Hothouse, Icehouse, and Impacts:
The Late Eocene Earth

Monte Cònero (Ancona), Italy ▪ 3–6 October 2007

Conveners

Alessandro Montanari, *Osservatorio Geologico di Coldigioco, I-62020 Frontale di Apiro (MC), Italy; sandro.ogc@fastnet.it*

Christian Koeberl, *Center of Earth Sciences, University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria; christian.koeberl@univie.ac.at*

Frits Hilgen, *Institute of Paleoenvironment and Paleoclimate, Budapestlaan 4, 3584 CD Utrecht, The Netherlands; fhilgen@geo.uu.nl*

Rodolfo Coccioni, *Istituto di Geologia e Centro di Geobiologia dell'Università, Campus Scientifico, Località Crocicchia, 61209 Urbino, Italy; cron@info-net.it*

The late Eocene and the Eocene-Oligocene (E-O) transition mark the most profound oceanographic and climatic changes of the past 50 m.y. of Earth's history, with cooling beginning in the middle Eocene and culminating in the major earliest Oligocene Oi-1 isotopic event. The late Eocene is characterized by an accelerated global cooling, with a sharp temperature drop of about 2 °C near the Eocene-Oligocene (E-O) boundary, and significant stepwise floral and faunal turnovers. These global climate changes, which are reflected by a gradual increase of marine oxygen isotope values and biotic crises, are commonly attributed to the expansion of the Antarctic ice cap following its gradual isolation from other continental masses. However, multiple bolide impact events, possibly related to a comet shower lasting over 2 m.y., may have played an important role in the deterioration of the global climate at the end of the Eocene.

One of the best and most famous exposures of the late Eocene, as well as the site of the Eocene-Oligocene Global Stratotype Section and Point (GSSP), is at Massignano, at the Cònero Riviera near Ancona in east-central Italy; this was the subject and location of a meeting in 1987. The 2007 GSA Penrose Conference was held nearby at the Hotel Monteconero, a converted monastery. The meeting included three days of oral and poster presentations and a one-day field trip (visiting the E-O transition, late Eocene impact layers, K-T boundaries, and rock units in between, of the Umbria-Marche pelagic sequence). The oral and poster sessions covered the following topics: integrated stratigraphy of the late Eocene–early Oligocene transition and reevaluation of the GSSP; paleoecology and paleoclimate through the critical period of transition from hothouse to icehouse; and late Eocene impact processes and impact stratigraphy.

The first two days of sessions focused on a better understanding of the Eocene-Oligocene boundary transition using different climate proxies, improved time control, and climate models. Combined, the presentations gave an excellent overview and impression of the current exciting and detailed studies aiming to unravel this major climate transition.

The first morning session started with an overview by A. Montanari of the 20 years of scientific studies on the Massignano boundary stratotype section following the 1987 meeting. Next were two talks on the chronostratigraphic position and numerical age of the boundary. H. Brinkhuis convincingly showed that the E-O boundary as currently defined does not coincide with the top Priabonian, the youngest stage of the Eocene, or with the major Oi-1 isotope shift as expressed in the dinoflagellate sea-surface temperature record from Massignano. He started the discussion of whether it would be desirable to remove the boundary and place it at a stratigraphically higher level coincident with Oi-1 and the top Priabonian. F. Hilgen reviewed research aimed at numerical dating of the boundary and showed that age-dating using totally independent astronomical and radio-isotopic methods essentially reveal the same age of ca. 33.7 Ma, but that this is not necessarily the case if attempts to intercalibrate these methods are taken into account. Clearly, more research is necessary in this direction.

The afternoon session started with presentations dealing with deep marine stable isotope and cyclostratigraphic records and with the application of the marine osmium (Os) isotope record of the Eocene-Oligocene transition. S. Bohaty outlined recent progress in developing high-resolution benthic stable isotope records and orbital chronologies of deep-sea sections spanning the critical time interval. Ocean Drilling Project (ODP) Leg 199 site 1218 clearly revealed a two-step nature of the Oi-1 isotope shift and a potential link to favorable orbital configurations with a prolonged cool summer over Antarctica. Several sites reveal significant $\delta^{18}O$ variability throughout the late Eocene, including a ~0.5‰ increase associated with the iridium anomaly ca. 35.4 Ma. In addition, significant changes in carbonate content are observed, including a very interesting major dissolution horizon directly preceding Oi-1. However, Eocene carbonate dissolution also hampers the construction of an orbital-tuned continuous cyclostratigraphy necessary to unravel cause and effect across the boundary interval.

The stratigraphic utility of the marine Os isotope record of the Eocene-Oligocene transition was discussed by G. Ravizza, focusing on the marked latest Eocene minimum. The recovery following the minimum roughly coincides with the Oi-1 isotope shift, and similar values below and above the minimum do not point to a permanent change in global weathering patterns. Using the minimum as a time stratigraphic tool revealed that deposition of biosiliceous, organic-rich sediments along the West African margin culminated during Oi-1. B. McGowran presented the Auversian Facies Shift, which marks a fundamental shift in oceanic facies spanning the Bartonian and Priabonian stages and marking the changeover from the Eocene Climatic Optimum to the major Antarctic glaciation of Oi-1.

Further presentations focused on sea-level (and sea-surface and bottom water temperatures) history during the E-O transition as recorded on the shelves of the East Coast of the United States. B. Wade and others made a comparison between shelf-based sea-level reconstructions and high-resolution $\delta^{18}O$ records that suggests that no significant sea-level drop occurred during the first (precursor) step in $\delta^{18}O$ but that the second step is associated with a major 55-m sea-level fall. The resulting large Antarctic ice sheet then became the main driver of major changes in the ocean-climate system. The effect of the Oi-1–related sea-level drop is also evident in shelf successions found in the southeastern United States. R. Fluegeman showed that the boundary between the Jackson and Vicksburg Groups is marked by an erosional unconformity and a prominent benthic foraminiferal fauna turnover, neither of which coincide with the biostratigraphic E-O boundary—they are slightly higher, probably coincident with the Oi-1 shift. B. Wade presented sea-surface temperature data and sequence stratigraphic interpretations from the E-O transitional interval in Alabama; the former is clearly evidence of a substantial decrease in subtropical temperatures between 33.9 and 33.5 Ma. Finally, S. Galeotti showed the presence of orbitally controlled glaciomarine sequences in the E-O boundary interval in the CRP-3 core of the Cape Roberts project, noting marked changes in the astronomical frequencies and no major change in ice volume during Oi-1, but only later, in the middle of Chron C12r.

Participants inspecting the impact layers at the Massignano quarry at the Cònero Riviera, Italy (the GSSP for the Eocene-Oligocene boundary is in the very left front of the image).

The morning session of the second day focused on the biotic response to the E-O climate transition. S. Schellenberg presented a detailed ostracode study of ODP sites 698 (Maud Rise) and 744B (Kerguelen) separated by ~90° longitude. Major faunal changes coincide with the Oi-1 onset and imply a common response to enhanced surface productivity and a disparate (site) response to either subtle changes in productivity or changes in bottom water conditions. A significant size increase in ontogenetic stages may also be related to increased export production. L. Alegret discussed benthic foraminiferal assemblages from the Fuente Caldera section in Spain. No faunal changes occurred at the major Ni-rich spinel anomaly, which is indicative of an impact event. Higher in the section, two benthic foraminiferal turnovers are found. The first one is recorded at the E-O boundary and may be linked to the global cooling of deep waters at that time. The second one is recorded in the upper Rupelian and is related to a major shallowing event. B. Wade (on behalf of M. Aubry) presented the long-term evolutionary turnover in the coccolithophorids that took place from the late middle Eocene through early Oligocene. The E-O boundary itself appears to have been a drastic event at low latitudes but is essentially unmarked in assemblages from high latitudes.

S. Monechi presented calcareous nannofossil and benthic geochemical evidence from ODP site 1263 from Walvis Ridge (South Atlantic). Interestingly, changes in the calcareous nannofossil

Meeting participants in front of the church at the Hotel Monteconero, Italy (including some visiting undergraduate students from Carleton College, USA): Laia Alegret, Milly Alvarez, Walter Alvarez, Katerina Bartosowa, Steven Bohaty, Henk Brinkhuis, Rachel Brown, Philippe Claeys, Rodolfo Coccioni, Daniel Condon, Cameron Davidson, Robert DeConto, Ken Farley, Kristen Farley, Raquel Fenero, Chiara Fioroni, Richard Fluegemann, Simone Galeotti, Steven Goderis, David Griscom, Scott Harris, Frits Hilgen, Jerry Hooker, Dona Jalufka, Patricia Jannett, Simon Kelley, Christian Koeberl, Paul Kopsick, Brian McGowran, Paula Metallo, Simonetta Monechi, Alessandro Montanari, Silvia Ortiz Sainz-Aja, Mark Pagani, Francois Paquay, Isabella Premoli Silva, Aimee Pusz, Greg Ravizza, Stephen Schellenberg, Birger Schmitz, Nathan Sheldon, Jan Smit, Selena Smith, Dennis Terry, Flavia Tori, Simone Ulmer, Bridget Wade, Paul Wilson, and Alessandro Zanazzi.

assemblages coincident with a dramatic decrease in the discoaster abundance reveal that cooling of the surface waters started ca. 34.5 Ma (i.e., well before the Oi-1 event). This is followed by a second change concurrent with Oi-1. Furthermore, several brief pulses of warm and temperate taxa are found during Oi-1 and correlate with increases in benthic $\delta^{18}O$, indicating a possible decoupling of surface- and deep-water processes.

B. Wade presented patterns of diversity, extinction, and speciation in excellently preserved calcareous microfossil assemblages from hemipelagic sediments in Tanzania, covering the critical interval across the E-O boundary. Two major, rather closely spaced, planktonic foraminiferal extinction events of turborotalid species and of the five remaining species of the family Hantkeninidae were recognized. The latter coincides with the formally defined E-O boundary. After these extinctions, renewed speciation and diversification occurred, resulting in the characteristic Oligocene associations.

The first presentations on the afternoon of the second day dealt with the E-O boundary interval in the continental record. D. Terry presented data from the White River Group of northwestern Nebraska, which represents the most complete succession of continental deposits across the transition in this region. Paleosol characteristics are indicative of progressively drier climate conditions up-section. In contrast, vertebrate stable isotope records suggest no change in aridity but a temperature drop of up to 8 °C across the boundary. This contradiction may result from a considerable increase in sedimentation rate affecting soil development and explaining the weaker Oligocene paleosols. Clearly, an interdisciplinary approach is needed to decipher the E-O transition as recorded in such very complex terrestrial systems. N. Sheldon presented nonmarine records of climate change across the E-O boundary. He focused in particular on the application of paleosols as climate proxies and showed that, contrary to expectation, the data reveal relatively steady annual climate conditions across the E-O transition, suggesting that other climate variables, such as seasonality, may have driven faunal and floral turnovers. Furthermore, paleosol-derived records of chemical weathering are inconsistent with the timing of the Himalayan uplift hypothesis and reveal a reduction in chemical weathering associated with the E-O transition. J. Hooker summarized studies on the continental Eocene-Oligocene transition in the Hampshire Basin (UK), indicating no major paleo-temperature decrease across the boundary. This raises the question of whether the European mammal turnover, known as the Grande Coupure, is related to changes in seasonality rather than annual changes. However, interpretation of the expression of the E-O boundary also depends on the accuracy of the age model and the calibration of the magnetostratigraphy.

Climate modeling of the Antarctic ice sheet and the reconstruction of paleo-pCO_2 in the atmosphere across the E-O boundary was discussed next. R. DeConto presented results of climate modeling experiments that show an astronomical control on the size of the Antarctic ice sheet and a marked stepwise increase in ice volume—when pCO_2 is gradually reduced with time—that is markedly similar to that observed in the paleo-record. He further used a coupled general circulation–ice sheet model to explore whether the Oi-1 glaciation might have been a bipolar event. Major continent-sized northern hemisphere ice sheets could only start to grow with a significant reduction in atmospheric pCO_2 to near modern, pre-industrial values. This outcome would imply rapid carbon cycle feedbacks to significantly reduce pCO_2 at the Oi-1 in order to accomplish major bipolar glaciation at that time. M. Pagani focused on this role of pCO_2 during the Eocene-Oligocene transition and outlined the problems associated with using alkenones as a proxy for atmospheric pCO_2. His latest revised alkenone-based pCO_2 records across the boundary now reveal a possible rapid decrease in pCO_2.

Following the field trip, the last day of the meeting dealt with various aspects of the late Eocene impact events. C. Koeberl provided an overview of the impact structures currently known to have a late Eocene age (mainly the 100-km-diameter Popigai crater in Russia and the 85-km-diameter Chesapeake Bay structure in the United States, but also a few smaller structures), as well as of impact ejecta deposits of this age around the world. K. Farley discussed the pros and cons of the comet shower versus asteroid shower hypotheses that have been proposed to explain both the ^{3}He anomaly and the multiple impacts. B. Schmitz compared the extensive evidence for a large mid-Ordovician asteroid and meteorite shower with the situation at the end of the Eocene; R. Coccioni reviewed the evidence for multiple extraterrestrial signatures at the Massignano quarry; and P. Claeys presented geochemical evidence favoring the asteroid shower hypothesis because the impactors of several late Eocene craters have compositions similar to some ordinary chondritic meteorites. In the final talk of the morning, F. Paquay demonstrated the possible use of the osmium isotope system to derive information on the size of the impactors.

The final afternoon session began with a contribution by D. Griscom on some possible proximal ejecta from the Chesapeake Bay crater, and then S. Kelley showed convincingly that the often-cited apparent correlation between large igneous provinces and mass extinction is a statistical artifact. He also reported some new crater ages that suggest there may be up to half a dozen impact craters with late Eocene ages. This was followed by a report by A. Pusz on how the late Eocene impact events influenced the global carbon cycle. R. Brown demonstrated a disturbance in the Milankovich cyclicity at Massignano that coincided with the timing of the major impact events (Chesapeake Bay, Popigai), implying a causal relationship. The last presentation of the meeting was by A. Montanari, who reported on the Eocene-Oligocene transition in the Monte Cagnero section in central Italy and how it correlates with the GSSP of Massignano, noting that it might contain an even more complete record of the E-O transition than Massignano.

Discussion of the various accomplishments of the meeting and of the past 20 years of research concluded that, for the time being, the location of the GSSP at Massignano and its placement at meter level 19 is sufficient, despite some suggestions that the disturbance of the global carbon signature might be a more suitable time marker. Concerns were raised that some effort needs to be put into the correlation between the marine and terrestrial boundary time markers. The past 20 years of research also led to the discovery of several major impact events during the late Eocene—if as a result of a comet or an asteroid shower still requires more work—and also that these impacts caused only minor, but distinctly noticeable, disturbances in the global carbon cycle and thus global climate, with severe, but not catastrophic, implications for the earth system at the time.