous, possibly Cenomanian to Turonian. This means that the sediments are younger than their eastern extension N of Burgos, which Ciry reported to be of Albian age. Although the diachronic character of the formation is clear from these determinations, nothing can be yet said about the stratigraphical relationships which prevail in the southern border zone between Riello and Cervera de Pisuerga.

Fortunately black clays proved to occur in almost every section W of La Robla. In the hope of finding differences in the palynological content from E to W, samples were taken from practically all locations where black clays could be found. Thirteen samples were kindly examined with a view to their organic contents by Dr. Th. van der Hammen of the Palynological Department of the Municipal University of Amsterdam. The thirteen locations and the stratigraphical positions of these samples are stated in the correlation chart (Encl. XI).

No detailed study could be carried out in the time available, but a rough determination led to a distinction between:

Lower Cretaceous samples – devoid of pollen of Angiosperms – containing *Classopollis, Araucariacites, Abiaetineaepollinites, Cicatricosisporites/Plicatella*

Upper Cretaceous samples – rich in pollen of Angiosperms – belonging to and showing relationships to the association described by van Amerom (1965): *Turonipollis, Conclavipollis, Classidites,* several tricolporatae and triporatae, *Cicatricosisporites, Plicatella* etc.

The Upper Cretaceous samples probably have a Cenomanian to Turonian age. This distinction made clear that nine samples must be located in the Upper Cretaceous and three samples in the Lower Cretaceous. As a precaution, one sample (183, Section P) was located in the 'Middle Cretaceous' (Albian to Turonian). The samples belonging to the Lower Cretaceous form a 'time wedge', bounded by line I in the correlation chart (Encl. XI). This wedge widens towards the east (as is to be expected in a diachronic formation). The Lower Cretaceous/Upper Cretaceous boundary clearly runs through sections S and T, in which samples could be taken from the bottom and the top of the section.

Although, due to lack of time, a subdivision in stages was, unfortunately, impossible, the time/formation relationship is clear enough to show that the second hypothesis proposed by Ciry (1939), mentioned on p. 298, must be the only solution: The Voznuevo Formation grows younger towards the west.

As van Amerom, we believe that the Voznuevo Formation is approximately equivalent in time to the Upper Cretaceous sediments in Wealden facies, deposited on the Massif of Oroz-Betelu ENE of Pamplona, and described by Ciry, Amiot and Feuillée (1963). Here approximately the same situation is encountered: the continental sediments which belong to Rat's (1959) 'complexe supra-urgonien' have been classified, after correlation with nearby deposits, either in the lower Cenomanian or the upper Albian. Just as in our area, both Jurassic and the remainder of the Lower Cretaceous sediments proved to be absent. The Cenomanian transgression hardly invaded the massif towards the east. A regression obviously took place in the Turonian to Coniacian in this area, no deposits of this age having been encountered; the sea did not return before the Santonian.

There are no indications of such a drastic regression in our area, but as we have seen from Ciry's description of the Mesozoic limestones between Cervera de Pisuerga and Boñar, the Coniacian proved to be clearly regressive as compared with the overlying and underlying stages. The relationships between the Voznuevo Formation and the Mesozoic limestones will be still better understood as soon as a more precise determination of the palynological contents of the black clays has been carried out.

A COMPARISON OF THE VOZNUEVO FORMATION WITH OTHER SEDIMENTS IN WEALDEN FACIES

Anticipating the lithological descriptions of the Voznuevo Formation in Chapter V, we may say that the Voznuevo Formation is distinguished from most other deposits in Wealden facies by the abundance of kaolinite.

Both the stratigraphical position and lithological properties (complete absence of limestone, degree of cementation, composition) suggest that the formation can best be compared with the Utrillas Beds. The description of the Utrillas Beds in the Sierra de los Cameros as given by Beuther (1966) could, with the exception of the formation of asphaltic layers, be a description of the Voznuevo Formation. Even the transition into the overlying marine Upper Cretaceous is identical, as is the total thickness of the complex. The distinctly lower feldspar content found in the Voznuevo Formation (cf. Chapter VIII), as compared with the Utrillas Beds, might be explained by weathering of feldspar into kaolinite. The question, whether this process took place in the source area or in the sediment, will be considered later.

Stratigraphically and paleogeographically speaking, the Voznuevo Formation shows a strong resemblance to the transgressive Wealden facies deposits of Cenomanian age described by Ciry, Amiot and Feuillée (1963) on the Massif of Oroz-Betelu NE of Pamplona.

SUMMARY

Wealden sediments, by which sediments in Wealden facies are always indicated, have been reported from many parts of Spain. Their age is highly diverging; they may range from the Kimmeridgian up to the Turonian, thus occupying a much larger time span than anywhere else in Europe. All sediments in Wealden facies seem to have the following features in common:

1. Their mineralogical composition has a rather uniform character, quartz being the main constituent.
2. They are poor in fossils or even barren.
3. Most organic remains are unidentifiable wood fragments.
4. Red-coloured sediments always seem older than their white counterparts.
5. The predominant colours are white, yellow and red (in order of importance) and all gradations in between.
6. Paleocurrents, when reported, always indicate directions from W, SW, S or SE.

A high kaolinite content has been reported locally.

When we compare the stratigraphical position of the sediments in Wealden facies in various parts of Spain, one general trend becomes very clear: in most areas the continental sediments are bipartite and are separated by products of marine sedimentation of roughly Aptian age.

As for the Basco-Cantabrian area, to which the sediments of the Voznuevo Formation are geographically related, it was found that sediments in Wealden facies, with a generally unknown lower age limit, have been deposited until the beginning of the Cenomanian transgression. In the southern and southwestern part of that area, continuous continental sedimentation took place, while in the northern and northeastern part a Wealden s. s. and a supra-Urgonian complex could be distinguished, separated by the Urgonian complex (Aptian to Lower Albian).

In other parts of Spain the supra-Urgonian complex has commonly been referred to as Utrillas Beds. The Utrillas Beds are completely identical to the older continental deposits (Dupuy de Lôme and Sánchez Lozano, 1956). Other authors (Quintero Amador and Trigueros Molina, 1956; Beuther, 1966) only report a difference in cementation. As for the source area, the Castilian Massif and, more precisely, the Sierra de Guadarrama have been mentioned.

The sediments of the Voznuevo Formation along the southern border of the Cantabrian Mountains have been the object of stratigraphical discussions for many years, owing to the lack of fossils and the absence of a lower stratigraphical boundary. Decrease in thickness and increase in the content of detrital material of the Cenomanian and Turonian marls towards the W indicate a transgression from E to W during the Upper Cretaceous. The problem as to whether the lower Upper Cretaceous stages are absent towards the west or continue in Wealden facies could be solved by palynological analyses. The Lower Cretaceous/Upper Cretaceous time boundary was found to run obliquely through the Voznuevo Formation, forming a Lower Cretaceous 'time wedge' open to the west (cf. Encl. XI). Ciry's (1939) objections to the connection of the sediments of the Voznuevo Formation to successively younger stages towards the west are not valid.

The sediments proved to be best comparable, as regards their lithological properties, with the Utrillas Beds, especially those of the Iberian Chain. The paleogeographical history can be compared with the transgressive Upper Cretaceous continental sediments of the Massif of Oroz-Betelu.

CHAPTER V

A. THE SECTIONS

INTRODUCTION

In the following chapter a number of lithological and sedimentological features occurring in the Voznuevo Formation will be described. An attempt to interpret the phenomena found will be presented in part B of this chapter.

As regards the lithological description of the formation, we shall confine ourselves to the main points; for a more detailed outline the reader is referred to the extensive sections (Sections A to T and Sections I'* to III; Enclosures II to VIII). Reference to the sections is made by mentioning the height in the sections in metres (m); in each section the beginning has been marked m 0, irrespective of the distance from the underlying formations. The area will be dealt with in three parts.

Before occupying ourselves with the sections, a number of general lithological observations have to be borne in mind: The Voznuevo Formation has a very uniform lithological character which remains constant along the whole mountain border.

Schematically four lithological types according to grain size can be distinguished in the field:

a. Conglomerates, consisting of pebbles, cobbles and boulders, only exceptionally exceeding 10 cm in diameter. The largest cobble ever encountered in the Voznuevo Formation had a diameter of 25 cm. Where these conglomerates have for a long time been exposed to the surface, they were found to be consolidated by cementation. Recently excavated conglomerates are mainly unconsolidated, except for relatively thin layers (less than 100 cm thick), which can also be consolidated. The conglomerates have an abundant matrix consisting of sand, fine gravel and very white-coloured, powder-like kaolinite. Sand-size and gravel-size particles have often been completely pulverized to silt-size. Channelling, cut-and-fill structures and festoon-like cross-bedding are the most common structures which could be observed. The colour of the conglomerates is mainly white, yellow and buff; only locally are brown, purple or pink discolourations encountered. In remarkable contrast to this generally light-coloured sediment are the dark grey to black lydite pebbles.

* I as Roman numeral in sections indicated by I'.

b. Sands, from very coarse to fine-grained sands, frequently found in combination with pebbles. Coarse sand with gravel and pebbles between 1 and 4 cm in diameter are by far the main constituent of the Voznuevo Formation. The sands have often been deposited in cross-stratified units, generally of the planar type. Distinct longitudinal and vertical grading, both fining upwards (cf. part B of this chapter) could often be observed. Fine-grained sands were always found accompanied by muscovite. The main colour of the sand-sized sediments is buff. Yellow and pinkish discolourations are frequent. Consolidation of the sands has taken place in gullies which fall dry seasonally.

c. Silts, always accompanied by large quantities of muscovite as in the fine-grained sand. Never cross-bedded unless in combination with sand; pure silts are always horizontally bedded or laminated. Colours are predominantly white with pink superficial discolourations.

d. Clays, nearly almost accompanied by and mixed with silts. Heavy clays proved to be very rare. The clays often form the top of fining-upward cycles. They are clearly more susceptible to discolouration than are sediments of other grain sizes. Variegation in colour is very great, the main colours for fresh clays being: olive green, light green and all shades between light grey and black. The greenish clays turn into clays with lilac and purple shades when exposed to the atmosphere.

THE AREA BETWEEN RIELLO AND LA ROBLA

The isolated area between Riello and Bobia is intersected by a number of N–S running small rivers, whose recent alluvial deposits cover their valley bottoms. For this reason exposures in the Voznuevo Formation can only be found on the higher situated parts between the rivers. Three rather incomplete and poorly exposed sections were made in this region. Between Carrocera and La Robla one section through the upper part and one through the lower part of the formation are presented.

Section A. –, a section west of the village of Soto y Amío*, west of the small pass in the road shows

* On previous maps the village along the road from La Magdalena to Riello is called Amío. By recent revision one village name 'Soto y Amío' is used on the road signs.

30 metres of Voznuevo section at an unknown distance* above the Precambrian and some 100 metres below the location where the Voznuevo Formation passes into the Vegaquemada Formation. As we have seen in Chapter IV, the Mesozoic limestones are absent west of Llanos de Alba, and the Vegaquemada Formation immediately overlies the Voznuevo Formation.

The quantity of coarse components in this section is striking, clays, silts and sands without gravel being almost absent. The lowermost ten metres of this section strongly resemble those which will be described in greater detail in Section F near Brugos de Fenar. They are composed of cross-stratified units of 60 to 100 cm thickness, containing pebbles to medium coarse sand. The units show a distinct grading, with clay balls in their lower parts. The three metre thick layer of clay (m 12 to m 15) apparently forms the top of a sedimentary cycle** which is fining upwards. Between m 15 and m 20 another cycle begins, but its top is not exposed. The top of the section shows very coarse deposits with diameters of up to 20 cm. Clay balls attain diameters of 40 cm. From m 32 onwards, grading no longer occurs and dashes of pebbles and cobbles are characteristic of the sedimentation pattern. These conglomerates are closely packed and scarcely cemented. Channelling, cut-and-fill structures and imbrication were frequently observed. Channel fills can consist of silt or clay.

Determination of the Quartz/Quartzite ratio (Chapter VI) brought to light that the composition of the coarse dashes changes with changing paleocurrent directions; a high quartzite content seems to be related to a transport direction from northern directions. The quartzites seem to have been transported over a relatively short distance, many of them being block-shaped with rounded edges. The geometrical features of the quartzitic layers from which they have been derived are still visible on these quartzites.

Section B. – runs immediately E of Soto y Amío, both north and south of the road. The oldest exposed beds lie about 30 metres above the contact with the Precambrian. Like the sediments in the top of section A, we are here dealing with very coarse deposits: coarse sand and gravel with 30 cm thick pebble layers containing clay balls. From imbrication in pebbles and cobbles and cross-bedding (with set thicknesses of up to 135 cm) in the sands directional observations could be made. These coarse sediments, although less than 10 metres are exposed in the section, have a thickness of at least 20 metres. On the southern side of the road some poorly exposed cycles could be observed. Notwithstanding the continuing presence of cobbles and clay balls, clay and silt participate in the sedimentation pattern.

Sections C 1, C 2 and C 3. – were measured north of the road near the pass west of Bobia. The first section (C 1) begins at about 5 metres distance above the Precambrian. Approximately 11 metres, mainly pebbles and cobbles, are overlain by 10 metres of clays and silts, apparently without any grading. The silts and clays, which have suffered from intensive discolouration, originally had a grey to white colour. At the base of section C 2 very closely packed quartzite conglomerates occur, almost without matrix, with cobbles up to 25 cm in diameter. Between these, silty clay and silty sand layers were found, 30 to 40 cm thick. Their transition into the surrounding conglomerates is always very sharp. Apart from some clay pebbles and intensively crushed quartz fragments, up to 92% of the pebbles coarser than 3 cm diameter consist of quartzite. As could be deduced from imbrication, the quartzites have been supplied from northwesterly directions. After approximately 20 metres of sands and clays, coarse deposits reappear (m 119 to m 126). The pebbly intercalations are almost exclusively composed of quartz. Some tens of metres north of the road, section C 3 shows four cycles from pebbles via coarse sand, fine sand and silt to clay. An erosion surface at the top of each cycle marks the beginning of a next cycle. The pebble beds at the bottom have often been consolidated by iron (hydr)oxides. Some 50 metres or more may cover the top of section C 3, bringing the total thickness of the Voznuevo Formation in this location to more than 350 metres.

South of Benllera, where the Voznuevo Formation was recognized underlying the Vegaquemada Formation (Chapter II), fine-grained deposits form the top of the formation. The coarsest material found is coarse sand, grading into silts and clays. The mean thickness of the cycles is about 4 metres.

West of Benllera, on the eastern side of the road from Otero de las Dueñas to León, the same situation was found, with the almost complete absence of gravel. Both outcrops have strongly been affected by weathering.

As we have seen from the description of the contact between the Voznuevo Formation and the Vegaquemada Formation SE of Carrocera (Chapter III), the sediments in the vicinity of the contact also consist of sands and silts.

Section D. – At the eastern side of the pass in the road from Otero de las Dueñas to La Robla, section D was measured in a clay pit approximately 1250 m E of the village of Olleros de Alba, S of the road. In this section information was obtained from the uppermost deposits of the Voznuevo Formation. As can be deduced from the section, pebble diameters never exceed 5 cm. The sediments exposed in this section form a sequence of cycles with a maximum thickness of 5 metres. The proportion of elements coarser than sand-size probably

* All distances have been corrected for dip and topography.

** Grading proved to occur in several dimensions. A grading composed of more than one cross-stratified unit will be called a cycle (cf. e. g. Allen, 1965a). Grading within a cross-stratified unit (from less than 10 cm to more than 200 cm in thickness in the sediments studied) will simply be referred to as grading, while grading within a foreset will be called vertical grading.

forms about one tenth of the total thickness (the excavated part included). In the lowest part of the section (m 1 to m 3) laminations between sand and silty clay occur.

Section E. –, directly west of the village of Sorribos de Alba on the northern side of the road, begins some 40 metres above the contact with the Paleozoic. Although clays and silts with Paleozoic cobbles and boulders immediately overlie the contact, it is assumed that the majority of the 40 metres between the contact and the section consists of sand and gravel. In section E two cycles can be distinguished, the pebble diameters in their respective lower parts seldomly exceeding 3 cm. In the top of the first cycle two well-exposed parts (m 7.5 to m 9 and m 13 to m 17, respectively) are presented in detail. The first detailed section shows five gradings from coarse sand to clay. The tops of the gradings are marked by alternations of silt and clay, thinly laminated, with an increase in clay stringers towards the top. The stringers are only a few millimetres thick, wavy, with changing thicknesses, but generally continuous. They are often surrounded by a thin film of reddish iron oxide, by which they are accentuated. The contact with the sand of the overlying grading is always sharp and erosive. The second detailed section shows the presence of black clay with lignite and coal-like fragments. The black clay exhibits a kind of efflorescence of sulphur, which results in a light to dark yellow foam-like cover. Towards the top a very thinly laminated alternation of sand (light red to brick red) and clay (light grey) was found (Fig. 30). The laminations are laterally traceable as far as the exposure permits. Within a thickness of 5 centimetres, 62 alternations were counted. The transition into the overlying sand is again very sharp and erosive. Apart from some grading in the second cycle in this section, no structures could be observed.

The black clay horizon of this section was again found in an excavation between Sorribos de Alba and Llanos de Alba, north of the road. South of the road a very sandy limestone outcrops between the Voznuevo Formation and the Vegaquemada Formation, the last witness of the Mesozoic limestones further to the east.

When we summarize a number of typical features of the deposits in the area W of La Robla the following must be stressed:

Section A: Cross-bedded gradings and clays in the first 20 metres of the section, with a close resemblance to the deposits which will be described in section F. Very coarse deposits with sudden changes in grain size in the top of the section. Dashes of imbricated, poorly rounded cobbles and pebbles. The locally high quartzite content seems to be related to paleocurrent direction. Channelling and cut-and-fill structures are common.
Section B: Lowest part of the section comparable with the top of section A, finer-grained sediments in the upper part.
Section C: Rather coarse character of the deposits in at least the first 100 metres, especially in the bottom of section C 2. Sudden change in character of deposition in section C 3, where cycles occur with a maximum thickness of 10 metres and with pebbles of moderate sizes in their lower parts. They show a much more regular sedimentation pattern than the deposits encountered in sections C 1 and C 2.
Section D: Completely comparable to section C 3, with a predominance of silts and clays.
Section E: Indications of sedimentation under rather quiet conditions throughout the main part of the section. First occurrence of black clays with organic remains. Very thinly laminated alternations of fine-grained sand and silty clay.

THE AREA BETWEEN LA ROBLA AND CISTIERNA

In this part of the southern border, which is by far the best exposed, a relatively close spacing of the sections makes correlation easier (cf. part E of this chapter). Between La Robla and Campohermoso the lower part of the Voznuevo Formation exposed here, could be studied in sections F, H and I; the upper part in section G and in Section II. Section J near Campohermoso occupies an intermediate position. Between Campohermoso and Boñar the formation proved to be traceable as far as La Vecilla, coming from the west. From here onwards, Paleogene sediments cover the Voznuevo Formation as far as Boñar, except for a small exposure NW of La Mata de la Riba. East of Boñar, the formation continues in two branches; the most northern branch comes to a dead end near the village of Colle, the other forms the continuation along the southern border. Sections K, L, N and M were all taken and measured in the area between Boñar and Colle; the first three in the lower part of the formation. In the strip between La Devesa de Boñar and the Río Esla section O could be made north of Yugueros.

Section F. – represents a cross-section, more than 110 metres in length, through two arroyos (and partly sand pits) NW of Brugos de Fenar. The two exposures are each other's complements, the change-over taking place at m 46. This transition happens to coincide approximately with a transition in sedimentation pattern: In the stratigraphically oldest exposure very sudden changes in grain size take place; 1 to 2 metre thick pebble concentrations are present as dashes between sands, silts and clays. Grading is not ubiquitous; sometimes reversed grading (i. e. coarsening upwards) could be observed. The first 23 metres of the section show a considerable amount of clay. The youngest exposure presents a much more regular pattern, since at least seven cycles could be discerned. Four of these are presented in Section I' (Enclosure VIII). In order to facilitate reference, the units of this section have been numbered in the left column. The four cycles comprise units 1 to 36, 37 to 54, 55 to 81 and 82 to 99, respectively.

Schematically such a cycle consists of (from bottom to top):

A basal zone with pebbles in a coarse sand matrix, with a maximum diameter of 6 cm, often orientated in an imbricated position, and clay balls, obviously derived from the clayey top of an underlying cycle (or, thinking in environmental conceptions, derived from nearby swamps beyond the natural levees).

Gravel and coarse sand in cross-stratified units about 35 cm in thickness, passing into units with finer sands less than 10 cm in thickness. The thickness of the set of cross-strata decreases with decreasing mean grain size of the composing material. In the cross-stratified units longitudinal and vertical grading (cf. part B of this chapter), both fining upwards, could frequently be observed.

Silts, parallel laminated, occur near the top of a cycle. They are homogeneous or alternate with more clayey layers.

Clays at the very top of the cycles; sometimes not developed, always partly eroded. They are well homogenized; burrowing, however, could not be observed.

The thickness of such a cycle proved to be about 7 metres (Fig. 33). The contacts between the cycles are always very sharp, large pebbles were found to have sunk into the underlying clay. Evidence from cross-stratification proved to be rather poor. Theoretical models and classifications as proposed, for instance, by Allen (1963a) are based on observations on more than one plane of intersection. Since in the present outcrop – as in many others – only one plane can be studied, classification such as carried out by Allen is hardly possible. Using Allen's descriptive terms we may say that the cross-stratified sets, as observed in the cycles of Section I', are grouped, large-scale (more than 5 cm in thickness), erosional with planar or slightly undulating lower boundary surfaces and homogeneous in composition. They seem to have most features in common with Allen's omicron-cross-stratification (Allen, 1963a).

Near the top of the section a black clay horizon occurs at m 110.

Section G. – shows a section along the La Robla to Boñar railway, between Rabanal de Fenar and Candanedo de Fenar. The stratigraphical distance from the outcrop to the Mesozoic limestones is some 100 metres or less, so that we are here dealing with deposits from the upper part of the Voznuevo Formation. For this reason we are not surprised to find deposits which strongly resemble those of sections C 3 and D. The only difference, however, is the presence of black or grey clays at the top of almost each cycle. Plant and wood remains are widespread throughout the section. Only at two cycle bottoms were sediments with a diameter of over 2 cm found; both these horizons show an erosive character with respect to the sediments on which they were deposited. The gravel and sand layers are frequently cemented by iron (hydr)oxides, showing two different patterns:

a. Parallel to the stratification plane; this can have formed either before or after tectonical deformation of the Voznuevo Formation.

b. Parallel to the topographical surface (in this case approximately perpendicular to the plane of stratification); a post-deformational feature.

Section H. – In this section, north of the village of Solana de Fenar, we return to the lowermost part of the Voznuevo Formation. The exposure is schematically comparable with section F, since one can distinguish, from top to bottom:

5. Black clays
4. Clays and silts (m 57 to m 82)
3. Sands and gravel (m 18 to m 57)
2. Clays and silts (m 1 to m 18)
1. Paleozoic rocks

Unfortunately, structures are generally obscured by weathering, so that a direct comparison is very difficult to make. Grading proved rather common, but transitions in grain size are more abrupt. Clay pebbles and clay balls are ubiquitous, even when the underlying unit does not contain clay but silt or fine-grained sand. From this we may deduce that lateral changes in grain size occur over short distances. The maximum diameter of the material deposited in this section was 11 cm.

Section I. –, opposite the village of Naredo de Fenar, 300 m north of the road, is almost identical to the base of the previous section. About 19 metres of fine-grained sediments were found on top of the Paleozoic, then a sudden change in grain size takes place and gradings of coarse pebbles into coarse sand could be observed. The lowermost grading (m 20) contains some coaly fragments. A conglomerate with a thickness of several metres forms the top of this section; the cobbles' and pebbles' longest axes have a very clear orientation parallel to the plane of stratification, but their position does not permit of any conclusions as to the direction of transport.

Section II. – has been draughted according to data from the eastern border of the Río Torío. Only during low water level is study of this section possible. The distance from the top of the section to the Mesozoic limestones is about 75 metres, the first well discernible limestones are exposed immediately S of the passage of the road over the river. The sediments in this section strongly resemble those of section G, which are situated at a comparable stratigraphical distance from the Mesozoic limestones. The most salient feature in this section is the abundance of wood fragments, large trunks and branches, which attain diameters of more than 30 cm. Fining-upward grading could always be observed; the greater part of the grading consisting of clay and silt. Sediments coarser than coarse sand hardly occur.

Grading in the inorganic components is largely reflected in the organic components, since the following associations could be observed:

coarse sand : trunks and branches
sand : large wood remains
silt : small wood remains and stems
clay : minor plant remains forming felt-like layers

In a few locations cross-stratification indicates a paleocurrent direction from W or SW, but measurements are not very accurate. As mentioned before, many black clays show an efflorescence of sulphur in foam-like bubbles. The high sulphur content is also reflected in the complete pyritization of many wood remains. Burrowing and rooting seem to be a fairly common feature in the black clays. An exposure of a section parallel to the plane of stratification (Fig. 31) shows extensive rooting up which might have been caused by dense vegetation. The deposits of Section II can be traced as far as Robledo de la Valcueva, where they are exposed in a brooklet at the eastern exit of the village, south of the railway. Immediately south of the railway, an older black clay horizon was found; its stratigraphical height can be compared with the position of the black clays in sections F and G.

Section J. – is situated north of the village of Campohermoso. It begins some 50 metres above the contact with the Paleozoic. The first 32 metres consist mainly of sand and gravel; concentrations of pebbles occur locally, sometimes as fillings of channels. Grading is rare and not very clear. Apart from some channel-like structures, the sand-gravel complex proved to be rather structureless. From m 40 to m 79 the coarse character of the sediments disappears completely; their place is occupied by fine-grained sands with silts and clays. About 26 metres of this fine-grained complex is presented in detail in Section III. From this section the abundance of organic matter, such as black clays and plant and wood remains becomes clear. The plant remains often have a peat-like character: fibrous with a light brown colour. A jet-like organic product, with a dark brown to black colour and a conchoidal fracture is also frequent. In unit 14 of Section III clay pebbles, coated with gravel and coarse sand, so-called armoured mud balls, could often be observed. Not only clay, but also wood fragments can be coated; in this case they could be referred to as 'armoured wood balls'. Desiccation of the central part of an armoured mud ball can form rattle stones, but these have never been observed in the Voznuevo Formation. The black clays are often veined by thin sand stringers (cf. Fig. 32). The sandy intercalations, which are only mm-thick, are clearly discontinuous and are only traceable in bundles. Sand lenses with an originally circular cross-section have been compressed into oval-shaped lenses orientated parallel to the plane of stratification. Unit 39 is presented in Fig. 36. This unit shows about 60 small-scale gradings from fine-grained sand at the bottom to silt or clay at the top. Even the thinnest laminations could be traced along the height of the exposure (approximately 300 cm). One such grading consists of:

c. clay, light to dark grey
b. silt, white to purplish
a. fine-grained sand, white, locally cemented by iron (hydr)oxides; in that case light brown

The sand and silt units are very rich in muscovite and small wood fragments. The contacts between the gradings are always very sharp: The sand has often sunk into the underlying clay causing an undulating boundary, sometimes leading to loadcast-like structures.

On top of the partly excavated part of the section (m 65 to m 78), grading units with sharp boundaries are exposed, which can reach a maximum thickness of 12 metres. Cross-stratification could not be observed in these gradings, but might be present. In the coarse deposits at the bottom of each grading, channels frequently occur. They are often for their most part filled with clay balls. A distinct grading from pebbles to silt and clay could also be observed within the channels.

East of La Vecilla de Curueño the Voznuevo Formation is not exposed as far as Boñar, with the exception of a very small exposure NW of La Mata de la Riba and an exposure S of this village along the western bank of the Río Porma. The latter will be described separately in part B of this chapter. The former exposure does not contribute much to our knowledge of the Voznuevo Formation (only poorly exposed sand with a black clay layer has been found), but one can establish with certainty that the Voznuevo Formation is present below the Paleogene cover.

East of the Río Porma two strips occur, in which sediments of the Voznuevo Formation outcrop. The northern strip between Boñar and Colle will be the first object of our interest. In this area which, as was mentioned in Chapter III, has only been moderately affected by post-Cretaceous folding and faulting, the strata have a uniform dip of 25° to 30° to the SW. Many abandoned sand and clay pits provide a better exposure of the Cretaceous than anywhere else and make tracing of lithological units over a distance of several kilometres possible. Two sand excavations, one 1.5 km east of Boñar, north of the road to Sabero, one south of the village of Grandoso, produced such well-exposed sedimentary structures that they will be dealt with in detail in part B of this chapter. Fig. 8 shows a schematical correlation of some NE–SW sections in the area between Boñar and Colle. From this correlation it becomes clear that the formation begins in this area with two conglomerates separated by a clayey or silty layer. The lithological composition of these conglomerates is different; the oldest conglomerate contains much more quartzite pebbles and cobbles than the younger one (cf. Chapter VI). Some 100 to 150 metres from the contact with the Paleozoic a first black clay layer was found; a second at approximately 50 to 70 metres below the

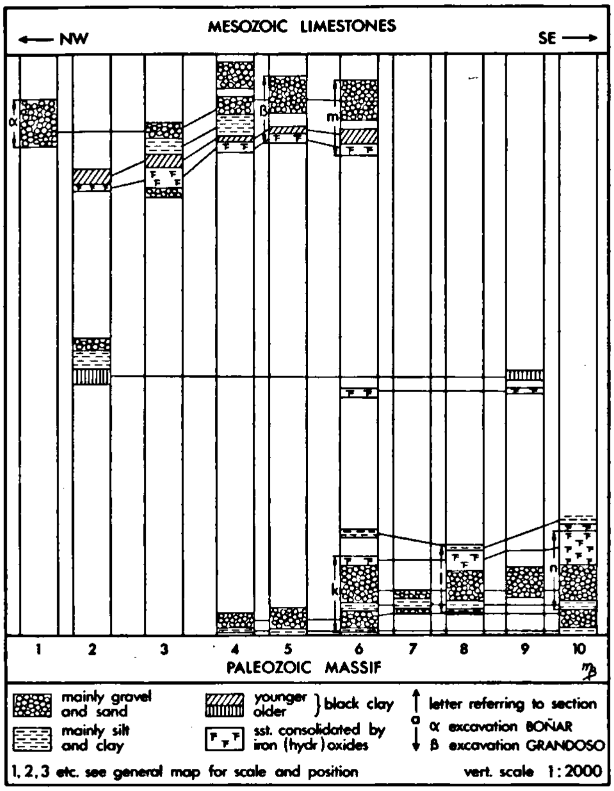


Fig. 8. Correlation of sections, excavations and exposures in the area between Boñar and Colle.

Mesozoic limestones. Between this layer and the limestones a mainly sandy complex with small pebbles has been deposited. The two sand pits mentioned above form part of this complex. The conglomerates near the contact with the Paleozoic are best exposed in the excavations in which sections K, L and N were made. They also outcrop in exposures which are not man-made, but in that case they have been cemented, such as east of the road from Boñar to Adrados, where Almela (1949) described the large consolidated blocks spread out over the surface (p. 298). This cementation continues as far as the exposure of the contact north of the village of Voznuevo (Chapter III).

Section K. – is situated between Grandoso and Colle, north of the road, some tens of metres west of km 6 on the Boñar to Sabero road. Both conglomerates (m 2 to m 7 and m 18 to m 32) are present. A few gradings could be observed between these conglomerates, but silts and clays form the main constituent of these sediments. The maximum diameter of the cobbles in the older conglomerate amounts to 16 cm, in the younger conglomerate to 13 cm. Imbrication is ubiquitous and has contributed considerably to the reconstruction of paleocurrent directions. The conglomerates hardly show any grading; the pebbles and cobbles rarely touch, floating as they are in a matrix of coarse sand and fine gravel. The coarse sediments at the top of the section (Fig. 34) seem to have been deposited under more tranquil conditions, the distinctly cross-bedded units with diverging paleocurrent directions are clearly different to the channelling in the lower part of this section.

Section L. – lies less than 100 metres east of section K. The second conglomerate, also about 14 metres thick in this section, is fully exposed. The components are somewhat coarser than in the previous locality, reaching diameters of more than 20 cm. Fig. 35 shows a detail of the conglomerate in which the very sudden changes, in lateral and vertical sense, can clearly be seen. The rest of the sediments encountered in this section do not differ very much from those of section K.

Section N. – West of the village of Colle, south of the church, section N was taken. From m 2 to m 20 the youngest conglomerate was again found. Especially between m 15 and m 20, a closely packed conglomerate was found in which a sandy or gravelly matrix is almost absent. Below the conglomerate in this section, 2 metres of the silts and clays which separate the two conglomerates are just exposed. The oldest conglomerate proved to occur east of section N in the village itself. The upper part of the section consists of considerably weathered gravel and sand. Only between m 32 and m 37 could some cross-bedding and channelling be observed.

Section M. – is a combination of three small sections south of the road from Grandoso to Colle. Compared with the sections from the lower part of the Voznuevo Formation, one notes a complete absence of pebbles larger than 5.5 cm in diameter. Sand and gravel, which are by far the most important constituents of this section, often show cross-stratification in which very accurate paleocurrent measurements could be carried out. The black clay horizon between m 19 and m 22, which was found in one location, can be correlated with the black clays of traverses 2, 3, 4 and 5 (Fig. 8). In the most easterly section this clay was found to be less dark; its colour changes from light grey to purple. The sediments of this section strongly resemble those of the sand pits near Boñar and Grandoso (Part B of this chapter).

In the southern strip only one usable exposure, some tens of metres below the Mesozoic limestones, was found between La Devesa de Boñar and La Ercina. Part of this exposure, the black clays occurring in the brooklet which flows in the bottom of the valley, will be described further on. About 20 metres below the Mesozoic limestones (approximately corresponding to the top of section M), the Voznuevo Formation can be studied over a stratigraphical distance of about 20 metres. As was to be expected, the sediments show a resemblance to those of section M. In contrast to the situation in section M, however, lateral traceability is not obscured by vegetation. The sediments mainly consist of gravel and coarse sand, grading into fine sand, silt or clay. The gradings have a thickness of between 70 and 100 cm; some beds contain cross-bedding with set thicknesses of 60 cm. The beds containing the coarsest material have been cemented by iron (hydr)oxides, they clearly stand out in topography, forming cuesta-like ridges. Comparing the gradings of this exposure with those of section M, the first seem to be more complete.

The exposures W and E of the village of La Ercina were found to be too decayed for detailed studies, so that only samples were taken in this area. Besides, tectonic movements must have been different here, since the strata have a dip of 15° to 20° to the SW in an excavation on the western border of the village, while a nearly vertical position was encountered everywhere else.

Section O. – is situated N of the village of Yugueros. A surprisingly small thickness of the formation was found in this location, the distance between the Paleozoic and the Mesozoic limestones being only approximately 127 metres. As in the exposure of the lower contact E of Carrocera, the Cretaceous is lithologically completely independent of the underlying rocks: in this location the Paleozoic consists of layered quartzites, while the conglomerates in the first 20 metres of the section are almost exclusively composed of quartz pebbles and cobbles. Only the first metres of the section show relatively coarse deposits, in the rest of the section pebble diameters to not exceed 2 to 3 cm. Sand and clay are found in approximately equal proportions. Grading is locally somewhat obscured by weathering. Between m 63 and m 73 strongly pyritized plant remains and black clays testify that vegetation played an important part during deposition. At m 82 armoured mud balls with black clay in their centres proved to be completely pyritized. Clay balls, found predominantly at the base of gradings, can reach diameters of 10 cm.

From Yugueros to the Río Esla, the Voznuevo Formation can only be traced by loose material in the soil; on the western side of the Esla valley the sediments lie in situ; coarse sand and pebbles up to 6 cm in diameter could be observed in this location. These deposits are completely cracked and disintegrated; their total thickness does not exceed 50 metres.

Summarizing the main points of the investigations of the sediments between the Río Bernesga and the Río Esla we can say that:

Section F: General pattern in the section based on grain size, from bottom to top: fine – coarse – grading units – fine. The coarse part of the section shows the same characteristics as those of sections A, B, C 1 and C 2. Sudden changes in grain size and scarcity of sedimentary structures (only channelling and imbrication occur). Clay layers are thin and show lateral thinning within short distances. In the part of the section which is covered by Section I' very well-developed fining-upward grading sequences with distinct mega cross-stratification show an obvious regularity of deposition. In the very top of the section a black clay horizon has formed.

Section H: This section shows a likeness to section F, it shows the same schematical division in grain sizes. Unfortunately the sediments in this exposure, especially in the part with the grading sequences, show a very poor degree of exposure.

Section I: The same distribution in grain sizes as found in the lower parts of sections F and H.

As in the area west of the Río Bernesga, the sediments of the upper part of the formation, as presented in section G and Section II, have a clearly different depositional character. Both sections are highly comparable and show predominantly fine-grained, upward-grading cycles between 50 and 300 cm thickness. Throughout both sections and throughout each grading organic remains proved to occur. The upper parts of the sequences consist almost exclusively of clays.

Section J: In this section, in which the contact with the Paleozoic is not exposed, the following division can be made:

1. A coarse-grained complex, structureless apart from some channelling.
2. A very fine-grained complex with black clays and sands, both with a very high organic content. Locally very thinly laminated alternations between sand and clay, in fact small-scale gradings, are exposed.
3. A complex with relatively coarse-grained grading-upward sequences.

Sections K, L, and N, which have all been made in the sediments which directly overlie the contact with the Paleozoic, are identical with the sediments in the same stratigraphical position further to the west.

Section M and section O, together with the exposure east of La Devesa de Boñar, all show the fining-upward gradings characteristic of the sediments in the upper part of the formation. The only difference with respect to section G and Section II is the scarcity of organic material in the cycles; only in section O do about ten metres of the section contain a considerable amount of wood remains and plant remains.

THE AREA BETWEEN CISTIERNA AND CERVERA DE PISUERGA

In part III of the area studied the Cretaceous, and particularly the Voznuevo Formation, is only exposed in a fragmentary manner as far as Guardo; from here to the east a continuous strip extends as far as the village of Traspeña. West of Guardo only one section could be made, situated SE of Cistierna, east of the road to Sahagún. Sections Q, R, and S, all three representing the lower sediments of the formation, are located between Guardo and Villaverde de la Peña. Section T, in the extreme east of the area studied, provides information on the sediments over the entire thickness of the formation. This section runs from Cervera de Pisuerga to Vado de Cervera, parallel to the south bank of the Río Rivera.

Section P. –, in the southeastern part of the village of Cistierna, shows that only 61 metres of deposits belonging to the Voznuevo Formation outcrop in this location. Only at the bottom of this section (m 3 to m 10) were very fine-grained deposits encountered, the remaining part of the exposure predominantly shows very coarse-grained sediments the most striking characteristic of which is the broken state of nearly all pebbles and cobbles; due to intensive weathering they can be crushed by hand. At m 12 very large trunks, often strongly pyritized, float in clayey sands. The whole unit shows a light yellow colour in the field, due to efflorescence of sulphur at the surface. Some large-scale grading can be observed throughout the section, since the upper 12 metres only produced pebbles with a diameter of less than 3 cm. Between the conglomerates intercalations of clay, silt or sand indicate rapidly changing sedimentary conditions in a vertical sense.

The Voznuevo Formation could also be studied behind the brick factory north of Valmartino and in the arroyo between section P and the location mentioned above. In the arroyo about 15 metres of clays, silts and fine-grained sands overlie the contact with the Paleozoic, before gravel occurs in considerable quantities. Near the factory the fine-grained deposits of the base are approximately 18 metres thick. The total thickness of the formation has increased to 120 metres in this location. The components of pebble- and cobble-size in these two exposures are also highly crumbled and weathered.

Opposite the village of Valmartino, on the northern side of the road, some metres of black clays are exposed at approximately 35 metres above the contact with the Paleozoic. These clays, containing a large proportion of pyrite, are very sandy and contain nodule-like inclusions and lenses, the thin sections of which will be dealt with in Chapter VII. The clays are intensively burrowed and comprise circular sand-filled tubes. The sediments show a great deal of folding. Crystals of gypsum, with a length of up to several centimetres, were often found lying along the surface. Within the sediment gypsiferous layers seem restricted to fillings of voids and along slickensides.

A discussion on the presence of gypsum in this location will be presented in Chapter IX.

The exposures east of Prado de la Guzpeña and north of Cerezal are both too fragmentarily exposed to draw many conclusions. It could only be observed that breakage of pebbles and cobbles – and hence strong compression of the strata – has still taken place in both localities. North of the railway near Cerezal, gradings occur, about two metres in thickness, from pebbles with a longest axis of 5 cm to silts and clays. Thin coarse sand layers below the coarsest deposits at the bottom of some gradings suggest the occurrence of backflow phenomena in these deposits (cf. part B of this chapter).

Between Puente Almuhey and Guardo only very small, isolated spots of Cretaceous sediments occur. They suggest the presence of Cretaceous below the younger deposits on the surface, but are unsuitable for sedimentological study.

North and south of the road from Guardo to Cervera de Pisuerga, at the eastern exit of the village of Guardo, the Voznuevo Formation is again found in its full extent. On the northern side of the road, a few metres from the contact with the Paleozoic, some 40 metres of poorly exposed sediments show coarse-grained sand with pebbles up to 6 cm in diameter (mean diameter 3 cm), forming the main portion of this exposure. They consist of gradings, varying in thickness from 50 cm to more than 250 cm. The upper parts of these gradings, varying in thickness from 50 cm to more than 250 cm. The upper parts of these gradings may contain fine sand, silt or clay, while clay balls are frequent in the lower parts. On the southern side of the road the relatively coarse-grained character found on the northern side of the road has completely vanished, only fine-grained sands, silts and clays being exposed. At 90 metres south of the road the occurrence of Mesozoic limestones was observed.

North of the village of Muñeca, the first 30 metres of the Voznuevo Formation are identical to the deposits near the contact in Guardo. Gradings could be distinguished, about 2 metres in thickness, with silts, silty clays and clays at the top. Rather conspicuous is a 15 metre thick complex of coarse sand and gravel, in which the mean pebble diameter is 3.5 cm, while maxima of 8 cm were found. The pebbles are concentrated at certain horizons which form the lower part of cross-stratified sets. Paleocurrent directions, estimated from foreset dips, gave results with very diverging directions: From SW, E and NE. On top of these mainly coarse sediments, about 10 metres of predominantly fine-grained sands, silts and clays have been deposited. A 70 cm thick black clay layer with wood remains of up to 10 cm and stems shows the transition to conditions in an environment of much lower energy.

Section Q. – was surveyed on the western side of the village of Las Heras, north of the road. The lowest part of this section (the first 50 metres) is characterized by a predominance of silts and clays. Two black clay horizons were found at m 37 and at m 41 to m 42.5, respectively. The first black clay only contains a small proportion of sand, as compared, for instance, with the black clays of the section near Campohermoso, or with those described in part B of this chapter. Stems 0.5 cm in breadth and burrows are the only macroscopical witnesses of organisms. Between m 41 and m 42.5 one can distinguish:

g. 16 cm of black clay with lenticular sand bodies
f. 30 cm of black clay with trunks and stems
e. 10 cm of gravel with pebbles, maximum diameter 6 cm
d. 2 cm of black clay, laterally eroded
c. 22 cm of medium coarse sand with small pebbles and a number of black clay stringers
b. 16 cm of dark grey to black clay with sand stringers
a. 15 cm of light grey clay

Both occurrences of black clay are accompanied by pyritization of the wood fragments, small pyrite nodules and efflorescence of sulphur. Unit e of the second black clay complex represents a sudden invasion of very coarse-grained material.

At m 51, sedimentation of sand and gravel set in which will last until the end of the section. Especially the deposits between m 51 and m 55 closely resemble those of Section I' near Brugos de Fenar. The rest of the section shows alternations of coarse sand with gravel in units between 25 cm and 100 cm thick. The coarse-grained sand fraction is very rich in muscovite. In some units cross-bedding could be observed and measured.

Section R. – is a section on the eastern side of the old village of Santibañez de la Peña, east of the river on either side of the railway. In the first 17 metres which overlie the contact with the Paleozoic, sands, silts and clays are exposed in upward-grading complexes. At m 5, brown to grey coloured fine-grained sand with small pebbles and plant remains was found locally. This sand is full of roots. From m 17 to m 52 coarse sand, pebbles and cobbles were deposited with very little fine sand and clay. Mega cross-stratification is very common. Grading in these units is only longitudinal, but the boundary between the units is always very sharp. Locally clay balls could be observed with considerable dimensions (up to 15 cm in diameter). The thickness of the cross-stratified sets varies from 70 cm in very coarse components to about 15 cm in coarse- to medium-grained sands. At m 33 a 110 cm thick layer of black clay with isolated sand lenses occurs in which organic remains such as leaves, stems and black wood remains are frequent. Towards the top clay – white sand alternations were encountered comparable to those in Fig. 32. The black clay unit lies between coarse-grained deposits and represents a very sudden change in energetic circumstances in the environment. From m 45.5 clear gradings are observable, usually with sedimentation of clays in their upper parts. These cycles have a maximum thickness of 8 metres. They closely resemble those of Section I'. Especially from m 60 to m 67, where the sediments are exposed in a gully polished by water, gravel and sand with clear cross-stratification with obvious tangentiality could very well be discerned. As in the exposure near Brugos de Fenar, the thickness of the sets decreases with decreasing grain size. The sets in the bottom of the gradings have a mean thickness of 60 cm; towards the top they proved to be only 25 cm thick. Clay balls mark the vicinity of clay not deposited in the section exposed. The bottom of the grading at m 69 comprises pebbles 6 cm in diameter, clay balls containing organic material and large trunks. The latter are often filled with gravel and are strongly pyritized. At m 78, south of the railway, a fault with an unknown throw occurs. The rest of the section is not exposed until the road, where black clays were found at the northern side of the road, Mesozoic limestones at the southern side.

As will be clear from the short sections E and W of section R (Enclosure VI), the black clay horizon at m 33 is affected by laterally rapidly changing thickness. This is one of the few localities in which beds can be traced over more than merely a few metres, and in which it becomes clear that the black clays are lens-shaped bodies which probably do not have a very large lateral extent.

Section S. – lies on the northern side of the road between Aviñante and Villaverde de la Peña, about 300 metres east of the railway station of a nameless, abandoned mining village. The section begins with badly exposed quartzite cobbles, belonging to the basal conglomerate (cf. Chapter III). From m 10 to m 42 fine-grained sands, silts and thick layers of clay predominate. Upward-grading proved to occur everywhere. The sands and the silts are both very rich in muscovite. Only near m 36 does a 35 cm thick layer of coarse-grained sand with gravel and cobbles up to 9 cm in diameter testify to a temporary increase in capacity of the transporting agents. From m 42 two gradings are exposed with coarse pebbles and cobbles in their lower parts.

Section T. – is the only section in the whole area studied where exposures from the lower part as well as from the upper part of the formation occur. This section was surveyed as far as m 175 along the southern side of the road from Cervera de Pisuerga to Vado de Cervera and further to the south for the rest of the section. As the Voznuevo Formation has not been covered by scree material from the mountains as is the case everywhere else (the boundary between the Cantabrian Mountains and the Meseta is shifted to the north in this location), the sediments have been exposed to the surface during a considerable time. This is probably the reason why the silts, sands and gravels in this section are superficially consolidated by iron (hydr)oxides.

The first 10 metres of the section form the eastern continuation of the basal conglomerate of the previous section. Closer inspection of this conglomerate brought to light that finer-grained intercalations, composed of sand and clay, occur between the closely packed cobbles. These intercalations cannot be traced laterally over long distances, since erosion of the conglomerates precluded their preservation. The transition between the conglomerates and the sands or clays is never gradual. The fine-grained intercalations can have a downward convex lower boundary which can only have formed as fillings of formerly eroded channels (cut-and-fill structures); they always show a fining-upward grading. Sometimes clay has been preserved in the very top, rich in organic material and with a light grey to black colour. In two fine-grained layers remains of a seatearth are presumed: the sands or silty clays in which they occur show intensive rooting up. Tube-like structures with diameters of up to 2 cm are filled with blackish peaty material.

From m 11 to m 47 at least, structureless sands occur, which alternate with large gaps in the exposure.

From m 68 to m 112 cross-stratified units are exposed, which may reach thicknesses of more than 200 cm. The maximum diameter of the cobbles is approximately 8 to 9 cm, the mean pebble diameter between 2 and 3 cm. Pebbles consisting of sand and gravel derived from the Voznuevo Formation itself were hardly encountered. Their percentage is so low that they were not considered in the determinations of the pebble composition (Chapter VI). A well-exposed part of the section near m 105 showed that backflow phenomena in the form of bottomset structures (cf. this chapter, part B) may accompany some cross-stratified units.

From m 111 to m 203 a combination was made of a couple of excavations in which grading cross-stratified units, generally not exceeding 100 cm in thickness, are common. The maximum pebble diameter has also diminished; only in one case was a value of 8 cm reached. Clays form the top of the gradings, but in many cases they will have been eroded and will only be preserved in the form of clay balls in the lower parts of the overlying units. At m 117 a 2 to 3 metre thick grading complex was able to erode downward into three underlying units. The most important clay horizon at m 137 was found to change laterally into a strongly burrowed black clay rich in muscovite. An overgrown slope at m 174 apparently causes a hiatus of about 200 metres in the exposure of the section. Closer examination of the structures in the Voznuevo Formation in this location by small-scale mapping revealed that the formation has been folded into a syncline which runs approximately parallel to the road from Cervera de Pisuerga to Vado de Cervera. This syncline is flanked to the south by an anticline. Both structures have an eastward dipping fold axis. Taking these structures into consideration we suggest that the overgrown slope must in the main follow the folded plane of stratification and that the hiatus in exposure comprises no more than only a few metres. This assumption was strengthened on finding a black clay horizon half-way the slope which may be correlated with the black clay at m 223.

From m 177 to m 189 mainly coarse-grained sand and fine-grained gravel of a buff colour form the cover of a hill which is shaped by the anticline. Strike measurements in the strata exposed on the hill-top turn round through nearly 270°. Cross-stratified units not exceeding 100 cm in thickness give rather diverging paleocurrent directions. The units are sometimes topped by a thin silt or silty clay layer. By far the most important contribution to the insight into the geometrical properties of these cross-bedded units is the exposure of a principal bedding plane, the only one in the area studied. From this exposure it became clear that the cross-stratified units in this part of the formation have straight to very slightly undulating ripple crests (Fig. 37). On top of the unexposed part at m 190 similar sands and gravels occur as those covering the top of the hill, but red to purple discolourations give them a different appearance.

From m 202.5 onwards fine-grained deposits prevail. Thick clay layers may reach a thickness of more than 500 cm. The uppermost clay is divided in two by a consolidated coarse-grained sand layer which shows an alternation of light grey shale-like clay and sand in its top. The latter contains brown plant remains, leaves and stems. The clay underlying these sandy intercalations does not contain any macroscopic plant remains; its colour varies from light grey to light green. The overlying clay, again with a shale-like appearance, is thinly laminated and has a light grey to brown-grey colour. It is very rich in muscovite and shows an abundance of wood remains, plant remains and stem fragments. Layers with exclusively organic remains occur locally. Some tens of metres towards the west the intermediate sand layer reaches a thickness of 400 cm, thus forming a lens-like sand body within the black clay horizon. From m 175 to m 225 many slickensides indicate the presence of – probably small – faults. Approximately at m 252.5 the first appearance of Mesozoic limestones was observed. On top of about 15 metres (estimated value) of limestones some 16 metres of deposits closely resembling those of the Voznuevo Formation are exposed before the Mesozoic limestones reappear. At a distance of 100 cm from the top of the first limestone layer one may distinguish:

f. see e, calcareous.
e. 600 cm of medium to fine sand, cross-bedded, locally accentuated by thin dark brown stringers consisting of muscovite and light brown wood remains.
d. presumably black clays.
c. 200 cm of medium to fine sand, consolidated, cross-bedding common.
b. 150 cm not exposed.
a. 400 cm of medium sand to silt, locally consolidated by iron (hydr)oxides and very rich in muscovite. Large concentric concretion-like bodies several metres in width and approximately 50 cm thick have formed in these sands. Thin black clay layers are frequent.

We have drawn the boundary between the Voznuevo Formation and the Mesozoic limestones between units e and f.

The sediments between the limestones are lithologically not distinguishable from the sediments at the top of Section T and in all probability belong to the Voznuevo Formation. The only difference which can be observed are the traces of intensive tectonic deformation which manifest themselves as folds, faults and slickensides. An approximately 40 cm thick consolidated sand layer which has been broken and compressed into imbricated scales constitutes evidence of strong movements. The doubling of the contact between the Voznuevo Formation and the Mesozoic limestones was presumably caused by faulting in the upper part of the Voznuevo Formation in which the black clay horizons could have acted as lubricating layers.

A number of features from the sediments in the area between Cistierna and Cervera de Pisuerga can be summarized as follows:

Section P: Transition from sediments comparable to those of sections K, L and N in the lower part of the section to sediments with a certain cyclicity and of a smaller grain size. The influence of tectonic movements in this part of the area is striking. This is reflected by a strongly reduced thickness of the formation in this location and by intensive crumbling, especially of the coarsest components.

North of the villages of Guardo and Muñeca, gradings from pebbles or even cobbles into silts or clays form by far the main portion of the sediments exposed. Paleocurrent directions measured in cross-stratified units are very divergent.

Section Q: This section is clearly bipartite, with a predominance of clays and silts in the lower part of the section and grading units consisting of gravel and sand in the upper part. The coarser sediments of this section and those of the excavations near Guardo and Muñeca are devoid of the rapid changes in grain size characteristic of the sediments in the lower part of the Voznuevo Formation further to the west.

Section R: Sediments resembling those of, for instance, the upper part of Section F. Fining-upward grading units are common. In this section it becomes clear that the black clay horizons are in fact lens-shaped bodies with a maximum extension of only some tens of metres.

Section S: Apart from a quartzitic basal conglomerate, predominance of relatively fine-grained deposits in fining-upward grading sequences. They resemble the sediments encountered in the upper part of the formation further to the west, for instance those of Section D.

Section T: Fragmentary exposure of the entire formation, beginning with the continuation of the basal conglomerate found in Section S. From m 68 to the upper end of the section at m 252.5 a fining-upward trend of the formation as a whole could be observed. The transition into the overlying Mesozoic limestones is very gradual. Faulting in the upper part of the formation is probably responsible for doubling of the contact.

B. SEDIMENTARY STRUCTURES OUTSIDE SECTIONS A TO T AND I' TO III

TYPES OF STRUCTURES IN GENERAL

The sedimentary structures occurring in the Voznuevo Formation can be roughly subdivided into three groups, depending upon their grain sizes:

a. Structures in fine sand, silt and clay, as described, for instance, in Section J and in this part of the chapter (locations La Mata de la Riba, La Devesa de Boñar and the excavation near Grandoso), consisting mainly of parallel lamination, with occasional small-scale cross-stratification in the coarsest constituents. This kind of sediment is very often intensively burrowed by organic activity. The clays are frequently grey to black coloured due to organic remains.

b. Structures in medium sand to gravel (up to medium pebble size, 3 cm in diameter), frequently showing mega cross-stratification, with tangential foresets. The crestline pattern of these mega current ripples is straight to slightly undulating. Although transverse sections are very rare, we believe that the type of mega cross-stratification is intermediate between planar- and trough-type cross-stratification, tending much more towards the planar type. Bottomset structures such as backflow phenomena, and related structures, proved to be common. They will be extensively dealt with in this chapter.

c. Structures in coarse sand to pebbles and boulders; often found as eroding channels with a width of a few metres and a width:depth ratio (x100) varying from 400 to 600.

CHANNELS BETWEEN BOÑAR AND VOZNUEVO

As the structures mentioned under a and b will be described separately in this part of the chapter, we shall first consider the coarsest deposits. From the description of the sections we have seen that E of La Robla the deposits of pebble and cobble size only occur in the lower part of the Voznuevo Formation. Unfortunately, we usually obtain information from exposures in walls of excavations, in which only channels eroding each other can be recognized. The width:depth ratio, as well as the paleocurrent direction, can only be estimated, both with doubtful accuracy. Circumstances are much more favourable between Boñar and Voznuevo, near the contact with the Paleozoic. Here the formation is locally superficially consolidated on the SW dipping mountain slope. As a result of differential weathering, channels which can be studied in three dimensions have been weathered out. In two locations, NW of the village of Boñar (directly E of the tarmac road to Adrados) and N of the village of Voznuevo, the axes of a number of channels, and hence the paleocurrent direction, could be determined in the field. In both locations we are dealing with coarse deposits directly overlying the Paleozoic.

The results of the paleocurrent direction measurements are given in Fig. 9 and on the general map (Enclosure I). Distribution of current directions proved to be rather small. In the location Boñar all measurements lie within an angle of 90°, at Voznuevo even within an angle of 45°. The median direction for the Boñar area was approximately from the W (262°); for the Voznuevo area from the WSW (249°). These data fit perfectly with the directions found from measurements on foreset-dips in mega cross-stratification in comparable levels in the formation.

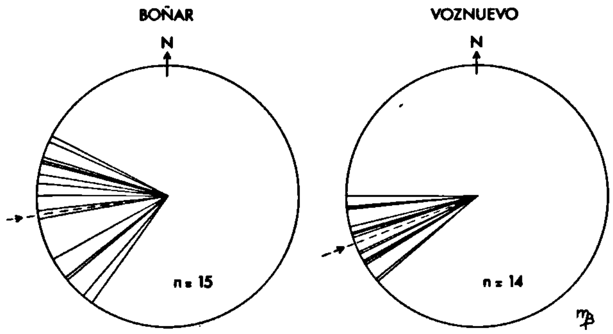


Fig. 9. Compass-cards of paleocurrent measurements in channels NE of Boñar and N of Voznuevo. Arrow indicates mean direction of supply (n= number of measurements).

Two examples from the Boñar area have been chosen in order to illustrate these channels. Fig. 38 shows two channels; the left one, just visible on the left hand side of the figure, with a current direction from 280°, the right one with a direction from 295°. The photograph is taken approximately in the direction of the channels, looking downstream. On the principal bedding plane a slightly undulating boundary between the channels can be seen. Differences in grain size are well-pronounced as a result of weathering.

THE MECHANISM OF BACKFLOW

Uncommon types of mega cross-stratification were encountered in the Voznuevo Formation. In order to compare these types with findings by other investigators, a short introduction with a description of similar phenomena will be presented here. These phenomena have been described as having been generated by reverse circulation or countercurrent or, more frequently, by backflow. These three names are used for one and the same process. Following the use in recent literature (Boersma, 1967) we shall use the term backflow (Jopling, 1961).

One of the first descriptions of backflow sedimentation was given by Allen and Narayan (1964) in their sedimentological investigation of the Folkstone Beds (Lower Albian) of the English Weald. The lithological composition and the presence of ammonites, together with wood remains, indicate a relatively shallow marine environment. Here, two types of cross-stratification based on foreset shape are distinguished:

Type I, with straight foresets which form an acute angle to the base of the unit. They show a concentration of coarse grains at the base of the layer (longitudinal grading) and a grading from fine to coarse in the foreset layer, perpendicular to the stratification of the foresets (vertical grading).

Type II, subdivided into subtypes a and b. In subtype IIa the foresets meet the base of the layer tangentially. Longitudinal grading is lacking, the median grain size at the base being even smaller than the median grain size in the foresets, while vertical grading has developed as in type I. Subtype IIb is similar to subtype IIa, but with silt bands between the foresets and the bottomsets. The angle between the foresets and the base of the unit is generally very small (less than 10 degrees). The bottomsets between the silt bands show an internal small-scale cross-stratification, which can have a direction either opposite to the direction of the foreset in the same unit or in the same direction as the foreset (reported in fewer cases). These two directions can appear together, the oppositely directed small-scale ripples always being closer to the adjoining foreset.

According to experiments carried out by Allen (1965d), vertical grading in the foresets, as found in all three types, is caused by filtering of finer grains through coarser ones, when avalanching takes place on the lee-side of a large-scale ripple. The coarser grains, moving on the surface, overtake the finer ones and concentrate near the toe of the foreset. This causes longitudinal grading as described in type I. With increasing flow velocity, avalanching becomes more frequent; there is insufficient time for filtering and therefore longitudinal grading becomes less well developed. This means that relatively higher flow velocities over the large-scale ripple crests were involved in types IIa and IIb than in type I. The silt bands formed between the groups of foresets seem to be in contradiction with an increase in flow velocity and must be explained in a different manner. This process could be visualized experimentally by varying the speed of the flow. China clay was used to replace the silt and marine conditions were imitated by adding salt to the water, in order to accelerate the process by flocculation. According to Allen and Narayan, the three types of mega cross-stratification as found in the Folkstone Beds are thought to have been formed under shallow-tidal conditions, the types I and IIa originated under normal tidal flow conditions, while type IIb '... could have been formed from ripples that travelled only when enhancing storm currents arose, silt being deposited on the stationary ripples during normal tidal conditions'.

Nothing has as yet been said about the process creating the small-scale ripples in the bottomset layer. The mechanism involved is best visualized in Fig. 10, according to Jopling (1964) and Boersma (1967). Expansion of the water-body at the lee-side of the ripple leads to flow separation. The remaining space is filled by a reverse circulation system (backflow) capable of forming oppositely directed small-scale ripples in the bottomset layer. The main flow is also responsible for the small-scale ripples directed in the same sense as the mega ripple (coflow, see Fig. 10). Between these two small-scale ripple systems, at the place where the main flow impinges the bed, an 'erosion hollow' (Allen, 1965d) is formed. The backflow is able to sweep relatively coarse grains up the foreset surface; this leads to the formation of upward directed wedges ('nose-like intrusions') between the foreset beds.

More detailed information on small-scale structures

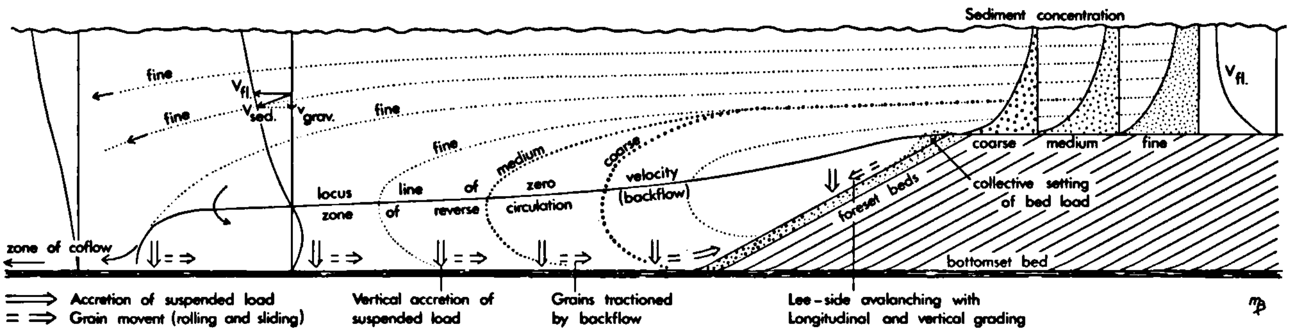


Fig. 10. Geometry of flow over a ripple with long stoss-side demonstrating topset-material differentiation and lee-side area transport and sedimentation under the action of a reverse circulation (backflow) (According to Jopling, 1963, modified by Boersma, 1967).

accompanying mega cross-stratification was given by Boersma (1967). In this case, the sedimentary environment in which the structures were found is known with certainty, the sediment studied being a subrecent deposit in a meander bend of the River Rhine. In this exposure, a large weir-lock excavation near Amerongen (The Netherlands), Boersma distinguished eight types of mega cross-stratification with bottomset structures, arbitrarily chosen from constantly changing patterns. In one of the best developed examples, from which a lacquer peel was made, the large-scale foresets are underlain by:

4. subhorizontal coflow sets
3. irregular transition zone
2. climbing backflow sets
1. even lamination

Boersma's statement that vertical grading in the large-scale ripples may be from fine to coarse (from bottom to top), but '...exceptionally was a distinct 'reversed' vertical grading from coarse to fine upward encountered' is of great importance since this is in contradiction to vertical grading as described by Allen and Narayan.

Characteristics of the bottomset layers are: climbing and tangential backflow cross-stratification, both indicating supply from suspension, and cross-stratification resembling wave-built ripples in the transitional zone, due to fluctuations in stream velocity in this zone. The supply of suspended material must have been sufficiently strong to cause deposition in the transitional zone and in the coflow zone, notwithstanding the fact that these zones are expected to be exposed to erosion.

According to Allen, tangentiality of the large-scale foresets was caused by a high rate of suspension plus a high rate of flow velocity. The apparent connection between these two factors, however, is caused by the deficiency in Allen's experiments. As Allen used a closed system for his experiments, no material from outside was available and the stoss-side of a ripple was therefore the only supplier of material deposited on the lee-side of the same (or next) ripple. For this reason it is expected that a lower current velocity with a larger supply of suspended load may produce the same structures as a higher current velocity with constant avalanching.

The greatest difference between the backflow cross-stratification in a fluvial environment and in a tidal environment is the occurrence of silt bands in the latter deposits. These silt bands always seem to be related to backflow cross-stratification and are superimposed on the mega foresets without interacting with them. Boersma explains these phenomena, which are described from the Folkstone Beds, as belonging to purely tidal water movements. The backflow ripples and the silt bands both originated during a slackwater period, the first during a short one, the latter during a long one, respectively. Boersma does not explain why this clay and silt cover is not eroded by the next main tidal phase. Cohesion of clay particles, as observed on tidal flats, is probably the cause.

Though (a) climbing backflow ripples, (b) deposition in areas expected to be erosional and (c) tangential foresets are the three main phenomena indicating a large supply by suspension, Boersma's fourth indication that 'thick bottomset layers in some instances make up as much as 50% of the total set thickness' does not seem quite reliable to us, since an unknown part of the total set might have been eroded.

Other properties of backflow cross-stratification were reported in relation to the mega cross-stratification of one and the same set, again from the Amerongen excavation, by Boersma et al. (1968). Measurements comparing ripple crest orientation of both mega and backflow ripples brought to light that the ripple crests are oblique and sometimes perpendicular to each other, the deviation varying from 10° to slightly more than 90°. This divergence from the theoretical picture was ascribed to transverse, or radial, flow, which is common in meandering rivers. Deviations in the Amerongen exposure proved all to have the same direction, indicating a right hand turn of the river. As in this case subrecent sediments are involved, the configuration of the river bend was easily reconstructible. A schematic plan view of the interaction between main flow, radial flow, and backflow in front of a mega ripple-front is presented in Fig. 11. Boersma et al. propose to name the backflow current with a deviation of 90° 'secondary flow'. In our opinion this term might cause much confusion, backflow itself being a secondary flow! We therefore propose to use the term 'sideflow' in cases where the angle between main flow and backflow is less than 120°.

With these facts on backflow cross-stratification in

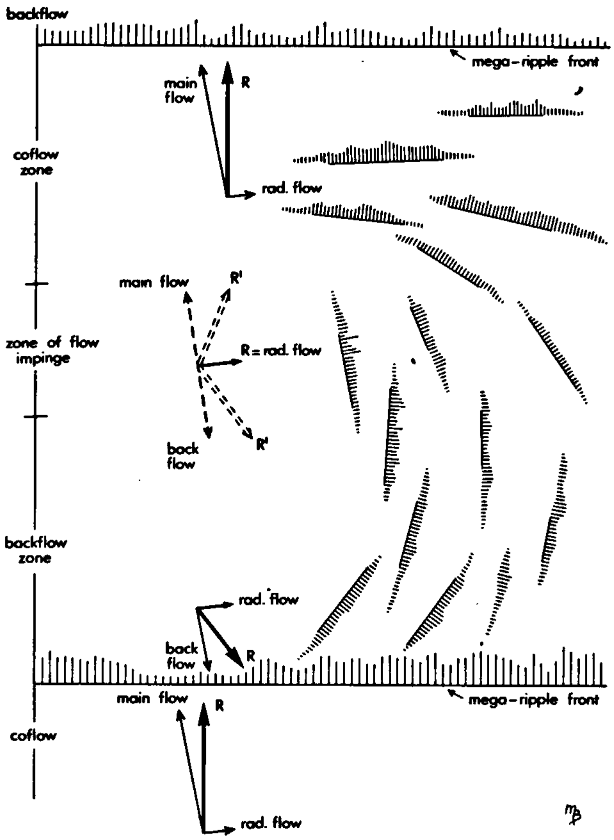


Fig. 11. Strongly simplified plan view of the area between two mega ripple fronts drawn with straight crests. The local flow (R) is the resultant of radial flow and mainflow (or backflow) (According to Boersma et al., 1968).

mind we shall now take a closer look at two excavations in the area between Boñar and Colle.

THE EXCAVATION S OF GRANDOSO

The excavation situated directly on the southern border of the village of Grandoso is the only sand pit still in use. Consequently, the appearance of the quarry changes daily, especially in its south-eastern part. In the summer of 1970 the excavation was about 130 m long and some 40 m broad. The sand that is exploited is situated between two horizons, consisting mainly of clay and silt, which probably formed two levels on top of which ground waters accumulated before tectonic deformation of the formation took place. On top of the lowest layer, a thickness of about 10 m of the overlying sediments is more or less consolidated by the formation of iron crusts. These have generally developed parallel to the stratification and show a preference towards pebble-size sediments since these have the highest permeability. In addition, these coarser parts are nearly always found at the base of a grading sequence, on the fine-grained top of the underlying one. Sometimes pockets extending to an underlying coarse-grained horizon may occur. In these first 10 metres thin clay horizons have developed which never reach a thickness of more than 10 cm.

The lowest fine-grained layer consists of at least 300 cm of fine-grained sand, silt and clay. The clay is rich in organic matter, and has a light grey to black colour. Cross-lamination rarely occurs in this layer, while even lamination is common. Only in a 20 cm thick clay layer was. some cross-lamination encountered in sand bands 3 mm in thickness. A closer look at these 300 cm revealed them to consist of a number of units with a grading fining upwards. Fine sand and silt contain finely spun wavy clay stringers, generally traceable in bundles and not individually. The maximum thickness of these stringers is 1 cm. Concentration of iron (hydr)oxides appears mainly to take place in the silt fraction, which results in light brown coloured, sometimes isolated patches. Apart from this, some flow-like structures of unknown origin occur in these deposits. The sediment must have been very soft at the time of its deposition. The black to grey coloured clays are rich in sand lenses; many tube-like sandy structures are formed by burrowing organisms and/or plant roots. These small-scale structures are again comparable to those found in section J near Campohermoso.

The following 10 metres, already mentioned above, are poorly exposed, but probably do not differ very much from the 13 metres by which they are overlain (apart from the iron content). The latter, mainly cross-bedded, 13 metres of sediment are chiefly composed of coarse to medium-grained sand, never exceeding pebble-size, not even at the bottomsets of the cross-stratified units. Except for one case with a thickness of a cross-bedded unit of 250 cm, no units thicker than 150 cm were found; 15 cm proved to be the minimum thickness.

Enclosure X gives a general view of the SW wall of the pit; this wall is exposed in its full width. Here 7 sections were made with a mutual distance of 10 metres (I–VII), 3 with a mutual distance of 20 metres (VIII–X). Measurements of paleocurrent direction were carried out according to the technique described elsewhere in this chapter. The results are subdivided according to four quadrants on the compass-card, from 1 to 4 (see Enclosure X). From this it became clear that paleocurrent directions vary between directions from NW to SW, except for the area between the dashed lines, where paleocurrent directions from SE to S prevail, together with a number of cross-stratified units, laterally not traceable further than 15 metres, with varying directions, some of which from the NE. The base of the area with almost opposite directions is clearly elevated in the SE part of the wall, the total thickness of this unit diminishing to 90 cm in section IX.

The mega cross-stratified units belong to Allen's planar type, with sometimes a very slight tendency towards his trough type. It is, however, very difficult to pass a definite judgement on a special type of cross-stratification, as a principal bedding-plane section is never exposed. Using descriptive terms, these current ripples can be designated as: large-scale, grouped, erosional, mainly planar and homogeneous. It is very surprising and highly peculiar that backflow phenomena appear to be the rule rather than the exception. In many cases small-scale backflow ripples could be assumed from the grain size in the bottomset layer of the cross-stratified unit, or could be studied in the 'natural' section (cleaned by wind action). In seven cases, as indicated in Enclosure X by BF, the direction of the backflow foresets could be determined accurately and compared to the direction of the foresets of the mega ripples belonging to them. The angle between the flow direction of the mega ripple and the small-scale ripple ranged from 83° to 180°, always in a clock-wise direction. Applying Boersma's relation between these two directions and the radial flow in a meandering river, all these structures could originate in a river bend with a right hand turn.

Backflow structures can manifest themselves in various ways:

1. As fine-grained bottomset layers, laterally traceable along several metres.
2. As individual 'bottomset channels'.
3. Only visible as 'nose-like intrusions'.
4. As oppositely directed small-scale ripples in mega ripple foresets.

It is unfeasible and of little use to describe the wall in its entirety in as detailed a manner as possible. A few illustrative examples of sedimentary structures, elucidated by figures, will therefore be selected. Fig. 39 gives an outline of a mega cross-stratified topset with backflow structures in the foresets and of a bottomset layer built up by backflow (section I). This unit can be traced laterally for about 20 metres. The bottomset structures consist of backflow crossbedding in two channels, each 100 cm wide and with a maximum depth of 10 cm. The thickness of the backflow set in the mega ripple is 8 cm, while the thickness of the mega ripple foreset varies between 5 and 8 cm. The sediment affected by backflow looks much finer-grained than its surrounding sediment. This apparent difference in grain size has been ascertained by determining the grain-size distribution of a sample from the backflow zone (063) and a sample from the mega set (064). From these data two cumulative curves were constructed (Fig. 12 A). As was to be expected, sample 063 is much finer-grained; it

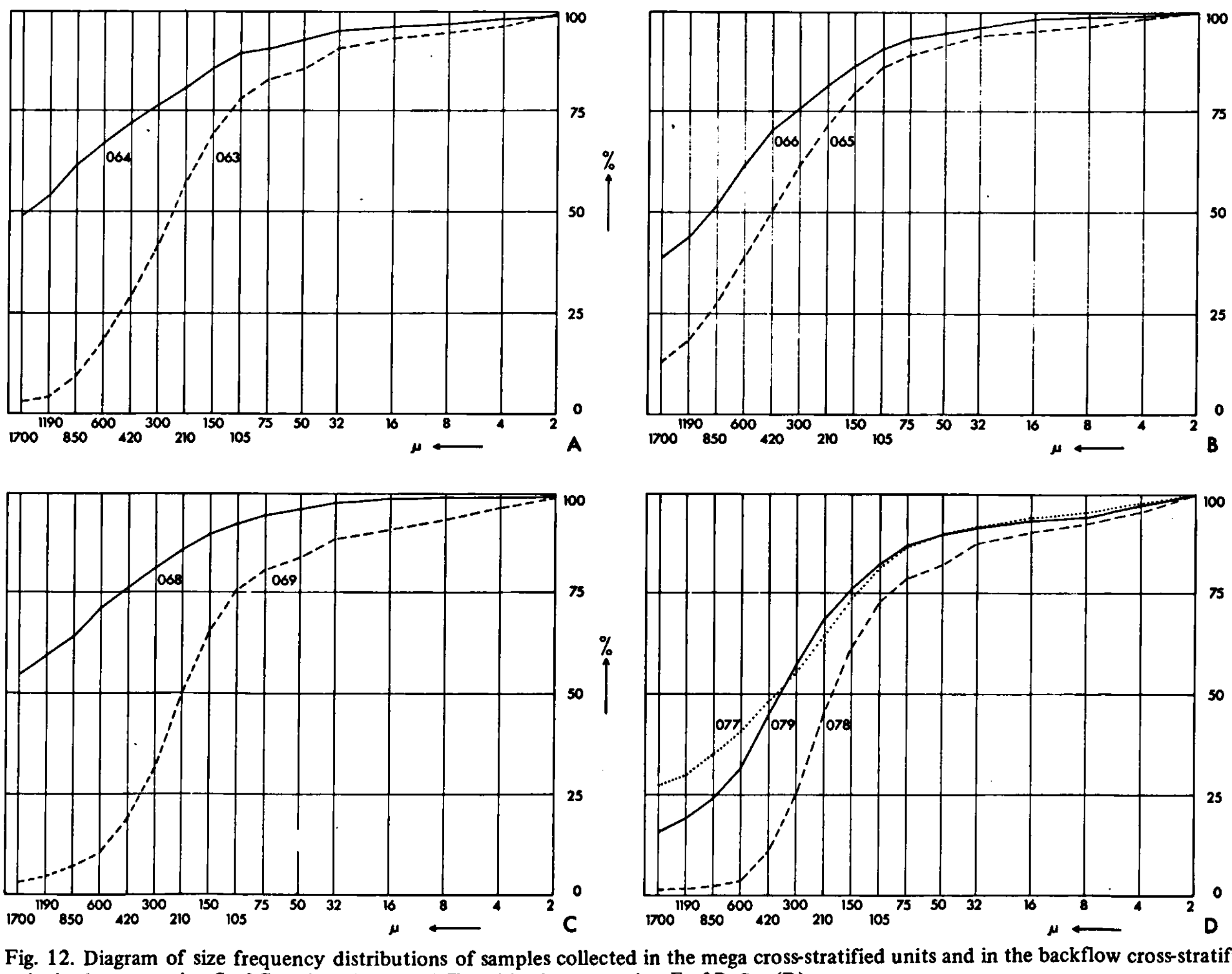


Fig. 12. Diagram of size frequency distributions of samples collected in the mega cross-stratified units and in the backflow cross-stratified units in the excavation S of Grandoso (A, B and C) and in the excavation E of Boñar (D).

consists almost exclusively of sand; almost 50% of sample 064, on the other hand, is composed of gravel. Tangentiality is a common feature, both in the mega set and in the small-scale set. Fig. 40, photographed from nearer by, gives an impression of the longitudinal grading in the backflow unit. The direction of the backflow foreset is accentuated by the setting of small pebbles along the foreset plane. A channel with backflow structures is exposed bodily laterally of section I (Fig. 41). Again two samples are compared with respect to their grain-size distribution. Though less well developed than in the previous example, differences are still very clear (Fig. 12 B).

Fig. 42 represents the situation in section III, at the transition from the area where current directions from the SE predominate, to the area with directions from the W. This transition is thought to be erosive, as is concluded from the occurrence of big clay balls with diameters of up to 20 cm (centre of figure). Below the horizon of changing current directions, two cross-stratified units are seen to replace (erode) each other.

A different, not very common structure, referred to as 'upward turned nose-like intrusions' (Boersma et al., 1968), was encountered in section IV (Fig. 43). Samples from the gravel (068) and the medium to fine sand (069) are again compared in cumulative curves. In Fig. 12 C the great differences in grain-size distribution are visualized. The generation of these kinds of fine-grained noses is shown in Fig. 13 (after Boersma et al.).

In some cases it could be observed how a megaset unit without bottomset structures passes laterally into a unit with a very distinct foreset layer and a bottomset layer with backflow, the latter not developed in channel-like bodies but as a continuous layer. An instance of such a structure was found between sections III and IV (Fig. 45). The foreset layer at the left hand side, in the centre of the figure, is seen to split up into a foreset and a bottomset layer. With Boersma's observations in mind, this splitting may be caused by a sudden increase in the quantity of suspended material or/and by an increase in flow velocity. The unit in which this phenomenon was encountered is overlain by a unit in which the stream direction changes (transition from β to γ, Enclosure X).

In section V the transition boundary just mentioned is clearly erosive (Fig. 44). Unit B, with a thickness of 60 cm in the left part of the figure, diminishes considerably within a few metres and is finally cut off by the overlying unit A, which belongs to direction unit γ. On the transition boundary clay balls and pebbles occur with a diameter up to 4 cm.

Near the top of section VI a mega cross-stratified unit 30 cm in thickness is exposed, with a fine-grained bottomset with a maximum thickness of 4 cm in which indistinct backflow structures have been formed. In the foresets irregularities occur, of a type which seems to be very rare. It concerns a phenomenon that could be described as 'coflow in the ripple'. Fig. 47 gives a general view of this kind of structure; Fig. 48 is a close-up, with three (incomplete) foresets, showing this 'internal cross-

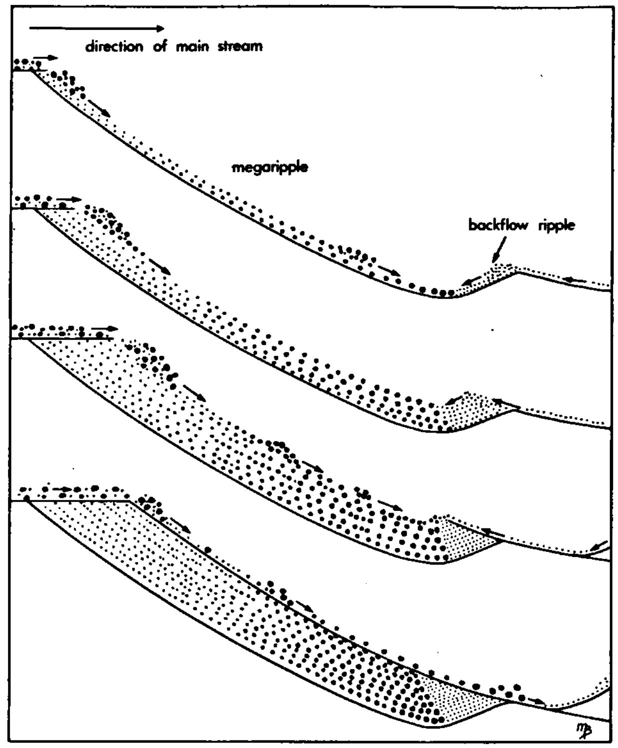


Fig. 13. Interaction between avalanching of coarse-grained material along a mega foreset plane and fine-grained material from backflow ripples, leading to the formation of 'upward turned fine-grained noses' consisting of cross-stratified material in the mega foresets (According to Boersma et al., 1968).

bedding'. In the mega foresets vertical grading is very well developed, from a coarse bottom to a fine top. In the small-scale foresets of the internal cross-bedding a distinct longitudinal grading is present. Measurements in the mega foresets and in the small-scale foresets gave a difference in paleocurrent direction of only 8 degrees. This value lies well within the accuracy which may be expected with these measurements: both types of ripples therefore have roughly the same direction.

As we noticed before, vertical grading in the foresets of both mega ripples and backflow ripples is opposite to the grading from fine to coarse (bottom to top) found by Allen and Boersma. Fig. 46 clearly shows this difference.

Wood remains, probably trunks and branches, were frequently observed on the foreset planes. They may reach considerable dimensions (up to a few decimetres). Probably they were left behind after having become waterlogged.

All sections in the SW wall are covered by a conspicuous pebble bed, 30 cm thick, consisting of pebbles with a maximum diameter of 6 cm in a coarse sand matrix. This layer is followed by 20 cm of mainly coarse sand, fining upwards, with clay balls in the top. In this layer a paleocurrent direction from the SW was observed. In the final 300 cm, which are exposed on top of this sand, the character of the sediment changes completely. Grading alternations, consisting of sand, silt and clay were found in layers with a maximum thickness of 70 cm. Like the sediments that were encountered near the base of the excavation, all sand-sized and coarser sediments are very rich in iron and have a dark red-brown to yellow-brown colour. The silts and clays are orange-red and light grey respectively. All fractions are very rich in muscovite. The sands do not display any structures, the silts and clays on the other hand have been very intensively influenced by organic activity, probably both by burrowing and by rooting up by vegetation. Some of the grey clays are very rich in organic material and have a seatearth-like appearance.

THE EXCAVATION E OF BOÑAR

Along the road from Boñar to Sabero, a second sand pit with remarkable structures is exposed at km 1.5. Some 26 m of the upper part of the Voznuevo Formation can be observed here. The distance from the Mesozoic limestones is approximately equal to that found near Grandoso. This pit is also one of the rare locations where very well preserved structures were found. This exposure and the one S of Grandoso are supposed to belong to the same lithostratigraphical unit. In contrast to the Grandoso pit, we do not receive much lateral information from the units exposed. Only the upper 5 metres of the sequence could be traced for some tens of metres, since they form the SW wall of the exposure. As in the entire area between Boñar and Colle, the stratification plane dips, on an average, 26° to the SW.

The clayey and silty sediments, which form the bottom and the top of the Grandoso sequence, are not exposed here. Clay is only found as thin layers in the tops of fining-upward gradations. The main constituents of this pit are again the fractions between medium sand and fine gravel. Cross-bedding in sets with a maximum thickness of 100 cm is common; paleocurrent directions could frequently be observed. In minutely exposed units, backflow phenomena could be observed and measured. Current directions change very rapidly in a vertical sense, with a preference to directions from NE. A section through this excavation is presented in Enclosure VIII. In order to facilitate reference, the units have been marked with letters (A to D') left of the section. In the following paragraphs attention will be drawn to some well-developed features.

In unit A foresets of mega cross-bedding are accentuated by differential weathering. It is worth noting that finer-grained beds (i. e. very fine-grained sand) appear to be more resistant to weathering than the coarser beds. The latter are probably less well packed, and disintegrate more easily. Perpendicular to the foreset planes vertical grading is well developed, again from a coarse-grained bottom to a fine-grained top.

In unit B the plane of intersection exposes a number of channel-like bodies of relatively small dimensions. The example of Fig. 53 has a width of 75 cm and a depth of 13 cm. The bottom of this channel is covered by a relatively fine-grained layer with a maximum thickness of 2 cm. The filling of the channel is clearly asymmetrical and shows foresets, dipping to the left of the figure, in which longitudinal grading is perfectly developed. In this example, too, the finer beds stand out in relief.

Unit E could be closer examined in the summer of 1970 as a result of new sand exploitation activities in part of the pit. Both mega ripple foreset-dips and backflow ripple foreset-dips could accurately be determined. Backflow directions proved to form an angle varying from 171° to 90° to the direction of the flow producing mega ripples. Concentrations of gravel along the foresets underwent discolouration by iron (hydr)oxides, accentuating the cross-stratification. Large wood fragments, armoured with gravel, were frequently found in the top of unit E.

The transition from unit F to unit G is clearly erosional. Here a tripartite mega ripple backflow complex is exposed, composed of subunits a, b and c (compare Fig. 49). The total thickness of the unit is 65 to 75 cm.

'a' is a 'normal' cross-bedded set, 40 to 45 cm thick, composed of medium to fine-grained sand to fine gravel, only very few fragments coarser than 1 cm in diameter. The median thickness of the foresets is 3.5 cm. Flow direction was from NE (47°).
'b' is a backflow zone, 0 to 15 cm thick, composed of coarse to fine-grained sand, gravel being practically absent. The flow giving rise to these ripples came from SSW (197°).
'c' is a continuous bottomset layer with channel-like thickenings, with a total thickness of 6 to 15 cm, nearly exclusively composed of gravel. The coarsest fragments are 1.5 cm in diameter. Flow direction proved to be the same as that observed in 'a'.

The generation of this tripartite complex can be explained as follows: Subunit 'c' represents the fractions that immediately slide down the foreset plane; they are in almost constant contact with the bottom, and are capable of eroding channel-like bodies into the underlying unit. This sedimentation is followed by the backflow ripple in front of the mega ripple, which appears to be common in this type of sediment. Finally both subunits are covered by large-scale ripples.

Grain-size distribution of a sample from each subunit was determined and represented in a cumulative curve (Fig. 12 D). Laboratory determination of grain size of the sample does not differ very much from the grain size estimated in the field. As was to be expected, the grain size of the mega rippled sediment is intermediate between the finer-grained backflow and the coarser-grained material transported along the bottom.

The next unit, which merits our special attention, is unit R. Here five gradations were distinguishable. Four of them contain angular clay fragments in the top. Besides, clay fragments have developed in the lowermost

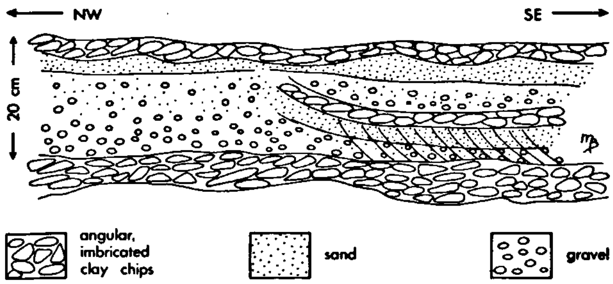


Fig. 14. Detail of small-scale grading units in the excavation E of Boñar with broken clay chips in their upper parts.

gradation as armoured mud balls, distributed over the entire gradation, but more concentrated in two horizons, one of them at the top. The field sketch in Fig. 14 shows a detailed part of unit R in which grading is developed between two clay pebble horizons. In the right of the figure two gradations were visible, separated by a NW dipping upward bent clay layer. Below this clay pebble horizon, small-scale cross-bedding is visible, with foresets dipping to the SE. Yet another directional feature is found in the angular clay fragments: they show a clearly NW-dipping imbrication, thus indicating the same flow direction as the sand. It is worth noting that these clay fragments are scarcely rounded and still very flattened. The only possible conclusion as to these clay fragments is that the distance of transport must have been very short.

Unit T, exposed in the SE part of the excavation, is composed of a megaripple unit consisting of gravel and coarse sand. In the foresets, with a maximum thickness of 6 cm, vertical grading from coarse to fine is perfectly developed.

The showpiece of this pit is the SW wall, in which units U to D' are exposed in a considerable lateral extension. Figures 51, 52 and 50 show a general view of the exposed wall, the easternmost part in detail and a detail of units V to Y, respectively. A cursory survey already brings some salient features to light:

1. A drastic change in current direction between units U and X, separated by two relatively coarse-grained units V and W.
2. A decrease in the number of distinguishable cross-bedded units towards the NW of the wall: unit X proves to be replaced by the overlying unit Y, which in its turn is overlain and replaced by unit Z. The total thickness, however, thins very little.

In unit U a paleocurrent direction from the W (and in the top from the NNW) was found. Just below unit V (Fig. 52) cross-bedding seems to be generated 'out of nowhere'. A sudden supply of coarse-grained material seems to be the best explanation for this curious structure. Apart from this feature in the top part, the unit looks rather structureless. This is, however, not the case; a close examination brought to light that at least seven cross-bedded units are present, varying in thickness from 12 to 21 cm. Several sets do not clearly manifest themselves due to lack of differences in grain size. With unit V the current direction changes into a direction from the E; this situation lasts up to the top of the section.

Unit V is 14 cm thick and consists of a 5 cm thick, very coarse-grained, bottomset layer, with cobbles 8 cm in diameter, which is overlain by cross-bedded coarse sand and fine gravel (Fig. 50).

Unit W is one of the most pronounced layers of this excavation, thanks to its coarseness. It consists of a concentration of pebbles, with a maximum diameter of 5 cm, floating in a matrix of coarse sand to fine gravel. This unit belongs to the same generation as unit X, and represents that part of the mega cross-bedded set which has been exclusively transported along the bottom. Some metres on the left hand side of Fig. 50, finer-grained sand, affected by backflow, was found in which a current direction from the NW (304°) was measured. The angle between the flow directions of mega cross-stratification and of backflow cross-stratification proved in this case to be 135°. In the hope of finding some regularity in the flow directions of units X, Y and Z in a lateral sense (e. g. a river bend), measurements were carried out in the locations marked X1, X2, X3, Y1 etc. in Fig. 51. The results are as follows:

X1: from 79°	X2: from 99°	X3: from 108°
Y1: from 95°	Y2: from 80°	Y3: from 106°
Z1: from 85°	Z1: from 96°	Z3: from 76°

It is seen that differences are very small and that there is no regularity in the changes in the values. We must therefore assume that replacement of cross-bedded units, as occurring in this wall, is not the result of a changing river configuration. One could also assume that the exposed wall is an intermediate section between the dip-section and the strike-section of a sequence of nearly identically directed cross-stratified sets. Erosional planar or slightly trough-shaped cross-stratification should then be responsible for the successive replacement of units X and Y. There are, however, much more indications pointing towards a third solution. This third possibility is based on the fact that grain size in the cross-bedded units decreases towards the right hand side of Fig. 51 (i. e. to the NW). This is best demonstrated in two detailed photographs (Figs. 54 and 55) from unit Y, taken some 10 metres apart. Fig. 54 represents the situation in the SE part of the wall: the mega cross-stratification is composed of coarse sand to fine gravel. On top of the boundary with the underlying unit (marked by a pebble just above the ruler) a much finer-grained backflow zone, 6 cm in thickness and with a lateral extension of 160 cm, has developed. In Fig. 55 we see the same unit Y, further to the NW, composed of a much finer-grained sandy sediment, between silt to fine sand layers with a maximum thickness of 1 cm. Between the fine-grained horizons, which are in fact very flat dipping foresets, backflow has developed. Obviously the flow, which in the second case carried finer material, was still strong enough to whirl up the sediment into backflow ripples. These were covered by a silty top. Lack of sediment, however, brought this process to an end: the unit became thinner and finally disappeared.

Another interesting phenomenon was encountered on the boundary plane between units V and W. Pockets containing material ranging from fine gravel to very large pebbles, have sunk into the underlying unit, locally nearly replacing this unit. These pockets do not give any directional information, they are symmetrical and show a vertical grading which is fining upwards. They may either be pot-holes or load casts.

THE EXPOSURE OF LA MATA DE LA RIBA AND LA DEVESA DE BOÑAR

A very interesting exposure is located S of the village of La Mata de la Riba, on the western bank of the Río Porma. Here two anticlines, in their cores sediments belonging to the Voznuevo Formation, are cut by the river. The small exposure in the northernmost anticline, in which minute structures could be observed, merits detailed description (Fig. 15).

We are dealing with a complex with a stratigraphical thickness of 4.5 m, in which the main constituents are the fractions from fine-grained sand to clay. The clays are black to grey coloured and are rich in plant remains. From the clay of this exposure van Amerom (1965) took one of his samples for palynological analysis. Hereafter, a brief description of the various units, as classified in Fig. 15, will be given:

A. More than 100 cm of yellow coloured fine gravel to coarse sand, consolidated at the surface.
B. 80 cm of medium to coarse sand with light yellow to dark yellow discolourations due to iron (hydr)oxides and clay stringers, generally less than 1 mm thick, with an interweaving pattern. The stringers are traceable as bundles; individually they have a wavy appearance. Isolated flasers are rare. Two sand-filled burrows or tube-like structures formed by plant roots could be found, both with a clear inclination to the S. In the top 20 cm, small-scale cross-stratification in coarse sand with N-dipping foresets were distinguished. Yet the clay stringers have a slight tendency towards inclination to the S, as compared with the overlying unit. Small wood fragments are abundant.
C. In the southern part of the exposure: a 12.5 cm thick alternation of medium sand to fine sand with some coarse particles and some clay stringers and bands with a maximum thickness of 0.5 cm in equal proportions. This is overlain by 5.5 cm of clay with sand linsen. In the northern part of the exposure these two layers amalgamate into 18 cm of chiefly black clay with sand lenses up to 1 cm in thickness, often dipping to the N and frequently showing a curious S-shape. The sand, which is locally rather coarse, contains a large number of small black coloured wood fragments, soft and dull or hard and lustrous. The unit thins to the N; in the northernmost part the total thickness does not exceed 5 cm.
D. 105–110 cm of sand and clay, clearly dipping to the N with regard to the underlying clay horizon. The influence of grain size on the inclination of the sedimentation plane is shown by the circumstance that

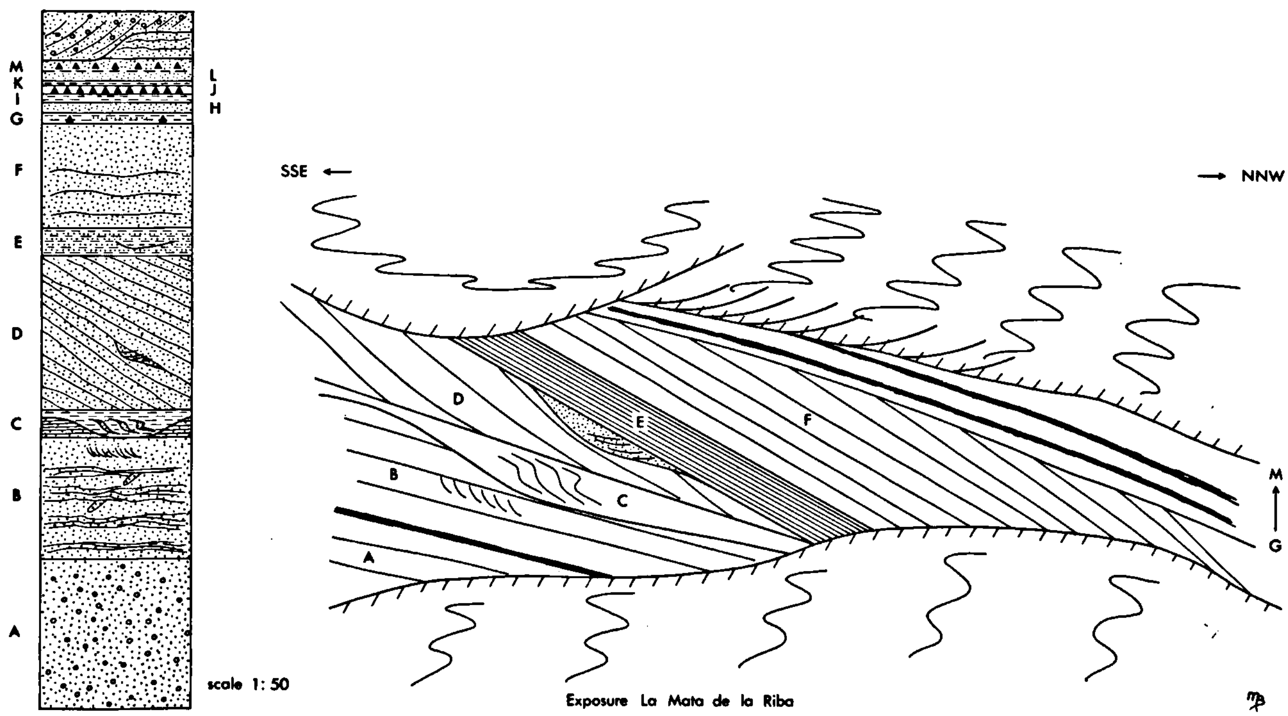


Fig. 15. Section and situation in the field of the exposure S of La Mata de la Riba.

parts of the unit which are relatively richer in clay approach the base of the unit at a much lower angle than its coarser counterparts. In the top of the unit a sand lens was found with a channel-like shape, showing clear asymmetry; the southern flank proved to be considerably steeper than the northern flank. Cross-bedding shows that filling of this channel clearly took place from a northerly direction. Immediately on top of this channel the following unit is developed.

E. 18 cm of a very thinly layered alternation of sand and clay, comparable to the alternations found in section J. This unit is very strongly burrowed. A small channel with a width of only 10 cm, filled with sand, has the same asymmetry as the one described in unit D. To the N, unit E is in direct contact with unit C.

F. 70 cm of fine to coarse-grained sand, with a number of small, traceable, silty stringers, slightly discoloured by iron (hydr)oxides. This unit also gently dips to the N.

G. 8 cm of black clay with small sand lenses.

H. 10 cm of medium sand, consolidated by iron (hydr)oxides.

I. 8 cm, as G, clay partly replaced by felt-like fragmentary plant remains and jet-like pieces of wood.

J. 7 cm of almost exclusively lignite with a number of small sand lenses.

K. 6 cm of white coloured very fine-grained sand grading into:

L. 1 cm of very well traceable light grey clay.

M. 8 cm of fine-grained white sand with plant remains in layers with a maximum thickness of 3 cm. This latter unit is eroded, in the southern part of the exposure, by fine gravel and coarse sand with cross-stratification. The foresets are inclined to the S, thus indicating currents from northerly directions.

Fig. 15 shows a schematical lithological section of the exposure, together with a drawing of the situation in the field. A photograph illustrating this exposure is added in Fig. 57.

Strongly simplifying the situation in this exposure, we may say that there are two horizons (C and G to M) in which finer fractions are concentrated. Mainly sandy and silty sediments surround them. From the structures found in the latter, the following depositional history may be deduced:

In the units A and B a supply of material took place from S to N, as demonstrated by small-scale cross-bedding in some sandy parts. Unit C represents a depression, which has been filled by an alternation of mainly clay and sand. After deposition of unit C, the sediments were placed in an inclined position, causing a considerable angle (10°–20°) between unit C and the overlying units D, E and F. An angle of a few degrees could, for instance, have represented a natural slope on a floodplain; the angle observed, however, is much too large to have originated from other than tectonic causes. A slight tectonic tilting probably caused the slump-like structures in unit C. The three overlying units are parallel to each other. Cross-bedding in small channels indicates a supply from northerly directions. The plane of sedimentation apparently turned back into a position comparable to that in unit C.

In units G to M deposition of alternating sandy and clayey layers, without any directional indications, was accompanied by intense vegetation. The cross-stratified gravels and sands, that erode units G to M successively to the south, definitely brought to an end the sedimentation under low energetic conditions, like the units G to M.

In the area between Palazuelo de Boñar and La Ercina, the Voznuevo Formation proved to be badly exposed. Only in a very small outcrop in the brooklet NE of La Devesa de Boñar (the Arroyo de Valle de las Fuentes) were some small-scale structures strongly resembling those mentioned near the bottom and top of the Grandoso excavation and S of La Mata de la Riba, exposed just above the water level (Fig. 56). The sediment is composed of medium sand to fine sand and of white and black clays. A striking fact is the scarcity or absence of silt-sized components. The frequently mm-thick clay stringers are again not traceable singly, but only in bundles. Organic activity played an important role; egg-shaped burrow-like sand lenses with a maximum width of 2 cm and a maximum height of 1 cm, have developed locally in the clay layers. All clay stringers with a thickness of less than 1 mm have the tendency to incline to the W (on the right hand side of the figure), as compared with thicker clay layers. Dark organic remains clearly illustrate the easterly direction of the flow that produced this kind of structures.

On top of these structures very little clay was deposited. The black colour in this part is caused by black organic material which is very rich in muscovite. Slight disturbances are caused by small faults.

C. PALEOCURRENT DIRECTIONS

INTRODUCTION AND TECHNIQUE

Paleocurrent directions were mainly determined from foreset orientation in mega cross-stratified units. Use was occasionally made of the orientation of imbricated flattened pebbles or cobbles. A foreset plane in cross-stratification can be fixed in space, when the inclination of the plane is known in two measurable planes, or, in rare cases, when the foreset plane itself is exposed. The requirement that two other planes have to be determined, already causes difficulties in these sediments, on account of the following property: planes

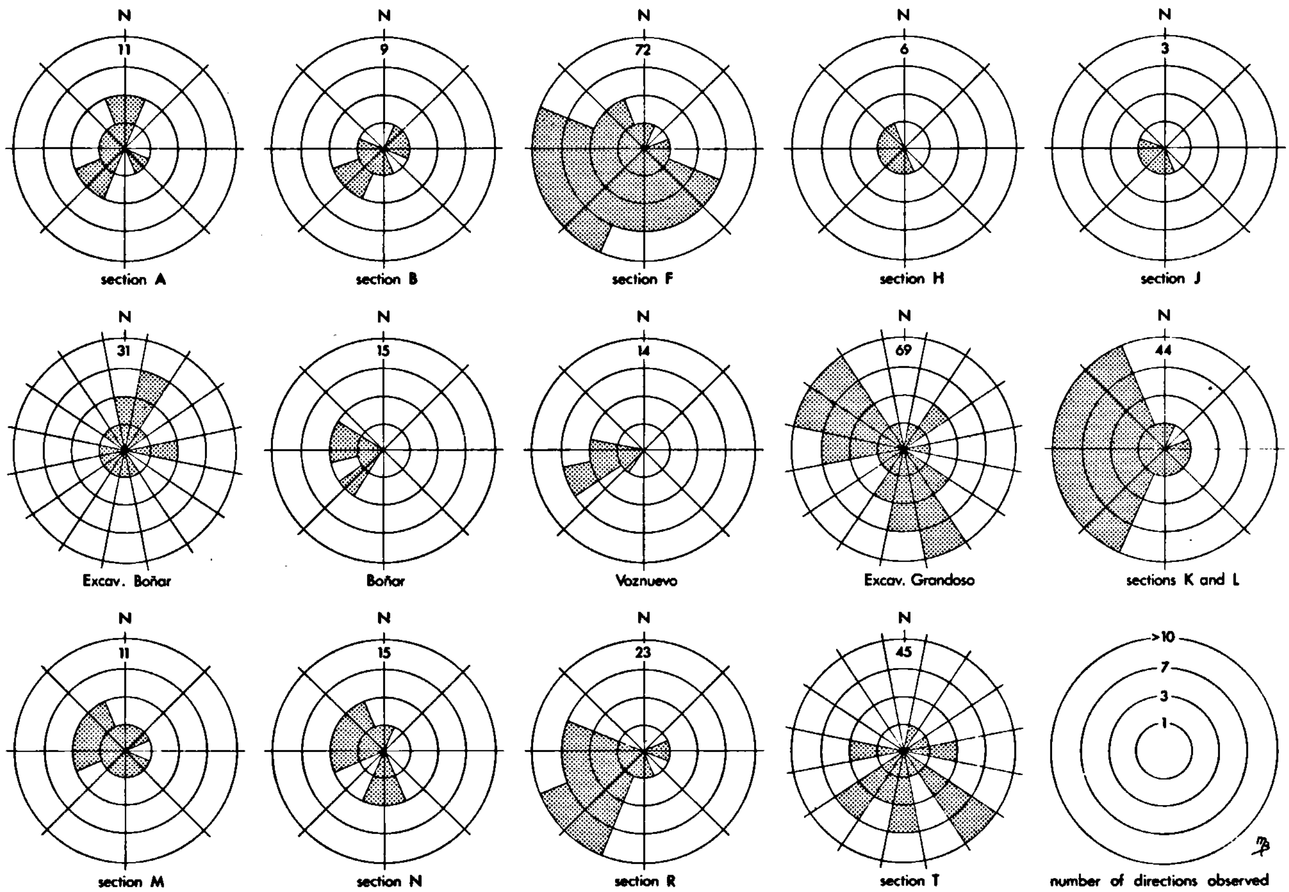


Fig. 16. Compass-cards of paleocurrent directions in the Voznuevo Formation (for exact position see Enclosure I). Figures refer to number of measurements.

of foresets can often only be seen in walls that have been weathered out by atmospheric influences such as wind and water. Artificial planes of intersection seldom show clear structures, and foreset planes can only be determined with great difficulty. Apart from this, the material involved is in a semi-consolidated state; it is too hard to make sharp intersections. The creation of a second plane is altogether impossible in gullies polished by water, where the sediment proved to be even more consolidated than elsewhere. Any artificial changes will cause destruction of the structures. In such exposures (e. g. in section F) the position of the foreset plane has been estimated. Tangentiality, which, as we have seen, proved to be superabundant in mega cross-stratified units, can be the cause of considerable misreadings in foreset dips, when the construction of two measuring planes can only be realized with some distance between these planes. In this case, measurements must be carried out at the same height in the cross-stratified unit and in material of the same grain size.

A well-known technique for processing measurements on foreset planes was proposed by Illies (1949). Illies used a polar Gnomonic projection net for the reconstruction of the foreset plane. Some disadvantages of his technique are:

a. The utility is limited to foreset angles of between 7° and 45°.
b. The planes in which foreset angles are measured must be perpendicular to a third plane.
c. Corrections for tectonic changes must be carried out in a different net.
d. Extensive tectonic corrections give rise to mistakes (of up to 40°).

In the excavations near Grandoso and Boñar, where the construction of perpendicular planes did not give any problem, and where the tectonic correction is not very great, Illies' technique proved satisfactory. In order to have a comparable procedure for all measurements, however, use was made of a Schmidt net in which corrections for tectonics were also made. This somewhat cumbrous technique has the advantage that the drawbacks of Illies' technique listed above are eliminated.

The measurements that proved useful, either by quality or by quantity, in the reconstruction of paleocurrent directions are presented in Fig. 16 and in Enclosure I, the general map, in compass-cards. Concentric circles give, from the centre, the number of directions observed (1, 3, 7, 10 or more). Where exact measurements could be carried out, 16 directions were distinguished; less accurate readings (due to estimation or to a low number of readings) are presented in eight main directions. The directions near the northern border of the formation, between Boñar and Voznuevo, were found by measuring channel axes (cf. part B of this chapter).

RESULTS AND DIFFERENCES

With the exception of the results found in the excavations of Grandoso and Boñar, and in sections T and M (in the latter to a lesser extent, as the number of measurements is unfortunately very low), directions from SW to NW prevail in all locations. The important direction from the N in section A is caused by a local supply of 'foreign' material from the area which now forms the Cantabrian Mountains. A review of the directions found in the Grandoso excavation gives a diffuse pattern, with two prevailing directions from the NW and the SSE. This trend already became clear from the sections in this pit (Enclosure X). The patterns from the excavation of Boñar and from section T are scattered as well, with NNE and SE respectively as main source directions. The direction from the SE is very rare, and was only found in the extreme E of the area. This is in keeping with values found by van de Graaff-Trouwborst (1970), but due to a very low number of measurements carried out by her, directions from S and SW, which were also frequently encountered, did not appear.

The observation that scattering of paleoccurent directions is more frequent in the upper part of the Voznuevo Formation than in its lower part is of great importance. As we have seen from the description of the sections and shall see in part D of this chapter, the sediments near the base of the formation are considerably coarser than the sediments at the top. Especially in the area between La Robla and Colle, where our information on the deposits as a whole is relatively more extensive, this trend is very conspicuous. In the channelling cobble-, pebble- and coarse sand-size sediments, which form the lion's share of the lower part of the formation (clay layers or bodies are only modestly represented), distribution of paleocurrent directions proved to be relatively small; with a maximum of 180°, in most cases smaller, however.

The sediments from the top of the formation are in sharp contrast to the lower ones; they seldom exceed the coarse sand fraction. Multicoloured clays form an important constituent of this part. Paleocurrent directions diverge widely: up to 270°, and change more frequently and more suddenly.

All these facts indicate that we are dealing with sediments which are the result of two different river models; a mainly braiding pattern in the older history of the formation, changing into a mainly meandering pattern towards the end of its deposition.

D. INTERPRETATION OF THE CHARACTERISTICS OF THE VOZNUEVO FORMATION

Even in the few localities in which the Voznuevo Formation can be studied with more precision than only to establish its presence, sedimentary structures cannot be described and classified without certain reservations. Nevertheless, some criteria such as variations in grain size (grading, abrupt transitions etc.) have been used as expedients in the reconstruction of the circumstances under which deposition of the sediments of the Voznuevo Formation took place. As we have already mentioned several times, a fluvial origin is ascribed to the sediments of the present study. The most important grounds on which this assertion is based are:

1. The presence of a large spectrum of grain sizes.
2. The absence of a fossil fauna, except for an abundance of worm tracks.
3. The presence of a rich fossil flora, such as trunks, stems, leaves, as well as of lignite, peat etc.
4. The absence of limestones.
5. Cross-stratification, mainly as mega cross-stratification. Indications of eolian transport are absent.
6. The ubiquity of backflow phenomena, especially in the upper part of the formation.
7. The abundant matrix commonly present between the conglomerates.
8. Channelling and cut-and-fill structures, especially in the lower part of the formation.
9. The presence of fining-upward cycles in every section.
10. The paleocurrent directions, based on foreset dip, imbrication and channel direction.
11. The frequent occurrence of clay balls and the presence of armoured mud balls.
12. The flatness and roundness of the pebbles (Chapter VI).
13. The grain-size distribution (Chapter VII).

In the following paragraphs some attention will be paid to the features described in part A of this chapter which are important in solving the question by which type of river the sediments under consideration could have been deposited.

Section A. – In section A we are dealing with predominantly coarse deposits; only in the lower part of the section do cross-stratified units, composed of mainly coarse sand with pebbles in their lower parts, remind us of deposition commonly found in point bars. The very coarse upper part of the section with its rapidly changing alternations of pebbles and cobbles with coarse sand, giving the sediment the appearance of having been supplied as 'dashes', are for the most part devoid of sedimentary structures. Large-scale cross-stratification can occasionally be found in the sands, but horizontal stratification is predominant. In some very well exposed parts imbrication was frequently observed, as were channels with cut-and-fill structures. Clay and silt are only present as large clay galls or clay balls and as the uppermost fillings of channels. All these features indicate deposition by a braided river.

Section B. – The first tens of metres of this section show the same pattern of deposition as the top of the previous section and were also presumably deposited under braided-river conditions. The top of this section is hardly interpretable due to poor exposure.

Section C. – This section is marked by the braided-river characteristics of the sediment in its lower 100 metres, especially in the bottom of section C 2, in which fine-grained sand to silt layers separate rather closely packed conglomerates with pebbles up to 25 cm in diameter. The picture which this part of the section presents in the field is exactly the same as that of the alternation between facies G and D, as described and shown by Williams and Rust (1969; Fig. 20). The sudden change to finer-grained deposits in cycles less than ten metres in thickness, as encountered in section C 3, suggests a more regular mode of sedimentation by waters of a much smaller transporting capacity than found in the lower part of this section. A mechanism of transport by a meandering river seems much more appropriate in this case.

Section D. – This section is highly comparable to section C 3, and shows an even more impressive predominance of silts and clays. These cycles can also be ascribed to deposition by meandering rivers.

Section E. – Indications of sedimentation under quiet conditions are present in the part of section E in which the black clays are found. As the clays in the previous section, these clays were probably deposited by vertical accretion. Although one may assume with certainty that the deposits in the lower part of section E, especially those of the two detailed sections, represent topstratum deposits, a further subdivision seems rather uncertain, as a consequence of the limited exposure (often less than 50 cm wide). The gradings of the oldest detailed section might have formed on a natural levee, since their most important constituent falls within the silt class. Lateral sediment movement could not be observed, crevasse-splays therefore do not seem very likely, while the sediment is too coarse for pure backswamp deposits. The lower part of the second detailed section with its root-bearing black clays and its abundance of plant remains may very well represent the sediment of a backswamp; the sand – silty clay alternations, very thinly laminated, which overlie the black clays may have been formed by seasonal inundations of the backswamp, perhaps as the extreme ends of crevasse-splays. The laminations can be exceptionally well preserved since regular floods prevented growth of vegetation.

Section F. – In the lower, coarse part of section F characteristics occur of braided-river deposits. This supposition is based on the sudden changes in grain size which could be observed and the scarcity of sedimentary structures (only horizontal stratification could be observed).

The seven cycles which form the main part of the second excavation are fine examples of alluvial cyclothems. They can be subdivided into four parts:

a. a pebbly basal part, interpreted as channel-lag deposit,
b. a sandy, cross-stratified, fining-upward part, forming the essence of the cycle, interpreted as typical point bar deposits,
c. a part with parallel laminated silts, sometimes in alternation with silty clays, interpreted as levee deposits,
d. a burrowed, homogenized silty clay at the top of the cycle, interpreted as levee-top or backswamp deposits.

Although point bars can be found in both braided and meandering rivers, their occurrence in braided streams is apparently very rare (Williams and Rust, 1969), so that we are most probably dealing with deposits of meandering streams in this part of the section. The thickness of the point bar deposits – in this case 6 to 7 metres – can give some indication of the dimension of the river which produced these point bars, since the thickness of the bar deposits is related to the depth of the river channel (Allen, 1965b). For small rivers the point bar deposits have a thickness of approximately 1 metre; very large rivers, like the Mississippi, have mean values of 15 metres, with maxima of 25 metres. The point bar deposits in the floodplain of the Niger delta are 9 to 12 metres in thickness. A comparison with these data suggests that the point bars in section F of the present study indicate deposition by a river of considerable dimensions.

Section G. – The fluvial cycles of section G, with their abundance of wood fragments and plant remains, are not basically different from the cycles of sections C 3 and D. The content of organic remains, which indicates the presence of dense vegetation in this location, apparently changes from place to place. The vegetation responsible for the richness in organic matter in this section must have been very persistent, since its traces are recognizable throughout the whole section.

Section H. – In this section a transition from braided-river deposits into meandering-river deposits can only be presumed on account of the clear transition from coarse-grained sediments into fine-grained sediments at m 57 and on account of the grain-size distribution on a large scale, which is the image of section F. The very muscovite-rich fine sands and the black clay in the uppermost part of the section suggest deposition in almost stagnant water.

Section I. – The thick conglomerate at the top of this section, devoid of other stratification than horizontal, strengthens the assumption of the braided-river origin in the oldest part of section H, since the stratigraphical position of this section is comparable to that of the previous section.

Section II. – The upper part of the formation, as we could already establish in the sections further to the west, is different to the sediments near the contact with the Paleozoic. Section II with its fining-upward grading, distinctly fluvial, cycles shows an even greater abundance of organic remains than section G. The thick black clay which covers each cycle is presumably the remnant of densely vegetated backswamps.

Section J. – In section J, in which three parts were distinguished, an attempt at an interpretation would be as follows (numbering from bottom to top):

1. Braided-river deposits, assumed on account of the presence of horizontal stratification with scattered channels and the absence of silts and clays.

2. Indistinct transition into the predominantly topstratum deposits of Section III. This section (cf. Enclosure VIII) shows rapid vertical changes in grain size along its entire length. Four light grey to dark grey clay layers of considerable thickness (between 135 and 275 cm) occur (units 4, 12, 38 and 43). All four units contain plant remains and burrows, sometimes wood remains. These clays are often silty or sandy and contain a great number of thin sand lenses. They are fairly uniform and show no distinct bedding due to absence of lithological contrasts. We therefore assume them to represent floodbasin deposits. The occurrence of a fining-upward grading 'cycle' (units 13 to 22), about 4.50 m thick, within these generally fine-grained sediments is striking. The lowermost 2.50 m, which is almost exclusively composed of gravel, is much too coarse to have been deposited by vertical accretion as a topstratum deposit, and must be the result of sedimentation by an active stream channel. The eroding capacity of the stream is reflected by the presence of a large quantity of armoured mud balls. The cross-stratified units at the top of this cycle announce the return of calmer conditions. Nevertheless, the coarse sand beds observed between the peaty beds in units 22 to 35 witness the presence of a nearby active stream channel. Unit 39 of Section III shows the typical rapid interbedding of fine-grained and coarse-grained sediments so characteristic of levee deposits. Other characteristic features such as burrowing and reddish to brown oxidation rims (limiting the sandy parts) are distinctly present. Local small-scale cross-stratification may occur in the sandy parts; horizontal lamination or very thin bedding (classification of McKee and Weir, 1953) is, however, preponderant. The mean thickness of a fining-upward grading sand-clay bed is about 5 centimetres. From unit 45 onwards, the sedimentation of topstratum deposits comes to an end and clearly cross-stratified point bar deposits take their place.

3. Although the fining-upward gradings in this section are somewhat coarser than the gradings in the previous sections (and for this reason also thicker), they still show the regularity and graduality of the cycles commonly reported from meandering rivers.

The exposure S of La Mata de la Riba. – For the subdivision used below of the sediments encountered in this exposure, the reader is referred to the lithological description (p. 321). As is emphasized there, units C and G to M are relatively fine-grained sediments amid more sandy deposits (locally consisting of very coarse sand). The following depositional interpretations can be assumed:

A: Point bar sands; absence of remnants of vegetation and burrows.
B: Upper point bar or natural-levee deposits; small-scale cross-stratification, burrowing and wood fragments present.
C: Crevasse-splay deposits; coarse-grained sand penetrated into fairly pure clays, small, drifted wood remains. Silts almost absent.
D: Crevasse-splay deposits; laterally wedging out; presence of sand-filled channels. Silts almost absent.
E: Natural-levee deposits; alternations comparable to those mentioned under 2 in section J. Intensive burrowing.
F: Comparable to E; somewhat coarser sediment.
G to M: Mainly floodbasin deposits with pure lignitic layers. Unit H, the only coarse-grained layer, might represent a crevasse-splay deposit.

The exposure E of La Devesa de Boñar. – The sand-clay alternations in this small exposure show a resemblance to units C and D of the previous exposure with regard to the scarcity of silt. However, the sediments of this exposure lack the coarse and sometimes gravelly sands which usually accompany crevasse-splay deposits. The high content of organic remains and the organic activity expressed by remainders of roots and burrows advocate deposition on a natural levee. The intermittent character of the sediment is also evidence in favour of this interpretation.

The excavations E of Boñar and S of Grandoso. – By far the majority of the sediments in these excavations consist of sand. These sands are almost exclusively composed of cross-stratified units with thicknesses generally between 15 cm and 150 cm. Large-scale cross-stratification proved to be commonly of the planar type, but festoon-type cross-stratification occasionally occurred as well (e. g. in the excavation near Boñar, unit B). Gravel, only of small pebble size, is mainly concentrated in the bottomsets of the cross-stratified units. The ubiquity of backflow phenomena which accompany the cross-stratified units is extraordinary. Especially with the description of the subrecent meander-bend deposits of the River Rhine (Boersma, 1967) in mind, an interpretation of the sediments under consideration will lead to the assumption of point bar sediments, deposited by a meandering river. The divergency of paleocurrent directions had already suggested such an interpretation. The question may arise, whether the scarcity of clays and silts would not suggest an interpretation in favour of a braided-river mechanism of the distal type, the cross-stratified units being formed by deposition on the downstream side of transverse bars. One should bear in mind, however, that topstratum deposits on top of point bar deposits can easily have been eroded after their deposition. This hypothesis is corroborated by the presence of clay balls of variable dimensions observed at the boundaries between the cross-stratified units. Where a drastic change in paleocurrent direction takes place in a vertical sense, these clay balls, up to 20 cm in diameter in the Grandoso excavation, could be the remnants of such eroded topstratum deposits.

As could be established in the Grandoso section, the sand beds are flanked at their bottom and their top by layers of unknown thickness consisting of silts and clays. The fine-grained beds which underlie the Grandoso sands show the typical, fining-upward alternations between sand, silt and clay interpreted in previous sections and exposures as natural levee deposits. The fine-grained layers on top of the Grandoso sands are much thicker bedded. Intensively burrowed clay beds with a maximum thickness of 75 cm and almost purely organic, peaty layers are likely to be floodbasin deposits rather than natural levee deposits. Pebbly sands at the very top could mark the return of point bar sediments, but evidence is very weak.

In the Boñar excavation topstratum deposits are only reflected as thin clay layers or as broken clay chips at the top of grading units or as clay balls. The predominance of sand in these two excavations need not be surprising as far as the interpretation which leads to point bar deposits is concerned, since – as we have already stressed – the information obtained from the exposures in the Voznuevo Formation can be misleading. This is caused by the circumstance that the excavations do not present a random selection of the sediments which can be found in the Voznuevo Formation, but have been carried out with a certain (mainly economical) purpose.

Sections K, L and N. – With the exception of the uppermost 15 metres of section K and the uppermost 20 metres of section N, in which sands and silts prevail, all phenomena characteristic of deposition under braided-river conditions are present. The most important features on which this assumption is based are:

1. The coarse character of the deposits with abrupt changes into sediments of fine sand to clay size. This phenomenon is very clear in the sediments between m 7 and m 22 in section L (Fig. 35).
2. Scour-and-fill structures such as channels, trough cross-stratification and festoon cross-stratification.
3. Very coarse-grained beds with horizontal stratification in which imbrication is the only observable structure.
4. The fairly uniform paleocurrent directions.
5. The scarcity of clays (the thick clay horizon at m 15 in section K could represent swale-fill or channel-fill deposits).
6. The absence of typical fluvial cycles with gradational decrease in grain size in an upward direction (the grading marks added to the sections, left of the lithological column, only mark a fining-upward trend; they do not, however, indicate a smooth decrease in grain size).

Sections M and O. – Sections M and O and the exposure immediately below the contact with the Mesozoic limestones E of La Devesa de Boñar show the – meanwhile familiar – picture of fining-upward cycles which seldom exceed sand size. As we have seen before, the organic content of these cycles is subject to lateral changes; while black clays are practically absent in section M (where they were found to change laterally into clays without organic remains) and near La Devesa, about 10 metres of section O show a large quantity of plant and wood remains.

Especially the deposits of the first two exposures, containing a far greater percentage of sand, frequently display cross-stratification. The majority of the sediments of these exposures will have a meandering-river origin. Whether the sands and gravels between m 18 and m 27 in section O are thick channel-lag deposits or for the most part point bar deposits could not be determined.

Section P. – Apart from a thin layer of silty sediments at the base, this section shows a gradual change from coarse conglomeratic deposits with abrupt transitions into thin clayey and sandy layers to sediments with smaller pebble sizes with a tendency towards cyclicity in fining-upward cycles. Roughly speaking, a transition from sediments with predominantly braided-river characteristics into sediments with predominantly meandering characteristics might take place about at m 30.

Section Q. – In this section all braided-river features are completely absent. In the lowermost 50 metres of the section clays, silts and sands are by far the most important lithological constituents. The greater part of these sediments consists possibly of topstratum deposits which do not merit a further subdivision; only between m 35 and m 50 could the clays have a floodbasin origin. The thin pebbly layers, for instance the one described near m 42 (unit e, cf. p. 310), may be a crevasse-splay with which very coarse sediments, alien to those of the flood-basin, were carried into the backswamp. From m 50 onwards, the more active part of the river is reflected by the sediments. Above all, the deposits between m 51 and m 55, with their close resemblance to the fining-upward cycles described in Section I', are good examples of point bar sediments. The rest of the section, too, exhibits sediments which were probably partly formed as channel-lag deposits, partly as point bar deposits.

Section R. – Notwithstanding the coarse-grained character of the deposits encountered in this section, braided-river features are not present. Typical fining-upward grading units generally not exceeding 8 metres in thickness occur throughout the entire section. Especially the upper part of the section shows many conformities with the point bar sediments of section F. The abrupt transition at m 32 from gravelly sands to silty clay may have been caused by a sudden diversion of the active stream channel, for instance by avulsion (Allen, 1965b). Relatively thin clay layers commonly form the upper part of the cycles. In some locations they have, however, only been preserved as clay balls.

Section S. – This section shows a more striking predominance of fines than any other section. Fining-upward grading units proved to occur everywhere. The fineness of the sediment and the relatively thick clay layers suggest that the gradings originated at some distance from the active part of the stream channel. They represent upper point bar deposits and topstratum deposits; a further subdivision does not seem warranted. The thin, sharply limited pebble and cobble layer at m 36 could have a crevasse-splay origin. Towards the top of the section the cycles become more complete, with coarse sediments in their lower parts. A meandering-river origin is obvious for the sediments of this section.

Section T. – This section can be described as consisting of three parts: At the base of the section the cobble conglomerate clearly distinguishes itself from the sediments lying on top of it. From m 11 to m 50 fine-grained sediments, generally not exceeding sand-size, prevail. From m 70 to at least m 225 there is a clear decrease in mean grain size; the Voznuevo Formation shows a fining-upward grading on a large scale.

The basal conglomerate shows features highly comparable to those of section C 2 with respect to the very abrupt changes in grain size existing between the conglomeratic parts and the intercalated sandy, silty or even clayey parts. Cut-and-fill structures and plant remains, some of which probably in situ, are rather common. As in section C 2, we must assume that the river which produced these kind of sediments had a braided character.

Evidence from the fine-grained part of the section between m 11 and m 50 is very poor; a number of fining-upward units could be observed.

From m 70 onwards, fining-upward grading is also common, mainly in cross-stratified units in the coarser-grained lower part and in units which grade into silt or clay in the finer-grained upper part. Although the scarcity of sediments of clay- and silt-size up to approximately m 200 does not favour an interpretation suggesting deposition by a meandering river, the regularity, the frequently changing paleocurrent directions and the gradual changes in grain size are strongly in favour of a meandering-river origin. Especially between m 110 and m 203, the sediments are highly comparable to those reported from the upper part of the Voznuevo Formation between Boñar and Cistierna, as for instance in the excavations near Boñar and near Grandoso. These predominantly sandy and gravelly sediments, almost without silts and clays, probably represent thick point bar accumulations. The presence of backflow phenomena also suggests deposition under conditions comparable to those found in the excavations mentioned above. From m 203 onwards, and especially between m 218 and m 225, topstratum deposits predominate.

E. CORRELATION OF THE SECTIONS

Enclosure XI gives an impression of sections A to T with a very strong vertical exaggeration in order to improve readability. We have already made reference to this enclosure in order to show the Lower Cretaceous 'time wedge' which was found by means of pollen analysis (Chapter IV). Correlation of the sections lands us in great difficulties since the sections, which themselves suffer from poor exposure in a lateral sense, are generally separated by large unexposed areas. Only in the area between Boñar and Colle could the sections at the base of the formation (sections K, L and N) be correlated in the field by tracing the outcrops between the sections (cf. Fig. 8). The correlation between sections F, H and I and that between sections Q, R, S and, to a lesser extent, T is also fairly obvious, since in both cases the horizontal distances are relatively small.

In order to find other relationships between the sections, the sediments have been lithologically subdivided in a schematical manner according to grain size into:

clays and silts
sands (grain diameter up to 2 mm)
pebbles (diameter from 2 mm to 2 cm)
pebbles (diameter from 2 cm to 6 cm)
pebbles, cobbles and boulders (diameter > 6 cm)

The black clay horizons are indicated separately since they proved useful in an earlier study (Jonker, 1970) for correlating sections E to N (cf. Fig. 8). In some sections or parts of sections, where cyclicity causes a great diversity in grain sizes, the symbol 'cy' has been used to indicate lithology. In these cases, however, the sediments involved rarely exceed sand-size.

From this simple subdivision it becomes clear that the sediments whose components exceed 2 cm in diameter are almost exclusively limited to the lowermost 150 metres of the formation's total thickness. Line IV on the correlation chart approximately separates these two grain-size fields. Only in the extreme west of the area (section A) can this line not be continued in a satisfactory manner. Nevertheless, there is a general trend along the entire southern border of the Cantabrian Mountains towards a decrease in mean grain size with decreasing age. The apparent transition from a braided-river regime to a meandering one, a fact which we previously assumed from the paleocurrent directions (p. 324) is in close connection with a fining-upward grading on a large scale. This transition is marked by line II on the correlation chart which separates those parts of the sections which are interpreted as having been deposited under braiding conditions from the sediments typical of meandering rivers. In the western part of the formation (sections A and B) the separation appears to lie higher up in the section; both irregularities in lines II and IV must be sought in an intensified influence of tributaries in the west, indications of which were found in the composition of the gravel and in divergent paleocurrent directions. The thickness of the braided-river deposits clearly increases towards the west and proved to be zero in the sections east of Guardo (sections Q to T). Since braided-river deposits are generally coarser-grained than their meandering counterparts, this difference may explain the fact that the total thickness of the formation increases in a westerly direction (line III on the correlation chart).

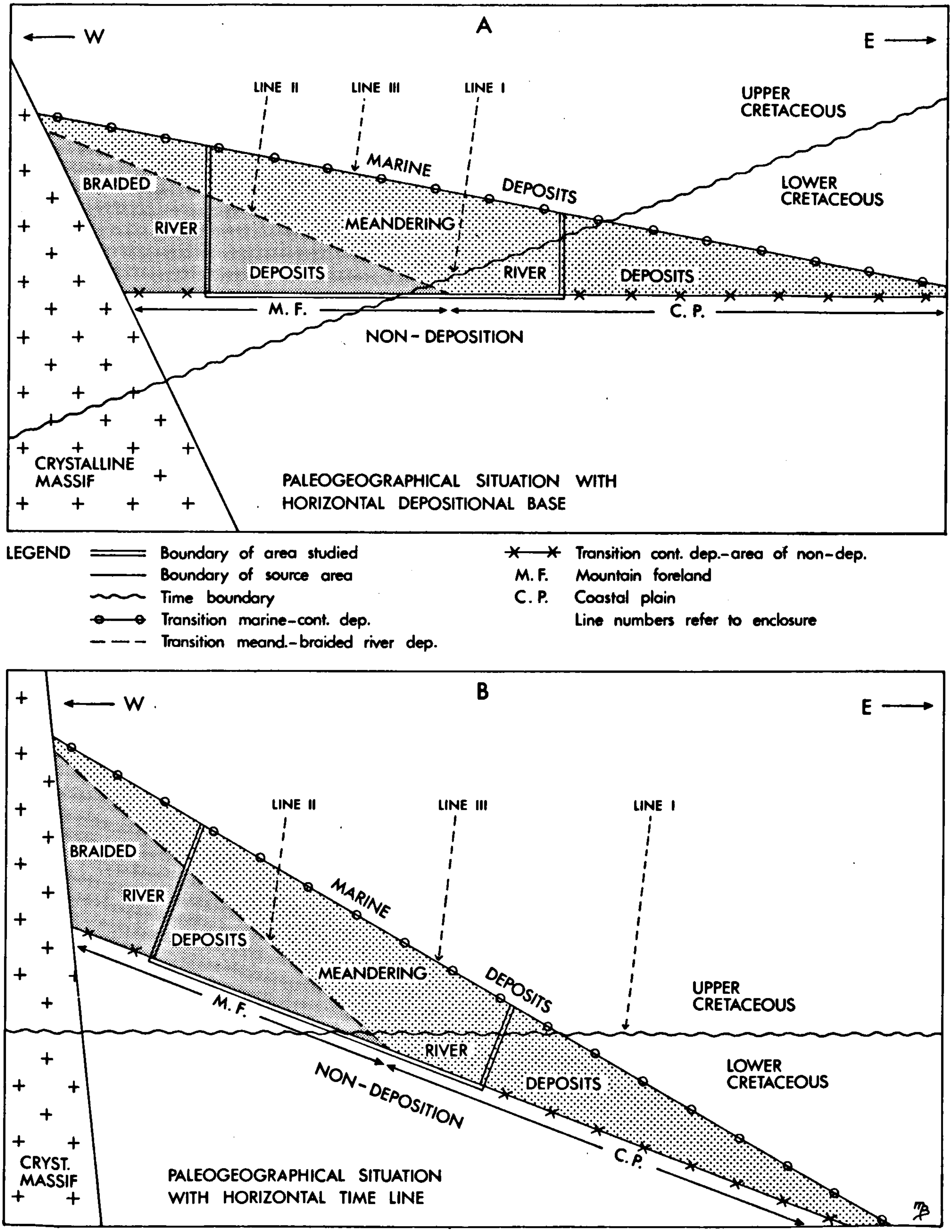
The black clays cannot be used for the correlation over great distances. From sections R and T, in which the black clay horizons could be traced laterally, we have learned that the black clays are lens-shaped bodies, with a thickness of a few metres and a width of some tens of metres. In all probability the black clay horizons distinguished in sections E to J and in the area between Boñar and Colle (Fig. 8) do not belong to one and the same clay bodies, but only indicate a level in the Voznuevo Formation in which black clay layers occur frequently. Such a level could reflect certain topographical conditions in which extensive backswamps could form behind the levees, as for instance in times of small supply of clastic material.

F. PALEOGEOGRAPHY

Since braiding of a river is accompanied by a relatively strong gradient of the river bed or/and a high discharge (variable, but periodically) of the river itself, we must assume that one or both conditions mentioned above have been more important in the western part of the area studied than in the eastern part, and that they appear to be of increasing influence towards the west (line II, Enclosure XI).

Other data important to the reconstruction of the circumstances under which the sediments of the Voznuevo Formation have accumulated are the paleocurrent directions. They could be reconstructed from cross-stratification, imbrication and channel axes (Chapter V, part C), and the history of the Cenomanian transgression which is well known in the provinces of Vizcaya, Burgos and Santander (cf. Chapter IV). As for the paleocurrent directions, we have learned that transport of the sediments of the Voznuevo Formation took place from directions between west and south. In relation to this observation it should be stressed that this general trend in paleocurrent direction is only indicative of the direction of the transporting agent – i. e. a river – in the locations where they have been observed. In other words, from the observations made in the Voznuevo Formation one may only conclude that a river, or a system of rivers, had flowed from southwesterly directions to northeasterly directions between Riello and Cervera de Pisuerga; it does not, however, follow as a matter of course, that the source area which provided the sediments was situated in the same direction as the area to which paleocurrent measurements indicate. An attempt to make some concluding remarks concerning the source area will not be ventured, however, before we have considered the petrological composition of the sands, the silts and the clays (Chapters VII and VIII).

Applying the division into proximal and distal braided-river deposits, the adjectives referring to the distance from the source area, as introduced by Smith (1970), we shall in the present case be dealing with distal braided-river deposits, since planar large-scale cross-stratification clearly dominates over horizontal stratification. A second feature in favour of distal deposition is the circumstance that the braided-river deposits are immediately overlain by meandering river deposits. This argument does not apply, of course, to the tributaries which introduced material from the present Cantabrian Mountains (cf. Section A, for instance); they have, most probably, more proximal characteristics but they could


A
← W
E →
LINE II
LINE III
LINE I
UPPER CRETACEOUS
LOWER CRETACEOUS
MARINE
DEPOSITS
BRAIDED
RIVER
DEPOSITS
MEANDERING
RIVER
DEPOSITS
M. F.
C. P.
NON - DEPOSITION
CRYSTALLINE MASSIF
PALEOGEOGRAPHICAL SITUATION WITH HORIZONTAL DEPOSITIONAL BASE
LEGEND
Boundary of area studied
Boundary of source area
Time boundary
Transition marine-cont. dep.
Transition meand.-braided river dep.
Transition cont. dep.-area of non-dep.
M. F. Mountain foreland
C. P. Coastal plain
Line numbers refer to enclosure
B
← W
E →
LINE II
LINE III
LINE I
BRAIDED
RIVER
DEPOSITS
MARINE
DEPOSITS
MEANDERING
RIVER
DEPOSITS
UPPER CRETACEOUS
LOWER CRETACEOUS
M. F.
NON - DEPOSITION
C. P.
CRYST. MASSIF
PALEOGEOGRAPHICAL SITUATION WITH HORIZONTAL TIME LINE

only be occasionally observed in the field so that no definite conclusions can be made.

A possibility for the paleogeographical conditions which caused the deposition of the sediments of the Voznuevo Formation is presented in Figs. 17 A and 17 B. These figures show a schematic representation of the results of the investigations described in Chapter IV and in this chapter. It is also a simplification of the correlation chart (Enclosure XI), in so far as use has been made of lines I, II and III. In Fig. 17 A a horizontal line represents the level where the transition from Paleozoic to Cretaceous sediments is situated. Fig. 17 B is in fact entirely identical to Fig. 17 A, but it has been tilted so that the time line becomes horizontal (line I). All lines parallel to line I represent a moment in the history of the Cretaceous transgression. Considering such a moment in Upper Cretaceous times we may expect from east to west (numbers referring to Fig. 17 B):

1. Shallow marine deposits, becoming sandier towards the coastline,
2. meandering-river deposits,
3. braided-river deposits (only deposited after the transition from the Lower Cretaceous to the Upper Cretaceous).

Comparing the findings in the present study with the hypothetical models as introduced by Allen (1965b), only relationships with his braided stream model (Model B, Fig. 35) and his strongly meandering stream model (Model D, Fig. 35) could be ascertained. The intermediate model – the low sinuosity stream – is rather rare and could not be distinguished in the present investigation. The relatively thick sand accumulations with only thin clay layers, encountered in the excavations near Boñar and Grandoso, could well be presumed to represent the deposits of such a low sinuosity stream. The strongly diverging paleocurrent directions, however, do not favour such a hypothesis.

Although it is not very difficult to classify the findings concerning the sediments of the Voznuevo Formation into theoretical alluvial facies, the association of these facies apparently does not fit into the hypothetical models proposed by Allen (1965b), since this author does not present a direct combination of a braided-river facies with a meandering one. Allen's association of alluvial fans with a meandering stream (Model A, Fig. 36), which coincides with the paleogeographical model of the Old Red Sandstone of Anglesey (Allen, 1965c) shows no resemblance to the situation in the present study, since the coarse-grained deposits of the Voznuevo Formation lack the field relationships, the composition and the texture of alluvial fan deposits. Allen's alluvial facies association of the delta and the coastal plain type (Models B and C, Fig. 36) can both occur in the meandering part of the formation.

The transition from marine deposits via deposits of a meandering river system to those of a braided river system from east to west, which must have occurred during Cretaceous times, indicates that the coastal plain, considered at one moment, is replaced towards the west by a floodbasin in which slope and discharge – or one of both – gain much more importance. An increasingly small coastal plain and steeper slopes at the foothills of the massif, against which the Upper Cretaceous transgression came to a dead end, may be responsible for the greater thickness of the braided-river deposits towards the west.

CHAPTER VI

SEDIMENTARY PETROGRAPHY OF COMPONENTS COARSER THAN 2 mm IN DIAMETER

THE QUARTZ/QUARTZITE/LYDITE RATIO

Introduction

At first sight, the main constituent of the Voznuevo Formation appears to be quartz, with the exception of the clays. Yet considerable quantities of quartzite and lydite are present, the latter quite eye-catching in these generally light coloured sediments. Some of the lydites proved to be carbonaceous quartz phyllites (cf. Chapter VII), nevertheless, they will be referred to as lydites in this chapter. Very few sand pebbles, consisting of consolidated Voznuevo sand particles, were also found.

Fig. 17. Model of the possible geographical situation in Cretaceous times.
A: With horizontal depositional base.
B: With horizontal time line.

Only after a short field inspection did it become clear that there is a higher percentage of quartzites near the base of the formation. This led to the determination of the quartz/quartzite/lydite ratio in several locations. As the quartzites seemed coarser than the medium size of the gravel*, an arbitrary limit was chosen at a longest axis value of 3 cm, in order to compare the ratios in both size classes. The samples were taken as far as possible at random, not with 'eyes closed', which can lead to a deceptively high proportion of coarser material, but by means of a frame in which samples were taken as close together as possible. A number of 25 measure-

* 'Gravel' is used as equivalent for 'unconsolidated conglomerate' and includes all particles > 2 mm diameter.

>3 cm ∅			<3 cm ∅			
Q	Qe	Lyd	Q	Qe	Lyd	Location
•80	20	x	84	12	4	section A (Q/Qe A1)
46	48	6	80	18	2	section A (Q/Qe A2)
84	16	-	100	x	x	section B (Q/Qe B1)
100	x	x	100	x	x	section B (Q/Qe B2)
28	72	-	80	20	-	section C (Q/Qe C1)
8	92	-	68	28	4	section C (Q/Qe C2)
96	4	-	96	4	-	section C (Q/Qe C3)
80	12	8	84	8	8	E of Carrocera
72	16	12	100	-	x	Sorribos de Alba
80	12	8	92	-	8	section F (Q/Qe F1)
68	20	12	92	-	8	section H (Q/Qe H1)
92	4	4	96	-	4	section H (Q/Qe H2)
44	48	8	72	20	8	section I (Q/Qe I1)
76	12	12	84	-	16	section J (Q/Qe J1)
88	8	4	84	8	8	section J (Q/Qe J2)
36	62	2	90	10	x	Voznuevo
28	64	8	76	12	12	Voznuevo-Grandoso a
32	60	8	68	20	12	Voznuevo-Grandoso b
24	68	4	80	12	8	section K a (Q/Qe K1)
36	56	8	72	16	12	section K b (Q/Qe K2)
76	12	12	84	8	8	section K (Q/Qe K3)
28	68	4	60	28	12	section N a (Q/Qe N1)
46	52	2	76	24	-	section N b (Q/Qe N2)
64	24	12	84	12	4	section N (Q/Qe N3)
88	8	4	88	-	12	Yugueros
90	x	10	90	x	10	section P (Q/Qe P1,2)
85	-	15				Valmartino
80	16	4	88	4	8	Prado de la Guzpeña
50	50	-				Frontier León - Palencia
100	x	x	100	x	x	Guardo
92	x	8	96	x	4	Muñeca
100	-	-	100	-	x	section Q (Q/Qe Q1)
84	x	16	84	x	16	section Q (Q/Qe Q2)
-	100	-	16	84	-	Villaverde
			84	-	16	section S (Q/Qe S1)
36	56	8	72	24	4	section S (Q/Qe S2)
-	100	-				section T (Q/Qe T1)
90	7	3	100	x	x	section T (Q/Qe T2)

Table II. The Quartz/Quartzite/Lydite ratio from W to E (top to bottom). Q/Qe + section letter and number refers to position in the sections (Enclosures II to VII).

ments are considered to be representative of the gravel composition of each location.

Results

The results of this investigation are listed in Table II, from the westernmost location (W of Soto y Amío) to the easternmost location (Cervera de Pisuerga). The first name of the same location is always situated closer to the Paleozoic than the name below it. From the table it became clear that the oldest sediments from the same location have a relatively higher content of quartzites. This does not hold for the locations W of La Magdalena, where the differences in composition are due to other causes (Chapter V).

From Table II the following conclusions can be drawn:

Number of measurements	Size	Quartz >50%	Quartzite >50%	Quartz >75%	both<50% or both 50%
37	> 3cm	22	12		3
35	< 3cm	34	1		
35	< 3cm			28	

The predominance of quartz is very clear, although this enumeration is not representative of the Voznuevo Formation as a whole, since relatively more localities rich in quartzite were chosen. Absolute ratio values will therefore be much higher in favour of quartz. Comparing the results in the two size classes, it is also evident that the mean diameter of the quartzites is larger than that of the quartzes.

Local differences

In the small isolated area between Boñar and Colle, a relatively good exposure of the lowermost part of the formation is found. Here two gravel layers could be distinguished, both near the bottom of the formation (cf. Fig. 8). In the fraction > 3 cm, which proved to be more representative, there is a striking difference in composition between the two layers. The percentage of quartzites decreases with decreasing age (from a to b, these letters following the location name in Table II). The oldest gravel layer is developed as a basal conglomerate in the 'Voznuevo contact' location, unconformably overlying the Paleozoic (i. e. Barrios Formation). Still one third of the coarse fraction, and even 90% of the fine fraction, consists of quartz.

In the eastern part of the area a basal conglomerate, consisting exclusively of quartzites (in the coarse fraction), was found in four locations at the contact with the underlying Paleozoic between Aviñante and Cervera de Pisuerga. There is also a very clear increase in thickness of this basal conglomerate from W to E, from 80 cm N of Aviñante to 300 cm N of Villaverde and to more than 1000 cm at the base of Section T.

Generally speaking, we may say that only the first tens of metres of the Voznuevo Formation are relatively rich in quartzites, and that in the remainder of the formation the quartzite percentage will not exceed 20%. The lydite ratio was never found to exceed 16%. The lydites are always in a more weathered state than the other constituents, and are frequently broken.

Comparison with surrounding formations

Comparing the lithological composition of the Voznuevo Formation with the composition of the formations surrounding it, we may say that, although quartz/quartzite/lydite ratios have never been reported from elsewhere, the Voznuevo Formation has a very special aspect. Some features typical of the formation are found again in the Vegaquemada Formation, between La Robla and Cistierna, studied by Kuyp (1969). This should not surprise us, since a considerable part of the sediments of this formation are an erosion product of the Voznuevo Formation (cf. Chapter VIII and de Jong, 1971). Kuyp reports very well rounded pebbles, consisting of quartz, with longest axes from 2 cm to 6 cm, and muscovite flakes with a maximum diameter of 2 cm, which must have been transported over a very short distance. Erosion products of the Voznuevo Formation, however, are only limited to the base of the Vegaquemada Formation. The Voznuevo Formation must have been almost completely independent of the rocks which nowadays form the Cantabrian Mountains since the predominance of quartz in the Voznuevo sediments is alien to any other erosion product of the Paleozoic rocks in this area. The only remnants that testify to the presence of erosion of nearby Paleozoic rocks are the quartzites. The predominance of this erosion only lasted for a relatively short time. The quartzites were probably derived from previously weathered Paleozoic rocks, which covered the area before the Cretaceous deposits were laid down. At that time there must have been little or no relief in the Paleozoic mountain chain. Assuming a Paleozoic massif with a strong relief, comparable to the present situation, we should expect that, apart from quartzites, a considerable quantity of limestone would be present. No limestone, however, either macroscopical or in the thin sections, proved to be present.

MEASUREMENTS OF FLATNESS AND ROUNDNESS

Introduction

As might be clear from the above, the composition of the gravels is rather monotonous, quartz pebbles being the only constituent sufficiently abundant for the determination of flatness and roundness indices. Nevertheless, in three locations (in sections A, C and T) a comparison was made between flatness and roundness of quartz gravel and of quartzite gravel (Table IV).

For the gravels the well-known formulae of Cailleux (Cailleux and Tricart, 1959) were used for calculating the index of flatness and the index of roundness. These indices appear to be very popular, although many workers have proposed alternative solutions for the representation of morphometrical properties of pebbles and cobbles (see, e. g., Mabesoone, 1959; Köster, 1964). The measurements in the field suffered from practical difficulties, since many pebbles and cobbles proved to be broken. This was caused by:

1. Tectonic forces.
2. Weathering (both chemical and mechanical).
3. Taking the gravel out of the wall.
4. A combination of 1, 2 and 3.

Especially tectonic forces are very harmful to the conservation of unbroken material, probably much more than the influences of weathering. This was very obvious in the exposures along the Esla valley near Cistierna, where the Voznuevo Formation has been strongly squeezed together and where, as a consequence, unbroken pebbles are rare. In each location at least 25 unbroken specimens were taken.

Results and interpretation

Measurements in 22 locations, covering the whole area, yielded indices of flatness of between 1.54 and 1.93, and indices of roundness of between 223 and 416. Comparing these values with the values found by Cailleux (Cailleux and Tricart, 1959) from 12 different environments, the main cause of flattening and rounding of the gravel of the Voznuevo Formation must have taken place in a fluvial environment. Since rivers were responsible for the supply of material from southwesterly directions, it seems reasonable to expect that in the area studied, which has a lateral extent of about 150 km, approximately parallel to the paleocurrent direction, differences in the indices of flatness and roundness might exist between W and E. Comparing the median index values for three regions, separated by the rivers Bernesga and Esla (Table III), we find a distinct decrease in the median index of flatness, together with an increase in the median index of roundness. This contributes to the many other indications that sedimentary transport in the area studied took place from W to E.

Local differences in flatness and roundness values

As mentioned before, a comparison was made in three locations between two successive gravel beds with a different lithological composition; one consisting predominantly of quartz, the other of quartzite. The result of this comparison is given in Table IV. The median index values of flatness are in each case smaller for quartz than for quartzite; for the index values of roundness the situation is reverse. Differences are much

LOCATION:	NUMBER OF MEASUREMENTS: x 25	MEDIAN LONGEST AXIS:	MEDIAN INDEX VALUE:
region I			
section A	2	6.4;6.2	
section B	1	6.0	Flatness: 1.74
section C	1	4.4	Roundness: 272
region II			
section F	4	4.9;5.2;3.7;4.3	
section H	3	6.1;4.1;4.4	
section I	1	7.8	
La Valcueva	1	4.3	Flatness: 1.72
section Boñar	2	4.5;4.0	Roundness: 323
section K	1	7.6	
section L	1	6.2	
section N	2	6.0;5.2	
region III			
Prado de la Guzpeña	1	4.2	
Muñeca	1	4.3	Flatness: 1.54
section T	1	4.8	Roundness: 388

I: W of Río Bernesga
II: Between Río Bernesga and Río Esla
III: E of Río Esla

Table III. Median index values for flatness and roundness of quartz gravel calculated for three parts of the area.

LOCATION:	MATERIAL:	MEDIAN INDEX VALUE: Flatness:	Roundness:
section A	quartz gravel	1.82	240
	quartzite gravel	2.21	121
section C	quartz gravel	1.63	325
	quartzite gravel	1.75	281
section T	quartz gravel	1.54	413
	quartzite gravel	1.67	399

Table IV. Comparison of flatness and roundness indices of gravel of varying lithological composition.

larger in section A than in the other two sections, probably because of the fact that the median longest axis for the gravel is 7.8 cm in section A and smaller in section C (6.3 cm) and section T (5.5 cm). The fact that the quartzites in section T are so much better rounded may be explained by:

1. A greater distance from the source area.
2. More intensive shaping as a result of more than one sedimentary cycle.

Using the previously mentioned assumption that the quartzites were derived from the Paleozoic rocks of the present Cantabrian Mountains, the quartzite gravels in sections A and C could be directly derived from quartzite layers, the gravels of section T from a Paleozoic conglomerate. A second possibility is that the sediments in sections A and C originated in Paleozoic conglomerates, while the sediments of section T, which had the same source, underwent a second cycle in Permo-Triassic times (see discussion below).

Comparison with surrounding sediments

Measurements on gravels of underlying and overlying sediments were carried out by Papa (1964) and Smit (1966) on the Permo-Triassic NE of Cervera de Pisuerga, and by Kuyp (1969) and Mabesoone (1959) on the Paleogene and younger deposits on the southern and southwestern border of the area studied by the present author. Papa and Smit did not report whether they made any distinction between quartz and quartzite pebbles in calculating Cailleux's indices. Yet they mentioned an increase in the percentage of quartz pebbles towards the top of the Permo-Triassic sediments, accompanied by a decrease of the mean grain size. The flatness and roundness indices of the components of the older conglomerate of Permo-Triassic age indicate derivation from the Carboniferous Curavacas Conglomerates. According to Papa, the younger Permo-Triassic conglomerates had a source area described as: 'quartz veins in the hinterland'. Together with the observation that the mean pebble size decreases in an eastward direction, and consequently a supply from the W must have taken place, it is very likely that the top of these Permo-Triassic sediments have the same source area, or at least a similar source area, as the sediments of the Voznuevo Formation. The general upward decrease in grain size throughout the Permo-Triassic sequence can be interpreted – according to Papa – as a combination of a longer distance of transport and an aplanation of the hinterland. Seen in this light, the well-rounded quartzites in section T could have been derived from eroded Permo-Triassic sediments (only present in this part of the area studied!), mainly from the older conglomerate in which quartzites are abundant.

An example of gravel-bearing formations overlying the Voznuevo Formation is the Candanedo Formation studied by Kuyp (1969). This formation is rich in quartzite and limestone gravel since material derived from the Voznuevo Formation only forms a very small part of these mountain debris sediments. As is to be expected, the limestone gravel is better rounded and less flattened than the quartzitic gravel.

Even the very comprehensive morphometrical gravel analysis by Mabesoone (1959) in sediments of the Duero Basin in the province of Palencia (including the Cuevas Formation, comparable to Kuyp's Candanedo Formation, and the overlying Vega de Riacos Formation) cannot be of any help in our investigations, because in that case, too, only quartzite and limestone gravels were considered. The striking difference in lithological composition as compared with the sediments of the Voznuevo Formation and part of the Permo-Triassic sediments shows us that the latter deposits occupy a very special place in the post-hercynian history of the Cantabrian Mountains.

Surface features of pebbles and cobbles and climatic conditions

Little is known of surface textures of gravels since most investigators use fractions between 0.3 and 2.0 mm (Köster, 1964). Since comparison with findings by other investigators is not possible, we shall confine ourselves to a few brief remarks. Quartzites have in general a mat and dull appearance with a rough surface; they are never translucent or transparent. In contrast to the quartzites, the quartzes generally show a greasy to mat lustre, they are nearly always transparent, sometimes translucent. Discolourations caused by iron (hydr)oxides occur almost everywhere, giving the gravel a yellowish brown to pinkish aspect. Very intensive discolourations, such as appear on the northern slope of the valley between Boñar and Colle, were caused by ferriferous waters flowing down from the Paleozoic rocks, which are topographically higher. Although the quartz gravel is generally well-rounded and the surface looks rather smooth from a distance it proves to be very much corroded. As the intensity of this corrosion differs from place to place, it is assumed that most of this corrosion took place after deposition of the material. Grooves and holes on the surface are filled with white-coloured kaolinitic material and pulverized sand particles.

It may be clear that data obtained from gravel flatness and roundness, only contribute to a very small extent to the reconstruction of paleoclimate. As no evidence of eolian transport was found on the surface of the gravel, climate during the deposition of the Voznuevo Formation probably was not very dry. This assumption is supported by the strong chemical weathering to which the sediments must have been exposed (Chapter VIII). Other factors, such as the absence of limestone and the presence of kaolinite are not only in favour of strong chemical weathering, but are also indicative of an acid environment. According to values found by Cailleux, morphometrical values as reported from the Voznuevo Formation can best be ascribed to deposition in a temperate or warm-humid climate. The presence of kaolinite also indicates warm and rather humid climatic conditions.

Fraction: 8-13 mm	I (n=300)	II (n=300)	III (n=300)
1 white milky quartz	7.0	4.7	2.7
2 red quartz (+quartzite)	9.0	10.0	49.9
3 grey quartz (+quartzite)	4.0	6.0	4.2
4 yellow quartz (+quartzite)	69.1	75.9	31.4
5 crystalline	0.3	–	0.8
6 lydite, hornfels, phtanite	2.7	0.7	1.1
7 rest: miscellaneous red components	0.3	1.0	0.4
8 red ferriferous quartz	0.3	–	–
9 miscellaneous components, not red	7.3	1.7	9.5
	100.0	100.0	100.0
percentage of red components	16.9	11.0	50.3
percentage of quartz and quartzite, groups 7,8 and 9 excepted	89.1	96.6	88.2

1 vein quartz s.s. (not translucent)
2 vein quartz s.l. , other quartz,and quartzite resembling to quartz, red colour caused by secondary pigment
3 other quartz and quartzite resembling to quartz
4 see 2
5 crystalline - miscellaneous
6 lydite, hornfels, phtanite, light and dark coloured rocks, layered
7 rest: miscellaneous red, quartzite-like (not resembling to quartz)
8 rest: red ferriferous quartz
9 rest: miscellaneous, not red; mainly grey quartzites, also muscovite-rich sandstone and other components

Table V. Composition of the small pebbles (in percentages).

COMPOSITION OF PEBBLES OF BETWEEN 8 AND 12 mm IN DIAMETER

Since in the field no differentiation was made between the various kinds of quartz, a number of samples of small pebble size were counted in the laboratory of the Geological Survey of The Netherlands in Haarlem. Counting was carried out in the fractions between 8 and 12 mm. The result of the grouping of various types of quartz is given in Table V. No difference was made between quartz and quartzite, as they strongly resemble each other in this fraction. Three representative samples from the locations of Grandoso (I), Campohermoso (II) and Sorribos de Alba (III) were submitted to examination.

In all three samples about 90% of the material proved to be quartz (quartzite). This is not very surprising after our knowledge of the composition of the coarser fractions. The difference in the red quartz/yellow quartz ratio in sample III as compared to samples I and II is more striking. Yet the sum of the percentages of red and yellow quartz has approximately the same value in all three samples, and as the red colour is caused by secondary pigment, there is no obvious primary difference between the three samples.

We may assume that these three samples are representative of the composition of the small pebble fraction of the Voznuevo Formation (the very base of the formation excepted) with the restriction that the results of the countings are not altogether reliable, the material used being more or less pulverized.

SUMMARY

Summarizing the main points of our investigations in the Voznuevo Formation with respect to the composition of the gravels and their morphometrical properties, we must bear in mind a few striking facts. First of all there is the predominance of quartz, only accompanied by modest percentages of quartzites and lydites. This composition was never found in any other formation known in the Cantabrian area with the exception of the upper part of the Permo-Triassic sediments N of Cervera de Pisuerga described by Papa and Smit. Quartzites, with certainty coming from a region which nowadays forms the Cantabrian Mountains, are limited to the base of the Voznuevo Formation. Limestone gravel is absolutely absent in these sediments. Indices of flatness and roundness indicate a fluvial mode of transport in a temperate or warm humid climate. For quartz gravel a decrease in flatness and an increase in roundness from W to E are obvious. In one and the same location, quartzite gravel proved to be flatter and less well-rounded than quartz gravel. Probably fluvial transport took place from W to E, the quartzes travelling over a greater distance than the quartzites.

CHAPTER VII

THE SAMPLES

THE THIN SECTIONS

The following part of this chapter is based on observations in thin sections of cemented sandstones and argillaceous sandstones of the Voznuevo Formation, of pebbles collected in the Voznuevo Formation and, for comparison, of a number of sandstones of Paleozoic age. It should be mentioned that the thin sections of the cemented sediments are not representative of the Voznuevo Formation as a whole, since only a subordinate part of the formation proved to be consolidated. The conclusions from the study of thin sections, which are summarized below, are based on thin sections of 32 samples.

The sandstones

When studying the sandstones of the Voznuevo Formation it becomes clear that in each of them detrital components and a cement can be distinguished.

The detrital components. – The detrital components may be said to range from pebble-size to silt-size, often in one and the same thin section. Consequently, sorting is very poor in the majority of the thin sections; moderate to good sorting appears to be rather exceptional. The original shape of most grains (i. e. the degree of roundness at the time of their deposition) can hardly be determined, corrosion having been very extensive. Especially quartz grains on which indications both of overgrowth and of solution – sometimes on one and the same grain – could be observed, are not very suitable for even a rough estimation of the degree of roundness. This phenomenon indicates migration of silica as described by van der Waals (1967) in the unconsolidated sands of the Tertiary of South Limburg, The Netherlands. There, it has been concluded that the mobilization of silica was favoured by a humid, tropical to subtropical climate. Quartzite grains are generally less worn, they proved to be rounded to well-rounded.

In a number of samples the grains were found to be intensively broken, which gives them a jigsaw puzzle-like appearance. The cracks between the fragments have been filled with cement; they may reach a width of several tens of microns. Unlike the sediments of pebble-size, there is no apparent relationship between tectonic deformation observable in the field and the degree of breakage of the detrital grains in the thin sections.

In many instances the detrital grains float in the cement; thin coatings of clay occasionally surround the grains without filling the entire space between the grains: the sediment is highly porous. Where contacts occur between the grains they are almost exclusively tangential or straight contacts, proving that there has been no or hardly any intrastratal solution.

The detrital grains are mainly composed of undulous quartz and of quartzite. Chert grains, clay grains, phyllitic quartz grains, feldspars and muscovite flakes are of minor importance. As we have learned from the composition of the pebbles and the cobbles (Chapter VI), high percentages of quartzite, exceeding the percentages of quartz, are restricted to the very lowest part of the Voznuevo Formation. This tendency is also reflected in the sand-sized sediments. Although quartzite grains are present in almost every thin section, they are more abundant in the basal part of the formation. Among the quartz spheroidal and volcanic quartz could sometimes be observed. Chert grains were encountered in most samples in moderate quantities.

Feldspars are rare in the average Voznuevo sandstone. They have commonly been altered into kaolinite or are unrecognizably worn. In one sample it could be observed that the few feldspar fragments present presumably resisted weathering due to a coating of iron (hydr)oxides. Furthermore, it is evident that feldspars are better preserved in samples containing lime or whose position in the field suggests the vicinity of sands with a certain lime content which will have given protection against weathering of the feldspars. Examples of the latter possibility are samples Va 2 and Va 4 which were collected at the very top of section T, where the Voznuevo sands are found between two Mesozoic limestone layers as a consequence of faulting. In the field and in the hand specimen both samples have the appearance of a decalcified sandstone. Microscopically, the composition of the samples does not differ from that of other samples except for their content in feldspar. Values of 10% of feldspar for sample Va 2 and of 20% of feldspar for sample Va 4 were estimated in the respective thin sections. Staining of small cubes of these samples (about 1 cm^3) with hemateine and sodium cobaltinitrite (see Chapter VIII) showed that we are dealing exclusively with alkali feldspars. The estimated percentages in these stained samples conform to the values found in the thin sections. Fig. 58 shows a part of the stained surface. The quartz has remained translucent and glass-like, it shows up on the photograph as darker grains. The feldspars have a light yellow colour (white in Fig. 58) and a dull surface; they are not translucent. The rough surface of the sample under the microscope does not permit the counting of points. Moreover, many quartz grains are partially or entirely covered by a thin feldspar skin. These skins accumulate particularly in pits and other damage which are to be found on the surface of the quartz grains. For this reason no more than a rough estimate of the composition in percentages is justified. Using the Travis' classification (1970), the samples mentioned above just fall outside the 'arkose' area and have to be designated as: 'feldspathic (quartz) sandstone'.

Part of the kaolinite in the Voznuevo Formation proved to have a detrital origin since it is found as rolled-up vermicular aggregates in which the grain shape is accentuated by a thin iron skin (Fig. 59).

Quartz phyllite grains were observed exclusively in the samples from the oldest part of the formation. They also proved to occur as pebbles, especially in the westernmost part of the area, W of La Magdalena. In all probability this metamorphic material is derived from Precambrian rocks which outcrop in the western part of the area.

Detrital muscovite flakes are present in most of the samples, although they are much more abundant in samples of fine sand- to silt-size than in coarse-grained sands. Most of the muscovite flakes, however, probably have an authigenic origin. The detrital muscovite flakes can be distinguished from the latter by their more corroded appearance and by the fact that they are often found crumpled and split between detrital grains (Fig. 60).

A number of slightly pleochroitic flakes suggest that few of the muscovites are actually biotites which, under oxidizing conditions, have been altered into muscovite. This could also explain the large quantity of iron (hydr)oxides between the grains. Rutile skeletons (sagenite), which could be observed in some grains (e. g. Fig. 61), prove that we are dealing with discoloured and altered biotites. Only in exceptional circumstances are biotites preserved as surprisingly fresh, brown pleochroitic flakes. Fig. 62 shows a biotite flake embedded in a large quartz grain along three sides which flake is shut off at the other side by authigenic quartz. In this manner the biotite fragment has escaped alteration and could be preserved.

Heavy minerals are relatively rare in the thin sections. Tourmaline and zircon are present in most of the samples, whereas staurolite, anatase and epidote were found in but a few samples.

The cement. – Much more characteristic than the detrital part of the samples is the cement. In all samples the following sequence was met with:

The first cement which precipitated between the grains had a quartzose composition, generally of a cryptocrystalline to silt-size texture. The solution which brought the quartz cement has had a destructive influence on some of the detrital grains (cf. Fig. 63), but also caused secondary overgrowth. The dust-rings, which become visible after overgrowth of quartzose matter, are less abundant than in sandstones of Paleozoic age. The dissolved quartz is thought to have been derived from the sediment itself. This conclusion is drawn from the observation that a transition from weathered quartz(ite) fragments to a silt-sized cement occurs locally.

Secondly, in the cement a high percentage of kaolinite could be observed in most of the samples (Fig. 64). This kaolinite was found to replace the previous quartz cement and is assumed to be mainly derived from detrital feldspars. The authigenic kaolinite is – at least partly – of early diagenetic origin, before compaction of the sediment took place. This can be concluded from kaolinite crystals which were found compressed between detrital quartz grains (Fig. 65). In many cases kaolinite has formed characteristic sheaf-like arrangements.

The third cement in the history of cementation is composed of iron (hydr)oxides which clearly replace the previous cements. In the initial stage of infiltration by iron (hydr)oxides small isolated specks, approximately 20 microns in diameter, form. They are generally dark red to blood-red and in the description of the thin sections have been referred to as hematite. X-ray analyses of silt-sized samples (Chapter VIII) showed that most of the supposed hematite is in fact goethite. Orange-red iron in the thin sections is possibly limonite.

Some of the light grey, fine sand-sized to silt-sized sediments of the Voznuevo Formation show typical weathering with orange-red and dark purple discolourations, giving the sediment a mottled aspect in the field. In a thin section it could be observed that the difference in colour is only caused by differences in cement. In the lighter coloured part of the sample the original kaolinitic cement has been replaced by yellowish-brown iron hydroxide showing colloform, radial aggregates (Fig. 66). In the deep purple part of the sample the iron hydroxides have changed into almost opaque to dark brown-red hematite. Strong magnification shows that most of this hematite cement is composed of small circular specks, between 5 and 10 microns in diameter. Other samples from comparable outcrops also proved to have the findings in this sample in common, so that we shall restrict ourselves to the description of this sample only.

In sands rich in organic remains, disseminated sulphur is present besides iron hydroxides. One cannot establish whether this sulphur replaces or has been replaced by goethite, but the fact that the typical yellow crust-like sulphur overgrowths are only a superficial phenomenon in the field suggests that the formation of sulphur was posterior to all other events and limited to that part of the sediment which was recently exposed to the atmosphere.

The argillaceous sandstones

The argillaceous sandstones, representing fine-grained topstratum deposits, show an abundance of muscovite which can amount to more than 25%. In all samples in which muscovite is abundant, a clear orientation of the flakes was evident. The finer-grained samples generally contain a higher percentage of iron hydroxides, giving them a brownish colour in the field. In these samples one may also observe that sorting is very poor, since grains of medium sand-size to very fine silt-size were often encountered together. Detrital material other than quartz grains, muscovite flakes and organic remains is rare. Although many muscovite flakes are supposed to have a detrital origin, a number of flakes – generally of larger dimensions – lack the distorted appearance of the smaller flakes; an authigenic origin seems more appropriate.

Especially in the coarser grained parts, so often encountered accompanying the black clays, organic activity is conspicuous. Microscopical analysis showed that these parts are composed of ferruginous, orientated mica flakes with quartz grains of silt-size and organic fragments. Small lens-shaped bodies, probably partly the compressed remnants of burrows, are filled with sand- and silt-sized quartz grains. The mica content is considerably lower in these lenses; some kaolinization may have taken place in them. As regards the formation of these lenses the following is assumed: a very loose complex of muddy sediments – with a certain percentage of detrital mica flakes – in which organic activity must have been abundant, was subjected to compression as can be deduced from the shape of the sand- and silt-filled burrows. Pinching out of very thin sand layers, causing small sand lenses, may be the origin of part of these lenses, especially when they are present as strings in which the lenses are connected by horizons with a higher quartz concentration; other lenses, in which this association is not clear, are presumably of organic origin.

Black stringers consisting of organic matter are frequent; in one sample the black stringers are not parallel to the orientation of the muscovite flakes but arranged approximately perpendicular to the plane of stratification (Fig. 67). This could indicate preservation of rootlets in situ.

Thin silt-clay laminations, found in many locations in the field, proved under the microscope to consist of alternations of:

a. Bands, approximately 1 mm thick, of loosely packed quartz fragments of fine sand- to silt-size (occasionally of course sand-size) in a kaolinitic to illitic ground mass. A number of large authigenic muscovite flakes more than 1 mm in length and about 5% of black lignitic substance.
b. Bands, approximately 0.5 mm thick, with generally smaller quartz grains and a much higher content of organic material. Many small muscovite-like flakes as well as iron (hydr)oxide can be observed between the detrital grains. A strong and marked orientation of muscovite flakes and organic stringers, parallel to the bedding plane, is apparent.

The thick and large muscovite flakes, particularly frequent in the coarse-grained laminae of the alternations, are, judging from their fresh appearance, more likely to be of authigenic origin.

The calcareous sandstones
As was to be expected, the calcareous sands in the top of the Voznuevo Formation are – also in the thin sections – not basically different to the sediments which they overlie. With the exception of one sample, the calcite is clearly the result of precipitation from waters rich in lime between the detrital grains. Detrital carbonate material such as limestone grains and remnants of fossils were observed, but they form a very small part of the total detrital content. The exceptional composition of one sample, consisting of grainstone (sample 129, from the contact near Brugos de Fenar) can be explained by the fact that tectonic deformation has been very active in the location where the sample was taken. For this reason the sample might not be representative of the sediments immediately overlying the non-calcareous sands of the Voznuevo Formation.

From the observed contacts of the various cementing minerals, it is clear that the cements first had a quartzose to kaolinitic composition. The subsequent replacement of these cements by sparry calcite was of very great influence on the detrital quartz grains which became strongly corroded. The last stage in replacement, of calcite by ferric calcite, is only of minor importance, probably only taking place at the sediment's surface.

It must finally be noted that the feldspars, if present, have a remarkably fresher appearance than the feldspars in the samples which do not have a calcitic cement. They will have been protected from weathering since the calcite was formed.

Calcareous sediments within the Voznuevo Formation
Two samples, one from Section II (sample 140) and one from Valmartino (sample 201), are of special interest since they are the only calcareous sediments which were encountered within the Voznuevo Formation and not in the very upper part. A mineral is found, together with calcite, which is absent in all other samples, viz. glauconite.

It is generally accepted that sea water is required for the formation of glauconite (see e. g. Pettijohn, 1957; Millot, 1964; Chilingar, 1956; Fairbridge, 1967; Müller, 1967) and that glauconite is mainly formed by halmyrolysis. The depth of its formation is thought to lie between 20 and 700 metres below sea level. The questions now arise how the presence of these glauconite-bearing sands can be explained in the entirely continental, fluvial deposits of the Voznuevo Formation, and how it is possible that kaolinite and glauconite, which are known to be stable under diverging pH conditions, occur together.

As to the first problem we must remark that both occurrences of glauconite are situated in the upper part of the Voznuevo Formation, at a relatively short vertical distance (some tens of metres) from the transition to the Mesozoic limestones. Keeping in mind that the meandering-river sediments in the upper part of the formation probably formed on a coastal plain, it is very likely that temporary invasions of sea water took place which became stagnant, for instance in lagoons, so that marine sediments were subsequently incorporated in the fluvial deposits.

The mechanism described above also leads to the solution of the second question. It is well known that glauconite is resistant to mechanical influences such as reworking, but susceptible to chemical changes. Chilingar (1956), however, mentions two examples in Russia and one in the United States, where associations of glauconite with minerals characteristic of an acid environment (e.g. authigenic chlorite) have been encountered. The associations have been explained by formation of glauconite in shallow marine water which has been cut off and converted to lakes. The pH became much lower, giving rise to the formation of a chloritic clay cement. The low pH, which can reach values below 7.0, brought about bleaching of the glauconite grains (oxidation leads to alteration into goethite). To a certain extent this is also applicable to the glauconite grains in the present samples; the glauconites of sample 140 are even clearly corroded. Concluding, the glauconite which proved to occur in a few locations in the upper part of the Voznuevo Formation is suggested to be a forerunner of the Upper Cretaceous transgression.

The locally relative high feldspar content, encountered both in the basal part (sample 022; near Boñar) and in the upper part of the formation (samples Va 2 and Va 4; Section T) makes it clear that the fluvial sediments were not devoid of feldspar at the time of their deposition. This can also be concluded from the high percentage of newly formed kaolinite which may be viewed as an alteration product of feldspars.

Comparison with Paleozoic samples
Although many samples collected on both sides of the contact with the Paleozoic proved to be unsuitable for study in thin sections, the few remaining samples show that Paleozoic samples can fairly easily be distinguished from Cretaceous samples. In general the following characteristics could be observed:

Paleozoic samples	Cretaceous samples:
good sorting	poor sorting
concavo-convex and sutured contacts between the detrital grains prevail	point and straight contacts between the detrital grains prevail
dust rings common	dust rings present
cement: chlorite, illite, kaolinite and sericite	cement: first quartzose, then kaolinite, sometimes illite

Figs. 68 and 69, representing a Paleozoic and a Cretaceous sample, respectively, show most of the differences listed above. In general no differences could be established in the heavy mineral content, since heavy minerals are only represented in very modest quantities; besides, only the most resistant heavy minerals such as tourmaline, zircon and titaniferous minerals were encountered in both the Paleozoic and the Cretaceous samples. Only one Paleozoic sample showed a strikingly high zircon and epidote content. As we shall find in Chapter VIII, the latter mineral is extremely rare in the Voznuevo sediments.

The pebble composition
A sample from the basal conglomerate of the Voznuevo Formation east of Santibañez de la Peña showed that the pebbles and cobbles consist of almost pure quartzites with a very small amount of clay (kaolinite?) specks between the grains. The contours of the individual grains are still visible, but pressure solution has led to concavo-convex and sutured contacts between them. In the thin section this quartzite shows a close resemblance to the quartzites of the Barrios Formation between Boñar and Voznuevo.

From the composition of the pebbles in the conglomerates near Soto y Amío it became clear that part of the components of these conglomerates are strongly folded quartz phyllites, in all probability of Precambrian origin, such rocks having been encountered in the Precambrian (Boelens, pers. comm.). From the geological map of northern Spain we learn that Precambrian rocks border the Cantabrian Mountains in the northwest, the west and the southwest (cf. Fig. 1) and that they presumably continue below the post-Cretaceous deposits which form the present 'Castilian Meseta'. The pebbles and cobbles in the conglomerates mentioned above have not necessarily covered a long distance of transport since the Cretaceous west of La Magdalena is surrounded by Precambrian rocks.

Pebbles consisting of 'lydite'
Following the subdivision and the description of radiolarites by Carozzi (1960), the samples, hitherto described as lydites, which were collected among the pebbles in the Voznuevo Formation must be classified among the carbonaceous radiolarites (black radiolarian cherts). As to these, Carozzi reports (p. 310): ... 'An increasing content of argillaceous matter provides many transitional varieties toward black siliceous shales *(Kieselschiefer)*. The carbonaceous radiolarites are also known under the French name of *phtanites* and the German designation of *Lydite* (Correns, 1924; Cayeux, 1929; Heritsch and Heritsch, 1943).' ... It was Cayeux (1929), however, who made a clear distinction between lydiennes (lydite, quartz lydien, jaspe noir, pierre de touche) and phtanites. According to this author, lydienne is a variety of jasper and this term can only be used to designate black jaspers with radiolaria. A high content of carbonaceous material is characteristic. Phtanites are siliceous stratified rocks synonymous with the German Kieselschiefer. They are much harder than the lydiennes.

Microscopical analysis of the pebbles brought to light that only samples 112, P 1, 021 and 044 are unchanged radiolarites. We are dealing with carbonaceous radiolarites (with an iron content of less than 1%) which have a black to dark brown colour in the field and a light brown to dark brown colour in plain light in the thin sections. In this dark ground mass undeformed casts of radiolarites stand out clearly. Veins filled with polycrystalline quartz are of minor importance in the samples from the Vegamián Formation (Tournaisian) near Olleros de Alba, but are thick and abundant in samples 021 and 044.

The second group of samples, numbers 132, 157, 235, 269 and 309, underwent the evolution from (p. 305): ... 'a cement composed almost wholly of amorphous silica' ... to ... 'a holocrystalline aggregate of quartz granules' ... (Carozzi, 1960). The original amorphous ground mass has largely been replaced by a complex of interlocking quartz grains. The quartzes in the ground mass have the same undulatory extinction as the quartzes in the veins which are also abundant in these sections. Radiolarites occur in all these thin sections, especially in parts where the amorphous ground mass is still present. A high content of carbonaceous matter (up to 5%) causes the black colour in the hand specimen and under the microscope. Laboratory analyses made clear that the carbonaceous matter is graphite. The samples of this group have undergone intensive tectonical deformation, in contrast to the samples of the first group, which show parallel lamination or no structures at all. Following Cayeux's classification, these samples are in fact phtanites, their appearance in the thin section is identical to folded varieties of Cayeux's 'phtanite feuilleté (et amygdaloïde)' (Cayeux, 1929; Planche XXI, Figs. 80 and 81).

The third group, samples 093C, 093D and 094B, collected in the conglomerates W and E of the village of Soto y Amío, does not – in contrast to the samples mentioned above – contain any casts of radiolarites. It is doubtful whether these strongly folded and metamorphic rocks are completely recrystallized radiolarites (pseudoquartzites, Pantin, 1957) or quartz phyllites. Samples 093C and 094B contain many orientated mica flakes (Fig. 73). About 25% of graphitic matter (in the thin section, 5% by means of quantitative analysis) causes the dark colour in the sample. These quartz phyllites or pseudoquartzites closely resemble those of the Precambrian Mora Formation. As we have mentioned before, the Voznuevo Formation is enclosed W of La Magdalena by these Precambrian rocks which could be the suppliers of the dark coloured pebbles and cobbles in this part of the area. Other indications such as paleocurrent directions and differences in pebble composition previously led to the conclusion that part of the sediments – especially those of gravel-size – were derived from nearby rocks. Another feature which makes a supply of real quartz phyllites more probable is the presence of many muscovite flakes. These can also accompany pseudoquartzites, but in that case only a small quantity of muscovite is present (Carozzi, 1960).

Concluding remarks regarding the radiolarites in the Voznuevo Formation

There is no reason to assume that the radiolarites, being such a characteristic component of the Voznuevo Formation, were not derived for a small part from the Vegamián Formation, although the typical interveining by quartz was not encountered in the radiolarites of Olleros de Alba. This difference can be explained by local differences in the Vegamián Formation or by changes after deposition in the Voznuevo Formation. Such a source is, however, only applicable to the two samples of the first group.

There are many reasons to suppose that most of the dark coloured pebbles and cobbles in the Voznuevo Formation (i. e. those of the second and the third group) were derived from a source other than the Vegamián Formation:

1. If all radiolarites had come from the Vegamián Formation, the question arises why they are present in a constant proportion throughout the entire formation, while other rocks of Paleozoic derivation are mainly limited to the lower part of the formation.
2. The thickness of the individual beds in the Vegamián Formation rarely exceeds 2 cm. The strata are commonly laminated (less than 1 cm thick) or 'finely laminated' (van Veen, 1965). A very large proportion of the dark pebbles in the conglomerates of the Voznuevo Formation, however, attains a diameter which often exceeds 4 cm.
3. The samples of the second and the third group are intensively folded, often isoclinally, whereas the Vegamián samples show no folding at all.
4. The samples of the second and the third group have been recrystallized under the influence of metamorphism, in contrast to the Vegamián samples.
5. The composition of the samples of the third group suggests that they are not radiolarites, but quartz phyllites.
6. The samples of the second group show most resemblance to the phtanites described by Cayeux (1929). All examples of phtanites given by Cayeux are of Precambrian age.

In view of this, it is much more likely that by far the majority of the dark coloured pebbles in the Voznuevo Formation was not derived from the radiolarites of the Vegamián Formation. The phtanites probably have a source area identical to the area which supplied the other sediments of the Voznuevo Formation, while the quartz phyllites probably came from the Precambrian strata which outcrop in the extreme west of the present area.

Differences in the assumed lydites are clearly visualized in Figs. 70, 71, 72 and 73 in which a radiolarite of the Vegamián Formation, a radiolarite of the Voznuevo Formation, a phtanite and a quartz phyllite, respectively, are presented in a thin section.

Remarks on diagenesis

The diagenetic processes which have taken place in the sandstones of the Voznuevo Formation can be compared, for instance, with those in the Triassic Stubensandstein (Germany) as described by von Engelhardt (1967). Von Engelhardt distinguishes two diagenetic phases, the first marked by decomposition of feldspars and garnet, with solution of quartz by pressure, and neoformation of kaolinite and quartz. The following reactions are thought to be involved:

$$2\ KAlSi_3O_8 + 16\ H_2O \rightarrow 2\ K^+ + 2\ Al^{3+} + 8\,OH^- + 6\ H_4SiO_4 \rightarrow Al_2(OH)_4 + Si_2O_5 + 4\ SiO_2 + 2\ K^+ + 2\,OH^- + 13\ H_2O$$

This mechanism takes place preferably in acid environments, a condition which will also be responsible for the solution of detrital garnet grains.

The second diagenetic phase, always posterior to the first, is marked by the deposition of calcite and dolomite in the pore spaces of the sandstones. According to von Engelhardt, the results of both diagenetic stages can be observed in one and the same bed. Chemically, the main difference between the first and the second period is a change in pH conditions. In the case of the Voznuevo Formation a transition can be inferred from acid conditions, in which pH values lie below 7.0, to alkaline conditions at the very top of the formation, the latter caused by marine influences during deposition or after deposition of the overlying complex of Mesozoic limestones.

As we already have concluded in this chapter, feldspars in the top of the formation are more frequent and better preserved than in the samples from other levels of the formation, with exception of sample 022. They must have escaped alteration by local, more alkaline conditions. The acid environment in the remainder of the formation is also reflected in the scarcity of the garnets among the heavy minerals (cf. Chapter VIII).

The fact that both diagenetic stages have been acting almost simultaneously in the top of the formation is proved by the incomplete alteration of feldspars before cementation by calcite took place.

The diagenetic processes which have taken place in the sediments of the Voznuevo Formation can be classified according to the nomenclature proposed by Nagtegaal (1969) in his excellent review of classifications used, for instance, by many Russian authors and by Siever (1959), Fairbridge (1967), Dapples (1967a and b) and Müller (1967). Nagtegaal distinguishes three stages in diagenesis, viz. (a) Early Diagenesis (both subaerial and subaqueous), (b) Advanced Diagenesis and (c) Late Diagenesis.

Surveying the characteristics of each diagenetic stage and relating them to the findings in the present deposits, it is found that the second stage, that of advanced diagenesis in which compaction, cementation, authigenesis and replacement are the main processes, is nowhere exceeded; the fact that dickitization of kaolinites, a characteristic feature of late diagenesis (Dunoyer de Segonzac, 1970) has not developed, favours this assumption.

In general, temperatures probably did not exceed 100°C, while the depth of burial was less than 2000 metres. The latter can easily be calculated from the estimated thicknesses of the formations which cover the Voznuevo Formation. According to Mabesoone (1959), more than 1600 metres of Upper Cretaceous and Paleogene sediments occur upon those of the Voznuevo Formation; according to Evers (1967), between 1500 and 2000 metres. The Neogene and younger deposits, with a total thickness of 1200 metres, have never covered the sediments of the Voznuevo Formation studied in this investigation.

GRAIN-SIZE DISTRIBUTION

General remarks

Grain-size distributions of 176 samples of sand-sized sediments from the Voznuevo Formation were determined in the sedimentological laboratory of the University of Leiden. For a detailed description of the laboratory proceedings the reader is referred to Koldijk (1968a), whose samples were processed in the same laboratory in a similar manner. Calculations on statistical parameters of the grain-size distributions were carried out with the help of a PL/1 computer programme on grain-size parameters, composed by Koldijk (1968b). The favourable circumstance that the processing of the samples and the calculations involved were identical creates the possibility of a comparison between Koldijk's geologically recent samples and the present samples of Cretaceous age. Nineteen samples proved to contain too much gravel, so that 157 samples are considered in the following investigation.

The output of the PL/1 programme provides percentile measures according to Trask (1932) and Folk (in: Folk and Ward, 1957; Mason and Folk, 1958) and moment measures according to Friedman (1961, 1962, 1966 and 1967). Since Trask's and Folk's measures often could not be calculated, only moment measures were used. Percentile measures have the disadvantage that they cannot be calculated when the weight percentage of the finest and the coarsest grain-size class exceeds a certain figure. When both graphic and moment measures are available the latter are to be preferred since their sensitivity is greater, especially of the third and the fourth moment (skewness and kurtosis, respectively). The moment measure most sensitive to environment is the third moment, while the fourth moment proved to be less indicative (Friedman, 1961). Skewness, thus being one of the most useful criteria for the separation of sands from various environments, is negative for beach sands and positive for river sands, for example.

For the present grain-size study the area was subdivided into four parts:

I : West of the Río Bernesga (23 samples).
IIa: Between the Río Bernesga and the Río Porma (47 samples);
IIb: Between the Río Porma and the Río Esla (51 samples).
III : East of the Río Esla (36 samples).

The results

In Table VI the percentage values of the second, the third and the fourth moment are listed, for each moment for twelve value intervals. These percentages were calculated for each individual part of the area and for the area as a whole (lowermost series of each moment). Before permitting ourselves to draw conclusions concerning the percentages in Table VI it should

σ_φ	2.1	2.1–2.2	2.2–2.3	2.3–2.4	2.4–2.5	2.5–2.6	2.6–2.7	2.7–2.8	2.8–2.9	2.9–3.0	3.0–3.1	3.1
I	4	4	4	9	9	13	9	-	9	-	4	35
IIA	85	65	85	85	65	4	13	85	4	85	85	15
IIB	25	4	14	10	12	17	8	4	6	-	-	-
III	32	3	22	14	14	3	6	3	-	-	3	-
TOTAL	19	4	13	10	10	10	9	4	4	3	4	10
$\alpha_{3\varphi}$	-15	-15 – -10	-10 – -05	-05 – 0	0 – +05	+05 – +10	+10 – +15	+15 – +20	+20 – +25	+25 – +30	+30 – +35	+35
I	-	-	4	-	9	31	39	13	4	-	-	-
IIA	-	-	11	-	13	40	34	2	-	-	-	-
IIB	-	-	-	10	12	10	33	31	4	-	-	-
III	-	-	-	-	3	31	41	14	8	3	-	-
TOTAL	-	-	4	3	9	27	36	16	4	1	-	-
$\alpha_{4\varphi}$	1.0–2.0	2.0–3.0	3.0–4.0	4.0–5.0	5.0–6.0	6.0–7.0	7.0–8.0	8.0–9.0	9.0–10.0	10.0–11.0	11.0–12.0	12.0–13.0
I	9	39	30	9	9	4	-	-	-	-	-	-
IIA	11	34	40	13	2	-	-	-	-	-	-	-
IIB	16	12	17	14	25	6	6	4	-	-	-	-
III	-	55	47	22	9	55	-	55	-	-	55	-
TOTAL	9	21	33	15	12	4	2	3	-	-	1	-

Table VI. Percentage values for various value intervals of standard deviation ($\sigma\varphi$), skewness ($a_3\varphi$) and kurtosis ($a_4\varphi$) for four parts of the area (I, IIa, IIb, III) and for the entire area (TOTAL).

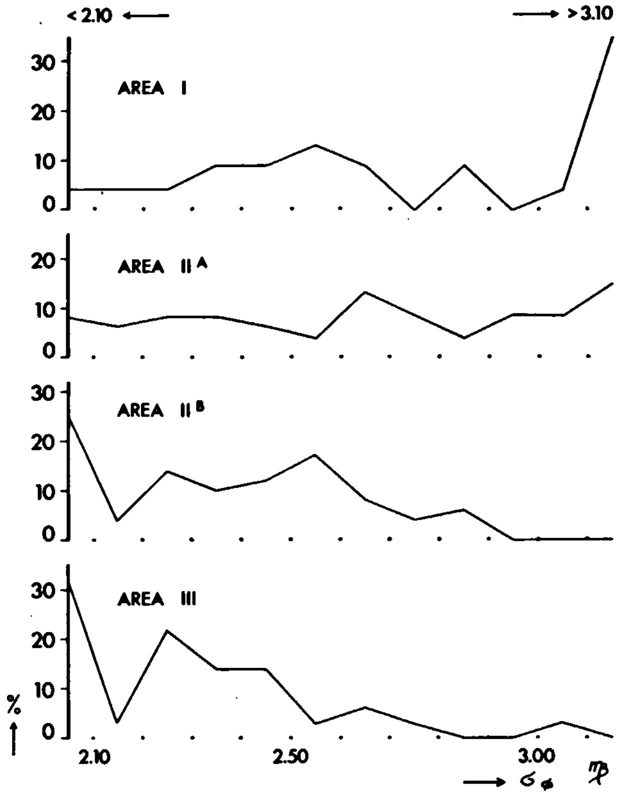


Fig. 18. Standard deviation (second moment) plotted against frequency in percentages for four parts of the Voznuevo Formation.

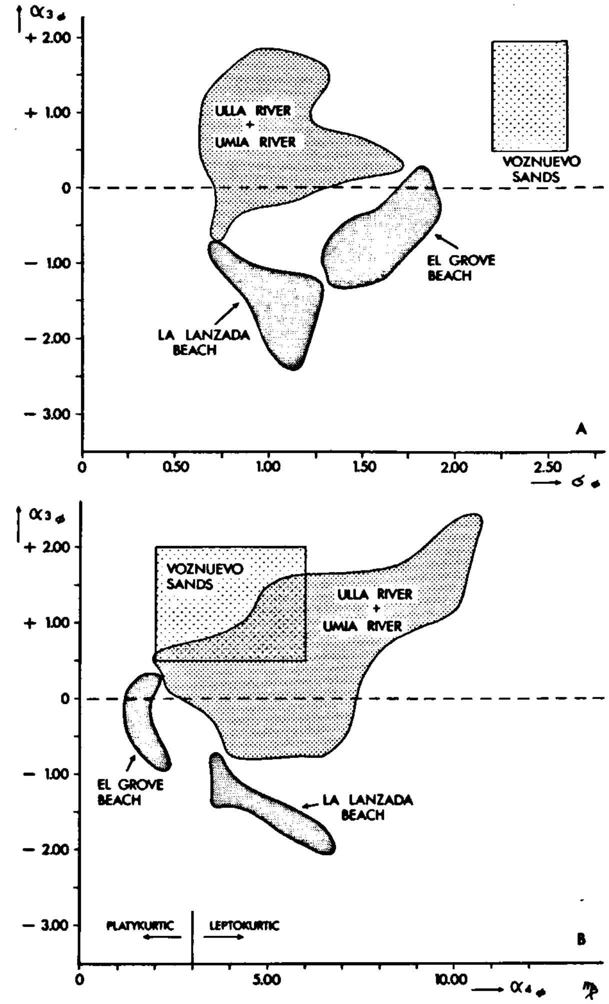


Fig. 19: A: Standard deviation plotted against skewness (second against third moment) for Voznuevo samples, compared with results obtained by Koldijk (1968b).
B: Kurtosis plotted against skewness (fourth against third moment) for Voznuevo samples, compared with results obtained by Koldijk (1968b).

be noted that the extreme columns of the second moment are a compilation of all values smaller than 2.10 and larger than 3.10; they are not absolute percentage values.

Three very significant trends can be observed from this listing: from west to east the values of the standard deviation ($\sigma\varphi$) decrease, while those of skewness and kurtosis of the frequency distribution increase. In simpler words, this means that sorting of the sands improves in an easterly direction, that the frequency distribution shows an increasingly 'fine tail' in the same direction and that the curves become sharper towards the east. Especially the better sorting in the same direction as was previously assumed, by means of paleocurrent measuments (Chapter V), to be the direction of transport is significant. The rigid gradation of improved sorting from west to east is visualized in Fig. 18.

Finally we have availed ourselves of the opportunity of comparing the results obtained by grain-size separation of Voznuevo samples with those of recent beach and river sediments from Galicia (northwestern Spain) studied by Koldijk (1968b). This is done in Fig. 19A, in which the standard deviation is plotted against skewness, and in Fig. 19B, in which kurtosis is plotted against skewness. The irregular fields sketched in these figures are the approximate contours of the values plotted by Koldijk. For the Voznuevo Formation highly schematical fields are given in which more than 10% (measured in the formation as a whole) of the values observed must be ranged. From this comparison we must conclude that:

1. The Voznuevo Formation consists of sands which are of fluvial origin (other possibilities such as dunes, barrier sands, lake and desert sands are out of the question), since the skewness of their distribution curves is positive.
2. The Voznuevo sands are very poorly sorted, much poorer than Koldijk's river sands.
3. The shapes of the distribution curves are more normal than those of the Galician samples, but there is still a clear tendency towards leptokurtic (sharp) curves.

CHAPTER VIII

THE MINERAL ASSOCIATIONS

THE HEAVY MINERALS

Introduction

In order to obtain a better insight into the composition and the provenance of the sediments of the Voznuevo Formation, a fairly extensive study was carried out of the heavy-mineral content of the sands. Of a great number of samples slides were prepared of the material between 50 and 500 microns, of a large number of them also fractionated slides of the fractions between 50 and 150 microns, between 150 and 300 microns and between 300 and 500 microns. Sixty-four samples were selected as representing the heavy-mineral composition. The position of these samples is shown schematically in Fig. 21, which is a simplification of the correlation chart of Enclosure XI. In order to compare the samples as objectively as possible (fractionating proved impossible or incomplete for a great number of the samples) the collective slides from 50 to 500 microns were used where possible. In samples in which the number of heavy-mineral grains was too low, use was made of the 150 to 300 micron fraction (which had been prepared prior to the collective slides). The results of countings of the translucent grains are listed in Table VII, arranged from west to east (left to right) for three imaginary levels (lower, middle and upper part of the Voznuevo Formation).

The results

Before taking a closer look at each of the minerals or mineral groups of Table VII, let us first retain the following generalities:

1. The heavy-mineral content of the sands of the Voznuevo Formation is low.
2. Many grains, several of which possibly belong to the light-mineral fraction, are coated with iron; under the microscope they are completely opaque. The percentage of opaque grains can be very high: over 90% of the total number of grains. In a previous study, in which only samples from the area between Sorribos de Alba and Colle were considered, a number of 300 grains had been counted in each sample, alterites and opaque grains included. The mean percentage for alterites and opaque grains, calculated from 59 samples, proved to be 25% and 38%, respectively.
3. Since the number of translucent grains per sample is relatively low, the number of grains counted generally did not exceed one hundred. In some samples, in which the number of countable grains was lower, the percentages were converted accordingly.

The most conspicuous fact which can be gathered from the heavy-mineral composition is the predominance of six mineral groups. Other mineral groups, of which only titanite, epidote and topaz were observed, are completely subordinate. They are listed in Table VII among 'others'.

Five of the six mineral groups are represented graphically in Fig. 20, in order to examine possible trends and/or differences from west to east. The conclusions from this figure will be given in the description of each individual mineral group.

Tourmaline. – is the most abundant heavy mineral observed in the Voznuevo Formation. It occurs in all samples, its percentage generally fluctuating around 50%. Light to dark brown and yellowish brown tourmalines were observed most, followed by the green variety. Black and blue tourmalines occur in most samples, but their share is always of subordinate importance. The tourmaline grains are generally fresh, and all transitions from prismatic to perfectly rounded specimens were observed. Most of the grains appear to be little rounded, however, while well-rounded grains are rare. One might assume that the rounded tourmalines are multicycle, Paleozoic-derived grains, while the less abraded grains have a different origin. A similar observation was made by Leguey and Rodríguez (1970a), with respect to zircons of recent fluvial sediments in the Esla and Pisuerga basins: they made a distinction between Paleozoic and post-Paleozoic zircons.

The percentage of tourmaline remains constant over the entire area (viz. from west to east and from the lower part of the formation to the upper part). Anticipating the conclusions from the observations on the fractionated samples, we must bear in mind that the tourmaline:zircon ratio is largely dependent upon the grain size of the sample. When we take this fact into consideration it is easily seen that irregularities in the representation of the percentages in Fig. 20 may be directly attributed to grain-size differences. For this reason the results of the grain-size analyses of most of the samples have been added in Table VII. Where the percentage ratios of grain-size distribution differ distinctly from the mean composition of the sands, i. e. less than 60% of sand, more than 50% of silt and more than 20% of clay (these values were chosen at random), this is marked in the lower part of each column. Where the grain-size distribution could have influenced the smooth continuation of the percentage lines in Fig. 20 (samples S 4, Col 17, 180, 160 and Z 6), the result of the heavy-mineral counting is represented by a dashed line, while the solid line connects the values for the adjacent samples. The position of sample 240, at a very short distance from the Paleozoic, is held responsible for the extremely high percentage of zircon, so that the result of this counting will also have to be considered with some reserve.

LOWER PART

SAMPLE NUMBER	104	107	096	108	Sb8	Sb9	S3	S4	S15	S16	S22	C1	020	024	G13
TOURMALINE	61	58	1	1	51	40	32	31	59	30	46	50	56	62	57
ZIRCON	1	-	-	4	15	-	12	30	3	-	12	x	1	1	5
RUT.+ANAT.+BROOK.	2	2	-	-	15	-	-	15	3	-	6	3	4	4	8
GARNET	-	-	-	-	-	-	-	-	-	1	-	x	-	-	-
STAUROLITE	30	27	-	-	16	58	48	21	31	63	24	42	38	32	22
KYANITE	3	3	-	-	3	2	8	3	-	3	7	3	1	x	3
ANDALUSITE	3	10	99	95	-	x	-	-	4	3	5	2	x	1	5
OTHERS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	x
% gravel	0.9	0.0	1.8	0.0	0.0	0.0	0.0	0.1	0.8	0.0	4.7	0.6	0.0	1.2	0.8
% sand	74.4	82.2	81.6	84.4	28.5	75.2	66.9	27.7	66.2	67.8	57.8	69.4	91.5	82.1	86.1
% silt	12.4	6.7	13.7	5.7	60.4	17.7	21.7	46.5	24.9	5.2	26.8	20.1	7.5	12.7	9.7
% clay	13.4	12.7	4.5	10.4	12.7	7.3	12.9	24.8	8.1	25.1	12.1	9.4	1.5	3.2	3.9
>20% clay								x		x					
>50% silt					x										
<60% sand					x			x			x				

SAMPLE NUMBER	Col 17	Col 4	Col 6	180	176	210	236	224	227	228	240	242	244	253	268	269	C1T	C5T
TOURMALINE	33	66	22	3	50	43	35	46	64	76	1		20	56	42	31	15	17
ZIRCON	25	1	21	95	10	4	23	14	5	8	96		38	1	30	35	73	71
RUT.+ANAT.+BROOK.	35	1	31	2	10	12	21	18	4	5	3		16	7	14	18	12	12
GARNET	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-
STAUROLITE	7	30	19	-	19	29	21	22	27	11	-	OPAQUE	24	36	14	16	-	-
KYANITE	x	1	3	-	3	2	-	-	-	-	-		-	-	-	-	-	-
ANDALUSITE	-	1	3	-	8	10	-	-	-	-	-		2	-	-	-	-	-
OTHERS	x	-	-	-	-	-	-	-	x	-	-		-	x	-	-	-	-
% gravel	0.0	0.6	0.0	0.2	0.8	0.0	0.2	0.3	0.0	1.2			4.1	1.5		0.7	1.0	0.4
% sand	28.8	85.6	9.2	38.0	72.9	70.4	70.8	54.9	65.9	72.2			61.1	63.6		68.4	81.6	80.0
% silt	49.1	7.5	54.2	55.7	18.9	26.4	21.2	39.9	26.6	21.8			18.9	29.1		26.3	13.0	16.5
% clay	21.3	6.8	35.2	5.0	7.2	3.2	6.2	4.6	6.7	4.4			14.9	4.5		3.3	4.5	3.0
>20% clay	x		x															
>50% silt			x	x														
<60% sand	x		x	x														

MIDDLE PART

SAMPLE NUMBER	Sb 14	C16	025	033	160	212	256	312	310
TOURMALINE	24	42	61	33	43	56	32	90	81
ZIRCON	2	24	17	14	48	11	11	1	4
RUT.+ANAT.+BROOK.	1	22	5	5	4	6	7	-	6
GARNET	-	-	-	-	-	-	32	-	-
STAUROLITE	58	11	15	39	5	23	18	9	9
KYANITE	3	1	2	8	-	-	-	-	-
ANDALUSITE	12	-	-	-	-	4	-	-	-
OTHERS	-	x	-	1	-	-	-	-	-
% gravel	5.8	1.3	0.0	1.1	0.0	0.2	0.0	0.8	10.4
% sand	66.1	53.7	56.7	72.2	47.9	55.7	71.9	83.4	80.9
% silt	22.7	34.5	31.1	22.9	45.0	39.3	22.7	11.9	4.0
% clay	6.2	11.9	11.4	3.4	6.5	4.7	4.7	3.4	4.4
>20% clay									
>50% silt									
<60% sand		x	x		x	x			

UPPER PART

SAMPLE NUMBER	099	101	135	121	122	124*	117	147	137	080	083	057	059 b	Z6	Z9	047 b	034	169	203	237	259	313	Va6
TOURMALINE	40	63	44	45	30	23	21	30	46	34	36	68	57	47	36	44	34	70	36	79	38	23	65
ZIRCON	1	1	-	5	29	1	x	4	x	6	5	8	-	26	2	3	3	-	-	-	40	67	12
RUT.+ANAT.+BROOK.	-	1	x	x	7	1	x	-	x	3	-	x	-	14	-	10	3	-	1	x	12	10	15
GARNET									2						x				5	1			3
STAUROLITE	50	27	49	18	17	10	37	56	42	37	57	20	40	13	56	30	54	28	55	15	10	-	5
KYANITE	4	2	4	x	1	-	-	5	1	1	1	4	3	-	4	10	3	2	2	4	-	-	-
ANDALUSITE	5	5	3	32	16	65	42	5	9	19	1	-	x	-	2	3	-	-	1	1	-	-	-
OTHERS	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3	-	x	-	-	-	-
% gravel	2.4	3.4				1.9	0.3	0.1	0.4	1.0	0.0	0.0	0.2	0.0	0.5	0.3	0.2	0.1	0.0	9.3	0.0	0.0	0.3
% sand	84.5	73.1				75.6	81.0	76.1	71.7	79.2	78.7	72.0	83.5	34.7	87.8	73.5	70.3	59.9	68.6	64.5	63.2	77.5	77.5
% silt	8.1	10.1				10.6	14.4	9.9	23.3	15.4	17.8	25.8	11.6	46.2	8.5	19.5	21.1	26.2	26.9	22.3	25.9	11.3	20.6
% clay	5.9	14.9				11.7	4.4	3.1	1.6	4.5	4.3	1.0	3.4	19.1	2.5	3.9	4.2	13.1	2.9	2.4	9.9	10.6	1.8
>20% clay																							
>50% silt																							
<60% sand														x				x					

* VEGAQUEMADA FORMATION

Table VII. Heavy-mineral composition and grain-size distribution in percentages of 64 samples in three parts of the area, arranged from W to E. Samples with an extraordinary composition are indicated by 'x'.

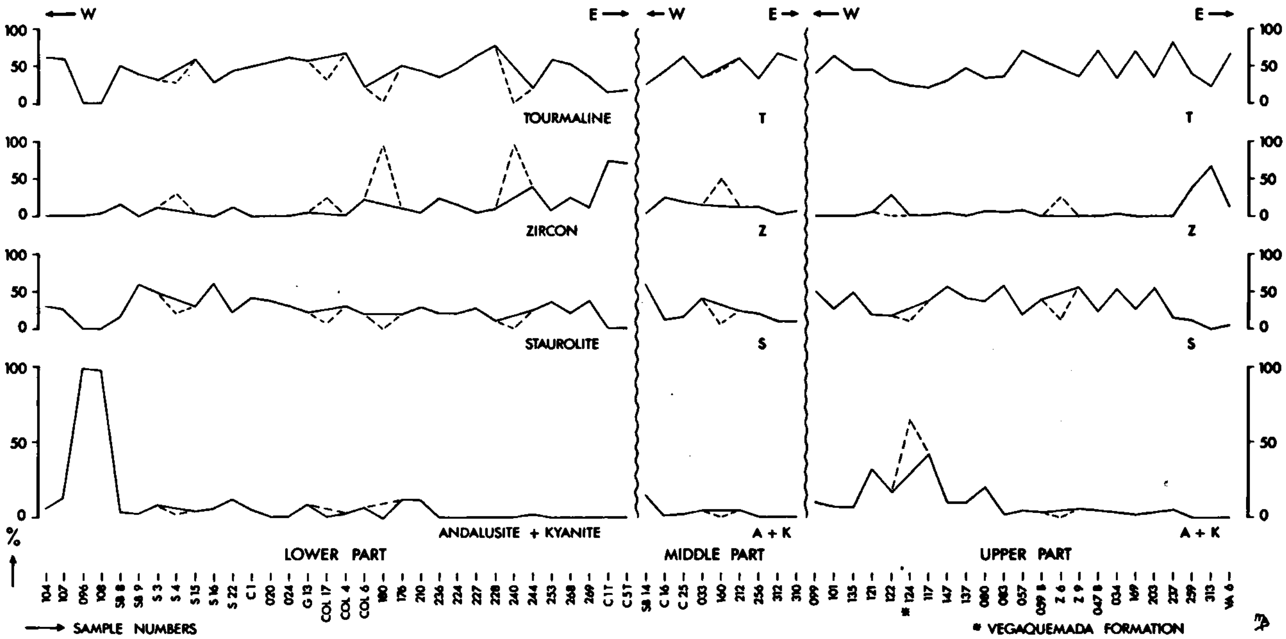


Fig. 20. Frequency in percentages of the most common heavy minerals for three parts of the Voznuevo Formation. Dashed lines: values uncertain due to extraordinary grain-size composition.

Zircon. – is found in almost every sample, both as small, egg-shaped grains and as hardly worn bipyramidal grains, so that two different sources, as mentioned above, are also applicable to the zircons. The first category is far more frequent, but examples of both generations are commonly found in one sample. As we stated before, the percentages of tourmaline and zircon are closely related, the zircons, generally smaller in size, being almost exclusively restricted to the grain size between 50 and 150 microns. The zircons are rarely strongly corroded. From Fig. 20 it becomes clear that the percentages of zircon decrease from east to west in both the lower and the upper part of the formation.

Rutile, Anatase and Brookite. – taken together as titaniferous minerals, are not plotted in Fig. 20, since their percentage does not exceed 20% except in four samples. The titaniferous minerals show no special characteristics, apart from the fact that two types of rutile grains can be observed: a dark red and a yellow variety.

From Table VII one can see that there is a plain relationship between zircons and titaniferous minerals. This relationship is not only caused by them being related in grain size, but also by the fact that the percentage of titaniferous minerals decreases from east to west. It is also worth noting that the percentage of titaniferous minerals shows a marked diminution from the lower part of the formation to the upper part, a fact which could not be observed in the case of the zircons.

Garnet. – is rare; only sample 256 shows a high percentage of minerals of the garnet group (32%). This may be explained by a temporary erosion of a garnet-rich rock and/or increased influence of a tributary. It is also possible that small-scale environmental circumstances have favoured their preservation in this location. All garnets observed are of the colourless to pink variety.

Staurolite. – is a mineral characteristic of the Voznuevo Formation, being the mineral second in importance. It is only absent in three samples of an extraordinary composition (Samples 096, 108 and 180) and in the lower part of the easternmost section. The staurolites proved to be susceptible to corrosion, which is not surprising in view of the position of staurolite in the heavy-mineral stability sequence and in the order of persistence (cf. Pettijohn, 1957, p. 504 and p. 506). They show an obvious decolouration from brown via orange-red and yellow to colourless grains with a very faint or absent pleochroism in many samples. Thin staurolite scales with low interference colours (grey) can easily cause confusion with other heavy minerals. The staurolites generally contain a large number of black (carbonaceous) inclusions. Grains with 'concertina' boundaries have occasionally been observed. According to Milner (1962) this can probably be regarded as a solution phenomenon. From Fig. 20 we can see that the percentage of staurolite shows a slight decrease from west to east in the lower and middle part of the formation and remains rather constant in the upper part.

Kyanite. – is a very common heavy mineral but its percentage never exceeds 10%. It is, however, most remarkable that kyanite is absent in the easternmost samples at all levels in the Voznuevo Formation. The grains are often badly corroded, but they are still easily recognizable.

Andalusite. – is the most remarkable heavy mineral in the present study, since it occurs in extremely diverging percentages. As kyanite, andalusite is absent in the eastern part of the formation; apparently both minerals are closely related as to their distribution pattern. Very high percentages of andalusite are limited to the area west of the Río Bernesga. The andalusites are generally found in large grains with a pleochroism from colourless to pink, occasionally to vivid red. As observed in the case of the rutiles, two types of andalusite occur, one with many black graphite or carbonaceous inclusions, the other devoid of inclusions. In the exposure where the direct transition from the Voznuevo Formation to the overlying Vegaquemada Formation was encountered, the sample collected in the latter contains a much higher percentage of andalusite and a lower percentage of tourmaline than the Voznuevo samples in this location (sample 124 in Table VII). This may be a coincidence, since heavy-mineral studies of the Vegaquemada Formation (Kuyp, 1969) showed that the percentage of andalusite generally does not exceed 5%.

The combined percentages of andalusite and kyanite, represented in Fig. 20, show a marked decrease in an easterly direction (caused mainly by the percentage of andalusite; the percentages of kyanite are smaller and more constant). Besides, the andalusite grains proved to become conspicuously smaller towards the east.

Conclusions based on the heavy-mineral content

Summarizing the distribution of the heavy minerals in the Voznuevo Formation from west to east and from bottom to top we must state that:

a. The percentage of tourmaline is constant.

b. The percentage of zircon increases towards the east, especially in the lower and the upper part of the formation.

c. The percentage of titaniferous minerals is constant from west to east but decreases in a vertical sense (towards the top).

d. The percentage of staurolite decreases towards the east except for the upper part of the formation where it remains constant.

e. The percentage of kyanite is constant, but zero in the eastern part of the formation.

f. The percentage of andalusite decreases considerably towards the east in three levels of the formation.

In Fig. 21 an attempt is made to relate the distribution of the heavy minerals to the diachronic character of the Voznuevo Formation. In this simplification of Enclosure XI we recognize the Lower Cretaceous – Upper Cretaceous boundary (line U=I) which has been established by pollen analysis (Chapter IV). Lines V to Z have the following significance:

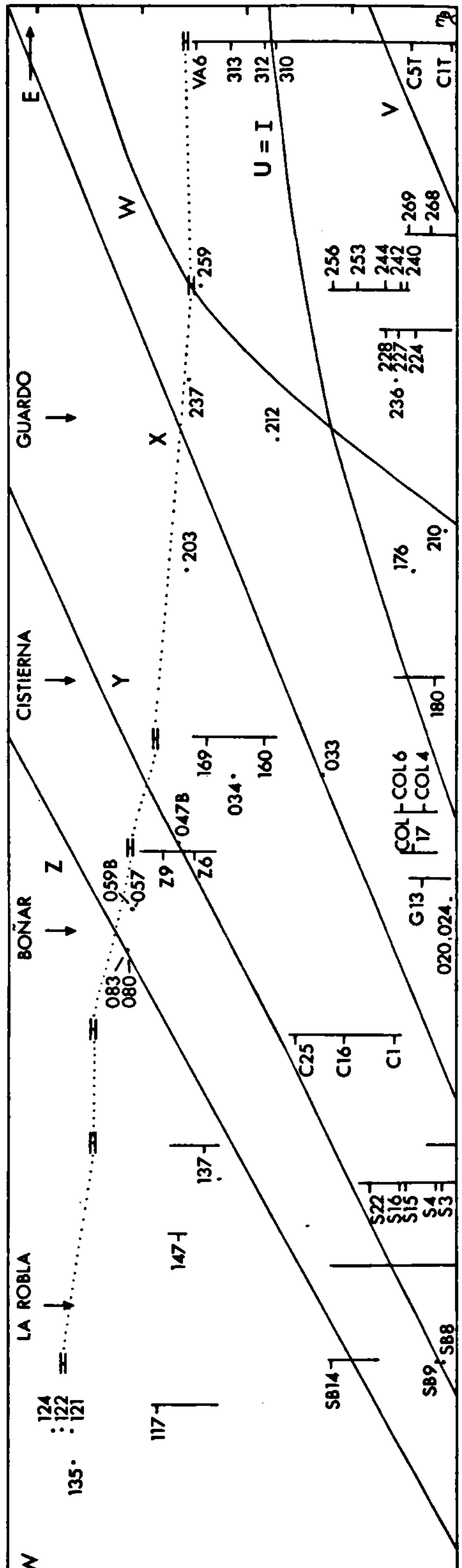


Fig. 21. Schematical chart of the Voznuevo Formation with position of sections A to T and of the heavy-mineral samples studied. For explanation of lines U to Z see text.

Line V separates the area where the percentage of zircon exceeds 70% (not caused by small grain size) (right) from the area where it is less than 70% (left).
Line W: Kyanite and andalusite absent (right) and present (left).
Line X: Staurolite less than 40% (right) and exceeding 40% (left).
Line Y: Titaniferous minerals generally exceeding 10% (right) and always lower than 10% (left).
Line Z: Andalusite less than 10% (right) and exceeding 10% (left).

It is a most remarkable result that these separating lines run approximately parallel to line U, the time boundary, which means that changes in mineralogical composition of the source area extended their influence almost synchronously over the area studied. Chronologically speaking, one may observe a predominance of an association of very stable heavy minerals (zircon, rutile, anatase and brookite) which gradually passes into an association in which less stable heavy minerals of metamorphic origin (staurolite, kyanite and especially andalusite) gain in importance. This is in accordance with the common observation that heavy-mineral associations become more complex with decreasing age. A comparable trend was observed, on a larger scale, in the heavy-mineral assemblages in the sediments of the southern border of the Cantabrian Mountains in general, from Paleozoic to Tertiary (de Jong, 1971).

The influence of grain size on the heavy-mineral composition

As we have remarked above, grain size influences the heavy-mineral composition in a large measure. Calculation of the heavy-mineral percentages of some tens of fractionated samples showed that the following trends are always found: an increase in grain size results in an increase in the percentages of tourmaline and especially of andalusite, and in a decrease in the percentages of zircon, titaniferous minerals, staurolite and kyanite. The corrections made in Fig. 20 show that the addition of grain-size distribution data (as added in Table VII) can be of great help in understanding the differences in heavy-mineral composition which may arise. It is to be regretted that in many publications grain-size distribution or even the size grades studied have been omitted.

Comparison with the heavy-mineral composition of other formations

In Table VIII a comparison is presented of the results of heavy-mineral counts obtained by investigators of the University of Leiden in rocks of various ages in the Cantabrian area. This table has been slightly modified and extended in accordance with de Jong (1971). In order to make comparison more reliable, only the seven most important mineral groups are listed, with omission of the category 'Others' so that the remaining percentages had to be recalculated. Moreover, recalculation proved necessary since some investigators only listed the

T	17	8	30	39	82	4	65	19	52	50	43	23	27	30	16	47
Z	61	50	36	36	9	2	9	3	30	10	48	49	2	9	45	18
R+A+B	12	35	16	8	9	-	26	16	12	10	4	20	5	38	9	12
G	10	7	7	10	-	-	-	-	-	*	*	1	-	-	-	-
S	-	-	11	7	-	24	-	-	6	19	5	4	40	15	19	17
K	-	-	-	-	-	22	-	-	-	3	-	*	*	*	11	6
And	-	-	-	-	-	48	-	62	-	8	-	3	26	8		
Author	Nossin (1959)	Nossin (1959)	Nossin (1959)	Nossin (1959)	Smit (1966)	Smit (1966)	Papa (1964)	Papa (1964)	Nossin (1959)	Jonker (1972)	Jonker (1972)	Kuyp * * (1969)	Kuyp * * (1969)	Kuyp (1969)	Mabesoone (1962)	Mabesoone (1962)
Age	Devonian	Westphalian	Westphalian	Triassic	Triassic	Triassic	Triassic	Triassic	Cretaceous	Cretaceous	Cretaceous	Paleogene	Paleogene	Paleogene	Neogene	Neogene

T=Tourmaline
Z=Zircon
R+A+B=Rutile+Anatase+Brookite
G=Garnet
S=Staurolite
K=Kyanite
And=Andalusite

* Present in many other samples
* * Size grade: 50-150 micron

Table VIII. Heavy-mineral composition of representative samples of rocks of various ages in the southern Cantabrian area (in percentages). Size grade: 50 to 500 microns.

alterites among 'others', while others did not consider the alterites at all in calculating their total percentage.

As we have noted previously, and as is clearly illustrated in Table VIII, the heavy-mineral assemblage becomes more complex with decreasing age, due to the introduction of metamorphic minerals. The very resistant heavy minerals of the tourmaline, the zircon and the titaniferous group are generally present throughout the sequences of formations in percentages which seem rather varying. Comparing the percentages of Table VIII with the percentages found in the Voznuevo Formation only, the latter based on a large number of samples, one observes that the percentages vary within one formation as much as in the whole sequence from Devonian to Tertiary. The percentage of garnet decreases with decreasing age, although its presence has been reported by all investigators listed in Table VIII. The metamorphic minerals only gain in importance after the transition from the Paleozoic to the Mesozoic (they have been observed in high percentages in the upper Triassic deposits only). Staurolite, however, is also present in Westphalian deposits (Nossin, 1959; van Loon, 1972).

The behaviour and the trends shown by these seven mineral groups are in perfect accordance with the frequency of occurrence of heavy minerals in rocks of all ages from different locations (Pettijohn, 1941, 1957) from which frequency Pettijohn (1957) established his order of persistence of heavy minerals. Other workers (Milner, 1962) remarked that andalusite, for instance, can range back as far as the Paleozoic, but that its occurrence becomes very rare with increasing geological age. The same may be said of kyanite and, to a lesser extent, of staurolite.

A sudden increase in metamorphic minerals, which occurred in the Triassic makes a derivation from nearby Paleozoic rocks (i.e. from the Cantabrian Mountains) rather unlikely. Moreover, the minerals of the staurolite, kyanite and andalusite group are, according to Milner (1962), derived from: crystalline schists and contact metamorphic rocks (staurolite); metamorphic rocks, especially mica schists and certain gneisses (kyanite); granites and contact metamorphic rocks (andalusite). A provenance in a granitic area with contact metamorphic aureoles is therefore much more probable. As we have stated before (p. 334), the extensive investigations by Papa (1964) in the Triassic rocks north of Cervera de Pisuerga showed an increase in quartzose gravel with decreasing age. The mean diameter of the pebbles indicates a more distant source area than the one from which the oldest clastic Triassic deposits are thought to have been derived. Differences in pebble size indicate a transport from west to east, so that the upper-Triassic sediments were probably supplied from an area which must have been situated in a westerly direction. Both the composition and the heavy-mineral content of the Triassic rocks and the Voznuevo Formation indicate a common source area, different from that of the Paleozoic rocks. This assumption can readily explain the abrupt change in heavy-mineral content between the Paleozoic and the post-Paleozoic sediments.

The possibility that the sediments of the Voznuevo Formation, as studied in the present area, are produced by Triassic sediments being reworked must be rejected, since Triassic deposits are only known in the very eastern part of the area, while transport of the sediments, as shown by paleocurrent measuments, has taken place from west to east. Besides, there is no evidence, that Triassic deposits ever covered the Paleozoic west of the line Potes – Guardo, although de Jong (1971) suggests that they may have extended for some distance to the W.

The first post-Cretaceous sediments in the present area are the Lower Tertiary clastic wedge deposits (de Jong, 1971) which are thought to have been derived from the uplifting Cantabrian massif. The Vegaquemada Formation and the Candanedo Formation (Evers, 1967; Kuyp, 1969) were distinguished in the western part of the area (west of the Río Esla), while Mabesoone (1959) made no subdivision and designated them as Cuevas facies in the eastern area.

According to most investigators, these deposits unconformably overlie the Mesozoic limestones, the angle of unconformity generally being too small to be observed in the field. Other, mainly sedimentological, features (see Evers, 1967, p. 121) are better indications of a hiatus in the sequence of events.

The heavy-mineral composition in the Vegaquemada Formation and in the Candanedo Formation shows no significant differences to the assemblage observed in the Voznuevo Formation. The only data available (Kuyp, 1969) show that tourmaline, zircon and the titaniferous minerals are present as a resistant association, staurolite, kyanite and andalusite as a metamorphic association. To what degree the Voznuevo Formation has contributed to the supply of the Tertiary sediments will be the object of a brief discussion at the end of this chapter.

In the triangle Palencia – Guardo – Cervera de Pisuerga, in which a sedimentological study was carried out by Mabesoone (1959), two distinct heavy-mineral associations could be distinguished, a tourmaline-staurolite association in the northeastern part of his area and a zircon-rutile association in the southwestern part. According to Mabesoone, the various associations are the result of different supply areas, the group with the resistant minerals being derived from Paleozoic sediments with little influence from Cretaceous deposits, since the Mesozoic complex between Cistierna and Guardo is very thin or completely absent. The group with the metamorphic minerals, found in the northeastern part, the drainage area of the Río Pisuerga, shows a clear connection with the Mesozoic sediments which are much more widespread and thicker in this location. Mabesoone (1959) stated that the heavy-mineral association in the Quaternary sediments is closely connected with the Tertiary association, with a slightly higher epidote content.

In 1962 Mabesoone contributed another paper on the Tertiary in the northern part of the Duero basin, with the red beds (comparable to the Vega de Riacos Formation, Evers (1967), and the Riacos Formation, van den Bosch (1969)) between La Robla and Villadiego (32 km NW of Burgos) as main subject. The presence of blue tourmaline in some of his samples led him to reconstruct the ancient river course of the river which deposited the red beds. The course runs in a southeasterly direction, approximately parallel to the present southern border of the mountain chain. As we have stated above, the resistant minerals (zircon, rutile and tourmaline) are thought to have been supplied by Paleozoic rocks. According to Mabesoone, metamorphic minerals, especially staurolite, were supplied by Triassic rocks, while the Voznuevo sediments were considered to be the supplier of tourmaline. In this same study it becomes clear that the easternmost part of the area was influenced by the increasing importance of Mesozoic rocks towards the east, reflected in an increase in metamorphic minerals. Nevertheless, Mesozoic sediments, present as a narrow strip along the greater part of the southern flank of the Cantabrian mountains, will have had some influence on the mineralogical composition of the Tertiary red beds. Mabesoone (1962) was faced with the problem from where the staurolites in the western part of the area studied by him were derived; he stated (p. 243): '... But here (the area west of the Río Pisuerga is meant, remark by the present author) no sediments of Triassic age have been found, so that the high staurolite content, especially in the Porma region, remains unexplained. Although it is possible that the Triassic belt could have extended somewhat farther to the W, this distance seems to be too great (more than 70 km) ...' In search of a solution to this problem Mabesoone (1962) proposed two different supply directions for the two heavy-mineral associations which he distinguished. The zircon-rutile association was to have a northern provenance (Paleozoic rocks!); the staurolite-tourmaline association a western provenance. Following Mabesoone's train of thought, the staurolites in the red beds '... have been derived from Paleozoic deposits sedimented at the foot of the Galician block itself ...' (p. 244). The metamorphic erosion products would thus have been deposited in the eastern part of the Galician area, in lower Paleozoic sediments, to be retransported further to the east in Tertiary times. Quoting Mabesoone (p. 245) '... Evidently they did not undergo any solution during that long period ...' (Previously he mentioned that the staurolites in his samples had lost their pleochroism but show very few signs of solution and corrosion).

In our opinion this assumption is very debatable, since the staurolites of the Voznuevo Formation, which are thought to have a common or comparable source area, already show signs of solution and slight corrosion in many samples. For this reason it is highly improbable that the staurolites escaped intensive or complete solution and corrosion in the time-span from lower Paleozoic to Tertiary. In this connection the Voznuevo Formation can be considered as the 'missing link' between the Paleozoic and the Tertiary sediments, since we know that this formation is very rich in staurolite, and can easily be responsible for the high staurolite content in some of the Tertiary red bed samples. This supposition is strengthened by Mabesoone's observation that staurolites are found especially in the western part of the area investigated by him. This is also the location where the Mesozoic limestone cover on the Voznuevo sediments was much thinner, so that Voznuevo material could more easily reach Tertiary sediments.

Leguey and Rodríguez (1969, 1970a, 1970b, 1971) have made an extensive study of the heavy-mineral content of the recent river sediments in the northern part of the Duero basin, subdivided into: (a) the Esla basin with, from west to east, the rivers Tera, Orbigo, Bernesga (with the Torío as affluent), Esla (with the Porma as affluent) and Cea, and (b) the Pisuerga basin with, from west to east, the rivers Carrión, Pisuerga, Arlanzón and Arlanza. The distribution of the heavy minerals in these rivers as found by the above-mentioned authors can be represented as follows (heavy-mineral names abbreviated):

	Dominant	Frequent
Tera	and., hbl., sillim.	tourm., garnet
Orbigo	and., zirc., tourm.	rutile
Bernesga	tourm., zirc., and.	staurol., rutile
Esla	zirc., tourm., and.	rutile, hbl., garnet
Cea	zirc., tourm., rutile	and., titanite
Carrión	zirc., tourm., and.	rutile, hbl., garnet
Pisuerga	tourm., zirc.	rutile, garnet, and., staurol.
Arlanzón	tourm., diopsite	garnet, zirc., staurol., and., rutile
Arlanza	tourm., garnet	rutile, staurol., zirc., and.

In the following discussion on this result the heavy-mineral composition of the Río Tera will be left out of consideration on account of its irrelevance.

The most salient feature of this enumeration is the decreasing importance from west to east of andalusite, a fact also observed in the Voznuevo Formation. The high andalusite content of the latter is bound to have influenced the mineralogical composition of its overlying sediments (e. g. the Vegaquemada Formation) and consequently also the composition of the recent alluvial sediments of the rivers which cut through these formations. In this connection it should be kept in mind that the influence of Cretaceous heavy minerals on the recent fluvial deposits is mainly of an indirect nature since the sediments in which eroded Voznuevo material is present are many times thicker than the Voznuevo Formation itself, so that their influence upon the recent sediments will be much greater. Other facts which may be concluded from the findings by Leguey and Rodríguez seem to be in contradiction to the trends observed in the Voznuevo Formation. They are: a decrease in the importance of zircon towards the east and an increase in the percentages of tourmaline and staurolite in the same direction. Unfortunately Leguey and Rodríguez never mention the size grade of the heavy-mineral residues. This could have influenced the zircon:tourmaline ratio considerably. Another fact which may lead to this difference from west to east can be caused by the three easternmost rivers crossing Paleozoic rocks (the main supplier of zircon, and scarce in staurolite) along a very small part of their courses only. Finally it is worth noting that tourmaline is always dominant, while staurolite is often abundant, but never dominant.

The recent fluvial deposits show a relative abundance of tourmaline and especially of andalusite, with much higher percentages than those found in Paleozoic and Tertiary rocks. Leguey and Rodríguez ascribe this difference to the grain-size distribution of the sand of the recent deposits. Poor sorting can, for example, cause a high percentage of andalusite, since andalusite crystals are – on an average – much larger than other crystals. The high percentage of tourmaline may have the same cause.

Staurolite is only important in the lower part of the Río Pisuerga, since only Tertiary deposits show a relative abundance in this mineral. Leguey and Rodríguez (1969) try to explain the supply of staurolite as follows (p. 534): '... otra conclusión que deducimos es que como este mineral no pudo llegar al Terciario procedente del Paleozoico, tuvo de hacerlo de otras formaciones que actualmente no existen en las proximidades ...'. As we have seen in the above, the Triassic rocks near Cervera de Pisuerga could have supplied the staurolites (Nossin, 1959), but their occurrence further to the west cannot be explained. Mabesoone (1962) assumed the staurolites in the red beds to have come from the Galician massif. As we have seen, however, Cretaceous deposits could easily have supplied the staurolite to the Tertiary sediments and consequently also to the Quaternary sediments. This is already assumed by Leguey and

Rodrîguez when they state (p. 235): '... de lo expuesto anteriormente se desprende una clara influencia de los sedimentos wealdenses en los diversos niveles de este tramo alto del Pisuerga ...'.

In the discussion on the results of their investigations, the Spanish authors arrive at the conclusion that the tourmalines derived from Paleozoic rocks are generally better developed (show a higher stage of evolution) than those from the Cretaceous and Tertiary rocks. As to the zircons, two different cycles could be observed as well; those derived from Paleozoic rocks (first cycle) which are subrounded, rounded and angular (in order of importance) and a second cycle with an increase in the number of rounded and broken grains.

Concluding remarks on the heavy-mineral content of the Voznuevo Formation

Summarizing the results obtained by heavy-mineral counts, one may say that the composition of the heavy-mineral assemblage reflects a development in the source area. The stratigraphically oldest deposits show a higher percentage of very resistant heavy minerals; with decreasing age an association comes to the fore in which metamorphic minerals become more and more important. It is especially the latter association which has had a strong influence upon all post-Cretaceous sediments.

The source area which supplied the material of the Voznuevo Formation had presumably already been active in Triassic times, since the Triassic sediments N of Cervera de Pisuerga described by Papa (1964) show, in their upper part, close analogies to the findings in the Voznuevo Formation. However, this supply area became dominant in Cretaceous times.

The Paleogene, Neogene and Quaternary sediments, which were deposited successively further to the south, bear the stamp of the Voznuevo Formation. Of course this influence gradually decreases with decreasing age, as complexity increases. Especially the staurolite and andalusite content of the post-Cretaceous formations need no longer be the object of unfounded conjectures since the Cretaceous could supply part of their sediments. Still the problem remains whether the Cretaceous sands could be eroded although they were covered by the Mesozoic limestones.

Let us for a moment dwell upon the provenance of the Paleogene sediments: Deposition began with relatively fine-grained deposits, Ciry's 'Grès de las Bodas' (lower part of the Vegaquemada Formation), which formed with the beginning uplift of the Cantabrian mountain chain. They could be traced as far east as a location S of the Villaverde-Tarilonte railway station (Mabesoone, 1959). The Grès de las Bodas complex consists of fining-upward grading fluvial cycles with a close resemblance to those of the Voznuevo Formation. A distinct feature, however, is the presence of caliches (Kuyp, 1969) or limnic limestone layers (de Jong, 1971) at the top of these sequences. According to de Jong (p. 409) 'The fact that so many elements known from the Cretaceous formations are found, points to a supply with at least a northern component. The heavy-mineral assemblage ... recalls the continental Cretaceous Voznuevo Formation, from which it must have partly derived'. This derivation does not cause many problems for the western part of the area studied, since it has become clear from the present study that Mesozoic limestones have never been present between the Voznuevo Formation and the Vegaquemada Formation in the western part of the area. But Mabesoone (1959), too, reported layers consisting of conglomerates of quartz pebbles in alternation with massive limestone layers from that part of his area considered by Ciry (1939) as the continuation of the Grès de las Bodas to the east. The absence of clastic limestone fragments is apparently not in accordance with the fact that Voznuevo sediments supplied most of the material for the Grès de las Bodas. In our opinion it is much more logical to assume that the oldest deposits of the Vegaquemada Formation still had the same source area as the Voznuevo Formation as far as the coarse detrital parts of the cycles is concerned. The high lime content in the upper part of the fining-upward sequences could have formed from waters rich in lime which had been in contact with the Mesozoic limestones.

The upper part of the Vegaquemada Formation interfingers with the conglomerates of the Candanedo Formation, which for this reason represent the distal and the proximal part of clastic wedges (de Jong, 1971); the conglomerates, being the proximal parts, show quite a different composition. Limestone pebbles, both of Paleozoic and Mesozoic origin, are met with in these conglomerates. In the eastern part of the area Mabesoone (1959) found limestone conglomerates, with sandy intercalations, containing pebbles, mainly derived from Mesozoic rocks, while Kuyp (1969) reported conglomerates consisting of quartzites and 30% of Paleozoic limestone pebbles in a sandy matrix. These findings are in accordance with the observation that the Mesozoic limestone cover gradually thins towards the west, being even absent in the extreme west. The sandy intercalations between the conglomerates in the east seem difficult to explain since their possible source, the Voznuevo Formation, must have been covered by Mesozoic limestones. In order to explain this de Jong proposes the following possibilities:

a. Valleys cutting through the Mesozoic limestones provided the sandy material.
b. Sediments of Garumnian age, on top of the Mesozoic limestones, could have supplied the sands.
c. The sands were derived from areas not covered by Mesozoic limestones.

In this connection we should like to add three other possibilities:

d. The sands were supplied from the western part of the area, where the Mesozoic limestone cover had been eroded. This assumption is based on Kuyp's statement

that a direction of transport from west to east could be observed in the Vegaquemada Formation.
e. The sands are the erosion product of a part of the Grès de las Bodas further to the west, which, as we know, strongly resemble the sediments of the Voznuevo Formation.
f. The mountain uplift, active since the beginning of the sedimentation of the Vegaquemada Formation and even more active at the time of deposition of the clastic wedges of the Candanedo Formation,has dragged the Cretaceous sediments into an inclined position so that the Voznuevo sediments could be exposed to the surface in a narrow strip, which is comparable to the present situation, although with less steep dips.

The reader must have noticed that some heavy-mineral groups, especially hornblende and augite, have not been encountered in the Voznuevo Formation, while a mineral such as epidote, frequently observed in the Quaternary deposits of the southern border, is extremely rare. The absence or scarcity of these groups can be explained by considering the stability scale for heavy and light minerals with regard to chemical and mechanical attack as listed by Leguey and Rodrĩguez (1970b, p. 176), composed after data by many previous authors on this subject. From this order of stability it becomes clear that heavy minerals such as epidote and augite may be compared, as regards their resistance to mechanical decomposition, with, for instance, garnet and staurolite and that they are much more resistant in this respect than kyanite or andalusite. The values of their resistance to chemical attack – as well as the value for hornblende – are, however, many times lower than those of the metamorphic heavy minerals observed in the Voznuevo Formation.

From this fact one must conclude that minerals such as hornblende, augite and epidote, reported from the sediments overlying the Voznuevo Formation (Mabesoone, 1959; Nossin, 1959; Kuyp, 1969), are absent in the Cretaceous sands as a consequence of strong chemical weathering in these deposits.

In this respect the sediments of the present study can be compared with the white Miocene sands of southern Limburg (The Netherlands) (de Jong and van der Waals, 1971) in which the following percentages of heavy minerals were determined: tourmaline 20–55%, zircon+rutile+anatase 0–32%, metamorphic minerals 2–64%. The authors remark that 'less stable minerals (apparently chemically less stable minerals, remark by the present author) such as epidote, hornblende and garnet, occasionally occur in very subordinate amounts but are generally absent'. The heavy-mineral assemblage in which only stable minerals occur is one of the reasons why the sediments are thought to have occurred along the surface of a former peneplain. Strong leaching and chemical weathering in a subtropical climate under conditions in which sedimentation kept abreast of weathering are supposed to have prevailed in these Miocene deposits.

In a later chapter, when the composition of the light minerals and the clays will have been described, we shall see how far these conditions have also affected the sediments of the Voznuevo Formation.

THE LIGHT MINERALS

Introduction

The light-mineral assemblage of the Voznuevo Formation – as is to be expected after study of the heavy-mineral content of the formation – is mainly composed of minerals and rock fragments resistant to chemical alteration. Consequently only quartz, quartzite, muscovite and feldspars were observed in the light fraction.

A number of thin sections, prepared from unconsolidated samples mounted in Araldit, showed that quartz is the predominant component, followed by quartzite, and that muscovite occurs in varying quantities (0–15%). Since the quartz(ite) : muscovite ratio is highly dependent upon grain size it will not be considered in detail, especially in the knowledge that some of the micas were possibly dissolved during preliminary treatment (Mabesoone, 1959).

For this reason we have concentrated upon the quartz:feldspar ratio with a supplementary distinction between alkali feldspars and plagioclases. For the sake of distinction the fraction between 50 and 500 microns was stained by means of hemateine and sodium cobaltinitrite (Doeglas et al., 1965). Staining was carried out on two parts of each sample, yielding a blue colouration for all feldspars in one part, a yellow colouration for alkali feldspars only in the other part. The quartz is not influenced by colouring. The samples were studied under the binocular by means of reflected light. The quartz:feldspar and the quartz:alkali feldspar ratios were determined by means of line counting; for each determination a number of 200 grains was counted. A total of 41 samples was studied, distributed over the entire formation.

The results

The results can be summarized as follows:
Out of 41 samples:
Nine samples contained no feldspar at all; in the other samples the feldspar percentage varies between 1 and 30%.
Twenty samples showed equal percentages of blue- and yellow-stained grains or a difference between the percentages not exceeding 2%.
Eight samples showed a higher percentage of yellow grains than of blue grains. This indicates that the yellow staining is more sensitive and apparently more accurate.
Only four samples had a distinctly higher percentage of blue grains (difference more than 2%). This means that only four samples have a certain plagioclase content.

Comparing the quartz grains and the feldspars it is evident that the feldspars are, in general, of much

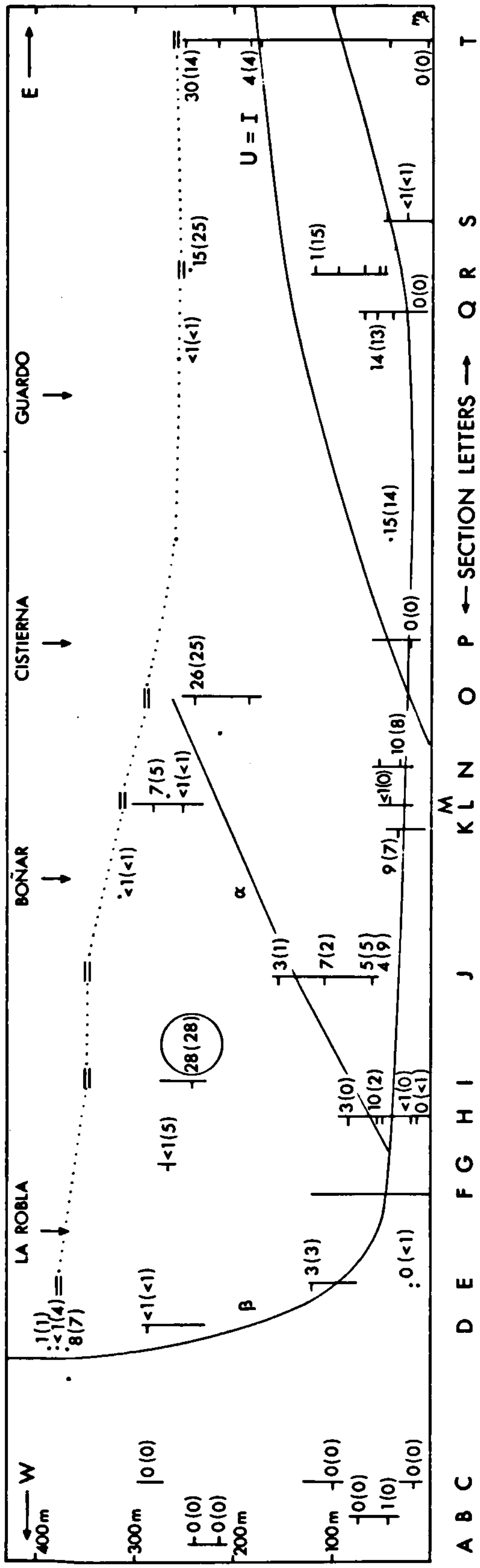


Fig. 22. See Fig. 21, with position of the samples in which the feldspar content was determined. Figures refer to the total feldspar content with the alkali feldspar content in brackets (both in percentages).

smaller dimensions than the quartz. Many cracks and fissures in the quartz grains display a feldspar colouring. This is presumably caused by very fine-grained feldspar 'dust' which accumulated in these locations.

The percentages observed show that only 3 samples have a total feldspar content of more than 20%; 3 samples of between 10 and 20%; 6 samples of between 5 and 10% and 29 samples of less than 5%. It is clear that the feldspar content of the Voznuevo Formation is rather low, generally lower than 5%. By far the majority of the feldspars are alkali feldspars, which are known to be more resistant than plagioclases.

The values have been plotted on the simplified correlation chart (Fig. 22), the first figure referring to the total percentage of feldspars, the value in brackets to the percentage of alkali feldspars. Exceptionally high percentages were found locally near the contact with the Mesozoic limestones, where they were probably protected by a relatively alkaline milieu. The high percentage south of section I (encircled in Fig. 22) was presumably caused by marine influences (occurrence of glauconite!) which were observed in this location (cf. Chapter VII). Neglecting this value, one may draw a line in Fig. 22 (line α) which separates an area in which the feldspar percentage does not exceed 10% (left) from an area in which the feldspar percentage appears to be higher in many samples. Line α runs approximately parallel to line U=I (the time line). Another striking feature is the area of values less than 1% (bounded by line β) which is limited to the lowest part of the formation as far as section E (coming from the east), but covers the entire formation further to the west. As the attentive reader will remember, the area west of section E is the part of the Voznuevo Formation not covered by Mesozoic limestones!

Comparative and concluding remarks

Comparing the results obtained from the present investigation with those found by Mabesoone (1959, 1962) in Tertiary and Quaternary deposits, we find that the feldspar content of the Voznuevo Formation is higher than that of the younger deposits (between 2 and 4% in Tertiary deposits; generally absent in Quaternary deposits). The main reason for this difference is presumed to be the source area. According to Mabesoone, the Cantabrian Mountains, the source area of the sediments studied by him, did not provide much feldspar. A second reason may be the different methods used for the determination of feldspars (Mabesoone did not use a staining method but the refractive index method).

Further-reaching conclusions may be drawn from Beuther's (1966) observations in the Sierra de los Cameros (cf. Chapter IV). He reported a feldspar content generally exceeding 10% in his quartz sandstones and a percentage of 25% of feldspar in the arkosic lenses within the Utrillas Beds. Since these values coincide with the maximum percentages observed in the Voznuevo Formation it may be suggested that the loss of feldspar in the Voznuevo Formation occurred in situ, the feldspars being preserved in locations where they were protected against disappearance by alkaline conditions, and being transformed into kaolinite in locations where no limestone cover was present (west of section E).

The low feldspar content in the extreme lower part of the formation is difficult to explain; alteration and/or dissolution in the lower part of the complex, near the contact with the Paleozoic rocks, may have played a part.

As found by Beuther, part of the sediments in Wealden facies in the Sierra de los Cameros have been eroded. Although it is not very likely that the Voznuevo sediments are an erosion product of the Lower Cretaceous sediments of the Sierra (paleocurrent directions suggest a source area further to the west), it is quite possible that the present sediments are a second cycle product, derived from an area which received its material from a granitic mass in Lower Cretaceous times and was subsequently eroded to supply the area S of the Cantabrian Mountains. Such an area could have been situated, for instance, N of Zamora, near the Portuguese border. The presence of detrital kaolinite grains corroborates such a second cycle origin.

THE CLAY MINERALS

The clay minerals of the Voznuevo Formation

Samples of clay-sized materials (smaller than 2 microns) were studied by means of X-ray diffractograms. A total of 80 samples, covering the entire Voznuevo Formation, and of 9 Paleozoic samples near the contact with the Voznuevo Formation are taken to be representative of the finest-grained sediments. From this investigation it became clear that kaolinite, illite and quartz are to be found in most of the samples, while mixed-layer clays can be observed in 70% of the samples. The clays were distinguished according to their colour in the field; they comprise black, green and red or purple coloured clays. The most conspicuous results are:

a. Kaolinite is predominant in by far the majority of the samples.
b. Quartz is never predominant but nearly always present.
c. Illite is hardly ever dominant in Cretaceous samples, but always predominant in Paleozoic samples.
d. Black coloured clays show a higher illite content than green and red coloured clays, and a lower kaolinite content.
e. The kaolinite/illite ratio is higher in red clays than in green clays.

Although iron was for the most part removed by laboratory treatment in this fraction, there were still traces of iron (hydr)oxide in 14 samples. Except for one sample in which hematite was observed, goethite proved to be the iron mineral present.

Traces of feldspars, both alkali feldspars and plagioclases, were observed in 10 samples. They are rare and limited to the extreme upper part of the formation in the area W of Guardo; E of Guardo they are more abundant and spread over the entire formation.

In two samples traces of nacrite are thought to be present.

Study of 32 samples of the fraction between 2 and 37 microns, in which the iron (hydr)oxides were not removed, showed that quartz is predominant in all samples, while muscovite and kaolinite are ubiquitous. In 15 samples iron (hydr)oxide was found, in 8 samples in the form of goethite, in 7 samples in the form of hematite. Of the samples containing hematite only three are situated within the Voznuevo Formation. One sample is of Paleozoic origin, whereas the other three samples were collected at the contact between the Voznuevo Formation and the Vegaquemada Formation SE of Carrocera (Chapter III), one of which samples must be included in the Vegaquemada Formation. As we have also seen from the composition of the material smaller than 2 microns, goethite is much more abundant than hematite.

Of 5 samples containing alkali feldspars, only three belong to the Voznuevo Formation; they were all collected in the very upper part of the formation.

Clay minerals in comparable sediments

An investigation of the clay-mineral content of deposits similar to those of the Voznuevo Formation was carried out by López Aguado et al. (1971). It refers to a study of clay minerals from two exposures of kaolinitic sands and clays of Cretaceous age ('facies Wealdense y Utrillas'), underlying the marine Aptain in the province of Valencia. A number of interesting points of this investigation must be borne in mind. Interpretation of X-ray diffractograms of eight samples led to the conclusion that the most important constituent of nearly all samples is quartz (unfortunately the authors do not give the fractions studied but they remark that a high percentage of quartz is limited to the coarser-grained samples). The second in importance is kaolinite, followed by illite. Mixed-layers are of minor importance (0–10%). Only in one exposure were feldspars (less than 10%) observed, both alkali feldspars and plagioclases. The feldspar content decreases with decreasing age of the sediments. The kaolinite/illite ratio was found to be higher in the sandy samples than in the argillaceous samples.

According to López Aguado et al., the sediments in Wealden facies in this area were derived from a lateritic soil which was eroded in its entirety in the source area. The requirements for the formation of such a lateritic soil are a warm and humid climate, or a warm climate with dry and humid alternations, pluviosity being, in both cases, more than 1500 mm/year. Under such conditions organic matter is absent or scarce (Loughnan, 1969). The sediments in the Valencian area are thought to have formed from a kaolinitic laterite without iron crusts. Siliceous parent rocks (such as granites and gneisses) with sufficient leaching and of medium acidity will favour kaolinization and form sediments with a low iron content. Basic parent rocks will lead to the formation of soils rich in iron. These generally accepted facts suggest, according to those authors, that in this area the kaolinitic sands were derived from acid rocks. López Aguado et al. presume that the decrease in the feldspar content with a simultaneous increase in the kaolinite content with decreasing age is caused by an intensified maturity of the source area together with an alteration of feldspars into kaolinite. The probability of this explanation and the question as to how far the circumstances found in these sediments can be applied to our Voznuevo deposits will be subjected to closer examination in Chapter X.

Clay minerals in the formations overlying the Voznuevo Formation

It was Mabesoone (1959; 1962) who reported on the clay-mineral associations in Tertiary and Quaternary sediments along the southern border of the Cantabrian Mountains.

In Mabesoone's Cuevas facies illite proved to be the predominant clay mineral (approx. 55%), while kaolinite may be present up to 35%. Measurements of the pH value showed that the environment is alkaline. The presence of kaolinite in such quantities indicates a warm and rather humid climate. Since Mabesoone, from pebble analyses, assumed a warm and rather dry climate, the kaolinite is thought to have originated in the Cuevas sediments during later alterations or to have been inherited 'from the source, that is weathering products of Mesozoic marine and brackish water limestones which occur in the mountains, where a more humid climate could have prevailed'. In this connection it should be remarked that the deposits of the Voznuevo Formation, so rich in kaolinite, could also have supplied part of the clays now present in the Cuevas facies.

In the Vega de Riacos facies two clay-mineral associations can be found, one with an equal proportion of kaolinite and illite, one with a clearly higher illite percentage (60 – 70%). A strong red weathering in a warm and humid climate was again assumed in the source area. The Vega de Riacos sediments were cemented with calcite at a later stage. The very high local percentage of kaolinite appears to be limited to locations where pH values are low (5.0 – 5.5) as a result of the presence of lignitic layers. Here, a change in colour has taken place from red into white and grey.

The other Tertiary facies distinguished by Mabesoone contain 75 – 90% of illite, with the exception of the Zorita facies in which up to 30% of kaolinite may be present.

The Quaternary sediments are, in general, a reflection of the Tertiary sediments as regards their clay-mineral associations.

A later study of the Tertiary red beds (Mabesoone, 1962) showed that illite is dominant in all samples. Kaolinite occurs in varying quantities, from abundant to traces. Mabesoone's observation that kaolinite is more abundant in the western part of the area studied by him, can be related to the fact that this clay mineral could be more easily derived from Mesozoic sediments such as the Voznuevo Formation in that part of the area than in the eastern part.

Mabesoone (1962) came to the conclusion that the red pigment of the red beds was due to red weathering in the source area (the Cantabrian Mountains). This area was believed to have been covered by thick red soils, indicative of a warm climate with high precipitation. Although laterites may form under these conditions, they apparently did not form in the Cantabrian area. The area in which the sediments were deposited is supposed to have had a drier climate (occurrence of gypsum layers!), favouring the preservation of the red colour.

Reflections on the presence of kaolinite and on paleoclimate

It is generally accepted that warm climates with much rainfall, moderate to strong leaching and low pH values lead to the formation of kaolinite as the most important clay mineral. Eh conditions can be oxidizing or reducing (e. g. in the case of abundance of organic matter). Kaolinite is formed, since loss of soluble constituents (alkalies, alkaline earths, some silica) leads to enrichment in alumina. Ferric oxide minerals (hematite and goethite) may become dominant when the rate of destruction of organic matter is high.

High permeability of loosely packed sands favours infiltration of rain-water and the mobility of ground water; the texture of the sands of the Voznuevo Formation probably facilitated leaching.

On trying to place the Voznuevo sediments in relation to one of the great soil groups, most agreement appears to be found with red-yellow podzolics (ultisols), typical of humid subtropical climates (such as a Ca- and, to a lesser extent, an Aw-climate according to the Köppen–Trewartha classification). These soils are formed in warmer and wetter climates than other podzolic soils; they may extend into tropical areas. Although such a climate may also have prevailed at the time when the Tertiary sediments formed in the Cantabrian area – laterization having taken place in neither Cretaceous nor Tertiary sediments – the striking difference in colour between these deposits must be sought either in different source areas, or in differences in the depositional environment, or in both. As observed by Mabesoone (1959), a local occurrence of lignitic layers caused a conspicuous decrease in the pH value together with a change in the colour of the sediments from red to white and grey. In this connection it is worth noting that the Voznuevo Formation is relatively rich in organic matter, while it is almost absent in the overlying formations. According to Loughnan (1969), kaolinite with some illite, some hematite and some organic matter can be expected in temperate to warm climates, already with moderate leaching and rainfall between 625 and 1300 mm/year under acid pH and oxidizing to reducing Eh conditions. On the other hand, hematite, goethite, gibbsite and boehmite with some kaolinite, without organic matter are supposed to form in climates with extensive leaching and rainfall over 1300 mm/year under acid pH and exclusively oxidizing conditions. Of course many transitional environments may be encountered. The exceptional composition of the Voznuevo sediments can be explained by the juxtaposition of oxidizing conditions (point bars, natural levees) and reducing conditions (backswamps).

From the predominance of authigenic kaolinite over detrital kaolinite (Chapter VII) one may assume that kaolinization of the Voznuevo sediments occurred particularly in the area of sedimentation. This is in contrast to the formation of clay minerals in the Tertiary sediments, which is believed to have occurred in the source area (the Cantabrian Mountains).

The parent material of strongly weathered and leached sediments is, of course, difficult to recover. The composition of the heavy and light minerals, however, suggests a granitic origin. Weathering of rocks with a granitic composition often leads to sediments like those encountered in the Voznuevo Formation. On weathering of granites Ollier (1969), for example, remarked that: 'deep weathering is common ... extreme weathering leads to china clay deposits consisting of almost pure kaolin and quartz grains'. As we have seen in Chapter IV, the derivation from granitic rocks was assumed as early as 1850, when Casiano de Prado referred to the Voznuevo sediments as 'destroyed granite'. Translation of the word 'destroyed' into 'strongly chemically weathered' apparently gives a better picture of the process involved.

CHAPTER IX

REMARKS ON INORGANIC AND ORGANIC COMPONENTS OF THE VOZNUEVO FORMATION

IRON (HYDR)OXIDES AND PYRITE

Iron may occur in sediments in a ferrous compound or in the form of ferric oxides, depending upon Eh conditions during or after deposition. The change from divalent into trivalent iron occurs under the influence of atmospheric O_2. Reduction from ferric to ferrous compounds takes place as a result of bacterial activity which makes use of organic carbon. This reduction also causes the transformation of sulphates to sulphides.

The formation of ferric oxides, especially of hematite, requires oxidizing conditions with positive Eh values. These conditions can only prevail if organic matter is absent or scarce, as for instance in semi-arid regions. Another possibility is that aerobic bacterial activity in the soil is so rapid that organic matter is destroyed before burial; a process which can take place in warm subtropical regions. In this case no reduction of the iron takes place.

Since there is no evidence of a semi-arid climate during deposition of the Voznuevo sediments, as concluded, for instance, from the abundance of kaolinite, the second possibility seems much more applicable, although there is still a considerable amount of vegetation remains. These remnants of an extensive flora, found in black clay layers as leaves and wood remains of small dimensions, in the sands as larger wood fragments, suggest the occurrence of Eh conditions which were in contrast to those favouring the formation of hematite. Although the stability fields for hematite and pyrite cannot precisely be delimited (well-crystallized hematite may persist under conditions in which pyrite is stable), the juxtaposition of different Eh milieus in the sediments studied is typical of river flood plains.

The superficial discolouration in sediments of silt- and clay-size, giving rise to red and purple coloured mottles, which was supposed to be the result of differences in iron content, led to a quantitative chemical analysis of the iron content of samples of different colours. The grey coloured samples were found to contain less than 1% of ferric oxides, the lilac coloured samples less than 2% and the, rarely found, purple to red coloured samples approximately 16 %. In none of the samples was ferrous oxide encountered.

The question may arise why there is such a striking difference in colour between the sediments of the Voznuevo Formation and those of the Vegaquemada Formation and the Red Beds. The content of ferric oxides and hydroxides, responsible for this difference, is apparently lower in the Voznuevo sediments, although small changes in the percentage of iron are generally required to bring about considerable optical changes. The lower content of ferric (hydr)-oxides is certainly not the result of more acid conditions which prevailed during deposition of the Voznuevo Formation, since ferric oxides do not become unstable before pH values drop below 2 (Berner, 1970). The Eh milieu is more important. It must have been highly oxidizing and free of organic matter during the formation of the red beds and less oxidizing, on an average, during the deposition of the Voznuevo Formation. Another possibility could be a stronger leaching of the Voznuevo sediments, in which process iron was removed in solution. This may have been caused by a wetter climate during Cretaceous times. Another reason why the iron content is different may be the source area. As Mabesoone (1962) demonstrated, the Red Beds are 'primary detrital' in the sense of Krynine (1949); they were derived from red soils which originated in the source area (i.e. the Cantabrian Mountains). The sediments of the Voznuevo Formation have a different source area and could have been derived from soils in which yellow colours prevailed over red colours.

Many black clay horizons proved to be rich in pyrite; concretions were encountered more than 1 cm in diameter. A number of wood fragments were also found to be partially pyritized. The reduction of ferric oxides by H_2S (formed by decomposition of organic matter by reduction of sulphate) into ferrous ions which react with hydrogen sulphide to form iron sulphide, is believed to take place in two steps: formation of black iron monosulphides (FeS) with subsequent oxidation (brought about by elemental sulphur as oxidizing agent) to pyrite.

GYPSUM

A problem with which we are confronted is the presence of euhedral gypsum crystals, up to several centrimetres in length, in the black clays near Valmartino. It is hardly likely that the gypsum crystals scattered throughout the black clay are the product of evaporation, the more so as this requires abrupt climatic changes (i. e. a semi-arid or arid climate) in the generally wet climate which is supposed to have prevailed.

The formation of gypsum must have been the result of the oxidation of pyrite, the mineral so frequently observed in the black clays. Oxidation of pyrite leads to the formation of sulphuric acid. The latter will react with carbonate according to the following reaction:

$$H_2SO_4 + CaCO_3 + 2H_2O \rightarrow CaSO_4.2H_2O + H_2CO_3$$
(Reeves, 1968)

It is highly probable that the supply of waters rich in carbonate took place at a late stage in the sediment's history in this location and that the formation of gypsum in the black clays is only a superficial feature, which was already assumed on account of its occurrence in cracks and fissures. This assumption is corroborated by the presence of Paleozoic limestones at only a few metres from the black clay exposure. Run-off of waters rich in lime can easily have caused a chemical reaction with the sulphuric acid in the black clays and have led to the formation of gypsum.

A similar process may have produced the gypsum (1.94 %) in the black clay horizon N of Las Heras (Section Q).

SULPHUR

In the description of the thin sections (Chapter VII) it was already mentioned that the formation of pure sulphur is limited to the very surface of the black clay deposits. A few chemical reactions possibly involved in the formation of pure sulphur are (Reeves, 1968):

The oxidation of H_2S:
$$3H_2S + 2Fe^{3+} \rightarrow 6H^+ + 2FeS + S\downarrow$$

The oxidation of FeS:
$$4FeS + 3O_2 \rightarrow 2Fe_2O_3 + 4S\downarrow$$

The oxidation of thiosulphate:
$$5Na_2S_2O_3 + H_2O + 4O_2 \rightarrow 5Na_2SO_4 + H_2SO_4 + 4S$$

ORGANIC REMAINS

The only organic remains occurring in the Voznuevo Formation are unidentifiable plant remains, varying from trunks of several cubic decimetres to paper-thin stems and leaves. By far the majority of the larger wood fragments are allochthonous, they can be found as isolated pieces, coated with sand and gravel. The sand pit south of Grandoso (cf. Chapter V, part B) frequently contains such drifted wood fragments, incorporated in cross-stratified units.

All plant remains encountered in the Voznuevo Formation show a low degree of coalification; they must be ranged among the brown coals. The term 'lignite' may cause confusion, since it is synonymous with 'brown coal' in Britain, while '... in Germany and other parts of Europe the term brown coal is restricted to megascopically compact structural varieties, while lignite is restricted to individual pieces of wood enclosed in brown coal' (Tomkeieff, 1954). According to a North American classification, brown coal is an unconsolidated deposit, whereas lignite is consolidated (Williamson, 1967).

According to Tomkeieff 'one may subdivide brown coal (sensu Anglice) inlo low-grade brown coal made of visible vegetable remains, and high-grade brown coal, a compact, homogeneous and tough rock'. The more recent classification by Williamson gives a subdivision into brown lignites and black lignites (sub-bituminous coals in North America) which form the transition into bituminous coal.

The brown coal in the Voznuevo Formation occurs in the form of:

1. Felt-like tissues of leaves and small stems; macroscopically closely resembling paper coal (cf. Williamson, 1967; Plate 15b).
2. Isolated small wood fragments with external characteristics of recent wood.
3. Black coloured, hard, jet-like fragments – clean to the touch – with a conchoidal fracture.
4. Fusain, macroscopically resembling charcoal, dirty to the touch and highly friable. In one thin section containing these charcoal fragments, the cellular structure of wood fibre is evident (fusite) (Fig. 74).

The presence of these types of organic remains shows that coalification has not been very intensive in the sediments of the Voznuevo Formation. This may be ascribed to low temperatures in the sediments and to a relatively small amount of overburden; two facts previously concluded from the abundance of kaolinite (Chapter VII).

The felt-like plant remains probably form the brown coal variety of paper peat and, together with the wood fragments mentioned in 2, belong to the brown lignites. The jet-like material must be ranged among the black lignites. The charcoal mentioned in 4 cannot be related to a coalification stage, but represents a coal constituent which is not necessarily limited to bituminous hard coal, but can also be a constituent of brown coal (Kreulen, 1948). The occurrence of mineral charcoal is still somewhat obscure; forest fires are held responsible for its formation.

Compared with the overlying Tertiary deposits, the Voznuevo Formation is rich in vegetable matter, being a remnant of local luxuriant vegetation. One of the factors by which this difference is controlled may be a wetter climate during Cretaceous times than during succeeding times.

CHAPTER X

DISCUSSION AND CONCLUSIONS

Surveying the principal points yielded by the present investigation, we must first of all stress that all data, gathered both in the field and in laboratory-processed samples, indicate deposition of the Voznuevo sediments in an almost purely fluvial environment. This eliminates other environments which have been proposed in the course of time, such as eolian, deltaic or limnic environments.

The sediment shows a large spectrum of grain sizes, but components exceeding about 6 cm in diameter (pebble size) are very rare. The megascopical composition is rather monotonous, showing a very impressive predominance of quartz and muscovite in the smaller grain sizes. The absence of limestone components is one of the most conspicuous aspects. Quartzite proved to be of local importance only, while the content of black radiolarites (+ phtanites and quartz phyllites), probably derived from the Precambrian strata which outcrop in the extreme W of the area studied, remains fairly constant (generally 8–12 %). The microscopical composition, too, shows a striking monotony, which is a reflection of the megascopical composition. Moreover, the detrital parts of the thin sections contain a small percentage of detrital kaolinite grains and of detrital muscovite flakes.

The Voznuevo sediments are cemented by cryptocrystalline quartz and kaolinite in the first generation and by iron (hydr)oxides in the second generation. Overgrowth of quartz on grains may occur, but is not very common. This feature is in clear contrast to overgrowth as observed in samples of Paleozoic origin. In the samples containing feldspars, alterations of the latter into kaolinite could frequently be observed.

An extensive study of the heavy-mineral composition resulted in the observation that an enrichment occurs in the composition of the heavy-mineral assemblage with decreasing age, as a result of the introduction of metamorphic heavy minerals; yet only stable heavy minerals occur, those susceptible to chemical weathering such as hornblende, epidote and augite being completely absent. The Voznuevo sands contain a generally high percentage of staurolite. The composition of the light minerals is even simpler; they consist almost exclusively of quartz and muscovite. Feldspar may be present in some locations but its proportion decreases with decreasing age.

The clay-mineral assemblage makes it clear that the predominant clay mineral is kaolinite, while illite is generally of minor importance. The reddish colour of the sediment in some locations must be ascribed to the formation of goethite; hematite proved to be very rare.

Black clay layers, rich in organic remains, of lens-like shape, are fairly common. They contain many, sometimes pyritized, wood fragments and other organic remains which do not exceed the brown coal stage in coalification. In few locations oxidation of pyrite, in combination with superficial waters rich in lime, has led to the formation of gypsum crystals on the surface of the black clays. Oxidation also caused efflorescence of sulphur.

The fluvial origin of the sediments studied was based on observations in the field in which many fluvial characteristics became evident. Two fluvial sedimentation patterns could be distinguished, represented by braided-river sediments and by meandering-river sediments. The importance of the braided pattern clearly increases towards the west. Paleocurrent directions incontrovertibly showed that transport of the sediments in this area took place from directions between S and W. A clearly fluvial origin of the sediments may also be deduced from flatness and roundness indices of the pebbles and from grain-size distribution features such as poor sorting and positive skewness.

As regards the source area of the sediments we are still faced with a number of problems. Some investigators of lithologically similar deposits proposed that such sediments could have been derived from granitic masses which occur in a broad strip from Galicia to central Spain (cf. Fig. 1). One of these granitic masses, partly hidden below Tertiary, is supposed to have supplied the Voznuevo sediments as well. The best described and most similar deposits are those of the Sierra de los Cameros, which are believed to have originated in the northern part of the Sierra de Guadarrama, N of Madrid. Only feldspars are clearly more abundant and better preserved in the sediments of the Sierra de los Cameros than in those of the Voznuevo Formation. This might indicate a longer distance of transport of the latter. One could assume that the sediments in the Cantabrian area were deposited for a second time, having been eroded from sediments which were situated nearer to the original source area. The relatively simple composition, consisting of stable constituents, and the relative scarcity of feldspar is in favour of such a sedimentary history.

According to López Aguado et al. (1971) the decrease in feldspar with decreasing age, as found in the sediments in Wealden facies studied by them, indicates an increased maturity of the source area. Two remarks must be made, however, with respect to their reasoning:

1. Continued erosion will rather cut into increasingly fresh rocks, which will lead to an increase in feldspar with decreasing age.
2. Transformation of feldspar into kaolinite will take place particularly in the younger levels of a porous complex such as sands in Wealden facies; this transformation therefore taking place after deposition.

In the Voznuevo Formation in which the feldspar content also shows a decrease with decreasing age, the abundance of authigenic kaolinite suggests the presence of feldspar during sedimentation. We also see that the percentage of feldspar is much higher in the upper part of the formation, where the presence of limestone made preservation of the feldspars possible. In the extreme west of the area, where the Mesozoic limestone cover is absent, no feldspar was encountered. For this reason we assume that transformation of feldspars and other weathering phenomena occurred after deposition of the Voznuevo sediments and that they were not previously subjected to intensive weathering.

The stratigraphical position of the Voznuevo Formation posed a problem consisting of two parts. First, the position of the deposits, as compared with other sediments in Wealden facies reported from other parts of Spain, had to be determined; secondly we were faced with the problem, whether the Voznuevo Formation is independent of the overlying transgressive deposits, or had to be correlated laterally with these deposits.

Comparing the stratigraphical position (based on palynological studies) of the Voznuevo sediments with deposits, identical in facies, in northern, eastern and central Spain, it became clear that the sediments studied must be ranged in the upper Lower Cretaceous or in the lower Upper Cretaceous. They must be included in the supra-Urgonian complex and may be connected with sediments commonly referred to as Utrillas Beds. Palynological analyses brought to light that the Voznuevo Formation grows younger in a westerly direction; the distribution of age determinations showed that pollen samples of Lower Cretaceous age are limited to the lowermost deposits in the east, the remainder being of Upper Cretaceous age. The larger part of the Voznuevo deposits occupies a rather exceptional position in comparison with other locations in which supra-Urgonian deposits occur, with the exception of the transgressive continental sediments of Upper Cretaceous age of the Massif of Oroz-Betelu NE of Pamplona. In these two areas continental deposition apparently still continued, whereas other parts in which continental sedimentation had taken place were already reached by the Cenomanian transgression.

The Voznuevo Formation, which is a clearly diachronic deposit along the southern border of the Cantabrian Mountains, must be the continental continuation of the transgressive shallow marine deposits belonging to Upper Cretaceous stages. These deposits wedge out towards the west, where the Voznuevo Formation can be connected with successively younger stages. The transgression which began in the Cenomanian, slowly crept up along the southern border of the Asturian Massif from an easterly direction, pushing ahead a strip of continental deposits. These continental deposits, as mentioned above, were supplied from southwesterly directions since they show paleocurrent directions with a supply from between W and S.

Although the Voznuevo sediments are monotonous at first sight, there proved to exist many significant differences in the deposits from E to W and from bottom to top (approximately from N to S). Among these differences we shall mention:

a. A decrease in grain size from bottom to top, observable in almost every section.
b. An increasing thickness towards the west of the lower part of the formation consisting of braided-river deposits. In the eastern part of the area braided-river deposits are altogether absent.
c. A slight increase in the formation's total thickness from 250 m in the east to more than 350 m in the extreme west.
d. A greater divergence of paleocurrent directions in the top of the formation as a result of meandering of the river(s).
e. A decrease in flatness and an increase in roundness of pebbles towards the east.
f. A better sorting of the sands towards the east.
g. The introduction of new heavy-mineral assemblages parallel to the transition from the Lower Cretaceous to the Upper Cretaceous, causing an extremely stable association in the oldest part of the formation in the east to a more diversified assemblage in the west.
h. The slight decrease in the feldspar content towards the west, supposed to have been caused by alteration into kaolinite after deposition.

The contacts between the Paleozoic and the Mesozoic proved to be unconformable in most locations. They could not be observed in the central part of the area studied where fault movements of considerable importance are believed to have taken place. The influence of the Paleozoic rocks on the composition of the Voznuevo sediments has been very small, however. Relief in the Cantabrian Mountains must have been very low, although there are no indications that Cretaceous deposits ever covered a large part of the present Cantabrian area. Relatively little material was supplied to the Voznuevo Formation. Apart from paleocurrent directions and heavy minerals, this must also be concluded from the fact that not a single limestone fragment, derived from Paleozoic rocks, was ever encountered in the Voznuevo Formation. A relatively high percentage of quartzites in the very lowest part of the formation reflects a small influence of short duration of the Paleozoic. In one exposure it became clear that tributaries, rich in quartzite, locally introduced materials from the Cantabrian Mountains into the formation. Paleocurrent directions in these deposits indicate supply from the N.

From the degree of cementation in the thin sections and the clay-mineral content, Paleozoic samples can easily be distinguished from Mesozoic samples, the boundary between these sediments always being very distinct.

A clearly gradual transition could be observed in the top of the formation where sandy sediments pass into identical sediments with a cement consisting of sparry calcite. In these parts of the formation preservation of feldspars was observed.

The Voznuevo sediments have certainly had an important influence upon the younger Tertiary and Quaternary deposits, since the latter were mainly derived from the Cantabrian area, of which the Cretaceous sediments formed a part. The introduction into the Cantabrian area of heavy minerals such as staurolite and andalusite, and of kaolinite since the Voznuevo Formation began to be deposited, with subsequent erosion and redeposition in younger deposits, can readily explain their occurrence in these latter sediments.

Although some weathering must have occurred in the source area (as deduced from the presence of detrital kaolinite), we believe that most weathering has taken place after deposition.

The abundance of kaolinite and the ubiquity of plant remains and other organic matter, as well as the flatness and roundness indices of the pebbles, are indicative of a temperate to warm climate with considerable pluviosity, giving rise to relatively strong leaching (a Ca- or possibly an Aw-climate according to the Köppen-Trewartha classification). Both oxidizing and reducing conditions – in an acid environment – must have prevailed at one and the same time, a phenomenon characteristic of fluvial environments, the first on point bars and natural levees, the latter in backswamps. The absence of gibbsite and other aluminium oxides shows that laterization did not occur, so that formation of red-yellow podzolic soils must be assumed. The rather warm and humid climate fits in with the, on an average, warm climates generally assumed for Cretaceous times (e. g. Schwarzbach, 1961). After the Mesozoic the temperature gradually diminished while the climate became more arid south of the Cantabrian Mountains (cf. Mabesoone, 1962).

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