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Provenance of Cambro-Ordovician to Oligocene sandstones in the Southern Pyrenees, Spain

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Abstract

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The Cambro-Ordovician, Silurian and Devonian sedimentary sequences in the Southern Pyrenees were deposited on the northern, then passive, margin of the early Iberian plate. Supply of an increasingly mature clastic assemblage was sourced from the south. In pre-Variscan Carboniferous time this margin was activated as is evident from the appearance of abundant metamorphic and volcanic lithics in the sandstones. The Variscan chain, which had emerged in the Late Westphalian, dictated a new clastic dispersal pattern with southwards-directed paleotransport. The sandstones of these early post-Variscan times typically represent a 'recycled orogen' facies with variations in composition that can be attributed to contemporaneous volcanism, relief and paleoclimate (Westphalian D - Early Triassic).

Towards the end of the Mesozoic (Santonian) southern clastic sources, collectively referred to as the 'Ebro High', had again become active. They supplied stable terrigeneous assemblages until the end of the Maastrichtian. As a result of the Late-Cretaceous collision of Iberia with stable Europe, the main clastic dispersal systems changed drastically and in Paleocene time supply was from the northeast where uplifted Mesozoic carbonates were subjected to erosion. This dispersal system, which gradually also involved supply directly from the north and from deeper stratigraphic levels, became very important in Eocene and in Oligocene time, and, in essence, even persists today.

Introduction

Recent advances in provenance studies of clastics include a much improved understanding of the relationship between sand composition, often expressed in the form of 'detrital modes' and plate tectonic position (Potter 1977, Dickinson & Suczek 1979, Dickinson & Valloni 1980, Dickinson et al. 1983). Apart from mirroring tectonic regime, sand composition is also influenced by relief and climate (Suttner 1974, Basu 1976).

The aim of the present study is to apply these ideas on sand composition and provenance in a reconnaissance of the geodynamic and climatic history of the Southern Pyrenees in Spain.

The stratigraphic interval considered corresponds to the full geologic record exposed, which is from the Cambro-Ordovician to the Oligocene.

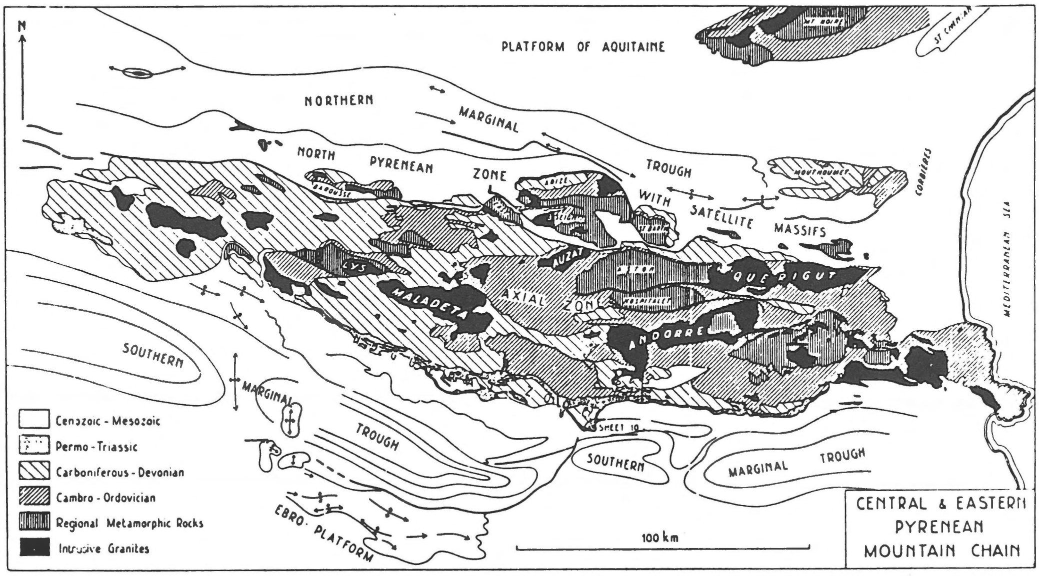


Fig. 1. Geological sketch-map of the Central and Eastern Pyrenees, after De Sitter (1964).

The area investigated stretches roughly from a southern line from Jaca in the west to just beyond Seo de Urgel in the east, northwards to the Spanish/French border (Figs. 1 and 2).

The present study is based on a suite of some hundred samples collected especially for the purpose. The results of petrographic analyses of 67 of these samples are included (Table 1). The petrographic analyses consisted of point counting of thin sections (300 points), feldspar staining (Bailey & Stevens 1960) and cathodoluminescence of quartz following the pioneering work of Zinkernagel (1978). All of these analyses were the responsibility of the second author.

In view of the wide scope and very limited sampling density (approx. 1 sample per 200 km^2) this study bears the character of a first reconnaissance only.

Clastic dispersal patterns and basin-filling sequences, Cambro-Ordovician to Oligocene

Three main groups of basin-filling sequences can be distinguished:

A. *The pre-Variscan group of sequences* (Cambro-Ordovician to Early Westphalian).

B. *The Variscan to Pyrenean group of sequences* (Westphalian D to Early Eocene).

C. *The post-Pyrenean group of sequences* (Late Eocene to Oligocene and younger).

This subdivision is directly related to the geodynamic history of the area. Group A largely consists of stable platform deposits and ends with deposits that were, facies-wise, already strongly influenced by the approaching Variscan orogeny. Group B starts with the clastics shed by the Variscan orogen, includes the Mesozoic stable (carbonate) platform deposits and ends with deposits already reflecting the onset of the Pyrenean orogeny, while Group C represents deposits largely derived from the Tertiary Pyrenean orogen.

A. The pre-Variscan group of sequences

The following three main basin-filling sequences are recognised: a series of formations making up the Cambro-Ordovician, formations of Silurian and Devonian age, and deposits of pre-Variscan Carboniferous age.

The *Cambro-Ordovician* basin-filling sequence is well represented in the Central and Eastern Pyrenees where it has been analysed extensively by Hartevelt (1970). The N-S cross-section through

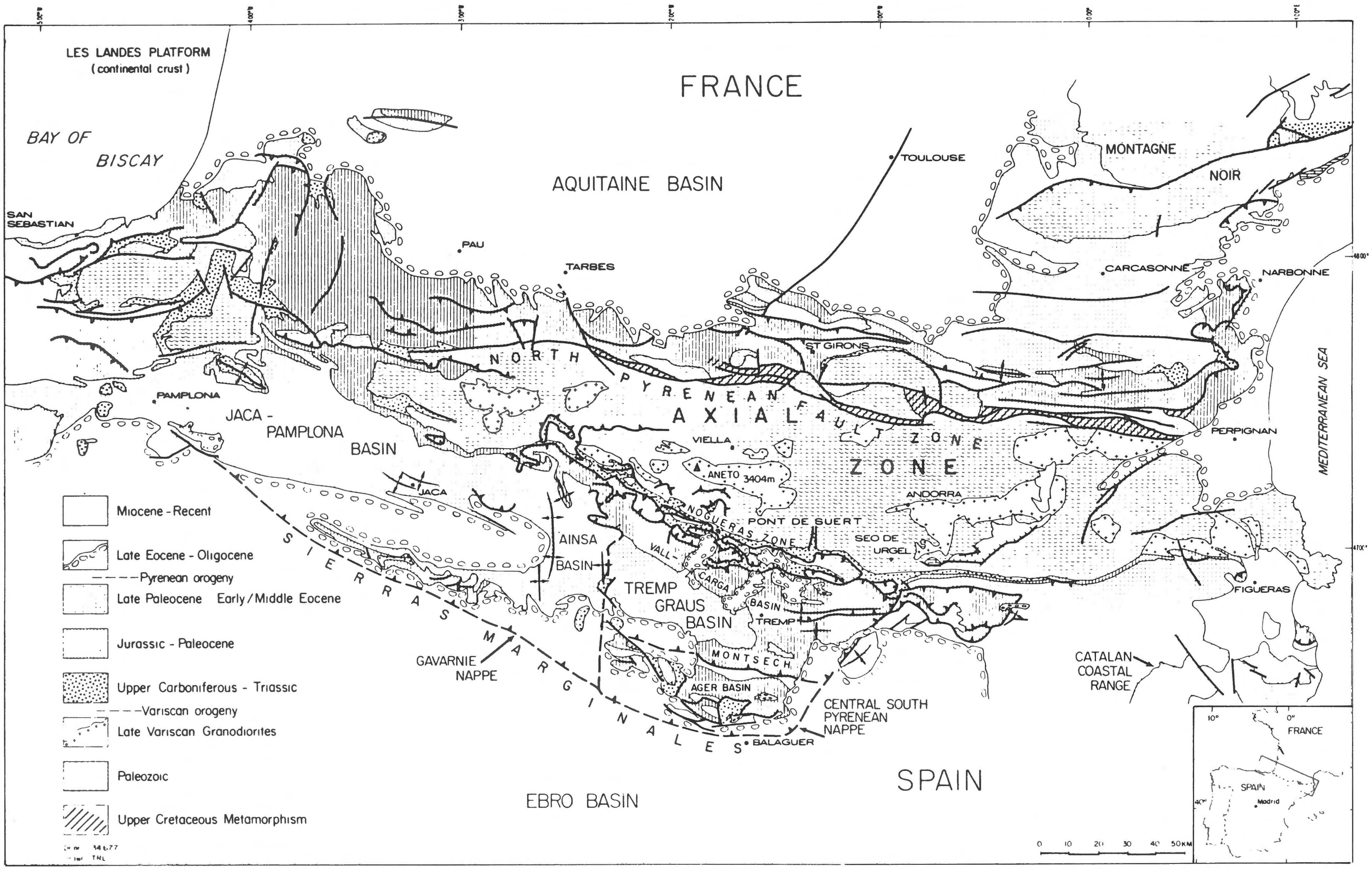


Fig. 2. Geological sketch-map of the Pyrenees, redrawn and simplified, after Choukroune et al. (1973 B).

the Cambro-Ordovician shown in Fig. 3 is from the same author.

The sequence largely consists of very fine-grained clastics, subordinate limestones and one outstanding coarse clastic wedge which is made up of the so-called Rabassa Conglomerate and the Cava Formation. This clastic wedge shales out towards the north (Fig. 3). Depositional environments range from shallow marine to coastal and terrestrial with paleotransport directions generally from south to north (Hartevelt 1970; Zwart 1979).

Detrital Modes. The sandstones analysed are from the Cava Formation as exposed just north of Seo de Urgel (Table 1, No. 1). They are from the more mature, upper part of the Cava Formation and have a high quartz and very low feldspar content. The maturity of these deposits was also noted by Stattegger (1978). The somewhat elevated lithics content (nearly all metamorphics) still reflects the composition of the underlying greywackes and Rabassa Conglomerate, which are high in metamorphic components and, locally, in volcanic-derived feldspar, according to Hartevelt (1970). The significance of the occurrence of these immature assemblages is not yet understood.

Cambro-Ordovician sedimentation ended with the widespread transgression of the *Silurian*. Generally anoxic bottom conditions developed and a 200-250 m thick black shale sequence was formed. This transgression immobilised clastic sources in already mature low relief provenance areas while it also marked the transition to the carbonate-rich deposits of the Devonian.

The *Devonian*, entirely developed in a marine facies, is characterised by a distinct compartimentalisation of the originally very extensive Cambro-Ordovician to Silurian basin. Several so-called 'facies-areas' developed during this period (Mey 1967, Zwart 1979).

Two major coarse clastic wedges are known. The first is found in the Emsian Basibé Formation (Mey 1968, Habermehl 1970; Fig. 4), and a second is of probable Frasnian to Lower Famennian age and is

Table 1. Detrital modes of Cambro-Ordovician to Oligocene sandstones from the Southern Pyrenees.

No.	Age/Formation	Location	Q	F	L	Type	Samples
1	Cambro-Ordovician/Cava Fm.	Seo de Urgel	93.3	0.5	6.2	L_{mt}	3
2	Emsian/Basibé Fm.	Las Paules	99.2	0.5	0.3		4
3	Frasnian/Las Bordas Sst.	Viella	98.0	–	2.0		4
4	Pre-Variscan Carboniferous	N. of Benasque	74.0	11.0	15.0	L_{mt} L_{vo}	2
5	Pre-Variscan Carboniferous	Bellver	59.4	4.1	36.5	L_{mt} L_{vo}	3
6	Westphalian D/Aguiró Fm.	Aguiró	24.7	1.7	73.6	L_{mt} L_{vo}	4
7	Stephanian/Malpás Fm.	Malpás	59.7	0.2	40.1	L_{vo}	2
8	Permian Peranera Fm.	La Mola d'Amunt	12.0	7.7	80.3	L_{mt}	4
9	E. Triassic/'Bunter Fm.'	La Mola d'Amunt	79.2	2.7	18.1	L_{mt}	4
10	Albian/San Martin Fm.	Bonansa	54.9	0.1	45.0	L_{ci}	3
11	Santonian/'Clastic horizon'	Montsec	42.0	14.0	44.0	L_{ci}	2
12	Campanian/Vallcarga Fm.	Pobla de Segur	37.3	1.3	61.4	L_{ci}	6
13	Maastrichtian/Arén Sst.	Isona-Tremp	47.3	3.4	49.3	L_{ci}	7
14	Paleocene/Tremp Fm.	Tremp	9.8	0.2	90.0	L_{ce}	3
15	E. Eocene/Montllobat Fm.	Montllobat	34.7	16.5	48.8	L_{ce}	3
16	E. Eocene/Montaña Fm.	Montllobat	6.0	1.2	92.8	L_{ce} L_{mt}	2
17	E. Eocene/Castisent Sst.	S. Miguel Pass	43.0	17.5	39.1	L_{ce}	2
18	E. Eocene/Vicente Fm.	Ainsa	38.9	12.8	48.3	L_{ce}	3
19	E. Eocene/Hecho Gr.	Broto	28.2	12.8	59.0	L_{ce}	4
20	Oligocene/Collegats Congl.	Graus	41.0	7.7	51.3	L_{mt} L_{ce}	2

(Q = Quartz, F = Feldspar, L = Lithics, mt = metamorphic, vo = volcanic, ce = extrabasinal carbonates, ci = intrabasinal carbonates)

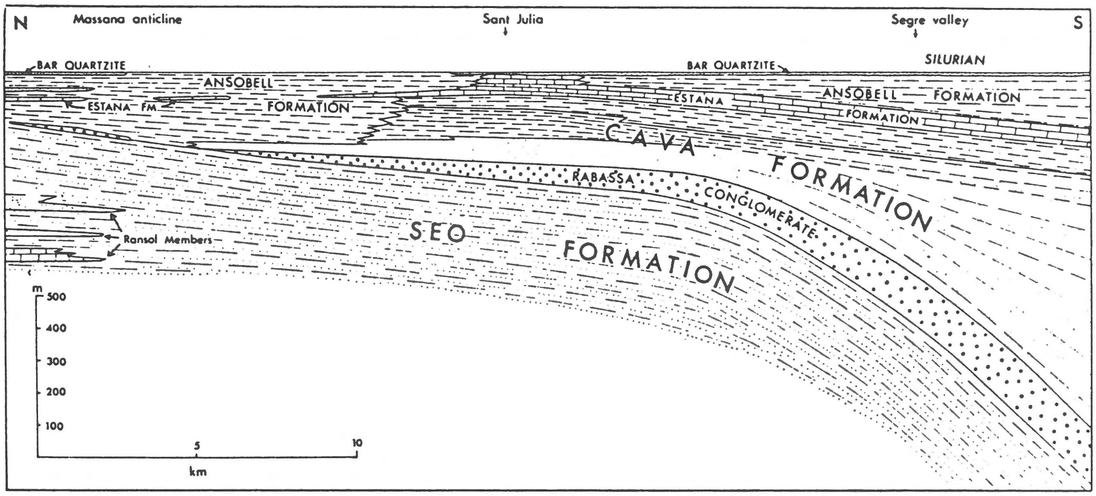


Fig. 3. Schematic stratigraphic N-S section through the Cambro-Ordovician in the South-Eastern Pyrenees, after Hartevelt (1970).

called the Las Bordas Sandstone (Zwart 1979). The depositional environments of these sandstone units contrast markedly; the Las Bordas Sandstone represents a west to east oriented turbidite fill of a separate small basin (one of the Devonian 'compartments') whilst the Basibé Formation is a shoreline sand deposit thinning and wedging out northwards (Habermehl 1970).

Detrital Modes. The two Devonian sandstone units have been investigated petrographically (Table 1, Nos. 2 and 3). The detrital modes are remarkably similar: both represent very mature quartz arenites. The composition of these Devonian sandstones also closely resembles that of the Cambro-Ordovician Cava sandstones investigated (Table 1, No. 1).

The mineralogical similarity of the Cambro-Ordovician and Devonian sandstones is confirmed by cathodoluminescence. In all cases the quartz grains represent a mixture of 60-80% brownish-luminescing and a remaining 20-40% of bluish-luminescing grains. The bluish grains tend to occur mostly in the coarser fractions. These bluish grains represent an assemblage of presumed igneous origin, while the brownish luminescing grains are probably of metamorphic origin (Zinkernagel 1978).

In the *pre-Variscan Carboniferous* clastic sedimentation was resumed after the widespread accumulation of pelagic limestones ('griotte limestones') of the Famennian (Fig. 4). Locally the start of clastic deposition corresponded to a dramatic change in depositional regime, such as for instance, at Bellver (just east of Seo de Urgel, Fig. 2) where deeper marine debris flow conglomerates directly overlie pelagic griotte limestones. The pre-Variscan Carboniferous clearly is a time of dramatic change in facies: unmistakably deltaic, shallow marine and coarse clastic turbiditic depositional environments can be recognised, but the regional facies patterns remain to be deciphered.

Detrital Modes. The marked overall change of facies from the Devonian to the Carboniferous is clearly reflected in the strongly changed composition of the clastics. In contrast to the underlying sandstones, those in the Carboniferous are typically immature and demonstrate the influence of new clastic sources. Feldspar and lithics content are strongly increased (Table 1, Nos. 4 and 5). The lithics include both metamorphic and volcanic components. Micas are a characteristic constituent of these sandstones as well. Buchroithner & Milan (1977) made similar observations, while Stattegger (1978) also concluded, on the basis of the heavy mineral assemblage, that new, magmatic/metamorphic sources became active in the Carboniferous.

The composition of the pre-Carboniferous sandstones north of Benasque and at Bellver differs to the extent that different provenances may be assumed (Table 1, Nos. 4 and 5). Cathodoluminescence images clearly show the increased feldspar content. They also show that quartz of a metamorphic origin (brownish colours) dominates with a percentage of 80-90% and represents the coarsest fraction. The remaining bluish-violet quartz, of presumed igneous origin, is concentrated in the finer fractions (Plate I, B).

B. The Variscan to Pyrenean group of basin-filling sequences

Depositional complexity is much greater in this group of sequences. This difference with the underlying sequences may, in part, be apparent because these deposits are tectonically much less disturbed, are more accessible, and have therefore been studied more intensively. The difference is also real, however, because of the strongly varying tectonic regimes which caused frequent lateral changes of facies.

Four basin-filling sequences can be distinguished (Fig. 5):
The post-Variscan terrestrial clastics (Westphalian D to Early Triassic),
The Mesozoic marine platform evaporites and carbonates (Late Triassic to Early Cretaceous),
The Late Cretaceous shallow to deeper marine basin filling sequence (Aptian to Maastrichtian),
The Tertiary deltaic to deeper marine basin filling sequence (Paleocene to Oligocene).

The post-Variscan terrestrial clastics
Along the southern border of the Palaeozoic core of the Pyrenees isolated packages are found ranging in age from Westphalian D to Permian (Figs. 1,

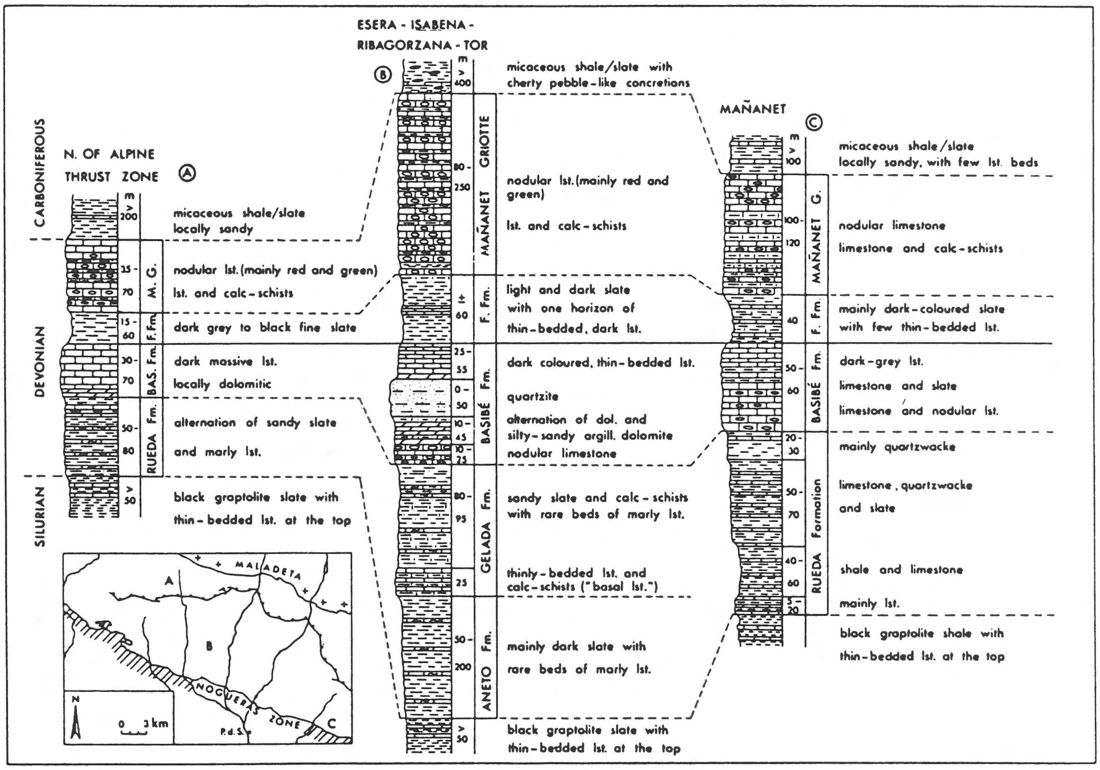


Fig. 4. Schematic stratigraphic sections of the Devonian in the southern part of the Central Pyrenees, after Habermehl (1970).

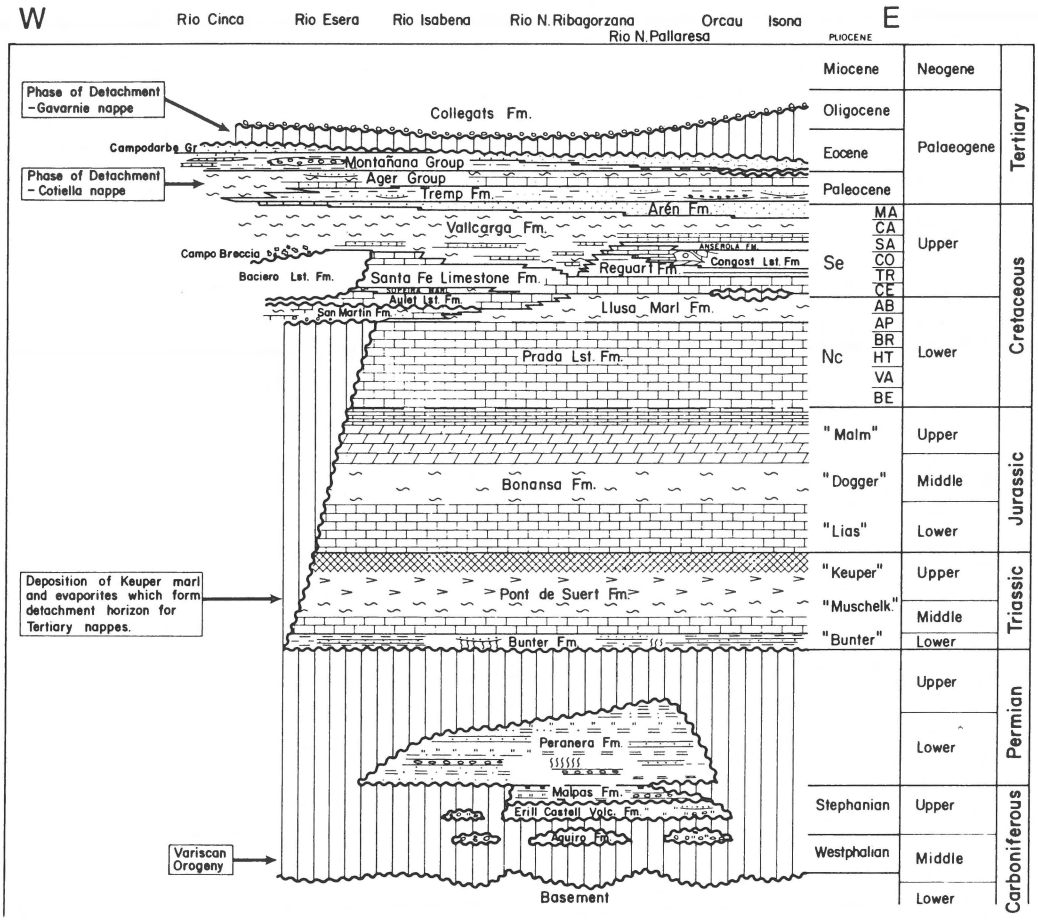


Fig. 5. Schematic stratigraphic section of the Post-Variscan in the Southern Pyrenees, after M. Wiemer (pers. comm.), and Mey et al. (1968).

2). Careful analysis in the field has shown that these isolated sequences correspond to small fault-bounded basin fills (Gisbert 1981, Speksnijder 1984). The Westphalian D (Aguiró Fm.) and Stephanian (Malpás Fm.), which form part of these packages, are developed in an intramontane 'coal basin facies' and contain important volcanic deposits in the form of terrestrial lavas and tuffs. The Permian (Peranera Fm.) is represented by red beds in an alluvial fan and floodplain facies (Fig. 5).

The isolated sequences are invariably overlain by Early Triassic (Bunter Fm.) terrestrial, dominantly fluvial red beds which, in contrast to the directly underlying deposits, are continuous over very large areas. An angular unconformity is present at many places between the Permian and the overlying Bunter red beds.

Detrital Modes. The sandstones of Westphalian D, Stephanian, Permian and Early Triassic age were petrographically analysed (Table 1, Nos. 6-9). All of these sandstones, except the Early Triassic ones, are highly immature, forming part of the first debris shed by the newly emerged Variscan chain (Nagtegaal 1969). The Westphalian D sandstones are characterised by high percentages of phyllite and quartzite grains mainly of Cambro-Ordovician and Devonian origin (Table 1, No. 6; Plate I, C). Volcanic admixture is already evident in the top part of the Aguiró Fm. The Stephanian Malpás sandstones (Table 1, No. 7; Plate I, E & F) are almost entirely derived from the penecontemporaneous volcanics. The low feldspar content in this case is thought to be the result of early alteration of the feldspars into kaolinite (Nagtegaal 1969).

In Permian time the Palaeozoic sources were reactivated and the lithics in the sandstones of the Peranera Fm. are largely similar to those found in the Aguiró sandstones. In addition they contain abundant Devonian limestone clasts, the preservation of which presumably was made possible by the semi-arid paleoclimate.

The cathodoluminescence of these sandstones shows predominantly pale-brownish quartzes in the Aguiró Fm. (interpreted as metamorphic varieties Plate I, D), and a general appearance of reddish-brown quartz in the Stephanian (probably volcanic quartzes, Plate I, F). Brownish quartz reappears in the Peranera Fm. (Plate II, G) and is also dominantly present in the Bunter sandstones. Bluish quartz, which may have been supplied by the granodiorites in the Axial Zone of the Pyrenees, is generally present in the Bunter sandstones as well (Plate II, H). This confirms an earlier conclusion that these granodiorites had become exposed in the Early Triassic (Nagtegaal 1969).

The Mesozoic marine platform evaporites and carbonates

In the area of study this sequence generally conforms to a stable platform setting and facies changes are gradual. A low energy transgression, with widespread lagoonal facies, marked the end of the Lower Triassic terrestrial red bed deposition. These lagoonal deposits are followed by limestones ('Muschelkalk'), which, in turn, are overlain by lagoonal variegated marls with interbedded solution breccia. Then followed important evaporite development with gypsum and rock salt (Pont de Suert Fm., Fig. 5). These Middle and Upper Triassic evaporites are widely developed in the whole northern and eastern part of Spain (Rios 1968).

The Jurassic starts with widespread but shallow marine dolomitic limestones and very fossiliferous marls. These are followed by dolomites which are transitional into the Early Cretaceous limestones (the 'Prada Limestone Formation', Fig. 5). Facies similar to those described here are widely represented in the northern Pyrenees, the western Pyrenees, Cantabrian offshore and the Provence.

In summary, the period from the Mid-Triassic up to and including the Early Cretaceous (pre-Aptian) is strongly carbonate-dominated and is characterised by overall stability, laterally similar facies over extensive areas and regional facies differentiation against basin rims and paleo-highs (Fig. 5).

Paleogeographically the period is of great significance because during this time the area formerly occupied by the Variscan Pyrenees started to subside generally. Slowly in the Late Triassic, Jurassic and Early Cretaceous but much more rapidly and regionally variable in the Aptian with the start of the eastward rotational shift of the Iberian plate (Le Pichon et al. 1970, 1971; Choukroune et al. 1973 a, b; Choukroune & Mattauer 1978). An important high, the Ebro Massif, established itself in the area now occupied by the Tertiary Ebro Basin from the Early Mesozoic onwards (Figs. 1 and 2).

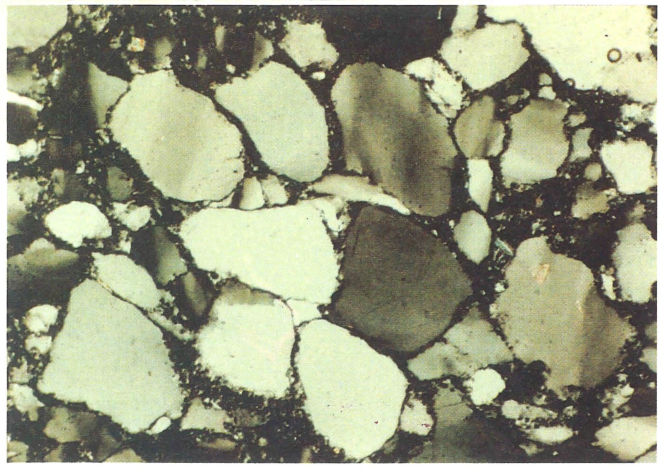
The Late Cretaceous shallow to deeper marine basin-filling sequence

This sequence extends in age from the Aptian up to and including the Maastrichtian, which is exactly the time during which the rotational transform movement along the North Pyrenean Fault is thought to have taken place (see above). In contrast to the preceding period, the facies pattern is now highly varied, with frequent and important lateral facies changes reflecting syntectonic sedimentation (Fig. 5).

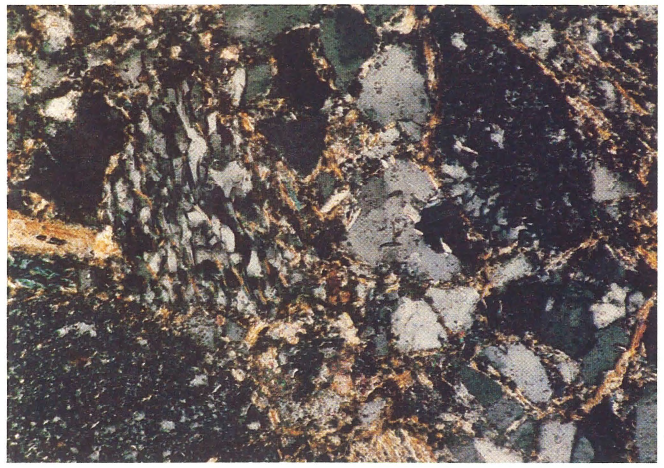
The sequence starts with a series of finely stratified marls and interbedded siltstones indicating renewed terrigeneous input, of large but variable thickness (Llusa Marl Fm., Fig. 5).

The age is Aptian-Albian to Lower Cenomanian. On the basis of the fauna and lithology the environment of deposition is assumed to have been generally open neritic ('deeper shallow marine offshore'; Souquet 1967). The southern limit of deposition was the Sierra de Montsec (Fig. 2). A clastic terrestrial facies (the so-called 'Utrillas' facies; locally the San Martin Formation; Table 1, No. 10) developed in the Albian, in areas which must have been near highs at the time.

During the Late Albian - Early Cenomanian the environments in the Southern Pyrenees generally shallowed, changed locally into a carbonate facies

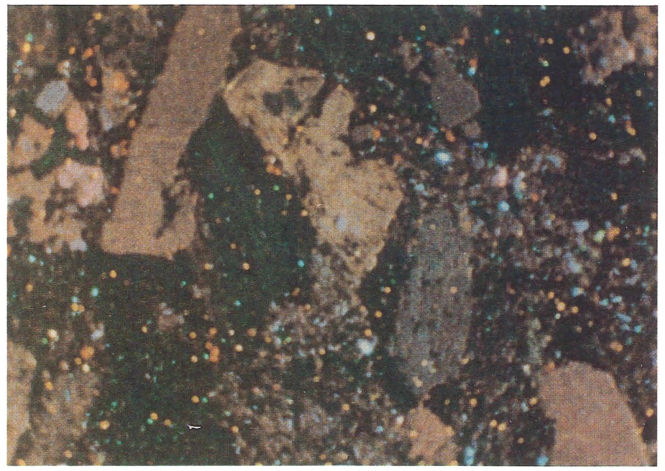


A. Frasnian (Las Bordas Fm.) medium-grained, highly mature quartz sandstone of presumed stable craton origin. No. 3 in table 1.

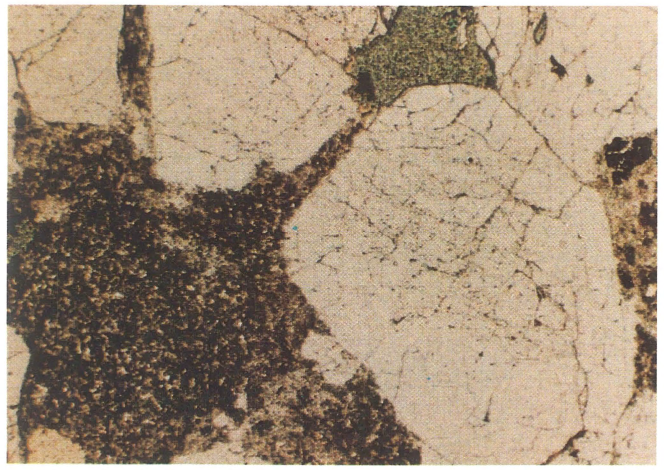


B. Pre-Variscan Carboniferous, coarse-grained, immature sandstone. Note grains of volcanic and metamorphic origin, formed during time when continent margin was activated. No. 5 in table 1.

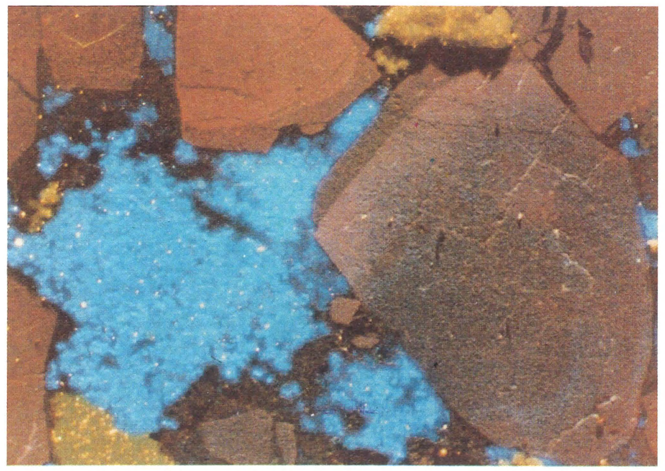
C. Westphalian D (Aguiró Fm.), coarse-grained, highly immature sandstone. Grains are mostly phyllite and micaceous quartzite ('recycled orogen'). No. 6 in table 1.



D. Same as C, cathodoluminescence image. Quartz grains show brownish colours, indicating metamorphic origin.



E. Stephanian (Malpás Fm.), coarse-grained sandstone. Large grains are all quartz, dark matrix is altered feldspar (kaolinised). No. 7 in table 1.



F. Same as E, cathodoluminescence image. Note reddish colours, indicating volcanic origin of quartz (postorogenic volcanism, in this case).

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PLATE I
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PLATE II
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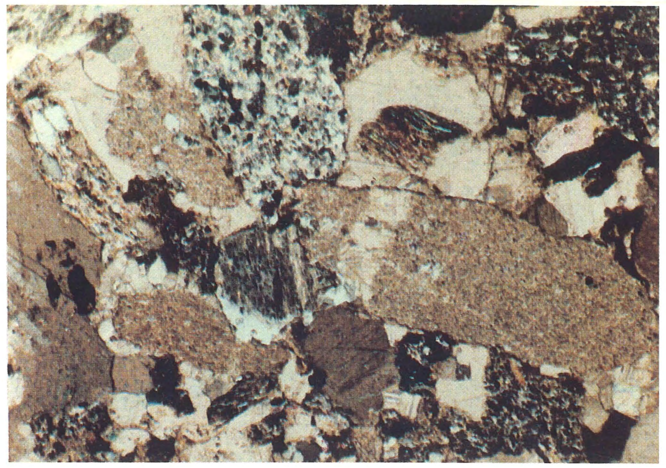
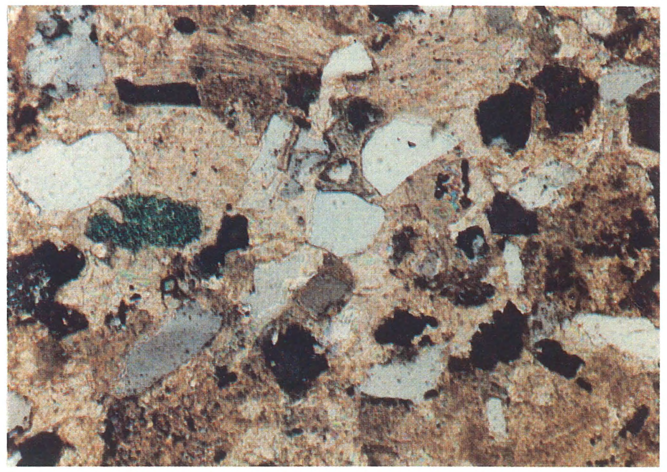
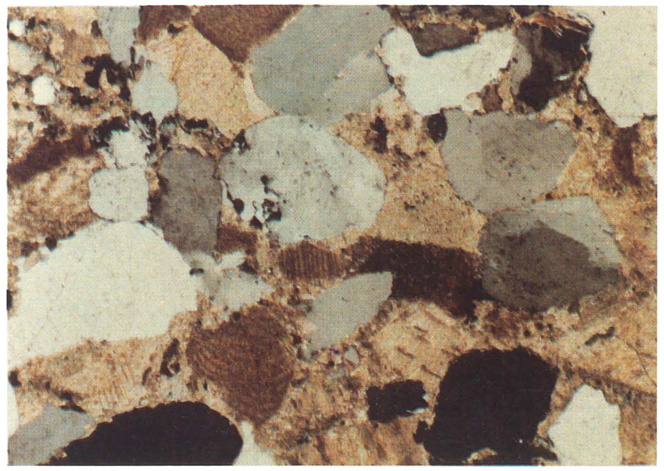


G. Permian (Peranera Fm.), medium-grained, highly immature lithic sandstone. Note carbonate and micaceous quartzite grains, both derived from exposed Palaeozoic ('recycled orogen'). No. 8 in table 1.

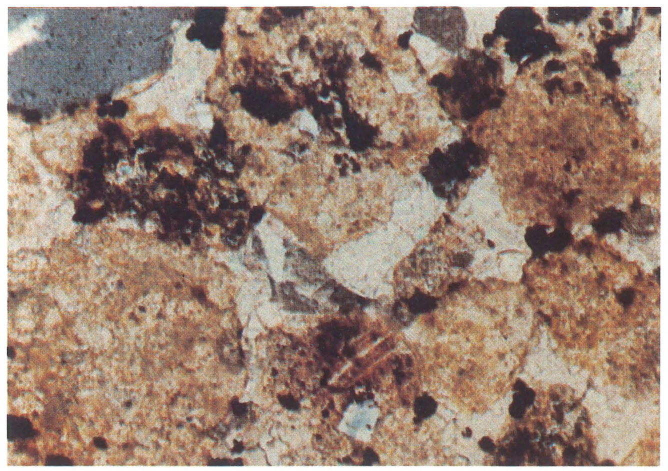
H. Triassic (Bunter Fm.), medium grained, mature quartz sandstone. The large micas were probably derived from the first exposed Axial Zone granodiorites (Figs. 1, 2). Variscan orogen was largely peneplained at this time. No. 9 in table 1.



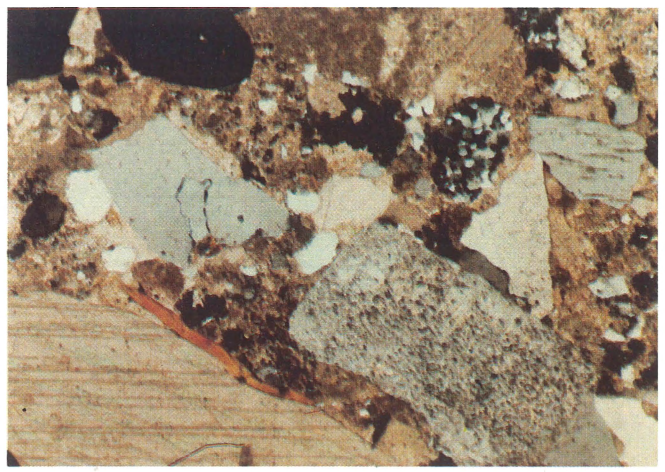
I. Campanian (Vallcarga Fm.), fine-grained, mixed origin sandstone. Quartz is terrigenous, carbonate debris (and glauconite) are intrabasinal. No. 12 in table 1.



J. Maastrichtian (Arén Sst.), medium-grained, mixed origin sandstone. Terrigenous quartz, as in the sandstone on the left (I), was derived from SE sources. Intrabasinal carbonate grains are of shallow marine origin. No. 13 in table 1.



K. Paleocene (Tremp Fm.), medium-grained, highly immature lithic sandstone. Carbonate grains are extrabasinal, derived from Mesozoic carbonates then covering the Axial Zone (Figs. 1,2). No. 14 in table 1.



L. Early Eocene (Montllobat Fm.), coarse-grained, highly immature sandstone. Note large feldspar grain, probably from Axial Zone granodiorites (Figs. 1, 2) and mostly extrabasinal carbonate grains. No. 15 in table 1.

and even became emergent locally. Rates of subsidence during this time were highly variable (Souquet 1967). The environments gradually evolved into shallow marine carbonates with bioclastic limestones and subordinate marls in the transgressive Late Cenomanian, and later locally into a well-developed reef facies in the Coniacian (Nagtegaal 1972).

In the Late Cenomanian a deep-water turbidite basin had already formed in the Northern Pyrenees. In the Southern Pyrenees increased rates of subsidence and deepening started only in the Santonian and the development of a turbidite facies with dominant west-directed paleotransport began in the Campanian (Van Hoorn 1970, Nagtegaal 1972). The Vallcarga Basin, which was probably connected across the area of the Central Pyrenees with the North Pyrenean turbidite basins and which was strongly segmented, then formed (Fig. 2). The southward shallowing against the Ebro Massif, in Santonian time, is well documented (Llompart 1979).

The Maastrichtian is regressive. The Arén Sandstone shoreline facies of this age prograded into the South-Central Pyrenees from the south-east with probably the last supply of terrigeneous clastics from southern directions (Nagtegaal et al. 1982).

The deposits directly overlying the Arén Sandstonee, the terrestrial clastics of the Tremp Fm., indicate a dramatic switch of source area: they were derived from the north-east, where the Iberian plate had first collided with stable Europe. The resulting uplift led to the erosion of the widely developed blanket of Mesozoic carbonates (Nagtegaal et al. op. cit.).

Detrital Modes. The gradual regional change in paleogeography involving a switch to northward and westward oriented depositional gradients during the Mesozoic is reflected in the petrography of the sandstones (Table 1, Nos. 10-13; Plate II, I & J). A general characteristic of these sandstones is that they are nearly all rich to very rich in intrabasinal carbonate fragments (L_{ci}). These are all carbonate fossil fragments, micritised grains, and intra-clasts taken together.

The Albian sandstones from Bonanza (San Martin Fm., Table 1, No. 10) have only rare feldspar while the quartz grains are a little diagnostic mixture of mainly bluish and some brownish luminescing types. The source of the terrigeneous components of these sandstones is not clear. The clastics supplied from southern sources are rather similar from the Santonian onwards. The Santonian 'clastic horizon' in the Montsec, the Vallcarga turbidites at Pobla de Segur and the Arén Sandstone in the Tremp-Isona area are all characterised by 70-80% of bluish and 20-30% brownish luminescing quartzes with often a few percent of deep violet quartz, and feldspars in the finer fractions. This apparently is the typical assemblage supplied by the Ebro Massif in the south (Table 1, Nos. 11-13).

The sandstones of the Paleocene Tremp Formation contain extraordinarily large amounts of lithics which are nearly all composed of Mesozoic limestones (Table 1, No. 14; Plate II, K). They mark the very first signs of the emergence of the new, Tertiary Pyrenees which started with the Late Cretaceous collision of Iberia with Europe.

The Tertiary deltaic to deeper marine basin-filling sequences

As in the Late Cretaceous basin, sedimentation in the Tertiary basin was syntectonic (Nijman & Nio 1975). This is also directly evident from the geological map: the basin can be readily subdivided into three compartments which are separated by important structural elements active during sedimentation. These basin compartments are the Tremp-Graus, the Ainsa and the much larger Jaca-Pamplona basins (Fig. 2). They are separated by the western boundary fault of the Central South Pyrenean detachment structure (first two basins) and the Boltaña anticline between the second and the third basin (Fig. 2).

An important regional transgression in the South-Central Pyrenees brought the terrestrial sedimentation of the Paleocene Tremp Formation to a halt and a limestone sequence of strongly variable thickness followed by Early Eocene shallow marine to marine bay facies marls (Ager Group) were deposited (Fig. 5).

During this time (Early Eocene), large nappe structures were emplaced (Seguret 1972). On the Central-South Pyrenean Nappe the continuing sedimentation was strongly affected by the tectonics and a westward prograding delta developed (Montllobat Formation Fig. 5). Compression and uplift in the Axial Zone of the Pyrenees, which had caused these movements, resulted somewhat later in the supply of large quantities of coarse clastics and the formation of southwards prograding fan deltas.

The deltaic facies of the Montllobat Formation did not extend westwards into the Ainsa and Jaca-Pamplona basins (which are on the Gavarnie Nappe). Instead, a contemporaneous deep water turbidite facies (Vicente Fm., Hecho Group; Table 1, Nos. 18, 19) characterised these basins (Nijman & Nio 1975).

The Early Eocene paleotransport directions are very complex and therefore cannot be considered here in detail. Only the general provenance of the clastics will be discussed.

Detrital Modes. A general characteristic of the Early Eocene (and locally the Oligocene) sandstones is the high content of extrabasinal carbonate lithics (L_{ce}) which, as in the Paleocene Tremp Fm., are largely derived from Mesozoic carbonates presumably still covering parts of the Central Pyrenees, and also from exposed parts of the nappe structures themselves (Table 1, Nos. 15-20; Plate II, L). The non-carbonate fraction of the Early Eocene (and Oligocene) sandstones consists largely of quartz and feldspars of approximately the same grain-size range.

The feldspar content is typically high. The only sources that can be readily identified for these feldspars are the Late Carboniferous granodiorites and the metamorphic complexes in the central and eastern part of the Axial Zone of the Pyrenees (Fig. 1). A high content of blue-luminescing quartz, thought to originate from igneous rocks (Zinkernagel 1978), suggests that quartz supply was dominantly from the granodiorites.

C. The post-Pyrenean group of basin-filling sequences

These sequences, which are of Late Eocene and Oligocene age, represent deposits which formed after the main, Pyrenean, orogenic phase. In the area of study they are mostly alluvial fan conglomerates (Collegats Conglomerates, Fig. 5) which are prominent in the landscape with their characteristic steep and vertical cliffs.

The composition of these conglomerates and the paleotransport directions indicated by the many current structures leave no doubt as to supply from the north, often locally influenced in direction by the pronounced paleorelief marking the basal unconformity.

Late Eocene and Oligocene sedimentation reach their maximum development further south, in the Ebro Basin, in the form of thousands of metres thick lacustrine, partly evaporitic sequences.

Detrital Modes. The sandstones of the Collegats Conglomerates are again very immature, with high contents of lithics. These lithics vary strongly in composition from dominantly carbonates (L_{ce}) of usually strictly local supply to dominantly siliciclastics with rock types from the Cambro-Ordovician to Bunter red beds, all widely exposed to the north. The luminescence of the quartz grains, and the feldspar content, are similar to those in the Early Eocene sandstones discussed earlier.

Tectonic regimes and sedimentation

The foregoing analysis of facies and sandstone petrography forms an important element in the reconstruction of the geodynamic history of the area of study and its control on sedimentation.

Cambro-Ordovician to end Devonian facies and sandstone petrography would agree well with a model of a passive margin on the north side of the proto Iberian plate. Terrigenous supply was dominantly from a stable cratonic area to the south.

Mineralogical maturity peaked in the Devonian and the craton by that time may have been considerably worn down. The dramatic change in sandstone petrography to immature assemblages with volcanic and metamorphic admixture in the pre-Variscan Carboniferous indicates that during this time the passive northern margin of the Iberian plate was converted into an active, margin the nature of which cannot be deduced from present data. Northward drift of Iberia finally resulted in collision with the European continental plate to the north, and the development of the Variscan Pyrenees (Ziegler 1984). Clastic dispersal patterns, initially originating from southern directions, now switched around to supply from northern sources as a result of the emerging mountain chain (Westphalian D, Aguiró Fm., Table 1, No. 6; Plate I, C). This new dispersal pattern persisted into the Triassic with Bunter supply, in the area of study, still from the north.

During the Mesozoic, with its important development of carbonate platform facies, the supply directions gradually turned around again with terrigenous clastics starting to come from the Ebro High in the south. The southern source areas remained active until the Maastrichtian (Arén Sandstone, Table 1, No. 13; Plate II, J).

In the Paleocene, directly after the Late Cretaceous collision of the Iberian plate with stable Europe in the area of the North Eastern Pyrenees, the dispersal system was once again drastically changed. Supply was now initiated from the uplifted Mesozoic carbonates in the newly emergent Tertiary Pyrenees (Tremp Formation, Table 1, No. 14; Plate II, K).

These Mesozoic carbonates remained an important source and are responsible for the high percentages of carbonate lithics in the Eocene and, locally, in the Oligocene sandstones. The siliciclastic components in these sandstones, mainly quartz, ever present feldspars, and a wide range of low-grade metamorphic lithics were supplied by the lithologies of the Central Pyrenees (Late Carboniferous granodiorites, and Cambro-Ordovician to Bunter strata).

The dispersal system which had its beginnings in the Paleocene became very important in the Eocene and Oligocene, taking care of much of the clastic infilling of the southern foreland basins (Tremp-Graus, Ainsa, Jaca-Pamplona, and Ebro Basins, Fig. 2). Although the same Tertiary dispersal system is essentially still intact, accumulation in the foreland basins has now largely ceased and the Pyrenean clastic debris of the studied area is transported further onwards, to the Ebro delta.

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