THE PALEOCENE/EOCENE BOUNDARY INTERVAL IN THE ZUMAIA SECTION (GIPUZKOA, BASQUE BASIN): MAGNETOSTRATIGRAPHY AND HIGH-RESOLUTION LITHOSTRATIGRAPHY

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Abstract: The Zumaia section, in the Basque Basin, has been proposed by several previous authors as a prospective candidate for the Global Stratotype Section and Point of the Paleocene/Eocene (P/E) boundary. In support of such a proposition, we want to present in this paper new data on this section, which includes: (a) an analysis of the effects on the stratigraphic succession of several small faults that disjoin the P/E boundary interval; (b) a bed-to-bed lithological column of the succession, that provides a firm base for future high-resolution studies of the section; (c) the results of a magnetostratigraphic analysis of the lower part of the P/E boundary interval, which have led to the location of the geomagnetic Chron C25n; (d) the initial results of ongoing high resolution biostratigraphic studies of planktic foraminifers and calcareous nannofossils. Zumaia contains one of the most expansive P/E boundary sections with deep-water marine deposits so far reported, and has already been the subject of several detailed biostratigraphic, mineralogical and chemostratigraphic investigations. Together with these previous studies, the new data presented here contributes to make it one of the best documented P/E boundary sections to date. Zumaia, therefore, will remain as an important reference section even if eventually it is not singled out as the P/E Global Stratotype.

Key words: Paleocene/Eocene boundary, Zumaia, Basque Basin, magnetostratigraphy, lithostratigraphy, calcareous plankton

Resumen: La sección de Zumaia, en la Cuenca Vasca, ha sido propuesta por varios autores previos como potencial estratotipo global del límite Paleoceno/Eoceno (P/E). En apoyo de tal proposición, en este trabajo presentamos nuevos datos sobre la sección, que incluyen: (a) un análisis de los efectos sobre la sucesión estratigráfica de diversas fallas de pequeña entidad que segmentan el intervalo P/E; (b) una columna litológica «capa-a-capa», que puede servir de base para futuros estudios de alta resolución de la sección; (c) los resultados de un estudio magnetoestratigráfico que ha permitido aproximar la posición del Cron C25n; (d) los resultados iniciales de investigaciones en curso sobre foraminíferos planctónicos y nannofósiles calcáreos. Zumaia contiene una de las secciones más expandidas del intervalo del límite P/E en facies marino profundas conocidas hasta la fecha, y ha sido ya objetivo de numerosas investigaciones biostratigráficas, mineralógicas y quimioestratigráficas. Conjuntamente con tales estudios previos, la nueva información ahora aportada contribuye a hacer de Zumaia una de las secciones del límite P/E mejor documentadas de las descritas hasta la fecha. Ello hace de Zumaia una importante sección de referencia, incluso en el caso de que eventualmente no sea elegida como estratotipo global del límite Paleoceno/Eoceno.

Palabras clave: Límite Paleoceno/Eoceno, Zumaia, Cuenca Vasca, magnetoestratigrafía, litoestratigrafía, plancton calcáreo

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The Paleocene and the Eocene Series/Epochs were originally defined with a paleontological objective, which was to separate ancient life forms (Paleo-cene) from modern ones (Eo-cene) (Lyell, 1833; Schimper, 1874). However, different fossil groups chose dissimilar moments to evolve and, consequently, there currently exist several non-coeval Paleocene/Eocene (P/E) boundaries (see Aubry and Berggren, 2000, and Aubry, *in press*, for updated reviews). Needless to say, the use of non-coeval criteria to define the same nominal boundary is a source of confusion for non-specialists and students of Historical Geology alike.

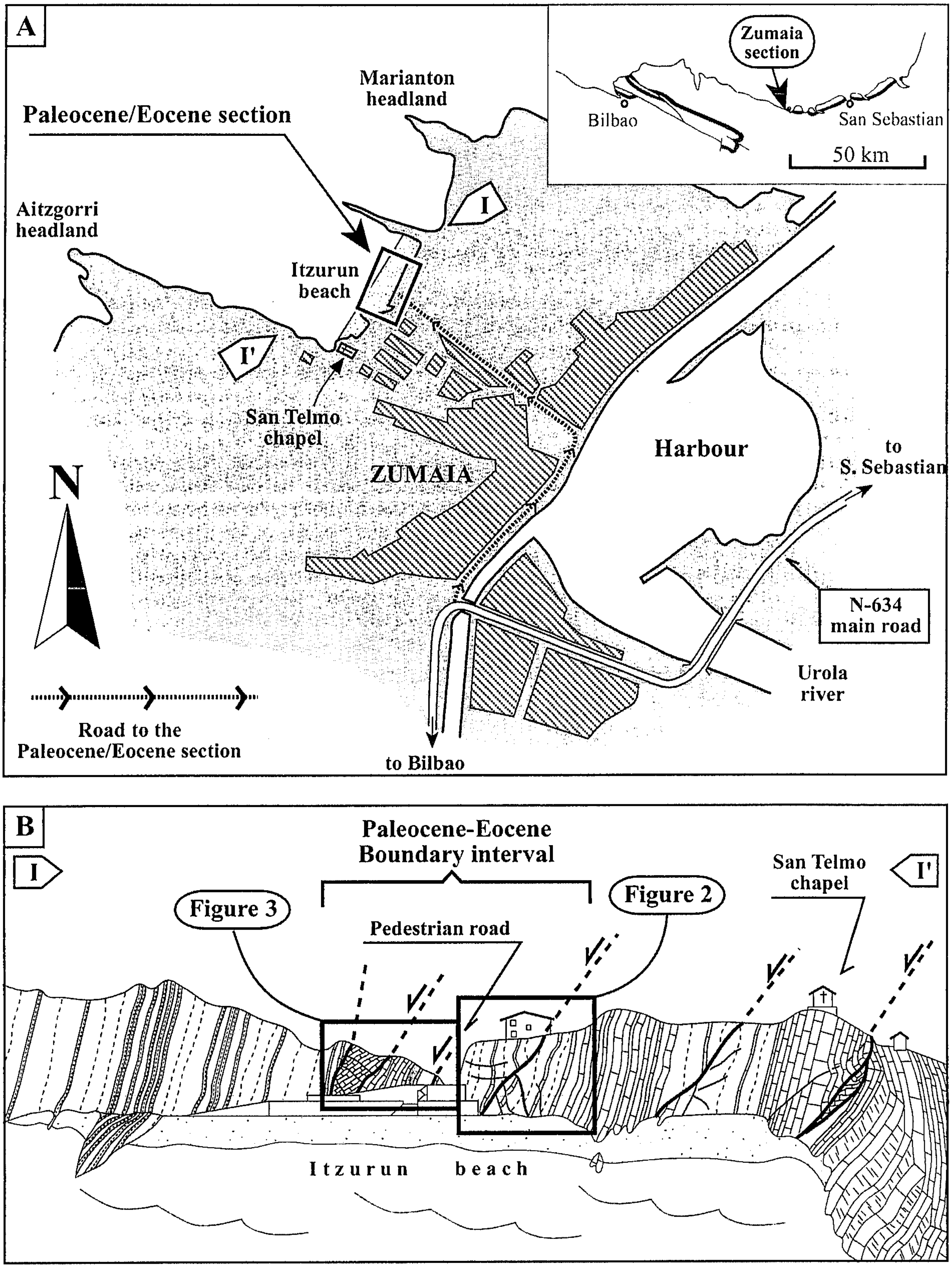

Figure 1.- (A) Location of the Zumaia Paleocene/Eocene boundary section; (B) Field-sketch of the outcrop, in the cliffs of the Itzurun beach. The limestones in the right hand (SW) side of the outcrop are of Danian age, while the turbiditic succession in the left hand (NE) side correspond to the early Eocene.

To resolve this undesirable situation, an International Working Group was created in 1988 (i.e., IGCP Project 308, Paleocene/Eocene Boundary Events in Time and Space), with the specific objectives of (i) to agree on a single defining criterion to mark the P/E boundary, and (ii) to select a new Global Boundary Stratotype. A decision about the former issue is soon to be taken, the most likely criterion to be chosen being the important extinction event of deep-marine benthic foraminifers (BEE) and the coeval negative excursion of carbon isotopes (CIE) (Schmitz *et al.*, 2000). As per the boundary stratotype, several sections have already been proposed, among which Zumaia ranks high in the preferences of many Working Group participants (e.g., Molina, 1996; Schmitz *et al.*, 1998). The Zumaia section, in effect, complies with most of the requirements listed by the International Commission on Stratigraphy (ICS, see Remane *et al.*, 1996), namely: (a) it posses an adequate thickness of exposed sediments, since the P/E boundary interval in Zumaia is in fact but a small segment of a near-continuous section spanning from the Campanian to the lowest Lutetian; (b) no biostratigraphic gap or condensation are recognizable; (c) a high sedimentation rate, Zumaia being in fact one of the most expansive open marine successions of the P/E interval so far reported (Molina, 1994, 1996; Molina *et al.*, 1999; and below); (d) identifiable geochemical and geomagnetic signals (Schmitz *et al.*, 1997 and below), a clear proof of minor diagenetic alteration; (e) abundant, well diversified open marine fossils, including planktic foraminifers and calcareous nannofossils; (f) good exposure and easy accessibility.

While we support Zumaia as the Global Stratotype, we must also state that the P/E boundary interval do has some problems, which in our opinion have not been properly addressed in previous papers on this section. One of these is the existence of several small faults, and it is the first aim of this paper to analyze their character and to discus their relevance for the reconstruction of the original stratigraphic succession.

The other two main objectives of this paper are to locate the position of the geomagnetic Chron C25n, and to present an up-dated high-resolution columnar litholog of the P/E boundary interval at Zumaia, with which we intend to provide a firm foundation for ongoing and future studies of the section.

Setting, location and previous works

The P/E boundary interval (P/E BI) is mostly represented at the Zumaia section by alternating hemipelagic limestones and marlstones, plus numerous intercalations of thin-bedded turbidites (see below). These deposits were laid down in an offshore basin (here called the Basque Basin) at an estimated water-depth of about 1000 m (Pujalte *et al.*, 1998a, and references therein). Following later compression, these deep-water deposits were uplifted and are currently outcropped next to the township of Zumaia, in the Itzurun beach (often wrongly referred to in the geological literature as the S. Telmo beach; however, S. Telmo is but the name of the small chapel overlooking the beach, see Fig. 1A). More specifically, the P/E BI occurs in and around the pedestrian road leading from the town to the beach (Fig. 1A). In fact, the road splits the outcrop in two segments, referred to below as the southern and northern ones. The lower part of the P/E BI is exposed in the southern segment, whereas the middle and upper parts of the P/E BI occur in the northern one (Fig. 1B). We have calculated that the thickness of succession hidden by the road between both segments is about 3 m, assuming that no faulting occurs in the unexposed part.

Due to its easy accessibility and superb quality of exposure, the Zumaia section already attracted the attention of pioneer workers in the region (e.g., Gómez de Llarena, 1946). It was later the subject of general studies about planktic foraminifers (Hillebrandt, 1965), calcareous nannofossils (Kapellos, 1974; Van Vliet, 1982) or sequence stratigraphy (Baceta, 1996; Pujalte *et al.*, 1998a), to mention but a few. Several other papers have focused in the analysis of the P/E BI, including Canudo and Molina (1992), Canudo *et al.* (1995), Ortiz (1995), Schmitz *et al.* (1997, 1998), Knox (1998) and Addatte *et al.* (2000), which have covered topics such as biostratigraphy (planktic and deep-benthic foraminifers, calcareous nannofossils), stable isotopes and clay-mineral analysis.

Tectonic deformation of the Zumaia P/E boundary interval

The existence of several small faults or «tectonic disturbance zones» has been quoted in most published descriptions of the Zumaia section (e.g., Hillebrandt, 1965; Gawenda *et al.*, 1999). However, as far as we are aware, none of the previous accounts of the section made any specific mention about whether these faults omit or repeat parts of the stratigraphic succession. To investigate this point, we have made a careful correlation of the successions exposed in both the hangingwalls and footwalls of these faults, the results being shown in figures 2 and 3.

Figure 2 depicts the succession outcropped in the southern segment of the P/E BI (see location in figure 1B). The main tectonic disturbance in this outcrop is the fault labeled F1, which is accompanied by a swarm of smaller, satellite faults. Clearly, the main effect of fault F1 has been the duplication of the interval comprised between reference beds F and K (Fig. 2). Our data show that this duplication would not be detected by biostratigraphic methods, as the whole duplicated interval is situated within the same planktic foraminiferal and calcareous nannofossil biozones (see below). Nevertheless, failure to recognize the tectonic duplication would result in an overestimated stratigraphic thickness. It is also relevant to mention that the lower half of this outcrop is no longer visible, because of the recent construction of a concrete staircase descending to the beach. Therefore, the duplication illustrated in figure 2 is even more difficult to appreciate nowadays than it was five years ago.

The northern outcrop is affected by three additional faults (F2, F3 and F4 in figure 3). The attitudes and the effects of faults F2 and F3 are similar to that of fault F1, having both produced duplications of parts of the succession (Fig. 3). These three fractures might be in-

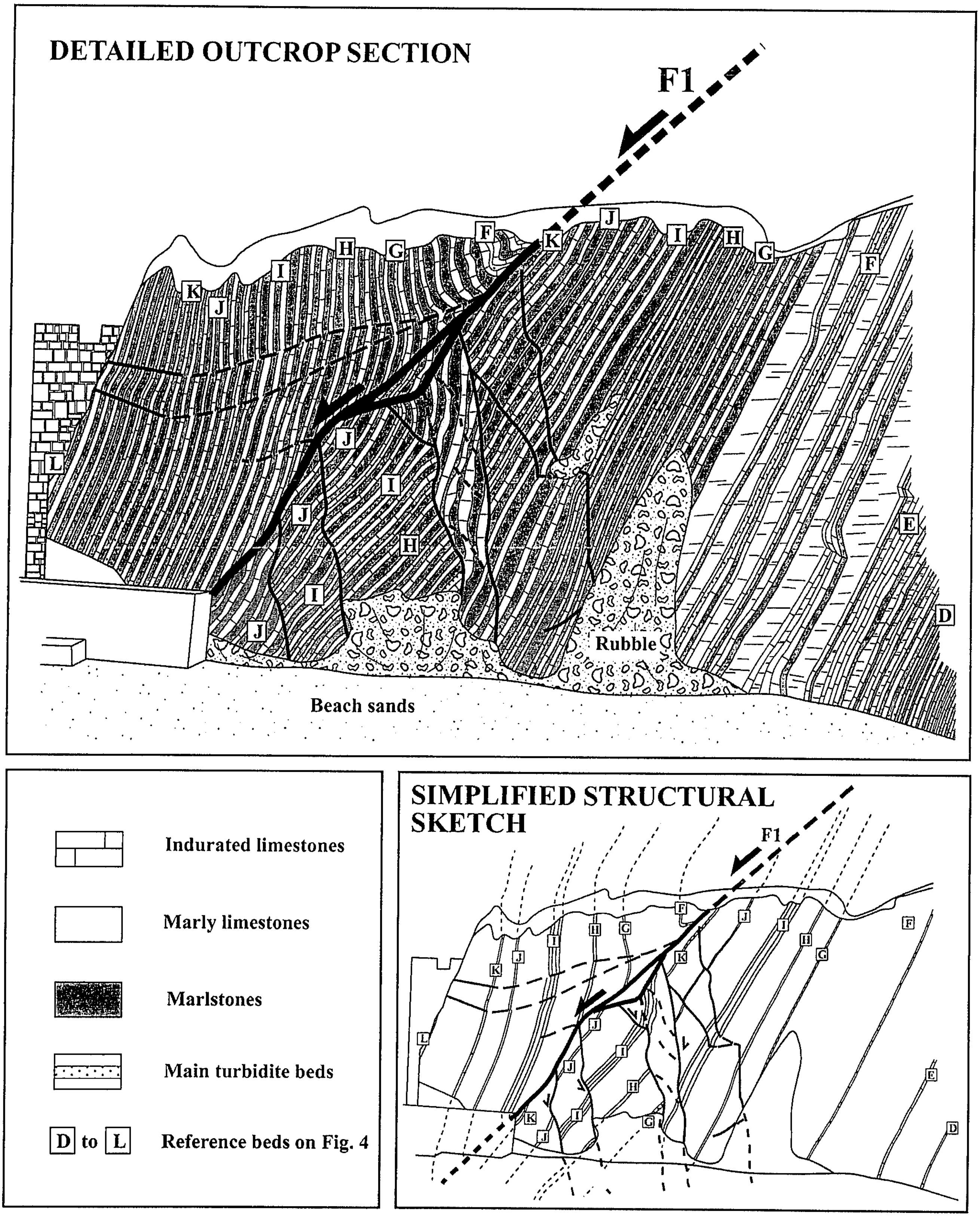

Figure 2.- Field-sketch of the southern segment of the Paleocene/Eocene boundary interval of the Zumaia section (for situation, see figure 1B). Explanation within the text.

terpreted as normal faults, with their fault planes dipping now about 40° /50° toward their apparently downthrown blocks. However, regional data discussed elsewhere (Baceta, 1996) suggest two additional alternative interpretations: (a) the faults represent small ramps of reverse fractures of a large-scale duplex system, created during early phases of compression and rotated to their present position during the folding of the succession: the same compressional forces would be responsible for the inter-stratal shear zones, which are relatively common throughout the studied interval (Fig. 4); (b) the faults are strike-slip fractures, created in the

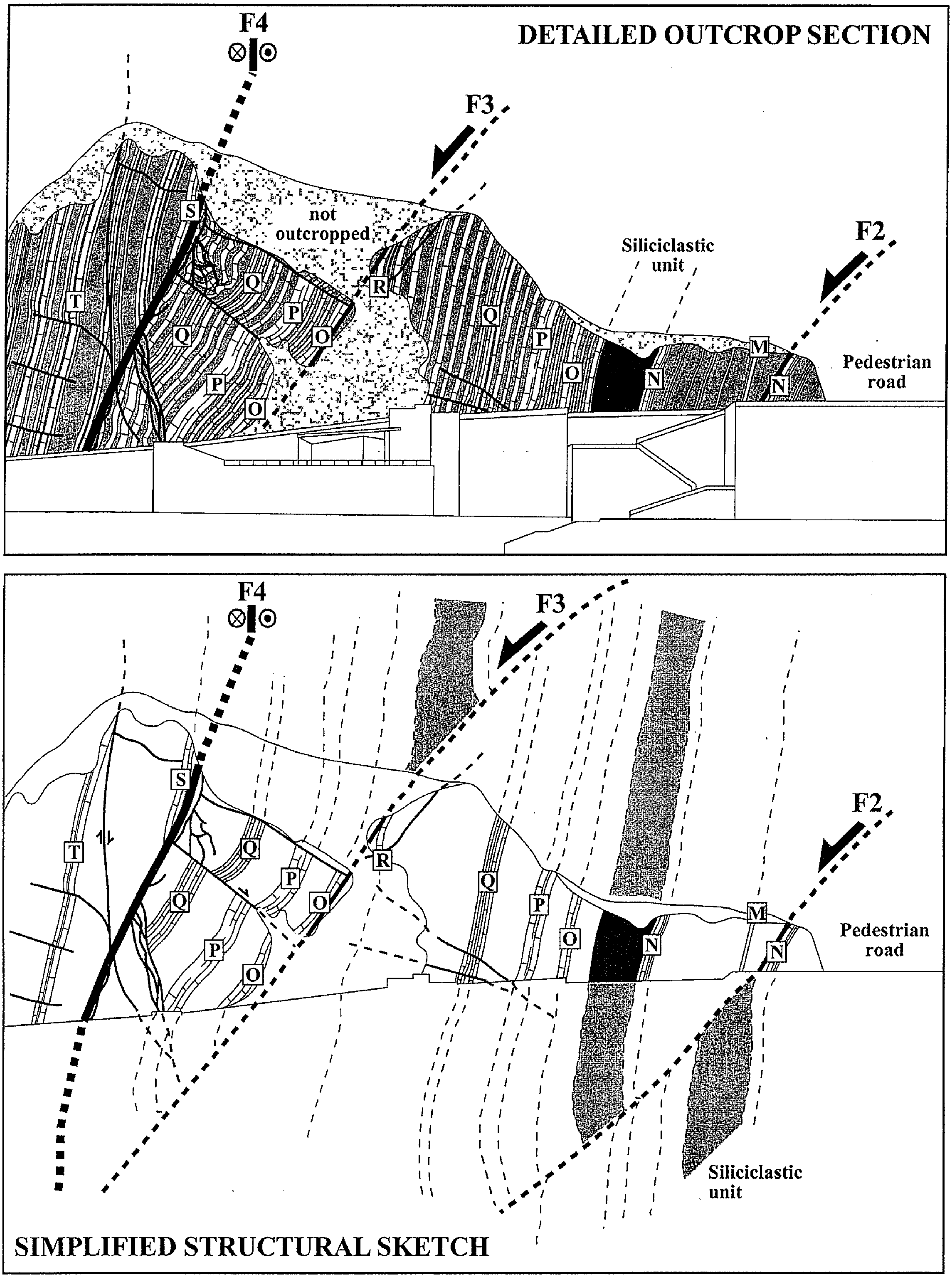

Figure 3.- Field-sketch of the northern segment of the Paleocene/Eocene boundary interval of the Zumaia section (for situation, see figure 1B). Explanation within the text.

latest phases of compression. A full discussion of the pros and the cons of each alternative is, however, beyond the scope of this paper.

Fault F4 is different from faults F1, F2 and F3, ha-

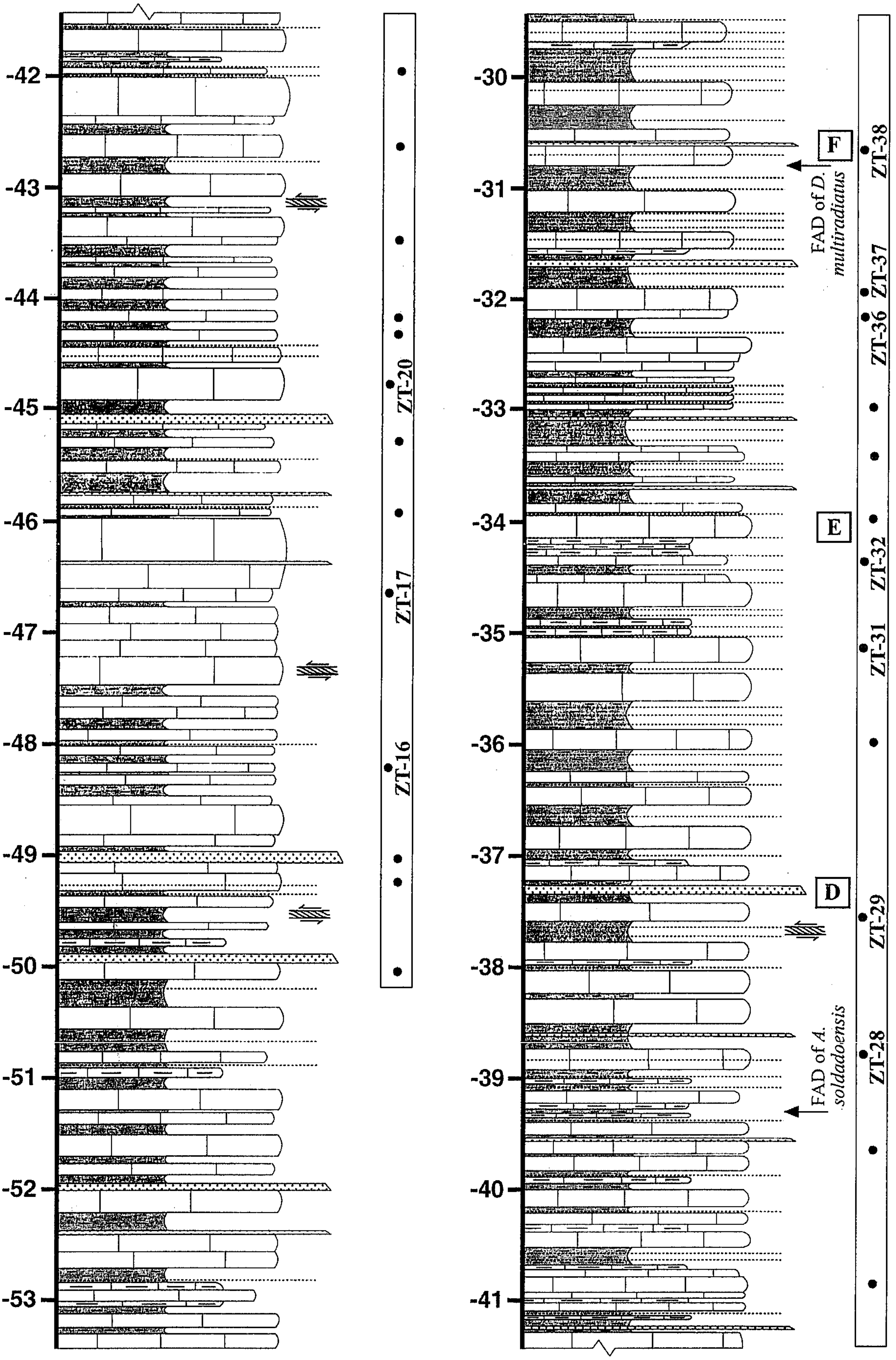

Figure 4A.- Detailed columnar section of the lower part of the Paleocene/Eocene boundary interval of the Zumaia section, showing location of reference levels D, E and F (also indicated in figure 2) paleomagnetic samples (ZT) and selected biostratigraphic events. For lithological key, see Fig. 4D.

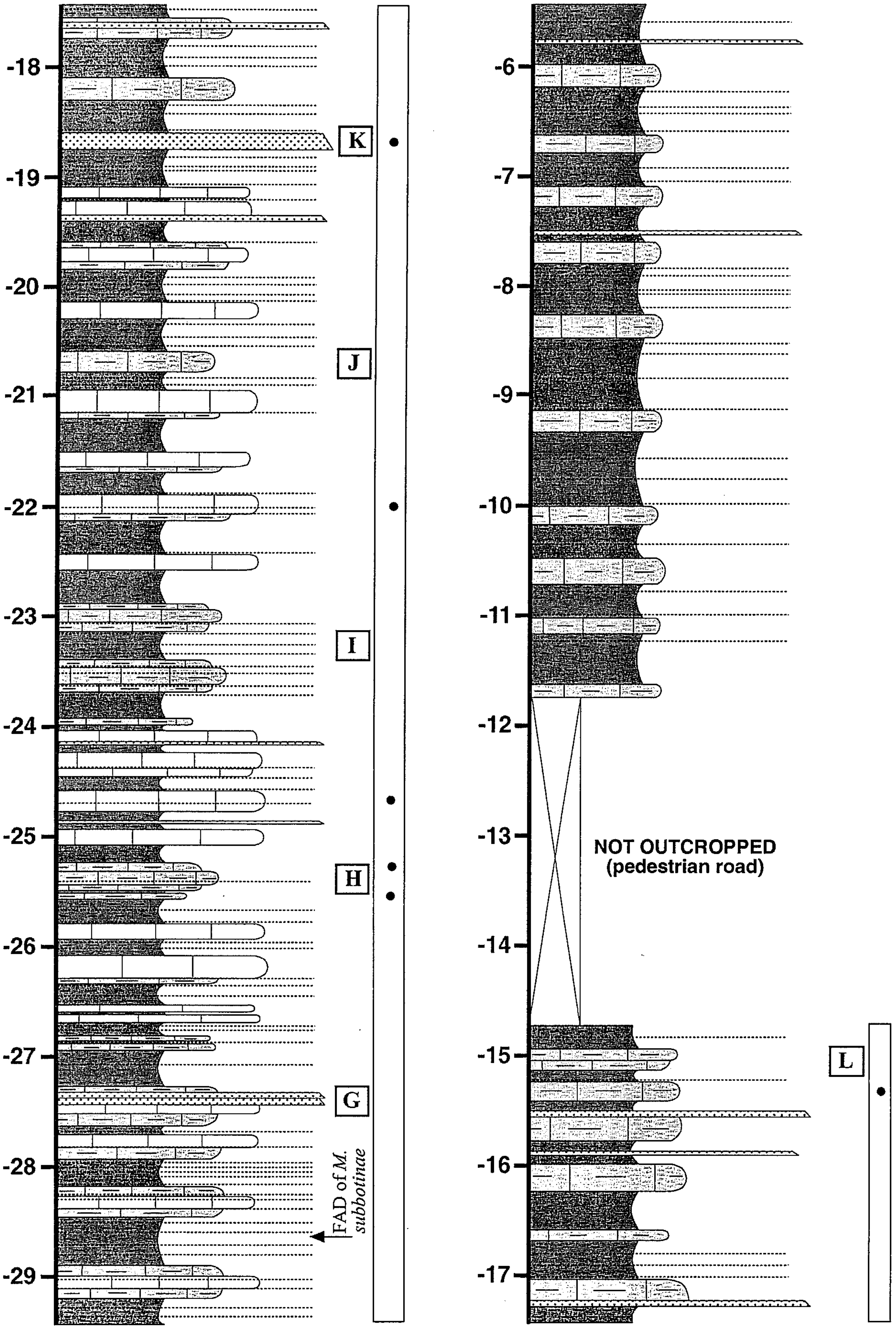

Figure 4B.- Detailed columnar section of the lower-middle part of the Paleocene/Eocene boundary interval of the Zumaia section, showing location of reference levels G, H, I, J, K and L (also indicated in figure 2) paleomagnetic samples (black dots) and selected biostratigraphic events. For lithological key, see Fig. 4D.

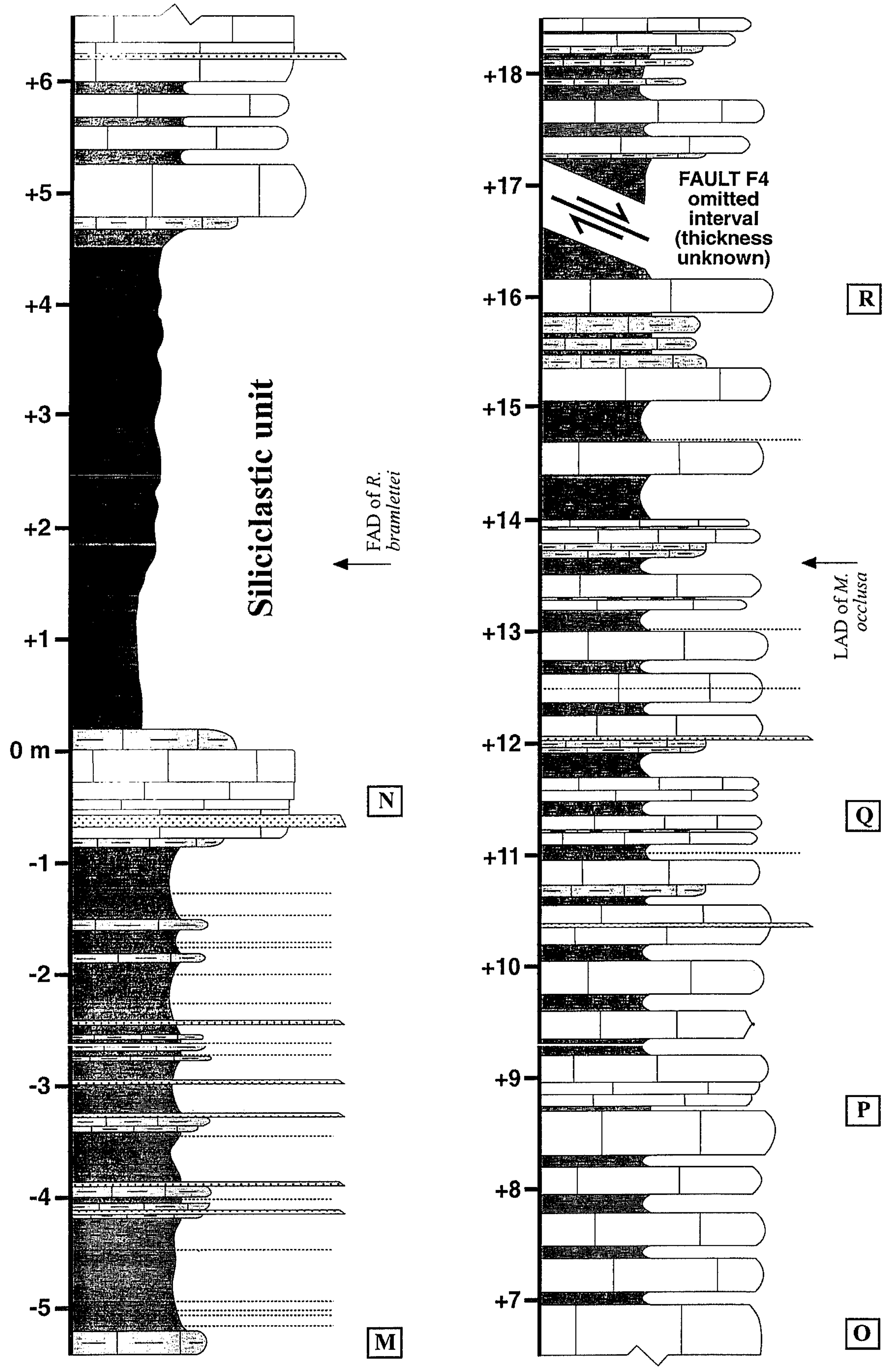

Figure 4C.- Detailed columnar section of the upper-middle part of the Paleocene/Eocene boundary interval of the Zumaia section, showing location of reference levels M, N, O, P, Q and R (also indicated in figure 3) and selected biostratigraphic events. For lithological key, see Fig. 4D.

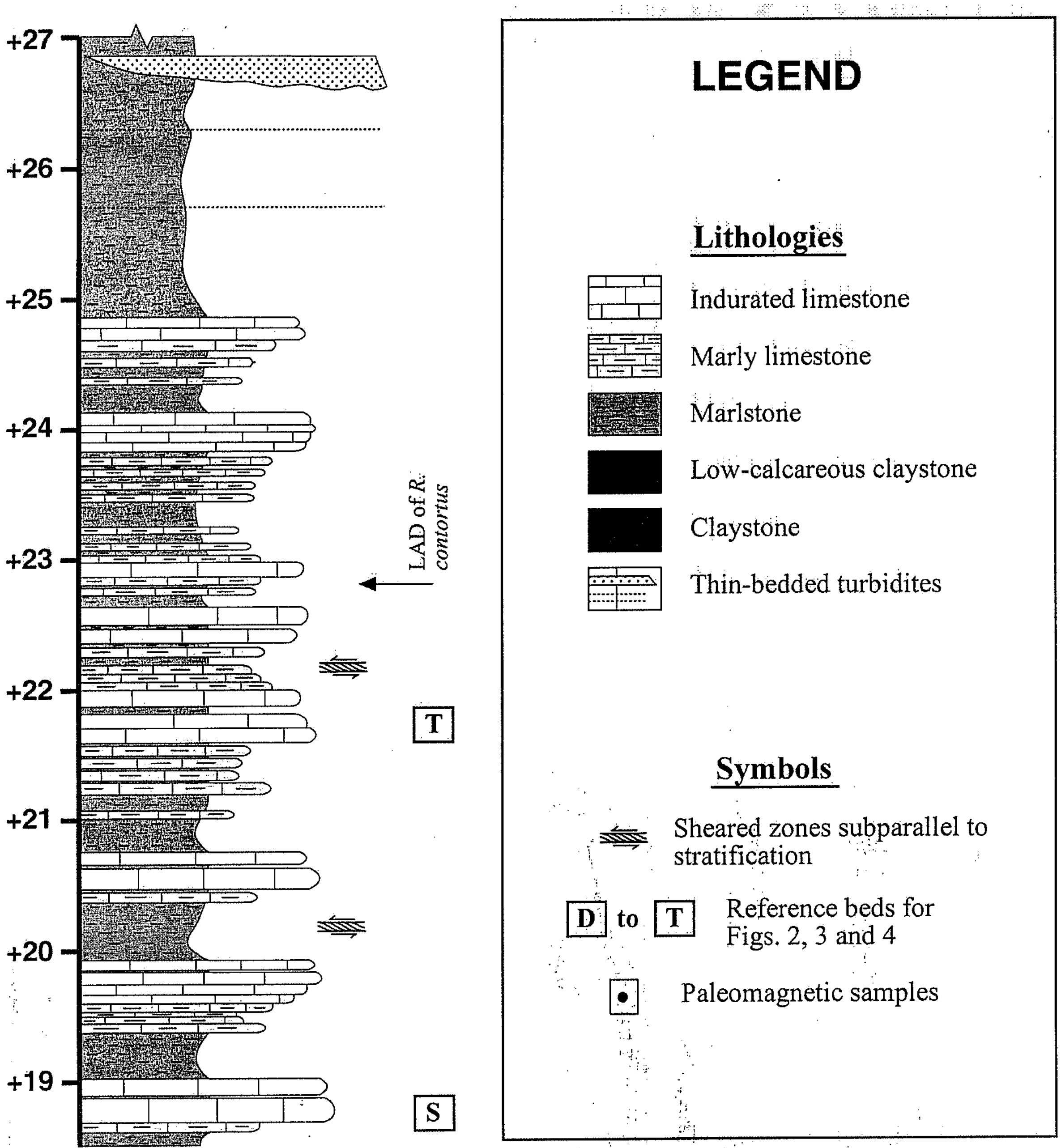

Figure 4D.- Detailed columnar section of the upper part of the Paleocene/Eocene boundary interval of the Zumaia section, showing location of reference levels S and T (also indicated in figure 3) and selected biostratigraphic events.

ving a steeper fault plane (75°/80°). More important, however, is that no match can be attained between the stratigraphic successions separated by fault F4 (Fig. 3). Such a mismatch is clear proof that fault F4 omits an interval of the stratigraphic succession. The extent of this missing interval is unknown, although ongoing biostratigraphic studies indicate that it is comparatively small.

Thus, it can be affirmed that most faults segmenting the P/E BI of the Zumaia section just repeat parts of the succession, the one exception being the minor omission of fault F4. Properly dealt with, the disruption of these faults can be removed, and the original stratigraphic succession can be successfully reconstructed. These faults, therefore, do not subtract merits to Zumaia as a reference section.

High resolution lithostratigraphy

Despite the comparatively large number of studies carried out in the Zumaia section, a detailed litholog of the succession has never been published. Thus, in the most classic biostratigraphic paper about the section (Hillebrandt, 1965), the lithological column showing the sample location and planktic foraminiferal zonation was drawn at the 1:2,500 scale. More recent works focusing on the P/E BI have produced somewhat more detailed logs, with scales ranging between 1:500 (e.g.,

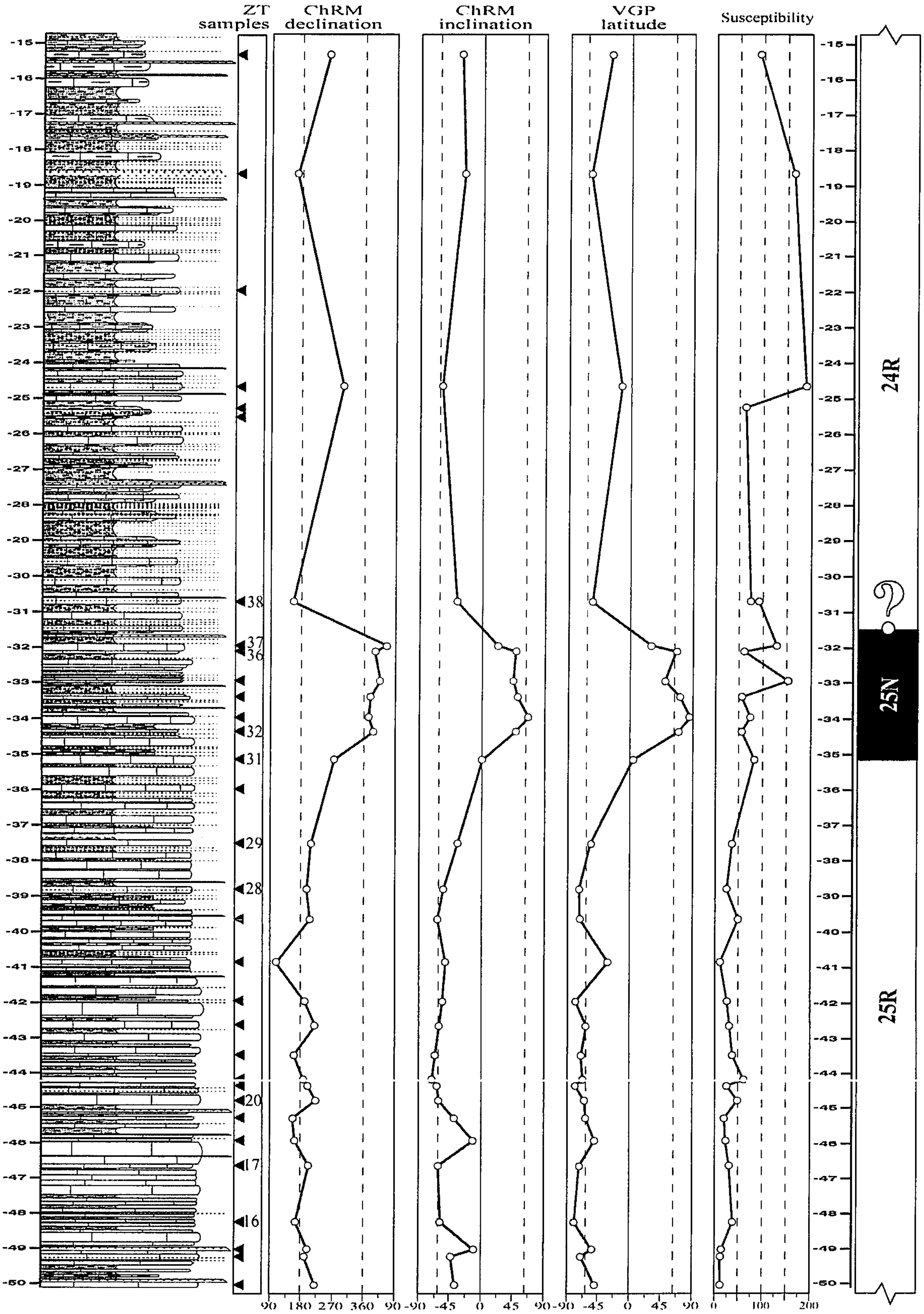

Figure 5.- Stratigraphic variations of declination, inclination of ChRM vectors, VGP latitude and magnetic susceptibility, all of them plotted against the synthetic columnar section of the Paleocene/Eocene boundary interval of the Zumaia section. Explanation within the text.

Canudo and Molina, 1992) and 1:200 (e.g., Schmitz *et al.*, 1997). We agree that logs drawn at such scales are usually sufficient for most useful purposes. However, such type of columns lack the necessary detail to pinpoint with accuracy the location of samples, making it difficult to establish comparisons between results of different authors. Since one of the purposes of a reference section is to facilitate the testing of data by different researchers, we believe that a detailed litholog should be a necessary requisite in any reference section, particularly in one proposed as Global Stratotype.

In accord with the reasoning above, we present in figures 4A to 4D a high-resolution litholog of the P/E boundary interval, drawn at a scale of 1:50. Strata thicker than a few cm can be resolved at such a scale, and thus the litholog in figure 4 can be considered a bed-by-bed reconstruction of the succession. Furthermore, to facilitate the identification of the different intervals of the succession, we have cross-referenced the litholog and the outcrop section (letters D to T in figures 2, 3 and 4) .

Following the usage of some previous authors , we have placed the zero level of our litholog at the horizon in which Schmitz *et al.* (1997) found the onset of the negative Carbon Isotopic Excursion (CIE) and the Benthic Extinction Event (BEE). As mentioned above, there is a strong possibility that the CIE/BEE will be chosen by the IGCP 308 Working Group to define the P/E boundary. If such possibility eventually materializes, the deposits below and above our zero level will belong respectively to the Paleocene and to the Eocene.

As shown in figure 4, the studied succession is mostly composed of alternations of hemipelagic limestone, marly limestone and marlstone, plus intercalations of thin-bedded turbidites (mostly 1-4 cm thick, but some up to 10 cm thick). The proportion of these lithologies varies throughout the studied interval. Thus, the lower part of the studied Paleocene interval (from -53 m to -42 m) is mostly made up of gray hemipelagic limestones with subordinate marlstone intercalations. On average, this part of the succession contains about 2 turbidite beds per meter (20 turbidites in all). From -42 m to -19 m, the hemipelagic limestones and marlstones occur in similar proportion, whereas marlstone is the predominant lithology from -19 m to - 1 m. The number of turbidites in the interval comprised between -42 m and -1 m averages 5 per meter. However, in the interval between -32 m and -28 m, this value increases to 9 turbidite beds per meter. Interestingly, this interval can be correlated with the lowstand deposits of a third-order depositional sequence recognized in the basin margin (Baceta, 1996; Pujalte *et al.*, 1998a).

The uppermost part of the Paleocene succession is represented by a conspicuous 0,8 m thick unit (coded «N» in figures 3 and 4C) that mostly consists of hemipelagic limestone, but also includes one carbonate turbidite bed. In fresh cuts, the limestone is usually light green, a color caused by the presence of glauconite, mainly as fillings of planktic foraminifer tests. This «green» limestone unit is now known to be a widespread deposit, having been observed in several other sections of the Basque Basin (Baceta, 1996; Pujalte *et al.*, 1998a; Schmitz *et al.*, submitted).

The limestone unit is overlain by a marlstone bed, 0.35 m thick, in which Schmitz *et al.* (1997) reported the BEE and the onset of the CIE. This bed may therefore eventually mark the P/E boundary in the Zumaia section. Immediately above it, there exists a 4 m thick interval made up almost exclusively of claystone and silty claystone which, to avoid genetic implications, Pujalte *et al.* (1998b) and Schmitz *et al.* (submitted), named the «Siliciclastic Unit». In its lower 1.7 meters, this Siliciclastic Unit is devoid of carbonate (and of carbonate microfossils), but in the remaining part becomes slightly calcareous (Schmitz *et al.*, 1997).The succession above the Siliciclastic Unit is composed again of alternating limestones and marls, the transition being rapid but gradual (Fig. 4C). The interval between +5 m and + 10 m is dominated by hemipelagic limestones and contains only one turbidite. Higher up, the proportion of marlstones increases and the turbidites are somewhat more abundant (1 turbidite bed per meter). Marlstone become the predominant lithology in the part of the succession situated above the interval omitted by fault F4, whereas higher up than +27 m (not shown in Fig. 4D) the frequency of turbidites increases dramatically (Fig. 1B).

Paleomagnetic sampling and methods

Workers of IGCP 308 unanimously agree that the P/E boundary must be placed within reverse Chron C24r. Therefore, normal polarity Chron C25n marks the lower limit of the so-called P/E boundary interval. In order to locate it in Zumaia, a total of 32 samples spanning about 35 m of Upper Paleocene strata where collected, of which 30 were analyzed (Figs. 4 and 5). Most samples were obtained from grayish colored limestones, but a few of them were taken from marly limestones, marlstones and turbidites. Samples were cored (2.54 cm in diameter) with a portable gasoline-powered drill. Cores were cut in the laboratory into standard specimens (2.2 cm in length) for paleomagnetic measurements. The natural remanent magnetization (NRM) and its response to stepwise thermal (TH) demagnetization were measured in a GM400 three-axis cryogenic magnetometer (CCL) at the Institut de Ciencies de la Terra of the CSIC, in Barcelona. Characteristic remanent magnetizations (ChRM) were computed by least-squares fitting (Kirschvink, 1980) on the orthogonal demagnetization plots (Zijderveld, 1967). The initial low-field susceptibility was measured on a Kappabridge (KLY-2, Geophysika Brno) instrument. The mean declination and inclination of the ChRM component of each sample has been used to derive the latitude of the virtual geomagnetic pole (VGP). This parameter has been used as an indicator of the polarity (normal polarity for positive VGP latitudes and reverse polarity for negative VGP latitudes).

Paleomagnetic results

NRM intensities are weak and range from 4 x 10^{-3} mA/m to 88 x10^{-3} mA/m. Low filed-susceptibility va-

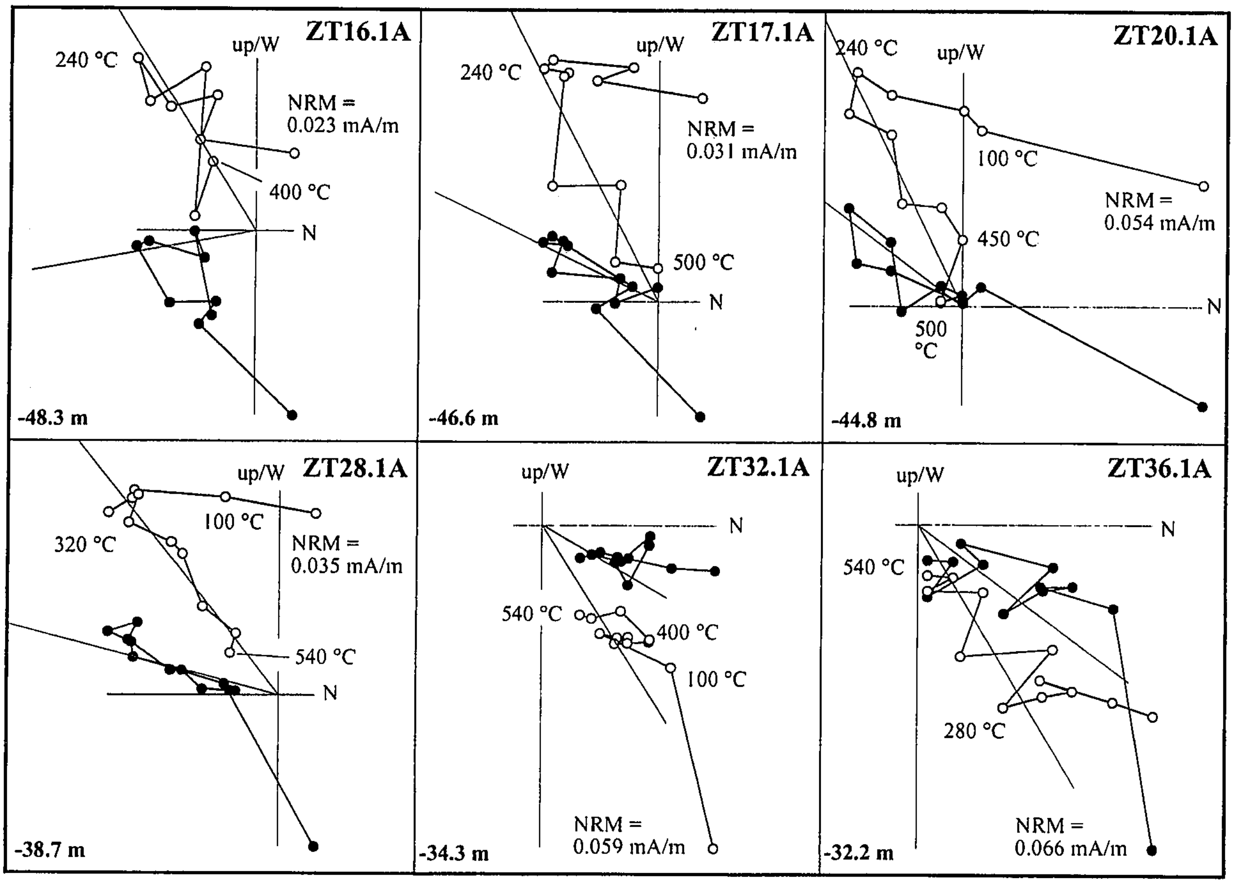

Figure 6.- Tilt-corrected orthogonal plots of thermal demagnetization data from representative specimens. Temperature steps in degrees Celsius are, 100°, 150°, 200°, 240°, 280°, 320°, 360°, 400°, 450°, 500° and 540°. Solid (open) symbols represent projections onto the horizontal (vertical) plane. The fitted ChRM direction and the stratigraphic level is indicated in each example. Samples ZT16 to ZT28 are of reverse polarity and samples ZT32 and ZT36 are of normal polarity.

ries from 9 x10^{-6} SI to 192 x10^{-6} SI and does not correlate to the NRM intensity suggesting that paramagnetic phases (clays) probably dominate the susceptibility signal. All studied samples show similar behavior during NRM demagnetization. Two remanent magnetization components can be identified, in addition to a third component, which is removed below 100-150°C and seems to be related to a drilling or storage viscous acquisition. A low-temperature, low-coercivity component (L) with unblocking temperatures of less than 300°C is then removed (Fig. 6). This component conforms to the present geomagnetic field direction in in-situ coordinates and, therefore, is regarded as a secondary recent overprint. Finally, a high-temperature component (H) with unblocking temperatures distributed from about 250°C to 450-540°C or above is observed. The high-temperature components decay toward the origin in their orthogonal vector plots although some samples show a somewhat noisier behavior (i.e., ZT16.1A and ZT36.1A in Fig. 6). This noisy signal is probably related to the low intensities measured in addition to spurious behavior due to growth of secondary mineral phases upon heating. In two out of the 30 analyzed samples no components could be calculated. The polarity of the high-temperature component is dominantly reverse and only six samples with a normal polarity component are observed in the central part of the studied interval. Due to similar bedding attitude along the section (about 60 toward N-NE), a fold test is not available. However, the direction of the H-component in terms of the geographic (in-situ) coordinates (excluding sample ZT31 at -35 m, which has an intermediate direction) is meaningless (Dec/Inc = 209.8/ 67.7, N = 27, k = 8, $Å_{95}$ = 10.5), while the tilt corrected mean direction has a Tertiary-compatible inclination (Inc = 51.8, all directions flipped to normal polarity). The tilt-corrected declination (Dec = 14) is comparable with results previously reported for the lowest Paleocene part of the Zumaia section (Roggentthen, 1976) and Paleocene data from the Trabakua section located 20 km SW in the Biscay Synclinorium (Pujalte *et al.*, 1995). Hence, the primary nature of the high-temperature component in Zumaia is fully justified. Biostratigraphic constraints described below indicate that the interval of normal polarity between -31.5 and -35 m corresponds to Chron C25n.

However, qualifications need to be made about the extent of Chron C25n at Zumaia. The lower C25n reversal has to be located between the uppermost reverse polarity sample ZT29 at -37.5 m and the normal polarity sample ZT32 at -34.5 m. Sample ZT31 at -35 m records a transitional direction which defi-

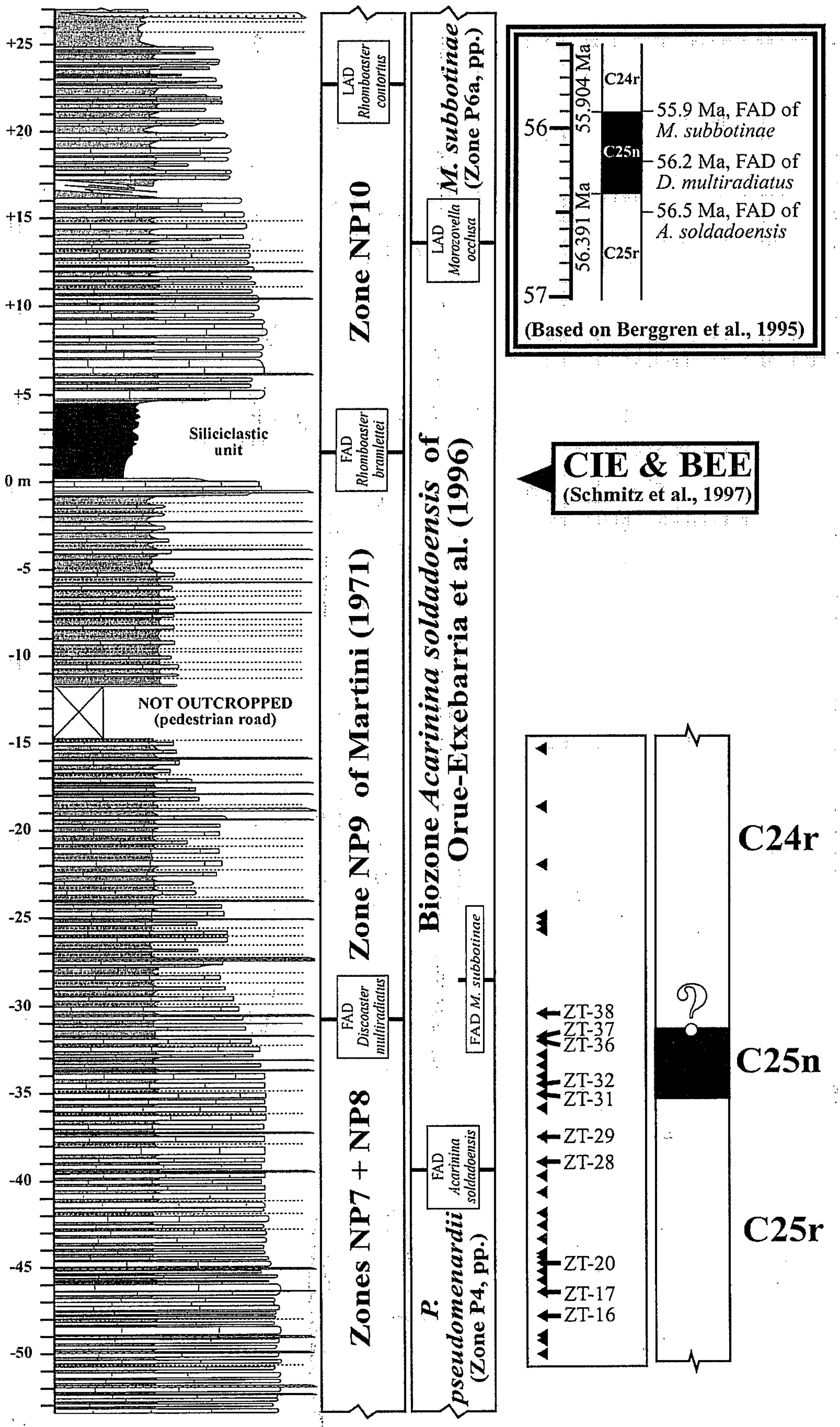

Figure 7.- Synthetic columnar section of the Paleocene/Eocene boundary interval of the Zumaia section, showing the position of calcareous nannofossil and planktic foraminifer events, geomagnetic Chron C25r, Carbon Isotopic Excursion (CIE) and Benthic Extinction Event (BEE). Inset: Magnetobiochronologic calibration of different events according to Berggren *et al.* (1995).

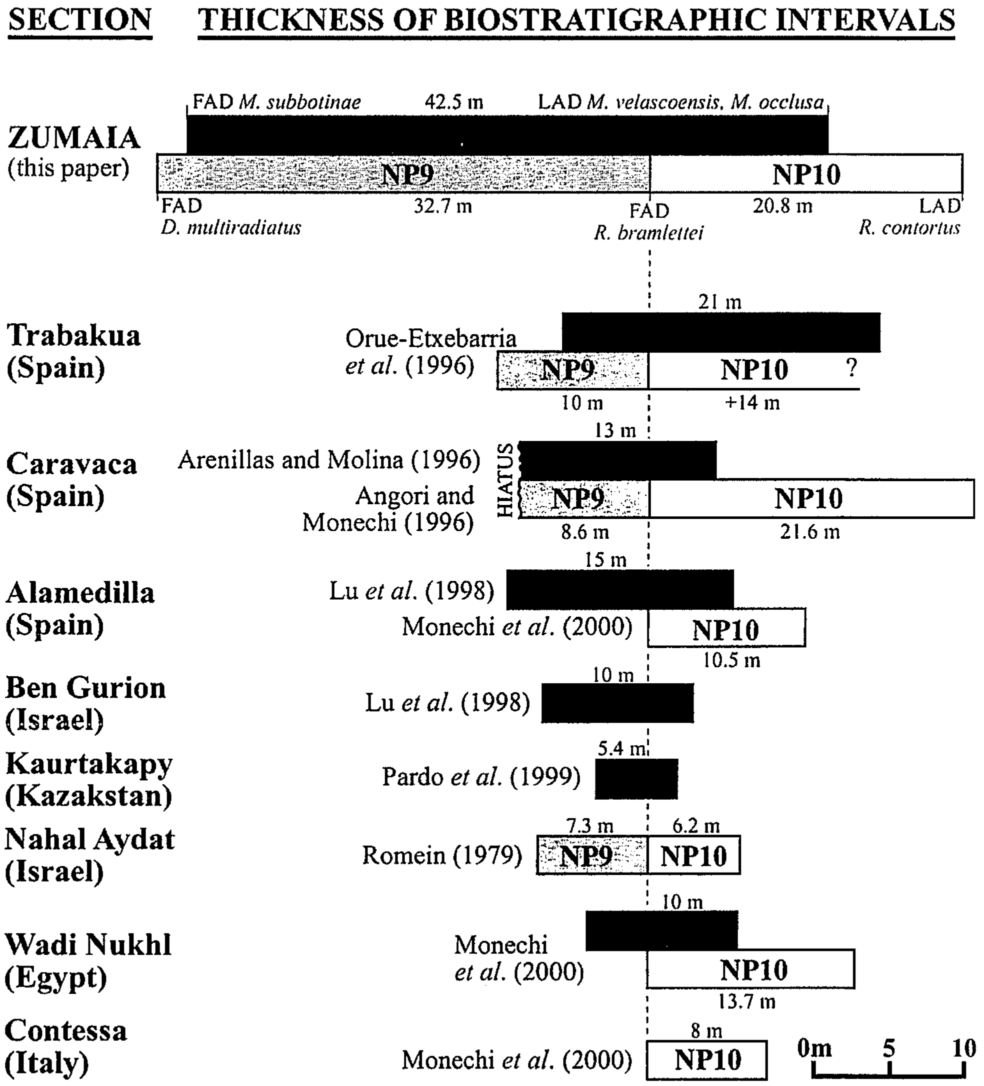

Figure 8.- Thickness of selected biostratigraphic intervals of the Zumaia section, and comparison with published thicknesses of the same intervals elsewhere. Black boxes, interval between the FAD of *M. subbotinae* and the LAD of *M. velascoensis/M. occlusa*; gray and white boxes, thicknesses of Zone NP9 and of Zone NP10 of Martini (1971). Note that Zumaia is generally the most expanded succession, with the sole exception of Zone NP10 in the Caravaca section.

nes a shallow VGP (Fig. 5). Therefore, we believe that the actual lower C25n reversal is located close to that sample although no data is available for the ~2 m interval below. We have located the upper C25n reversal between the uppermost normal polarity sample ZT37 (-32 m) and the reverse polarity sample ZT38 (-30.5 m). However, we note that only a few samples are present in the interval above up to the top of the sampled section. These samples appear to be of reverse polarity but the demagnetization is somewhat noisy and therefore the reliability of this part of the section is lower than in the interval comprised between -50 m and -32 m. We are consequently aware that the upper C25n reversal position at Zumaia will need further refinement.

Biostratigraphic zonation

As mentioned above, the P/E BI interval of Zumaia has been the subject of several previous studies, most of which included data about planktic foraminifers and calcareous nannofossils (Canudo and Molina, 1992; Canudo *et al.*, 1995; Schmitz *et al.*, 1997; Gawenda *et al.*, 1999). However, a comparison between them readily demonstrates differences between their respective results, reflecting perhaps divergent taxonomic concepts. Partly for this reason, we have conducted our own high-resolution sampling of the succession, as a base for a re-study of calcareous nannofossils and planktic foraminifers. Our results (still unfinished) will be published elsewhere at a later date. However, from our preliminary results, six events can be identified in the section (see figure 4):

Event 1: First Apparition Datum (FAD) of *Discoaster multiradiatus*, approximately found at -31 m. This species marks the base of the calcareous nannofossil Zone NP9 of Martini (1971).

Event 2: FAD of *Rhomboaster bramlettei* (sensu Bybel and Self-Trail, 1995), which is the marker of the base of Zone NP10 of Martini (1971), observed at +1.70 m. However, as mentioned above, the lowermost 1.7 m of the Siliciclastic Unit is devoid of carbonate. Therefore, it is possible that the base of Zone NP10 actually occurs within this carbonate-free interval.

Event 3: Last Apparition Datum (LAD) of *R. contortus*, an event often used to mark the top of Zone NP10, has been observed approximately at +22.5 m.

Event 4: FAD of *Acarinina soldadoensis*, found near -39.5 m. This planktic foraminifer species is used to mark the base of both Zone P4c of Berggren *et al.* (1995) and Biozone *A. soldadoensis* of Orue-Etxebarria *et al.* (1996).

Event 5: FAD of *Morozovella subbotinae*, seen around -28.5 m. Our current data suggest the FAD of this species is a more accurate marker than the LAD of *Planorotalites pseudomenardii*, in spite of the fact that the latter is often used to position the base of Zone P5 of Berggren *et al.* (1995).

Event 6: LADs of *Morozovella velascoensis* and of *M. occlusa*, which in this section take place near simultaneously just below +14 m. These LADs respectively mark the top of Zone P5 of Berggren *et al.* (1995) and of Biozone *A. soldadoensis* of Orue-Etxebarria *et al.* (1996).

The six events above permit to test the reliability of our magnetostratigraphic data. In effect, according to the magnetobiochronologic calibration of Berggren *et al.* (1995), the FAD of *A. soldadoensis* slightly predates the base of geomagnetic Chron C25n (Fig. 7, inset), just as we have found in our study of the section. Therefore, the boundary between Chron C25n and Chron C25r shown in figures 5 and 7 can be considered accurate. On the other hand, Wei (1992) has reported the FAD of *D. multiradiatus* within geomagnetic Chron C25n, while according to Berggren *et al.* (1995) the FAD of *M. subbotinae* is placed just above the upper limit of Chron C25n (Fig. 7, inset). We have found these two biotic events at a position higher than our uppermost normal polarity sample (ZT 37, see Fig. 4A). This fact suggests that the uncertain zone above our normal polarity interval may also belong to Chron C25n (Figs. 5 and 7).

The six biotic events can also be used to make a preliminary comparison between Zumaia and other P/E boundary sections. The brief survey of data obtained the literature, and compiled in figure 8, confirms earlier claims (e.g., Molina, 1996) that Zumaia may contain the most expansive P/E boundary sections reported so far in outcropped deep-water deposits, at least within the Tethyan domain. Such large thickness, in part a consequence of the relatively great number of turbidite beds intercalated in the succession, makes it much easier to carry out high-resolution studies in Zumaia than in the other more condensed sections so far reported.

Concluding remarks

In addition to Zumaia, there exists in the Basque Basin another P/E boundary section in deep-water deposits, namely the Trabakua pass section. This section occurs in an inland exposure created around 1990 by the enlargement of the local road from Berriz to Markina (province of Biscay). On the base of biostratigraphic and magnetostratigraphic analysis, the Trabakua pass section was put forward as a prospective P/E boundary stratotype by Coccioni *et al.* (1994) and by Orue-Etxebarria *et al.* (1996). Ever since, the quality of its exposure has deteriorated by weathering. More important, studies carried out by Bolle et al. (1998) have convincingly demonstrated that the clay mineralogy signals of the succession are deeply imprinted by deep burial diagenesis. These circumstances rule out Trabakua pass as a potential boundary section, which leaves Zumaia as the obvious and sole candidate in the Basque Basin to become the P/E stratotype. Other aspects of the Zumaia section have to be taken into consideration, in addition to its intrinsic qualities outlined above. For instance, as pointed out by Schmitz *et al.* (1998), the (paleo)geographical situation of Zumaia may provide an important link between the original early Paleogene stratotype sections in the North Sea area and the important sections more recently discovered in Egypt and neighboring regions.

However, in our opinion, the most important asset of the Zumaia section is its regional context. The Zumaia section is placed within the Pyrenean domain, an area in which early Paleogene deposits of a whole range of facies can be found in outcrops (Plaziat, 1981). Some sections of this range have long been known, such as Tremp (terrestrial/intermediate deposits), Campo (shallow-marine deposits) or Ermua (base-of-slope deposits), and several others are currently being documented (Pujalte *et al.*, 1998b). A precise correlation between the Ermua and Zumaia sections has recently been established (Schmitz *et al.*, submitted). Correlations between shallow-marine and deep-water deposits have also been attempted (Pujalte *et al.*, 2000; Orue-Etxebarria *et al.*, submitted). Finally, recent work on paleomammals from the Tremp sections has produced very promising results (López-Martínez and Peláez-Campomanes, 1999). Thus, there is a very strong possibility that a continuous transect from terrestrial to deep-marine environments entailing the P/E boundary will soon be reconstructed in the Pyrenees.

The Earth experienced the warmest climatic interval of the Cenozoic during the late Paleocene-early Eocene and, in recent years, many workers of the IGCP 308 project are focusing their research efforts to deciphering the physical and biological consequences of such thermal maximum. The Pyrenean sections, with their potential to offer data from a broad range of ancient environments, may provide many answers in the now critical issue of understanding global warming events.

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