

**Cyclostratigraphy and recent developments in the
astronomical calibration of the Geological Time Scale**

Astronomical calibration of the Valanginian “Weissert” episode: the Orpierre marl-limestone succession (Vocontian Basin, southeastern France)

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A high-resolution, biostratigraphic (calcareous nannofossils, calpionellids) chemostratigraphic (C and O isotopes) and cyclostratigraphic (magnetic susceptibility) study was performed on the marl-limestone alternations of the upper Berriasian–Valanginian Orpierre section, deposited in the hemipelagic setting of the Vocontian Basin (SE France). The main aims of this study were to demonstrate that orbital forcing was the primary driver of the formation of the marl-limestone alternations and to estimate the duration of the Valanginian “Weissert” episode. The detailed calcareous nannofossil biochronology allowed the recognition of upper Berriasian–lower Hauterivian Tethyan standard biozones and sub-biozones. The general trends of the $\delta^{13}\text{C}$ curve and the major positive C-isotope excursion (amplitude of 1.8‰) recorded at the Orpierre section are similar in other sections worldwide. Spectral analysis applied on high-resolution magnetic susceptibility (MS) variations coupled with frequency ratio method reveals a strong cyclic pattern related to the Earth’s orbital parameters (precession, obliquity and eccentricity). The 405 kyr eccentricity cycle is prominent in the MS signal and has been used as a geochronometer to time calibrate the section. Such orbital calibration provided a minimal duration of 4.4 Myr for the Valanginian stage. The duration of the Weissert episode, as defined by the $\delta^{13}\text{C}$ curve, has been estimated at 2.08 Myr. This duration is coherent with that obtained from the composite section in the Umbria Marche Basin (~2.3 Myr), but contrasts with the estimation (1.5 Myr) proposed from the composite section of the Vocontian Basin.

Keywords: positive carbon isotope excursion, magnetic susceptibility, cyclostratigraphy, Valanginian, calcareous nannofossils, Vocontian Basin.

Orbital chronology of the Lower-Middle Aptian: palaeoenvironmental implications (Serre Chaitieu section, Vocontian Basin)

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A detailed cyclostratigraphic study conducted on several proxies including spectral gamma ray, magnetic susceptibility, clay minerals and carbonate content suggests that the return to equilibrium in the carbon cycle after the major disturbance linked with Oceanic Anoxic Event 1a occurs in about 2 myr. The minimum duration of the *D. furcata* zone is estimated at 0.46 myr, that of the *E. subnodosocostatium* zone at 1.45 myr. Strengthening of the obliquity record in the *furcata* zone confirms the cooling that characterises this period.

Keywords: Aptian, Cyclostratigraphy, Oceanic Anoxic Event 1a, Vocontian Basin, Serre Chaitieu.

Extending back the paleogene astronomical time scale: an integrated analysis of the Upper Maastrichtian strata in the basque basin

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We present a comprehensive, integrated, cyclo-magnetostratigraphic analysis and study of the calcareous nannofossils of the Upper Maastrichtian hemipelagic succession in three sections of the Basque Basin (Zumaia, Sopelana and Hendaia). The sections were correlated at bed-by-bed scale through careful analysis of the lithological stacking pattern and significant sedimentary features. For spectral analysis we used an available carbonate proxy record spanning 64 m of section below the K/Pg (Cretaceous/Palaeogene) boundary at Zumaia containing 72 precession-related limestone-marl couplets. The continuous wavelet spectrum helped to determine and visualize the orbital forcing at both the short (~100-ky) and long (405-ky) eccentricity band. We applied bandpass Gaussian filters to the carbonate record to extract the relevant periodicities and provide a cycle-numbering scheme starting at the K/Pg boundary. The full hierarchy of precession cycles and eccentricity-related bundles is then extended toward the base of the section in question, which contains a total of 33 short eccentricity-related bundles, thus spanning more than 3 Ma. The C31r/C31n chron boundary (estimated to occur at ~3.08 Ma below the K/Pg boundary) in the lower part of the succession was determined unambiguously in all three sections studied although the C30n/C29r reversal could not be determined due to a pervasive reverse magnetization acting on the purplish lithologies in the upper part of the succession. Relevant calcareous plankton bioevents could be accurately placed on the cyclo-magnetostratigraphic template. The cyclostratigraphic framework also allowed us to estimate the duration of previously defined sea-level-related 3rd-order depositional sequences in the basin, which appear to be strongly paced by the long-term 1.2 Ma obliquity amplitude modulating cycle.

Keywords: Milankovitch, magnetostratigraphy, calcareous nannofossils, cyclostratigraphy, depositional sequences.

Settling the Danian astronomical time scale: a prospective global unit stratotype at Zumaia, Basque Basin

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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 brings magnetostratigraphy and the short- and long eccentricity cycle patterns compatible among the records. A new whole-rock $\delta^{13}\text{C}$ isotope record at Zumaia is compared to that of Site 1262. This allows testing whether the Danian consists of 10 or 11 consecutive 405-ky eccentricity cycles. The new consistent stratigraphic framework allows accurate estimate 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 have hampered the proper identification of cycles in the past. Notably, we challenge the correlation to the Pacific Sites 1209-1210 that were offset by as much as one 405-ky cycle in the previous interpretations (i.e.

the *Fasciculithus* spp. LO, that approximates the Danian/Selandian boundary and the TC27n event were at odds between oceans in Hilgen et al., 2010 interpretation). Finally, we envisage that the Zumaia section, which already hosts the Selandian GSSP, could serve as the global Danian stratotype.

Keywords: orbital tuning; magnetostratigraphy; cyclostratigraphy, ODP.

Age of the FCs and K/Pg boundary

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Uncertainties in the age of the K/Pg boundary and the Fish Canyon Ar/Ar sanidine dating (FCs) standard, and in the number and tuning of 405-kyr eccentricity related cycles hamper the construction of a reliable tuned time scale for the Paleogene, a critical time period marked by the occurrence of hyperthermals and the onset of ice house conditions. Here we present new results from integrated stratigraphic studies, including U/Pb, Ar/Ar and astronomical intercalibration. These studies were largely carried out within the framework of the Marie Curie ITN GTSnext in an attempt to solve discrepancies. Our results are overall consistent with an age of ~28.20 Ma for the FCs, the presence of 25 x 405-kyr cycles in the Paleocene and an age of ~65.95 Ma for the K/Pg boundary.

Keywords: Geological Time Scale, U/Pb dating, Ar/Ar dating, astronomical dating, K/Pg boundary, FCs.

A 65 million year long astronomical time scale for the Mesozoic deep-sea sequence (Inuyama, Japan): implications for the Triassic-Jurassic time scale

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The astronomical time scale (ATS) for geologic records is nearly complete for Cenozoic strata, and attempts have been made to extend it to Mesozoic and older ages. However, construction of the Mesozoic ATS is hampered by the chaotic behavior of Solar planets and the lack of continuous pelagic sequence of the early Mesozoic due to the subduction of the ocean floor. Here we present the astronomical time scale constructed from the early Mesozoic deep-sea sequence of the Inuyama area, central Japan. The sedimentary rhythms of bedded chert display a full range of climatic precession related cycles; ~20 kyr cycle as a chert-shale couplet and ~100 kyr, 405 kyr, ~2000 to 4000 kyr, and ~10,000 kyr (~10 Myr) cycles as chert bed thickness variations, which principally reflect changes in the burial rate of biogenic silica, most likely due to the changes in silicate weathering rate. The newly established ATS tuned by 405 kyr cycle and anchored at the end-Triassic radiolarian extinction level gives ages consistent with radiometric ages projected to the sequence using biostratigraphy. Thus, the cyclostratigraphy of the Inuyama bedded chert provides numerical ages for the Triassic to Lower Jurassic stage boundaries, constraints on the chaotic behavior of Solar planets, and the information on biogeochemical silica cycle dynamics.

Keywords: Milankovitch cycle, Permian/Triassic, chert, chaos, nutrient, weathering.

Cyclostratigraphy of a Tithonian-Valanginian carbonate ramp succession, Southern Mendoza, Argentina: implications for the Jurassic-Cretaceous boundary in the Neuquén Basin

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Detailed sedimentological, sequence stratigraphical and cyclostratigraphical analyses have been made from four sections of the Vaca Muerta Formation. This unit is characterized by a decimetre-scale rhythmic alternation of marls and limestones. It consists of five facies associations, which represent basin to middle carbonate ramp deposits. Rhythmic vertical organization shows a well-ordered hierarchy of cycles, where elementary cycles, bundles of cycles and superbundles within the Milankovitch frequency band have been recognized. Cyclostratigraphic data allowed us to build a floating orbital scale for the Lower Tithonian-Lower Valanginian interval in the Neuquén Basin. Orbital calibration of these sections is consistent with Riccardi's biostratigraphic scheme, which places the Jurassic-Cretaceous boundary within the *Substeueroceras koeneni* Ammonite Zone (equivalent to *Durangites* spp., *Jacobi/Grandis* and initial *Occitanica* Standard Zones).

Keywords: Orbital cycles, Milankovitch, Biostratigraphy, Jurassic-Cretaceous boundary.

Astrochronology of the Valanginian Stage from GSSP candidates and hypostratotype

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The Valanginian Stage currently displays no radiometric age, which severely impacts on the palaeoceanographic reconstructions for this time interval. An astrochronology of the Valanginian Stage using the stable 405-kyr eccentricity cycle was performed on biostratigraphically well-calibrated, standard sections from the Vocontian Basin (SE France). High-resolution gamma-ray spectrometry signals were obtained from orbitally-driven marl-limestone alternations from five sections throughout the basin, and display the same long-term trends. The spectral analyses display the pervasive record of the 405-kyr eccentricity cycle together with precession, obliquity and 2.4-myrr eccentricity. Based on the identification of the 405-kyr eccentricity cycle, the duration of the Valanginian Stage is assessed at 5.08 myr. Since the Weissert Event appears ~3 myr older than the onset of the Paraná-Etendeka Large Igneous Province activity, a link between these events is unlikely. We thus propose, following GRÖCKE *et al.* (2005) and WESTERMANN *et al.* (2010), that continental carbon organic storage and carbonate platform demise are responsible for the onset of the $\delta^{13}\text{C}$ positive excursion. In addition, a stronger obliquity control appears in the *O. (O.) nicklesi* and *C. furcillata* subzones. This may be linked to limited production of polar ice suggested for this time interval.

Keywords: Valanginian, astrochronology, gamma-ray spectrometry, Weissert Event, Paraná-Etendeka.

Permian stratigraphic record within Volga-Kama region: cyclic and fractal properties

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In present paper some aspects of Permian cyclostratigraphy within Volga-Kama region at the east of Russian plate were regarded. Analysis of geological data was based on cyclic and fractal properties of stratigraphic record. Some important sedimentary characteristics such as data on grain size composition, magnetic susceptibility, carbonate content were chosen to analyze by maximum entropy and Fourier methods. Variations of coarse and fine grains contents and magnetic susceptibility were revealed as respectively main and additional factors forming sedimentary cycles in outcrops of Biarmian and Tatarian ages on Kama and Volga river banks. The grain size composition as cyclic response was also revealed in undersurface sections through gamma-ray logs Fourier spectra in Volga-Kama interfluvial area. On summarized spectra of maximum entropy method one could distinguish Milankovitch cycles. It was received log-log plot of cycles thicknesses, sedimentation rates and times, pointed on fractal nature of investigated stratigraphic record. Interpretation of fractal properties on Cantor set model and Hurst exponent model allowed to estimate timing and completeness of stratigraphic record characterized by a lot of breaks in sedimentary history of Biarmian and Tatarian.

Keywords: Permian sediments, Volga-Kama region, stratigraphic record, spectral analysis, fractal properties.

Limitations of the astronomically-tuned timescale: case study from the Newark Basin

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An astronomically-tuned timescale has been applied successfully to most of the Cenozoic record, but remains problematic for much of the Mesozoic. We examine the reliability of the cyclostratigraphy of the Upper Triassic of the Newark basin and find that a strict application of an astronomic timescale is contradicted by biostratigraphy. The greatest weakness of the application appears to be the ability, or lack thereof, to verify the completeness of the Newark stratigraphic record.

Keywords: Cyclostratigraphy, Newark basin, Norian, Van Houten cycles, McLaughlin cycles.

An astronomically calibrated timing, mineralogy and geochemistry of the Late Campanian *Radotruncana calcarata* planktonic foraminifer Zone

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Two sections spanning the planktonic foraminifer *Radotruncana (Globotruncanita) calcarata* Zone of Late Campanian (Upper Cretaceous) age are investigated in the Alps. Periodicity was obtained by power spectral

analysis, sinusoidal regression, and Morlet wavelets. The duration of the *calcarata* Total Range Zone is calculated by orbital cyclicity expressed primarily in thickness data. Precessional, obliquity, and short and long eccentricity cycles are identified and result in a duration of c. 806 kyr for the zone.

Keywords: Late Cretaceous, *Radotruncana calcarata*, Austria.

Orbital chronology of the middle to late Eocene from high-resolution equatorial Pacific and N Atlantic Ocean sections

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The astronomical calibration of the late Eocene and the Eocene/Oligocene transition, important time intervals mediating between the greenhouse and icehouse worlds, is still challenging. Crucial new records for reconstructing the late Eocene and Oligocene epochs were recovered during ODP Leg 199. For example, the Site 1218 record for the first time allowed the astronomical calibration of the entire Oligocene, but the lack of carbonate in the uppermost Eocene at this site made the time control as available for the Oligocene much less certain in all details for the late Eocene. Land-based marine sections in Italy have been intensively studied to establish orbitally tuned ages for the E/O boundary (Massignano, Monte Canero) and the middle Eocene (Contessa). Despite these efforts a robust astronomically calibrated time scale for the Bartonian and Priabonian is still lacking. In order to facilitate the development of an integrated magneto- and biostratigraphic framework with a stable isotope stratigraphy (necessary to enable global correlation), the recovery of carbonate sediment with a high quality magnetostratigraphy was targeted and successfully retrieved during IODP Expedition 320/321 (Pacific Equatorial Age Transect – PEAT). Here we present XRF core scanning data for more than 1200 meters of sediment from IODP Exp. 320 (Sites U1331-U1334) and ODP Leg 199 (Sites 1218-1220) spanning magnetic polarity chrons C12n to C21n (31 to 47 Ma). We generated high-resolution bulk carbon and oxygen stable isotope records from 33 to 39 Ma for Sites U1333/U1334 and investigated the phase relationship to XRF core scanning data. Subsequently we used high-resolution XRF core scanning and bulk stable isotope data to establish a stratigraphic framework based on the identification of the stable long eccentricity cycle (405 kyr) and applied orbital tuning to the records. In addition we integrated and refined records from ODP Site 1052 (C16-C17) and 1260 (C19-C20) to establish a stratigraphic framework for the middle to late Eocene. Our new time scale revises and refines the existing orbitally tuned age model from 31 to 41 Ma. The new astronomically tuned absolute age for the Eocene/Oligocene boundary (C13r.14) is 33.89 Ma validating the astronomical tuned age from the Massignano (Italy) global stratotype section and point. Our results from ODP Site 1260 indicate that the tuned Contessa record is offset by a half 405-kyr cycle. Astronomically tuned ages for magnetostratigraphic boundaries show a discrepancy to GPTS2012 of less than 400 kyr and provide the basis to extend the orbitally tuned time scale into the early to middle Eocene based on the identification of the stable long eccentricity cycle.

Keywords: IODP, Eocene, orbital tuning, magnetostratigraphy, bulk stable isotopes.

Upper Tithonian-Lower Berriasian meter-scale cyclicity and magnetic susceptibility changes along the peritidal carbonate succession, central Taurides, southern Turkey

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An Upper Tithonian- Lower Berriasian peritidal carbonate succession has been studied on the Tauride platform in the Beysehir area in southern Turkey. Peritidal carbonates are devoid of any siliciclastic fragments and display cyclic facies changes throughout the succession. This cyclicity is generally seen as meter-scale shallowing upward type and interpreted as the records of high frequency sea-level changes.

Cycles start with subtidal dasyclad algal wackestone/packstone, foraminiferal wackestone/packstone/grainstone facies at the bottom and continue upward with intertidal birdseye/fenestral limestone, laminar stromatolite facies. They are capped by supratidal stromatolites facies and subaerial features such as mudcracks, dissolution vugs and microkarstic mantling breccias. Penetration depth of the karstification is limited to upper 1-2 meters. Therefore it is estimated that sea-level changes are in the order of meter, and not in the hundreds of meters.

Jurassic-Cretaceous boundary interval has been recorded within this cyclic peritidal carbonates based on foraminiferal and dasyclad algal paleontology. In the platform, the Tithonian/Berriasian boundary beds are transitional and there is no time gap or erosion within the interval. Meter-scale cycles can easily be traced below and above the boundary.

Within the Tithonian interval, stromatolites and subaerial exposure structures are less frequently recorded on the platform, however from the Berriasian onward stromatolites and subaerial exposure structures are more frequently recorded.

Magnetic susceptibility (MS) analysis has been applied to these peritidal carbonates by field measurements. According to the results, MS values display parallel fluctuations with cyclic facies changes and generally indicate rising values at the exposure surfaces of the meter-scale cycles and decreasing values at the middle and top of the cycles.

Large-scale MS changes present a general rising trend towards the J/C boundary and a sudden drop after the boundary. In the Berriasian, a rising trend following the sudden drop has been recorded.

This study presents the first MS records spanning the J/C boundary and indicates a possible link between sea-level variations and the effect of climate. Rising MS values coinciding with the exposure surfaces along the section may indicate the contribution of wind/surface run off during arid or rising temperature conditions parallel with the sea-level drop/early rise and decreasing values coinciding with middle or top of the cycles may indicate contribution of increased temperature/evaporation parallel with the rising sea-level.

Keywords: Upper Tithonian- Lower Berriasian, peritidal carbonates, cyclicity, Magnetic susceptibility.