attraction/avoidance responses to the presence of ROV systems.

See also

Acoustic Scattering by Marine Organisms. Autonomous Underwater Vehicles (AUVs). Carbon Cycle. Fish Larvae. Fluorometry for Biological Sensing. Inherent Optical Properties and Irradiance. Krill. Microbial Loops. Ocean Color from Satellites. Plankton. Plankton Viruses. Population Genetics of Marine Organisms. Remotely Operated Vehicles (ROVs).

Further Reading

Boddy L, Morris CW, Wilkins MF *et al.* (2000) Identification of 72 phytoplankton species by radial basis function neural network analysis of flow cytometric data. *Marine Ecology Progress Series* 195: 47–59.

Brussaard CPD, Marie D and Bratbak G (2000) Flow cytometric detection of viruses. *Journal of Virological Methods* 85: 175–182.

Davis CS, Gallager SM, Marra M and Stewart WK (1996) Rapid visualisation of plankton abundance and taxonomic composition using the video plankton recorder. *Deep-Sea Research II* 43: 1947–1970.

Dubelaar GBJ and Gerritzen PL (2000) CytoBuoy: a step forward towards using flow cytometry in operational oceanography. *Scientia Marina* 64: 255–265.

Gallienne CP and Robins DB (1998) Trans-oceanic characterisation of zooplankton community size structure using an Optical Plankton Counter. *Fisheries Oceanography* 7: 147–158.

Herman AW (1992) Design and calibration of a new optical plankton counter capable of sizing small zooplankton. *Deep Sea Research* 39(3/4): 395–415.

Jonker R, Groben R, Tarran G *et al.*, (2000) Automated identification and characterisation of microbial populations using flow cytometry: the AIMS project. *Scientia Marina* 64: 225–234.

Kachel V and Wietzorrek J (2000) Flow cytometry and integrated imaging. *Scientia Marina* 64: 247–254.

Olson RJ, Zettler ER and DuRand MD (1993) Phytoplankton analysis using flow cytometry. In: Kemp *et al.* (eds) *Handbook of Methods in Aquatic Microbial Ecology*, pp. 175–186. Boca Raton: Lewis.

Reckermann M and Colijn F (2000) Aquatic flow cytometry: achievements and prospects. *Scientia Marina* 64(2): 119–268.

Rice J, Sleigh MA, Burkill PH *et al.* (1997) Flow cytometric analysis of characteristics of hybridization of species-specific fluorescent oligonucleotide probes to rRNA of marine nanoflagellates. *Applied and Environmental Microbiology* 63: 938–944.

Rice J, O'Connor CD, Sleigh MA *et al.* (1997). Fluorescent oligonucleotide rDNA probes that specifically bind to a common nanoflagellate, *Paraphysomonas vestita*. *Microbiology* 143: 1717–1727.

Schultze PC, Williamson CE and Hargreaves BR (1995) Evaluation of a remotely operated vehicle (ROV) as a tool for studying the distribution and abundance of zooplankton. *Journal of Plankton Research* 17: 1233–1243.

Wood-Walker RS, Gallienne CP and Robins DB (2000) A test model for optical plankton counter (OPC) coincidence and a comparison of OPC derived and conventional measures of plankton abundance. *Journal of Plankton Research* 22: 473–484.

Zubkov MV, Fuchs BM, Sturmeyer H, Burkill PH and Amann R (1999) Determination of total protein content of bacterial cells using SYPRO staining and flow cytometry. *Applied and Environmental Microbiology* 65: 3251–3257.

ORBITALLY TUNED TIME SCALES

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Introduction

Geologists rely on a variety of 'clocks' built into sediments to place paleo-environmental events into a time frame. These include radiometric decay systems, annual banding in trees, corals, and some marine and lake sediments, and, increasingly, the correlation of isotopic, geochemical, and paleontological variations to pacing supplied by changes in the Earth's orbit. Variations in three parameters of the orbital system – eccentricity, obliquity, and precession – cause solar insolation to vary over the Earth as a function of latitude, season, and time, and hence cause global changes in climate. Because the timing of orbital changes can be calculated very precisely over the past 30 million years, and because their general character can be deduced for much longer intervals of geological time, orbital variations provide a template by which paleoceanographers can fix paleoclimatic variations to geological time. Paleoceanographers now commonly assign either numerical ages or elapsed time to sediment records by optimizing the fit of variations in sediment composition, fossil context, or isotopic ratios to a model of orbital forcing, a process referred to as ‘orbital tuning’. Although orbital tuning was first developed to create better timescales for studying the late Pleistocene (approximately the last 400 000 years) Ice Ages, it now finds applications to dating sediments and estimating sedimentary fluxes at least into the Mesozoic Era (65–210 Ma).

Orbital tuning came about because of the difficulty in assigning ages to long, continuous records of climate change that became available with ocean sediment coring. The simplest assumption – that sediment accumulates at a constant rate over long spans of time – is not likely to be true. Sediment compacts with burial, so that a layer 1 cm thick at 50 m burial depth represents significantly more time than the 1 cm of highly porous material at the top of the sediment column. Furthermore, we suspect that climate itself influences the rate of marine sediment accumulation over time, either by varying the production and preservation of biogenic components or by the supply of detrital materials from land. Random factors such as small-scale erosion or excess deposition surely occur as well. Some of these variations in deposition rate can be documented with radiometric systems such as carbon-14 and uranium disequilibrium series. Unfortunately, the radiocarbon clock cannot extend much past 4×10^4 y ago, and uranium series methods, which have more restrictive conditions to work well, extend to perhaps 3×10^5 y, ago. Strata that contain minerals with radiometric systems that date the age of the sediment (e.g. ^{40}Ar/^{39}Ar and other systems in appropriate minerals) are few and far between. Other techniques such as paleomagnetic stratigraphy provide valuable age constraints, but at resolution of 10^5–10^6 y.

The end product of orbital tuning is a mapping function of stratigraphic position (depth scale in the sediment column) to time using criteria discussed at more length below (**Figure 1**). Paleo-biological and paleoceanographic patterns can be placed into a time frame perhaps accurate to a few thousand years. Time-series studies benefit enormously, since removing the distorting effects of variations in sedimentation rate results in much ‘cleaner’ frequency spectra. Equally importantly, the large improvement in time resolution offered by orbital tuning in comparison to other stratigraphic techniques allows paleoceanographers to measure the dynamics of sedimentary records with far more precision. Did events recorded in different sedimentary locations occur simultaneously or with an age progression? How long did fundamental biological and geochemical turnovers in earth history take to occur? What are the precise durations of magnetic polarity intervals? How do marine sediment fluxes vary with climatic state? Orbital tuning methods have addressed these and other questions.

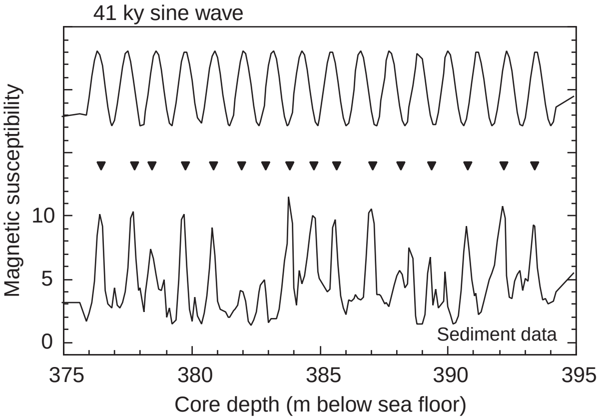

Figure 1 Example of how a sedimentary signal (e.g., magnetic susceptibility, a carbonate proxy) recorded as a function of depth below seafloor can be ‘tuned’ to an orbital chronometer. In this case, Shackleton and colleagues tuned the record of early Miocene sedimentation (lower curve) to a 41 ky obliquity cycle (upper curve). The triangles indicate position of consecutive obliquity cycles identified at ODP Site 926B. Note that the spacing of cycles is not constant, an indication of variation in deposition rate. Note also the presence of smaller higher-frequency features caused by precession (mean period of about 21 ky). Absolute ages can be determined by fitting the amplitude envelopes of the obliquity and precessional signals measured in the sediments to similar features in long-term numerical calculations of the orbital terms. Data adapted from Shackleton *et al.* (1999), courtesy of N.J. Shackleton.

Orbital Parameters and Potential Age Resolution by Orbital Tuning

Gravitational interactions with the other planets and the Earth’s moon perturb the orbit of our planet in three modes that affect the solar radiation received by the Earth as a function of latitude and season. Variations in eccentricity describe the quasiperiodic evolution of the Earth’s orbit around the Sun from more circular to more elliptical. Orbital eccentricity evolves in a complex manner, but has significant terms at about 95, 125, 404, 2000, and 2800 ky. The two shorter periods are close enough together to produce a beat pattern with a mean period of 109 ky, and the two longer terms produce a beat pattern at 2425 ky. Eccentricity is the only orbital cycle to alter the mean annual insolation, but its direct effect is very small. Axial tilt (obliquity) varies around its mean value of 23.5° by about 1.5° in a nearly sinusoidal pattern with a modern period of 41 ky. The obliquity cycle causes insolation to be distributed poleward during intervals of higher than average tilt, and equatorward during intervals of lower obliquity. Climatic precession affects the summer–winter insolation contrast and, unlike the other two orbital parameters, acts with opposite sign between the hemispheres. The precessional index is modulated by eccentricity, so that its amplitude bears the imprint of the ~ 109, 404, and 2425 ky eccentricity cycles mentioned above. Climatic precession has a mean modern value of 21.2 ky, but, because of the eccentricity amplitude modulation, it can range in repeat time from 14 to 28 ky. Its Fourier series representation has concentrations of variance at 1/23 and $1/19\,\mathrm{ky}^{-1}$.

Because the orbital cycles are not strictly periodic, one must consider secular changes on timescales $>10^6$ y. The observed slowing of the Earth's rotation rate due to tidal friction requires that the periods of obliquity and precessional cycles have changed gradually over geological time. Both cycles should repeat at shorter intervals as one moves back in time from the present. The predicted shortenings are less than 1% through the Cenozoic, but amount to several percent in the Mesozoic and more into the Paleozoic. One should also note that because the rate of tidal dissipation has probably not been constant over time, we do not have a good model for how obliquity and precessional periods have evolved over the entire history of the Earth–Moon system. A second significant uncertainty in using orbital variations as a time template comes from the weakly chaotic motion of the solar system. Any numerical solution of the orbital system will show an exponential dependence on initial conditions. There is therefore a limit in time beyond which one may not calculate the phases of the orbital cycles with confidence. This does not mean that one has no idea of the behavior of the orbital system, but rather that one has to rely on average statistical properties, or unusually stable elements of the orbit (the 404 ky eccentricity cycle is believed to be one such case) to perform orbital tuning in sediments older than about 30 Ma.

The fundamental limit on the accuracy of orbital calculations thus imposes a twofold division of Earth time amenable to orbital tuning. Sediments younger than 30 Ma can in theory be tuned to a precision and accuracy that depends solely on the match to an orbital template – perhaps to resolution of 1 ky to a numerical ('absolute') age. Orbital tuning in older sediments functions to measure elapsed time in a sediment record, since one can no longer precisely associate a sedimentary feature with a precisely known time value of the Earth's orbit. The latter approach resembles using a yardstick to measure distance from an independently agree datum. Datum points in Earth history come from magnetic reversal, biostratigraphic, or paleochemical events. Elapsed time can be measured to the errors in the mean properties of the orbital series. Reasonable estimates of the uncertainties in the latter approach lie in the range of 5–20 ky. Examples of both numerical dating and the 'yardstick' modes of orbital tuning will follow below. One should note, however, that the presumed stability of the 404 ky eccentricity cycle over great stretches of geological time may allow geologists to develop a numerical time frame based on the Earth's orbit, and therefore accurate to a fraction of the 404 ky period, for perhaps the past 100 Ma.

Methods of Orbital Tuning

No single approach to orbital tuning is appropriate to all stratigraphic problems. The ideal case, producing an age–depth model tied precisely to an 'absolute' timescale, can only be achieved in cases where the stratigrapher has a global orbitally forced signal that can be correlated to a precise astronomical reference frame. This situation obtains from late Pleistocene (~ 4 Ma) onward, when significant changes in global ice volume altered the entire ocean inventory of oxygen isotopes on orbital timescales. Despite the general decline in the amplitude of the oxygen isotope signal in older marine strata, orbital tuners can find the imprint of orbital forcing in other aspects of sedimentation – variables such as calcium carbonate content, redox state, and microfossil content. Such variations, because they originate from regional changes in the input of dust, biological productivity, and bottom water circulation, cannot provide a globally synchronous signal equal to that of isotopic measures. They can, however, be correlated with confidence to the numerical timescale up to limit of the accuracy of orbital solutions, or about 30 Ma. In older strata, orbital tuning generally produces 'floating' timescales.

One can choose among several approaches to matching sedimentary signals to an orbital forcing template. One can maximize the match of a sediment series to an orbital model by constructing an age–depth model that gives the largest correlation coefficient between presumed forcing and climatic response. An alternative is to work more selectively with the sediment record to extract the orbital components from the natural record, and to maximize the coherence of these to the corresponding orbital components. Such methods generally involve working in the frequency domain, and techniques such as bandpass filtering and complex demodulation.

The most straightforward tactic relies on visual correlation of successive peaks in a sedimentary time series to a presumed orbital signal. A new timescale emerges as peaks and troughs of a stratigraphic signal are aligned to the orbital template. The alignment may be performed visually, or by designing an objective mapping function that optimizes the fit of stratigraphic signal to orbital template (see Martinson *et al.*, 1987, in Further Reading). Such time-domain tuning, while it offers the highest possible age resolution, is quite sensitive to the orbital model chosen and to noise in the geological series. The possibility clearly exists to produce a tuned sedimentary series that has been forced to resemble an orbital template by over-enthusiastic correlation. Several strategies exist to lessen the subjectivity and heighten the reliability of time (depth) domain tuning. The first recognizes that higher-frequency orbital cycles such as precession and obliquity have low-frequency 'envelopes' that cause their amplitude to vary systematically. The technique of complex demodulation detects such features in time series data, and the envelopes of 'tuned' stratigraphic cycles can be compared to those of the orbital cycles themselves. Erroneous tuning of individual 21 ky or 41 ky peaks and valleys in a stratigraphic series will be revealed by the misalignment of the envelopes of the geological cycles relative to orbital forcing.

Moving-window ('evolutive') spectral analysis also works effectively to produce smooth tunings of stratigraphic signals to time. Here the analyst divides the data into segments of a specified stratigraphic length, and searches in the frequency domain for strong signals associated with orbital components. The average sedimentation rate is deduced by optimizing the match of scaling of stratigraphic frequency (cm^{-1}) to orbital frequencies. By subdividing the data into relatively short (usually 300–500 ky length) windows, the technique reduces spectral distortions associated with changes in sedimentation rate along section, and with the nonstationarity of climate response to orbital forcing. A conceptual example of how evolutive spectral analyses can detect and tune for gradual changes in sedimentation rate is illustrated in **Figure 2**. Moving-window analyses have the virtue of producing smooth estimates of sedimentation rate, since they rely on the average spectral properties of stratigraphic signals over a depth or time range.

It is essential to remember that any 'cyclostratigraphy' carries an implicit climate model, and in many cases an implicit sedimentation model. Our knowledge of the climate system is not adequate to predict the precise response of the Earth's climate to orbital forcing over time; our correlation of paleoclimate records to orbital forcing must allow the recipe of orbital influences – which reflect changes over time in key climatic regions of the globe and in climatic feedbacks – to vary. Study of the relatively well-dated Pleistocene marine record demonstrates that one orbital recipe may not describe the evolving Ice Ages, as the relative importance of ~21, 41, and 100 ky ice volume cycles changes significantly over the past 2 million years owing to processes internal to the climate system. Orbital tuning should therefore include a healthy amount of flexibility and regard for independent checks on the quality of the result.

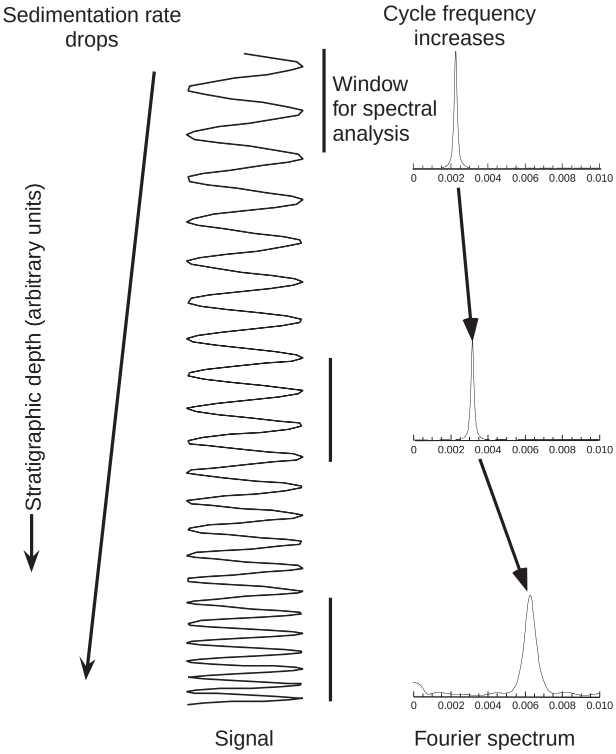

Figure 2 Changes in sedimentation rate act as frequency modulations of cyclic signals. In this synthetic example, sedimentation rate was made to decrease by a factor of 4 from the youngest to oldest interval of the record. Note that the repeat distance in the stratigraphic record is greatest where sediment accumulation is highest, and tapers toward the base of the sequence where accumulation rate is low. Such changes can be traced objectively by the moving-window spectral method, which produces sliding estimates of the local stratigraphic frequency (the inverse of stratigraphic period) down section. In this case, the cycle frequency moves (top–base) from low to high as the cycles become more condensed at lower sedimentation rates.

Criteria for Success

Orbital tuning is rarely applied to sediments without first considering independent age constraints from fossil events and paleomagnetic reversals. These provide a preliminary age scale and therefore a guide to approximate, time-averaged sedimentation rates to be modified by orbital tuning. Independent age markers also provide important tests of the quality of orbital tuning. For example, one can compare the results of orbital timescales to 'known' ages of events such as magnetic reversals where high-quality radiometric ages are available. Work conducted during the last decade suggests that orbital methods yield impressively consistent estimates of the ages of biostratigraphic and magnetostratigraphic datum points. For example, Wilson demonstrated that the revision, by Shackleton and colleagues, of the Plio-Pleistocene geomagnetic polarity timescale based on orbital tuning yielded smoother, and therefore more plausible, spreading rate histories on a number of midocean ridge systems than did the previous timescale based on K/Ar dates of basalts.

Continuity of sedimentation is clearly another necessary condition for success of the orbital approach. The best sections have the following characteristics: they lack observable breaks in sedimentation, either erosional or depositional (e.g. turbidities); they are composed of pelagic or hemipelagic facies; and they do not have strong changes in overall sediment composition (e.g., major break from calcareous to detrital sedimentation) that tend to accompany strong changes in deposition rate. In the ideal case, sections will span millions of years of deposition and accumulate at a sufficient rate (empirically at $>3\,\mathrm{cm\,ky}^{-1}$) to resolve precessional variations if such exist. Paleooceanographers have also learned to drill multiple offset holes at sites of interest and to splice records across coring gaps in individual holes to create 'composite sections' that are verifiably complete.

One can test the accuracy of orbital tuning solutions with various consistency checks. External checks exist in the form of independent datum points such as magnetic polarity reversals and biostratigraphic events. A good orbital tuning solution should produce consistent estimates of the numerical age of the datum event or the duration between datum events at a number of sites. Such concordant results have been demonstrated at least into the middle Miocene, and new studies continue to extend continuous tuning farther back in time. Another powerful test of an orbital tuning model comes from time-series analysis. Orbital signals have quite distinctive 'fingerprints' due to amplitude modulations. The modulations are most pronounced in the case of the eccentricity and precessional cycles, but also exist in the more sinusoidal obliquity cycle. Spectral analyses should therefore detect a hierarchy of frequencies correctly corresponding to modulation terms of the central orbital frequencies in a successful tuning. For example, one would expect to recover the 95, 125, and 404 ky modulating terms in a time-series tuned to a presumed precessional signal.

Some Examples

A team of Dutch stratigraphers, paleontologists and paleomagnetists has made significant progress in dating marine sedimentary successions in the Mediterranean region in the age range 0–12 Ma by astronomical tuning. The dates are particularly valuable to stratigraphers because many of the sections studied define classical substages of the Pleistocene, Pliocene, and Miocene epochs. Furthermore, many of the studied sections have good magnetic properties, permitting the Dutch team to propose an astronomical chronology for the geomagnetic polarity timescale (GPTS). As magnetic polarity reversal boundaries constitute globally synchronous events recorded in many types of sediments and frozen into the ocean crust by the process of seafloor spreading, improving the GPTS has widespread implications. Hilgen and co-workers recognized orbital forcing by a grouping of sapropels (dark, organic-rich beds) into units of 100 and 400 ky by eccentricity modulation of precessional climate changes. Their resulting calibration of the GPTS yielded significantly greater ages for magnetic reversal boundaries than the previously accepted dates based on K/Ar radiometric age dating. While controversial, the ages proposed by Hilgen and others have largely been verified by recent advance in $^{40}\mathrm{Ar}/^{39}\mathrm{Ar}$ dating of volcanic ash layers at a number of magnetic reversal boundaries.

The power of orbital tuning to resolve sedimentation rates at high precision for paleoceanographic studies is nicely illustrated by Shackleton's analysis of cyclic deep sea sediments recovered from the western equatorial Atlantic by Ocean Drilling Program Leg 154. Coring was designed to aquire long records at variable water depths. Depth largely controls carbonate sedimentation rate in the region, owing to a direct pressure relationship (carbonate minerals are more soluble at greater pressures) and through the indirect effect of vertical variations in water mass carbon chemistry. Carbonate sedimentation in turn largely determines overall sediment accumulation. **Figure 3** displays the results of tuning

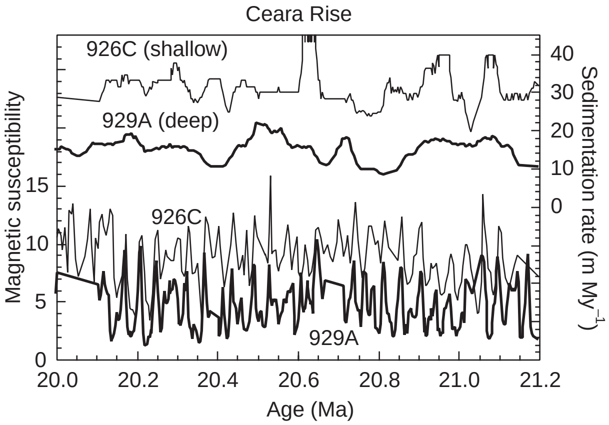

Figure 3 High-resolution orbital tuning of sediment records from different water depths allows paleoceanographers to study variations on a common, accurate time base. 41 ky variations driven by obliquity forcing were identified at both shallower (ODP 926B) and deeper (ODP 929A) sites (Shackleton *et al.*, 1998). Tuning generates mapping functions of depth to time that reflect sedimentation rates at each site. Data adapted from Shackleton, Crowhurst *et al.* (1999), courtesy of N.J. Shackleton.

variations in magnetic susceptibility, a means of estimating the noncarbonate fraction of the sediment, to an obliquity (41 ky) pacing over an interval of early Miocene age. Sediment variations at Site 926C can be matched one-for-one to variations at drill Site 929A, approximately 750 m deeper in the water column (lower two curves, **Figure 3**). The orbital tuning also generates a sedimentation rate function at each site, displayed as the upper two curves in **Figure 3**. Higher sedimentation rates at Site 926C throughout the interval agree with expectations that carbonate dissolution should be less intense at the shallower location, while changes in the difference between the sites documents changing gradients in dissolution over time. It is important to note that conventional dating methods based on biostratigraphic or magnetic polarity stratigraphy would not have the resolving power to monitor the carbonate deep water chemistry proxy at the resolution afforded by orbital tuning.

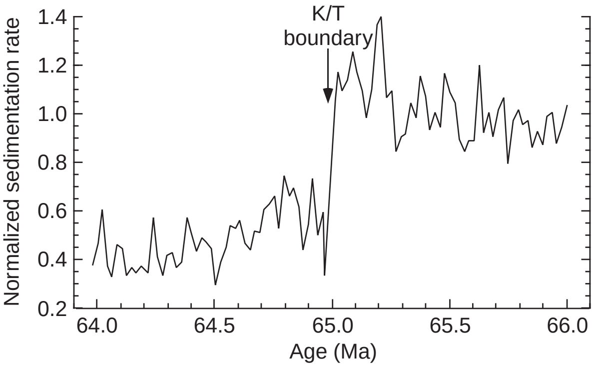

Figure 4 Composite record of pelagic sedimentation rates in the South Atlantic across the Cretaceous/Tertiary (K/T) boundary, deduced from tuning variations in sediment carbonate content and color to ~ 21 ky precessional cycles. Note the absence of a decline in sedimentation rate prior to the K/T boundary (lack of 'precursor' events) and the prolonged interval of dramatically reduced sedimentation rate following the extinction event. (Adapted from Herbert and D'Hondt (1990).)

Orbital chronology also has played a role in studying events across one of the truly catastrophic passages of geological time at the Cretaceous/Tertiary (K/T) boundary. While a number of observations suggest that the paleontological transition was very abrupt, it has proved difficult to constrain the timing of events before and after the boundary, and to differentiate rates of change across the K/T boundary quantitatively from background variability. Work by Herbert and others demonstrates that precessional cycles can be recognized at many deep-sea sites that contain K/T boundary sequences. These provide a yardstick for dating events to within about 10 ky (one-half precessional wavelength) across the boundary. As one example of the information recovered, **Figure 4** displays a composite of sedimentation rates in South Atlantic pelagic sites across the K/T boundary, using precessional cycles as an accumulation rate gauge. Data at each site were normalized to a value of unity for the mean late Cretaceous accumulation rate. The step-function drop in sedimentation rate coincident with the K/T boundary reveals not only a catastrophic drop in the flux of biogenic material to the deep sea following the extinction event, but also a prolonged period of low flux in the early Tertiary as the planktonic ecosystem slowly recovered.

Where the Field is Headed

Paleoceanographers constantly search for new tools to generate objective sediment data for spectral and stratigraphic analysis. Sediment proxy measurements such as color reflectance, magnetic susceptibility, Gamma Ray Attenuation Porosity Evaluator, p-wave velocity, and downhole geophysical and geochemical logging have produced long, densely sampled time-series from many sediment coring locations. Variations in the measured parameters all in some way reflect changes in the sediment composition (generally the proportion of carbonate to noncarbonate sediment). The variables measured yield less insight into the mechanisms of climate change than data such as stable isotopic measurements and analyses of microfossil populations, but they have the virtue of being inexpensive, rapid, and nondestructive.

At least three important conceptual targets remain to be solved by improvements in orbital tuning. The first relates directly to questions of the climate system itself. Paleoceanographers are becoming more aware of the climatic insights to be gained by comparing leads and lags in responses of various measured parameters. These can be ascertained by measuring multiple proxies in the same core, so that phase relations determined by cross-spectral analyses are independent of the absolute time scale, and between coring sites if one has a common, synchronous, tuning variable. Benthic $\delta^{18}O$ is generally assumed to provide such a chronological tie in late Pleistocene sediments. By measuring different components in the same cores, Clemens and colleagues demonstrate that the relative timing of different aspects of the monsoon system in the Indian Ocean has clearly evolved over the past 6 million years. While each component senses orbital forcing, the linkages between winds, ice volume, and sea surface temperature change have varied over time.

We can also expect significant insights from orbital tuning into the processes by which pelagic and hemipelagic sediments accumulate. Since orbital tuning inherently contains a sedimentation rate model, one can begin to study rigorously the relation between climate change and changes in the accumulation of different sediment components. Improved sediment models will help paleo-oceanographers to construct the dynamics of orbitally forced climate change by measuring eolian fluxes, an important clue to aridity on land and potentially an important radiative feedback to climate, and variations in biogenic flux, which monitor both the productivity of microfossil organisms in the surface ocean and deep water chemistry. Improvements in budgeting carbonate carbon and organic carbon accumulations in the deep sea will in particular yield insights into the sensitivity of the global carbon cycle to orbital forcing.

Lastly, one can anticipate that the improved chronology afforded by orbital tuning will have significant implications for the earth sciences as orbital chronology extends its reach into the early Tertiary and Mesozoic. Improvements in estimating the duration of magnetic polarity chrons will allow geophysicists to study variations in ocean spreading rate at least into the Cretaceous without the constraint of having to specify a constant-spreading-rate ridge system. Members of the radiometric dating community have proposed that an intercalibration of radiometric and orbital dating systems may be the most accurate way to choose age standards for the $^{40}Ar/^{39}Ar$ dating system. The possibility that orbital signals preserved in marine sediments will supply celestial mechanicists with constraints on the long-term evolution of the Earth–Sun–Moon system also appears on the horizon.

See also

Calcium Carbonates. Deep-sea Drilling Methodology. Deep-sea Drilling Results. Geomagnetic Polarity Timescale. Oxygen Isotopes in the Ocean. Paleoceanography, Climate Models in.

Further Reading

Clemens SC, Murray DW and Prell WL (1996) Nonstationary phase of the Plio-Pleistocene Asian monsoon. *Science* 274: 943–948.

Herbert TD and D'Hondt SL (1990) Precessional climate cyclicity in late Cretaceous–early Tertiary marine sediments: a high resolution chronometer of Cretaceous–Tertiary boundary events. *Earth and Planetary Science Letters* 99: 263–275.

Hilgen FJ (1991) Astronomical calibration of Gauss to Matuyama sapropels in the Mediterranean and implication for the geomagnetic polarity time scale. *Earth and Planetary Science Letters* 104: 226–244.

Laskar J (1999) The limits of Earth orbital calculations for geological time-scale use. *Philosophical Transaction of the Royal Society of London A* 357: 1731–2007.

Martinson DG, Pisias NG, Hays JD *et al.* (1987) Age dating and the orbital theory of the ice ages: development of a high-resolution 0 to 300,000-year stratigraphy. *Quaternary Research* 27: 1–29.

Norris RD and Rohl U (1999) Carbon cycling and chronology of climate warming during the Palaeocene/Eocene transition. *Nature* 401: 775–778.

Renne PR, Deino AL, Walter RC *et al.* (1994) Intercalibration of astronomical and radioisotopic time. *Geology* 22: 783–786.

Shackleton NJ, Crowhurst SJ , Weedon GP and Laskar J (1999) Astronomical calibration of Oligocene–Miocene time. *Philosophical Transaction of the Royal Society of London A* 357: 1907–1929.

Shackleton NJ, McCave IN and Weedon GP (eds) (1999) Astronomical (Milankovitch) calibration of the geological time-scale. *Philosophical Transactions of the Royal Society of London A* 357: 1731–2007.

Wilson, DS (1993) Confirmation of the astronomical calibration of the magnetic polarity time scale from sea-floor spreading rates. *Nature* 364: 788–790.

Zachos JC, Flower BP and Paul H (1997) Orbitally paced climate oscillations across the Oligocene/Miocene boundary. *Nature* 388: 567–570.