Settling the Danian Astronomical Time Scale: A Prospective Global Unit Stratotype at Zumaia, Basque Basin

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Abstract We present a new Danian correlation framework between the land-based Zumaia and Sopelana sections from the Basque Basin and marine-based sections drilled during ODP Legs 198 (Shatsky Rise, North Pacific) and 208 (Walvis Ridge, South Atlantic) that reconciles magnetostratigraphy and the short and long eccentricity cycle patterns among the records. A new whole-rock $\delta^{13}C$ isotope record at Zumaia is compared to that of Site 1262. This allows the question of whether the Danian consists of 10 or 11 consecutive 405-kyr eccentricity cycles to be tested. The new consistent stratigraphic framework enables accurate estimates to be made of ages for magnetostratigraphic boundaries, bioevents, and sedimentation rates. Low sedimentation rates appear common in all records in the mid-Danian interval along the upper part of chron C28n, including conspicuous condensed intervals in some of the oceanic records that in the past have hampered the proper identification of cycles. Notably, we challenge the correlation to the Pacific Sites 1209–1210 that were offset by as much as one 405-kyr cycle in previous interpretations (i.e., the *Fasciculithus* spp. LO, which approximates the Danian–Selandian boundary, and the TC27n event were at odds between oceans in the interpretation of Hilgen et al. 2010). Finally, we envisage that the Zumaia section, which already hosts the Selandian GSSP, could serve as the global Danian stratotype.

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Introduction

The metronome of cyclic sedimentary sequences originated from astronomical climate forcing has become a chief tool for age calibration and the construction of the modern Geological Time Scale (Gradstein et al. 2012). Astronomical tuning of these sequences to precise orbital solutions has led to unprecedented accuracy, resolution, and stability in the geological record for the earliest part of the Cenozoic, which has benefited from methodological enhancements and improved astronomical models in recent years. Tuning the early Palaeogene has remained difficult despite new complete numerical solutions for the solar system (Varadi et al. 2003; Laskar et al. 2004), due to uncertainties and limitations inherent in the chaotic behaviour of the solar system, challenging radiometric age control.

Tuning of the Danian

A decade ago, Dinarès-Turell et al. (2003) provided the first orbital tuning for the Danian based on a new fully integrated astronomical solution and the hemipelagic succession at Zumaia. Earlier attempts made on this succession and elsewhere were partial, or represented floating calibrations (i.e., measured elapsed time), or were based on older orbital solutions (e.g., Ten Kate and Sprenger 1993; Herbert 1999; Röhl et al. 2001). Hence, using the first full numerical astronomical solution, Va03_R7, by Varadi et al. (2003), the K–Pg boundary at Zumaia was tuned to an age of 65.83 Ma (Dinarès-Turell et al. 2003), taking as a first anchoring point the expression of a node in the very long eccentricity cycle in the upper part of the Danian, and then tuning consecutive short-eccentricity-related bundles and precession cycles down to the K–Pg boundary, which is less accurate than tuning the 405-kyr eccentricity cycle for these older ages but still a good metronome. Subsequent integrated studies at Zumaia extended the orbital calibration to the entire Palaeocene (Dinarès-Turell et al. 2007, 2010, 2012).The Palaeocene tuning at Zumaia was revisited by Westerhold et al. (2008), Kuiper et al. (2008), and Hilgen et al. (2010) in light of a newly available solution (La2004; Laskar et al. 2004) and basing the tuning on the more stable 405-kyr cycle. The favoured tuning option to La2004 in Kuiper et al. (2008) and Hilgen et al. (2010) placed the K–Pg boundary at 65.95 Ma, which is basically the same as in Dinarès-Turell et al. (2003) (the difference arising from the interpretation of an additional 100-kyr eccentricity cycle in the Zumaia record), an age that was in accordance with the authors' new re-evaluation of the Fish Canyon Sanidine (FCS) monitor standard, at 28.201 Ma.

Detailed analysis and astronomical tuning of ocean-drilling cores from the Pleistocene (Channell et al. 2010) and from the Palaeocene to early Eocene (Westerhold et al. 2012) reach a different, very controversial conclusion. However, the key controversy for the Palaeocene time scale stems from the exact number of 405-kyr eccentricity cycles identified in the geological record. Hilgen et al. (2010) contested the 24 405-kyr cycles identified by Westerhold et al. (2008) from data records of ODP Legs 198 (Shatsky Rise, North Pacific) and 208 (Walvis Ridge, South Atlantic), and proposed a total of 25 long eccentricity cycles for the Palaeocene instead. The extra cycle mismatch arises from a diverse interpretation along the Danian portion of the involved deep-sea records. Hilgen et al. (2010) further proposed a different correlation between the Atlantic Leg 208 and Pacific Leg 199 records of Westerhold et al. (2008) that introduces considerable differences in age for a number of nannofossil bioevents.

Here, we scrutinise the Danian orbital cycle identification and tuning both at the land-based Zumaia section and the previously studied ODP Legs 198 and 208, with the aim of reconciling and settling the astronomical time scale for the lower Palaeocene. We set up a correlation framework at the 100-kyr eccentricity cycle level as a step towards deciphering the best astronomical solution for the early Palaeogene, as there is a current limitation on their accuracy for ages older than ~54 Ma (i.e., Laskar et al. 2011; Westerhold et al. 2012). Moreover, we propose a Danian global unit stratotype at Zumaia (in the sense of Hilgen et al. 2006) where the Selandian base GSSP is already defined, and where the full hierarchy of astronomical cycles, including precession, can be observed and even extended into the Maastrichtian (see Dinarès-Turell et al. 2013 and references therein).

Results

We reassessed the cycle identification and correlation of the Zumaia section and ODP Site 1262 from the South Atlantic as the master records, because both present excellent magnetostratigraphies for the Danian interval under consideration and after other oceanic records have been incorporated into the framework. The strategy has been to make compatible both the magnetostratigraphy and the cycle hierarchy pattern as defined visually or with the aid of spectral analysis of the previously published X-ray fluorescence (XRF) and magnetic susceptibility high-resolution records from the ODP sites. Moreover, a new bulk-rock $\delta^{13}C$ isotope record has been obtained at Zumaia at almost precession-cycle resolution for most of the Danian from the K–Pg boundary up to chron C27n that can be correlated to an equivalent dataset from Site 1262 (Kroon et al. 2007). The magnetostratigraphy and the cycle pattern from Zumaia has been augmented and confirmed throughout chron C28r with a new study at Sopelana (a section about 60 km from Zumaia).

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