1 An astronomical time scale for the Maastrichtian at the Zumaia and Sopelana
2 sections (Basque country, northern Spain)

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22 The rhythmically bedded limestone-marl alternations in the coastal cliffs of Sopelana and Zumaia in
23 the Basque country, northern Spain, permit testing and refining of existing Maastrichtian
24 chronologies (latest Cretaceous). The recently established astronomical time scale for the late
25 Maastrichtian at Zumaia is extended into C31n with the integrated stratigraphy of the Sopelana

26 section. The cyclic alternations of hemipelagic limestones and marls at Sopelana show a strong
27 influence of eccentricity-modulated precession. Together, the Zumaia and Sopelana sections span
28 almost the entire Maastrichtian, and encompass thirteen 405kyr cycles, spanning a total duration of
29 5.3Myr. From the K/Pg boundary downwards, 405kyr minima in the lithological, magnetic
30 susceptibility and reflectance data records are tuned to successive 405kyr minima in the new La2011
31 eccentricity solution. Assuming a K/Pg boundary age of 65.97Ma, we present orbitally tuned ages of
32 biostratigraphic and magnetostratigraphic events. While the bases of Chrons C29r and C30n were
33 reliably established at Zumaia and are in good agreement with previous studies, new data from
34 Sopelana provide a refinement of the basal age of Chron C31r. Additional planktonic foraminifera
35 and calcareous nannoplankton data from Zumaia, and new calcareous nannoplankton data from
36 Sopelana allow for worldwide correlation of the cyclostratigraphy of the Basque country.

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39 Supplementary materials: Identification of the 405 kyr minima; Geologic map; Paleomagnetic
40 results; Sopelana data; Redfit 3.8 power spectra (.pdf); data tables (.rtf)

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42 Introduction

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44 Recently, much progress has been made in improving the temporal resolution of the Maastrichtian
45 time scale by astronomical tuning of cyclic climate records. Originally, Ten Kate and Sprenger (1993)
46 used variations in carbonate content above and below the Cretaceous/Paleogene (K/Pg) boundary at
47 Zumaia to establish a cyclostratigraphic framework, extending ~1.7 Myr down into the
48 Maastrichtian. Later, Herbert et al. (1995) and Herbert (1999) identified the eccentricity modulation
49 of precessional cycles in reflectance records of South Atlantic Deep Sea Drilling Project (DSDP) Sites
50 357 (Leg 39), 516F (Leg 72), 525A, 527 and 528 (Leg 74) to obtain an orbital estimate for the
51 durations of Late Cretaceous magnetochrons C31n-C29r. Herbert (1999) arrived at an estimate for

the time between the K/Pg boundary and the C32r/C31n reversal of 3.107 Myr. Husson et al. (2011) produced an astronomical tuning of magnetic susceptibility records from Ocean Drilling Program (ODP) Hole 1258A (Equatorial Atlantic) and Hole 1267B (South Atlantic) and grey level variations from DSDP Site 525 (South Atlantic) and ODP Site 762 (Indian Ocean) and attempted to anchor this tuning to the absolute time scale, arriving at a duration from C31r/C31n to the K/Pg boundary of 3.22 Myr. Another cyclostratigraphic framework was presented by Thibault et al. (2012a) for ODP Hole 762C based on grey level variations, with an integrated magnetostratigraphy, a bulk-carbonate $\delta^{13}\text{C}$ profile, and planktonic foraminifera and calcareous nannofossil bio-events. A global correlation of carbon isotope curves from Campanian-Maastrichtian successions by Voigt et al. (2012) allows for direct correlation to the Global Stratotype Section and Point of the Campanian-Maastrichtian boundary at Tercis les-Bains (France).

Recently, a cyclostratigraphic framework for the late Maastrichtian, with magnetostratigraphy, biostratigraphy and a high resolution carbon isotope stratigraphy, has been obtained for the Zumaia section in the Basque country, northern Spain (Batenburg et al., 2012), confirming a duration between the K/Pg boundary and C31r/C31n of 3.22 Myr. This study elaborates on that work by extending the data records of reflectance and magnetic susceptibility with new data from the lower Maastrichtian Sopelana section, 60 km west of Zumaia. We also include the calcareous nannofossil biostratigraphy for Zumaia of Pérez-Rodríguez et al. (2012) and we present new calcareous nannofossil data from Sopelana and additional magnetostratigraphic data.

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72 Age of the K/Pg boundary

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The K/Pg boundary occurs near a minimum of the 405 kyr cycle of eccentricity, inferred from cyclostratigraphy of deep sea cores (Herbert, 1999; Herbert et al., 1995; Husson et al., 2011; Westerhold et al., 2008) and astronomical tuning of the Zumaia section, based on both the Paleocene (Kuiper et al., 2008) and the Maastrichtian part of the succession (Batenburg et al., 2012;

ten Kate and Sprenger, 1993). Following different tuning efforts of the Paleocene and Eocene, the ages of three successive minima of the 405 kyr eccentricity cycle have been assigned to the K/Pg boundary, ranging from 65.25 to 65.95 Ma (Hilgen et al., 2010; Kuiper et al., 2008; Westerhold et al., 2012, 2008). New $^{40}\text{Ar}/^{39}\text{Ar}$ and U-Pb data from bentonites in coals near the K/Pg boundary with a weighted mean age of $66.043 \pm 0.011/0.043$ Ma (uncertainties respectively excluding and including systematic sources) (Renne et al., 2013) agree with an astronomical age of the 405 kyr minimum of near 66.0 Ma, using the $^{40}\text{Ar}/^{39}\text{Ar}$ calibration of Kuiper et al. (2008) of the Fish Canyon sanidine (FCs) dating standard. As suggested tuning options that place the K/Pg boundary in younger 405 kyr minima are incongruent with independent intercalibration efforts of the Fish Canyon Sanidine (Kuiper et al., 2008; Rivera et al., 2011), an age of 65.97 Ma is adopted in this study, obtained by filtering of the new (nominal) La2011 solution (Laskar et al., 2011).

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90 **Geological setting and sections**

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The coastal cliffs of Zumaia and Sopelana, along the Bay of Biscay in northern Spain, display rhythmically bedded hemipelagic limestone-marl alternations (Fig. 1), deposited in the Basque-Cantabric Basin. From the Campanian to the Eocene, this basin was a deep elongated intra-plate trough, opening to the west into the Bay of Biscay, and surrounded by shallow shelf areas (Mathey, 1988; Rat, 1988; Pujalte et al., 1998). These successions were uplifted in late Eocene times during the Pyrenean orogeny. Major outcrops of Maastrichtian strata are found in the Biscay synclinorium, with the Sopelana section on the eastern flank, and in the Gipuzkoa monocline, with the Zumaia section being the westernmost outcrop (Supplementary figure 1) (Pujalte et al., 1998).

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101 Zumaia

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The Zumaia section is located beneath the Punta Aitzgorri Headland near the town of Zumaia, in the Gipuzkoa province of northern Spain. The section is composed of rhythmically bedded deposits of hemipelagic limestones, marls and turbidites of late Cretaceous to Eocene age, and is a classical site for paleoclimatic, magnetostratigraphic, biostratigraphic and cyclostratigraphic studies (Herm, 1965; Percival and Fischer, 1977; Lamolda, 1990; Ward et al., 1991; ten Kate and Sprenger, 1993; Ward and Kennedy, 1993; Pujalte et al., 1998; Elorza and García-Garmilla, 1998; Dinarès-Turell et al., 2003; 2013; Gómez –Alday et al., 2008; Kuiper et al., 2008) and a reference section for the K/Pg boundary (Molina et al., 2009). The upper Campanian and lower Maastrichtian of the Zumaia section are characterized by a thick turbidite succession, deposited during relatively rapid subsidence, which grades into upper Maastrichtian limestone-marl alternations with intercalated turbidites, deposited during relative tectonic quiescence (Pujalte et al., 1998). The upper Maastrichtian interval was first studied for cyclostratigraphy by Ten Kate and Sprenger (1993). A new cyclostratigraphic framework for the Zumaia section, with additional bio-, magneto-, and chemostratigraphic data, was obtained recently (Batenburg et al., 2012) and is displayed in Figure 2, together with the stratigraphic log of the lower Maastrichtian interval of the Sopelana section. Recently, a high resolution calcareous nannoplankton and planktonic foraminifera stratigraphy was obtained by Pérez-Rodríguez et al. (2012), together with magnetostratigraphic information, which is correlated with our log (Supplementary Table 1).

Sopelana

The upper Maastrichtian of the Sopelana section in the Vizcaya province of Northern Spain is characterized by a number of large faults, but the lower Maastrichtian is not disturbed and displays a very regular alternation of limestones and marl beds, without the occurrence of turbidites. We refer to the Sopelana 1 section along the Atxabiribil-Arriatera swimming beach, and not to the thinner Sopelana 2 section ~1 km further west (Ward, 1988; Ward et al., 1991). The section was studied for

planktonic foraminifera and calcareous nannoplankton by Lamolda et al. (1983). Mary et al. (1991) provided more planktonic foraminifera data and a magnetostratigraphy, and the potential acquisition of a chemical remagnetization signal, particularly by the marl horizons, was discussed by Moreau et al. (1994). The ammonite faunas from Sopelana and the sections of Zumaia, Bidart and Hendaye have been described by Ward and Kennedy (1993). The distribution and stable isotope ratios of inoceramids at Sopelana have been studied in detail (Elorza and García-Garmilla, 1998; Gómez-Alday et al., 2004; Gómez –Alday et al., 2008). Intervals at Sopelana were included in studies on CaCO₃ and stable isotope variations by Alvarez-Llano et al. (2006), Santander et al. (2007) Domínguez et al. (2007) and Jiménez Berrocoso et al. (2012). The tectonic setting of the Sopelana section has been described by Rodríguez et al. (2008).

Material and methods

Lithostratigraphy and geophysical properties

The Lower Maastrichtian limestone-marl alternations of the Sopelana section were logged and sampled by hammer at a resolution of approximately eight samples per limestone-marl couplet, with an average sampling space of 8 cm, and a standard deviation of 2.5 cm. Magnetic susceptibility was measured on the surface of rock fragments in the petrophysical laboratory of the IAMC-CNR in Naples (Italy) with a Bartington MS2E point sensor to measure low-field magnetic susceptibility (MS) (Fig. 3). As the values were generally low (below 16 SI), all samples were measured twice, and each measurement was alternated with blanks. The total light reflectance (L*, in %) of all samples was measured in the same laboratory with a Konica Minolta Spectrophotometer CM 2002 on the surface of the rock fragments (Fig. 3). All measurements were repeated and directly averaged by the instrument, which records the percentage of reflected energy (RSC) at 31 wavelengths in 10-nm steps, over the visible spectrum from 400 to 700 nm. Cycles 156 to 185 in the Zumaia section have

been correlated bed-to-bed to the Sopelana section (Batenburg et al., 2012) (Fig. 2). The Sopelana and Zumaia datasets were combined at depth level 135.47 m in cycle 169 located in the lowermost 405 kyr minimum at Zumaia and in the uppermost 405 kyr minimum at Sopelana.

Spectral analysis

Spectral analysis of the reflectance and magnetic susceptibility data records was performed with Redfit3.8, which is particularly suited for unevenly spaced paleoclimatic time series (Schulz and Mudelsee, 2002). Wavelet analyses were applied with a Matlab script (Grinsted et al., 2004) and the records were band-pass filtered with AnalySeries (Paillard et al., 1996), centred at the periodicities obtained from the Redfit3.8 analyses, and typically with a broad bandwidth of approximately 1/4 of the periodicity (details in results section). Spectral analyses were performed on the Sopelana data and on the combined Zumaia/Sopelana datasets.

Astronomical target curve

The recently published astronomical solution La2010, adjusted to the INPOP10a ephemeris (Fienga et al., 2011), pushed the reliability of full eccentricity back to 50 Ma (Laskar et al., 2011a). The new La2011 solutions, which take into account the individual contribution of the major asteroids, further extend this reliability to ~54 Ma (Westerhold et al., 2012). Four solutions were generated to evaluate the solution's stability, with slight differences in the initial positions of the planets and the asteroids, well within the current uncertainties in their position. Beyond 60 Ma, Earth's eccentricity cannot be precisely calculated, and only the stable 405 kyr cycle can be used for astronomical tuning (Laskar et al., 2011b). The 405 kyr minima as identified in the succession have been tuned to successive 405 kyr minima filtered from the nominal La2011 solution (Laskar et al., 2011b)

(bandwidth 300-623 kyr). The nominal La2011 solution was used, as the 1.2 Myr periodicity of eccentricity of this solution remains stable furthest back in time.

Biostratigraphy

37 samples from cycles 173 to 251 of the Sopelana section were investigated for calcareous nannofossil biostratigraphy and processed following the procedure described in Thibault et al. (2012a). This results in an average sample resolution of ca 50 kyr for the studied interval, with three additional samples in cycles 157, 159 and 161 (Figure 6, Supplementary Table 1). Semi-quantitative counts were performed on key and other potential additional stratigraphic markers at a magnification of $\times 1600$ ($\times 100$ oil objective with a $\times 1.6$ additional lens). Preservation of nannofossils ranges from poor (P) to very poor (VP) in the Sopelana section and this affects the overall abundance of identifiable specimens which is generally low. Counts were determined in the following fashion: a species was determined as few (F) if one specimen or more could be observed in every 10 fields of view, rare (R) if, on average, only one specimen could be observed in 11 to 50 fields, very rare (VR) if, on average, only one specimen could be observed in 51 to 100 fields, and single (S) if only one specimen was observed over a total of 200 fields of view. The biozonation of Burnett et al. (1998) was applied. Calcareous nannofossil species considered in this paper followed taxonomic concepts of Perch-Nielsen (1985) and Young and Bown (1997). Bibliographic references for the determined taxa are given in Perch-Nielsen (1985) and Bown (1998).

For planktonic foraminifer biostratigraphy, the results reported here are published in Batenburg et al. (2012) and Pérez-Rodríguez et al. (2012).

Magnetostratigraphy

Oriented cores for paleomagnetic analyses were taken with a gasoline-powered drill in the topmost and lowermost part of the lower Maastrichtian succession (Fig. 2). From each oriented sample level, one specimen was thermally demagnetized in a magnetically shielded furnace using numerous small temperature increments, at 20, 80, 120, 150, 180, 200, 220, 240, 300, 320, 340 and 360°C. For some samples, the thermal demagnetization was continued up to 550°C. The natural remanent magnetization (NRM) was measured on a 2G Enterprise horizontal cryogenic magnetometer equipped with DC SQUIDS (noise level $3 \times 10^{-12} \text{ Am}^2$) at the Paleomagnetic Laboratory Fort Hoofddijk, the Netherlands. The directions of the NRM components were calculated by principal component analysis (Kirschvink, 1980; Zijderveld, 1967). Mean directions were determined for the individual sections using standard Fisher statistics. The 58° tilt helped to distinguish primary (pre-tilt) from secondary (post-tilt) components and to recognise the present-day field overprint (Dec./Inc.; 359/58).

Results

Lithostratigraphy and geophysical properties

In the lower Maastrichtian of the Sopelana section, hemipelagic limestone marl alternations, on a scale of 50-60 cm per couplet, display variations in the colour and thickness of the marls, albeit less strongly than at Zumaia, and variations in the induration and thickness of the limestones. Intervals of distinct variations alternate with poorly expressed limestone-marl couplets, forming bundles of usually five, sometimes four or six, couplets, and groups of 18 to 20, bounded by particularly poorly expressed marls (Fig. 2). The interval from cycle 212 to 224 has a remarkably constant expression of the limestone-marl couplets and lacks signs of bundling or grouping. A total of 107 couplets has been identified at Sopelana, including three couplets with very poorly expressed marls that have been marked with “a” and “b” (Figs. 1 and 2).

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232 The magnetic susceptibility record (Fig. 3) displays variations that reflect the alternations in the
233 lithology on the scale of the limestone-marl couplets and on a longer scale of ~19 couplets. Values
234 are relatively low (2.5 to 15.5 SI) and short variations over 40-70 cm depth are typically around 5 SI.
235 The amplitude of these variations shows a pattern of gradual increase and decrease on a scale of ~12
236 m. The reflectance record, varying between 47 and 65%, also follows the lithological pattern, and
237 mostly displays gradual variations in average values with some variation in amplitude. Combining the
238 Sopelana and Zumaia datasets at 135.47 m does not introduce a shift in values; however, the Zumaia
239 datasets show a larger range of variability.

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241 Spectral analysis magnetic susceptibility series

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243 Spectral analysis by Redfit 38 of the magnetic susceptibility record of Sopelana shows main
244 periodicities of 10.7 m and 65 and 54 cm (95% confidence level), 82 cm (90% confidence level) and
245 2.4 m (80% confidence level). The wavelet analysis displays the presence of the periodicities
246 throughout the section, although especially in the upper two thirds. It shows a temporary shift to
247 slightly shorter periodicities between 156 and 168 m depth, mostly around the 2.4 m periodicity and
248 in the 50-60 cm periodicity band, indicating slightly lower sedimentation rates, which is in
249 agreement with a decreased thickness of the beds. The 65 cm filtered component (bandwidth 47-
250 106 cm) shows variations in amplitude on a depth scale of 2 to 3 m, which are also found in the 2.4
251 m filtered component (bandwidth 1.8-3.8 m). The 10.5 m filtered component (bandwidth 8.1-15.8
252 m) has five minima and four maxima.

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254 The combined magnetic susceptibility record (Fig. 4) of Sopelana and Zumaia reveals main
255 periodicities in the Redfit power spectrum of 17 and 12 m (95 % confidence level) and ~72 cm. The
256 wavelet diagram shows that the longer periodicity ~17 m is mostly present in the upper half of the

record, down to 110 m in Zumaia, and the 12 m periodicity in the lower half of the record, which coincides with a shift in bedding thickness in Zumaia and the generally thinner bedding at Sopelana. The wavelet spectrum shows the presence of periodicities slightly longer than 72 cm in the upper half of the data, from Zumaia, and slightly shorter than 72 cm in the lower part, from Sopelana. Outputs of band-pass filters, centred at 17 m (bandwidth 12-29 m) and 12 m (bandwidth 8.5-20 m) periodicities, show the presence of 13 cycles throughout the combined datasets.

Spectral analysis reflectance series

The reflectance record of Sopelana has its main periodicities at 62 cm (99% confidence level), at 10 and 2.9 m and at 85 cm (95% confidence level). The wavelet diagram shows the influence of the 2.9 and 10 m periodicity throughout the section, and the presence of the 2.9 m periodicity mostly in the upper half of the section. The output of the band-pass filtered centred at 10 m (bandwidth 7.7-14.3 m) shows five maxima and minima, and the 62 cm band-pass filtered component (bandwidth 45-102 cm) shows some bundling on a scale of approximately 3 m. The 2.9 m band-pass filtered component (bandwidth 2.0-5.0 m) shows approximately 17 maxima.

Redfit analysis of the reflectance data from the Zumaia and the Sopelana sections combined displays periodicities at 16 and 12 m (95% and 90% confidence level, respectively). The wavelet diagram displays a transitional interval around 110 m, where the main periodicity changes from a 12 m (below) to a 16 m periodicity (upwards). Other important periodicities are around 72 cm and 49 cm, with the 72 cm periodicity mostly visible in the upper half of the wavelet analyses, and the 49 cm periodicity in the lower part of the diagram. This agrees with a change in sedimentation rate at Zumaia and the generally thicker beds at Zumaia compared to Sopelana. The band-pass filtered components centred at 16 (bandwidth 12-24 m) and 12 m (bandwidth 8.8-19 m) display 13 cycles throughout the combined reflectance dataset.

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284 Calcareous nannofossil biostratigraphy

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286 For the part of the section of Zumaia investigated for cyclostratigraphy, we correlated the
287 lithological log of Pérez-Rodríguez et al. (2012) (Figure 6, Supplementary Table 1) to ours by
288 recognition of the large scale lithological intervals originally defined by Wiedman (1988) and Ward et
289 al. (1991)(Fig. 2). Semiquantitative data are not directly comparable between Pérez-Rodríguez et al.
290 (2012) and this study. Nannofossils were observed at 1250x magnification in Pérez-Rodríguez et al.
291 (2012) and at 1600x here. Among the species considered here, none of them was recorded as
292 common, e.g. corresponding to 1-10 specimens per field of view (fov). The category Frequent/Few
293 (F) is estimated in a similar fashion between the two studies, corresponding to 1 specimen per 2 to
294 20 fov. Pérez-Rodríguez et al. (2012) considered only one subsequent category, rare (R) for 1
295 specimen per >20 fov whereas in this study, we considered three following categories, rare (R), very
296 rare (VR) and single (S) (Supplementary Table 1). Although the categories are different, combination
297 of our results with those of Pérez-Rodríguez et al. (2012) highlights the ranges of key biostratigraphic
298 taxa (Supplementary Table 1).

299 A number of species identified in the lower part of the Zumaia section, which corresponds to the
300 upper part of Sopelana, were not found in this study. *Acuturris scotus* was found in only one sample,
301 and *Arkhangelskiella maastrichtiana* and *Eiffelithus eximius* are absent. The first occurrence (FO) of
302 *A. maastrichtiana* in Zumaia is was recorded at 49.91 m (Pérez-Rodríguez et al., 2012) which
303 corresponds to a composite depth of 137.29 m in our study (Precession cycle number 176, 69.69
304 Ma). Nannofossil bio-events such as the last occurrence (LO) of *A. scotus*, *Broinsonia parca*
305 *constricta*, *Cribracorona echinus*, *Reinhardtites levis*, *Tranolithus orionatus* and *Zeugrhabdotus*
306 *bicrescenticus* cannot be compared between the work of Pérez-Rodríguez et al. (2012) and this study
307 because the interval below 145 m at Zumaia (42.2 m in the scale of Pérez-Rodríguez et al., (2012) is
308 highly turbiditic, which prevents correlation to Sopelana. *Uniplanarius trifidus* was not found in

Sopelana and those identified for the Zumaia section were considered as highly questionable (Pérez-Rodríguez et al., 2012).

The applied biozonation (Figure 6, 7, Supplementary Table 1) should be considered here as a tentative interpretation from a record that bears large uncertainties. The top of zones UC17 and UC18 are respectively defined by the last occurrences of *T. orionatus* and *R. levis* which both have very inconsistent records across their ranges and when present are at best rare (Supplementary Table 1).

Magnetostratigraphy

The demagnetization data of the lower Maastrichtian at Sopelana are of limited quality, but the resulting magnetostratigraphy is relatively straightforward.

In all samples, a randomly oriented viscous component is first removed between 20 and 80°C. Upon further heating a second component is removed, in general up to 200/220°C. The direction of the second component is random in all samples. Heating up to 360°C did not yield reliable directions for all samples as many samples displayed a randomly oriented increase of natural remanent magnetization (NRM) intensity starting from 300°C (Supplementary figure 2). Post-depositional processes might have affected the paleomagnetic signal as has been described by Moreau et al. (1994). When the demagnetization revealed only one component and the NRM intensities at 220°C are extremely high (above 0.2 A/m; similar to suggestions of Moreau et al. (1994), we consider these directions as being related to the process of re-magnetization and therefore unreliable. These samples are mainly from the marly lithology, which agrees with the findings of Moreau et al. (1994). Some samples could be heated up to 550°C (Supplementary figure 2), and the resultant direction of this third component did not differ from the direction yielded between 200/220° and 300-360°C. Equal area projections (Supplementary figure 2) reveal a slight non-antipodality of the normal and reverse directions, but the data do not pass the reversal test. The slight non-antipodality is most

likely related to the weak NRM intensities, which make it difficult to isolate the primary component from an overprint component, related to overlapping blocking temperature of the magnetic carrier. The characteristic remanent magnetization (ChRM) directions of the third component of the logged lower Maastrichtian section (Batenburg et al., 2012)(Fig. 2) yielded reverse polarity, from cycle 161-166, and 173-180. Above cycle 161, the quality of the demagnetization data is too poor to yield any reliable polarity. New results show that the lowermost part of the section, from cycle 249 to 260, has stable normal polarity, whereas cycle 247-248 yielded only unreliable and uncertain directions. In particular, the inclination in this interval is too shallow to support a stable normal polarity.

Cyclostratigraphy and Astronomical tuning

The limestone-marl alternations at both the Zumaia and Sopelana sections display a hierarchy, with couplets grouped in bundles of (usually) five and groups of 18-20. This is a strong indication that eccentricity-modulated precession is the underlying cause of the sedimentary cyclicity. Intervals with maximal difference between lithologies, represent the maximal precessional amplitude within eccentricity maxima, which is the same phase relation as inferred by Dinarès-Turell (2003, 2013), Kuiper et al. (2008), Westerhold et al. (2008), Hilgen et al. (2010) and Batenburg et al. (2012) for the Paleocene and Maastrichtian of the Zumaia section. To obtain an orbitally tuned chronology, only the 405 kyr period of eccentricity provides a stable and reliable tuning target, which would correspond to the ~17 m periodicity in the upper two thirds of the Zumaia section, and the 10-12 m periodicity in the lower part of the Zumaia section and the whole of the Sopelana section. Time series analyses and lithological observations allow us to identify the positions of consecutive 405 kyr minima, depicted in Figure 2 and discussed in the supplementary information.

Age model

An astronomical age model was constructed by correlating the identified 405 kyr minima in the Sopelana section to successively older minima in the filtered 405 kyr cycle from the new La2011 solution (Laskar et al. 2011b) (band-pass filter centred at 405 kyr, bandwidth from 298 to 615 kyr), linked to the tuning of the 405 kyr cyclicity in the Zumaia section (Batenburg et al., 2012). Using the astronomical tie-points, time series were generated for the combined Zumaia/Sopelana datasets, on which time series analysis was performed (Supplementary figure 2). The Redfit power spectra of reflectance and magnetic susceptibility, respectively, show dominant periodicities of 415 and 409 kyr, but these are likely (partly) introduced by the tuning. Other important periodicities are 23.6 and 22.3 kyr (magnetic susceptibility, 99% confidence level) and 17.9 kyr (reflectance, 95% confidence level). The wavelet diagram shows a relatively constant behaviour of the major periodicities throughout the sections, with potentially some expression of the ~100 kyr periodicity. Ages were assigned to biostratigraphic events based on the 405 kyr tuning, the number of precessional beds between consecutive 405 kyr minima and the position of the event with respect to the precessional cyclicity (Supplementary Tables 1 and 2). The uncertainty estimate is based on the uncertainty in the position of the event, uncertainty in the correlation, the uncertainty in the cyclostratigraphic interpretation (20.8 kyr) and the astronomical tuning (taken here as 23 kyr, the maximal difference detected between 405 kyr minima in between the different La2011 solutions for the interval 65-72 million years ago).

Discussion

Biostratigraphy

The succession of calcareous nannofossil and planktic foraminiferal bio-horizons (Fig. 6, Table 1) is similar to other records from low-latitude, tropical sites (Gardin et al., 2012, and references therein; Voigt et al., 2012). Comparison of the ages of bio-events and associated bio-zonal boundaries

obtained from cyclostratigraphic studies points to diachronism of nannofossil and planktonic foraminifer events (and biozones) across a wide range of sites (Fig. 7). Among all studies for which biostratigraphic data are available, only two provide ages of calcareous plankton bio-horizons which are calibrated to the most recent late Campanian–Maastrichtian time scale (ODP Site 762C, Exmouth Plateau, Indian Ocean, Thibault et al., 2012a, and the Gubbio area, central Italy, Gardin et al., 2012). A slight discrepancy of 0.03 Myr for biostratigraphic events within magnetochron C29r between these studies and our results is accounted for because these authors considered the K-Pg boundary to have an age of 66 Myr instead of the 65.97 Myr used in our study. Comparison of our results with the Gubbio area and Site 762C further reinforces diachronism as a major feature of the upper Campanian–Maastrichtian interval (Supplementary Table 2). Of the 13 bio-horizons in common between Zumaia/Sopelana and the Gubbio area, 9 of them point to much younger ages in the Basque country (Figure 7, Supplementary Table 2). These discrepancies are much above the given ranges of uncertainties and in some cases account for up to 3.6 Myr (FO of *Planoglobulina acervulinoides*). With respect to the key planktic foraminifer and nannofossil biostratigraphic markers used for biozonation, discrepancies between the Basque country and the Gubbio area vary between a reasonable amount of 136 kyr (FO of *Lithraphidites quadratus*) and ca 1.5 Myr for the FOs of *Racemiguembelina fructicosa* and *Micula murus* (Supplementary Table 2). Discrepancies between the Basque country and the Indian Ocean are generally even more pronounced. Although correlation between Sopelana and Zumaia is imprecise below 145 m, it is possible to propose a linear estimation for the age of the LO of *Eiffelithus eximius* documented by Pérez-Rodríguez et al. (2012). This estimate points to the largest discrepancy with a very late age of 70.55 ± 0.05 Ma for the Basque country as compared to 73.90 ± 0.05 in the Indian Ocean and 75.60 ± 0.40 in the Gubbio area (Figure 7, Supplementary Table 2). However, this stratigraphic interval is turbiditic at Zumaia so these specimens of *E. eximius* may be reworked.

Overall, the observed diachronism may result from different sources of error. Different taxonomic concepts and the existence of intermediate evolutionary forms in planktonic foraminifers can be, for

instance, invoked to explain discrepant ages for the FOs of *Abathomphalus mayaroensis*,
Racemiguembelina fructicosa and *Contusotruncana contusa* between Pérez-Rodríguez et al. (2012)
and our study of the Zumaia and Sopelana sections (Supplementary Table 2). In this study, such a
source of error accounts for less than 500 kyr. Taxonomy is much less problematic for the key
nannofossil biostratigraphic markers and is unlikely to account for the observed discrepancy.
However, preservation might also play a role, especially for the calcareous nannofossil bio-horizons
at Zumaia and Sopelana because the assemblage is generally poorly to very poorly preserved.
Nevertheless, it is likely that these discrepancies are partly the result of true migration patterns
across latitudes and different oceanic basins, controlled by the high climate variability of the late
Campanian–Maastrichtian interval. Strongly diachronic succession and ages of late Campanian–
Maastrichtian calcareous plankton bio-horizons have already been interpreted as the expression of
climatically induced migration patterns between Tethyan, Transitional and Austral provinces (Huber
and Watkins 1992; Nifuku et al. 2009; Thibault et al. 2010; Thibault et al. 2012a). This potential
mechanism must be acknowledged, thoroughly assessed and quantified in the Late Cretaceous
because many studies use calcareous plankton biochronology to build their age-models.

Magnetostratigraphy

The upper part of the lower Maastrichtian interval of the Sopelana section has reversed polarity. The
magnetic reversal boundary C31r/C31n has been reliably detected slightly higher in the stratigraphy
in cycles 152/153 at Zumaia (Batenburg et al., 2012; Pérez-Rodríguez et al., 2012). In the lowermost
part of the section, normal polarity can be reliably detected, with uncertain polarity from cycles 247
to 249. The whole section was studied previously by Mary et al. (1991), who found reverse polarity
until 59 m downwards from the C31r/n boundary, which would correspond approximately to a
depth of 181 m, around cycle 245. The samples from the limestones of cycles 247 and 248 may
represent reverse polarity, and the reversal is interpreted to be within cycles 248–249, although the

exact position could be slightly higher in the stratigraphy. The reversal has been assigned an age of 71.22 +/- 0.09 Ma (Table 1, Supplementary Table 2), the uncertainty being based on the uncertainty in the stratigraphic position, in the cyclostratigraphic interpretation, and in the astronomical target curve.

The normal polarity in the lowermost part of the section likely represents C32n1n, the short normal polarity interval above the main normal polarity subchron C32n2n, which near its top contains the Campanian/Maastrichtian boundary.

The magnetostratigraphy from Zumaia and Sopelana compares well to the recently published chronologies of Husson et al. (2011) and Thibault et al. (2012a) (Figs. 5, 7 and Table 2). The base of C29r, which was obtained by correlation with Westerhold et al. (2008), at 66.31 ± 0.09 Ma, falls between the ages from these studies, at 66.3 ± 0.07 and 66.376 Ma, respectively. The total amount of time between the K/Pg boundary and the C31n/C31r reversal as reported by Husson et al. (2011) and Batenburg et al. (2012) is identical at 3.22 Myr. The position of C31n/C31r is in the middle of the stratigraphic range established by Pérez-Rodríguez et al. (2012). The total amount of time between the K/Pg boundary and the reversal C31r/C32n1n at Zumaia and Sopelana of 5.26 Myr is slightly less than the 5.4 Myr reported by Husson et al. (2011). The orbital estimate for this time-span by Husson et al. (2011), is based mostly on the grey level variations in Hole 762C, which show a strong presence of the 405 kyr period of eccentricity. However, obliquity cycle variability in the 405 kyr cycle spanning the C31r/C32n1n transition, cycle $Ma_{405}14$, seems to obscure the influence of the 100 kyr cycle of eccentricity (Husson et al., 2011), and there is a small uncertainty in the exact stratigraphic position of this transition. These factors may have contributed to a slightly longer estimate of the duration of Chron C31r by Husson et al. (2011)(Fig. 5).

Orbital pacing

The Zumaia section shows strong variability in the expression of the marls, which reflect the amplitude modulation of precession by eccentricity, likely caused by variations in clay supply by run-off (Batenburg et al., 2012; Mount and Ward, 1986). An enhanced seasonal contrast (in the northern hemisphere) during precession minima at times of eccentricity maxima may have led to an intensified hydrological cycle, leading to deposition of thicker, darker marls. The Zumaia section shows a strong influence of terrigenous input, and was likely closer to the source of clastic sediment than the Sopelana section, which is corroborated by the frequent occurrence of turbidites at Zumaia, and the substantial changes in sedimentation rate. In contrast, the marls in the Sopelana section vary less in expression than at Zumaia, whereas the carbonates vary more strongly in thickness and degree of weathering, displaying the combined influence of variations in productivity and clay input (dilution). As the marls correspond to precessional minima, it is logical to assume that limestones reflect precession maxima. The increased productivity may be due either to an increased input from nutrients through the enhanced hydrological cycle during the preceding precession minimum, or to an input of nutrients from eolian dust during periods of a weakened hydrological cycle during precession maxima. Whereas the phase relationship with eccentricity is clear, the phase relation with precession and the proposed climatic mechanism underlying the rhythmic sedimentation requires further testing, for instance through elemental analysis and climate modelling of orbital extremes, using Late Cretaceous boundary conditions. The influence of an approximately 31 kyr long periodicity can be observed in the Sopelana record, which could correspond to the ~39 kyr periodicity of obliquity in the Late Cretaceous, slightly shorter than the present day (Berger and Loutre, 1994). However, the records are dominated by eccentricity-modulated precession, indicating that regional climate was controlled by lower latitude insolation.

A potential influence of a 1.2 Myr cycle can be observed in the upper Maastrichtian of Zumaia and Sopelana, with strong shifts in lithologies from predominantly carbonates to predominantly marls. These shifts, at a ~50 m scale, or approximately 60 cycles apart (counting cycles marked with “a” and

“b”), are likely due to changes in relative sea level (Batenburg et al., 2012). In the lower Maastrichtian of Sopelana, no such shift in lithology can be observed. In cycle 191, which is 60 cycles below the lowermost shift in Zumaia in cycle 132 (counting cycles marked with “a” and “b”), the overall clay and carbonate content of the limestone-marl alternations does not change noticeably. However, the potential influence of a longer-term periodicity might be indicated by the varying strength of the ~100 kyr periodicity through the Sopelana section. A reduced amplitude of the ~100 kyr cycle can be observed in the interval from cycle 212 to 224, ~90 cycles below the lowermost shift in Zumaia. This could be the expression of a long-term eccentricity minimum as the expression of the 100 kyr cycle is minimal in such a minimum because the different ~100 kyr eccentricity components cancel each other out. If the potential 1.2 Myr cyclicity is indeed present throughout the succession, the weakening of the ~100 kyr cycle occurs in the opposite phase of the 1.2 Myr cyclicity as compared to the lithological shifts in the Zumaia section (Batenburg et al., 2012). The origin of a potential 1.2 Myr cyclicity is uncertain, as the influence of obliquity seems limited in the data records and comparison with the La2011 eccentricity is not possible as this cycle is not reliable in the solution further back in time than ~54 Ma (Westerhold et al., 2012).

Conclusions

For the first time, a high resolution cyclostratigraphic framework with the full range of periodicities of eccentricity modulated precession is available for the Maastrichtian. The rhythmic limestone-marl alternations at Sopelana and Zumaia encompass a total of thirteen 405 kyr cycles, spanning the last 5.3 Myr of the latest Cretaceous. The detailed cyclostratigraphic interpretation of the lithological record is supported by time series analysis of the high resolution proxy data and is tuned to the 405 kyr periodicity of the new La2011 solution (Laskar et al., 2011). The astronomically tuned time-scale for Zumaia and Sopelana is in good agreement with previously published astronomic time-scales by Herbert (1999), Husson et al. (2011) and Thibault et al. (2012a). This study indicates a slightly

younger and more tightly constrained age for the C31r/C32n1n chron boundary compared to the astronomically tuned age suggested by Husson et al. (2011), which is used in The Geologic Time Scale 2012 (Ogg and Hinnov, 2012). The astronomical tuning demonstrates that, while the reported durations of magnetostratigraphic chrons are consistent, several biostratigraphic events are not coeval on a global scale, which may be due to true diachroneity, or alternatively to migration patterns and/or misidentification and/or preservational factors. This emphasises the importance of establishing integrated stratigraphies with independent constraints on correlation, which can successfully be achieved by carbon isotope stratigraphy and magnetostratigraphy. The orbital pacing of latest Cretaceous climate by eccentricity modulated precession indicates the importance of climatic processes at lower latitudes, although the origin of a potential 1.2 Myr periodicity is uncertain. The close agreement between astronomical tunings is a confirmation that the Maastrichtian time-scale is now consistent and stable. However, to securely anchor the Mesozoic time-scale further intercalibration with radiometric dating techniques is required to solve the problem of the age of the K/Pg boundary.

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Figure captions

Figure 1: Overview photograph and stratigraphic log of the Sopelana section, along the Atxabiribil-Arriatera swimming beach, with cycle numbers indicated. See Figure 2 for legend. Due to merging of photographs, the distance between promontories, behind the people and behind the concrete reinforcement, is smaller than in reality, while the cliff wall is unaffected.

Figure 2: Stratigraphic logs of the Zumaia and Sopelana sections with key biostratigraphic events and magnetostratigraphy from this study. PF: planktonic foraminifera; CN: calcareous nannoplankton; Sop: in the Sopelana section. See Table 3 for uncertainties in the position of bio- and magnetostratigraphic events. Grey roman numerals indicate the intervals identified by Ward et al. (1991) and lilac numbers the units of Wiedmann (1988). The half circles in deep purple indicate the 405 kyr eccentricity minima, the lighter half circles indicate the 100 kyr bundling. White numbers are cycle numbers.

Figure 3: Stratigraphic logs of the Zumaia and Sopelana sections with grey roman numerals indicating the intervals identified by Ward et al. (1991) and lilac numbers the units of Wiedmann (1988). The total reflectance (L^* , left) and the magnetic susceptibility (MS, right) records from the Zumaia and Sopelana sections are connected at a composite depth of 135.47 m. The data are flanked by their band-pass filters, wavelet analyses and Redfit power spectra. The band-pass filters of reflectance are centred at 16 m (dark grey, top), 12 m (grey-purple, base), 4 m (light grey) and at 72 cm (purple, top), and 49 cm (lilac, base) (bandwidths of 12-29, 8.5-20, 3.0-6.0 and 0.53-1.1 m respectively). The band-pass filters of magnetic susceptibility are centred at 17 m (dark red, top), 12 m (purple, base), 4 m (red) and at 72 cm (pink) (bandwidths of 12-24, 8.8-19, 3.0-6.0 and 0.50-1.3 m respectively). The black Ma_{405} numbers indicate the 405 eccentricity cycles following the nomenclature of Husson et al. (2011).

796

797 Figure 4: The reflectance (L^*) and magnetic susceptibility (MS) data series in the time domain, with
798 their 415 kyr (dark grey, bandwidth of 311-621 kyr), 100 kyr (grey, bandwidth 75-150 kyr), 17.9 kyr
799 (light grey, bandwidth 13.4-27.2 kyr), 409 kyr (dark red, bandwidth 308-609 kyr), 100 kyr (red,
800 bandwidth 75-150 kyr) and 23.6 kyr (pink, bandwidth 17.8-35.3 kyr) band-pass filters, wavelet
801 analyses and Redfit power spectra (top). The 405 kyr eccentricity cycles (black Ma_{405} numbers follow
802 the nomenclature of Husson et al (2011). In the right hand panel, the 405 kyr band-pass filters
803 (bandwidth 300-600 kyr) are displayed of the different La2011 solutions.

804

805 Figure 5: Comparison of Maastrichtian astrochronologies, with grey bands indicating the identified
806 405 kyr cycles, numbered $Ma_{405}1$, $Ma_{405}2$, ... , from the K/Pg boundary downwards, following Husson
807 et al. (2011). From left to right the cyclostratigraphic interpretation of Husson et al. (2011) of the
808 grey level data of Hole 525A and Hole 762C, with their ~100 kyr and 405 kyr band-pass filters; the
809 cyclostratigraphic framework of Thibault et al. (2012a) of the grey level data of Hole 762C; the
810 magnetostratigraphy, 16 ,12 and 4.0 m band-pass filters (bandwidths 12-29, 8.5-20 and 3.0-6.0 m,
811 respectively) of reflectance, the reflectance data, the stratigraphic column, the magnetic
812 susceptibility data and the 17, 12 and 4.0 m band-pass filters of magnetic susceptibility (bandwidths
813 of 12-24, 8.8-19 and 3.0 to 6.0 m, respectivley) of Zumaia and Sopelana (this study and Batenburg et
814 al., 2012); the cyclostratigraphic interpretation of the magnetic susceptibility data of Hole 1267B by
815 Husson et al. (2011).

816

817 Figure 6: Cyclostratigraphy and tuned ages of biostratigraphic and magnetostratigraphic events, as
818 obtained in this study, Batenburg et al. (2012) and by correlation with Pérez-Rodríguez et al. (2012).

819

820 Figure 7: Maastrichtian time scales with magneto-, bio- and chemostratigraphic events according to
821 Cande and Kent (1995), Herbert et al. (1995), Herbert (1999), option 2 of Husson et al. (2011),

822 Thibault et al. (2012a), Batenburg et al. (2012), Pérez-Rodríguez et al. (2012), Ward and Kennedy
823 (1993), MacLeod (1994), Ward et al. (1991) and the summary of biozones based on correlation of
824 carbon isotope stratigraphies by Voigt et al. (2012), with ¹Bralower et al. (2002); ²Lees and Bown
825 (2005); ³Huber (1990); ⁴Huber (1992); ⁵Pospichal and Wise (1990); ⁶Li and Keller (1998); ⁷Manivit
826 (1984); ⁸Henriksson (1993); ⁹Thibault and Gardin (2007); ¹⁰Premoli-Silva and Sliter (1995); ¹¹Gardin et
827 al. (2012); ¹²Monechi and Thierstein (1985); ¹³Gardin et al. (2001); ¹⁴Küchler and Odin (2001), ¹⁵Odin
828 et al. (2001), ¹⁶Walaszczyk et al. (2002); ¹⁷Thibault et al. (2012b); ¹⁸Burnett (1990). For Herbert et al.
829 (1995) and Herbert (1999), who only report durations, a K/Pg-boundary age of 65.97 Ma has been
830 assigned for comparison.

831

Table captions

Table 1: Top and Bottom heights (or depths), and estimated ages of significant stratigraphic events recorded in the Zumaia and Sopelana sections compared to the Gubbio area, Italy and the Exmouth Plateau, Indian Ocean. Mag., magnetic reversal boundary; PF , planktic foraminifers; CN, calcareous nannofossils. Reported uncertainties are the sum of the uncertainty in the stratigraphic position (difference in top and bottom height), the uncertainty in the cyclostratigraphic interpretation (taken as two precessional cycles, 43.6 kyr), the uncertainty in the astronomical solution (taken as 23 kyr, the maximal differences in the position of the 405 kyr minima between the La2011 astronomical solutions) and, for the data of Pérez-Rodríguez (2012), an additional uncertainty of one precessional cycle (21.8 kyr) for the correlation. * Peréz-Rodríguez et al., (2012); † Gardin et al (2012); ‡ Thibault et al. (2012a); § Batenburg et al., 2012.

Table 2: Comparison of Maastrichtian magnetostratigraphies. ¹ Age of C29r/C30n from Herbert (1995), other boundaries from Herbert et al. (1999); ² A K/Pg boundary age of 65.97 Myr was assigned for comparison. * a possible hiatus causes this age to be less reliable.

Sopelana

stratigraphic events		orig. height (m)*	com- posite (m)	section	cycle	age (Myr)	average age (Myr)	average age Gubbio (Myr)†	average age ODP762C ((Myr)‡
Top C31r (mag.)	T	-	121.09		152	69.18			
	B	-	121.95	Zumaia §	153	69.21	69.19±0.08	-	69.220±0.070
Top C32n1n (mag.)	T	-	182.88		248	71.19			
	B	-	183.96	Sopelana	250	71.23	71.22±0.09	-	71.400±0.080
FO <i>Plummerita hantkeninoides</i> (PF)	T	-	3.60		5	66.05			
	B	-	4.57	Sopelana §	6	66.07	66.06±0.08	66.118±0.017	-
FO <i>Pseudoguembelina hariaensis</i> (PF)	T	170.90	18.03		24	66.44			
	B	168.40	20.50	Zumaia *	27	66.49	66.46±0.12	-	-
LO <i>Archaeoglobigerina cretacea</i> (PF)	T	157.00	31.76		41	66.77			
	B	150.90	37.78	Zumaia *	48	66.92	66.84±0.16	-	-
LO <i>Globotruncana bulloides</i> (PF)	T	150.90	37.78		48	66.92			
	B	145.32	43.29	Zumaia *	54	67.07	66.99±0.16	-	-
LO <i>Contusotruncana plummerae</i> (PF)	T	126.32	62.06		77	67.59			
	B	123.20	65.14	Zumaia *	81	67.67	67.63±0.13	-	-
FO <i>Rugoglobigerina scotti</i> (PF)	T	111.75	76.46		95	68.00			
	B	107.10	81.05	Zumaia *	102	68.13	68.07±0.16	-	-
LO <i>Contusotruncana fornicata</i> (PF)	T	103.00	85.10		107	68.26			
	B	99.80	88.24	Zumaia *	110	68.33	68.29±0.12	-	-
LO <i>Globotruncana linneiana</i> (PF)	T	99.80	88.24		110	68.33			
	B	97.60	90.40	Zumaia *	113	68.38	68.35±0.12	-	70.130±0.140
LO <i>Globotruncana ventricosa</i> (PF)	T	99.80	88.24		110	68.33			
	B	97.60	90.40	Zumaia *	113	68.38	68.35±0.12	-	-
FO <i>Abathomphalus mayaroensis</i> (PF)	T	87.80	100.02		123	68.59			
	B	86.60	101.20	Zumaia *	125	68.61	68.60±0.10	69.296±0.107	69.920±0.150
FO <i>Abathomphalus mayaroensis</i> (PF)	T	-	92.40		115	68.42			
	B	-	93.28	Zumaia §	116	68.44	68.43±0.08	69.296±0.107	69.920±0.150
FO <i>Globotruncanita conica</i> (PF)	T	79.55	108.12		131	68.74			
	B	78.80	108.86	Zumaia *	131	68.75	68.75±0.09	-	-
FO <i>Racemiguembelina fructicosa</i> (PF)	T	78.80	108.86		131	68.75			
	B	71.81	115.72	Zumaia *	143	68.99	68.87±0.21	70.137±0.133	67.660±0.220
FO <i>Racemiguembelina fructicosa</i> (PF)	T	-	105.00		128	68.69			
	B	-	106.03	Zumaia §	129	68.71	68.70±0.16	70.137±0.133	67.660±0.220
LO <i>Contusotruncana morozovae</i> (PF)	T	71.81	115.72		143	68.99			
	B	67.30	120.15	Zumaia *	151	69.15	69.07±0.17	-	-
FO <i>Planoglobulina acervulinoides</i> (PF)	T	58.80	128.40		164	69.42			
	B	52.80	134.40	Zumaia *	172	69.58	69.50±0.17	73.119±0.459	68.360±0.080
FO <i>Contusotruncana contusa</i> (PF)	T	52.80	134.40		172	69.58			
	B	47.90	139.30	Zumaia *	178	69.71	69.64±0.16	70.259±0.051	67.660±0.220
FO <i>Contusotruncana contusa</i> (PF)	T	-	119.90		150	69.14			
	B	-	120.48	Sopelana §	151	69.16	69.15±0.17	70.259±0.051	67.660±0.220
FO <i>Racemiguembelina powelli</i> (PF)	T	52.80	134.40		172	69.58			
	B	47.90	139.30	Zumaia *	178	69.71	69.64±0.16	-	68.180±0.180
FO <i>Micula prinsii</i> (CN)	T	188.10	1.72		3	66.01			
	B	185.90	2.08	Zumaia *	4	66.02	66.02±0.09	66.296±0.077	66.390±0.070
FO <i>Ceratolithoides kamptneri</i> (CN)	T	181.15	8.29		10	66.15			
	B	180.30	9.05	Zumaia *	11	66.17	66.16±0.10	-	66.980±0.100
FO <i>Micula murus</i> (CN)	T	175.90	13.09		17	66.29			
	B	170.90	18.03	Zumaia *	24	66.44	66.37±0.16	67.919±0.125	67.330±0.070
LO <i>Petrarhabdus vietus</i> (CN)	T	83.10	104.64		128	68.68			
	B	79.55	108.12	Zumaia *	131	68.74	68.71±0.12	-	67.790±0.060
FO <i>Lithraphidites quadratus</i> (CN)	T	72.62	114.93		142	68.97			
	B	70.94	116.58	Zumaia *	144	69.02	69.00±0.11	69.131±0.067	67.790±0.060
LO <i>Cribracorona echinus</i> (CN)	T	70.94	116.58		144	69.02			
	B	-	124.08	Sopelana	157	69.27	69.15±0.19	-	-
LO <i>Reinhardtites levis</i> (CN)	T	-	125.40		159	69.31			
	B	-	127.23	Sopelana	161	69.35	69.33±0.09	70.154±0.047	69.750±0.150
FO <i>Arhangeliskiella maastrichtiana</i> (CN)	T	49.91	137.29		176	69.69			
	B	40.21	~146.99	Zumaia *	~187	~69.8	69.78±0.28	70.590±0.483	-
LO <i>Zeugrhabdotus bicrescenticus</i> (CN)	T	-	151.96		196	70.12			
	B	-	153.03	Sopelana	198	70.17	70.15±0.09	-	69.750±0.150
LO <i>Tranolithus orionatus</i> (CN)	T	-	156.30		203	70.27			
	B	-	157.85	Sopelana	206	70.32	70.30±0.09	70.723±0.107	69.560±0.070
LO <i>Eiffelithus eximius</i> (CN)	T	22.21	~162.00		-	~70.5			
	B	25.30	~165.00	Zumaia *	-	~70.6	70.55±0.20	75.601±0.399	73.900±0.090
LO <i>Broinsonia parca constricta</i> (CN)	T	-	181.88		246	71.17	71.19±0.09	71.004±0.287	69.480±0.100

	Ages (Myr)						
	Batenburg et al. (2012)	Pérez-Rodríguez et al. (2012)	This study Sopelana	Thibault et al. (2012a)	Husson et al. (2011)	Cande & Kent (1995)	Herbert (1995 ¹ , 1999)
Events	Zumaia	Zumaia	Sopelana	ODP Hole 762C	ODP 1267B, 762C, DSDP 525A	Magnetic anomaly profiles	DSDP 357, 516F, 525A, 527-529
K/Pg boundary	65.97 ± 0.02	65.97 ± 0.02	65.97 ± 0.02	66	66 ± 0.07	65	65.97 ²
Mag.strat.							
C29r/C30n	66.31 ± 0.09			66.376	66.3 ± 0.07	65.578	66.347 ± 21 ¹
C30n/C30r				68.165	68.2 ± 0.07	67.61	68.047
C30r/C31n				68.338*	68.32 ± 0.07	67.735	68.152
C31n/C31r	69.19 ± 0.08	69.22 ± 0.21			69.22 ± 0.07	68.737	69.077
C31r/C32n1n			71.22 ± 0.09		71.4 ± 0.08	71.071	