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Chemostratigraphy, Magnetostratigraphy, Chronology, Palaeoenvironments and Correlations

Overview

James Ogg[1] & Jean François Deconinck[2]

[1] Department Earth, Atmosphere and Planetary Sciences, Purdue University, 550 Stadium Mall Dr., West Lafayette, IN 47907 USA; jogg@purdue.edu

[2] UMR 6282 CNRS Biogéosciences, Université de Bourgogne, 6 bd Gabriel, 21000 Dijon, France; Jean-Francois.Deconinck@u-bourgogne.fr

Summary

The tools of stable isotopes, natural radioactivity, radio-isotopes, paleomagnetic directions, magnetic susceptibility, chemical ratios, and other laboratory or physical-chemical logging methods can detect paleoenvironmental events and provide precise age-control calibrations that not always obvious from visual inspection of the sedimentary and paleontological records. When combined with cycle stratigraphy and other sedimentary features, one obtains fascinating insights into Earth's history. Two examples are the discovery of a pronounced mid-Valanginian (early Cretaceous) cooling event and the realization that the "100-kyr cycles" of late Pleistocene glaciations are partially an artifact of averaging of doublet and triplet "40-kyr" obliquity-driven glacial cycles.

Keywords**:** Carbon, Oxygen, Paleomagnetism, isotopes, Cretaceous, Valanginian, Weissert excursion, Quaternary, Pleistocene, paleoclimate, cycles, glaciation

The challenge of deciphering Earth's fascinating history requires an array of innovative tools and imaginative minds. Clues from fossils (*biostratigraphy, habitats*) and rock successions (*lithostratigraphy, sequence stratigraphy, cycle stratigraphy*) will always provide the most direct visual interpretations, but additional secrets can be teased from the strata by using stable isotopes, natural radioactivity, radio-isotopes, paleomagnetic directions, magnetic susceptibility, clay mineralogy, chemical ratios, and other laboratory or physical-chemical logging methods. In turn, when these non-visual measurements are merged with the more obvious lithologic and fossil evidence, then we can obtain insights into Earth's past and the feedbacks within the Earth system.

Rather than attempt a very incomplete overview of all of these methods and associated exciting discoveries of the past decade (and upset the numerous experts who are not mentioned), we will only give some very brief examples (and deliberately incompletely documented/cited) of how a few of these methods can work together to reveal the secrets of our planet's history. Reviews of some of the individual techniques and discoveries in stable isotope (carbon, oxygen, strontium, sulfur, osmium), radio-isotope (uranium-lead, potassium-argon, etc.), magnetostratigraphy, Quaternary dating methods and other aspects are in the various authored chapters in *The Geologic Time Scale 2012* (2012) (the ~40 contributors were coordinated by Gradstein, Ogg, Schmitz & Ogg).

Cause of an Early Cretaceous (mid-Valanginian) carbonate platform drowning

Prior to the late Valanginian, many of the margins of the tropical Tethyan seaway were active carbonate platforms that shed fine-grained micrite-rich sediment into the adjacent basins. There was a major platform-drowning episode near the Early/Late Valanginian boundary. Why, and how long did it last? Martinez *et al.* (2013) summarized how the application of various techniques by many different teams has aided in partly resolving this question.

The basinal sediments often yielded a continuous record with excellent ammonite zonations for inter-regional correlations. Spectral analysis of high-resolution gamma-ray measurements on key reference sections in southeastern France demonstrated that the visible cyclic bedding had an intrinsic dominance of long-eccentricity (405 kyr) cycles in clay abundance in addition to the shorter-term Milankovitch cycles; and this long-period cyclicity enabled derivation of a precise duration for each ammonite zone and the entire Valanginian (5.1 myr). Carbon-isotope measurements showed that a positive excursion coincided with platform drowning, but the different carbon-isotope shifts in carbonate versus terrestrial-organics (plants) following this event suggested that there was a decrease in atmospheric carbon-dioxide levels. Oxygen-isotope measurements on fossils in both western Tethys and Boreal realms also indicated that the drowning episode was followed by a short-term temperature decrease. The general decrease in strontium-isotope ratios (^{87}Sr/^{86}Sr) through the Valanginian was interrupted by a plateau at this time which, when combined with the observed decrease in kaolinite clay mineralogy and thickness of the 405-kyr cycles was consistent with lower runoff and detrital input, hence a transient cool and dry climate in these regions. Mineralogy of carbonates within some high-latitude deposits revealed glendonite, which is a form that requires near-freezing temperatures.

The magnetostratigraphy of the ammonite-defined current working base of the Valanginian has a unique match to the M-sequence of marine magnetic anomalies. In turn, cycle-stratigraphy of intervals of Early Cretaceous magnetostratigraphy indicates that the Pacific M-sequence formed during a remarkably near-constant spreading rate. Radio-isotopic measurements of drilled basalts on Pacific plateaus and seamounts that can be correlated to M-sequence polarity zones and of ash beds in ammonite-zoned and/or nannofossil-zoned strata in Argentina and California enable a numerical age assignment for the base-Valanginian of 140 Ma *in* GTS2012 age model. Cycle-stratigraphy from the gamma-ray logging in southeastern France implies that the peak of the carbon-isotope excursion and the coeval platform drowning was 2 myr later, therefore at 138 Ma.

But, what was the cause? Initially, the positive carbon-isotope excursion was thought to coincide with the first phases of massive volcanic eruptions of the Parana-Etendeka traps of Uruguay to southern Brazil. However, the initial formation stages of some other large igneous provinces, such as the North Atlantic Igneous Province spanning the Paleocene-Eocene boundary or the end-Permian Siberian Traps, seem to coincide with brief negative carbon-isotope excursions, not positive ones. Current radio-isotopic dating of the Parana-Etendeka traps indicates that the initial volcanic flows post-date the mid-Valanginian positive carbon-isotope excursion by perhaps 4 myr according to the GTS2012 age model. An alternate proposed explanation is that the carbon-isotope excursion was caused by organic-carbon storage (hence burial of "light" carbon) in continental and/or marine settings, thereby creating a decline in atmospheric carbon dioxide, which led to the cooler and more arid climates and the possibly triggering of localized high-latitude glaciations.

In summary, the combined efforts of many studies and methods, ranging from gamma-ray logging and carbon-isotope stratigraphy to the radio-isotopic dating of Pacific marine magnetic anomalies have enabled a detailed age model for the Valanginian and revealed a dramatic climate change in the middle of that stage. The resulting hypotheses now require quantification and modeling of the organic-carbon cycle; plus further examination of the precursor stages to the Parana-Etendeka traps, which may have released climate-cooling sulfur-rich gasses. One must also apply these techniques to a high-resolution analysis of the following

Hauterivian stage to determine if the main Parana-Etendeka traps left carbon-isotope and strontium-isotope signatures. As in many geological investigations, the tentative solution of one problem leads to other fascinating questions.

Obliquity, not Precession and Eccentricity, drives Pleistocene glaciations

Having a reliable chronology that is free from assumptions is very important. Oxygen-isotope records from deep-sea microfossils and Antarctic ice cores showed that late Pleistocene glaciations occurred at approximately 100 000 year average intervals consisting of long glacials with relatively short inter-glacials. Therefore, based on this average frequency and the lack of an independent more precise chronology, it was assumed that the pace-maker for these major glacial advances and retreats was associated with the short-term eccentricity (100 kyr) envelope on the amplitude of Earth's precession. Indeed, the intensity of summer insolation is controlled by precession. Therefore, the age models for this oxygen-isotope stratigraphy were aligned with the orbital parameters.

However, the Early Pleistocene glacial cycles had a distinctive 40-kyr periodicity, which would imply obliquity (tilt of Earth) was the major control. There seemed to be a fundamental "mid-Pleistocene transition" change in Earth's glacial periodicity at about 1 Ma. Huybers (2007) concluded that part of the problem was an artificial one caused by the "100-kyr tuning" that had been applied to derive the chronology for the oxygen-isotope stratigraphy from corings. The combination of applying magnetostratigraphic age controls to these core records to derive age-depth models and the stacking of an array of de-compacted sites produced a different chronology of glaciations. The "100-kyr" cycle of Late Pleistocene glaciations was instead a suite of 80-kyr or 120-kyr intervals. Obliquity controls the duration of summer heat at high latitudes; indeed, the integrated summer heat that results from the obliquity-controlled summer duration is probably more important to glaciations than the eccentricity-precession-induced maximums in summer heat. Rather than a dramatic "mid-Pleistocene transition", it was a gradual trend in an increasing frequency of "missed obliquity beats", perhaps associated with external factors (trends in ocean circulation, atmospheric composition, etc.) that influenced the threshold on deglaciation. If this conclusion is supported by additional chronological methods to add details within the relatively wide magnetic polarity ones, then the Pleistocene question shifts to a search and explanation for these external factors that resulted in double- or triple-duration glacial intervals.

These are only two selected stories of how the merger of chemostratigraphy, magnetostratigraphy and chronology with other stratigraphic tools can provide insights on past paleoenvironmental changes. However, any application of such tools requires both imaginative and careful reconsideration of any interpretations and hidden assumptions. A geologist, like any detective, must always work with multiple hypotheses and as many tools as possible to help narrow the possibilities and to discover the fascinating history of our world.

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