Abrupt increase in seasonal extreme precipitation at the Paleocene-Eocene boundary

Birger Schmitz Department of Geology, University of Lund, Sölvegatan 12, SE-22362 Lund, Sweden
Victoriano Pujalte Department of Stratigraphy and Paleontology, University of the Basque Country, Ap. 644, 48080 Bilbao, Spain

ABSTRACT

A prominent increase in atmospheric CO_2 at the Paleocene-Eocene boundary, ca. 55 Ma, led to the warmest Earth of the Cenozoic for ~100 k.y. High-resolution studies of continental flood-plain sediment records across this boundary can provide crucial information on how the hydrological cycle responds to rapidly changing CO_2. Here we show from continental records across the Paleocene-Eocene boundary in the Spanish Pyrenees, a subtropical paleosetting, that during the early, most intense phase of CO_2 rise, normal, semiarid coastal plains with few river channels of 10–200 m width were abruptly replaced by a vast conglomeratic braid plain, covering at least 500 km^2 and most likely more than 2000 km^2. This braid plain is interpreted as the proximal parts of a megafan. Carbonate nodules in the megafan deposits attest to seasonally dry periods and together with megafan development imply a dramatic increase in seasonal rain and an increased intra-annual humidity gradient. The megafan formed over a few thousand years to ~10 k.y. directly after the Paleocene-Eocene boundary. Only repeated severe floods and rainstorms could have contributed the water energy required to transport the enormous amounts of large boulders and gravel of the megafan during this short time span. The findings represent evidence for considerable changes in regional hydrological cycles following greenhouse gas emissions.

Keywords: Paleocene-Eocene boundary, fluvial megafan, greenhouse warming, hydrological cycle, carbon isotope excursion.

INTRODUCTION

The Paleocene-Eocene (P-E) boundary event ca. 55 Ma represents one of the major global environmental perturbations during the Cenozoic (Kennett and Stott, 1991; Zachos et al., 2003). The event is characterized by a 2‰–6‰ negative carbon isotope excursion (CIE) in terrestrial and marine records, rapidly escalating global warming and important floral and faunal turnovers (Clyde and Gingerich, 1998; Thomas et al., 2002; Schmitz and Pujalte, 2003; Wing et al., 2005). A major part of the CIE developed within a few thousand years throughout the Earth's exchangeable carbon reservoir, which requires addition of isotopically light carbon at a scale similar to that from present anthropogenic carbon dioxide emissions (Dickens et al., 1995; Thomas et al., 2002). The light carbon may have originated from dissociated seafloor methane hydrates or organic-rich sediments heated by flood basalt volcanism (Dickens et al., 1995; Svensen et al., 2004). The P-E boundary event may provide empirical tests of model predictions of global and regional change as atmospheric CO_2 rises on an Earth-like planet. Predictions for the future Earth say that on a global scale evaporation and precipitation will increase, i.e., the hydrological cycle will be enhanced (Houghton et al., 2001). Most tropical areas and high latitudes will receive increased precipitation, whereas most subtropical areas will have decreased mean precipitation, but the frequency of extreme precipitation events will increase worldwide. Here we reconstruct high-resolution changes in the hydrological cycle at the P-E boundary in the subtropical region, at a paleolatitude of ~35 °N, from alluvial deposits now exposed in the south-central Pyrenees, Spain.

GEOLOGIC SETTING

In the study area, the Tremp-Graus basin (Fig. 1; GSA Data Repository Fig. DR1[1]), latest Cretaceous and early Paleogene continental deposits, the "Garumnian" facies, are well preserved and can be studied in a number of exposures in a transect over ~80 km (Cuevas, 1992; Rosell et al., 2001). In the central part of the study area, the Paleocene to earliest Eocene record is exemplified by the Esplugafreda section (Fig. 2; Figs. DR2 and DR3 [see footnote 1]). This section is made up of ~250 m of red mudstones with abundant paleosols and contains numerous multi-episodic channel-like bodies of calcareous conglomerates and calcarenites made up of clasts and grains of Cretaceous carbonates. Paleocurrent directions indicate a northeastern sediment source. The sediments have been dated by palynomorphs, charophytes, and mammal teeth (Feist and Colombo, 1983; Médus and Colombo, 1991; Lopéz-Martínez and Peláez-Campomanes, 1999). The paleosols contain abundant centimeter-sized soil nodules and gypsum indicating a semiarid to arid paleoenvironment. The P-E boundary has been located near the top of the continental section, based on a 6‰ negative CIE measured in soil nodules (Fig. 2; Fig. DR2) (Schmitz and Pujalte, 2003). The CIE spans more than 15–20 m of cumulate paleosols that have a characteristic yellowish color when weathered. The soils in the CIE interval formed during the Paleocene-Eocene thermal maximum (PETM; also referred to as the initial Eocene thermal maximum), when global temperatures were anomalously high for ~100 k.y. The 1–4-m-thick conglomeratic unit, called the Claret Conglomerate (CC) (Pujalte and Schmitz, 2005), is at the base of the PETM soils unit. The post-PETM interval in the Esplugafreda section comprises 20 m of red paleosols rich in gypsum and has rare soil nodules with normal $\delta^{13}C$ values. Above are marine deposits related to the Ilerdian transgression (Fig. 2; Figs. DR2–DR4). In the western part of the study area, closer to the ancient sea, brackish or marine intervals are intermingled with the Paleocene continental facies, reflecting retreating and advancing coastlines, but the stratigraphic interval representing the PETM is always in continental facies.

CLARET CONGLOMERATE

For this study we have mapped the distribution of the Claret Conglomerate and the overlying PETM soils in the abundant exposures throughout the study area shown in Figure 1. We have performed carbon isotope analyses of carbonate nodules (for methods, see Schmitz and Pujalte, 2003) from the soils overlying and underlying the CC at several places representative of different parts of the study area. We have also focused on trying to establish the precise age of the CC relative to the P-E boundary; at one locality, Berganuy, we could analyze carbonate nodules from rare soil horizons within the conglomeratic unit. At two other sites, Esplugafreda-B and Campo, where the CC shows a conformable fining-upward sequence into sandstone and intercalated thin soil before passing into the yellowish soils, we analyzed soil nodules representing the final stage of conglomerate formation.

[1]GSA Data Repository item 2007048, discussion and Figures DR1–DR8, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

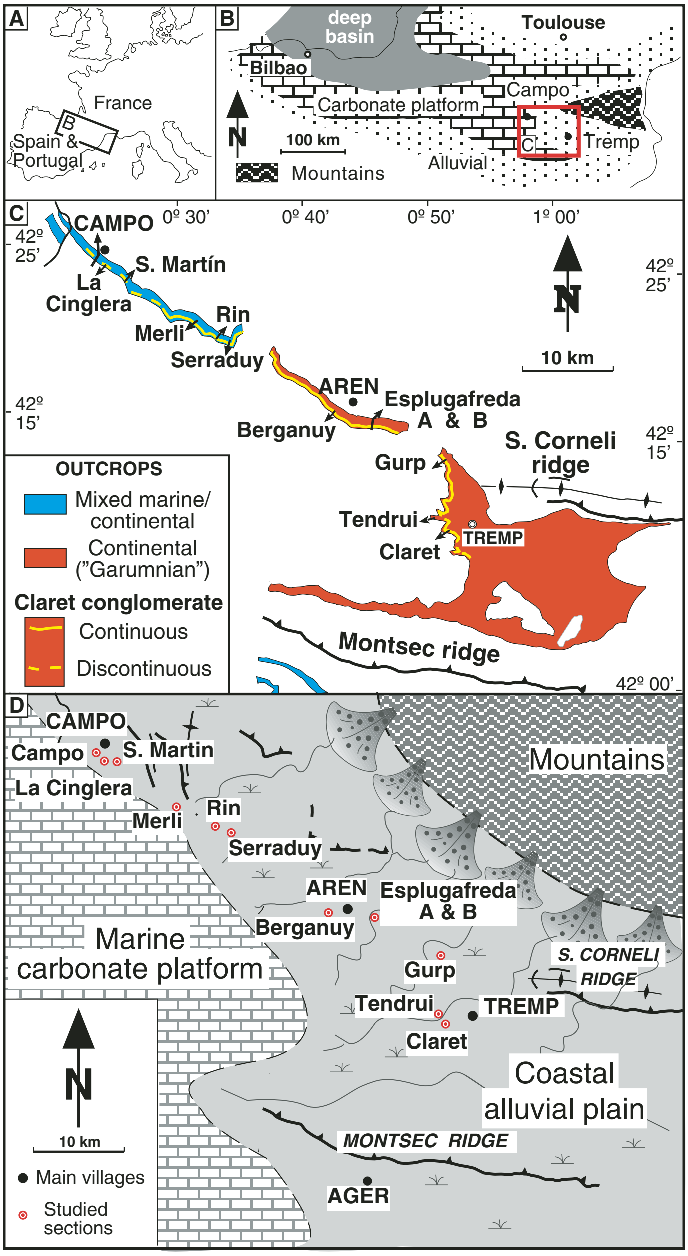

Figure 1. Setting of study area. A, B: Geographic and paleogeographic location. C: Early Paleogene outcrops. D: Paleogeographic reconstruction for latest Paleocene, before Claret Conglomerate formed.

Distribution

The CC, the yellowish soils, and the basal marine Ilerdian deposits represent prominent lithostratigraphic features readily traceable throughout the study area. We found that the yellowish soils are laterally persistent throughout the study area and are almost always underlain by the usually ~1–4-m-thick (occasionally as much as 8 m) CC (Figs. DR2–DR5; see footnote 1). The most unusual characteristic of this conglomerate is its extreme lateral persistence (Fig. 2; Fig. DR5). It has been found at the same stratigraphic position in numerous exposures over ~50 × 10 km in strike and dip directions, respectively (i.e., from Gurp to Campo and from Gurp to Claret, Fig. 1), indicating that it formed over an area of at least 500 km^2. At Esplugafreda and Berganuy in the central study area, the CC can be followed below the yellowish soils in outcrops for nearly 6 km as one horizontal continuous unit (Fig. 2). From Gurp to Claret, in the eastern part of the study area, the CC can be traced continuously in the landscape for nearly 6 km (Fig. DR5); it is then absent for a short stretch to the south of Tendrui, and then reappears for at least another 2 km (Claret section, Fig. DR2). In the west, from Serraduy to Merli, the CC can also be traced for kilometer distances (Fig. DR5). In the northwestern study area, e.g., at Campo, the CC is represented by distal, pebbly channel sands (Fig. DR4). In distinct contrast to the CC, channel deposits of the underlying Paleocene alluvial beds typically have lateral extensions of only 10–200 m (Fig. 2).

The CC probably formed over an area larger than where it is found today. Paleocurrent and tectonic reconstructions place the source area more than 10 km to the north of the present-day outcrops (Fig. 1; Fig. DR1). It is very likely that the CC also formed to the east of Tremp, where the uppermost Garumnian has been removed or the absence of outcrops prevents its detection. A conservative estimate is that the CC formed over at least 2000 km^2. Silty to sandy, clast-free sediments representing the distal extension of the CC must have been deposited over an additional many thousand square kilometers to the south and west.

Age

Throughout the study area carbonate nodules from the yellowish soils always have very negative $\delta^{13}C$ values (–13‰), representative of peak CIE conditions. Nodules from paleosols just below the CC always have typical Paleocene $\delta^{13}C$ values (–8‰ to –6‰) (Figs. DR2–DR4; see footnote 1). At sites such as Esplugafreda-A and Berganuy, the nodules immediately above the CC and throughout the major part of the yellowish PETM paleosols have values from –14‰ to –11‰; most values are in the lower part of the range (Fig. 3; Figs. DR2–DR4). In contrast, nodules from soils in the CC (including upper sandy part) at three sites have isotopic values intermediate between those below and above the CC (Figs. DR3 and DR4). For example, nodules from a soil horizon in the middle part of the CC at Berganuy range from –13‰ to –9‰, and most values are in the upper part of this range (Fig. 3). The intermediate $\delta^{13}C$ values within the CC indicate that the CC formed during the earliest part of the PETM, when a rapid buildup of ^{12}C-enriched carbon dioxide occurred in the atmosphere.

Deep-sea core $\delta^{13}C$ and ^{3}He data show that the major part of the CIE evolved very rapidly, within (less than) a few thousand years, but it took an additional ~20 k.y. for peak CIE values to develop (Farley and Eltgroth, 2003). From our isotopic data we can determine that, in the Esplugafreda-Berganuy and Campo areas, the CC was forming when the CIE had just begun to develop, but had ceased to form when the CIE had peaked. The CC has generally similar thickness over most of the study area, and the overlying PETM soils show no systematic change in thickness from one region to another. Invoking a considerable diachroneity for the CC over the study area would require highly variable conglomerate and soil formation rates in the different parts of the study area. Considering the three sites where the isotopic results show that the CC formed coincident with the climatic changes generally attributed to the P-E boundary, it seems very likely that these changes affected the entire basin at the same time. In general, conglomerates in alluvial deposits form on geologically short time scales. Although uncertainties exist, we estimate that the CC formed over the entire study area during a few thousand years to 10 k.y. at the start of the PETM period.

Sedimentology

The CC has a low-relief, erosional base and was deposited on an essentially flat landscape. Internal channeling and lateral accretion surfaces and clast fabric indicate a polyphased origin, i.e., it did not form as a result of one catastrophic flooding event (Fig. DR6; see footnote 1), but rather represents laterally interfingering river channel deposits, caused by both lateral accretion and avulsion processes. Generally thin (10–20 cm), but occasionally well-developed (2 m) horizons with paleosols containing centimeter-sized soil nodules occur between meter-thick conglomer-

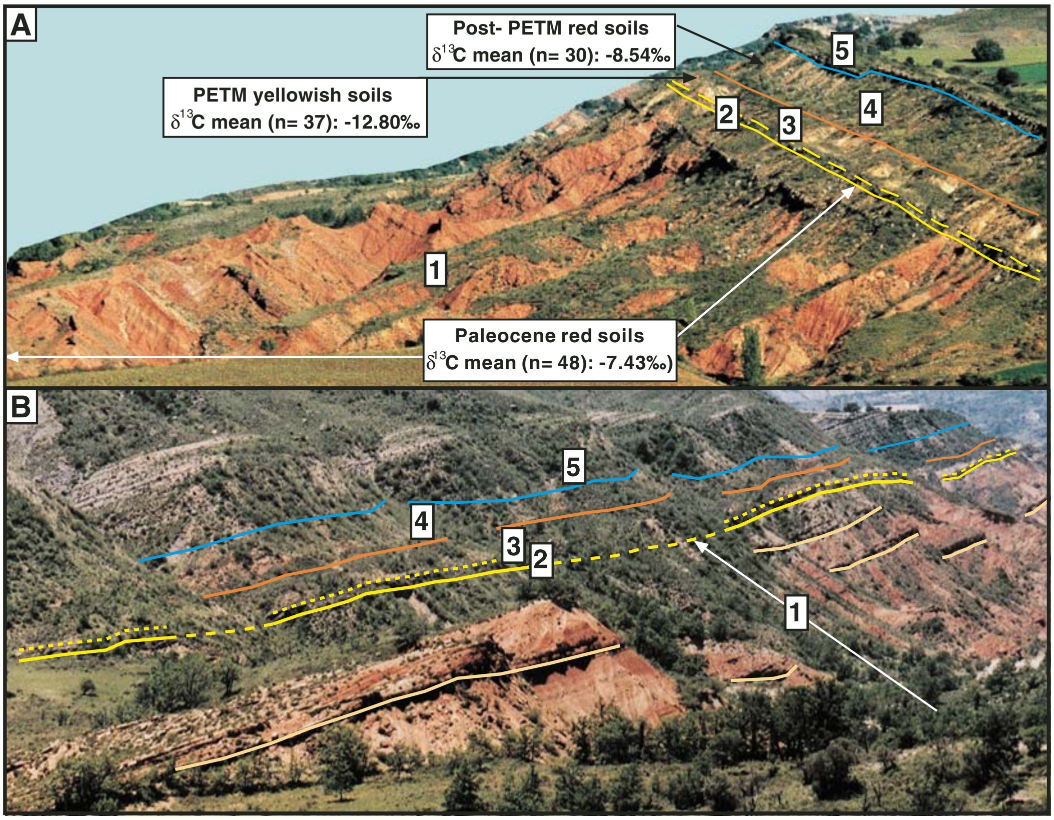

Figure 2. Early Paleogene "Garumnian" continental succession. A: Overview 2 km west of Esplugafreda section with summary of isotopic results for soil nodules (Schmitz and Pujalte, 2003). B: Esplugafreda, overview demonstrating much greater lateral continuity of Claret Conglomerate (CC; yellow line) relative to underlying Paleocene channel-fill deposits (light brown lines). Lateral extent of view is ~2 km. 1—Paleocene red beds; 2—CC, base of Paleocene-Eocene thermal maximum (PETM) interval; 3—yellowish soils of PETM interval; 4—post-PETM red soils; 5—base of marine Ilerdian (lower Ypresian) deposits. For scale, PETM soil of unit 3 is ~20 m thick.

atic subunits (Fig. DR3). This shows that channels were moving laterally and soils were forming next to prevailing active channels. The CC most likely formed in 10 k.y. or less, indicating that channels were moving laterally on short time scales. The conglomerate is clast supported and often imbricated, denoting tractive currents (Fig. DR7). Conglomerate clasts are rounded and as long as 65 cm, indicating high stream energies. The clasts are more coarse grained than in any of the conglomerates of the underlying channels, where they rarely exceed 25 cm.

Origin

The sudden appearance at the onset of the PETM of an ~1–4-m-thick conglomerate persistent over 500–2000 km^2 indicates a dramatic change in the hydrologic cycle. A tectonic origin is ruled out by the rapid formation of the conglomerate and absence of any other evidence for tectonism in the region at this time (Data Repository discussion and Fig. DR8; see footnote 1). We interpret the CC as representing the proximal parts of a megafan, characterized by frequent avulsion and rapid channel migration. Modern fluvial megafans are distinguished from stream-dominated alluvial fans by their unusually large areas, 10^3–10^5 km^2 compared to <100 km^2 for alluvial fans, and they are primarily restricted to lat 15°–35°, corresponding to the subtropical net evaporation zones (Leier et al., 2005). Modern fluvial megafans in actively aggrading basins are formed by rivers with extreme seasonal fluctuations in discharge related to highly seasonal precipitation patterns. On a global scale there is no relationship between megafan occurrence and drainage-basin relief or area (Leier et al., 2005). Modern megafans are characterized by a change from boulders near the apex to predominantly silt and mud at their toes, which is also observed for the CC in the Pyrenean transect from the central study area, where the thickest conglomerate occurs, to the northwest, where there is a gradual transition into alternations of pebbly sandstone, silt, and mud (e.g., from Merli to La Cinglera-Campo, Fig. 1). Fluvial megafans are devoid of sediment gravity flows (Leier et al., 2005), which are also almost absent from the CC.

The reason modern river systems with large seasonal fluctuations in discharge produce megafans is related to lateral instability that promotes rapid channel migration and frequent avulsion (Leier et al., 2005). An example is the Kosi River megafan in northeastern India, where the river has migrated westward on average 0.5 km/yr the past 228 yr (Wells and Dorr, 1987). Satellite images of megafans show that overbank areas are replete with abandoned channels. Floods, related to extreme precipitation events, serve as avulsion-triggering events. Typically the annual flooding during the wet season serves as an effective catalyst for avulsion, for example, through erosion of river banks by peak stream powers (Leier et al., 2005). High sediment yields when extreme flash floods erode a vegetation-barren dry landscape can also catalyze avulsion and rapid channel migration.

PETM CLIMATE CHANGES

The development of vast braid plains or a megafan at the P-E boundary in the Pyrenees is consistent with model predictions of increased intra-annual humidity gradients and associated seasonal flash floods in the subtropics in a strengthened greenhouse situation (Houghton et al., 2001). The reddish-brown color, high calcite content, and relatively large soil nodules of the soils within the CC indicate a generally semiarid climate when the CC formed (Retallack, 2001; van Breemen and Buurman, 2002). The CC disappeared as abruptly as it appeared and is directly overlaid by fine-grained yellowish soils of the main phase of the PETM. The hydrological cycle apparently shifted again, leading to rapid soil formation, but still in a generally semiarid setting (Schmitz and Pujalte, 2003). Drying immediately after the PETM is indicated by the appearance of thick gypsum beds in some areas of the Tremp Basin (Fig. DR2; see footnote 1).

Continental sections may provide the most informative records of the detailed succession of climatic change during the PETM, but reconstructions are only applicable on a regional scale. In the early Paleogene our study area was in the northern parts of the subtropical netevapora-

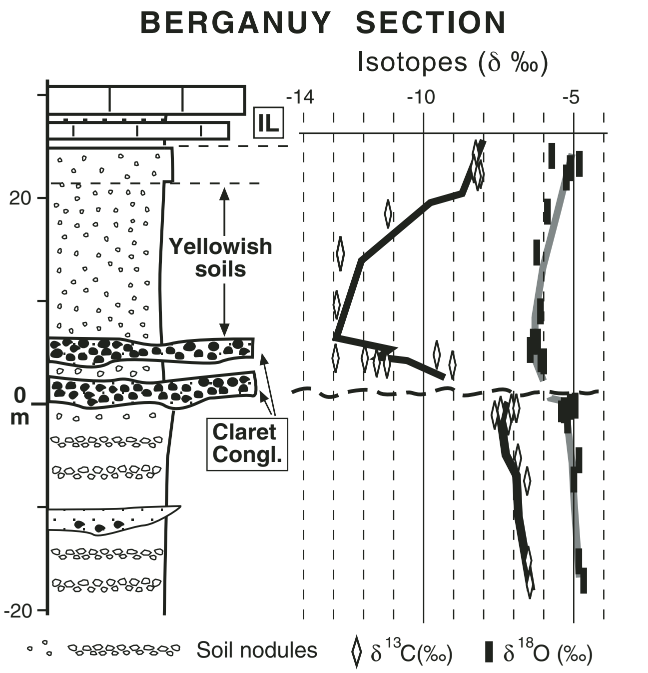

Figure 3. Carbonate nodule isotopic profiles for Berganuy section where paleosols within Claret Conglomerate have intermediate $\delta^{13}C$ values compared to overlying Paleocene-Eocene thermal maximum yellowish paleosols and underlying Paleocene red paleosols. Solid lines are for 3-point running averages. IL—Ilerdian marine limestones.

tion zone, a region generally very sensitive to changes in precipitation. Paleosol and paleobotanical features at another continental PETM record studied in detail, in Wyoming, provide evidence for a change to a drier climate during the early PETM phase but increasing precipitation in the later phase (Kraus and Riggins, 2005; Wing et al., 2005). No basal, laterally extensive conglomerate is known in Wyoming, but the sediments formed far from the major oceans where the most severe storms originate. Modeling scenarios based on a greater amplitude of the CIE in pedogenic carbonate nodules than in marine carbonates suggest a generally more humid climate during the PETM (Bowen et al., 2004); however, this issue is complex because shallow- or surface-marine records also show enhanced CIE amplitudes compared to deep-sea records (Thomas et al., 2002).

The frequencies of the most severe tropical storms have increased since the 1970s, possibly as a result of global warming (Emanuel, 2005; Webster et al., 2005). Prediction of storm frequencies when atmospheric CO_2 is rising faces complex climatic issues, and various modeling simulations give different results. The CC at the base of the PETM interval in the Pyrenees may represent empirical evidence for the dramatic effects of rapidly increasing CO_2 concentrations on the hydrological cycle in arid to semiarid subtropical regions.

ACKNOWLEDGMENTS

This research was supported by the Swedish Research Council, the University of the Basque Country, and the Ministerio de Educación y Ciencia. We thank H. Brinkhuis, S. Robinson, and two anonymous referees for valuable comments.

REFERENCES CITED

Bowen, G.J., Beerling, D.J., Koch, P.L., Zachos, J.C., and Quattlebaum, T., 2004, A humid climate state during the Palaeocene/Eocene thermal maximum: Nature, v. 432, p. 495–498, doi: 10.1038/nature03115.

Clyde, W.C., and Gingerich, P.D., 1998, Mammalian community response to the latest Paleocene thermal maximum: An isotaphonomic study in the northern Bighorn Basin, Wyoming: Geology, v. 26, p. 1011–1014, doi: 10.1130/0091–7613(1998)026<1011:MCRTTL>2.3.CO;2.

Cuevas, J.L., 1992, Estratigrafía del Garumniense de la Conca de Tremp. Prepirineo de Lérida: Acta Geológica Hispánica, v. 27, p. 95–108.

Dickens, G.R., O'Neil, J.R., Rea, D.K., and Owen, R.M., 1995, Dissociation of oceanic methane hydrate as a cause of the carbon isotope excursion at the end of the Paleocene: Paleoceanography, v. 10, p. 965–971, doi: 10.1029/95PA02087.

Emanuel, K., 2005, Increasing destructiveness of tropical cyclones over the past 30 years: Nature, v. 436, p. 686–688, doi: 10.1038/nature03906.

Farley, K.A., and Eltgroth, S.F., 2003, An alternative age model for the Paleocene-Eocene thermal maximum using extraterrestrial ^{3}He: Earth and Planetary Science Letters, v. 208, p. 135–148, doi: 10.1016/S0012–821X(03)00017–7.

Feist, M., and Colombo, F., 1983, La limite Crétacé-Tertiaire dans le nord-est de l'Espagne, du point de vue des charophytes: Géologie Méditerranéenne, v. 10, p. 303–326.

Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., and Johnson, C.A., eds., 2001, Climate change—2001: The scientific basis: Cambridge, Cambridge University Press, 881 p.

Kennett, J.P., and Stott, L.D., 1991, Abrupt deep-sea warming, palaeoceanographic changes and benthic extinctions at the end of the Palaeocene: Nature, v. 353, p. 225–229, doi: 10.1038/353225a0.

Kraus, M.J., and Riggins, S., 2005, Transient drying during the Paleocene-Eocene thermal maximum (PETM): Analysis of paleosols in the Bighorn Basin, Wyoming: Geological Society of America Abstracts with Programs, v. 37, no. 7, p. 266.

Leier, A.L., DeCelles, P.G., and Pelletier, J.D., 2005, Mountains, monsoons, and megafans: Geology, v. 33, p. 289–292, doi: 10.1130/G21228.1.

Lopéz-Martínez, N., and Peláez-Campomanes, P., 1999, New mammals from south-central Pyrenees (Tremp Formation, Spain) and their bearing on late Paleocene marine-continental correlations: Bulletin de la Société Géologique de France, v. 170, p. 681–696.

Médus, J., and Colombo, F., 1991, Succession climatique et limite stratigraphique Crétacé-Tertiaire dans le N.E. de l Espagne: Acta Geológica Hispánica, v. 26, p. 173–179.

Pujalte, V., and Schmitz, B., 2005, Revisión de la estratigrafía del Grupo Tremp ("Garumniense", Cuenca de Tremp-Graus, Pirineos meridionales): Geogaceta, v. 38, p. 79–82.

Retallack, G.J., 2001, Soils of the past: Oxford, Blackwell Science, 404 p.

Rosell, J., Linares, R., and Llompart, C., 2001, El "Garumniense" Prepirenaico: Revista de la Sociedad Geológica de España, v. 14, p. 47–56.

Schmitz, B., and Pujalte, V., 2003, Sea-level, humidity, and land-erosion records across the initial Eocene thermal maximum from a continental-marine transect in northern Spain: Geology, v. 31, p. 689–692, doi: 10.1130/G19527.1.

Svensen, H., Planke, S., Malthe-Sørenssen, A., Jamtveit, B., Myklebust, R., Eidem, T.R., and Rey, S.S., 2004, Release of methane from a volcanic basin as a mechanism for initial Eocene global warming: Nature, v. 429, p. 542–545, doi: 10.1038/nature02566.

Thomas, D.J., Zachos, J.C., Bralower, T.J., Thomas, E., and Bohaty, S., 2002, Warming the fuel for the fire: Evidence for the thermal dissociation of methane hydrate during the Paleocene-Eocene thermal maximum: Geology, v. 30, p. 1067–1070, doi: 10.1130/0091–7613(2002)030<1067:WTFFTF>2.0.CO;2.

van Breemen, N., and Buurman, P., 2002, Soil formation: Dordrecht, Netherlands, Kluwer Academic Publishers, 404 p.

Webster, P.J., Holland, G.J., Curry, J.A., and Chang, H.-R., 2005, Changes in tropical cyclone number, duration, and intensity in a warming environment: Science, v. 309, p. 1844–1846, doi: 10.1126/science.1116448.

Wells, N.A., and Dorr, J.A., Jr., 1987, Shifting of the Kosi River, northern India: Geology, v. 15, p. 204–207, doi: 10.1130/0091–7613(1987)15<204:SOTKRN>2.0.CO;2.

Wing, S.L., Harrington, G.J., Smith, F.A., Bloch, J.I., Boyer, D.M., and Freeman, K.H., 2005, Transient floral change and rapid global warming at the Paleocene-Eocene boundary: Science, v. 310, p. 993–996, doi: 10.1126/science.1116913.

Zachos, J.C., Wara, M.W., Bohaty, S., Delaney, M.L., Petrizzo, M.R., Brill, A., Bralower, T.J., and Premoli-Silva, I., 2003, A transient rise in tropical sea surface temperature during the Paleocene-Eocene thermal maximum: Science, v. 302, p. 1551–1554, doi: 10.1126/science.1090110.

Manuscript received 21 August 2006
Revised manuscript received 25 October 2006
Manuscript accepted 27 October 2006

Printed in USA