# Time is of the Essence

BY TED MOORE AND HEIKO PÄLIKE

From the age of the Earth itself, to the rates at which mountains erode and species evolve, time and rates of change have been the "holy grail" of geologic knowledge. In the study of sedimentary layers (stratigraphy), time has been the essential unknown in tying the sequence of layers to something more meaningful than the thickness of deposits. William Smith, considered by many to be the first practical stratigrapher, used marine fossils to distinguish different layers of limestone. By using the "law of superposition," he ordered the layers in terms of their relative age (see Winchester, 2001; also see basic early geologic texts: Playfair, 1802 and Lyell, 1872). Radiometric dating was one of the first and greatest breakthroughs in this search for a "clock" that could put the geologic record into an absolute time context. Even though radiometric dating techniques have greatly improved with time, three serious restrictions remain on their use: (1) the half-life of some radiogenic isotopes is too short to investigate events in the distant past (e.g., $^{14}C$ is difficult to use for samples older than about 60 kyr), (2) only certain materials can be dated and those materials are not always found in the sections we wish to date, and (3) the uncertainty associated with any radiometric dating technique gets larger as the age of the dated material gets older. Radiometric dating is thus "near sighted" and gives us a somewhat fuzzy vision of when and how fast things happened tens of millions of years ago.

The development of a radiometrically calibrated paleomagnetic timescale was critical both to the construction of the plate tectonic paradigm and to the dating of both igneous rocks (e.g., Cox et al., 1963) and sedimentary deposits (e.g., Harrison, 1964). When extended beyond five million years ago, however, the paleomagnetic timescale also has its shortcomings. First, the time element of the scale is dependent on a model of the rate at which new seafloor is being formed, using such simplifying assumptions as constant spreading rates to define the age of the older seafloor magnetic anomalies. Second, each reversal in the magnetic field was spaced irregularly in time, from tens to hundreds of thousands of years apart; thus, we have to rely on interpolation between these control points to estimate the age of any particular sample. And finally, when used to date sediment cores, any given, relatively short sequence of magnetic reversals requires some other form of stratigraphy (e.g., biostratigraphy) to verify the identity of that sequence.

Having these tools for dating stratigraphic sequences in hand, we have sought to apply a timescale to the geologic record, realizing that the paleomagnetic timescale still had its problems and that the geologic record on land was far from complete. Thus, the deep-sea sediments recovered by ocean drilling pro-

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vided a better, more complete geologic record and an opportunity for improvements in the time yardstick that we used.

## SCIENTIFIC OCEAN DRILLING AND TIME

### Marine Sediments

The oceans have always been considered the ultimate graveyard of debris from the land and the seas and, as such, deep-sea sediments in today's oceans contain a detailed and nearly continuous record of the last 100 million years of Earth history (the oldest seafloor found today is about 190 million years old). The great challenge of marine geology has been to recover and decipher that record. In the late 1960s, we took the first steps toward recovering this record by establishing the Deep Sea Drilling Project (DSDP). Among the many early successes of this effort was the verification that the age of the seafloor became older away from the active spreading centers in a way that was consistent with the paleomagnetic anomaly signature of the oceanic crust (Maxwell et al., 1970). A more unheralded, but still very important, accomplishment was the rapid development of biostratigraphies for calcareous nannofossils, diatoms, radiolarians, and dinoflagellates. Prior to DSDP, only foraminifera had a well-established stratigraphy that was in wide use by industry and academic scientists. The creation, further development of the stratigraphies, and intercorrelation of all of these microfossil groups gave us a robust method of "dating" marine sediments from different oceanic environments. Stratigraphers still struggled to provide radiometric constraints on the biostratigraphic datums and zonations that were being rapidly developed (e.g., Berggren, 1969, 1971, 1972) and to improve what still provided only relative dates and approximate ages of the recovered sections.

We soon realized not only that the marine stratigraphic record was not everywhere as complete as we had hoped, but also that the method of recovering these sediments (standard rotary coring used by the oil industry) badly disturbed the sedimentary record and missed important pieces of the stratigraphic puzzle. Each 9-m-long core was not a true stratigraphic sample of 9 m of marine sediments and parts of the section drilled appeared to be missing between each core (Moore, 1972). With the strong physical disturbance of many of the recovered sections, the application of paleomagnetic stratigraphy to these cores would have been futile. A new technology was needed to improve the recovery of the sediments.

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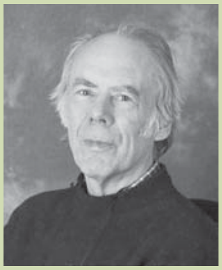
### Improved Coring Technology

Late in the 1970s, DSDP engineers developed a coring device that shot a core barrel ahead of the drill bit into the soft marine sediments (Prell and Gardner, 1982). This technology was a major breakthrough for marine stratigraphers, extending the value of piston-core sampling of near-surface sediments deeper into the marine-sediment record. The recovery of 9 m of virtually undisturbed sediments meant that we could sample and study the marine record limited only by resolution of the section cored (i.e., the sedimentation rate) and the depth to which the piston-coring devise could penetrate into the deposits (usually on the order of 200 m). This depth limit was pushed farther into the section by the development of a spring-loaded extended core barrel that stuck out ahead of the bit and could be rotated. With these advances in core recovery, paleomagnetic and isotopic stratigraphies could be determined for the cores and verified using the recently developed microfossil stratigraphies.

### Chronostratigraphy

There remained some nagging worries about establishing a true chronostratigraphy. First, the paleomagnetic timescale itself required interpolation and was dependent on a model of seafloor-spreading rates. Second, many biostratigraphic events were demonstrably diachronous.

## SIR NICHOLAS J. SHACKLETON (1937–2006)



Sir Nicholas J. Shackleton played a key role in the development of the mass spectrometer that allowed stable isotope measurements to be made on very small samples of carbonate microfossil material. He was also one of the major contributors of data and scientific insights into the roles of temperature and ice volume in the Pleistocene and throughout the Cenozoic. Sir Nicholas was co-author on the seminal paper (Hays et al., 1976) that demonstrated the presence of Milankovitch orbital variations in the Pleistocene records and was one of the first to use the paleoceanographic records to orbitally tune parts of the geologic timescale. He also was one of the first to use a composite section obtained by splicing different ODP holes at a single site to obtain a more complete litho- and biostratigraphic records. His career was marked by his great contributions to our scientific understanding and by his generosity in mentoring students and in sharing his data.

## THE PLEISTOCENE RECORD

The detailed oxygen isotope record of the Pleistocene shows large oscillations that are thought to be dominated by large changes in the volume of ice stored on land. The waxing and waning of the continental ice sheets are related to changes in Earth's orbital parameters as shown by Hays et al. (1976). Spectral analysis and cross-spectral analysis has shown a strong relationship between the oxygen-isotope record of the Pleistocene and the calculated variations in insolation caused by changes in the eccentricity of Earth's orbit, the tilt of Earth's axis of rotation, and the precession of the equinoxes. This relationship was used to fine tune the Pleistocene timescale (Martinson et al., 1987).

And finally, we were still not positive that we were recovering all of the section present at the drill site. By the mid to late 1970s, students of the Pleistocene (the last ~ 2 million years) were making rapid advances in developing a detailed chronostratigraphy for the time when the Northern Hemisphere ice sheets were actively waxing and waning (see Shackleton sidebar). Using conventional wireline piston cores, these studies depended on measurements of oxygen isotopes in the calcareous shells of marine organisms to develop a record of climate change that was synchronous within the mixing time of the oceans (see sidebar: The Pleistocene Record). Records in different piston cores from around the world could thus be accurately correlated. These records required hundreds of closely spaced individual measurements to develop a characteristic "wiggly line" stratigraphy. Developing such a detailed stratigraphy for the whole of the Quaternary, Tertiary, and Cretaceous is ongoing, but remains a very time-consuming, expensive, and arduous task. We sought some other means of rapidly and easily correlating cores and establishing a detailed stratigraphy—at least regionally. Then, the more arduous approach to a global chronostratigraphy could concentrate on tying the regions together.

### The Scanning of Sediment Cores

The development of automated core scanning with multiple sensors and the pass-through magnetometer were additional significant technological advancements introduced in the mid-1980s during the Ocean Drilling Program (ODP). The measurement of density, magnetic susceptibility, and P-wave sonic velocity continuously at the centimeter scale down each recovered core could be accomplished in minutes. This instrument gave a digital record of variation in these properties that could be related to lithology. More recently, digital color and resistivity have been added to the arsenal of scanned measurements. Variations in the lithology of pelagic sediments, particularly carbonate concentration, could in turn be related to basin-wide changes in bottom-water chemistry or surface-water productivity, as well as to climatic oscillations that drove such changes. With good core recovery and a quick way to quantitatively characterize lithology, we could now construct "wiggly line" lithostratigraphies that could be correlated from one hole at a drill site to another nearby hole or even to another drill site within the same region. By comparing the records of individual overlapping cores in adjacent holes, we could detect any gaps that might exist between cores in a single hole. And indeed, gaps were found (Figure 1). But the detailed lithostratigraphy allowed us not only to detect such gaps, but also to splice together a truly continuous record of the sediments from adjacent holes at any single site. In addition, the continuous record from one site could be correlated to other sites in the region in order to develop a regional framework (Figure 2).

Now we had come close to achieving our ultimate goals. We had a complete stratigraphic record that could be put into a chronostratigraphic framework using the paleomagnetic timescale and checked against the biostratigraphic record. The microfossils and mineral components of the sediments told a story of ocean history and global climate change. If only we had not had that nettlesome worry about the accuracy and resolution of the paleomagnetic timescale, most of the major problems of time and stratigraphy would have been solvable.

## The Tuned Timescale

Scientists interested in the Pleistocene came to our aid in addressing this problem. They established that the "pacemaker" of the Pleistocene climate is related to variations in Earth's orbit, also known as Milankovich cycles (Hays et al., 1976; see sidebar: The Pleistocene Record).

The mathematical description of Earth's orbital variations has provided geologists with a "tuning fork" for time in the geologic record that allows us to adjust, or tune, the timescale of that record (Laskar et al., 2004). Given a geologic record of climate-related variation and an approximate timescale, we can stretch or shrink that record until it matches the calculated time series of orbital variation. Variation in the amplitude of the orbital time series can be matched against the geologic record of climate change as a check on the tuning effort and to avoid potential circular reasoning. The shortest period of orbital change is about 20 kyr; thus, we should be able to match the calculated and measured record with an accuracy of a few thousand years if this period is preserved in the geologic record.

The tuning approach has two obvious benefits. First, the accuracy of the resulting timescale does not change greatly with age as does a timescale based solely on, or calibrated by, radiometric dates. Thus, the accuracy of rates of climatic change and flux rates of sedimentary components measured for Pleistocene sections is not greatly different from that of such rates measured for an Oligocene

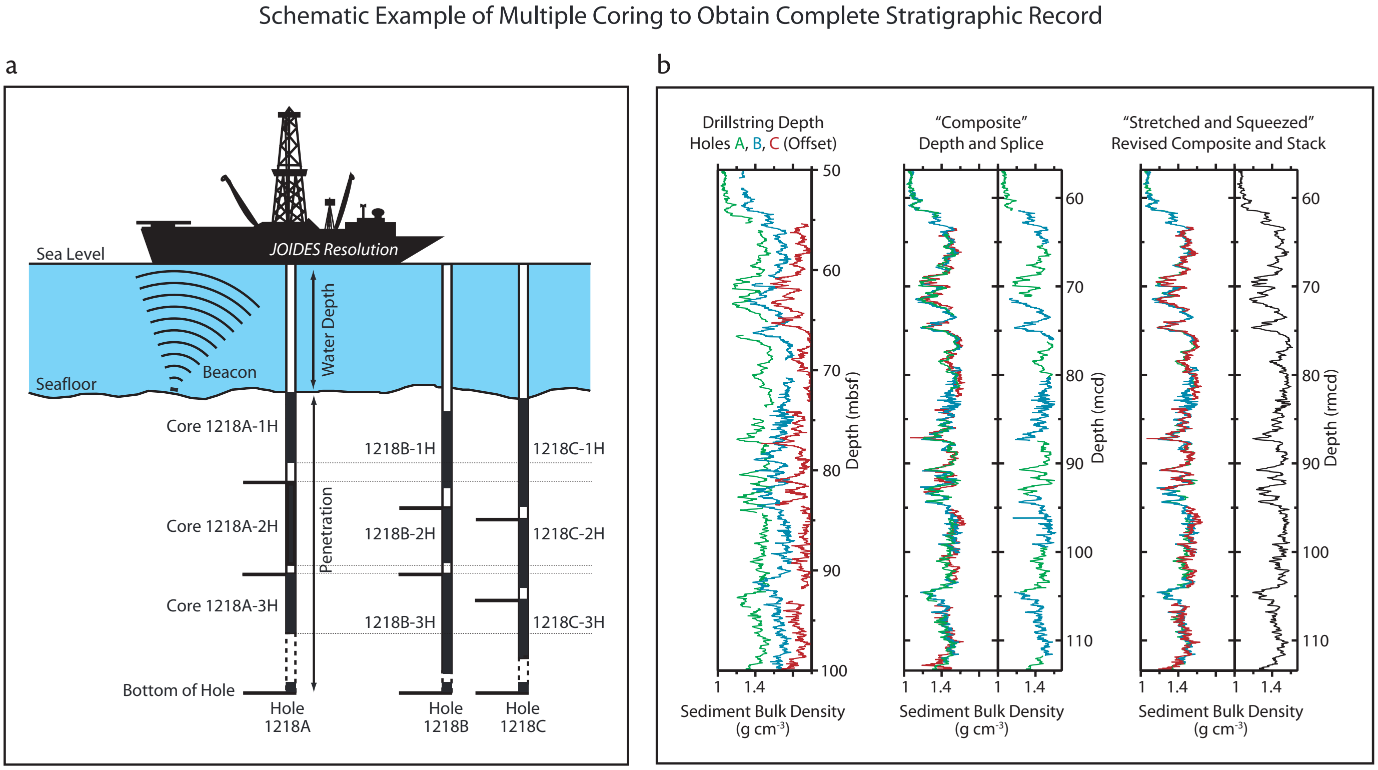


Figure 1. (a) Schematic set-up of drill locations with multiple holes to achieve complete stratigraphic recovery. Coring gaps that did not recover sediment in Hole A are attempted to be bridged in Holes B or C. (modified from Lyle, Wilson, Janecek et al., 2002). (b) Comparison of sediment density measurements from Holes A, B, and C at ODP Site 1218 (modified from Pälike et al., 2005). Note the similarity of density variations in cores at approximately the same depth level and the apparent presence of gaps in recovery between some of the cores. Given the overlap in cores from the different holes, a more complete, stacked composite section can be constructed for the Site (far right).

(~ 28 million years ago) section (Figure 3). Second, the duration of an individual magnetic chron can now be determined independently (i.e., how many cycles per chron), free from the assumptions, interpolations, and extrapolations of paleomagnetic-timescale models. This calibration of the chrons can, in turn, be used to evaluate variations in the rates of oceanic crustal formation.

## CONCLUSION

Work on material collected by scientific ocean drilling programs (DSDP and ODP) has made a major contribution in establishing an accurate geologic timescale essential to understanding geologic, biologic, climatic, and oceanographic processes. We have now tuned the geologic timescale back to about 30 million years ago. In the process, we have been able to evaluate different astronomical models of changes in Earth's orbit (Pälike et al., 2004). In the future we hope to extend the continuous tuned timescale into the Eocene, Paleocene, and Cretaceous. With this timescale, we can calculate and compare chemical and biological fluxes in the oceans through time. We can determine the duration of "events" and explore the process of biological speciation, assemblage migration, and rapid shifts in the loci of biologic productivity. As we develop more tuned records, we hope to define (and explain) the history of oceanic sensitivity to the primary orbital drivers of climate (i.e., why is the climatic/oceanographic variance at some times and in some regions dominated by eccentricity, while at other times and places by precession or tilt?)

This timescale is far more accurate and is likely to be far more stable in its calibration than any of its predecessors. It is limited only by the accuracy of the orbital equations and by the frequencies represented in the geologic record. The accuracy of the orbital models does degrade as they are extended back in time; however, as shown by Pälike et al. (2004), stratigraphers and astrophysicists can work hand in hand to improve the accuracy of the mathematical models of orbital variation. Whether other, higher-frequency drivers of environmental change (e.g., tidal forcing; Keeling and Whorf, 2000; Berger et al., 2004) will ever achieve the status of "geologic tuning fork" over significant portions of the record remains to be seen, but for now the next challenge is for astrophysicists and stratigraphers to verify and improve both astronomical calculations and geological records.

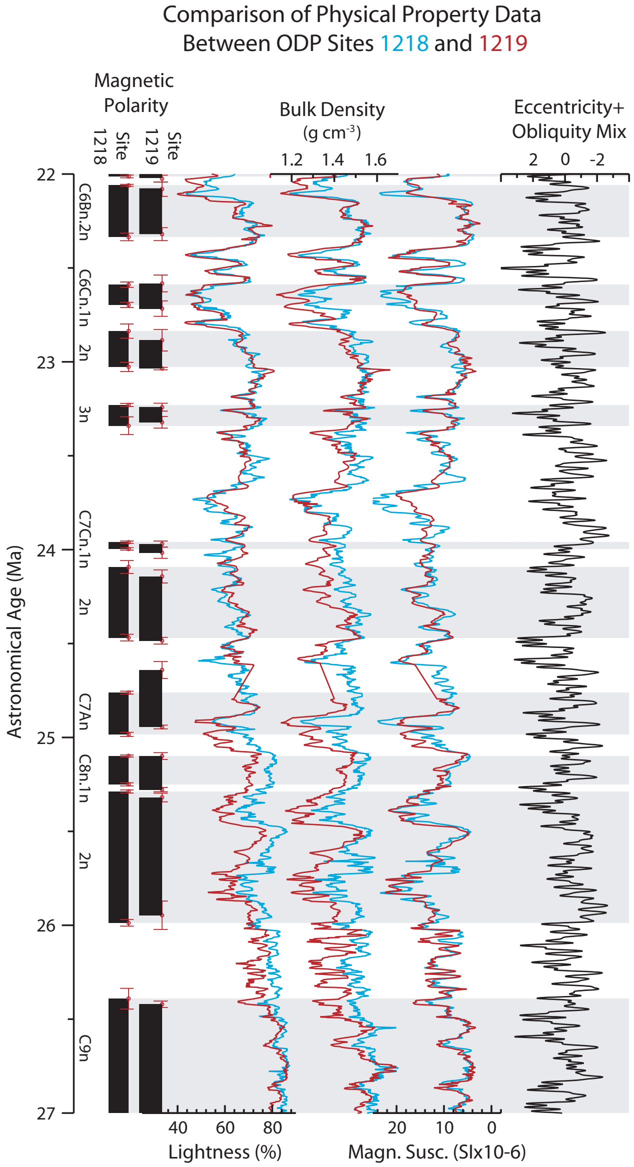


Figure 2. Comparison of stacked sediment density, magnetic susceptibility, sediment lightness, and paleomagnetic polarity measurements from the Oligocene section of ODP Sites 1218 (blue) and 1219 (red), tuned to the calculated orbital signal of eccentricity and obliquity (black, from Laskar et al., 2004). Paleomagnetic chrons defined in the two sites are shown adjacent to the curves with chrons identified, and their uncertainty in depth. Note the similarity in the lithostratigraphic records from the two sites separated by about 740 km.

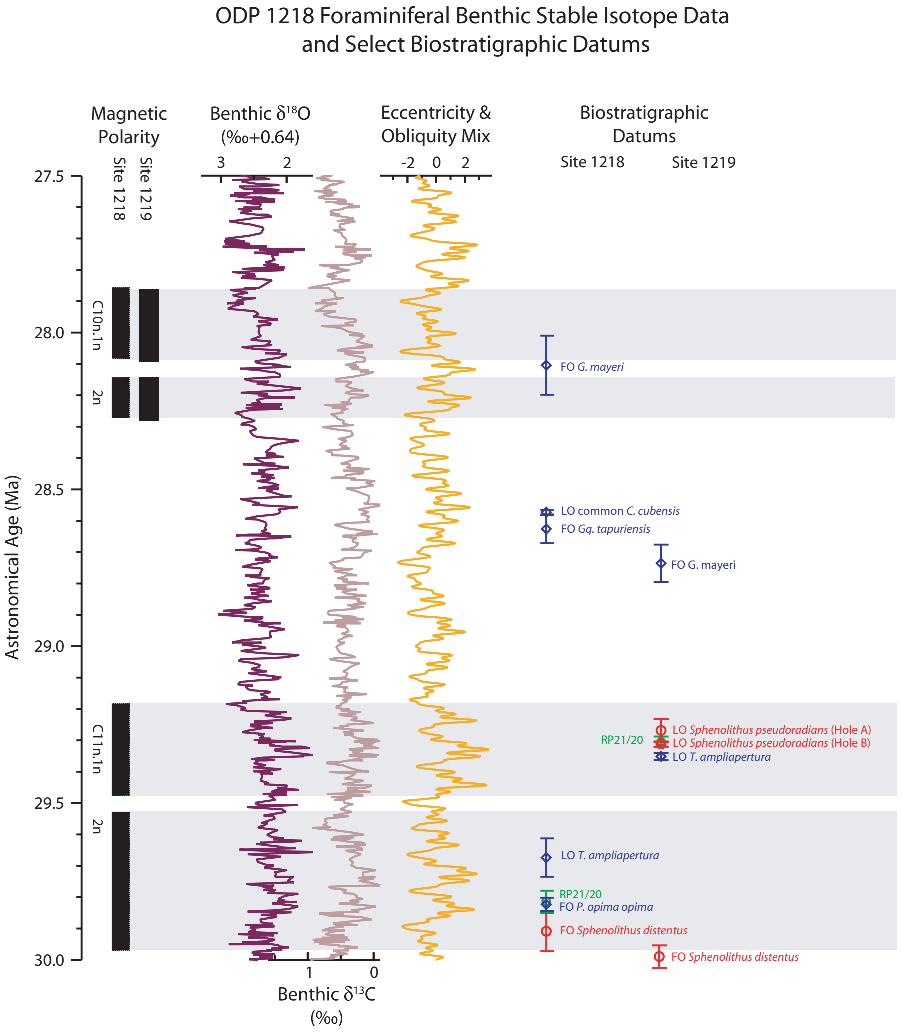


Figure 3. Biostratigraphic events tied to the tuned timescale of variations in oxygen and carbon isotopes. (Biostratigraphic datums from Pälike et al., 2005; Lyle, Wilson, Janecek et al., 2002. Stable isotope data from Wade and Pälike, 2004. Refined nannofossil data from Isabella Raffi, G. d'Annunzio University, Italy). Such comparisons allow evaluation of the individual biostratigraphic datum reliability and give insights into the tempo of evolution. The use of stable isotope data, even at moderate resolution, adds important additional paleoceanographic information that aids in the interpretation of variations in climate, ice volume, and sea level (Wade and Pälike, 2004).

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