

Excursion to the Zumaia Section: “from the Maastrichtian to the Ypresian”

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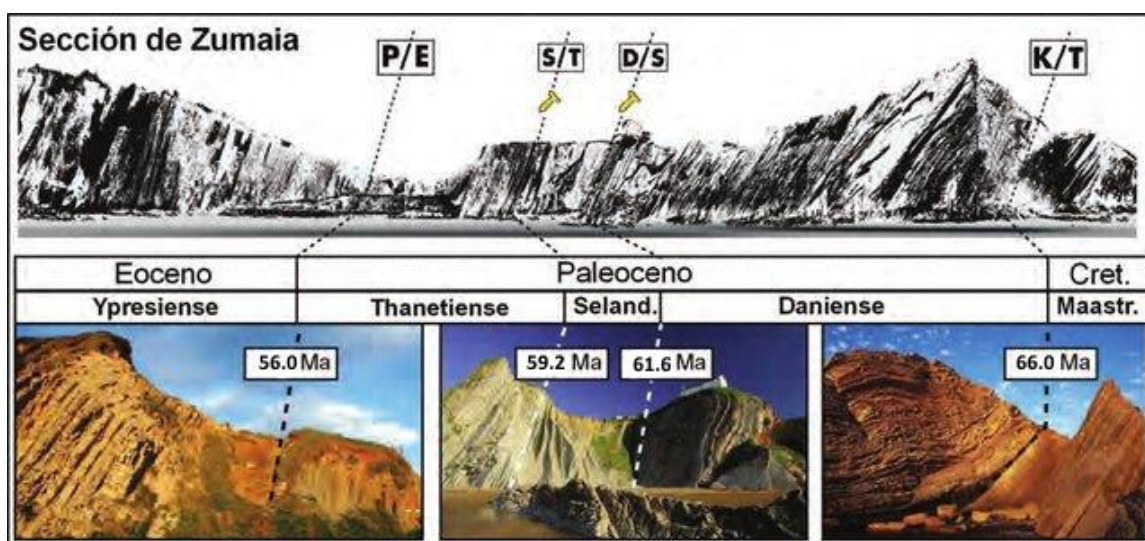


This exceptional outcrop offers a rare opportunity to study key global atmospheric, oceanographic, cosmic and volcanic events with remarkable clarity (Hilario, 2012).

Thanks to its steeply tilted strata and easily accessible coastal setting, the Zumaia Section offers a unique opportunity to quickly and thoroughly grasp the processes occurring around the time of the Cretaceous–Paleogene mass extinction event.

Note:

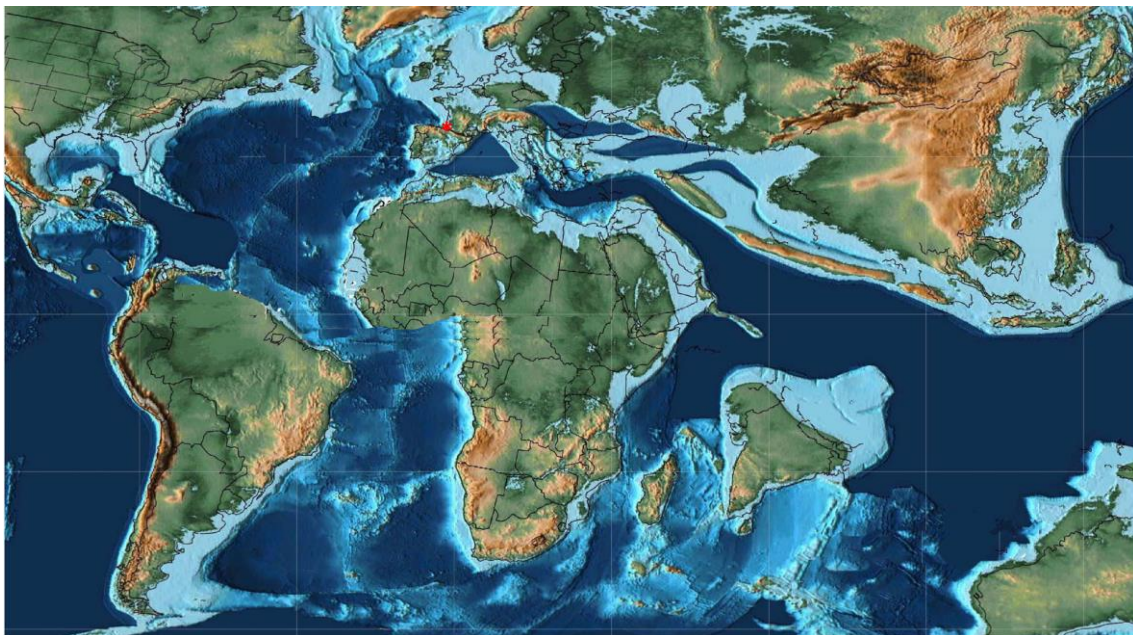
- Key concepts in **bold** are explained under section 9.
- "Ma" stands for "mega-annum," a Latin-derived term meaning "million years ago," while "ka" stands for "kilo-annum," meaning "thousand years ago".
- We will explore the Zumaia Section in reverse direction, from the youngest to the oldest strata—from the Ypresian to the Maastrichtian—due to tidal conditions.



Overview of the Zumaia Section (García-Cortés et al., 2017)

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The world at 68 Ma (Fischer *et al.*, 2025)

1. **Geologic Setting**

The Zumaia section is located in the Basque-Cantabrian Basin, northern Spain, along the Basque Coast Geopark. The sequence preserved at Zumaia is nearly continuous spanning from the Santonian (~86.3 Ma) to the Ypresian (~47.8 Ma). The depositional environment was bathyal, estimated from **benthonic foraminifera** at depths around 1000 meters, indicating a deep marine setting distal from the shoreline, but under continental influence. The climate during the deposition of this interval ranged from temperate in the Late Cretaceous to subtropical during the Paleocene-Eocene transition, consistent with greenhouse conditions due to variable but high CO₂ concentrations in the atmosphere related to the very active break up of the Super Continent Pangea. The basin formed within

a passive continental margin setting that evolved into a foreland basin during the Pyrenean orogeny. Sedimentation was primarily hemipelagic, with episodic turbidite deposition.

Zumaia's tectonic stability and high sedimentation rate make it ideal for **cyclostratigraphy** and biostratigraphic correlations, critical for interpreting and dating climatic and extinction events.

2. Chronostratigraphic Scheme

- Cretaceous:

Maastrichtian: ~72.1–66.0 Ma

- Paleogene:

Paleocene ~66.0–59.2 Ma

- Danian: ~66.0–61.6 Ma
- Selandian: ~61.6–59.2 Ma
- Thanetian: ~59.2–56.0 Ma

Eocene:

- Ypresian: ~56.0–47.8 Ma

Reference: International Commission on Stratigraphy (ICS), December 2024. URL: <http://www.stratigraphy.org/ICSchart/ChronostratChart2024-12.pdf>. (Cohen *et al.*, 2013; updated).

3. Scientific Interest of the Zumaia Section

The Zumaia section is internationally recognized for its stratigraphic completeness, continuity, and high-resolution records. It is a key site for calibrating the Maastrichtian–Paleogene interval using cyclostratigraphy, magnetostratigraphy, and biostratigraphy (Batenburg *et al.*, 2016). It includes GSSPs (Global Stratotype Sections and Points), which are international reference points for stage boundaries, for the Selandian and Thanetian stages (Schmitz *et al.*, 2011).

The section uniquely preserves biotic responses to the K–Pg boundary event and records major hyperthermal events like the **PETM** (Paleocene-Eocene Thermal Maximum). Notably, the **Mid Paleocene Hyperthermal Event**, which is less well-known than the **PETM**, is also recorded in Zumaia, providing critical insight into transient global warming episodes during the Paleocene and their expression in sedimentary and microfossil records. The richness of planktonic foraminifera and nannofossils enhances its utility for paleoceanographic reconstructions.

Moreover, Zumaia has played a critical role in elucidating the temporal relationship between Deccan Trap volcanism and the **K–Pg** (Cretaceous-Paleogene) extinction,

showing that multiple volcanic pulses were paced by orbital eccentricity maxima and had significant climatic consequences (Gilabert *et al.*, 2021). Similarly, during the **PETM**, orbitally paced carbon cycle perturbations have been linked to greenhouse gas release mechanisms, making Zumaia essential for understanding feedback mechanisms in Earth's climate system.

4. Sedimentological Description and Evolution

The stratigraphy is composed of rhythmic alternations of **hemipelagic** marls and limestones, modulated by orbital cycles (Batenburg *et al.*, 2016). Maastrichtian layers are cyclically bedded, which continues in the Danian while Late Paleocene units form the transition from carbonates to more siliciclastic-rich facies.

Turbidites punctuate the record, increasing in frequency toward the Eocene due to Pyrenean tectonism. Gawenda *et al.* (1999a, 1999b) reported that turbidites are sparse in the Maastrichtian and early Paleocene intervals but become markedly more frequent from the Selandian onwards. During the Thanetian and Ypresian, the Zumaia section contains frequent fine- to medium-grained turbidites, often interpreted as distal deposits from the deep-sea fan system. The increase in turbidite frequency correlates with tectonic uplift and reorganization of sediment transport systems in the Bay of Biscay. The **PETM** marks a shift to intensified siliciclastic influx and carbonate dissolution.

5. Chronological Units and Boundaries

- **Campanian/Maastrichtian (~72.1 Ma):** Defined by nannofossil and foraminiferal assemblages.
- **Maastrichtian/Danian (K–Pg, ~66.0 Ma):** Abrupt faunal turnover, carbon isotope anomaly (Gilabert *et al.*, 2021).
- **Danian/Selandian (~61.6 Ma):** Base marked by magnetic susceptibility and nannofossil turnover; **GSSP** (Schmitz *et al.*, 2011).
- **Selandian/Thanetian (~59.2 Ma):** Defined by the first occurrence of the calcareous nannofossil *Fasciculithus tympaniformis* and correlated to a carbon isotope shift; **GSSP** (Schmitz *et al.*, 2011).
- **Thanetian/Ypresian (~56.0 Ma):** **PETM**, defined by a major CIE and **benthic foraminiferal** extinction (Storme *et al.*, 2012).

6. Paleoclimatic Evolution and Events

From the Maastrichtian to the Ypresian, the Zumaia section records a series of significant paleoclimatic changes, reflecting a trend toward global warming interrupted by transient hyperthermal events. During the Maastrichtian (~72.1–66.0 Ma), Earth experienced warm greenhouse conditions with sea surface temperatures around 20–25°C. A notable **Late Maastrichtian Warming event** raised temperatures by ~2–4°C. Deep ocean warming is also evident from benthic $\delta^{18}\text{O}$ records. This warming was paced by 405-ka orbital eccentricity cycles. It

likely reflects combined effects of orbital forcing and long-term volcanic CO₂ emissions. (Batenburg *et al.*, 2016).

Following the K–Pg boundary, the Paleocene (~66–56 Ma) began with cooler conditions after the K–Pg extinction, followed by gradual warming. Mid-Paleocene climate was unstable, with transient hot events like the Latest Danian Hyperthermal (not yet discovered in Zumaia) and **Mid Paleocene Hyperthermal**.

In the Thanetian, the **Mid Paleocene Hyperthermal Event (MPHE)** is expressed in Zumaia through a negative carbon isotope excursion and increased siliciclastic sedimentation, indicating warmer temperatures and intensified hydrological cycles (Bernaola *et al.*, 2007). This event is crucial for understanding the Earth's sensitivity to carbon cycle perturbations in non-extinction contexts.

The **Paleocene–Eocene Thermal Maximum (PETM)** at ~56 Ma represents the most prominent hyperthermal of the Cenozoic, characterized by rapid warming, ocean acidification, and mass extinction of deep-sea benthic foraminifera (Alegret *et al.*, 2009). At Zumaia, it is marked by a sharp carbon isotope excursion (**CIE**), sedimentological shifts, and carbonate dissolution. Volcanically driven CO₂ emissions, particularly from hydrothermal and magmatic activity in the North Atlantic Igneous Province, are thought to have triggered the **PETM** (Le Callonnec *et al.*, 2014).

Planktic foraminifera provide insights into sea surface temperature variations during these events, while **benthic foraminifera** help reconstruct bottom water conditions, offering a comprehensive view of the climatic impact across oceanic layers.

7. K–Pg Boundary and Discussion of Impact and Volcanism

The **K–Pg** boundary at Zumaia exhibits a sharp $\delta^{13}\text{C}$ drop, iridium anomaly, and a major extinction horizon affecting **planktic** and **benthic fauna**. The layer marks the Chicxulub impact and is temporally associated with Deccan volcanism (Gilabert *et al.*, 2021). These events produced environmental stress via sulfate aerosols, dust, greenhouse gases, and ocean acidification. Zumaia's detailed record enables separation of impact-related effects from longer-term volcanic influence. Stratigraphic and geochemical data at Zumaia support a link between pulsed Deccan eruptions and orbital pacing, further refining the chronology of these events.

8. Cyclostratigraphic studies in Zumaia

The Zumaia section contains thirteen 405-ka eccentricity cycles in the Maastrichtian, and over 25 in the Paleocene (Batenburg *et al.*, 2016; Hilgen *et al.*, 2015). The limestone-marl rhythm reflects eccentricity-modulated precession. **Cyclostratigraphy** has provided precise age models for global correlations and calibrations of **magnetostratigraphy**, particularly C29r and C30n.

9. Key concepts

- **Benthic Foraminifera:** Bottom-dwelling single-celled organisms used to reconstruct bottom water temperatures and oxygenation conditions based on assemblage composition and isotopic signatures.
- **Carbon Isotope Excursion (CIE):** A shift in carbon isotope ratios ($\delta^{13}\text{C}$), indicating changes in carbon reservoirs, often linked to climatic or biotic events. These occur when large amounts of ^{12}C -rich carbon rapidly enter the ocean-atmosphere system, lowering the $^{13}\text{C}/^{12}\text{C}$ ratio. At the K–Pg boundary, this is linked to impact-related ecosystem collapse and Deccan volcanism. During the PETM, sources likely include volcanic CO_2 and methane hydrates. These shifts reflect major carbon cycle disruptions, leading to global warming and ocean acidification. CIEs are key markers for identifying climatic crises in Earth's history.
- **Cyclostratigraphy:** Analysis of sedimentary rhythms driven by Earth's orbital variations, used to build precise geological timescales. In well-preserved, high-sedimentation-rate sections like Zumaia, cyclostratigraphy can achieve resolutions of ~20 ka or finer, particularly when precession and obliquity signals are identifiable. This allows detailed reconstruction of climatic and depositional changes on sub-orbital to orbital timescales.
- **GSSP (Global Stratotype Section and Point):** International reference point for defining the base of a stratigraphic stage based on a globally recognizable event.
- **Hemipelagic:** Sediments from both deep-sea (pelagic) and land-derived (terrigenous) sources, deposited under calm conditions in deep marine settings.
- **Hyperthermal events:** These are brief, intense global warming episodes superimposed on longer-term greenhouse climates. They are marked by rapid temperature rises, negative carbon isotope excursions, ocean acidification, and biotic stress or turnover. Examples include the PETM and the Mid Paleocene Hyperthermal Event. These events are typically triggered by massive releases of ^{12}C -rich carbon from volcanic, methane, or organic sources. Hyperthermals offer key insights into Earth's climate sensitivity and carbon cycle feedbacks.
- **K–Pg (Cretaceous–Paleogene boundary):** A major geological boundary at approximately 66 Ma, marked by a mass extinction

event primarily attributed to a bolide impact, with additional contributions from prolonged volcanic activity according to some studies.

- **Late Maastrichtian Warming event:** This was a global climate warming phase occurring around 69–66 Ma, just before the Cretaceous–Paleogene boundary. It is characterized by a rise in deep-sea and surface temperatures, detected through stable isotope records. This warming likely resulted from increased volcanic CO₂ emissions and orbital forcing, influencing marine ecosystems prior to the K–Pg extinction (Batenberg *et al.*, 2016).
- **Magnetochron:** It refers to a time interval during which Earth's magnetic field maintained a single polarity—either normal or reversed. These intervals are recorded in sedimentary and volcanic rocks as magnetic signatures. By matching local magnetic patterns to the global geomagnetic polarity time scale (GPTS), geologists can date and correlate strata. Magnetochrons are numbered sequentially, such as C29r (reversed) and C30n (normal), commonly used in the Maastrichtian–Paleogene interval. They are crucial for building high-resolution chronological frameworks in stratigraphy.
- **Mid Paleocene Hyperthermal Event (MPHE):** A brief global warming event during the Thanetian marked by a negative carbon isotope excursion and climatic disruption. It provides insight into early Paleogene climate dynamics and carbon cycle sensitivity.
- **Milankovitch Cycles:** These are periodic variations in Earth's orbit and axial tilt that affect solar radiation distribution, driving long-term climate changes. The main components are eccentricity (~100 and 405 ka), obliquity (~41 ka), and precession (~19–23 ka). These cycles modulate seasonal contrasts and ice volume, influencing sedimentation patterns. Their imprint in geological records enables precise time calibration through cyclostratigraphy. Milankovitch theory underpins our understanding of Quaternary glaciations and past greenhouse climates.
- **PETM (Paleocene-Eocene Thermal Maximum):** It was a rapid global warming event around 56 Ma, lasting ~200,000 years. It is marked by a sharp negative carbon isotope excursion, massive carbon input, and global temperature rise of ~5–8°C. The event caused ocean acidification, widespread biotic turnover, especially in deep-sea benthic foraminifera, and shifts in sedimentation. Likely triggers include volcanic CO₂ emissions and methane hydrate

release. The **PETM** is a key analog for understanding future climate change scenarios.

- **Planktic Foraminifera:** Free-floating, single-celled marine organisms useful for reconstructing sea surface temperatures and surface ocean conditions.
- **Turbidites:** Gravity-driven sediment deposits with graded bedding, often interbedded in hemipelagic sequences and indicative of slope instability or tectonics.

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