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The South Pyrenean Eocene carbonate megabreccias revisited: new interpretation based on evidence from the Pamplona Basin

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Abstract

The South Pyrenean Foreland Basin contains numerous units of Eocene carbonate megabreccias intercalated with siliciclastic turbidites and derived by resedimentation of shallow-marine carbonate platforms. Previous studies were limited mainly to the foreland eastern part, known as the Jaca Basin. The present study from the Pamplona Basin, a western part of the foreland trough, sheds new light on the origin and regional significance of these South Pyrenean Eocene carbonate megabreccias (SPECMs). The number of the SPECM units in the foreland basin is higher than previously recognized and their age is somewhat older than originally assumed. The SPECM units appear to occur as time–stratigraphic clusters, which can be correlated with the relative sea-level lowstands and linked with phases of tectonic activity. The megabreccias were derived from a carbonate-platform system hosted by the foreland basin's southern (passive) margin. The episodic instability and mass wasting were triggered by phases of structural steepening (forebulge uplift) accompanied by high-magnitude earthquakes, with the former causing platform emergence, increased load stresses and excess pore-water pressure in the carbonate ramp. The SPECM deposits were emplaced by cohesive debris flows evolving into high-density turbidite currents. An ideal SPECM unit consists of (1) an immature, homogeneous debrite in the proximal part; (2) a differentiated, bipartite debrite and turbidite in the medial part; and (3) an incomplete, base-missing debrite overlain by turbidite, or a turbidite alone, in the distal part. The debrite component volumetrically predominates in the SPECM units, and the original terms 'megaturbidite' and 'seismoturbidite' thus seem to be inappropriate for these deposits.

Keywords: megabreccias; megaturbidites; debris flows; foreland basin; Eocene; Pyrenees

1. Introduction

The so-called South Pyrenean Eocene carbonate megabreccias (SPECMs) are among the most spectacular deposits of the Southern Pyrenean Foreland Basin. The origin of these extensive accumulations of carbonate debris has been attributed to the catastrophic events of resedimentation in a deep-water flysch trough. The scale of the mass-flow processes was impressive, as some of the breccia units have a strike-parallel lateral extent of more than 130 km and thickness of up to 200 m, with an estimated volume of 200 km^3. Equally impressive is the size of the component clasts, some reaching several hundreds of metres in length. Importantly, the SPECM units contain gas accumulations and are isochronous lithostratigraphic markers that provide important clues to

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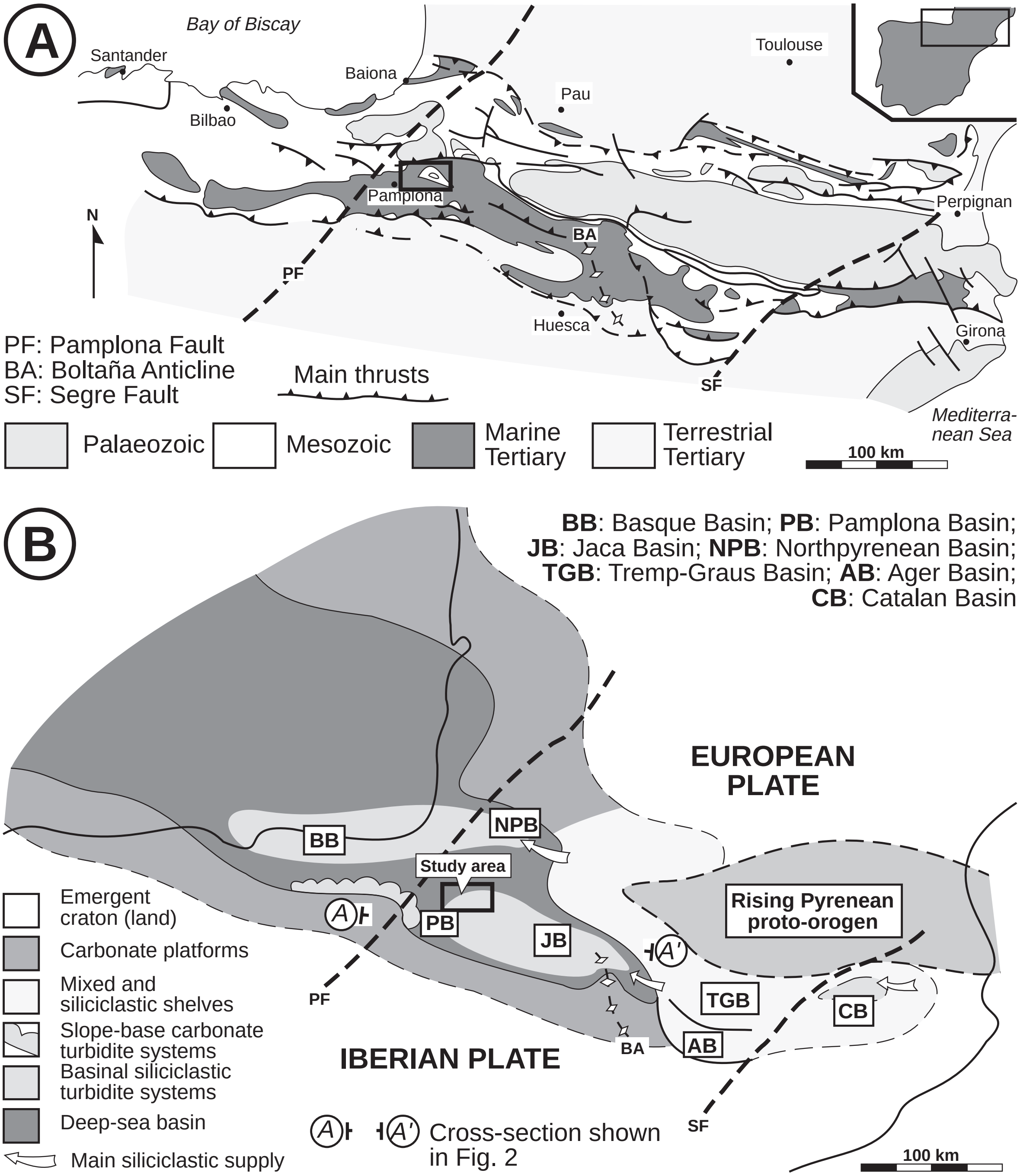


Fig. 1. (A) Simplified geological map of the Pyrenees. (B) Early–Middle Eocene palaeogeographic reconstruction of the Pyrenean domain, with the different depocentres (sub-basins) referred to in the text. The study area location is shown in each map. Compiled from Seguret (1972), Plaziat (1981), Labaume et al. (1985), Muñoz (1992), Verges et al. (1995), and our own data.

the geodynamic evolution of the basin. Therefore, the SPECMs have attracted the attention of many researchers (e.g., Ten Haaf, 1966; Ten Haaf et al., 1971; Mutti et al., 1972; Puigdefábregas et al., 1975; Rupke, 1976a,b; Johns et al., 1981; Labaume et al., 1983, 1985, 1987; Seguret et al., 1984; Cámara and Klimowitz, 1985; Puigdefábregas, 1986; Rosell and Wieczorek, 1989; Barnolas et al., 1992; Barnolas and Teixell, 1994). However, many crucial aspects of the SPECMs remain unsolved or controversial. The purpose of the present paper is to review some of the controversial issues and to discuss the origin and geological significance of the SPECMs in the light of new field evidence.

Most of the previous studies of the SPECMs were carried out in an area commonly referred to as the Jaca Basin, between Jaca and the Roncal Valley (Fig. 1), where these deposits are best exposed. The present study has been focused on the westernmost part of the South Pyrenean Basin, a zone referred to here as the Pamplona Basin (after Payros, 1997). The tectonic deformation in this area is less intense than in the Jaca Basin, which renders the lateral development of the SPECMs and their interfingering with the surrounding deposits much easier to investigate. Furthermore, the preservation of microfossils in the Pamplona Basin is much better, which allows a reliable palaeontological zonation of the sedimentary succession based on planktic forams.

2. Regional setting

The Pyrenees are a collision mountain belt formed by the N–S convergence of the European and Iberian cratonic plates in the Santonian–Early Miocene time (Muñoz, 1992). This orogenic belt consists largely of a series of E–W-trending fold/thrust systems with both southward and northward vergency. Superimposed on this structural trend are major NE–SW fault lines, such as the Segre and Pamplona faults (Fig. 1A), which have influenced the fold-belt development.

The tectonic deformation was diachronous due to an oblique plate convergence, commencing in the east and propagating westwards. This development is reflected clearly in the palaeogeographic evolution of the basinal area (Mutti et al., 1985; Puigdefábregas and Souquet, 1986; Puigdefábregas et al., 1992). The rate of tectonic shortening reached a maximum of 4.5 mm/yr during Early–Middle Eocene time (Verges et al., 1995), when the Pyrenean area was characterized by the following palaeogeographic domains (Fig. 1B).

(1) The Tremp–Graus and Ager basins — 'piggyback' depocentres developed on top of the allochthonous South Pyrenean Central Unit, comprised of the Monsec, Cotiella and Sierras Marginales thrust sheets (Seguret, 1972; Ori and Friend, 1984). These basins accumulated terrestrial and transitional-marine siliciclastic deposits, derived mostly from the rising orogen.

(2) The Jaca, Pamplona, Catalan and North Pyrenean basins — typical foreland depressions flanked by active thrust sheets on the hinterland side and carbonate platforms on the cratonic margin. These basins first accumulated turbidites (underfilled 'flysch' stage) and then transitional-marine and terrestrial deposits (overfilled 'molasse' stage).

(3) The Basque Basin — a depression west of the Pamplona Fault, at the transition to the remnant oceanic basin of the Bay of Biscay. It accumulated deposits of large-scale turbiditic systems and remained a deep-water basin until at least Oligocene time.

The SPECMs discussed here occur in the Jaca and Pamplona foreland basins, but similar deposits have been reported from the Catalan Basin (Rosell and Wieczorek, 1989) and the Basque Basin (Pujalte et al., 1997).

3. Lithostratigraphic succession

The lower Palaeogene sedimentary succession in the Jaca and Pamplona basins can be divided into three major units, or 'suites', representing main stages of the basin tectonostratigraphic evolution (Fig. 2). The following description focuses on suite 2, which contains the SPECMs, whereas suites 1 and 3 are only briefly described.

The pre-foreland suite 1 (Palaeocene–lowest Eocene) includes some terrigenous deposits (Tremp Group), but consists mainly of shallow-marine limestones (Ager Group). The limestones were deposited during a prolonged, punctuated transgression, which

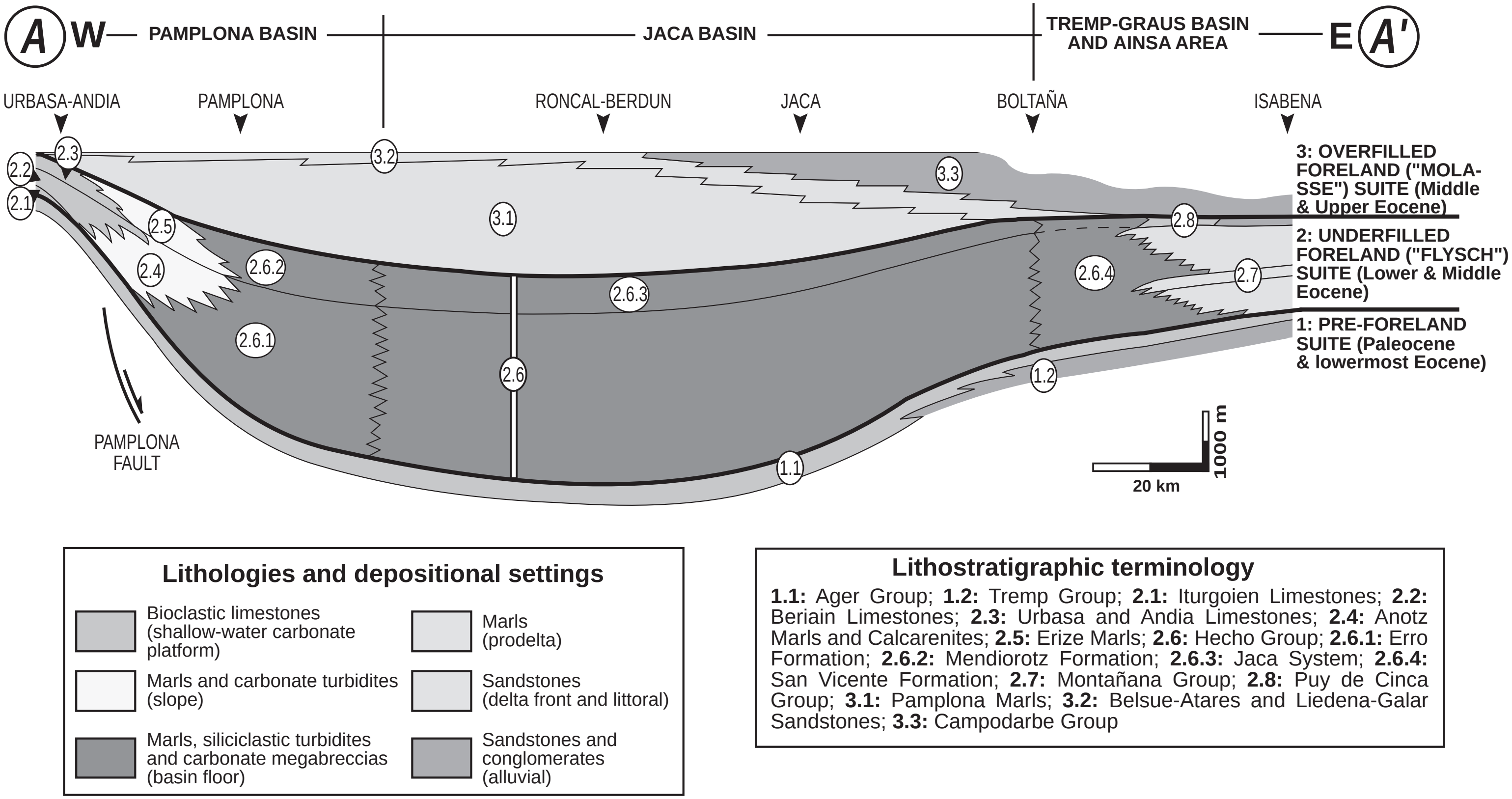


Fig. 2. Restored longitudinal cross-section through the Southern Pyrenees showing the lower Palaeogene lithostratigraphic succession (for location, see Fig. 1B). Based on Mutti et al. (1972, 1985), Puigdefábregas et al. (1975), and our own data.

culminated in the early 'Ilerdian' (latest Paleocene–earliest Eocene), when the bulk of the so-called Alveolina Limestone was deposited throughout most of the South Pyrenean domain. Suite 1 was formed during a period of relative tectonic stability (Puigdefábregas and Souquet, 1986; Verges et al., 1995), as is indicated by the great lateral extent and the uniform thickness and facies of the deposits (Fig. 2). Suite 3 (Middle and Upper Eocene) is an overfilled foreland-basin 'molasse', including the prodeltaic Pamplona Marls Formation, the deltaic Belsue-Atares and Liedena-Galar formations and the fluviatile Campodarbe Group (Fig. 2). These component units are diachronous and represent the late-stage infilling of the foreland basin.

Suite 2 (Lower and Middle Eocene) is an underfilled foreland 'flysch', whose thickness and facies show considerable lateral variation, reflecting active tectonics and the differences in coeval sedimentary systems (Fig. 1B). An important component facies of suite 2 are shallow-water limestones representing carbonate platforms of the southern, cratonic margin of the foreland basin. The development of these platforms varied laterally. Those located south of the Jaca Basin were subject to a punctuated backstepping related to the southwards migration of the foredeep trough (Barnolas et al., 1992; Barnolas and Teixell, 1994), whereas those in the western part of the Pamplona Basin (the Iturgoien, Beriain, and Urbasa-Andia Limestone formations) (Fig. 2) had first prograded and then retrograded, probably due to 2nd-order relative sea-level changes (Payros, 1997). Interestingly, the same pattern of progradation and retrogradation is observed in the slope deposits of these carbonate platforms (the Anotz and Erize formations) (Fig. 2).

The most representative lithostratigraphic unit of suite 2 is the Hecho Group (Mutti et al., 1972), a thick accumulation of siliciclastic turbidites and hemipelagic marls, referred to broadly as the 'background deposits' in the present paper. These turbidites were deposited by the westward axial currents derived from the shallow-marine and deltaic systems of the Montañana Group (Fig. 1B, Fig. 2), recording the incipient infilling of the South Pyrenean foredeep. The feeding palaeochannel system of the Hecho Group, at the transition between the Jaca Basin and the Tremp–Graus Basin (Ainsa area) has been distinguished as the San Vicente Formation (Van Lunsen, 1970), whereas the coeval succession in the Jaca Basin has been divided into four principal turbiditic units (Mutti et al., 1985). Similarly, the sedimentary succession in the Pamplona Basin has been divided into the Erro Formation (upper Ypresian–middle Lutetian) and the Mendiorotz Formation (upper Lutetian–lower Bartonian). The former is typified by a thickening- and coarsening-upward trend and the latter by a thinning- and fining-upward trend, reflecting, respectively, a progradation and subsequent retrogradation of the turbiditic system (Payros, 1997).

The SPECMs occur as intercalations in the Hecho Group and have previously been studied in the Jaca Basin by numerous authors (Ten Haaf, 1966; Ten Haaf et al., 1971; Mutti et al., 1972; Puigdefábregas et al., 1975; Rupke, 1976a,b; Johns et al., 1981; Labaume et al., 1983, 1985, 1987; Seguret et al., 1984; Cámara and Klimowitz, 1985; Puigdefábregas, 1986; Rosell and Wieczorek, 1989; Barnolas et al., 1992; Barnolas and Teixell, 1994). Based on the new data from the Pamplona Basin, the present study addresses some of the crucial aspects of the SPECMs that require clarification, namely the number, age, provenance and origin of these breccia units. A new, revised facies model for the SPECMs is also suggested.

4. The number of SPECMs

Nine units of Eocene megabreccia were recognized by Labaume et al. (1983, 1985, 1987) in the Jaca Basin. Each was given a specific name and a code symbol, from MT-1 (the oldest) to MT-9 (the youngest). According to the latter authors, only two of these megabreccia units, MT-4 and MT-5, were expected to extend westwards into the Pamplona Basin.

Our observations from the Pamplona Basin demonstrate, however, the occurrence of at least seven units that qualify as megabreccias (Figs. 3 and 4). In an ascending stratigraphic order, they have been named the Uritz, Espotz, Berrondo, Antxoritz, Orbaitz, Zalba and Irotz units, with code symbols SPECM-a to SPECM-g. Their details, including thickness and lateral extent, are summarized in Ta-

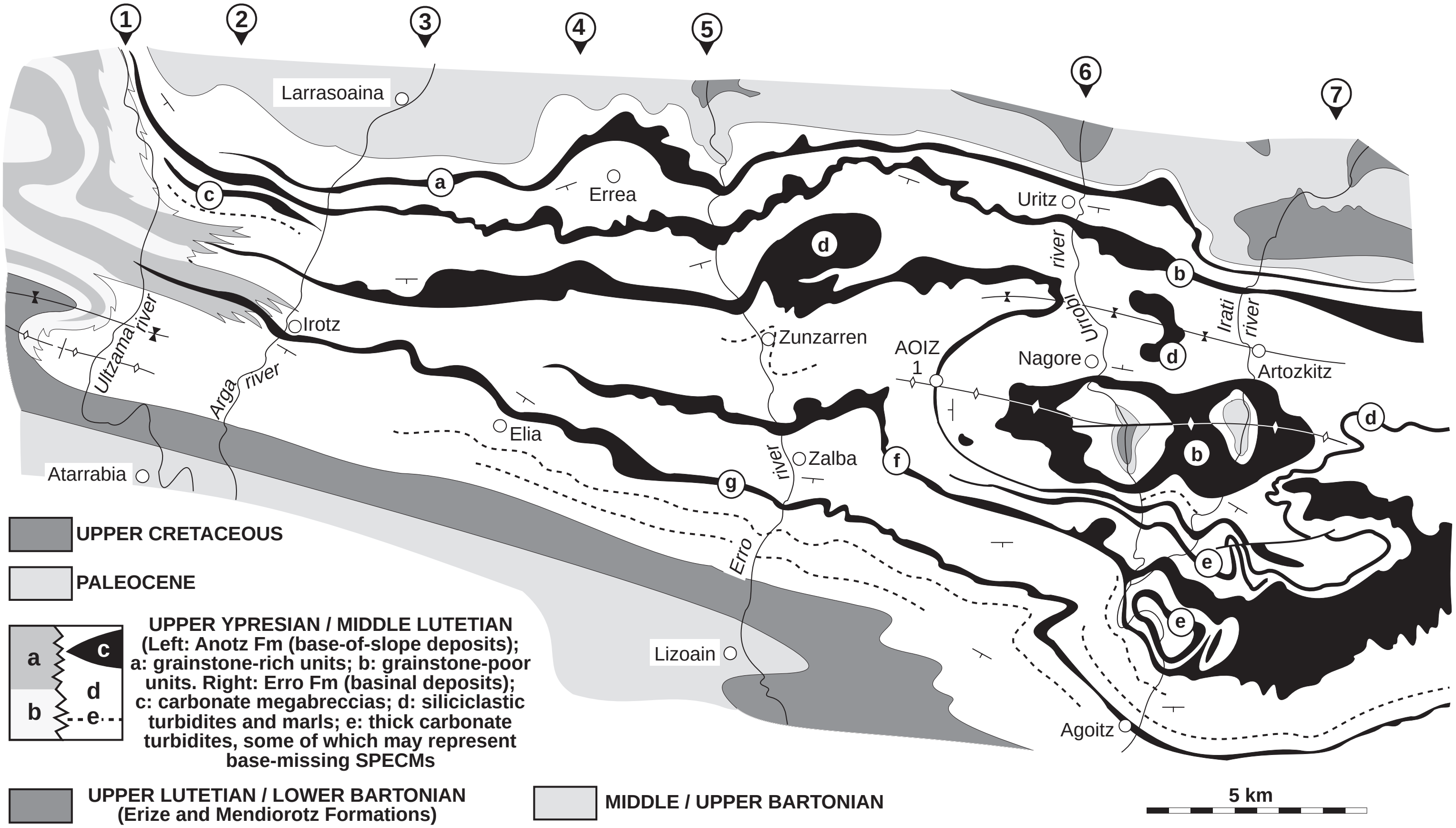


Fig. 3. Geological map of the Pamplona Basin (see location in Fig. 1). The SPECMs are shown in black, with the corresponding letter code as used in the text. Numbers *1* to *7* indicate the stratigraphic sections studied. Modified from Payros (1997).

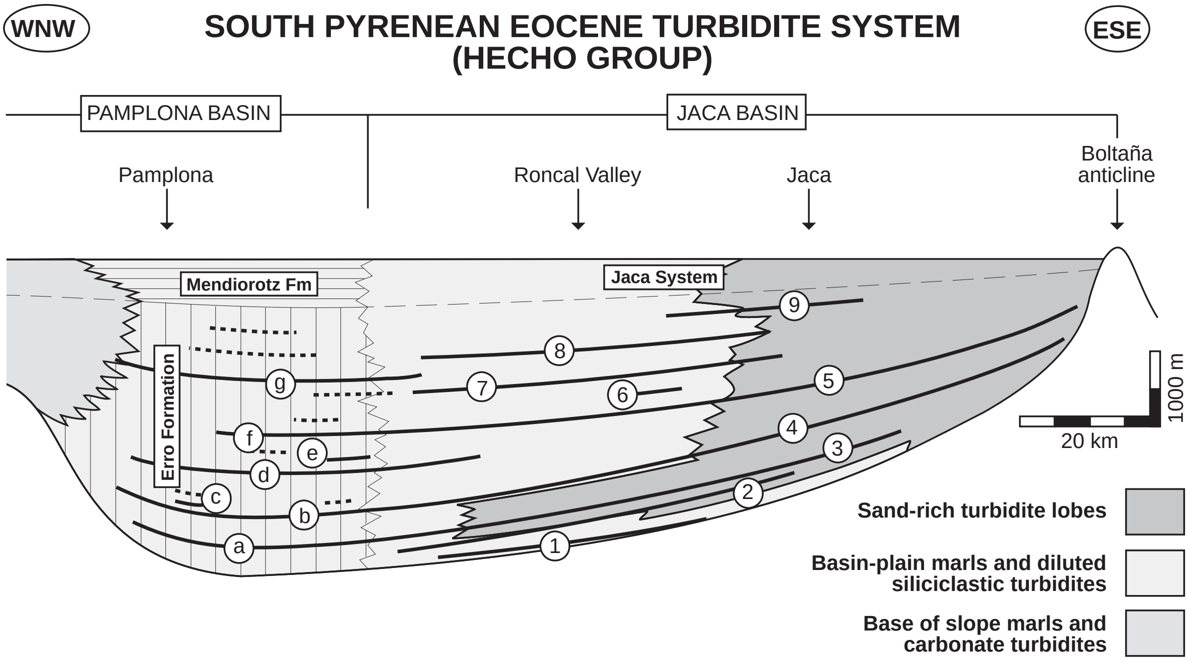


Fig. 4. Restored cross-section of the Hecho Group in the Jaca and Pamplona basins, showing the component formations, depositional systems and the relative position and extent of the SPECM units (shown by the solid black lines with letter/number code; the dashed lines indicate thick carbonate turbidites that may be base-missing SPECM units).

ble 1. A comparison of our map (Fig. 3) with that of Labaume et al. (1987, their fig. 4) indicates that the MT-4 and MT-5 units in the Jaca Basin correspond to the units SPECM-b and SPECM-f in the Pamplona Basin. According to Labaume et al. (1987), unit MT-3 pinches out in the Jaca Basin, whereas our observations indicate that the unit extends westwards into the Pamplona Basin, where it is represented by unit SPECM-a.

Taken together, the evidence from mapping shows at least 13 megabreccia units in the South Pyrenean foreland basins, a greater number than formerly assumed. Three of these units (MT-3/SPECM-a, MT-4/SPECM-b and MT-5/SPECM-f) have a very wide lateral extent, of 110 to 135 km in strike-parallel sections (Fig. 4, Table 1), corresponding almost to the total length of the Jaca and Pamplona basins. The other ten megabreccia units are of somewhat smaller lateral extent (Fig. 4, Table 1), limited to either the Jaca Basin (six units) or the Pamplona Basin (four units).

In addition to these mappable SPECMs, there is a number of subordinate megabreccia intercalations in the Pamplona Basin (shown by dashed lines in Figs. 3 and 4). However, these are of relatively modest thickness and lateral extent, and are not taken into account in the present study.

5. The age of SPECMs

While the Ypresian–Lutetian age of the Hecho Group was firmly established already in the seventies (e.g., Puigdefábregas et al., 1975), little effort has been done to specify the more exact age of the SPECM intercalations. The only previous attempt was by Labaume et al. (1985), who analyzed calcareous nannofossils in the marly deposits below and above the megabreccias in the Roncal Valley and concluded that unit MT-1 was emplaced within the time span of biozone NP-12, units MT-2 and MT-3 within the time span of biozones NP-13 and NP-14, and units MT-4 to MT-9 within the time span of biozone NP-15. Labaume et al. (1985) admitted, however, that the nannofossils were scarce and poorly preserved.

Table 1
Summary of the sedimentary charactersitics of the individual SPECMs in the Pamplona Basin

MEGA-BRECCIA	LENGTH in E-W direction. *In Pamplona Basin* **Total (Pamplona and Jaca Basins)**	MAXIMUM THICKNESS Turbidite interval *Debrite interval* **Total**	MAX. % MATRIX in debrite (1b interval)	CLAST SIZE in debrite Largest *Dominant*	CLAST NATURE in debrite 1a: Clast-supported breccia; 1b: Mud-supported breccia Dominant - *Accesory*	PALAEO-CURRENTS S: sense D: direction *Structure, Site*
SPECM-g (Irotz)	*29 km* **> 30 km**	12 m *75 m* **87 m**	50-60 %	25 m *0.05 m*	**1a:** Nummulite packstones; Alveolina grainstones (variable in age, from Paleocene to Lutetian); bioclasts; *coarse-grained sandstones (upper Palaeocene?).* **1b:** Planktic and benthic microforaminifera bearing mudstones and wackestones	**SECM-g:** D and S: N-115°-E, N-120°-E *Groove casts and prod marks, near Irotz.* D: N-45°-E *Groove casts, between Elia and the Erro valley.* D: N-40°-E *Groove casts, Erro valley*
SPECM-f (Zalba)	*20 km* **~135 km**	17 m *75 m* **92 m**	40-70 %	40 m thick, 640 m long, 280 m wide. *0.5 m*	**1a:** Nummulite packstones; Ypresian calcarenites with Alveolinids and Nummulitids; algal and coralline boundstones (Palaeocene?); *coarse-grained sandstones; planktic foraminifera bearing marly limestones; bioclasts; background (flysch) sediments; fine-grained calcarenites.* **1b:** Slope-derived marly limestones; *marls; fine-grained packstones; bioclasts*	
SPECM-e (Orbaitz)	*7 km* **~7 km**	8 m *30 m* **38 m**	40-60 %	8 m *~1 m*	**1b:** Marly and micrite limestones; *carbonate turbidites; bioclasts*	
SPECM-d (Antxoritz)	*18 km* **> 20 km**	60 m *100 m* **125 m**	Up to 70 %	40 m thick, 200 m long, 100 m wide. *0.5 m*	**1a:** Nummulite calcarenites; grainstones with Ypresian Alveolinids; grainstones with Lutetian Alveolinids, Soritids and miliolids; *bioclasts, massive algal boundstones.* **1b:** Mudstones and wackestones; fine-grained, marly packstones; *marls; bioclastic turbidites; bioclasts*	**SECM-d:** D: N-90°-E *Groove casts, in the Arga valley and between the Arga and Erro valleys.* D and S: N-40°-E *Groove casts and prod marks, in the Irati valley.*
SPECM-c (Berrondo)	*3 km* **3 km**	3 m *21 m* **24 m**	30-50 %	25 m *0.5 m*	**1a:** Nummulite packstones; Alveolina grainstones, middle Ypresian in age; fine-grained calcarenites; *glauconite-rich calcarenites; algal boundstones and wackestones (Palaeocene?); bioclasts.* **1b:** Mudstones; fine-grained calcarenites; bioclasts; *bioclastic calcarenites*	
SPECM-b (Espotz)	*26 km* **~135 km**	14 m *190 m* **190 m**	50-95 %	40 m *~0.2 m*	**1a:** Nummulite packstones; Alveolina grainstones; fine-grained calcarenites; *marls.* **1b:** Mudstones and wackestones; *background (flysch) sediments; bioclasts*	**SECM-c:** S: N-90°-E *Recumbent slump fold, between the Arga and Ultzama valleys*
SPECM-a (Uritz)	*26 km* **~110 km**	**62 m**	50-90 %	2 m *0.3-0.8 m*	Fine-grained packstones; slope-derived mudstones and wackestones; bioclasts; *contorted fragments of carbonate turbidites; massive limestones and algal boundstones (Palaeocene?)*	

In contrast, the planktic foraminifera in the Pamplona Basin are abundant and generally well-preserved. We have sampled the hemipelagic marls directly below and above each SPECM unit. For comparative purposes, we have sampled also the cartographically correlated SPECMs in the Jaca Basin and the exact age of units MT-3 to MT-9 has been established (see Figs. 5 and 6; Appendix A). The new micropalaeontological evidence leads to a number of important conclusions.

Firstly, the SPECMs appear to be older than previously assumed. For example, the MT-3 and MT-4 in the Jaca Basin were originally placed by Labaume et al. (1985) within biozones NP-14 and NP-15, and should thus correspond to the *Subbotina frontosa*, *Truncorotaloides praetopilensis* and *Globigerinatheka subconglobata* biozones in planktic foraminifera scale, whereas the present data place unit SPECM-a/MT-3 around the boundary of biozones *Morozovella aragonensis* and *Morozovella caucasica*, and unit SPECM-b/MT-4 in biozone *Subbotina frontosa*. These discrepancies may be due to the poor quality of the nannofossils on which the original considerations were based.

Secondly, the data shed new light on the time–stratigraphic character of the SPECMs. Labaume et al. (1983) calculated that the time frequency of the episodes of megabreccia emplacement was ca. 500,000 years, assuming that the SPECMs were deposited at equal time intervals. Our data (Figs. 5 and 6; Appendix A) do not support these assumptions. The data demonstrate, in fact, a chronostratigraphic clus-

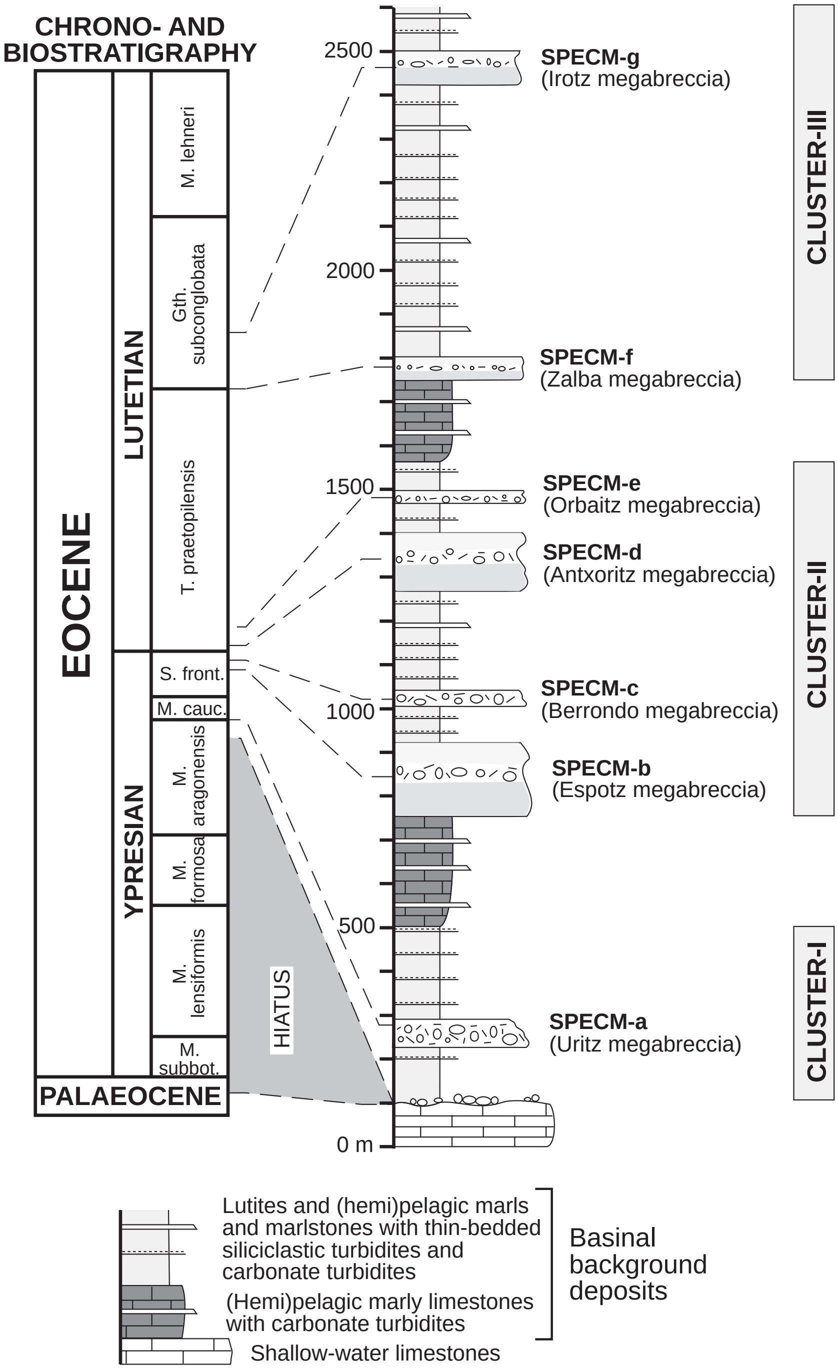


Fig. 5. Composite stratigraphic profile of the Pamplona Basin, showing the planktic foraminifera biozones, the vertical distribution of SPECMs and the types of background sedimentation. Note that the SPECM units are clustered in time–stratigraphic intervals dominated by siliciclastic 'background' sedimentation; the other intervals are dominated by fine-grained carbonate-rich facies.

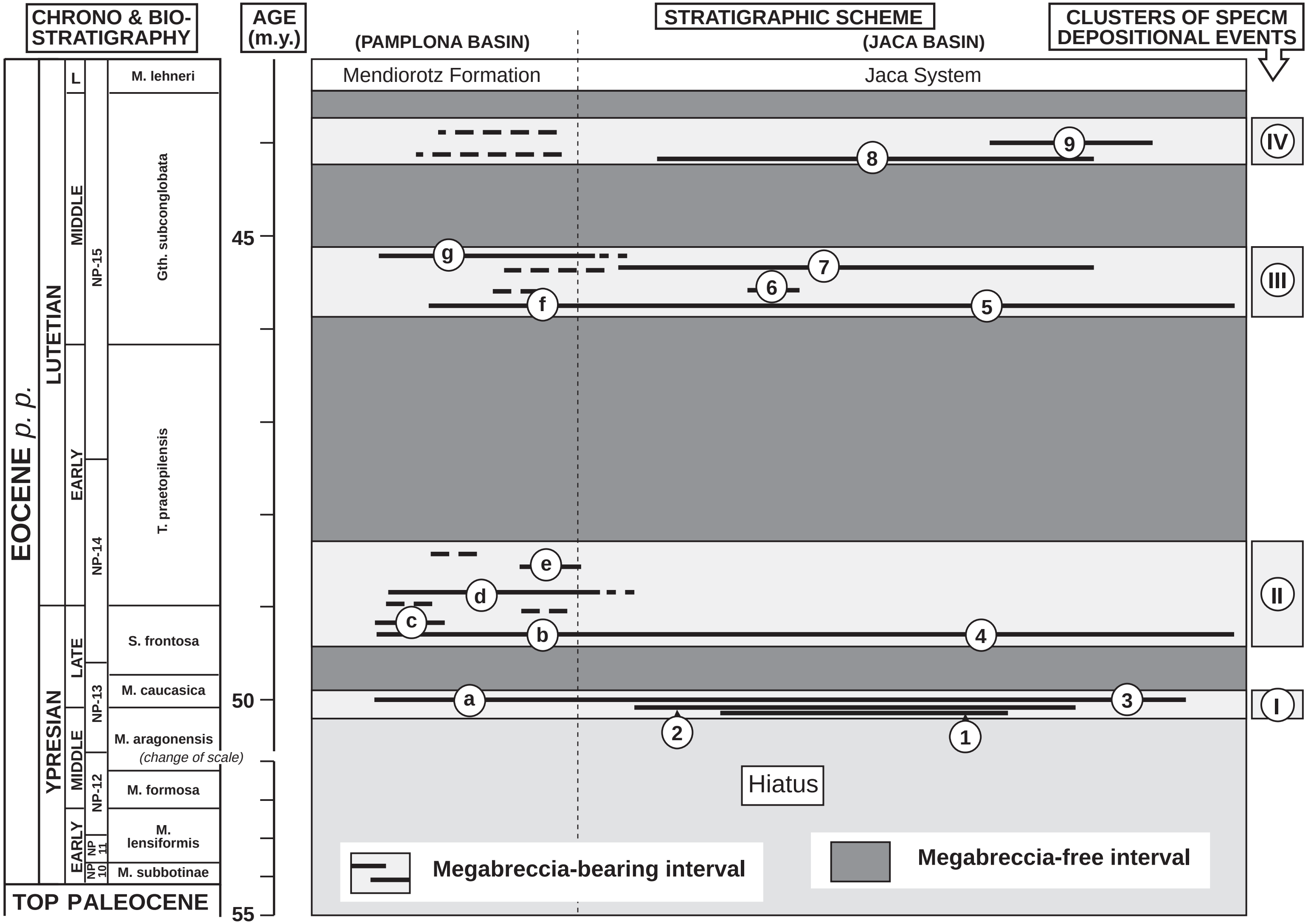


Fig. 6. Chronostratigraphic framework of the Hecho Group in the Pamplona and Jaca basins, based on planktic foraminifera (for details of the biostratigraphic zonation, see Appendix A). Note the correlation of the planktic foraminifera scale used in this study with the nannofossil biozonation used by Labaume et al. (1985) (for further explanation, see text).

tering for the SPECM emplacement episodes. These pronounced episodes of carbonate debris deposition, some of relatively short duration, are here referred to as clusters I to IV in their ascending order in the stratigraphic succession. It is also clear from the data that the duration of the intervening periods of turbiditic 'background' sedimentation was of the same order as that of the SPECM clusters themselves, and much longer in one case. As discussed further below, several lines of evidence suggest that the widespread emplacement of carbonate breccias was related to active tectonism, and temporal clustering of the SPECMs (Figs. 5 and 6; Appendix A) thus probably indicates an episodic nature of the tectonic activity.

6. Provenance

Although the character of the limestone debris in the SPECMs indicates clearly their derivation from contemporaneous shallow-water carbonate platforms, the actual location of these platforms has been a matter of considerable debate, mainly due to the scarcity of unambiguous palaeotransport indices.

In the Jaca Basin, Rupke (1976a,b) proposed a double source on the northern and southern margins of the flysch trough, based on the attitude of folds axes in the lower parts of the SPECM units, interpreted as 'slump sheets' (see below). In the same area, Johns et al. (1981), Labaume et al. (1983, 1985, 1987) and Seguret et al. (1984) used a variety of impact structures in the basal parts of the SPECM units to establish the palaeotransport directions and concluded that at least the MT-1 to MT-5 units were derived by the resedimentation of a coeval carbonate shelf developed along the northern, hinterland margin of the flysch trough. Those authors further suggested that the MT-6 to MT-9 units could be derived from the basin's southern margin, although such a provenance was well-established for unit MT-6 only. However, units MT-1 to MT-5 were considered to be the most typical SPECMs, and the provenance models were thus based mainly upon them. A northern provenance for the SPECMs was advocated also by Cámara and Klimowitz (1985) and Rosell and Wieczorek (1989). However, no relicts of a carbonate shelf are recognizable along the basin's northern margin, from which all Palaeogene deposits have been removed by later erosion.

More recently, Puigdefábregas (1986), Barnolas et al. (1992) and Barnolas and Teixell (1994) have suggested that the SPECMs in the Jaca Basin were derived from an extensive carbonate-platform system developed along the southern, cratonward margin of the flysch trough (see Fig. 1B). The supporting evidence includes some palaeocurrent directions based on flutes in unit MT-5, a northward-fining and -thinning trend in unit MT-3, and the occurrence of broad truncations in the southern margin's shallow-marine carbonate succession, considered to be a record of large-scale failures of the carbonate-platform margin.

In the Pamplona Basin, several lines of evidence point to a southern provenance for most, if not all, of the SPECMs. The evidence includes direct indicators (palaeotransport directions and lateral facies changes) and indirect ones (carbonate-platform backstepping, internal truncation surfaces and SPECM stacking pattern). The evidence is discussed in more detail below.

6.1. Palaeotransport

Directional structures are considered to be the most reliable indices of sediment dispersal pattern, and hence we have payed special attention to such features in the available outcrops. Unfortunately, directional structures are rare in the SPECMs in the Pamplona Basin. Merely eight measurements have been made, five in the basin's western part and three in the central and eastern parts, mainly on grooves and prod marks. These data, though insufficient for a statistical assessment, indicate sediment transport from the south or southwest (Table 1). Notably, the transport directions are consistently at a right angle to the margin of the southern carbonate platform, although the trend of this margin changes from ESE–WNW to nearly N–S across the Pamplona Fault (Fig. 7). Flutes are common in the siliciclastic turbidites of the 'background' facies, indicating clearly a westward transport along the basin axis (Fig. 7).

6.2. Lateral facies changes

The lateral variation of the SPECM units has been investigated in both strike- and dip-parallel

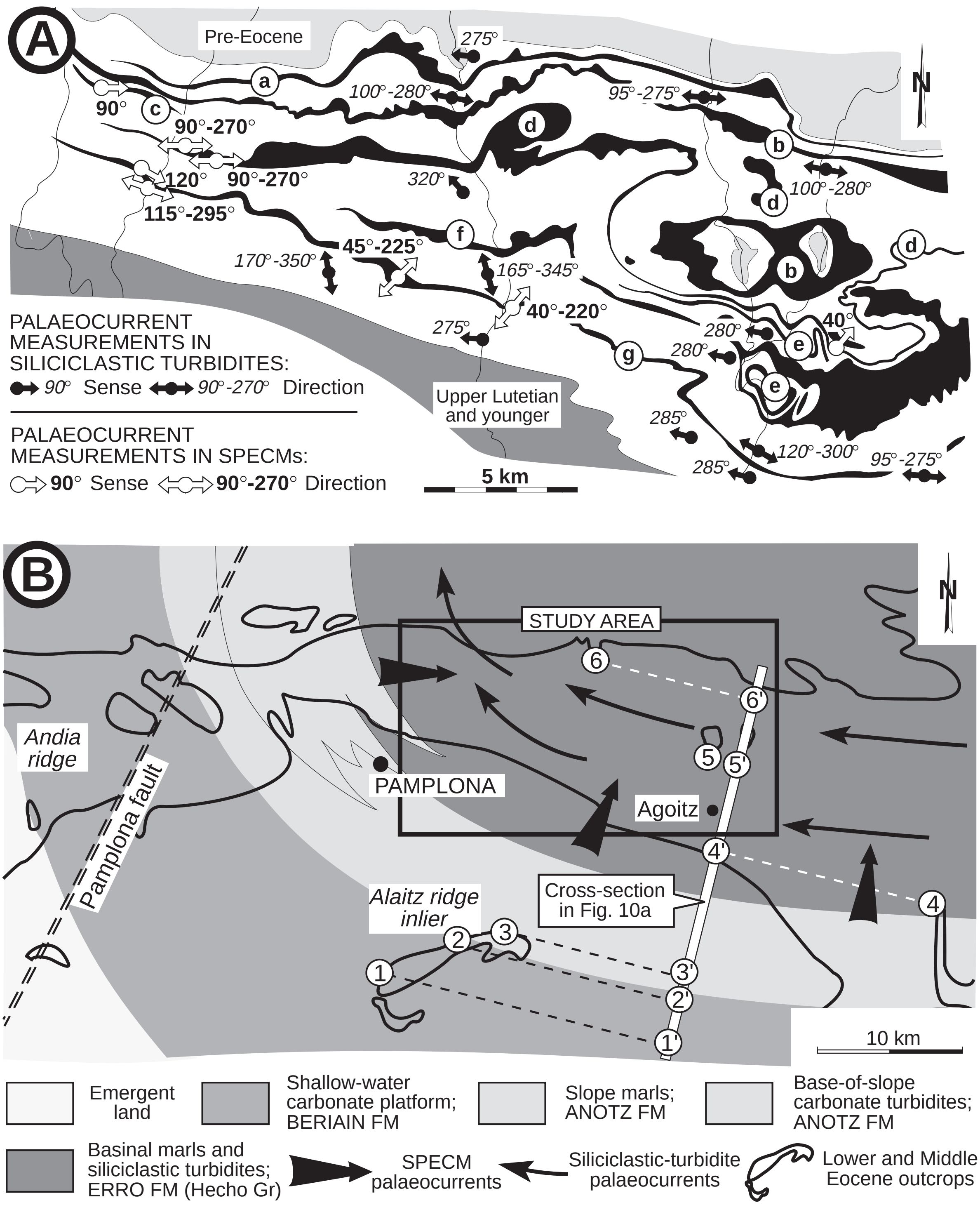


Fig. 7. (A) Graphic summary of the palaeocurrent data from the Pamplona Basin, including measurements of sole marks (flutes, grooves and prods) from SPECMs and siliciclastic turbidites (see also Talbe 1). (B) The Early–Middle Eocene palaeogeography and sediment dispersal pattern in the Pamplona Basin, reconstructed from outcrop facies and the palaeocurrent data above.

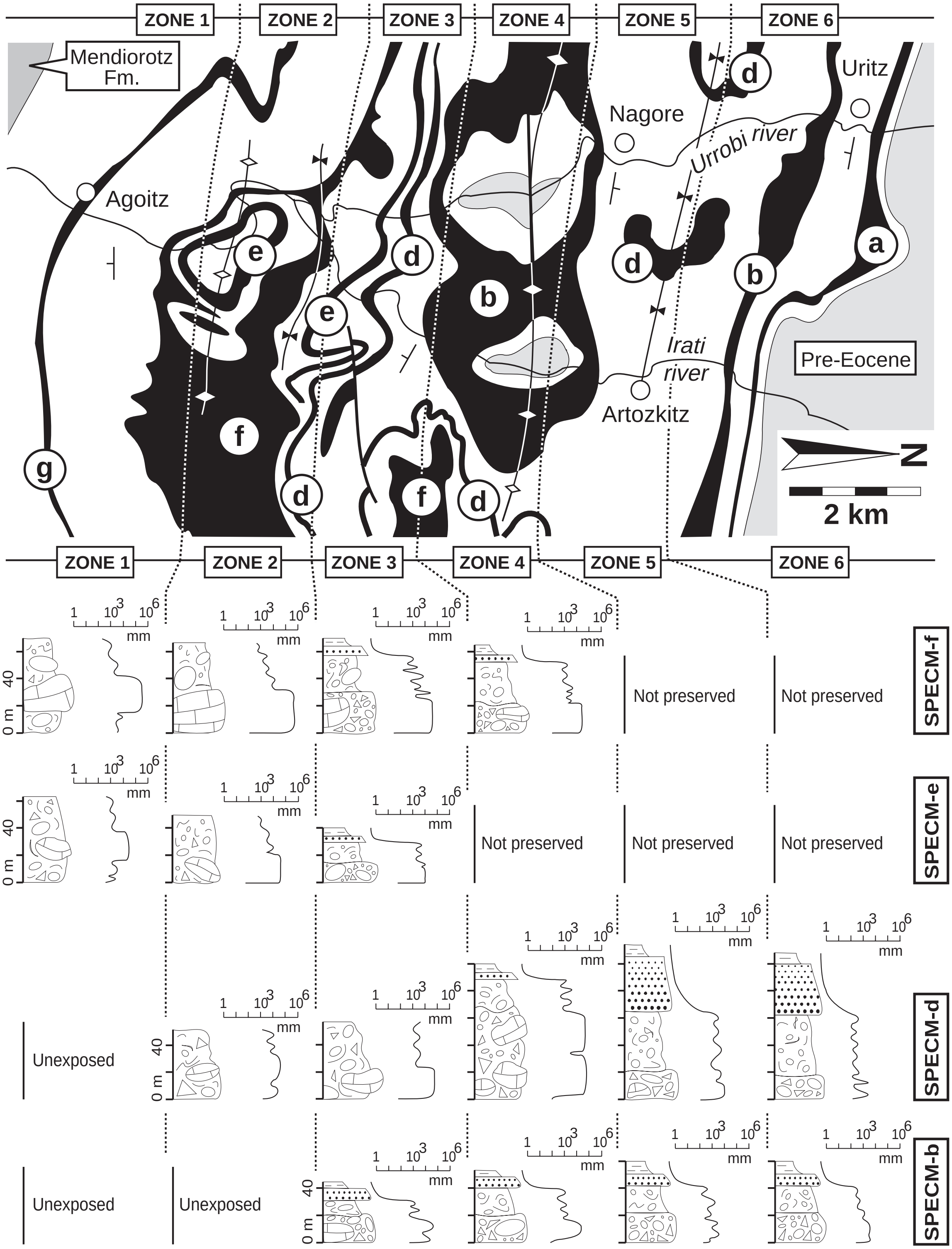


Fig. 8. Geological map of the eastern Pamplona Basin and representative logs of four SPECM units in different zones (1–6). Each log shows the vertical distribution of largest clast sizes. For further discussion, see text.

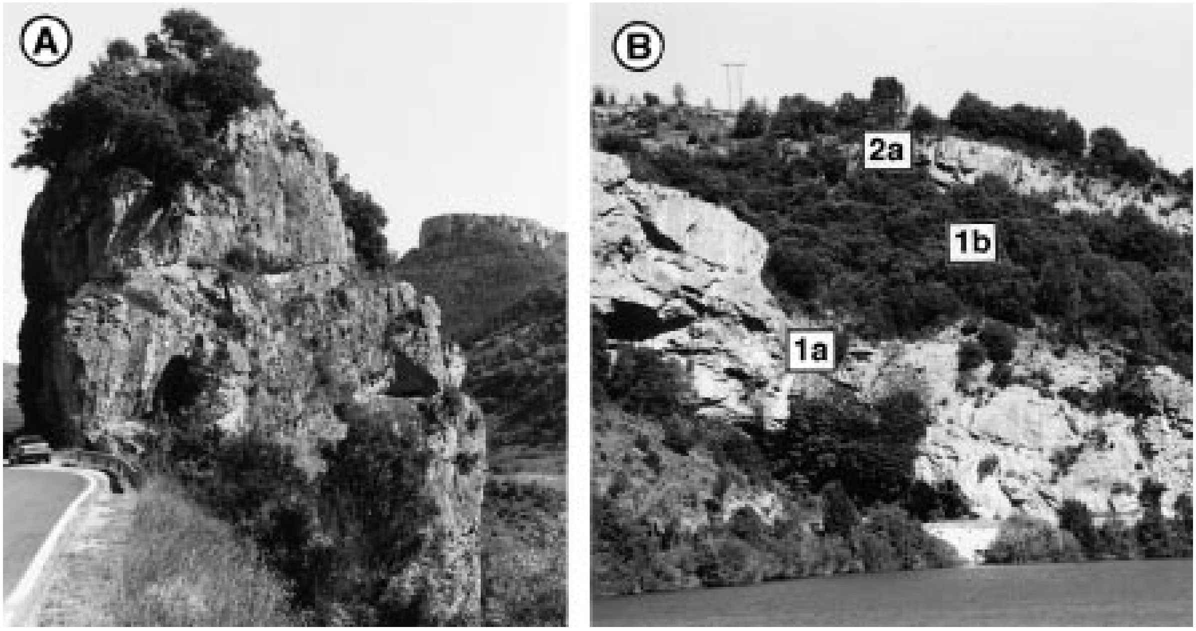


Fig. 9. Outcrops of SPECMs in the Irati Valley, eastern part of the Pamplona Basin. (A) An outcrop of SPECM-f in zone 2, showing blocks of Eocene shallow-water limestones (the one in the background is 640 × 280 × 40 m in size) floating in a homogeneous muddy debrite. (B) An outcrop of SPECM-b in zone 5, showing a complete differentiated sequence comprised of a clast-supported megabreccia division (*1a*), a mud-supported megabreccia division (*1b*, covered by vegetation) and a graded calcarenite division (*2a*); total thickness of the sequence is 70 m. The basinal zones are indicated in Fig. 8.

sections. The strike sections are up to 30 km long, because the Hecho Group in the study area forms a S- or SSW-dipping homocline (Fig. 3). However, these extensive outcrop sections show relatively little lateral change in the SPECM units in the E–W direction. Dip sections are available in the basin's eastern part only, due to some gentle folds (Fig. 3). Four of the SPECM units there can be followed in the N–S direction for distances of 4 to 8 km, all of them showing rapid facies changes. In order to document those changes, we have subdivided the area into six zones and compared the representative logs of each SPECM unit (Fig. 8). The following lateral changes have been recognized that indicate a southern provenance.

(a) A northward decrease of the maximum clast sizes. For example, the size of the largest clasts in unit SPECM-f decreases from 640 m in zones 1 and 2 (Fig. 9A) to 20 m in zone 4. A similar marked change is observed in the other three SPECM units (Fig. 8).

(b) A progressive northward change in the internal organization of a megabreccia unit, particularly well-recognizable in the SPECM-d to SPECM-f units. In the southern outcrops, the units consist of poorly sorted, mud-supported breccias, whereas the northern outcrops show each unit to consist of a clast-supported breccia overlain by a mud-supported breccia and capped with a graded calcarenite (Figs. 8 and 9B). These two end-members of the lateral development of a SPECM unit will further be referred to as an 'unorganized debrite' and a 'complete differentiated sequence' (see genetic discussion in subsequent Section 8).

6.3. Carbonate-platform architecture

In the Jaca Basin Barnolas et al. (1992) and Barnolas and Teixell (1994) have mapped extensive erosional surfaces truncating the basin margin's shallow-water carbonate platform, dipping basinwards and onlapped by the turbidites of the Hecho Group. The latter authors interpreted these surfaces as the scars left by large-scale collapses from which the SPECMs have originated. Barnolas et al. (1992) and

Barnolas and Teixell (1994) have also documented that the ages of the carbonates underlying the Hecho Group were consistently younger in the southward direction, which they attributed to a punctuated backstepping of the evolving carbonate-platform system. Most of these observations were made in the N-trending Boltaña anticline (see location in Fig. 1), where the boundary between the carbonates and the Hecho Group turbidites is exposed along a continuous dip section. Unfortunately, no comparable section is exposed in the Pamplona Basin, where a reconstruction of the carbonate-platform architecture and its relationship to the Hecho Group has thus been based on the correlation of representative vertical profiles (Fig. 10). The following features are of special interest here: the occurrence of truncation surfaces, the distribution of Eocene platform-margin facies and the significance of hiatal surfaces in the carbonate succession.

At least two internal truncation surfaces are recognizable at the outcrops in the northern and southern parts of the study area (Fig. 10). One is best exposed in section 6 (Erro), where the truncation is a sharp, irregular surface cut into the Danian carbonates of suite 1 and covered with a debris of Eocene limestones and marlstones, up to a few metres in size. The outcrop trace of the surface is arcuate, concave upwards (Fig. 11). The erosional relief of this surface is at least 80 m, as indicated by both regional data (the missing Thanetian carbonates are thicker elsewhere) and comparison with the adjacent section 5 (Orbaitz; see Fig. 10A). The other truncation surface is most evident in the carbonate platform in the southern part of the study area, as revealed by the mapping of the Alaitz ridge inlier and a correlation of sections 1, 2 and 3 (Fig. 10B). The full width and relief of the truncation cannot be established in the outcrop, but at least 100 m of the lower and middle Lutetian limestones have been removed along this surface. In either case, the underlying carbonates show no evidence of subaerial exposure and the overlying deposits are turbidites or marls of deep-water origin. It is likely, therefore, that these erosional surfaces were formed subaqueously. Their concave-upward shape suggests slump scars.

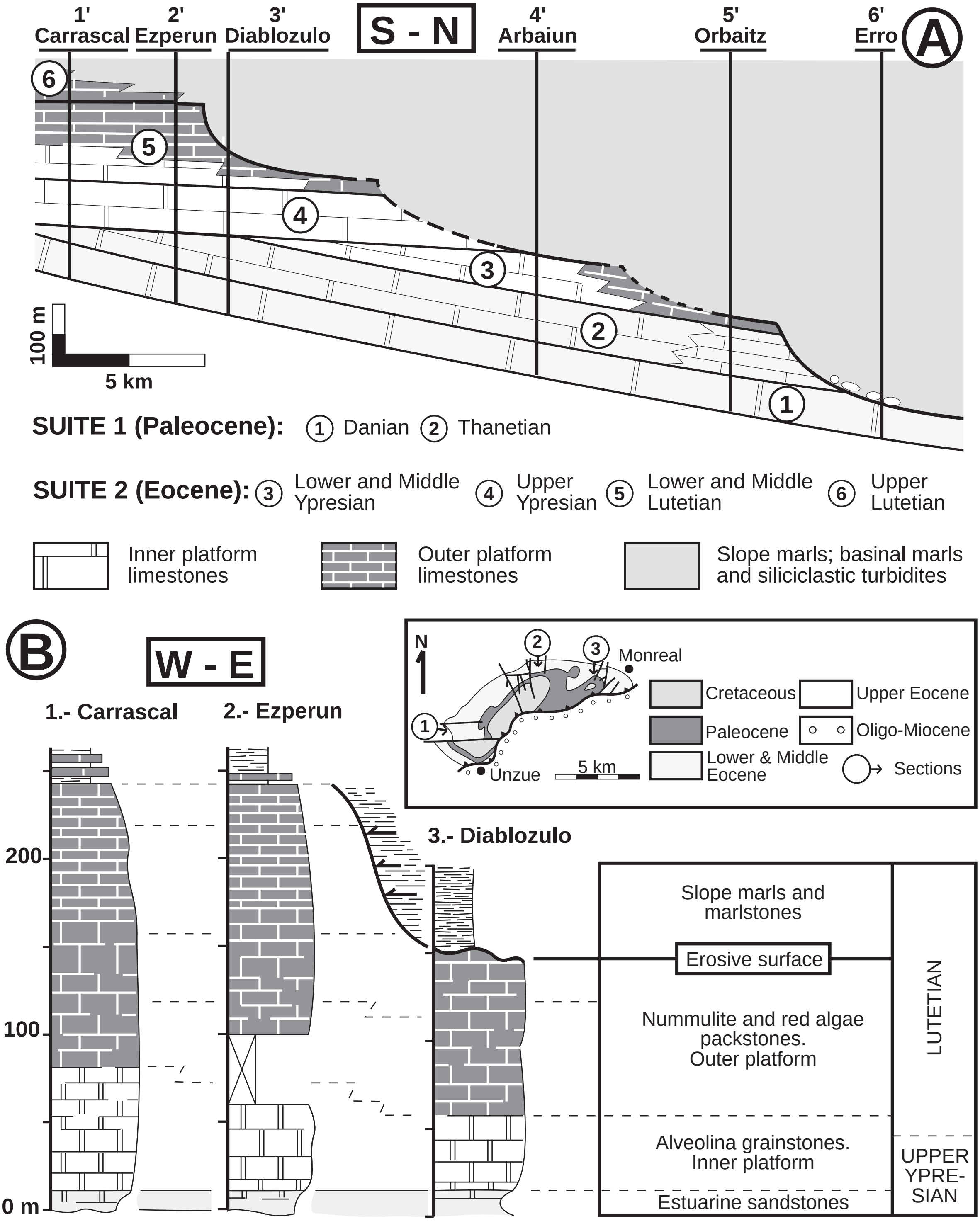
The Eocene carbonates include two diagnostic biofacies associations, typified, respectively, by alveolinid and nummulitid larger foraminifera (e.g., Hallock and Glenn, 1986). These facies are thought to represent a shallow, inner platform setting (alveolinids) and a deeper, outer platform or bank setting (nummulitids). Notably, the distribution of these biofacies in the outcrop sections (Fig. 10) indicates clearly an overall backstepping of the margin's carbonate platform during Eocene time. Section 4 (Arbaiun; Fig. 10A) shows a 110-m-thick succession of early and middle Ypresian carbonates that are entirely missing in the three sections at the Alaitz ridge (sections 1, 2 and 3 in Fig. 10), which can be best explained by an unconformity related to a gentle northward tilting of the carbonate succession.

In summary, the architecture of the carbonate succession of suite 2 at the basin's southern margin suggests episodic collapses (slump scars), landward retreat (facies backstepping) and probably basinward tilting (hiatal surfaces). This type of basin-margin behaviour supports the notion of a southern provenance of the SPECMs.

6.4. Vertical stacking pattern

The pattern of stacking of the successive SPECM deposits in the Pamplona Basin is a good evidence of their southern provenance. The style of stacking is more easily recognized in the Pamplona Basin because the tectonic deformation here is milder than in the Jaca Basin to the east. Consequently, the horizontal distance between the outcrops of the oldest and the youngest megabreccias is nearly 14 km in the Jaca Basin, but is only about 6 km in the Pamplona Basin (Figs. 3 and 12).

The stacking pattern of the SPECM deposits has some important implications, because the two margins of a foreland basin are known to be characterized by quite different dynamic behaviour (e.g., see Crampton and Allen, 1995; DeCelles and Giles, 1996; Sinclair, 1997). The SPECMs would be expected to show a different spatial arrangement depending on whether they have been derived from one or the other margin. The two conceptual possibilities are shown by the simplified model in Fig. 13, assuming a similar magnitude of the margin-collapse events. Fig. 13A shows the case of megabreccias being derived from a collapsing carbonate platform at the foreland basin's active hinterland (northern) margin, as proposed in the present case by Labaume et al.



1' Carrascal
2' Ezperun
3' Diablozulo
S - N
4' Arbaiun
5' Orbaitz
6' Erro
A
100 m
5 km
SUITE 1 (Paleocene): 1 Danian 2 Thanetian
SUITE 2 (Eocene): 3 Lower and Middle Ypresian 4 Upper Ypresian 5 Lower and Middle Lutetian 6 Upper Lutetian
Inner platform limestones
Outer platform limestones
Slope marls; basinal marls and siliciclastic turbidites
B
W - E
1.- Carrascal
2.- Ezperun
3.- Diablozulo
200
100
0 m
N
Monreal
Unzue
5 km
Cretaceous
Paleocene
Lower & Middle Eocene
Upper Eocene
Oligo-Miocene
Sections
Slope marls and marlstones
Erosive surface
Nummulite and red algae packstones. Outer platform
Alveolina grainstones. Inner platform
Estuarine sandstones
LUTETIAN
UPPER YPRE-SIAN

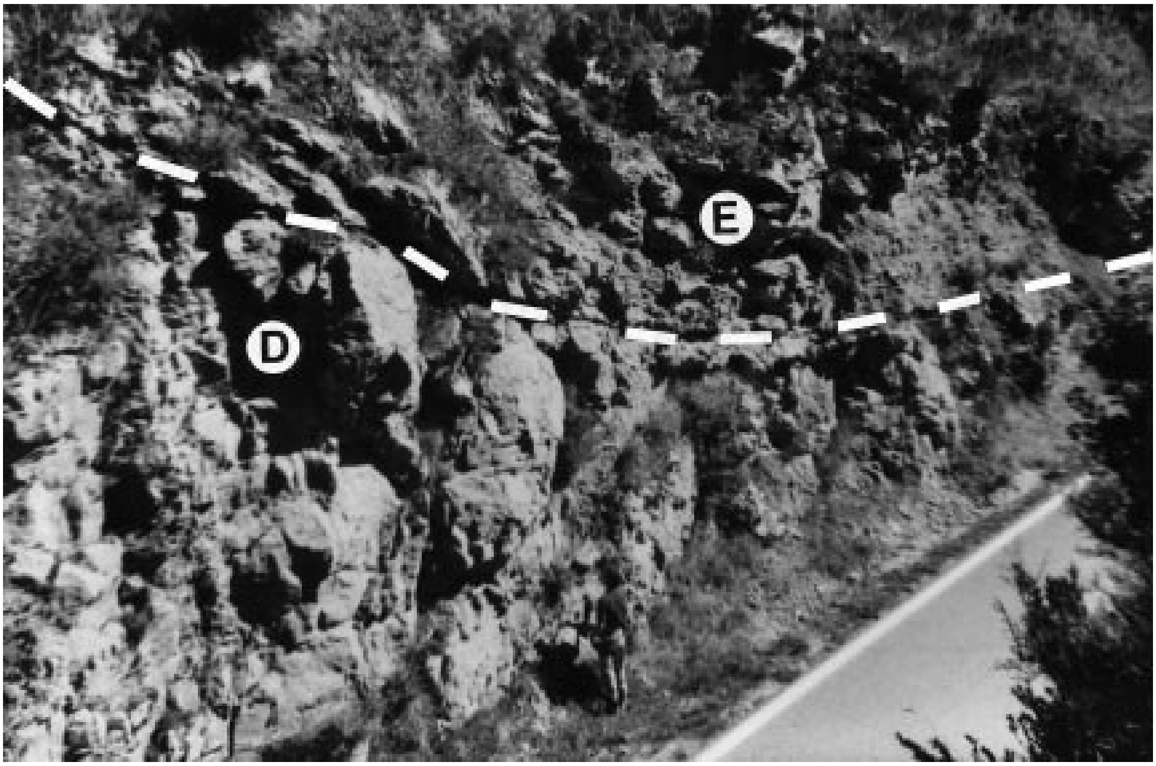


Fig. 11. A concave-upward erosional surface within a succession of shallow-water Danian carbonates (*D*), lined with a lag of Eocene limestone and marl debris. This debris lag is overlain by the siliciclastic turbidites of the Hecho Group (not shown in this photo). The Erro River section (locality 6 in Fig. 7B and Fig. 10).

(1983, 1985, 1987) and Seguret et al. (1984). Fig. 13B shows the alternative model of megabreccias being derived from a backstepping platform of the basin's cratonic (southern) margin. In either model, the successive megabreccias would accumulate somewhat further to the south, because the two foreland margins in the present case are migrating southwards. Such a shifting of the depocentre is indicated, indeed, by the progressive southward stepping of the southern tips of the SPECMs (Fig. 12), which Labaume et al. (1983, 1985, 1987) interpreted as the distal onlap of the megabreccias onto the basin's southern margin. In the first scenario (Fig. 13A), the carbonate source area is migrating southward and becoming progressively more 'proximal' to any arbitrary fixed point in the foreland trough (see locality 'P' in Fig. 13). Consequently, the megabreccias stacked upon one another at such a point would be expected to show a coarsening-upward trend. In the second scenario (Fig. 13B), the carbonate source area is being moved progressively away from the intrabasinal fixed point, and the stacking of breccias should thus result in a fining-upward trend. Importantly, the stacking of the SPECMs in the Pamplona Basin shows clearly a fining-upward overall trend (see subsequent section 8), which supports this latter scenario.

Fig. 10. (A) Tentative reconstruction (N–S cross-section) of the carbonate-platform succession at the southern, cratonic margin of the Pamplona Basin, based on the correlation of six lithostratigraphic profiles (for location see Fig. 7B). (B) Geological map and stratigraphic profiles of the Alaitz ridge inlier, with a reconstructed E–W cross-section. Note that the foreland suite 2 of the southern margin of the basin is represented mainly by a shallow-water carbonate platform, which has been partly removed by a prominent truncation in section 3 (Diablozulo).

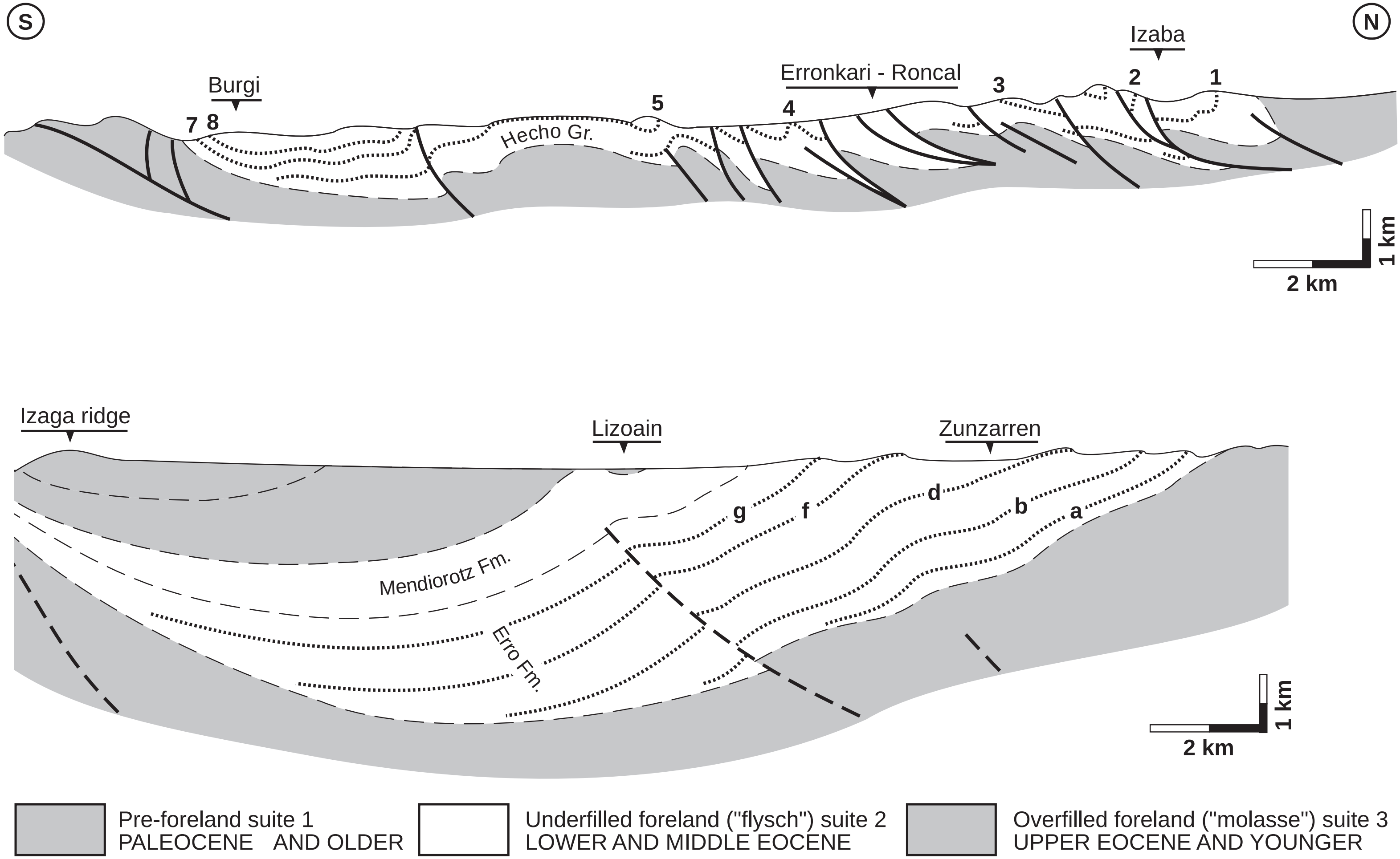


Fig. 12. Structural N–S cross-sections through the South Pyrenean Foreland Basin in the Roncal Valley area (Jaca Basin) and the Erro River valley (Pamplona Basin). The Jaca Basin cross-section (upper diagram) is modified from Labaume et al. (1985). Note that the tectonic deformation is much milder in the Pamplona Basin (lower diagram), probably reflecting the diachronous deformation in the Pyrenean domain.

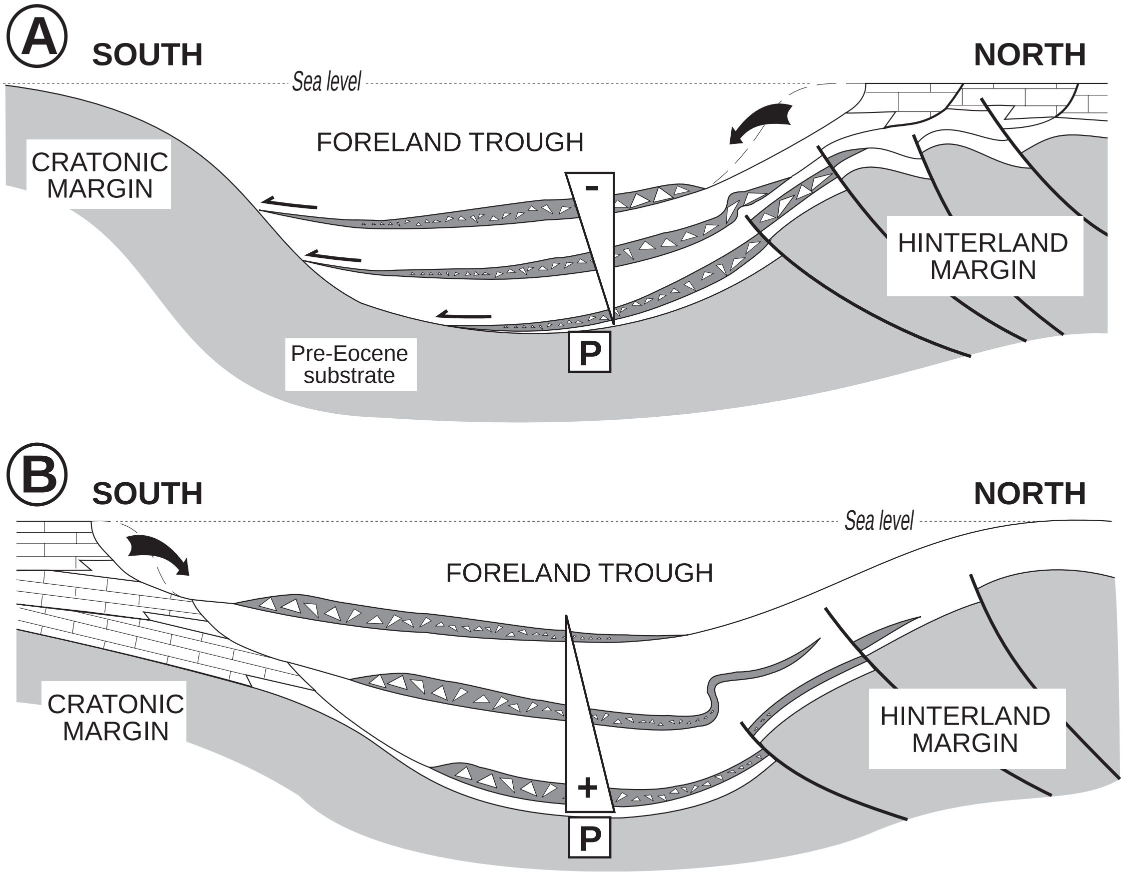


Fig. 13. An idealized model of the foreland basin showing the stacking trends of SPECM units expected from a northern (A) and a southern source (B), respectively. Not to scale; further discussion in the text.

7. The triggering mechanism for mass movements

There is a general agreement among researchers that the SPECMs have been emplaced by mass-movement processes and represent large-scale resedimentation phenomena. The nature of the mass flows will be discussed in some detail further in the text. However, the triggering mechanism for these episodic mass movements is an unsettled issue.

The previous authors have linked the resedimentation processes variously with seismicity, phases of a tectonic oversteepening of the basin margin or episodes of relative sea-level fall. In this section, we discuss the postulated triggers and propose an alternative model.

7.1. Seismicity

Earthquakes have been considered by many authors as the most likely cause of the emplacement of SPECMs (e.g., Rupke, 1976a,b; Johns et al., 1981; Labaume et al., 1983, 1985, 1987; Seguret et al., 1984). In fact, Mutti et al. (1984) have coined the genetic term ‘seismoturbidite’ for these deposits. The arguments invoked to support this interpretation included the large volume and areal extent of the SPECMs and their association with an active tectonic setting. Although the former argument is acceptable, the latter requires more careful evaluation. It should be kept in mind that the authors above assumed that the majority of the SPECMs were derived from the northern (hinterland) margin of the foreland basin, where tectonic compression was demonstrated by the southward movement of thrust sheets (Seguret, 1972) and strong earthquakes were likely to have occurred. A carbonate platform developed on that margin would likely be prone to large-scale collapses. However, the new evidence discussed in the previous section indicates that most, if not all, of the SPECMs were apparently derived from the basin's southern (cratonward) margin, where tectonic extension was more likely to prevail. The thrust loading of a foreland's hinterland margin often leads to a flexural bending of the foreland basin, with an uplift and extension of the cratonic margin (e.g., Crampton and Allen, 1995; DeCelles and Giles, 1996; see also below).

7.2. Tectonic oversteepening

Barnolas and Teixell (1994), assumed temporal variation in the thrust loading and postulated that the resedimentation processes responsible for the SPECMs were caused by the oversteepening and drowning of the southern margin's carbonate platform during phases of an increased thrust loading of the foreland's northern margin. Tectonics would still play a crucial role, but more indirectly than in the earthquake-trigger model. Importantly, this hypothesis is consistent with field data and supported by evidence of the southern margin oversteepening. However, the 'oversteepened' margin would be no steeper than about 4–6º, according to the estimation of Barnolas and Teixell (1994), which might not necessarily lead to any major collapses. Furthermore, it has recently been emphasized by Spence and Tucker (1997) that the "pore-water overpressure of confined aquifer horizons beneath the sea-floor, rather than slope oversteepening, is the critical control on megabreccia deposition".

7.3. Relative sea-level falls

The SPECMs in the Hecho Group are temporally clustered, rather than randomly distributed, in the basin's stratigraphic record (Fig. 6). Moreover, the evidence from the Pamplona Basin indicates that the sedimentary events of megabreccia emplacement coincided with periods of relative sea-level lowstand, whereas the highstand periods were free of resedimentation processes (Payros, 1997). The main corresponding evidence can be summarized as follows.

(1) The proportion of siliciclastic turbidites in the 'background' facies succession is significantly higher within the stratigraphic intervals containing the event clusters of megabreccia emplacement. Furthermore, the biostratigraphic data indicate that the background sedimentation rate during these time intervals was considerably higher (Figs. 5 and 6). The increase in the siliciclastic flux is thought to be a good indication of a sea-level lowstand (Mutti, 1985; Kolla and Macurda, 1988; Posamentier and Vail, 1988; Vail et al., 1991). The megabreccia-free stratigraphic intervals show a low proportion of siliciclastic turbidites, relative to marl layers and carbonate turbidites, and a lower overall sedimentation rate, which points to sea-level highstands. Many studies lend support to the notion of carbonate-platform-margin collapses related to sea-level lowstands, with bioclastic turbidites derived from the platform top during highstands (Schlager et al., 1994; Vecsei and Sanders, 1997).

(2) The Anotz Formation, a 'background' facies unit in the westernmost part of the basin (Figs. 2 and 3), contains several grainstone-rich members interpreted to be lowstand carbonate fans (Payros, 1997). At least two of the SPECM units (d and g) are intercalated within these deposits. The other SPECM units pinch out westwards without reaching the Anotz Formation, but the biostratigraphic data indicate that all of them are time-equivalent with the grainstone-rich members of the latter formation.

(3) The SPECMs are conspicuously absent from the Mendiorotz and Erize formations, the two units capping the Hecho Group (Figs. 2 and 3) and deposited during a relative sea-level rise (as indicated by the simultaneous marine flooding of the eastern and western flanks of the Hecho Group trough; Fig. 2).

(4) The inner carbonate-platform succession exposed in the Andia ridge (see Fig. 7B for location) contains four horizons with clear features of subaerial exposure (Payros, 1997). The dating of this succession with larger foraminifera (for details, see Payros, 1997) constrains the development of the subaerial horizons to middle–late Ypresian, late Ypresian–early Lutetian, early–middle Lutetian and middle Lutetian times. These data suggest that the platform area was emergent during the time span of the SPECM-event clusters.

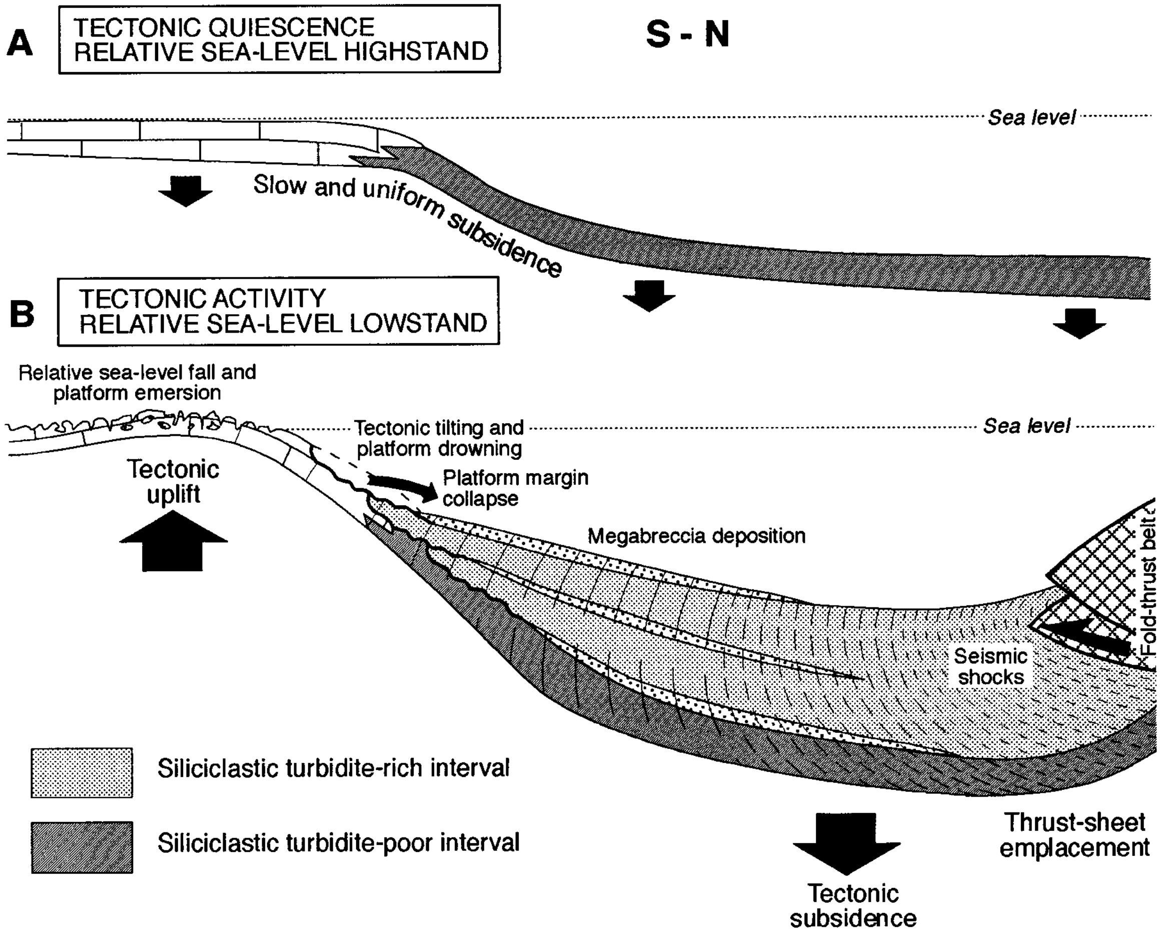


Fig. 14. An idealized model for the alternating phases of tectonic quiescence and activity, with the latter leading to the time–stratigraphic clusters of SPECM emplacement events. Not to scale; further discussion in the text.

According to Spence and Tucker (1997), sea-level falls generally favour the emplacement of carbonate megabreccias by causing overpressure beneath the seafloor and increasing the load stress in an exposed carbonate platform. However, the scale of ancient megabreccias attributed mainly or solely to sea-level falls is admittedly much smaller than that of the SPECMs (e.g., Obrador et al., 1992; García-Mondéjar and Fernández-Mendiola, 1993; Pujalte et al., 1993). Therefore, it is rather unlikely that the origin of the SPECMs could be due to the sea-level factor alone.

From the preceding discussion, we conclude that the origin of the SPECMs cannot be convincingly linked to a single failure-triggering factor, in spite of the previous suggestions by other authors. We postulate, instead, that a combination of the three factors may have been responsible for the emplacement of these carbonate megabreccias. The depositional model proposed here concurs with some of the interpretative points raised by Barnolas and Teixell (1994), particularly the assumption of an episodic tectonostratigraphic development of the foreland basin, with the alternating phases of tectonic activity and quiescence (Fig. 14). The notion of tectonic pulses implies variation in the basin-margin loading, which is consistent with the conditions inferred for many other foreland basins (e.g., Patton and O'Connor, 1988; Waschbusch and Royden, 1992; Crampton and Allen, 1995).

In the present model, the phases of tectonic quiescence would correspond with relative sea-level highstands (Fig. 14A), when the carbonate platform (or ramp) on the basin's southern, cratonic margin would be active and probably prograding basinwards. The amount of siliciclastic turbidity currents supplied to the basin axially from the east would decrease, while the basin would accumulate mainly carbonate mud and subordinate calcarenitic turbidites derived from the platform, along with the sediment from persistent 'pelagic rain'. The net sedimentation rate would be low to moderate, reflecting the reduced siliciclastic input.

During the phases of tectonic activity, by contrast, the southward advance of the thrust sheets at the foreland's northern margin would increase the crustal loading and the subsidence rate of the foreland trough (Fig. 14B). The axial siliciclastic influx would greatly increase due to the concurrent uplift and erosion of the foreland's hinterland margin, and the increased sediment accumulation would further add to the loading. The cratonward margin would likely be uplifted due to flexural rebound, a forebulge effect well documented from many foreland basins (e.g., Crampton and Allen, 1995; DeCelles and Giles, 1996). As a result, the carbonate platform hosted by that margin would become increasingly unstable, because of the structural steepening and the excess pore pressure caused by the emergence. Earthquakes would likely accompany the pulse of tectonic activity and contribute to the platform collapse.

8. Facies model

The SPECM units are commonly characterized by a distinct sequence of divisions, as already noted by most of the previous authors. In fact, this internal organization and the lack of intercalated siliciclastic 'background' turbidites are the strongest evidence supporting an episodic, catastrophic emplacement of the SPECMs. A fully developed sequence of bed divisions is here illustrated by SPECM-b in the Nagore section (Fig. 15; see also Fig. 9B). This field example is from the proximity of borehole Aoiz-1 (see location in Fig. 3), where the gamma-ray signature of the SPECM can directly be observed.

The vertical organization of the SPECM divisions have widely been recognized in the field, but different nomenclature and often different interpretation have been used in previous studies (Fig. 15). In our view, a fully developed SPECM unit is basically bipartite and each part consists of two divisions. The sedimentological characteristics of the successive divisions can be summarized as follows.

Division 1a is a clast-supported, poorly sorted carbonate megabreccia, composed mainly of shallow-marine limestone debris. The individual clasts may be up to several hundreds of metres in size (Table 1), and some of the largest slabs show hydroplastic deformation, a clear evidence that the resedimentation involved young, semiconsolidated deposits. The gamma-ray signature of division 1a is typified by low natural radioactivity and an overall cylindrical pattern, which corresponds well with the fairly homogeneous nature of this basal division.

Division 1b is a mud-supported megabreccia, dominated by slope-derived marlstone and marly limestone debris. Its high content of relatively 'weak', marly debris is reflected in both the weathering outcrop profile and the gamma-ray log (Fig. 15). The latter is essentially chaotic, but showing irregular intervals of moderately low and high natural radioactivity, apparently related to the component blocks and the muddy matrix.

Division 2a overlies sharply the previous division, with an erosional surface showing occasionally groove casts and other sole marks. The division consists of a coarse-grained rudstone in the lower part and a bioclastic grainstone and/or packstone in the upper one, with an overall more-or-less continuous upward fining, well recognizable in the weathering pattern. The rudstone is relatively rich in marl clasts, most probably eroded from the underlying division 1b, which may account for the upward decrease of the gamma-ray response of this division.

Division 2b overlies the former division conformably, with a gradational contact. This division consists exclusively of a calcareous marlstone, but its resedimented nature is evident from redeposited planktic forams. As demonstrated by Rupke (1976b), the division shows an upward fining that is best manifested by a gradual decrease of the size of the coarsest quartz grains, which can be traced throughout the entire thickness of division 2 (i.e., from the calcarenite base to the marlstone top). The upward

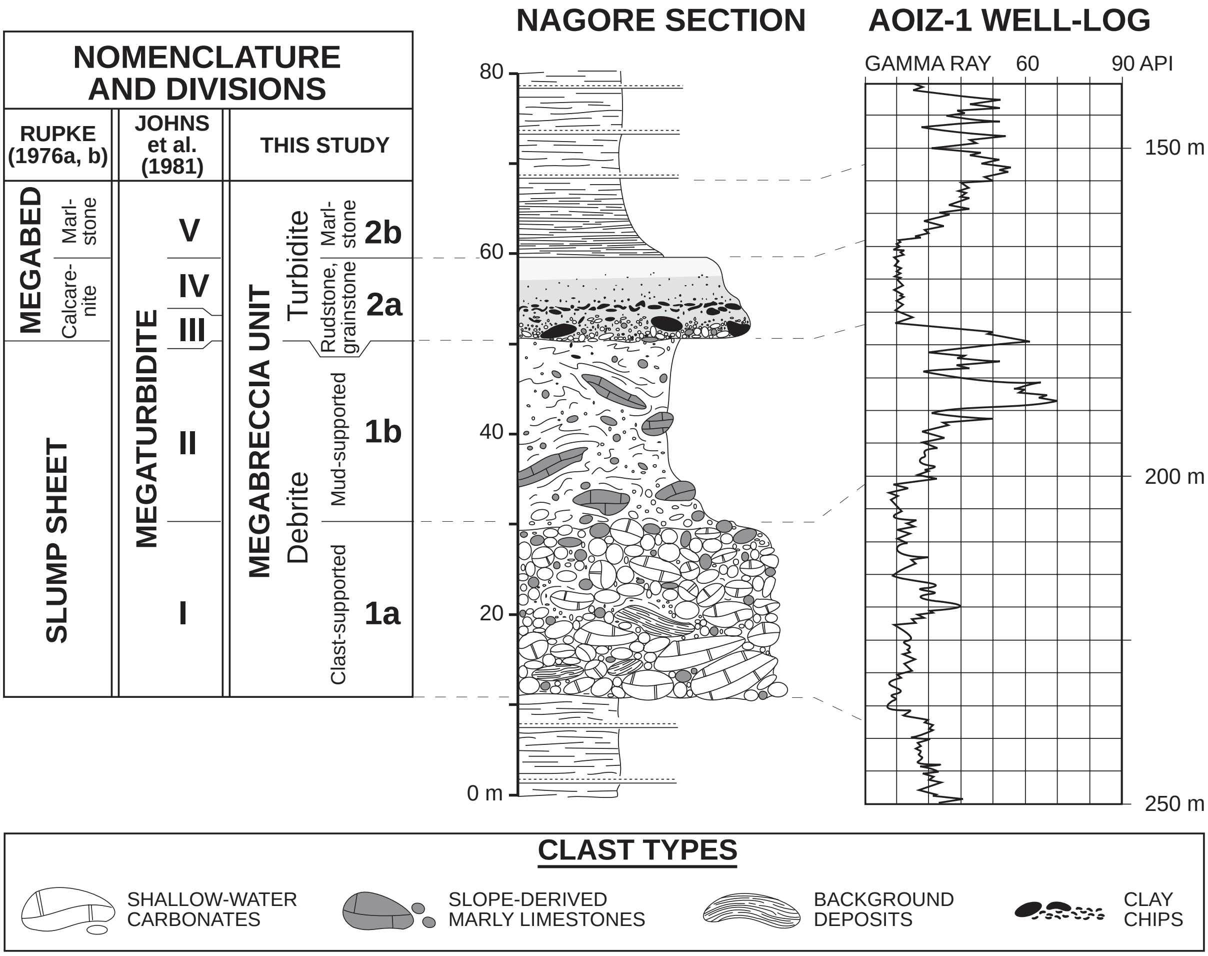


Fig. 15. A complete sequence of divisions characteristic of a SPECM unit (example from SPECM-b in Nagore section, Urrobi River) and the corresponding wireline log (SPECM-b in Aoiz-1 borehole). Note the deposit nomenclature and divisions used by the previous authors and the present study. The localities are shown in Fig. 3.

increase of the gamma-ray response of division 2b can be attributed to this textural trend, with the upward increase of the clay content.

The previous authors have used different names and different interpretations for the various divisions of the SPECM units. The bipartite 'slump-megabed' of Rupke (1976a,b) is similar to our model, except that he did not subdivide the 'slump' part itself. He considered the two divisions to be products of two independently originated, but essentially simultaneous, sediment-gravity movements (i.e., a slump and a turbidite current), likely triggered by an earthquake. Johns et al. (1981) suggested that the SPECM units might be 'megaturbidites' representing deposition from giant turbidite currents whose competence declined with time. The supporting evidence included the lack of mud matrix in the basal parts of the SPECMs, which was considered to rule out a debris flow, a slump or a slide mechanism for the lower division. In later papers, however, members of the same research group have attributed their divisions I and II to a debris flow or a modified grain flow, while retaining the term 'megaturbidite' as a descriptive label (e.g., Labaume et al., 1983, 1985, 1987).

Labaume et al. (1987) suggested also that the megaturbidites could be deposited on the flanking slopes directly downflow from a hydraulic-jump zone. The hydraulic jump would cause mass-flow dilution, turbulence and clast grading, and would favour the incorporation and upward migration of marlstone clasts "rip-up from the sea floor during the development of intense turbulences in the jump zone" (Labaume et al., op. cit., p. 100). The latter authors remarked also (p. 99) that "the lack of significant lateral variation in the internal sequence of each megaturbidite (...) implies that a similar organization must have been developed within the flow higher on the slope".

The outcrops of the SPECMs in the Pamplona Basin allow new insights to be made into the genetic issues reviewed above. Firstly, the longitudinal N–S changes in four SPECM units can directly be observed (Fig. 8). Secondly, there are numerous, closely spaced, N-trending valleys and road-cut sections (Fig. 3) that allow the E–W changes in the SPECM units to be established (Fig. 16). Thirdly, the vertical stacking of the successive SPECM units can be recognized and considered as a proxy record of their longitudinal development, with the oldest SPECM-a representing the most proximal deposition and the youngest SPECM-g representing the most distal development. Based on these data, a generalized conceptual model is suggested for the downslope development of an 'ideal' SPECM unit (Fig. 17). The proximal part of a deposit is here referred to as an 'unorganized debrite', the medial part, showing all the divisions (Fig. 15) is referred to as a 'complete differentiated sequence', and the distal part is referred to as a 'base-missing sequence'. The sedimentary characteristics and genetic significance of the three segments of an ideal SPECM are summarized below.

8.1. Unorganized debrite

These proximal parts of SPECM units are mud-supported breccias, containing an assorted mixture of slope-derived clasts (mainly marlstone and fine-grained calcarenite) and shelf limestone debris (Fig. 9A; see also SPECM-a cross-section in Figs. 16 and 17). A minor admixture of clasts derived from the siliciclastic 'background' turbidites may occur in the most distal, downslope portions of these debrites. The shelf-derived clasts may be either older or nearly contemporaneous with the SPECM deposit; the clasts in the latter case may appear to have been plastically deformed and show armoured surfaces. Clast sizes are highly varied, ranging from a few centimetres to hundreds of metres in length, but size segregation is generally lacking. The fabric of elongate/tabular clasts is mainly planar, sub-parallel with the SPECM base, but some clasts may be oriented transverse to the flow direction. Disorderly fabric is most common.

The debrite's matrix content ranges between 50 and 90 vol.%, varying irregularly in both vertical and lateral direction in almost every SPECM. The matrix is unsorted and unstratified, consisting of a pure marl, a plastically deformed marl rich in sand-sized carbonate clasts, or a marly calcarenite. Nummulite tests are the most abundant clast type within the matrix, but lithoclasts and other bioclasts are present, too.

The sedimentary features indicate a cohesive, immature debris flow, the kind of mass flow one would expect relatively close to a mass-wasting zone (Cook and Mullins, 1983). It is worth noting that the oldest SPECM unit in the Jaca Basin (unit MT-1) is a chaotic debris-flow deposit (see fig. 9 of Labaume et al., 1987), although this fact was apparently overlooked by the latter authors when suggesting the 'megaturbidite' model.

8.2. Complete differentiated sequence

This sequence of divisions is recognizable directly basinwards of the unorganized debrite part of a SPECM unit and is thus thought to be a result of a straightforward evolution of the debris flow. In fact, such a downflow evolution is recognizable in the eastern part of the Pamplona Basin (Fig. 8). Furthermore, the SPECM-a unit is an unorganized debrite (Fig. 16), but its extension in the Jaca Basin to the northeast (unit MT-3 in Fig. 4), shows a complete differentiated sequence (see also fig. 9 of Labaume et al., 1987). The two types of internal organization coexist laterally in the SPECM-b unit (Fig. 16). As a debris flow moved basinwards, its sediment concentration and strength are thought to have progressively decreased due to the entrainment of the ambient water. The reduced shear strength and decreased flow viscosity allowed vertical segregation of clasts, resulting in a two-storey debris flow, with the two different breccia divisions (divisions 1a and 1b in

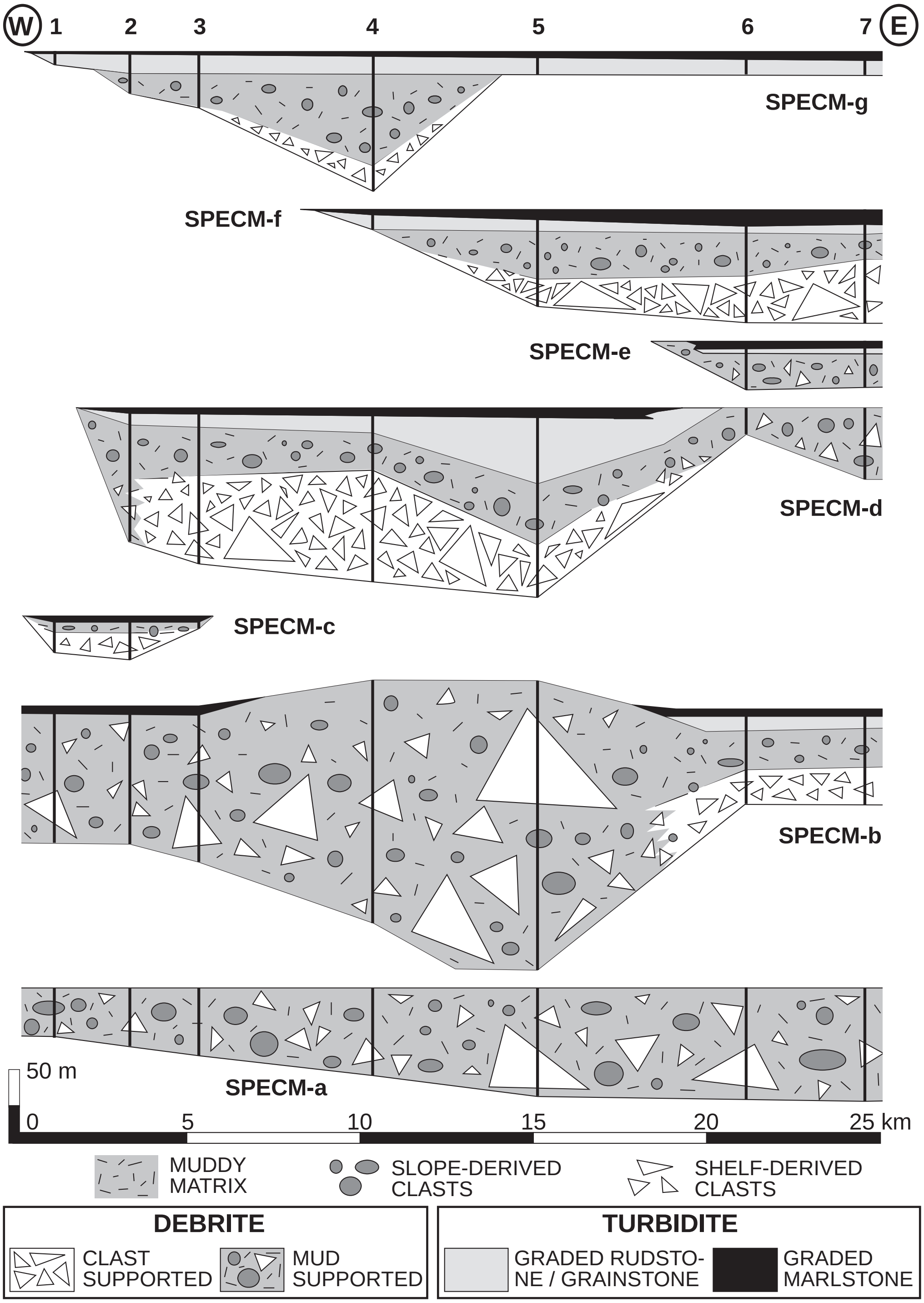


Fig. 16. Simplified E–W cross-sections of the SPECM units in the Pamplona Basin. The sections are transverse (approximately perpendicular to palaeocurrents) and based on seven stratigraphic profiles (see locations in Fig. 3).

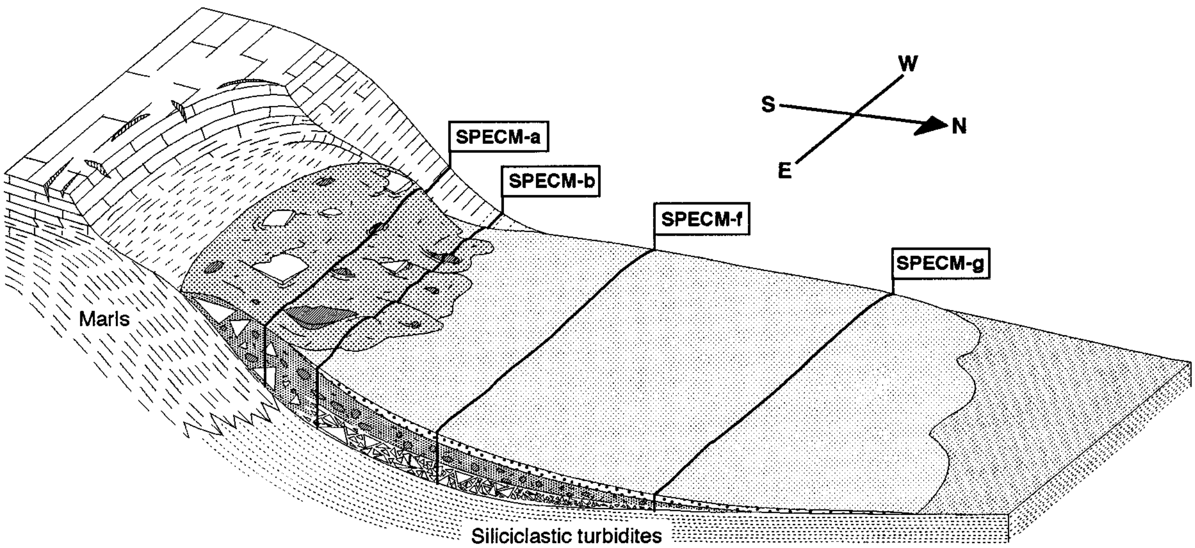


Fig. 17. Idealized depositional model for a SPECM unit (not to scale). For discussion, see text.

Fig. 15) superimposed upon each other in the form of a 'differentiated' sequence. The increased mobility and acceleration of the mass flow would eventually lead to the onset of turbulence and the ignition of a high-density turbidity current, from which the overlying carbonate turbidite (divisions 2a and 2b in Fig. 15) would be deposited. Debris flows evolving into turbidity currents have commonly been reported from modern submarine environments (e.g., Mulder and Cochonat, 1996) and laboratory experiments (e.g., Hampton, 1972). Contrary to the Labaume et al. (1987) suggestion, the development of a complete differentiated sequence, with divisions 1a,b and 2a,b, may not require a hydraulic jump at the base of slope.

8.3. Base-missing sequence

The more distal, basinward part of a SPECM unit consists of an organized sequence of divisions in which the basal clast-supported breccia (division 1a) and often also the mud-rich breccia (division 1b) are lacking. The sequence most frequently is a graded carbonate turbidite (see unit SPECM-g in Figs. 16 and 17). These basinward parts of the SPECMs are thinner and clearly reflect the natural capacity of a turbidite current to outrun its parental debris flow on a gently inclined seafloor.

9. Conclusions

The SPECMs are among the most spectacular, and probably most controversial, deposits of the Southern Pyrenean Foreland Basin. The present study from the foreland's western part (Pamplona Basin) has challenged some of the previous interpretations, derived mainly from the eastern part of the foreland (Jaca Basin). The two parts of the foreland trough have many features in common and obviously complement each other in terms of geological information, but the Pamplona Basin shows milder tectonic deformation and a greater proportion of fine-grained, fossiliferous hemipelagic deposits, which renders the western foreland a more convenient and crucial study area, where some of the earlier concepts can be tested and verified. The present study demonstrates that the Pamplona Basin provides clues to the origin and regional significance of the SPECMs.

By comparing the new interpretation with the previous views, the results of the present study can be summarized as follows.

(1) *The number of SPECMs*. Nine SPECMs were originally reported from the Jaca Basin (Labaume et al., 1983, 1985, 1987) and coded as units MT-1 to MT-9 (with specific names given in some cases). In the Pamplona Basin, seven SPECMs have been recognized, mapped and coded as units

SPECM-a to SPECM-g. Three of these units are physically correlative throughout the foreland trough (units MT-3/SPECM-a, MT-4/SPECM-b and MT-5/SPECM-f), whereas the others are limited in their lateral extent to one of the sub-basins only. Overall, there are at least 13 SPECM units in the foreland basin, a larger number than was previously recognized.

(2) *The age and stratigraphic distribution*. Only one study had previously been attempted to determine the age of the SPECMs (C. Seyve in Labaume et al., 1985) and concluded that these megabreccias were deposited within the time span of nannofossil biozones NP-12 to NP-15. Based on this conclusion, the events of breccia emplacement were estimated to have had a recurrence period of about 500,000 years (Labaume et al., 1983).

The present study has given a new biostratigraphic dating of the SPECMs, based on well-preserved planktic forams. The SPECMs appear to be slightly older than previously assumed. The data indicate that the events of megabreccia emplacement occurred as four time–stratigraphic clusters, thought to represent phases of an increased tectonic activity and lowered sea level in the foreland basin.

(3) *The provenance*. The SPECMs were recognized to have been derived by resedimentation of shallow-marine carbonate platform(s), but the actual location of the latter was uncertain. A northern provenance of the SPECMs was suggested by Rupke (1976a,b), Labaume et al. (1983, 1985, 1987), Seguret et al. (1984) and Rosell and Wieczorek (1989), whereas a southern provenance was postulated by Puigdefábregas (1986), Barnolas et al. (1992) and Barnolas and Teixell (1994). The present study strongly supports this latter suggestion.

(4) *The triggering factor for resedimentation*. Most of the previous authors considered earthquakes as the most likely trigger of the resedimentation events represented by the SPECMs, for which the term 'seismoturbidite' was adopted. Barnolas et al. (1992) and Barnolas and Teixell (1994) suggested tectonic oversteepening of the basin-margin carbonate platform as an alternative factor, although the structural slope there could not be steeper than 6º. The present study suggests that the resedimentation events were related to phases of tectonic activity, with the combination of a relative sea-level fall, fore-bulge steepening and seismic shocks acting as the trigger for platform-margin failures.

(5) *Facies model*. The present study concludes that the SPECM units have been emplaced by cohesive debris flows evolving into high-density turbidity currents. Spatial analysis of outcrop sections suggests that an ideal SPECM unit is comprised of an immature, homogeneous debrite in the proximal part, a differentiated, two-storey (bipartite) debrite and a turbidite in the medial part, and a base-missing debrite overlain by turbidite, or a turbidite alone, in the distal part. The SPECMs were previously referred to as 'megaturbidites' or 'seismoturbidites', which necessarily implied deposition from turbidity currents. Their debrite component, however, is volumetrically much more important than the derivative turbidite component. Therefore, the original terms are considered to be inappropriate for these deposits.

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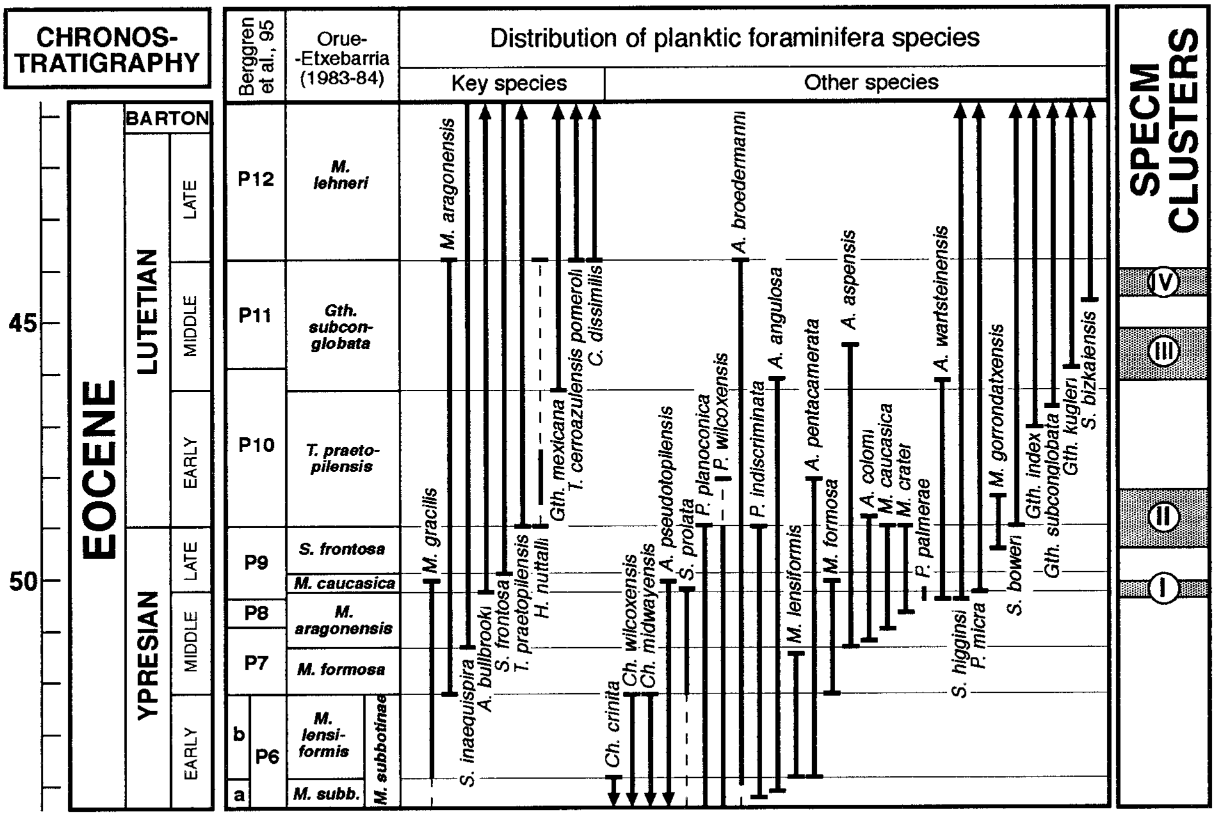
Appendix A. Summary of biostratigraphic data

The planktic foraminifera scale most widely used for the Cenozoic is the biozone scheme of Berggren et al. (1995). How-

Table 2
Planktic foraminifera biozonation of the Early–Middle Eocene in the South Pyrenean Foreland Basin



ever, a direct application of this scale to the present study area is hindered by the fact that several of the scale's key species are uncommon or absent in the Pyrenean Foreland Basin. Therefore, we have used the biozonation established by Orue-Etxebarria (1983–84) in the Basque Basin, where an expanded Palaeogene succession is well preserved. Table 2 summarizes the ranges of some of the most important planktic foraminifera species in the Basque Basin, along with the biozonation established for the Ypresian–Lutetian interval. The table shows also the corresponding biozonation of Berggren et al. (1995) and absolute time scale.

In this study, 75 samples were collected from the hemipelagic marls of the basinal 'background' facies, 58 in the Pamplona Basin and 17 in the adjacent Jaca Basin. The samples were washed, dried in an oven and studied under binocular microscope. The preservation of fossils in most cases was moderate to good. Based on these data, the stratigraphic positions of the SPECMs have been narrowly constrained by the co-occurrence of species with different ranges, which has revealed four distinct time–stratigraphic clusters of SPECM events (Table 2).

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