UPPERMOST CRETACEOUS-MIDDLE EOCENE STRATA OF THE BASQUE-CANTABRIAN REGION AND WESTERN PYRENEES: A SEQUENCE STRATIGRAPHIC PERSPECTIVE

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Abstract: Sequence stratigraphy has proved to be a powerful tool with which to subdivide and correlate most of the uppermost Cretaceous and lower Paleogene deposits of the Basque-Cantabrian Region and the western Pyrenees. Using that approach, studies carried out during the last decade now allow the integration of a large variety of lithofacies, ranging from terrestrial to deep marine deposits, into a comparatively small number of hierarchical genetic units. The characteristics and genesis of two of these units (a 2nd-order Transgressive-Regressive (T-R) facies cycle and several 3rd-order depositional sequences) are summarily described in this paper. The 2nd-order T-R facies cycle and the late Cretaceous, Paleocene and earliest Ilerdian 3rd-order depositional sequences have been recognized, and age-dated with planktic and larger foraminifers, in the whole study area. Early Eocene depositional sequences have been delineated and dated in the Pamplona Basin, but not in the Basque Basin. However, ongoing research in the deep-water Eocene deposits of the Guipúzcoa homocline has led to the recognition of 5 stacked turbiditic systems, typified by different paleocurrent patterns, facies arrangement and, in one case, by a distinctive lithology.

Key words: Sequence stratigraphy, latest Cretaceous, early Paleogene, western Pyrenees, Basque-Cantabrian Region, turbiditic systems, paleocurrents.

Resumen: La Estratigrafía secuencial ha demostrado ser un instrumento de gran utilidad para subdividir y correlacionar gran parte de los depósitos del Cretácico final y del Paleógeno inferior de la Región Vasco-Cantábrica y de los Pireneos occidentales. Utilizando esta metodología, estudios llevados a cabo durante la última década han permitido la integración de una extensa gama de litofacies, desde depósitos continentales a marinos profundos, en un número comparativamente reducido de unidades genéticas jerarquizadas. En este trabajo se describen de manera resumida el origen y las características de dos tipos de dichas unidades genéticas, concretamente de un ciclo Transgresivo-Regresivo mayor (2°-orden), y de diversas secuencias deposicionales (3er-orden) que lo integran. El ciclo Transgresivo-Regresivo mayor, y las secuencias deposicionales del Cretácico final, Paleoceno e Ilerdiense inferior, han sido reconocidas en toda el área de estudio y datadas con foraminiferos planctónicos y macroforaminíferos. Las secuencias deposicionales del Eoceno inferior han sido asimismo delineadas y datadas en la Cuenca de Pamplona, pero no aún en la Cuenca Vasca. Sin embargo, investigaciones en curso sobre los depósitos Eocenos del homoclinal de Guipúzcoa han permitido reconocer 5 sucesivos sistemas turbidíticos, tipificados por distintas pautas de paleocorrientes, arquitectura de facies y, en un caso, por una litología distintiva.

Palabras clave: Estratigrafía secuencial, Cretácico final, Paleogeno inferior, Pirineos occidentales, Region Vasco-Cantábrica, sistemas turbidíticos, paleocorrientes

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The Paleogene system is amply outcropped in the Basque-Cantabrian and western Pyrenean areas, and data about it can already be found in the pioneering papers of Adan de Yarza (1884, 1892). Despite such an early start, later progress in the study of these deposits was slow and somewhat uneven. Indeed, the first important contributions only appeared about fifty years ago, when Gómez de Llarena (1946, 1954) produced some remarkably accurate descriptions of the Cretaceous-Tertiary Flysch of Guipúzcoa. The real breakthrough, however, came with the doctoral theses of Mangin (1959-60) and Plaziat (1984), the former author centered on the Alava and Navarra provinces, the latter covering almost the whole Pyrenean domain. No-

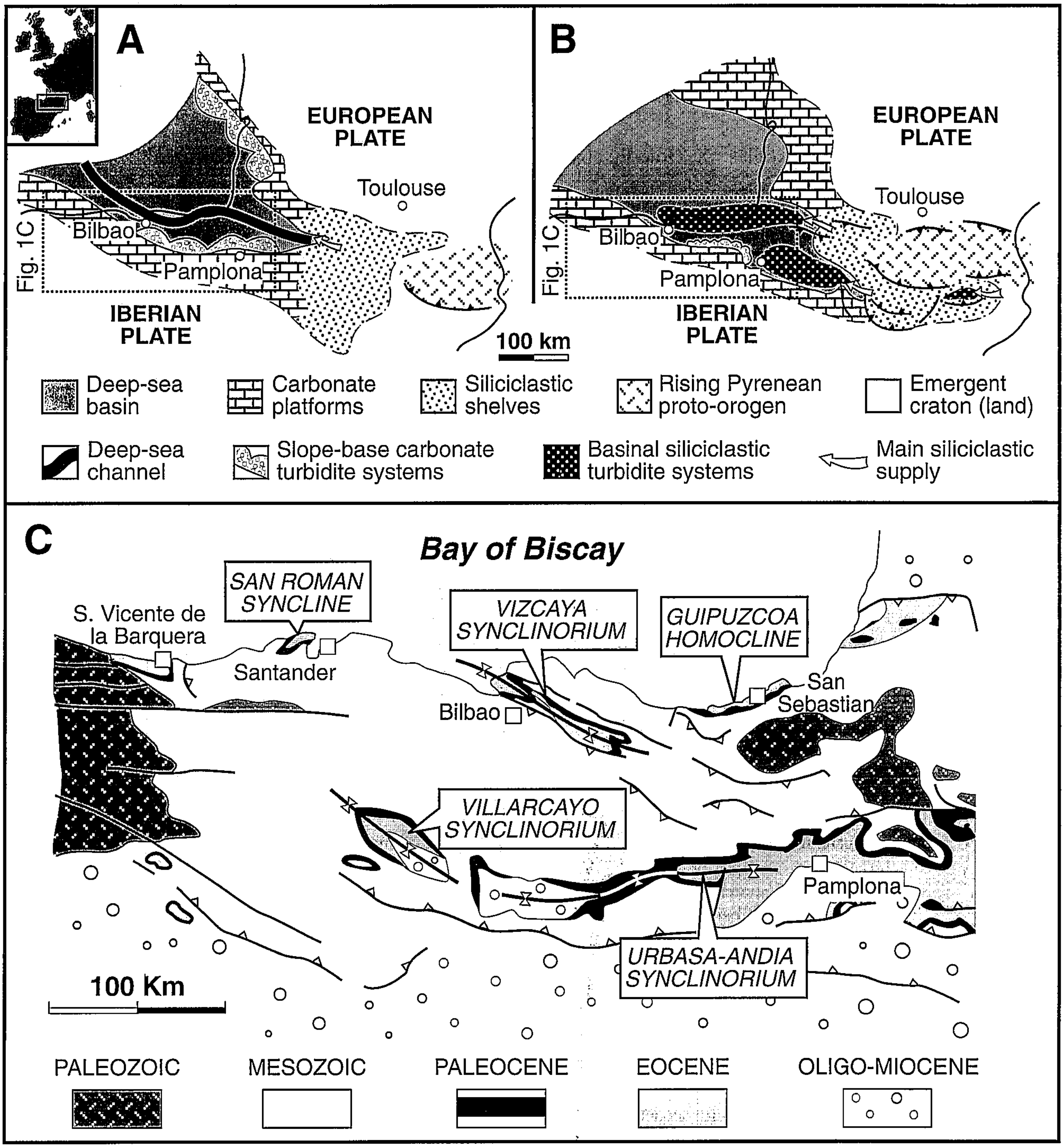

Figure 1.- A and B: simplified Paleocene (A) and early Eocene (B) paleogeographies of the Pyrenean domain. C: simplified geological map of the western Pyrenees and Basque Cantabrian Region showing the main groups of early Paleogene outcrops discussed in the text.

tably, both authors included shallow and deep-water deposits in their studies, a practice that was to become infrequent with later researchers, who mostly concerned themselves to a comparatively narrow range of facies or biofacies. Such «specialized» approach eventually derived on a relative divorce between «shallow-water» and «deep-water» authors.

The studies on which this paper is based were designed to narrow this gap, for it is obvious that shallow- and deep-water sedimentary and biological processes are so closely interrelated that they can not be fully understood without each other. The core of these studies are two doctoral thesis (Baceta, 1996; Payros, 1997), supervised by the seniors authors (VP, SR). Also important are biostratigraphic analysis of both planktic foraminifers (XO) and larger foraminifers (Serra-Kiel and co-workers, University of Barcelona) which, together with magnetostratigraphic data (Pujalte *et al.*, 1995), have made it possible to place the studied successions within a precise time framework.

To attain a fine-scale correlation between shallow- and deep water successions, however, sequence stratigraphy was used by Baceta (1996) and Payros (1997). In doing that, they followed the lead of Joan Rosell, to whom this publication is dedicated, who was the first author to apply such an approach to early Paleogene deposits of the Basque Basin (Rosell *et al.*, 1985). As it is now well known, the main goal of sequence stratigraphy is to subdivide the sedimentary record into packages of genetically related strata bounded by physical surfaces, usually unconformities and their correlative conformities. Mapping and correlation of these packages lead, in turn, to a more accurate basin analysis. There exist a whole rank of sequence stratigraphic units, differentiated by their time duration and scale (Duval *et al.*, 1998). Examples of units of different ranks have been recognized in uppermost Cretaceous to middle Eocene deposits of the western Pyrenees and the Basque-Cantabrian Region (Baceta, 1996; Payros, 1997; Pujalte *et al.*, 1998a; Payros and Pujalte, 1998).

In this review paper we will first summarize the characteristics of two of the different sequence stratigraphic units so far recognized, namely a second-order transgressive-regressive facies cycle and its constituent third-order depositional sequences; second, we will update the knowledge of the lower Eocene deep-water flysch succession of the Guipúzcoa homocline, in the Basque Basin, which is currently being revisited.

Geological setting

The latest Cretaceous-early Paleogene paleogeography of the western Pyrenean domain, in its simplest form, can be envisaged as an E-W elongated deep-water trough, which opened westwards into the Bay of Biscay (Fig. 1). It was flanked on its northern and southern sides by wide and relatively flat areas, which corresponded to distal margins of the foreland basins. During most of the late Cretaceous, the area situated to the south of the trough («north Iberian shelf») maintained a ramp geometry (Floquet, 1991), while throughout the early Paleogene (Paleocene and middle Eocene) was repeatedly encroached by carbonate platforms (distally-steepened ramps and rimmed shelves). During Paleocene times, carbonate platforms also dominated the northern flat area («south Aquitanian shelf»), although siliciclastic sedimentation became there increasingly important during Eocene times (Fig 1). Basinal areas, in addition to hemipelagic rain, were supplied with both coarse-grained carbonate and siliciclastic deposits. The former represent, in all cases, resedimentation from the flanking carbonate platforms; the latter were sourced mostly from the eastern Pyrenees, that were partly emergent during the early Paleogene and subjected to active erosion (Figs. 1a and 1b). Some of the resulting siliciclastic deposits were stored in fluvio-deltaic systems developed on «piggy-back basins», such as the Tremp-Graus (Barnolas *et al.*,1992). The remaining materials were exported to deep basins, where they accumulated in large siliciclastic turbiditic systems, such as those of the Hecho Group (Mutti *et al.*, 1985) or the Higuer-Getaria Formation (see below). As discussed below, the proportion of resedimented carbonate versus siliciclastic deposits within deep basins seems to have been closely controlled by relative sea level and rate of contemporaneous tectonism.

Remnants of early Paleogene terrestrial deposits occur in the north of the Palencia province, south of Cervera de Pisuerga. Extensive accumulations of shallow-water carbonate platform deposits have been preserved in the so-called Urbasa-Andia synclinorium, a large structure which forms a sort of raised plateau on the Alava and Navarra provinces, and in lesser outcrops situated in the north of Burgos (Villarcayo synclinorium) and Cantabria (S. Roman synclinorium and S. Vicente de la Barquera area). Base-of-slope deposits are mostly found in the western part of Navarra, although an important outcrop occurs near Eibar, in the Vizcaya-Guipúzcoa border (Pujalte *et al.*, 1989; Baceta *et al.*, 1991; Orue-Etxebarria *et al.*, 1996). Basin-floor deposits (hemipelagites, turbiditic deep-sea channel and fan deposits) are preserved in the eastern part of Navarra, in the Guipúzcoa homocline and the Bizkaia synclinorium (Fig. 1c). Thus, deposits of a whole range of settings exist in the study area, a circumstance allowing the reconstruction of a transect from shore-related to deep-sea environments. As summarized below, these very different types of deposits can be integrated in a coherent scheme using a sequence stratigraphic approach.

Transgressive-regressive facies cycle (2nd order)

A major transgressive-regressive (T-R) facies cycle developed in the study area from the latest Maastrichtian to the middle Eocene, a time span of about 23.5 m.y., as a result of a change of relative sea level of 2nd-order. Within this cycle, the following three main phases have been recognized: (1) Transgressive phase or overall transgression (from the latest Maastrichtian to the earliest Ilerdian); (2) Peak transgression (early-middle Ilerdian); and (3) Regressive phase or overall regression (middle Ilerdian-middle Lutetian). A correct understanding of this major genetic unit is essential to properly appreciate the early Paleogene evolution of the study area and, consequently, we will discuss it at some length.

Facies architecture

In the platform setting (i.e., Urbasa-Andia synclinorium), the T-R facies cycle is best expressed by the relative position of successive shallow-water carbonate platforms (Figs. 2 and 3). The transgressive phase began at the latest Maastrichtian with a rapid transgression and coastal onlap that reversed a previous regressive trend lasting during the Campanian-early Maastrichtian interval. Throughout Paleocene times, the relative sea-level rise led to the encroachment of wide shallow-water carbonate platforms, which were able to keep-up with the rise during Danian time (aggradational interval) but gave-up and back-stepped as the transgression proceeded during Thanetian time (Baceta, 1996). Such evolu-

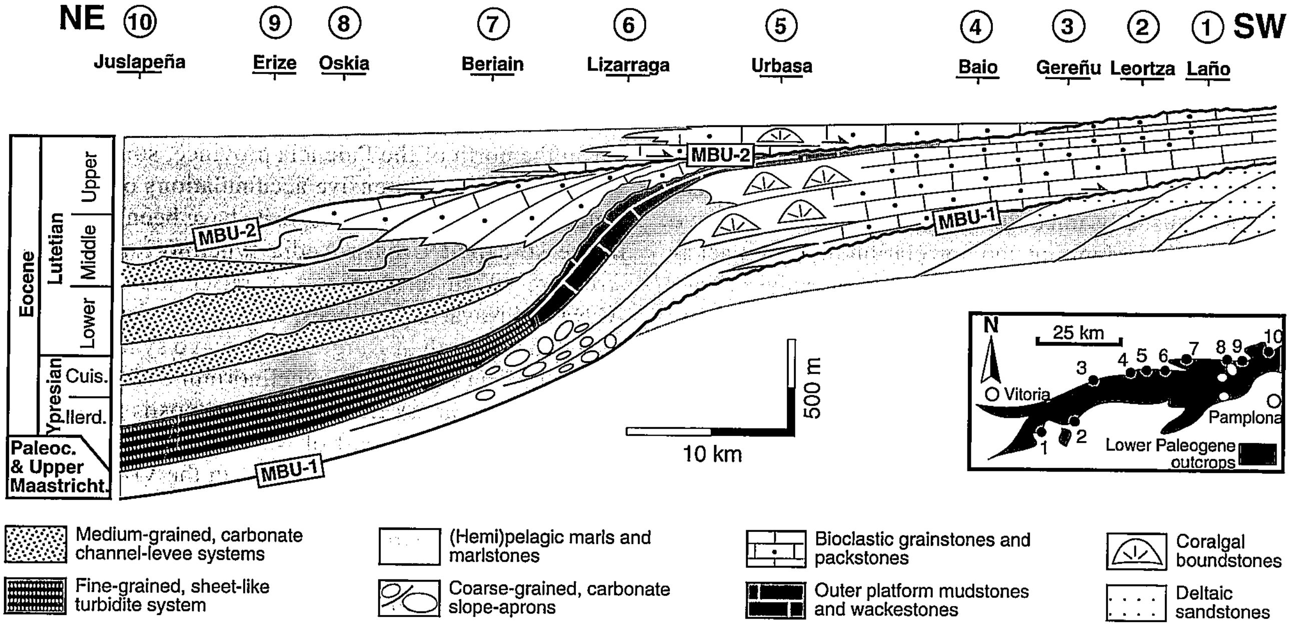

Figure 2.- Field expression of the uppermost Cretaceous-middle Eocene 2nd-order transgressive-regressive facies cycle as seen in the continuous cross-section exposed on the northern flank of the Urbasa synclinorium (Alava and Navarra provinces), when looking from the north. Explanation within the text.

tion clearly reflects an increase of accommodation space in the shallow setting. The transgression peaked during the early-middle Ilerdian (earliest Ypresian), when the former shelf-margin area was drowned, while the so-called «Alveolina Limestone» was deposited further inland. The ensuing overall regression forced a stepwise seaward displacement of the platforms, which was slow during late Ilerdian-Cuisian time (1st stage), but become rapid during the early and middle Lutetian (2nd stage), when most of the shelfal area became subaerially exposed and shallow-water carbonate deposition was constrained to a comparatively narrow belt in the former upper slope. Gently progradational carbonate ramps developed in the first stage of the overall regression, while offlaping platforms, bounded by angular unconformities, were constructed in the second stage (Payros, 1997). The regressive trend was reversed once again during the middle Lutetian, when another important relative sea level rise took place, which probably marks the onset of another 2nd-order cycle («Biarritzian transgression» of Hottinger and Schaub, 1961, and Plaziat 1981; Figs. 2 and 3).

The 2nd-order T-R facies cycle also influenced the accumulation into deep-water settings. In the base-of-slope, such influence is recorded in both the type of carbonate turbidite systems, created by resedimentation from the platforms, and in their respective grain-sizes: coarse-grained carbonate slope-aprons were deposited during the transgressive phase; fine-grained and sheet-like unconfined turbidites were accumulated during the peak transgression; and medium-grained channel-levee systems were developed during the overall regression (Pujalte *et al.*, 1998b). These variations, and geometrical relationships, clearly show that the characteristics of the resedimentation processes were largely determined by the position of the carbonate platforms with respect to the shelf-break (Figs. 2 and 3).

The T-R facies cycle is finally reflected in the deep basin by large-scale variations in the depositional rate and in the proportion and grain-size of siliciclastic turbidites. Thus, the overall transgression is represented in the Guipúzcoa homocline by a comparatively thin accumulation (80-200 m) of hemipelagic limestones, marls and thin-bedded carbonate turbidites. This «transgressive» accumulation overlies a 1,700 m thick turbiditic unit (the Campanian-lower Maastrichtian siliciclastic flysch, or Eibar Formation, of Mathey, 1987) deposited during a previous overall regressive episode. The peak transgression phase is recorded by a succession of variable thickness (50-300 m) composed of both diluted carbonate turbidites and fine-grained mixed carbonate-siliciclastic turbidites (the Hondarribia Formation of Rosell *et al.*, 1985). Finally, the regressive phase is typified in the Guipúzcoa homocline by a >2,000 m thick siliciclastic turbiditic unit (the Higuer-Getaria Formation, see below). Time spans of the Campanian-early Maastrichtian and Eocene regressional phases, and that of the latest Maastrichtian-Paleocene overall transgression were all roughly similar. However, while thick siliciclastic turbiditic units were deposited during the regressions, a comparatively thin hemipelagic succession was laid down during the transgression. In all likelihood, siliciclastic sediments reached the basin much more easily during the overall regressive phases partly because lowstand periods were then accentuated (see below), and also on account of a more active tecto-

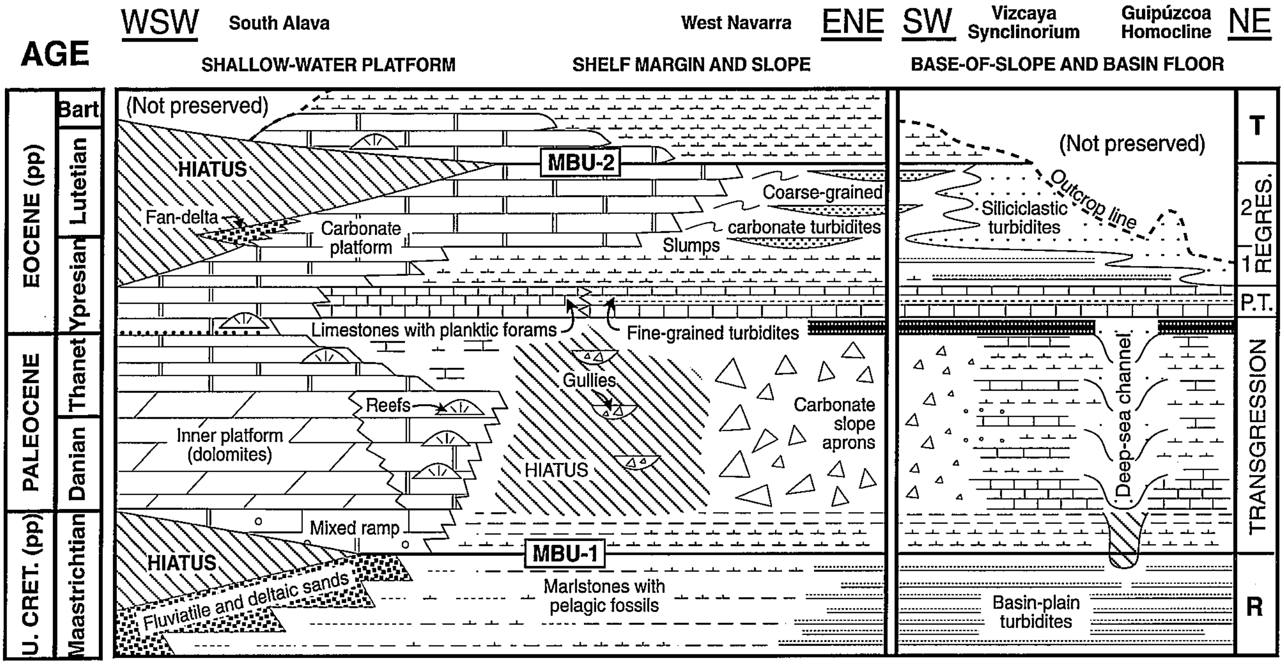

Figure 3.- Generalized chronostratigraphic framework of the upper Cretaceous-middle Eocene succession of the studied area (explanation within the text).

nism. By contrast, the basin tended to become starved of siliciclastic deposits during overall transgressions because of more lengthy highstand periods, and milder tectonism (Figs. 2 and 3).

It is important to mention that a deep-sea channel system was developed in the starved basin floor contemporaneously to the transgressive phase, a channel that lasted while the starvation persisted (i.e., until the early Ilerdian; Figs. 1a and 3). Consequently, it is strongly suspected that the creation and evolution of this channel was closely controlled by variations in sedimentary supply brought about by changes of sea level (Pujalte *et al.*, 1998c). In effect, according to Carter (1988), the fundamental control on the development of a deep-sea channel is the submarine base level, which operates in much the same way as the sea level does for land drainage systems. Thus, the low sedimentary supply during the overall transgression, unable to compensate the differential subsidence in the basin, would lower the submarine base-level, leading to the entrenchment of turbidite flows and excavation of the deep-sea channel. Later, the increased supply during the peak transgression would raise the base-level and promote its backfilling and burial.

Major Bounding Unconformities (MBU)

The T-R facies cycle is bounded in the shallow setting by two major unconformities, the character of which affords critical evidence about the origin of the cycle as a whole. The lower major bounding unconformity (MBU-1) was developed during the Maastrichtian; the upper one (MBU-2) during the middle Lutetian. Seaward, these unconformities are progressively less well marked, although their correlative conformities are still recognizable in the deep basin (Figs. 2, 3 and below).

The existence of the MBU-1 in the platform setting had long been noticed but, until recently, its stratigraphic position and meaning had been overlooked. For instance, 1:50,000 MAGNA maps do show that, on the southern flank of the Urbasa synclinorium, «Maastrichtian» rocks indistinctly overlay Campanian or Santonian deposits. Yet, this important break is not further mentioned in the accompanying memoirs (Carreras and Ramíres del Pozo, 1978). A more detailed analysis of this zone has recently been completed by Baceta *et al.* (1999), their results being summarized in figure 4.

Clearly, during the Campanian-early Maastrichtian interval both a gentle tectonic tilting and a relative lowering of sea level took place. The tilting is demonstrated by the truncation of strata situated below the MBU-1, the sea lowering by the regressive character of the Campanian-early Maastrichtian succession (marine limestones -> shallow marine and deltaic sandstones -> fluviatile sands rich in terrestrial vertebrate fauna, see *Astibia et al.*, 1999). Anticlinal and halokinetic structures were growing during that interval (Gómez-Alday *et al.*, 1994), while siliciclastic sediments were being flushed seaward, at increasing rates, along the intervening lows (Fig. 4). However, such overall regressive trend was reversed in the late Maastrichtian, as evidenced by the onlap of uppermost Cretaceous-lower Paleogene deposits onto the MBU-1 and by the increased marine influence in this same succession, which eventually resumed over the whole area. The creation of the

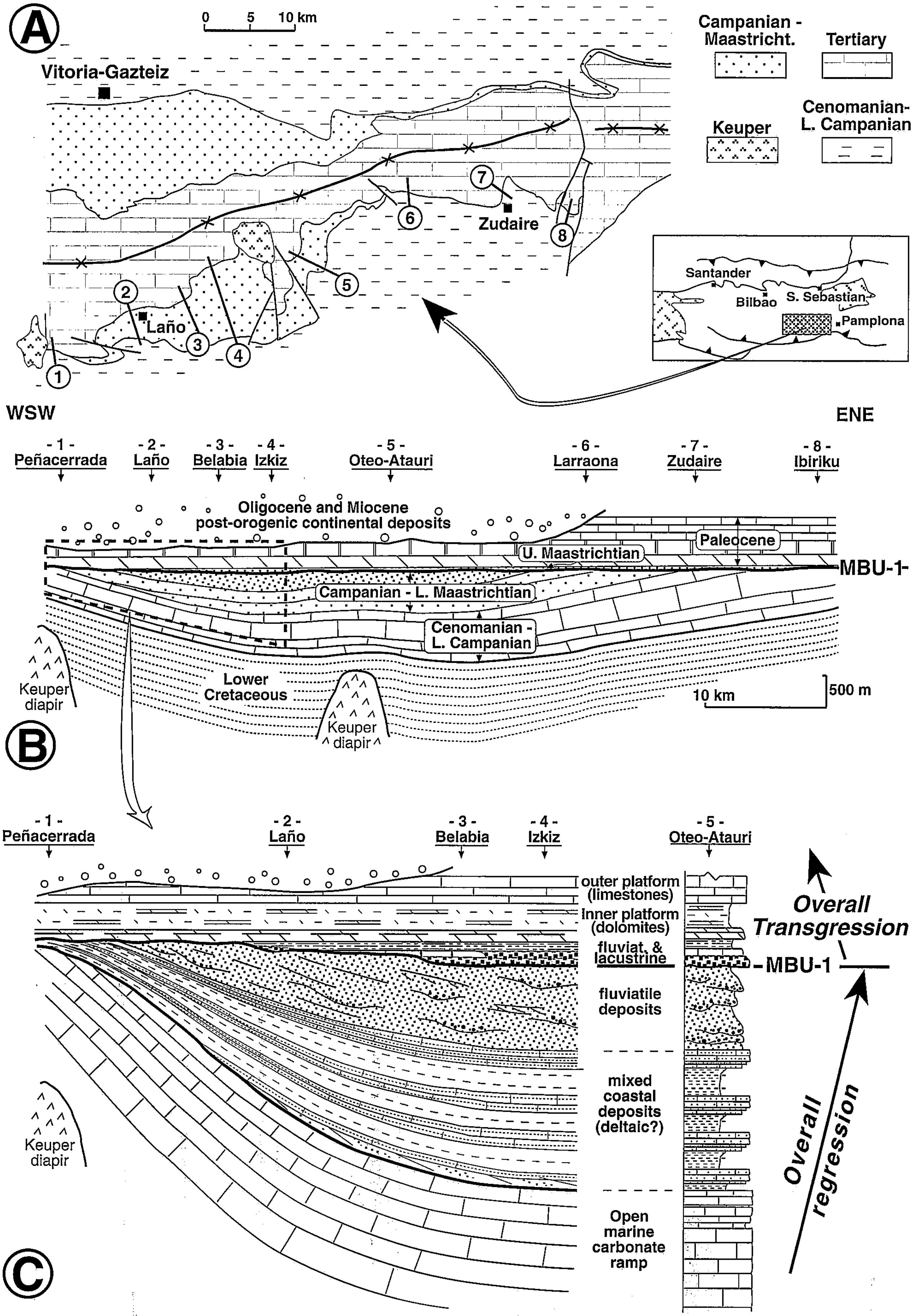

Figure 4.- Field expression of the lower Major Boundary Unconformity (MBU-1) of the 2nd-order transgressive-regressive facies cycle in the southern flank of the Urbasa synclinorium: A, location of key sections; B, general transversal section; C, detail of B.

MBU-1 was a consequence of that change in the overall trend (Fig. 4).

The origin of the MBU-2 (middle Lutetian) is similar to that of the MBU-1, since it also reflects a change from a tectonically active period with an overall regressive trend to another of subdued tectonism typified by overall transgression (Payros, 1997; Payros *et al.*, 1999a). Its field expression can be followed laterally from shallow to deep-water settings in a continuous transect from the Urbasa synclinorium to the Pamplona Basin (Fig. 2). In this transect, the overall regression can best be appreciated in the shallowing-upward character of the Eocene successions of the Lizarraga pass and the Beriain peak (Figs. 5A and D), and also in the offlaping shelfal wedges exposed on the northern flank of the Beriain syncline (Fig. 2). These wedges are separated by angular unconformities, a clear proof of active tectonism, which is also reflected in the contemporaneous catastrophic resedimentation of carbonate megabreccias (Payros *et al.*, 1999b). On the other hand, a later overall transgression is recorded by the landward displacement of middle Lutetian to Bartonian carbonate ramp deposits, which in the Lizarraga pass area unconformably overlie lowermost Lutetian carbonates (Figs. 3, 5B and 5D), while near Estella rest directly on Cretaceous rocks.

As mentioned above, both MBUs evolve basinwards to essentially conformable boundaries. Yet, they can still be pin-pointed in the deep-water setting at horizons in which there is a marked decrease in both sedimentation rates and grain-sizes of resedimented clastic deposits. Indeed, these boundaries separate turbidite-rich portions of the succession from turbidite-poor ones, and are recognizable basin-wide. Thus, in the Zumaia section (the most representative of the deep-water Basque Basin), sedimentation rates dropped from 200 m/my (compacted) for the lower Maastrichtian section, to less than 80 m/my for the upper Maastrichtian one (data of Ward, 1988), the change occurring precisely at a conformable boundary correlative of the MBU-1. A similar situation for the MBU-2 can be observed near the village of Erize, in the motorway section, approximately 13 km to the northwest of Pamplona (Fig. 5C).

Origin and areal extent

According to Vail *et al.* (1991) and Duval *et al.* (1998), T-R facies cycles are usually the stratigraphic expression of changes in the rate of tectonic subsidence. Indeed, the character of the MBUs discussed above clearly denotes a tectonic influence. Several lines of evidence further indicate that the latest Maastrichtian-early Ilerdian «transgressive» interval was a tectonically tranquil period, whereas middle Ilerdian-middle Lutetian «regressive» interval was characterized by active tectonism and crustal shortening (see, for instance, Puigdefabregas and Souquet, 1986; Razin, 1989; Burbank *et al.*, 1992; Baceta, 1996; Payros, 1997). Such timing, however, seems to contradict current models proposing that, in compressional settings, periods of active tectonism promote large-scale transgressions, while periods of little or no compression coincide with uplift and regression (e.g., Vail *et al.*, 1991). It is thus possible that our case study represents an exception or variation to the model of Vail *et al.* (1991). A likely cause to explain such seeming peculiarity is an overprinting by climatic forcing.

The existence of an early Paleogene cycle of global climate change has been pointed out by several authors. The most convincing evidences are oxygen isotope records from unaltered marine carbonates, especially from DSDP/ODP sites (e.g., Matthews and Poore, 1980; Miller *et al.*, 1987; Bralower *et al.*, 1995). According to Abreu *et al.* (1998), who have made a recent compilation of these results, three main isotopic cycles took place during the Cretaceous-Cenozoic interval, one of which encompasses most of the Paleogene (which they named Pi, Paleogene isotopic cycle). The Pi cycle probably started during the late Maastrichtian, when two positive events (cool climate) have been pinpointed. A trend towards lighter (negative) isotope values persisted during the Paleocene. The earliest Eocene yields the most negative values (- 0.5 %), this particular time being considered the warmest interval of the entire Cenozoic. Thereafter, a trend towards positive values developed, with a pronounced positive shift occurring in late Cuisian time. These results indicate that the overall transgression of the T-R cycle occurred during an interval of increasing global warming, the peak transgression was contemporaneous or near contemporaneous with the warmest interval of the Cenozoic, and the overall regression developed during a period of declining global temperatures, with the change from slow to rapid regression coinciding with a pronounced cooling.

An additional proof of this early Paleogene climatic cycle in the Basque Basin was afforded by the semiquantitative analysis of early Paleogene planktic foraminifers carried out by Orue-Etxebarria and Lamolda (1985). According to these authors, (i) the abundance of temperate-water globigeriforms declined from the early Paleocene to the early Eocene (i.e., overall transgression), indicating a progressive warming, (ii) the abundance of warm-water-loving keeled species of Morozovelids and Planorotalitids was only significant during the late Paleocene and early Eocene interval, and (iii) in the remainder of the Ypresian and Lutetian (i.e., overall regression) the proportion of Morozovelids and Planorotalitids decreased while those of globigeriforms increased. Assuming that such climatic variations ruled the position of global sea-levels, it can be concluded that the T-R facies cycle was largely driven by eustasy.

Depositional sequences (3^{rd} order)

The landward/seaward displacement of the uppermost Maastrichtian-Middle Eocene lithofacies descri-

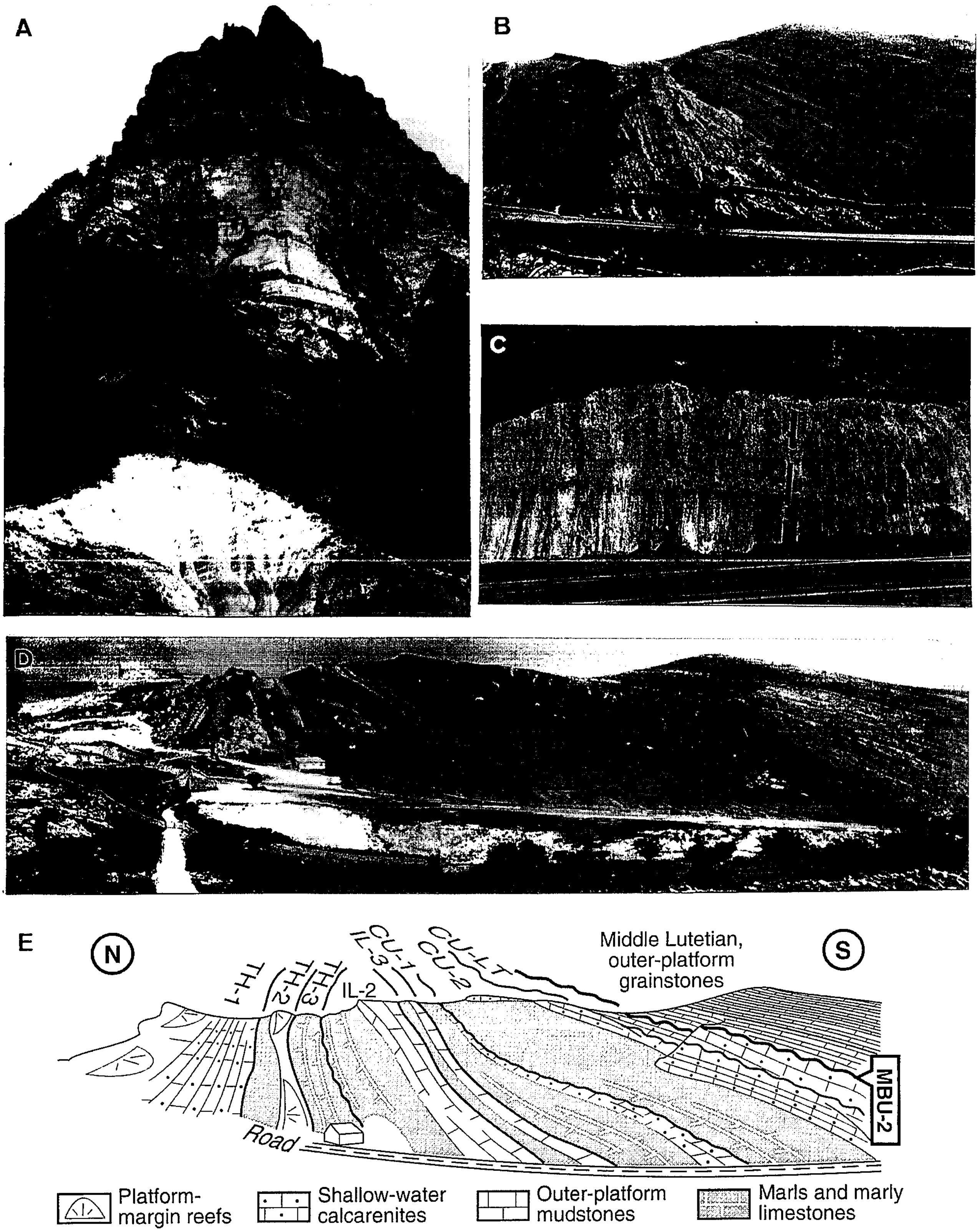

Figure 5.- Field photos of early Paleogene deposits of the Urbasa-Andia synclinorium, Navarra province: A, Eocene succession of the Berian Ridge outcrop (profile 7 in figure 2), showing the vertical transition from middle Ilerdian hemipelagic marls (lower part of the picture) to Lutetian shallow-water limestones (mountain top), a clear record of the second-order overall regression (thickness of the exposed succession = 700 m); B, the MBU-2 in the Lizarraga pass section (6 in figure 2), there represented by an angular unconformity between lower and middle Lutetian shallow-water limestones; C, the MBU-2 in the Erize section (motorway Pamplona-S. Sebastian, 9 in figure 2), there represented by a sharp but conformable transition from a turbidite-rich succession to a turbidite-poor one, both of middle Lutetian age (thickness of the exposed succession ca. 90 m); D and E, photo and line drawing of the middle and upper parts of the second-order T-R facies cycle in the Lizarraga pass section (6 in figure 2), showing also their constituent 3rd-order depositional sequences (thickness of the exposed succession ca. 200 m). Explanation within the text.

bed above is not a continuous one. Rather, it is punctuated by a number of more or less pronounced oscillations, readily attributable to 3rd-order variations of relative sea level. Their stratigraphic signature are the depositional sequences, which form the building blocks of the T-R facies cycle. Fifteen depositional sequences have been identified, which in the description that follows have been coded using the initial letters of their age (e.g., depositional sequence of the (uppermost) Maastrichtian-(lowermost) Danian = sequence Ma-Da). When more than one sequence developed during a stage, numbers are added (e.g., depositional sequences of the (lower) and (upper) Thanetian = sequences Th-1 and Th-2). The 9 sequences developed during the overall and peak transgression are recognized in the whole studied area. The remaining 6 sequences, developed during the overall regression, have been recognized so far only in the Pamplona Basin, although our results from this interval in the Basque Basin are still preliminary.

The character of these 15 depositional sequences varies depending on their position within the 2nd-order cycle. We have tried to explain these variations with the elementary model sketched in figure 6, which shows the relative changes of sea level (and of shelf accommodation space) resulting from the interaction of idealized curves of 2nd- and 3rd-order sea level variations. According to that model, during the overall transgression 3rd-order sea-level rises were reinforced, whereas falls were attenuated. Therefore, depositional sequences developed during the 2nd-order transgression would be expected to contain important transgressive and highstand systems tracts but poorly developed lowstand systems tracts. Although during the peak transgression the shape of the 3rd-order sea level curve was little affected, the sea level would always remain in a comparatively high position and, therefore, the shelf edge was never exposed subaerially. Finally, during the overall regression the situation would be more or less opposite to that of the overall transgression, with lowstand system tracts being now much better developed than transgressive and highstand ones. As shown in figure 7, and discussed below, although «intermediate» cases and exceptions do occur, the features of most of the 15 depositional sequences of the studied succession fit reasonably well with the predictions of the model in figure 6.

Sequences of the overall transgressive interval

Eight depositional sequences have been recognized within the succession deposited during the overall transgression. For descriptive purposes, they can be divided in two main groups, one comprising 3 sequences of late Maastrichtian and earliest Paleocene age (Ma-1, Ma-2 and Ma-Da), the other including 5 sequences of Paleocene and early Ilerdian age (Da-1, Da-2, Th-1, Th-2 and Il-1, see figure 8). Sequences of the first group have a mixed carbonate-siliciclastic character, while the other five have an essentially carbonate nature.

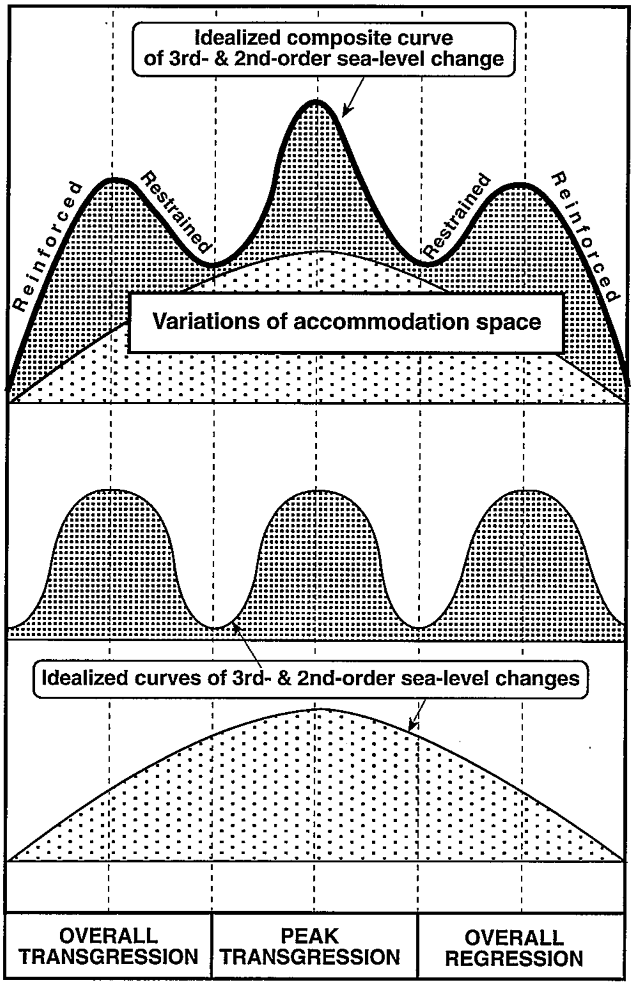

Figure 6.- Elementary model showing the sea-level changes resulting from the interaction of idealized 2nd- and 3rd-order changes of sea-level. Explanation within the text.

Late Maastrichtian and earliest Paleocene sequences. In the shallow setting, sequences Ma-1, Ma-2 and Ma-Da are bounded by erosional surfaces, which eventually merge into the MBU-1 of the 2nd-order T-R facies cycle (Figs. 4 and 8). The lower parts of sequences Ma-1 and Ma-2 are formed by aggradational to slightly progradational units of massive or thick-bedded sandy calcarenites rich in shallow-water larger foraminifers (orbitoids). They onlap abruptly their respective lower erosional boundaries, pinching out landwards and passing gradually basinwards to marls and marlstones with planktic foraminifers. These units are interpreted as lowstand wedges (LW).

The LW units are overlain in turn by retrogradational sets of well-stratified sandy calcarenites and marlstones, often floored by ravinement surfaces. These sets are interpreted as transgressive systems tracts (TST). Landwards of the pinching-out of LWs, TST deposits can either rest directly on the sequence boundaries, or else overlie cross-bedded conglomerates and sandstones that infill erosional features, which are thought to be incised valley fills (ivf) (Baceta *et al.*, 1994). The

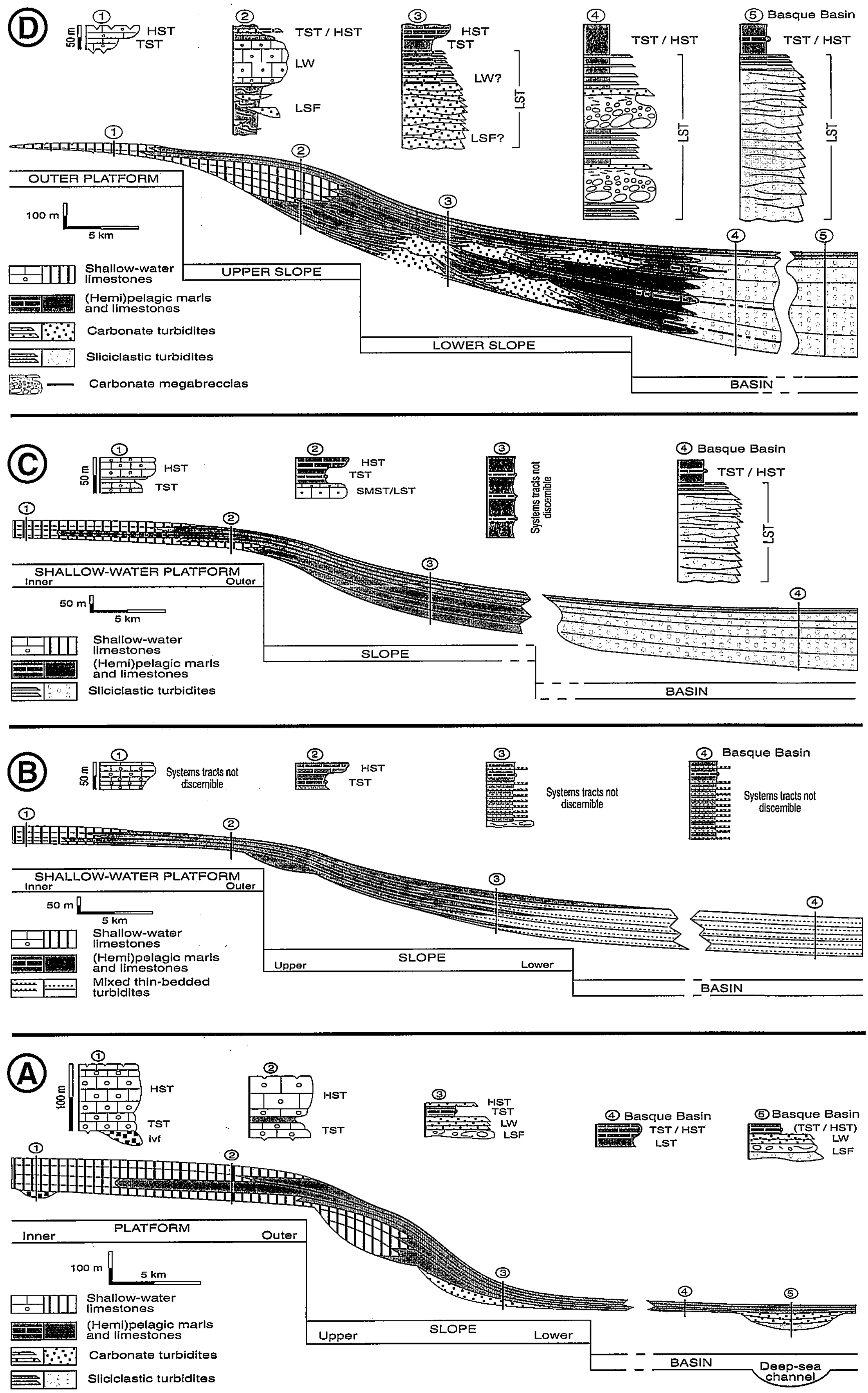

Figure 7.- Shelf-to-basin configurations of selected 3rd-order early Paleogene depositional sequences recognized in the studied succession (not to scale): A, Paleocene sequences, created during the overall 2nd-order transgression, showing well developed TST and HST systems tracts and poorly developed LST systems tracts; B, Early-middle Ilerdian sequence, created during the peak transgression, in which systems tracts are often difficult to recognize; C and D, late Ilerdian-middle Lutetian sequences, respectively created during the phase of slow and rapid (forced) regression, showing increasingly better developed LST systems tracts and poorly developed TST/HST systems tracts.

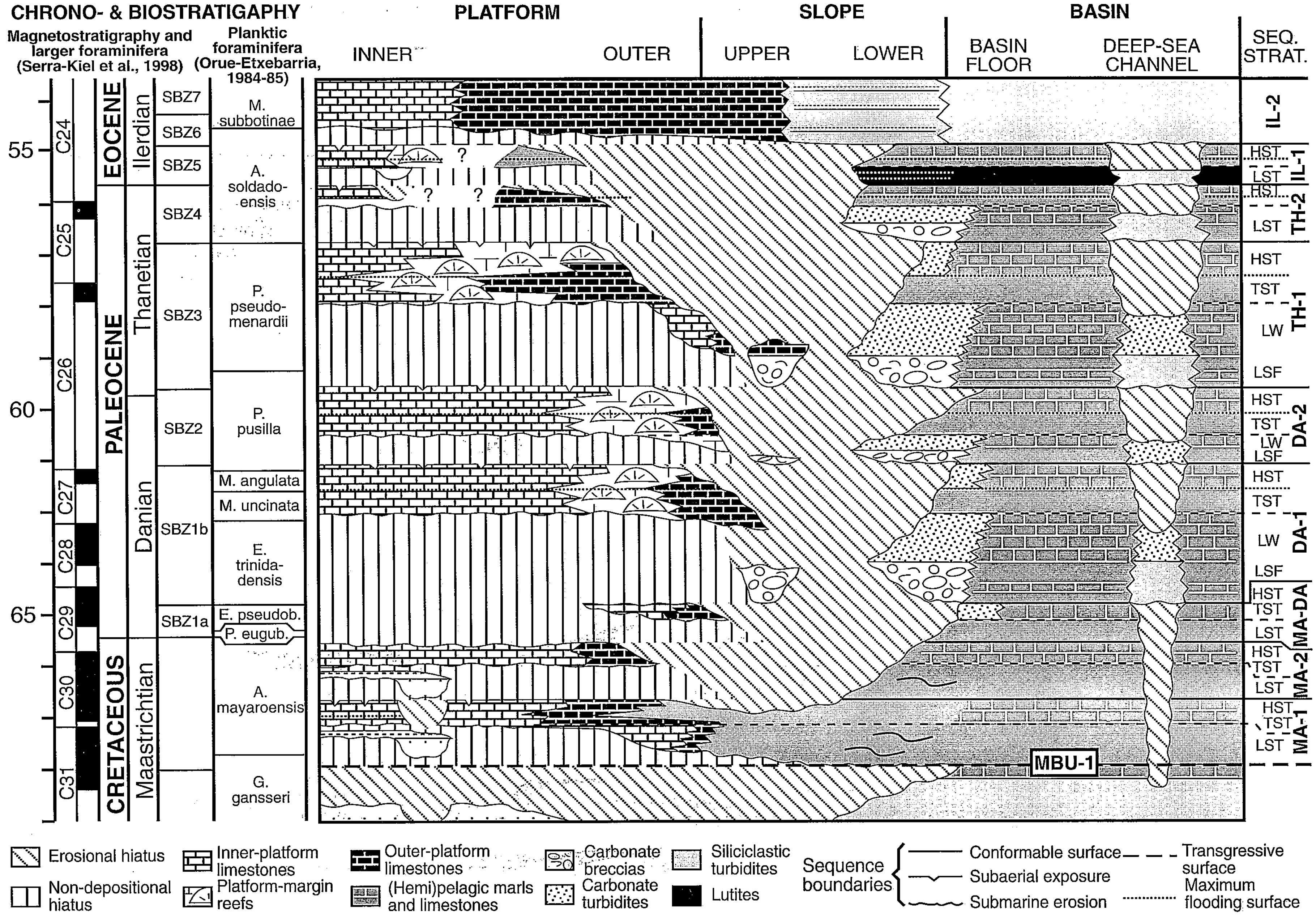

Figure 8.- Generalized chronostratigraphic framework of the latest Cretaceous-early Ilerdian 3rd-order depositional sequences recognized on the studied area. These sequences have been calibrated to the planktic foraminiferal zonation of Orue-Etxebarria (1983-84) and the benthic foraminiferal zonation of Serra-Kiel *et al.* (1998) and to magnetostratigraphy (after Baceta, 1996). Explanation within the text.

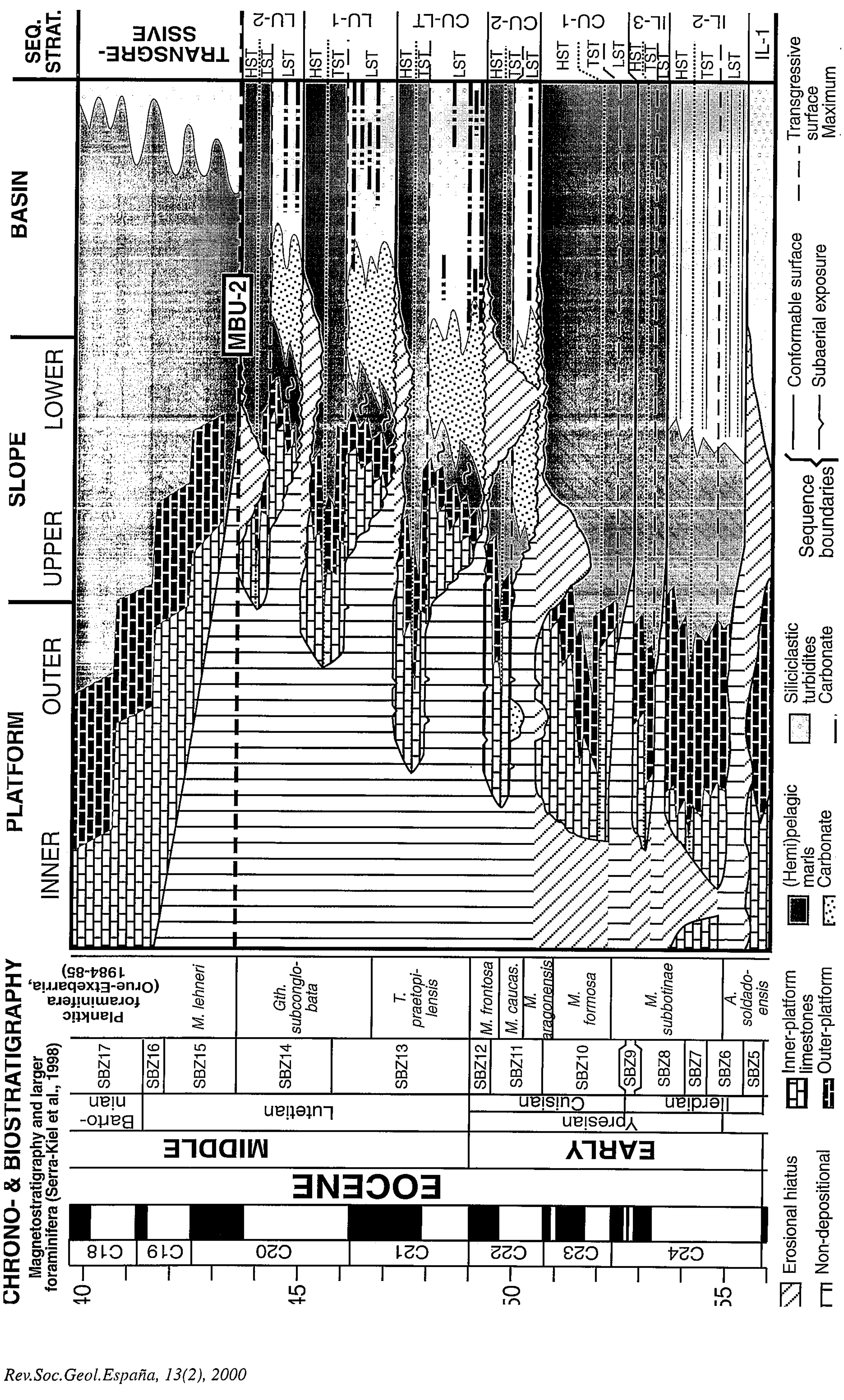

Figure 9.- Generalized chronostratigraphic framework of the early Ilerdian-Lutetian 3rd-order depositional sequences recognized on the Urbasa synclinorium and the Pamplona Basin. These sequences have been calibrated to the planktic foraminiferal zonation of Orue-Etxebarria (1983-84) and the benthic foraminiferal zonation of Serra-Kiel *et al.* (1998) and to magnetostratigraphy (after Payros, 1997). Explanation within the text.

remaining parts of sequences Ma-1 and Ma-2, ascribed to highstand system tracts (HST), are represented in the more landwards sections by fresh or brackish water limestones with occasional evaporite intercalations, probably lagoonal or palustrine deposits; elsewhere, they are formed by progradational stacks of marine marls and calcarenites. Depositional sequence Ma-Da has a poor development in the platform setting, having being found only in a few sections of the western part of Navarra. Thus, in the Urbasa pass it is represented by algal-rich limestones, whereas in the Lizarraga pass it is made up of alternating marls and limestones with planktic foraminifers, both examples being considered TST/HST deposits.

In the basinal setting, sequences Ma-1, Ma-2 and Ma-Da are composed of two parts. The lower ones mostly consist of purple and/or greenish marls, which in some sections intercalate thin-bedded turbidites. They are interpreted as muddy lowstand slope fan complexes (LSF). Their basal limits are abrupt but essentially nonerosional, neither of them implying a biostratigraphically recognizable hiatus. They most likely represent the distal, conformable surfaces of their respective sequence boundaries. The upper parts of sequences Ma-1, Ma-2 and Ma-Da are mostly made up of light grey or reddish hemipelagic limestones alternating with marls, with occasional intercalations of thin-bedded bioclastic turbidites. They are interpreted as TST/HST deposits (Fig. 8). The features and thicknesses of these three sequences in the basinal setting are remarkably similar in widely separated coastal sections of the Bay of Biscay, from Sopelana in the western tip of the Biscay synclinorium, to Hendaye in the French-Spanish border (Ward, 1988; Pujalte et al., 1995, 1998a). The K/T boundary is placed within sequence Ma-Da (see Apellaniz, 1999, for a recent detailed account).

Paleocene-early Ilerdian sequences. The latest Maastrichtian ramp first became distally steepened and then transformed into a rimmed carbonate platform at the beginning of the Paleocene. In the new paleogeographic arrangement (which persisted with minor variations during the remainder of Paleocene times), five different sedimentary domains can be recognized: *(i) The carbonate platform,* mainly represented by shallow water limestones and dolostones, with minor intercalations of sandstones and sandy marls. These deposits form a composite sedimentary body of relatively uniform thickness (around 300 m), tens of km wide and hundreds of km long. A wide variety of subenvironments (tidal flats, lagoons, reefs, etc.) can be recognized. *(ii) The upper slope*, a comparatively narrow belt of reduced sedimentation and widespread hiatuses, which sometimes comprise the whole Paleocene. The only deposits of this zone are carbonate breccias and coarse-grained carbonate turbidites that infill erosional gullies deeply excavated into upper Cretaceous marlstones. *(iii) The carbonate slope-apron,* made up of a variable proportion of carbonate breccias, coarse-grained and fine-grained carbonate turbidites and hemipelagic limestones and marlstones. These essentially resedimented carbonates fringe the carbonate platform, from which they were clearly shed, as evidenced by their position and paleocurrent directions. *(iv) The basin-floor,* represented by characteristic rhythmic alternations of marls and hemipelagic limestones (globigerinid mudstones and wackestones), usually with minor intercalations of thin-bedded turbidites. Thin accumulations of these deposits (30-100 m) mantle most of the basin floor downcurrent of the carbonate slope apron. *(v) The deep-sea channel*, a large-scale erosional feature, partly filled with coarse-grained carbonate turbidites and massive coarse-grained siliciclastic turbidites (Pujalte *et al.*, 1998c)

Five depositional sequences (Da-1, Da-2, Th-1, Th-2 and Il-1), and their constituent systems tracts, have been recognized on representative sections of each of these different domains (Fig. 8). The features of their systems tracts are summarized in the idealized reconstruction of figure 7a, their particulars being described by Baceta (1996). Note only that all of them are predominantly of a carbonate nature, and that their TSTs and HSTs are much better developed than their LSTs. The remaining sequence (Il-1) differs from the other four in having a lowstand system tract mostly composed of siliciclastic deposits, either coarse-grained sandstones in the shelf and deep-sea channel settings or fine-grained deposits (claystones, lutites) in the slope-apron and basin-floor. The reasons for the near absence of carbonate deposition during the accumulation of this system tract are not yet fully understood, although they seem to be related to an interval of unusual global climate, now known as the Late Paleocene Thermal Maximum (Pujalte *et al.*, 1998d; Schmitz et al., submitted).

Sequence of the peak transgression interval (early-middle Ilerdian)

The 2nd-order overall sea level rise peaked at the Early-Middle Ilerdian (earliest Eocene), causing the partial drowning of the outer platform and pushing the carbonate factory landwards. While the succession deposited during this interval does show marked lateral facies changes (see below), its vertical stacking pattern is generally very monotonous, making it hard to establish internal subdivisions of regional validity. Therefore, we have included the totality of the deposits of this succession into one single sequence (Il-2). In fact, the internal homogeneity of this sequence renders it difficult to recognize systems tracts.

Sequence Il-2 is represented in the inner platform setting by bioclastic grainstones and packstones rich in larger benthic foraminifers, notably alveolinids (i.e., Alveolina Limestone Formation of many authors). In the outer platform and upper slope settings, it is typified by alternating marly limestones and marls, both containing planktic foraminifers, an association that attests to the drowned character of the shelf-margin setting during the peak transgression. In the base-of-slope, sequence Il-2 consists of a comparatively thick succession of medium- and fine-grained plane-parallel turbidites of great lateral continuity. Their characteristic unconfined nature denotes deposition in a linear-sourced turbidite system, a further proof that during the accumulation of this sequence the sea level remained always above the shelf-break (Figs. 7b and 8). As a whole, these slope deposits smoothed out the inherited steep Paleocene platform-margin physiography (Fig. 2). In the basinal setting, sequence Il-2 has a mixed-character, being composed of an alternation of very diluted carbonate turbidites and of thin- to medium-bedded siliciclastic turbidites brought into the basin by axial flows. (This association is manificiently exposed in a famous cliff and wave-cut platform outcrop situated in the east part of the Zumaia beach, in Guipúzcoa. Photos of this outcrop have appeared in many publications, often as the cover photo, as is the case of the classic book of Pettijohn and Potter, 1964. Pictures of it can also be found on web pages of American Universities. At the village of Zumaia itself, the outcrop is currently advertised as a touristic attraction, with the name of «Flysch»).

Sequences of the overall regressive interval in the Pamplona Basin (middle Ilerdian-middle Lutetian)

As mentioned above, the overall regression occurred during an interval of increasing tectonic activity, in the course of which the study area became subdivided into different depocenters. Each of these depocenters has its own depositional style and, seemingly, its own specific set of sequences. Thus, carbonate-dominated deposition still continued in the west part of the Pamplona Basin, whereas in the Guipúzcoa homocline (Basque Basin) deposition had mainly a siliciclastic character (see below). Current knowledge of these two successions is dissimilar, our results from the Guipúzcoa homocline being still preliminary. Therefore, they will be described separately, and following different approaches.

Six depositional sequences have been recognized in the Pamplona Basin, two of them created during the slow phase of the overall regression (Il-3 and Cu-1), four during the rapid one (Cu-2, Cu-Lt, Lt-1 and Lt-2). Their full description can be found in Payros (1997), with a summary of their main features being given below and in figures 7c, 7d and 9.

Sequences Il-3 and Cu-1 are best delineated in the inner platform setting, where they are composed of TST and HST systems tracts and bounded by mildly erosive surfaces. TST deposits are made up of massive packstones rich in nummulitids that grade up into marly packstones with glauconite and planktic faunas, likely representing maximun flooding surfaces. HST deposits consist of shallowing-up successions of nummulitid-rich packstones passing up into grainstones rich in alveolinids and miliolids. These systems tracts are also recognized in the outer platform setting, TSTs being composed of alternating glauconitic marls and marly limestones with planktic fauna, and HSTs of wackestones and packstones with larger forams. Such facies associations indicate that, during the late Ilerdian and early Cuisian times, water depth at the outer platfom setting was generally relatively large, even surpassing the tolerance of larger foraminifers during transgressive intervals. Sequences Il-3 and Cu-1 can not be differentiated in basinal areas, where they are represented by a monotonous succession exclusively composed of hemipelagic marls (Figs. 5A and 9).

Sequences Cu-2, Cu-Lt, Lt-1 and Lt-2, which accumulated during the phase of rapid regression, show important differences with the two described above. First, these four sequences are absent from inner platform settings, areas that became permanently emergent during the middle Cuisian-middle Lutetian interval. In the outer platform setting, sequences Cu-2, Cu-Lt, Lt-1 and Lt-2 are mostly composed of TST/HST shallow-water bioclastic grainstones and bounded by surfaces with abundant features of meteoric diagenesis, a clear proof of long periods of subaerial exposure. Fan-delta conglomerates and incised-valley sandstone infills have also been recognized in sequence CU-2 .

However, the mort prominent feature of the sequences developed during the phase of rapid regression is the important development of their lowstand deposits, in accordance with the prediction of the model in figure 6. Thus, sequences Cu-2, Cu-Lt, Lt-1 and Lt-2 are bounded in the upper slope by large-scale scars, created during episodes of massive resedimentation recorded by accumulations of carbonate breccias and coarse-grained turbidites in the base-of-slope (LSF deposits). Lowstand wedges (LW) composed of shallow-water bioclastic grainstones were then developed above the large-scale scars. They wedge out landward by onlap onto their lower sequence boundaries and are internally typified by low angle clinoforms denoting a progradational character (Fig. 2). Seawards, they evolve to hemipelagic marls, which are often slumped and contain frequent gullies infilled by carbonate turbidites. In turn, this facies association passes downdip to carbonate turbiditic fans developed in the base of slope, in which the volume of bioclastic grainstone accumulation was similar to that of the shallow water wedges sourcing them, a fact implying an efficient mechanism of resedimentation. However, during TST/HST intervals, the resedimentation processes slowed down or halted, and the carbonate turbiditic fans systems were mantled with hemipelagic marls.

As it is well know, a large-scale siliciclastic turbiditic system was developed in the South-Central Pyrenean foreland Basin during the middle Cuisian-middle Lutetian interval (i.e., the Hecho Group of Mutti *et al.*, 1972, 1985). This axially-flowing system reached to the eastern part of the study area, where it is represented by stacks of plane-parallel siliciclastic turbidites alternating with hemipelagic marls. Age correlations demons-

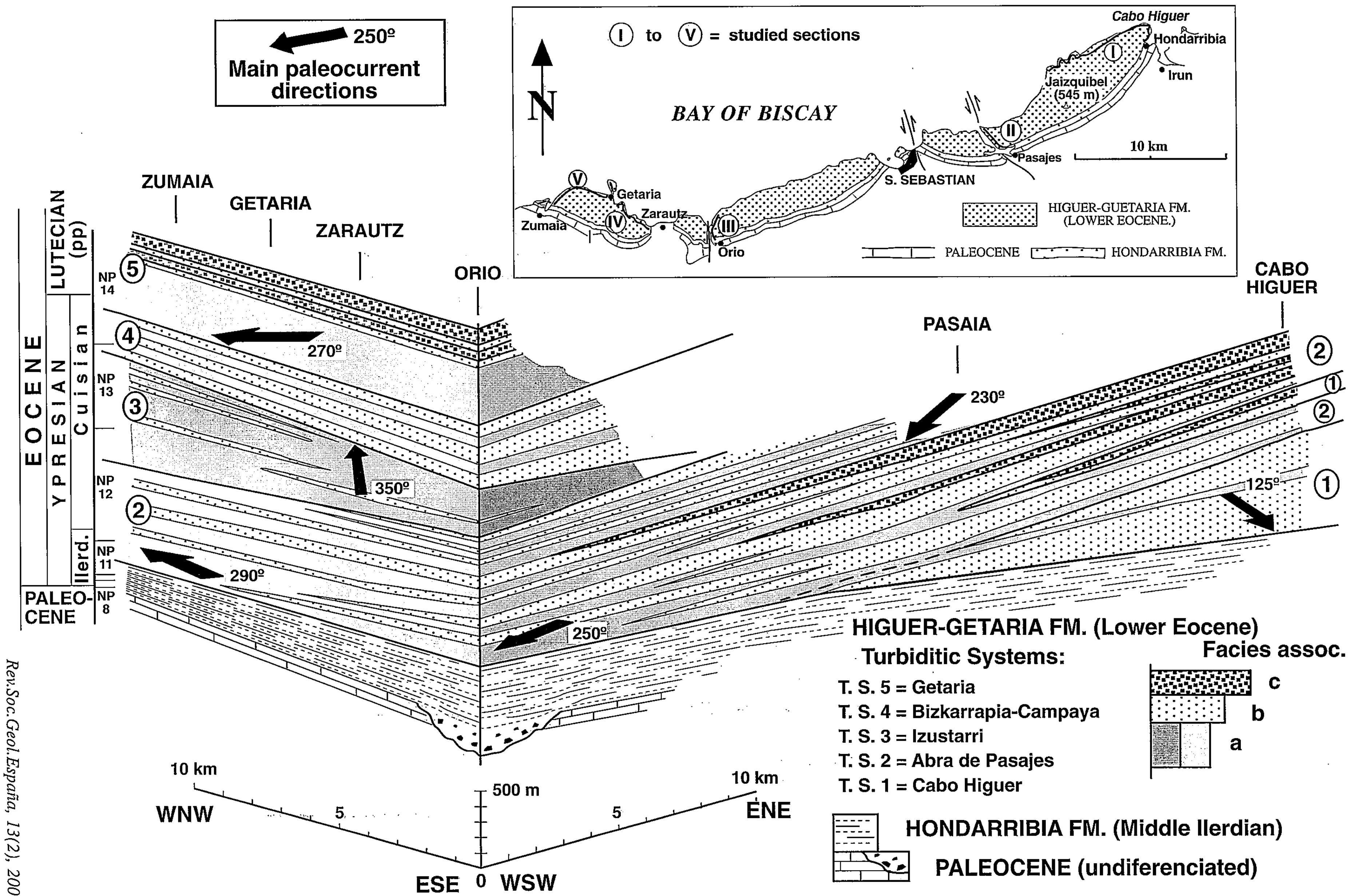

Figure 10.- Lithostratigraphic cross-section of the upper Ilerdian-lower Lutetian succession of the Gipuzkoa homocline showing distributions of facies associations, turbiditic systems and paleocurrents. Inset: outcrop map and location of studied sections.

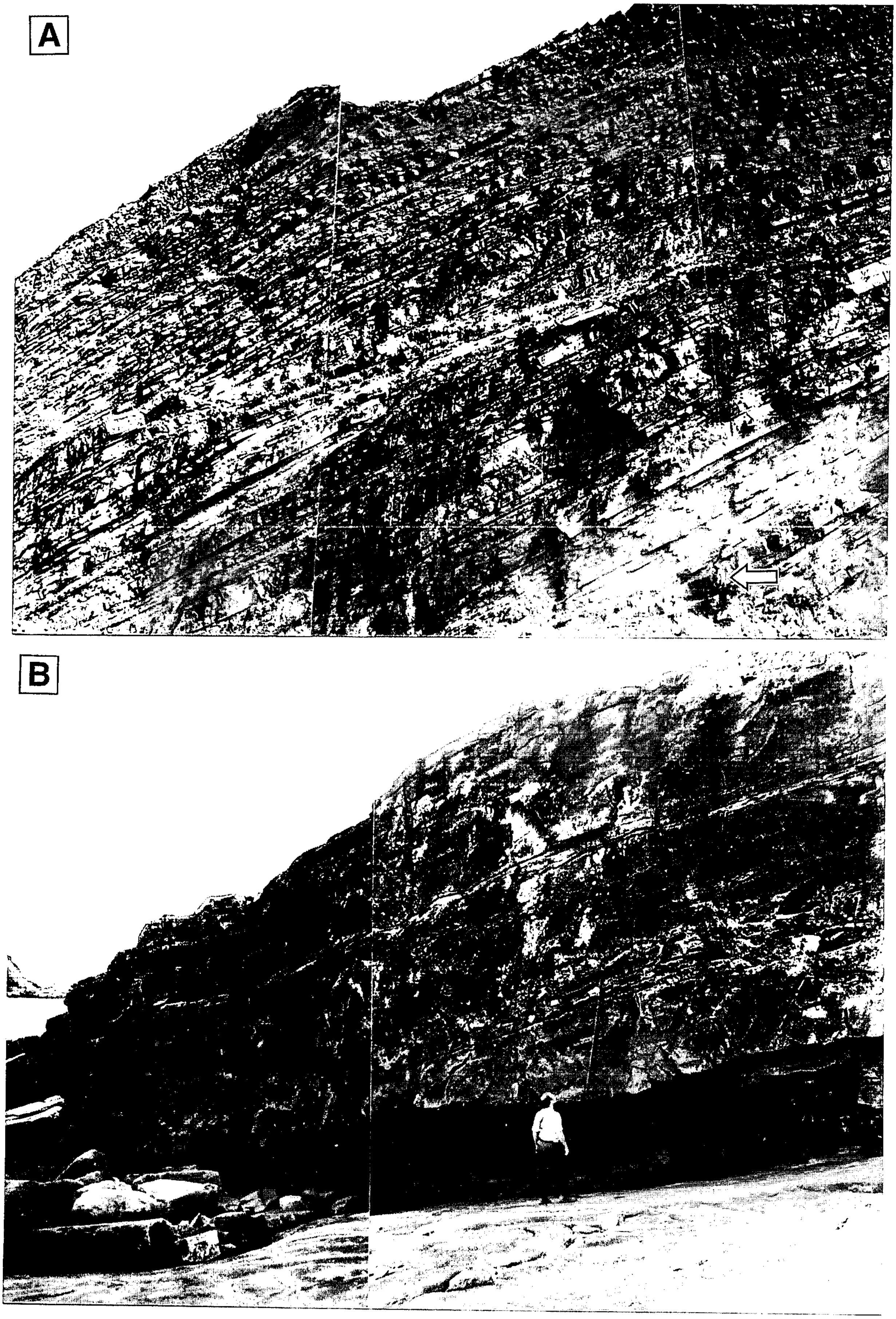

Figure 11.- Field photos of Eocene flysch deposits of the Gipúzcoa homocline: A, facies association A of turbiditic system 3 in the Zumaia-Getaria road. These plane-parallel beds are attributed to lobe deposits (road and geologist at the bottom gives scale). B, amalgamated beds of facies association B (turbiditic system 4, near Getaria), probably channel-lobe transition deposits.

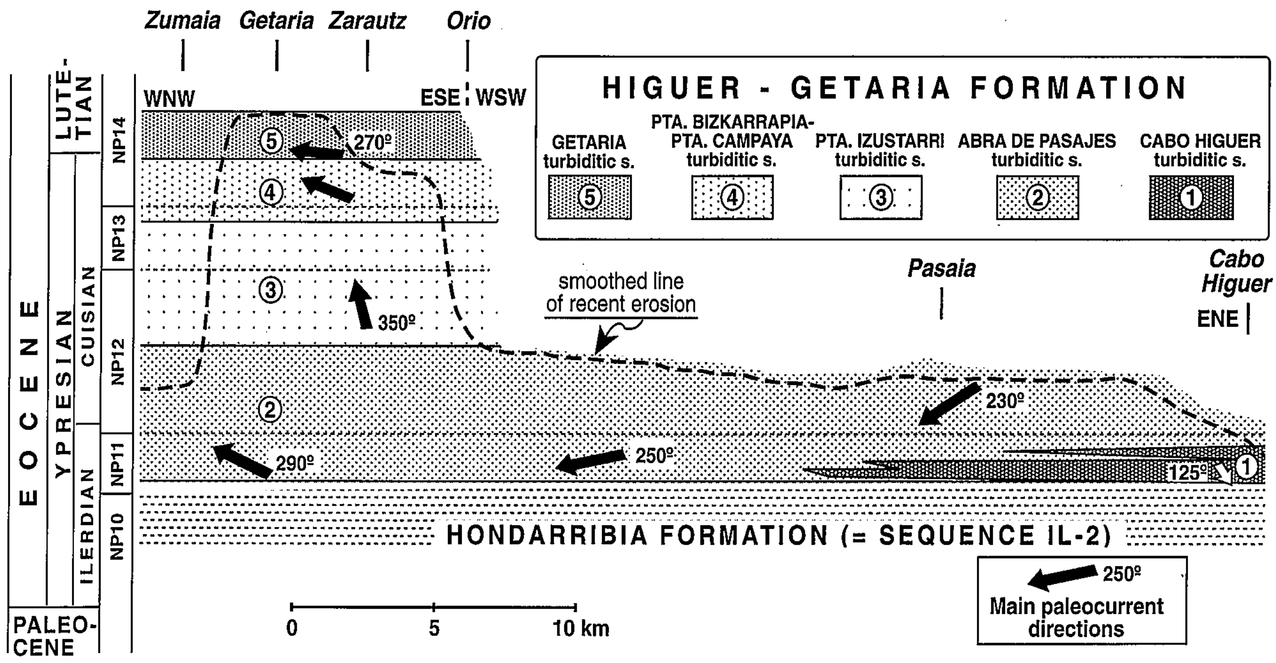

Figure 12.- Chronostratigraphic framework of the upper Ilerdian-lower Lutetian succession of the Gipúzcoa homocline. Calcareous nannofossil zonation after Van Vliet (1982).

trate that, during lowstand intervals on the west part of the Pamplona Basin, the siliciclastic turbidites in the east part are thicker and more frequent. Besides, these turbidite-rich intervals contain one or more intercalations of carbonate megabreccias, created by catastrophic collapses of the southern carbonate platforms (Payros *et al.*, 1999b). Such coincidences strongly suggest that the third-order variations of sea level recognized in the Pamplona Basin may have influenced the deposition of siliciclastic turbidites on the entire South-Central Pyrenean foreland Basin, and be also related with the large-scale resedimentation processes recorded by the carbonate megabreccias.

Upper Ilerdian-lower Lutetian deposits of the Guipúzcoa Homocline (Basque Basin)

As previosly mentioned, the Eocene is represented in the Basque Basin by a thick succession of siliciclastic turbidites, probably a stack of lowstand deposits accumulated during the overall regression of the 2nd-order T-R facies cycle (Fig. 3). These deposits, beautifully exposed on coastal cliffs, were the objective of sedimentological studies in the 70's and early 80's, those of Kruit *et al.* (1975) and Van Vliet (1978, 1982) being the most important. Our own study of the upper Ilerdian-lower Lutetian succession of the Guipúzcoa homocline began in 1998, our preliminary results being presented here.

Data base. Five stratigraphic profiles have been logged, their situation being shown in figure 10. Recent erosion has removed the upper part of the succession at diferent levels and, therefore, the stratigraphic spans of the profiles are variable, that of Zumaia-Getaria being the most complete. In every profile, lithologies, facies, facies associations and paleocurrents were systematically analized. Correlations between profiles were established whenever possible on the base of physical criteria, such as lateral tracing of thick beds in the field and/or air photos. Otherwise, a biostratigraphic correlation was established on the base of the calcareous nannoplankton information of Van Vliet (1982).

Results: Three main facies asocciation (A, B and C in figure 10) have been distinguished. Facies association A is composed of plane-parallel sandstone beds ranging in thickness between 0.1 and 1 m, of facies C1, C2, D1 and D2 of Mutti and Ricci-Luchi (1975). These beds have great lateral continuity and are usually intercalated in a background facies of fine-grained lutites with occasional hemipelagic limestone interbeds (Fig. 11A). Depending on the proportion of turbidites and background deposits, facies association A is attributed to sandy lobes, lobe fringes or basin-plain sub-environments.

Facies association B is made up of coarse- to very coarse-grained sandstones in beds 1 to 3 m thick, that are usually amalgamated in units 10 to 30 m thick (Fig. 11B). These beds exhibit large-scale erosional and depositional structures (megaflutes, dunes and cross-bedding), that are similar in dimensions, orientation in relation to paleocurrents and internal features to those described by Vicente Bravo and Robles (1995) in the Albian Black Flysch of Bizcay. Futhermore, they are frequently deformed by water-escape structures (dish, large-scale convoluted-bedding, etc.). These deformational structures are often truncated by comparatively thin beds (5 to 50 cm) that exhibit a range of structures generated by traction currents, from small current ripples (and current laminations) to 3-D dunes (and cross-stratification) with wave-length of up to 9 m. These tractive structures are thought to record by-passing turbidite currents. Facies association B probably was created in areas of rapid flow expansion and enhanced flow turbulence, conditions that often take place in the channel-lobe transition zones (Vicente Bravo and Robles, 1995).

Facies association C consists of coarse-grained sandstones and pebbly sandstones, in beds 1 to 4 m thick, which are amalgamated in 10-40 m thick units. These units may show pronounced channelling, but otherwise have similar structures to that of association B. Facies association C is therefore ascribed to turbidite channels and to proximal parts of the channel-lobe transition zones.

The correlation of the five studied profiles, coupled with the paleocurrent analysis, allowed the individualization of five different turbiditic systems (Figs. 10 and 12). These systems, fed from marginal zones, expanded axially within a deep-water sedimentary trough of an orientation similar to that of the Basque Arc. Turbiditic systems 1 (Cabo Higuer) and 2 (Abra de Pasajes), which are partly contemporaneous (upper Ilerdian-lower Cuisian) were fed from a siliciclastic source area situated to the north of the present-day outcrops. The turbiditic system 3 (Punta Izustarri, middle Cuisian, Fig. 11A) differs from the other four systems in two main features: (i) it is the only one originated in the southern margin of the trough, as demonstrated by its paleocurrent pattern (Figs. 10 and 12); and (ii) it has a mixed carbonate-siliciclastic nature, a fact further reinforcing a different source area. Turbiditic systems 4 (Pta. Bizkarrapia-Pta. Campaya, upper Cuisian) and 5 (Getaria, lower Lutetian) were again sourced from northern siliciclastic areas.

Concluding remarks

Sequence stratigraphy has revealed as a powerful tool with which to study most of the uppermost Cretaceous-middle Eocene succession of the Basque-Cantabrian Basin and the western Pyrenees. On the one hand, it has allowed the subdivision of the succession into a comparatively low number of units, and has therefore helped to simplify and rationalize the regional stratigraphic nomenclature. In the present case, at least, this has been a significant improvement, for the succession is made up of a wide range of facies, from coarse-grained continental conglomerates to deep marine hemipelagic marlstones. Use of classic stratigraphic methods in the past has indeed led to the creation of a plethora of local names (e.g., S. Justi Formation, Lithothamium Limestone, Danian Limestone, Alveolina Limestone, etc.) but failed to produce a coherent scheme of general acceptance. More important perhaps, sequence stratigraphy is helping to refine the correlation between shallow- and deep-water deposits. In the case of the studied succession, this correlation is difficult to establish with biostratigraphic criteria alone, since shallow deposits are mainly dated with larger foraminifera (e.g., Serra-Kiel *et al.*, 1998) whereas planktic foraminifera and calcareous nannofossils are used for deep-water successions. Yet, the exact intercalibration between the biostratigraphic scales of these fossil groups is still somewhat controversial, different stages being used in fact for some time periods (e.g., Ilerdian/Cuisian vs. Ypresian).

The position of the lower limit of the Ilerdian (an informal stage defined by Hottinger and Schaub, 1961, on the base of larger foraminifera) in the planktic foraminiferal scale is a good example to illustrate the point above. Following sequence stratigraphic criteria, Baceta (1996) suggested that the onset of the Ilerdian took place during the middle part of planktic foraminiferal biozone P5 (*Morozovela velascoensis* biozone, see also figure 8). Such proposition, which may eventually prove to be of importance for the redefinition of the Paleocene-Eocene boundary, did contradict the previously widely held idea that the bases of both the Ilerdian and the P5 biozone were approximately contemporaneous (e.g., Molina *et al.*, 1992). The outcome of this issue is still unsettled. However, a recent re-study of the Ilerdian parastratotype (Orue-Etxebarria *et al.*, submitted) has added much support to the proposition advanced by Baceta (1996).

Sequence stratigraphic units are, by definition, genetic ones. They are ideal therefore to reconstruct the paleogeography and evolution of a given area and to make comparisons with other basins (e.g., Pujalte *et al.*, 1998e; Neal and Hardenbold, 1998). Nevertheless, it is pertinent to point out that application of sequence stratigraphy has been greatly facilitated by the following qualities of the study area: (i) there exists a whole facies range of uppermost Cretaceous-middle Eocene strata, and they are widely outcropped; (ii) the platform-to-basin transition, a key zone to monitor sea-level changes, is preserved and accessible in the western part of the Navarra province (Baceta *et al.*, 1992); (iii) key sections of the succession can be biostratigraphically zoned with accuracy; and, (iv) tectonic deformation is usually mild, often making it possible to map out lateral facies changes.

In fact, in zones of the study area lacking these qualities, application of sequence stratigraphy is difficult. This is the case, for example, of the lower Eocene succession of the Guipúzcoa homocline, where 3rd-order depositional sequences have not yet been identified. As mentioned above, our knowledge of this particular area is still preliminary, and ongoing research might eventually delineate them. However, it is also possible that, because of the geographic restrictions of the outcrop and/or the non-accessibility of their shallow-water counterparts, a pure sedimentological approach -in the line of the one advanced here- is better suited to analyze this particular succession. In other words, while sequence stratigraphy is clearly a desirable approach to study sedimentary successions, its feasibility is by no means universal. Whether or not the use of alternative methods is preferable will be dictated in each case by the individual conditions of the succession under study.

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