

2007W9B2WE\_004; 2010X3PP8J\_003). L. Giusberti and F. Boscolo Galazzo are deeply indebted to Domenico Rio for the original idea of the “Paleogene Veneto Project”, the financial and material support, and for fruitful discussions during all these years. E. Thomas acknowledges financial support by the Leverhulme foundation (UK) and NSF Grant OCE 1232413.

## 5 References

- Agnini, C., Fornaciari, E., Rio, D., Tateo, F., Backman, J., and Giusberti, L.: Response to calcareous nannofossil assemblages, mineralogy and geochemistry to the environmental perturbations across the Paleocene/Eocene boundary in the Venetian Pre-Alps, *Mar. Micropaleontol.*, 63, 19–38, 2007.
- 10 Agnini, C., Macrì, P., Backman, J., Brinkhuis, H., Fornaciari, E., Giusberti, G., Luciani, V., Rio, D., Sluijs, A., and Speranza, F.: An early Eocene carbon cycle perturbation at ~ 52.5 Ma in the Southern Alps: chronology and biotic response, *Paleoceanography*, 24, PA2209, doi:10.1029/2008PA001649, 2009.
- Alegret, L., Molina, E., and Thomas, E.: Benthic foraminiferal faunal turnover across the cretaceous/tertiary boundary at Agost (Southeastern Spain), *Mar. Micropaleontol.*, 48, 251–279, 2003.
- 15 Alegret, L., Ortiz, N., and Molina, E.: Extinction and recovery of benthic foraminifera across the Paleocene–Eocene thermal maximum at the Alamedilla section (Southern Spain), *Palaeogeogr. Palaeoclimatol.*, 279, 186–200, 2009a.
- 20 Alegret, L., Ortiz, S., Orue-Extebarria, X., Bernaola, G., Baceta, J. I., Monechi, S., Apellaniz, E., Pujalte, V.: The Paleocene–Eocene thermal maximum: new data on microfossil turnover at the Zumaia section, Spain, *Palaios*, 24, 318–328, 2009b.
- Alegret, L., Ortiz, S., Arenillas, I., and Molina, E.: What happens when the ocean is overheated? The foraminiferal response across the Paleocene–Eocene thermal maximum at the Alamedilla section (Spain), *Geol. Soc. Am. Bull.*, 122, 1616–1624, 2010.
- 25 Alve, E. and Goldstein, S. T.: Propagule transport as a key method of dispersal in benthic foraminifera (protists), *Limnol. Oceanogr.*, 48, 2163–2170, 2003.
- Arndt, S., Jørgensen, B. B., LaRowe, D. E., **Middeburg**, J. J., Pancost, R. D., and Regnier, P., Quantifying the degradation of organic matter in marine sediments: a review and synthesis, *Earth-Sci. Rev.*, 123, 53–86, 2013.
- 30

4237

- Arreguín-Rodríguez, G. J., Alegret, L., and Ortiz, S.: *Glomospira acme* during the Paleocene–Eocene thermal maximum: response to CaCO<sub>3</sub> dissolution or to ecological forces?, *J. Foramin. Res.*, 43, 37–49, 2013.
- Arreguín-Rodríguez, G. J., Alegret, L., Sepúlveda, J., Newman, S., and Summons, R. E.: Enhanced terrestrial input supporting the *Glomospira acme* across the Paleocene–Eocene boundary in Southern Spain, *Micropaleontology*, 60, 43–51, 2014.
- 5 Aubry, M.-P., Ouda, K., Dupuis, C., Berggren, W. A., Van Couvering, J. A., Ali, J., Brinkhuis, H., Gingerich, P. R., Heilmann-Clausen, C., Hooker, J., Kent, D. V., King, C., Knox, R. W. O. B., Laga, P., Molina, E., Schmitz, B., Steurbaut, E., and Ward, D. R.: The global standard stratotype-section and point (GSSP) for the base of the Eocene series in the Dababiya section (Egypt), *Episodes*, 30, 271–286, 2007.
- 10 Aze, T., Pearson, P. N., Dickson, A. J., Badger, M. P. S., Bown, P. R., Pancost, R. D., Gibbs, S. J., Huber, B. T., Leng, M. J., Coe, A. L., Cohen, A. S., and Foster, G. L.: Extreme warming of tropical waters during the Paleocene–Eocene thermal maximum, *Geology*, 42, 739–742, 2014.
- 15 Bains, S., Corfield, R. M., and Norris, R. D.: Mechanisms of climate warming at the end of the Paleocene, *Science*, 285, 724–727, doi:10.1126/science.285.5428.724, 1999.
- Beckmann, J. P.: Distribution of benthonic foraminifera at the Cretaceous–Tertiary boundary of Trinidad (West Indies), in: Part 5: The Cretaceous–Tertiary boundary, International Geological Congress Report, 21 Session Norden, Copenhagen, 57–59, 1960.
- 20 Berggren, W. A. and Aubert, J.: Paleocene benthonic foraminiferal biostratigraphy, paleobiogeography and paleoecology of Atlantic-Tethyan regions: midway type fauna, **Palaeogeogr. Palaeoclimatol.**, 18, 73–192, 1975.
- Berggren, W. A. and Miller, K. G.: Cenozoic bathyal and abyssal calcareous benthic foraminiferal zonation, *Micropaleontology*, 35, 308–320, 1989.
- 25 Bernhard, J. M. and Sen Gupta, B. K.: Foraminifera of oxygen depleted environments, in: *Modern Foraminifera*, edited by: Sen Gupta, B. K., Kluwer Academic Publishers, Dordrecht, 201–216, 1999.
- Boltovskoy, E., Scott, D. B., and Medioli, F. S.: Morphological variations of benthic foraminiferal tests in response to changes in ecological parameters; a review, *J. Paleontol.*, 65, 175–185, 1991.
- 30

4238

- Bornemann, A., Norris, R. D., Lyman, J. A., D'haenens, S., Groeneveld, J., Röhl, U., Farley, K. A., and Speijer, R. P.: Persistent environmental change after the Paleocene–Eocene thermal maximum in the eastern North Atlantic, *Earth Planet. Sc. Lett.*, 394, 70–81, 2014.
- Boersma, A.: Oligocene and other Tertiary benthic foraminifers from a depth traverse down Walvis Ridge, Deep Sea Drilling Project Leg 74, Southeast Atlantic, Initial Rep. Deep Sea, 75, 1273–1300, doi:10.2973/dsdp.proc.75.150.1984, 1984.
- Boscolo Galazzo, F., Giusberti, L., Luciani, V., and Thomas, E.: Paleoenvironmental changes during the Middle Eocene climatic optimum (MECO) and its aftermath: the benthic foraminiferal record from the Alano section (NE Italy), *Palaeogeogr. Palaeoecol.*, 378, 22–35, 2013.
- Boscolo-Galazzo, F., Thomas, E., and Giusberti, L.: Benthic foraminiferal response to the Middle Eocene climatic optimum (MECO) in the Southeastern Atlantic (ODP Site 1263), *Palaeogeogr. Palaeoecol.*, 417, 432–444, 2015.
- Bowen, G. J., Beerling, D. J., Koch, P. L., Zachos, J. C., Quattlebaum, T.: A humid climate state during the Palaeocene/Eocene thermal maximum, *Nature*, 432, 495–499, 2004.
- Bowen, G. J., Maibauer, B. J., Kraus, M. J., Roehl, U., Westerhold, T., Steike, A., Gingerich, P. D., Wing, S. L., and Clyde, W. J.: Two massive, rapid release of carbon during the onset of the Palaeocene–Eocene thermal maximum, *Nat. Geosci.*, 8, 44–47, 2015.
- Braga, G., De Biase, R., Gruning, A., and Proto Decima, F.: Foraminiferi bentonici del Paleocene e dell'Eocene della sezione di Possagno, in: *Monografia micropaleontologica sul Paleocene e l'Eocene di Possagno, Provincia di Treviso, Italia*, edited by: Bolli, H. M., *Schweizerische Paläontologische Abhandlungen, Abhandlungen*, Basel, 97, 85–111, 1975.
- Bralower, T. J.: Evidence of surface water oligotrophy during the Paleocene–Eocene thermal maximum: nannofossil assemblage data from Ocean Drilling Program Site 690, Maud Rise, Weddell Sea, *Paleoceanography*, 17, 1023, doi:10.29/2001PA000662, 2002.
- Broecker, W. S. and Peng, T.-H.: *Tracers in the Sea*, Palisades, Eldigio Press, New York, 690 pp., 1982.
- Buzas, M. A., Culver, S. J., and Jorissen, F. J.: A statistical evaluation of the microhabitats of living (stained) infaunal benthic foraminifera, *Mar. Micropaleontol.*, 29, 73–76, 1993.
- Cetean, C., Setoyama, E., Kaminski, M. A., Neagu, T., Bubík, M., Filipescu, S., and Tyszka, J.: *Eobigenerina*, n. gen., a cosmopolitan deep-water agglutinated foraminifer, and remarks on species formerly assigned to the genera *Pseudobolivina* and *Bigenerina*, in: *Eight International Workshop on Agglutinated Foraminifera*, Abstract Volume, edited by: Filipescu, S. and

4239

- Kaminski, M. A., Grzybowski Foundation Special Publication, Presa Universitară Clujeană, Romania, 14, 6–7, 2008a.
- Cetean, C., Bălci, R., Kaminski, M. A., and Filipescu, S.: Biostratigraphy of the cenomanian-turonian boundary in the Eastern Carpathians (Dâmbovița Valley): preliminary observations, *Stud. Univ. Babeș-Bol., Geologia*, 53, 11–23, 2008b.
- Cetean, C., Setoyama, E., Kaminski, M. A., Neagu, T., Bubík, M., Filipescu, S., and Tyszka, J.: *Eobigenerina*, a cosmopolitan deep-water agglutinated foraminifer, and remarks on late Paleozoic to Mesozoic species formerly assigned to *Pseudobolivina* and *Bigenerina*, in: *Proceedings of the Eight International Workshop on Agglutinated Foraminifera*, edited by: Filipescu, S. and Kaminski, M. A., Grzybowski Foundation Special Publication, Grzybowski Foundation Special Publication, Presa Universitară Clujeană, Romania, , 16, 19–27, 2011.
- Chun, C. O. J., Delaney, M. L., and Zachos, J. C.: Paleoredox changes across the Paleocene–Eocene thermal maximum, Walvis Ridge (ODP sites 1262, 1263, and 1266): evidence from Mn and U enrichment factors, *Paleoceanography*, 25, PA4202, doi:10.1029/2009PA001861, 2010.
- Coccioni, R. and Galeotti, S.: Orbitally induced cycles in benthic foraminiferal morphogroups and trophic structure distribution patterns from the late Albian “Amadeus Segment” (Central Italy), *J. Micropalaeontol.*, 12, 227–239, 1993.
- Coccioni, R., Bancala, G., Catanzariti, R., Fornaciari, E., Frontalini, F., Giusberti, L., Jovane, L., Luciani, V., Savian, J., and Sprovieri, M.: An integrated stratigraphic record of the Palaeocene-lower Eocene at Gubbio (Italy): new insights into the early Palaeogene hyperthermals and carbon isotope excursions, *Terra Nova*, 45, 380–386, 2012.
- Collinson, M. E., Steart, D. C., Scott, A. C., Glasspool, I. J., and Hooker, J. J.: Episodic fire, runoff and deposition at the Palaeocene–Eocene boundary, *J. Geol. Soc. London*, 164, 87–97, 2007.
- Colosimo, A. B., Bralower, T. J., and Zachos, J. C.: Evidence of lysocline shoaling at the Paleocene/Eocene Thermal Maximum on Shatsky Rise, northwest Pacific, *Proceedings of the Ocean Drilling Program, Scientific Results*, 198, College Station, Texas, 1–36, 2006.
- Corliss, B. H.: Microhabitats of benthic foraminifera within deep-sea sediments, *Nature*, 314, 435–438, 1985.
- Corliss, B. H. and Chen, C.: Morphotype patterns of Norwegian Sea deep-sea benthic foraminifera and ecological implications, *Geology*, 16, 716–719, 1988.

4240

- Cramer, B. S., Wright, J. D., Kent, D. V., and Aubry, M.-P.: Orbital climate forcing of  $\delta^{13}\text{C}$  excursions in the late Paleocene-early Eocene (chrons C24n-C25n), *Paleoceanography*, 18, 1097, 2003.
- Crouch, E. M., Dickens, G. R., Brinkhuis, H., Aubry, M.-P., Hollis, C. J., Rogers, K. M., and Visscher, H.: The *Apectodinium* acme and terrestrial discharge during the Paleocene–Eocene thermal maximum: new palynological, geochemical and calcareous nannoplankton observations at Tawanui, New Zealand, *Palaeogeogr. Palaeoclimatol. 194*, 387–403, 2003.
- Dallanave, E., Tauxe, L., Muttoni, G., and Rio, D.: Silicate weathering machine at work: rock magnetic data from the late Paleocene–early Eocene Cicogna section, Italy, *Geochem. Geophys. Geosci.*, 11, Q07008, doi:10.1029/2010GC003142, 2010.
- Dallanave, E., Muttoni, G., Agnini, C., Tauxe, L., and Rio, D.: Is there a normal magnetic-polarity event during the Palaeocene–Eocene thermal maximum (~ 55 Ma)? Insights from the palaeomagnetic record of the Belluno Basin (Italy), *Geophys. J. Int.*, 191, 517–529, 2012.
- DeConto, R. M., Galeotti, S., Pagani, M., Tracy, D., Schaefer, K., Zhang, T., Pollard, D., and Beerling, D. J.: Past extreme warming events linked to massive carbon release from thawing permafrost, *Nature*, 484, 87–91, 2012.
- D’haenens, S., Bornemann, A., Stassen, P., and Speijer, R.: Multiple early Eocene benthic foraminiferal assemblage and  $\delta^{13}\text{C}$  fluctuations at DSDP site 401 (Bay of Biscay-NE Atlantic), *Mar. Micropaleontol.*, 88–89, 15–35, 2012.
- Dickens, G. R.: Down the Rabbit Hole: toward appropriate discussion of methane release from gas hydrate systems during the Paleocene–Eocene thermal maximum and other past hyperthermal events, *Clim. Past*, 7, 831–846, doi:10.5194/cp-7-831-2011, 2011.
- Dickens, G. R., Castillo, M. M., and Walker, J. C. G.: A blast of gas in the latest Paleocene: simulating first-order effects of massive dissociation of oceanic methane hydrate, *Geology*, 25, 259–262, 1997.
- Dickson, A. J., Rees-Owen, R. L., März, C., Coe, A. L., Cohen, A. S., Pancost, R. D., Taylor, K., and Shcherbinina, E.: The spread of marine anoxia on the northern Tethys margin during the Paleocene–Eocene thermal maximum, *Paleoceanography*, 29, 471–488, doi:10.1002/2014PA002629, 2014.
- Di Napoli Alliata, E., Proto Decima, F., and Pellegrini, G. B.: Studio geologico, stratigrafico e micropaleontologico dei dintorni di Belluno, *Memorie della Società Geologica Italiana*, 9, 1–28, 1970.

4241

- Dunkley Jones, T., Lunt, D. J., Schmidt, D. N., Ridgwell, A., Sluijs, A., Valdez, P. J., and Maslin, M. A.: Climate model and proxy data constraints on ocean warming across the Paleocene–Eocene Thermal Maximum, *Earth-Sci. Rev.*, 125, 123–145, 2013.
- Dypvik, H., Ribes, L., Burca, F., Rther, D., Jargvoll, D., Nagy, J., and Jochmann, M.: The Paleocene–Eocene thermal maximum (PETM) in Svalbard – clay mineral and geochemical signals, *Palaeogeogr. Palaeoclimatol. 302*, 156–169, 2011.
- Erger, H., Fenner, J., Heilmann-Clausen, C., Roegl, F., Sachsenhofer, R. F., and Schmitz, B.: Paleoproductivity of the northwestern Tethyan margin (Anthering section, Austria) across the Paleocene–Eocene transition, in: *Causes and Consequences of Globally Warm Climates in the Early Paleogene*, edited by: Wing, S. L., Gingerich, P. D., Schmitz, B., and Thomas, E., *Geol. S. Am. S., Boulder, Colorado*, The Geological Society of America, 369, 133–146, 2003.
- Erger, H., Homayoun, M., Huber, H., Roegl, F., and Schmitz, B.: Early Eocene climatic, volcanic, and biotic events in the northwestern Tethyan Untersberg section, Austria, *Palaeogeogr. Palaeoclimatol. 217*, 243–264, 2005.
- Erger, H., Heilmann-Clausen, C., and Schmitz, B.: From shelf to abyss: record of the Paleocene/Eocene-boundary in the Eastern Alps (Austria), *Geol. Acta*, 7, 215–227, doi:10.1344/105.000000266, 2009.
- Ernst, S. R., Guasti, E., Dupuis, C., and Speijer, R. P.: Environmental perturbation in the southern Tethys across the Paleocene/Eocene boundary (Dababyia, Egypt): foraminiferal and clay minerals record, *Mar. Micropaleontol.*, 60, 89–111, 2006.
- Fenero, R., Thomas, E., Alegret, L., and Molina, E.: Oligocene benthic foraminifera in the Fuente Caldera section (Betic Cordillera, Spain): paleoenvironmental inferences, *J. Foraminif. Res.*, 42, 286–304, 2012.
- Fontanier, C., Jorissen, F. J., Chaillou, G., Anschutz, P., Gremare, A., and Griveaud, C.: Live foraminiferal faunas from a 2800 m deep lower canyon station from the Bay of Biscay: faunal response to focusing of refractory organic matter, *Deep-Sea Res. I*, 52, 1189–1227, 2008.
- Foreman, B. Z., Heller, P. L., and Clementz, M. T.: Fluvial response to abrupt global warming at the Palaeocene/Eocene boundary, *Nature*, 491, 92–95, 2014.
- Fornaciari, E., Giusberti, L., Luciani, V., Tateo, F., Agnini, C., Backman, J., Oddone, M., and Rio, D.: An expanded Cretaceous–Tertiary transition in a pelagic setting of the Southern Alps (central–western Tethys), *Palaeogeogr. Palaeoclimatol. 255*, 98–131, 2007.

4242

- Frenzel, P.: Die benthischen Foraminiferen der Ruegener Schreibkreide (Unter Maastricht, NE Deutschland), *Neue Palaeontologische Abhandlungen*, Dresden, Germany, CPress Verlag, Band 3, 2000.
- Friedrich, O.: Benthic foraminifera and their role to decipher paleoenvironment during mid-Cretaceous Oceanic Anoxic Events—“the anoxic benthic foraminifera” paradox, *Revue de Micropaléontologie*, 177, 2–18, 2009.
- Friedrich, O., Nishi, H., Pross, J., Schmiedel, G., and Hemleben, C.: Millennial-to centennial scale interruptions of the Oceanic Anoxic Event 1b (early Albian, mid Cretaceous) inferred from benthic foraminiferal repopulation events, *Palaios*, 20, 64–77, 2005.
- Galeotti, S., Bellagamba, M., Kaminski, M. A., and Montanari, A.: Deep-sea benthic foraminiferal recolonisation following a volcanoclastic event in the lower Campanian of the Scaglia Rossa Formation (Umbria-Marche Basin, central Italy), *Mar. Micropaleontol.*, 44, 57–76, 2002.
- Galeotti, S., Kaminski, M. A., Coccioni, R., and Speijer, R.: High resolution deep water agglutinated foraminiferal record across the Paleocene/Eocene transition in the Contessa Road Section (central Italy), in: *Proceedings of the Sixth International Workshop on Agglutinated Foraminifera*, edited by: Bubik, M. and Kaminski, M. A., Grzybowski Foundation Special Publication, Grzybowski Foundation Special Publication, Drukarnia Narodowa, Kraków, 8, 83–103, 2004.
- Garel, S., Schnyder, J., Jacob, J., Dupuis, C., Boussafir, M., Le Milbeau, C., Storme, J.-Y., Iakovleva, A. I., Yans, J., Baudin, F., Fléhoc, C., and Quesnel, F.: Paleohydrological and paleoenvironmental changes recorded in terrestrial sediments of the Paleocene–Eocene boundary (Normandy, France), *Palaeogeogr. Palaeoclimatol.*, 376, 184–199, 2013.
- Gibbs, S. J., Bralower, T. J., Bown, P. R., Zachos, J. C., and Bybell, L. M.: Shelf and open-ocean calcareous phytoplankton assemblages across the Paleocene–Eocene thermal maximum: implications for global productivity gradients, *Geology*, 34, 233–236, 2006.
- Gibson, T. G., Bybell, L. M., and Owens, J. P.: Latest Paleocene lithologic and biotic events in neritic deposits of southwestern New-Jersey, *Paleoceanography*, 8, 495–514, 1993.
- Gibson, T. G., Bybell, L. M., and Mason, D. B.: Stratigraphic and climatic implications of clay mineral changes around the Paleocene/Eocene boundary of the northeastern US margin, *Sediment. Geol.*, 134, 65–92, 2000.
- Gingerich, P. D.: Mammalian response to climate change at the Paleocene–Eocene boundary: Polecat Bench record in the northern Bighorn Basin, Wyoming, in: *Causes and Conse-*

4243

- quences of Globally Warm Climates in the Early Paleogene, edited by: Wing, S. L., Gingerich, P. D., Schmitz, B., and Thomas, E., *Geol. Soc. Am. S. Boulder, Colorado*, The Geological Society of America, 369, 463–478, 2003.
- Giusberti, L., Rio, D., Agnini, C., Backman, J., Fornaciari, E., Tateo, F., and Oddone, M.: Mode and tempo of the Paleocene–Eocene thermal maximum from the Venetian pre-Alps, *Geol. Soc. Am. Bull.*, 119, 391–412, 2007.
- Giusberti, L., Coccioni, R., Sprovieri, M., and Tateo, F.: Perturbation at the sea floor during the Paleocene–Eocene thermal maximum: evidence from benthic foraminifera at Contessa Road, Italy, *Mar. Micropaleontol.*, 70, 102–119, 2009.
- Gooday, A. J.: Deep-sea benthic foraminiferal species which exploit phytodetritus: characteristic features and controls on distribution, *Mar. Micropaleontol.*, 22, 187–205, 1993.
- Gooday, A. J.: The biology of deep-sea Foraminifera: a review of some advances and their applications in paleoceanography, *Palaios*, 9, 14–31, 1994.
- Gooday, A. J.: Benthic foraminifera (Protista) as tools in deep-water paleoceanography: environmental influences on faunal characteristics, *Adv. Mar. Biol.*, 46, 1–90, 2003.
- Gooday, A. J., Hughes, J. A., and Levin, L. A.: The foraminiferan macrofauna from three North Carolina (USA) slope sites with contrasting carbon flux: a comparison with the metazoan macrofauna, *Deep-Sea Res. I*, 48, 1709–1739, 2001.
- Gooday, A. J., Nomaki, H., and Kitazato, H.: Modern deep-sea benthic foraminifera: a brief review of their morphology-based biodiversity and trophic diversity, in: *Biogeochemical Controls on Palaeoceanographic Environmental Proxies*, edited by: Austin, W. E. N. and James, R. H., *Geol. Soc. Spec. Publ.*, Bath, UK, The Geological Society Publishing House, 303, 97–119, 2008.
- Gupta, A. K. and Thomas, E.: Latest Miocene–Pleistocene productivity and deep-sea ventilation in the northwestern Indian Ocean (Deep Sea drilling project site 219), *Paleoceanography*, 14, 62–73, 1999.
- Gupta, A. K. and Thomas, E.: Initiation of Northern Hemisphere glaciation and strengthening of the northeast Indian monsoon: ocean drilling program site 758, eastern equatorial Indian Ocean, *Geology*, 31, 47–50, 2003.
- Gupta, A. K., Sundar Raj, M., Mohan, K., and De, S.: A major change in monsoon-driven productivity in the tropical Indian Ocean during ca 1.2–0.9 Myr: foraminiferal faunal and stable isotope data, *Palaeogeogr. Palaeoclimatol.*, 261, 234–245, 2008.

4244

- Hammer, Ø., Harper, D. A. T., and Ryan, P. D.: PAST: paleontological statistics software package for education and data analysis, *Palaeontol. Electron.*, 4, 1–9, 2001.
- Hancock, H. J. L. and Dickens, G. R.: Carbonate dissolution episodes in Paleocene and Eocene sediment, Shatsky Rise, west-central Pacific, in: *Proceedings of the Ocean Drilling Program*, edited by: Bralower, T. J., Premoli Silva, I., and Malone, M. J., Scientific Results, College Station, TX (Ocean Drilling Program), 1–24, doi:10.2973/odp.proc.sr.198.116, 2005. 2005.
- 5 Handley, L., Pearson, P. N., McMillan, I. K., and Pancost, R. D.: Large terrestrial and marine carbon and hydrogen isotope excursions in a new Paleocene/Eocene boundary section from Tanzania, *Earth Planet. Sc. Lett.*, 275, 17–25, 2008.
- 10 Handley, L., O'Halloran, A., Pearson, P. N., Hawkins, E., Nicholas, C. J., Schouten, S., McMillan, I. K., and Pancost, R. D.: Changes in the hydrological cycle in tropical East Africa during the Paleocene–Eocene thermal maximum, *Palaeogeogr. Palaeoclimatol.*, 329–330, 10–21, 2012.
- Harding, I. C., Charles, A. J., Marshall, J. E. A., Pälike, H., Roberts, A. P., Wilson, P. A., Jarvis, E., Thorne, R., Morris, E., Moremon, R., Pearce, R. B., and Akbari, S.: Sea-level and salinity fluctuations during the Paleocene–Eocene thermal maximum in Arctic Spitsbergen, 15 *Earth Planet. Sc. Lett.*, 303, 97–107, 2011.
- Harries, P. J. and Kauffman, E. G.: Patterns of survival and recovery following the Cenomanian–Turonian (Late Cretaceous) mass extinction in the Western Interior Basin, United States, in: *Extinction Events in Earth History*, edited by: Kauffman, E. G. and Walliser, O. H., Lect. Notes Earth Sci. Heidelberg, Germany, Springer-Verlag, 30, 277–298, 1990.
- 20 Harries, P. J., Kauffman, E. G., and Hansen, T. A.: Models for biotic survival following mass extinction, in: *Biotic Recovery from Mass Extinction Events*, edited by: Hart, M. B., *Geol. Soc. Spec. Publ.*, The Geological Society Publishing House, Bath, UK, 120, 41–60, 1996.
- Hayward, B. W., Johnson, K., Sabaa, A. T., Kawagata, S., and Thomas, E.: Cenozoic record of elongate, cylindrical, deep-sea benthic foraminifera in the North Atlantic and equatorial 25 Pacific Oceans, *Mar. Micropaleontol.*, 62, 141–162, 2010a.
- Hayward, B. W., Sabaa, A. T., Thomas, E., Kawagata, S., Nomura, R., Schroder Adams, C., Gupta, A. K., and Johnson, K.: Cenozoic record of elongate, cylindrical, deep-sea benthic foraminifera in the Indian Ocean (ODP sites 722, 738, 744, 758, and 763), *J. Foramin. Res.*, 30 40, 113–133, 2010b.
- Hess, S. and Jorissen, F. J.: Distribution patterns of living benthic foraminifera from Cap Breton canyon, Bay of Biscay: faunal response to sediment instability, *Deep-Sea Res. Pt. I*, 56, 1555–1578, doi:10.1016/j.dsr.2009.04.003, 2009.

4245

- Holbourn, A. and Kuhnt, W.: No extinctions during Oceanic Anoxic Event Ib: the Aptian-Albian benthic foraminiferal record of ODP Leg 171, in: *Western North Atlantic Palaeogene and Cretaceous Palaeoceanography*, edited by: Kroon, D., Norris, R. D., and Klaus, A., *Geol. Soc. London, Spec. Publ.*, Bath, UK, The Geological Society Publishing House, 183, 73–92, 5 2001.
- Holbourn, A., Kuhnt, W., and Erbacher, J.: Benthic foraminifera from lower Albian black shales (Site 1049, ODP Leg 171): evidence for a non “uniformitarian” record, *J. Foramin. Res.*, 31, 60–74, 2001.
- 10 Hönisch, B., Ridgwell, A., Schmidt, D. N., Thomas, E., Gibbs, S. J., Sluijs, A., Zeebe, R., Kump, L., Martindale, R. C., Greene, S. E., Kiessling, W., Ries, J., Zachos, J. C., Royer, D. L., Barker, S., Marchitto, T. M., Moyer, R., Pelejero, C., Ziveri, P., Foster, G. L., and Williams, B.: The geological record of ocean acidification, *Science*, 335, 1058–1963, 2012.
- Ishman, S. E. and Domack, E. W.: Oceanographic controls on benthic foraminifera from the Bellingshausen margin of the Antarctic Peninsula, *Mar. Micropaleontol.*, 24, 119–155, 2004.
- 15 Itambi, A. C., von Dobeneck, T., Mulitza, S., Bickert, T., and Heslop, D.: Millennial-scale northwest African droughts related to Heinrich events and Dansgaard-Oeschger cycles: evidence in marine sediments from offshore Senegal, *Paleoceanography*, 24, PA1205, doi:10.1029/2007PA001570, 2009.
- Jaramillo, C. A., Ochoa, D., Contreras, L., Pagani, M., Carvajal-Ortiz, H., Pratt, L. M., Krishnan, S., Cardona, A., Romero, M., Quiroz, L., Rodriguez, G., Rueda, M. J., De la Parra, F., Morón, S., Green, W., Bayona, G., Montes, C., Quintero, O., Ramirez, R., Mora, G., Schouten, S., Bermudez, H., Navarrete, R., Parra, F., Alvarán, M., Osorno, J., Crowley, J. L., Valencia, V., and Vervoort, J.: Effects of rapid global warming at the Paleocene–Eocene boundary on Neotropical vegetation, *Science*, 330, 957–961, 2010.
- 25 John, C. M., Bohaty, S. M., Zachos, J. C., Sluijs, A., Gibbs, S., Brinkhuis, H., and Bralower, T. J.: North American continental margin records of the Paleocene–Eocene thermal maximum: implications for global carbon and hydrological cycling, *Paleoceanography*, 23, PA2217, doi:10.1029/2007PA001465, 2008.
- 30 John, C. M., Banerjee, N. R., Longstaffe, F. J., Sica, C., Law, K. R., and Zachos, J. C.: Clay assemblage and oxygen isotopic constraints on the weathering response to the Paleocene–Eocene thermal maximum, east coast of North America, *Geology*, 40, 591–594, 2012.

4246

- John, E. H., Pearson, P. N., Coxall, H. K., Birch, H., Wade, B. S., and Foster, G. L.: Warm ocean processes and carbon cycling in the Eocene, *Philos. T. Roy. Soc. A*, 371, 20130099, doi:10.1098/rsta.2013.0099, 2013.
- John, E. H., Wilson, J. D., Pearson, P. N., and Ridgwell, A.: Temperature-dependent remineralization and carbon cycling in the warm Eocene oceans, *Palaeogeogr. Palaeoclimatol.*, 413, 158–166, 2014.
- Jones, B. and Manning, D. A. C.: Comparison of geochemical indices used for the interpretation of palaeoredox conditions in ancient mudstones, *Chem. Geol.*, 111, 111–194, doi:10.1016/0009-2541(94)90085-X, 1994.
- 10 Jones, R. W. and Charnock, M. A.: “Morphogroups” of agglutinated foraminifera, their life positions and feeding habits and potential applicability in (paleo)ecological studies, *Revue de Paléobiologie*, 4, 311–320, 1985.
- Jorissen, F. J.: Benthic foraminiferal successions across late Quaternary Mediterranean sapropels, 153, 91–101, 1999.
- 15 Jorissen, F. J., Fontanier, C., and Thomas, E.: Paleoceanographical proxies based on deep-sea benthic foraminiferal assemblage characteristics, in: *Proxies in Late Cenozoic Paleoceanography: Pt. 2: Biological tracers and biomarkers*, edited by: Hillaire-Marcel, C. and A. de Vernal, A., 1, Elsevier, Amsterdam, The Netherlands, 264–325, 2007.
- Kaiho, K.: Phylogeny of deep-sea calcareous trochospiral benthic foraminifera: evolution and diversification, *Micropaleontology*, 44, 291–311, 1998.
- 20 Kaiho, K., Arinobu, T., Ishiwatari, R., Morgans, H. E. G., Okada, H., Takeda, N., Tazaki, K., Zhou, G. P., Kajiwara, Y., Matsumoto, R., Hirai, A., Niitsuma, N., and Wada, H.: Latest Paleocene benthic foraminiferal extinction and environmental changes at Tawanui, New Zealand, *Paleoceanography*, 11, 447–465, 1996.
- 25 Kaminski, M. A. and Gradstein, F. M.: *An Atlas of Paleogene Cosmopolitan Deep-Water Agglutinated Foraminifera*, Grzybowski Foundation Special Publication, Drukarnia Narodowa, Kraków, 10, 547 pp., 2005.
- Kaminski, M. A., Kuhnt, W., and Radley, J. D.: Paleocene–Eocene deep water agglutinated foraminifera from the Numidian Flysch (Rift, Northern Morocco): their significance for the paleoceanography of the Gibraltar gateway, *J. Micropaleontol.*, 15, 1–19, 1996.
- 30 Katz, M. E., Wright, J. D., Katz, D. R., Miller, K. G., Pak, D. K., Shackleton, N. J., and Thomas, E.: Early Cenozoic benthic foraminiferal isotopes: species reliability and interspecies correction factors, *Paleoceanography*, 18, 1024, doi:10.1029/2002PA000798, 2003.

4247

- Kauffman, E. G. and Harries, P. J.: The importance of crisis progenitors in recovery from mass extinction, in: *Biotic Recovery from Mass Extinction Events*, edited by: Hart, M. B., *Geol. Soc. Spec. Publ.*, The Geological Society Publishing House, Bath, UK, 120, 41–60, 1996.
- Kelly, D. C., Bralower, T. J., Zachos, J. C., Premoli Silva, I., and Thomas, E.: Rapid diversification of planktonic foraminifera in the tropical Pacific (ODP site 865) during the late Paleocene thermal maximum, *Geology*, 24, 423–426, 1996.
- 5 Kelly, D. C., Bralower, T. J., and Zachos, J. C.: Evolutionary consequences of the latest Paleocene thermal maximum for tropical planktonic foraminifera, *Palaeogeogr. Palaeoclimatol.*, 141, 139–161, 1998.
- 10 Kelly, D. C., Nielsen, T. M. J., Mccarren, H. K., Zachos, J. C., and Röhl, U.: Spatiotemporal patterns of carbonate sedimentation in the South Atlantic: implications for carbon cycling during the Paleocene–Eocene thermal maximum, *Palaeogeogr. Palaeoclimatol.*, 293, 30–40, 2010.
- Kender, S., Stephenson, M. H., Riding, J. B., Leng, M. J., O’BKnox, R. W., Peck, V. L., Kendrick, C. P., Ellis, M. A., Vane, C. H., and Jamieson, R.: Marine and terrestrial environmental changes in NW Europe preceding carbon release at the Paleocene–Eocene transition, *Earth Planet. Sc. Lett.*, 353–354, 108–120, 2012.
- 15 Kennett, J. P. and Stott, L. D.: Abrupt deep-sea warming, paleoceanographic changes and benthic extinctions at the end of the Paleocene, *Nature*, 353, 225–229, 1991.
- Kirtland Turner, S. and Ridgwell, A.: Recovering the true size of an Eocene hyperthermal from the marine sedimentary record, *Paleoceanography*, 28, 700–712, 2013.
- 20 Koutsoukos, E. A. M., Leary, P. M., and Hart, M. B.: Latest Cenomanian–earliest Turonian low-oxygen tolerant benthonic foraminifera: a case study from the Sergipe Basin (N. E. Brazil) and the western Anglo-Paris Basin (southern England), *Palaeogeogr. Palaeoclimatol.*, 77, 145–177, 1990.
- 25 Kraus, M. J. and Riggins, S.: Transient drying during the Paleocene–Eocene thermal maximum (PETM): analysis of paleosols in the Bighorn Basin, Wyoming, *Palaeogeogr. Palaeoclimatol.*, 245, 444–461, 2007.
- Kraus, M. J., McInerney, F. A., Wing, S. L., Secord, R., Baczynski, A. A., and Bloch, J. I.: Paleohydrologic response to continental warming during the Paleocene–Eocene thermal maximum, Bighorn Basin, Wyoming, *Palaeogeogr. Palaeoclimatol.*, 370, 196–208, 2013.
- 30 Krishnan, S., Pagani, M., and Agnini, C.: Leaf waxes as recorders of paleoclimatic changes during the Paleocene–Eocene thermal maximum: regional expressions from the Belluno Basin, *Org. Geochem.*, 80, 8–17, 2015.

4248

- Kuhnt, W.: Abyssal recolonization by benthic foraminifera after the Cenomanian/Turonian boundary anoxic event in the North Atlantic, *Mar. Micropaleontol.*, 19, 257–274, 1992.
- Kuhnt, W.: Early Danian benthic foraminiferal community structures, Geulhmerberg, SE Netherlands, *Geol. Mijnbouw.*, 75, 163–172, 1996.
- 5 Kuhnt, W. and Kaminski, M. A.: Changes in the community structure of deep-water agglutinated foraminifers across the K/T boundary in the Basque Basin (northern Spain), *Revista Española de Micropaleontología*, 25, 57–92, 1993.
- Kuhnt, W. and Kaminski, M. A.: The reponse of benthic foraminifera to the K/T boundary event—a review, in: *Géologie de l’Afrique et de l’Atlantique Sud-Comptes Rendu des Colloques de géologie d’Angers*, 16–20 Juillet, 1994, edited by: Jardiné, S., de Klasz, I., and Debenay, J. P., B. Cent. Rech. Expl., Memoire, Pau, Société nationale Elf Aquitaine, 16, 433–442, 1996.
- 10 Kuhnt, W. and Collins, E. S.: Cretaceous to Paleogene benthic foraminifers from the Iberia abyssal plain, in: *Proceedings of the ODP*, edited by: Whitmarsh, R. B., Sawyer, D. S., Klaus, A., and Masson, D. G., Scientific Results, 149, College Station, TX Ocean Drilling Program, 203–316, 1996.
- Kuhnt, W., Collins, E., and Scott, D. B.: Deep water agglutinated foraminiferal assemblages across the Gulf Stream: distribution pattern and taphonomy, in: *Proceedings of the Fifth International Workshop on Agglutinated Foraminifera*, edited by: Hart, M. B., Kaminski, M. A., and Smart, C. W., Grzybowski Foundation Special Publication, Drukarnia Narodowa, Kraków, 7, 261–298, 2000.
- 20 Larrasoana, J. C., Roberts, A. P., Rohling, E. J., Winkhofer, M., and Wehausen, R.: Three million years of monsoon variability over the northern Sahara, *Clim. Dynam.*, 21, 689–698, doi:10.1007/s00382-003-0355-z, 2003.
- 25 Lirer, F.: A new technique for retrieving calcareous microfossils from lithified lime deposits, *Micropaleontology*, 46, 365–369, 2000.
- Littler, K., Röhl, U., Westerhold, T., and Zachos, J. C.: A high-resolution benthic stable-isotope record for the South Atlantic: implications for orbital-scale changes in Late Paleocene–Early Eocene climate and carbon cycling, *Palaeogeogr. Palaeoclimatol.*, 401, 18–30, 2014.
- 30 Luciani, V., Giusberti, L., Agnini, C., Backman, J., Fornaciari, E., and Rio, D.: The Paleocene–Eocene thermal maximum as recorded by Tethyan planktonic foraminifera in the Forada section (northern Italy), *Mar. Micropaleontol.*, 64, 189–214, 2007.

4249

- Ly, A. and Kuhnt, W.: Late Cretaceous benthic foraminiferal assemblages of the Casamance Shelf (Senegal, NW Africa) indication of a Late Cretaceous oxygen minimum zone, *Revue de Micropaléontologie*, 37, 49–74, 1994.
- Ma, Z., Gray, E., Thomas, E., Murphy, B., Zachos, J. C., and Paytan, A.: Carbon sequestration during the Paleocene–Eocene thermal maximum by an efficient biological pump, *Nat. Geosci.*, 7, 382–388, 2014.
- Mancin, N., Hayward, B. W., Trattenero, I., Cobianchi, M., and Lupi, C.: Can the morphology of deep-sea benthic foraminifera reveal what caused their extinction during the mid-Pleistocene Climate Transition?, *Mar. Micropaleontol.*, 104, 53–70, 2013.
- 10 McCarren, H., Thomas, E., Hasegawa, T., Röhl, U., and Zachos, J. C.: Depth dependency of the Paleocene–Eocene carbon isotope excursion: paired benthic and terrestrial biomarker records (ODP leg 208, Walvis Ridge), *Geochem. Geophys. Geosyst.*, 9, Q10008, doi:10.1029/2008GC002116, 2008.
- 15 McNerney, F. A. and Wing, S. L.: The Paleocene–Eocene thermal maximum: a perturbation of carbon cycle, climate, and biosphere with implications for the future, *Annu. Rev. Earth Pl. Sc.*, 39, 489–516, doi:10.1146/annurev-earth-040610-133431, 2011.
- Meissner, K. J., Bralower, T. J., Alexander, K., Dunkley Jones, T., Sijp, W., and Ward, M.: The Paleocene–Eocene Thermal Maximum: how much carbon is enough?, *Paleoceanography*, 29, 946–963, 2014.
- 20 Mohan, K., Gupta, A. K., and Bhaumik, A. K.: Distribution of deep-sea benthic foraminifera in the Neogene of Blake Ridge, NW Atlantic Ocean, *J. Micropalaeontol.*, 30, 33–74, 2011.
- Murphy, B. H., Farley, K. A., and Zachos, J. C.: An extraterrestrial <sup>3</sup>He-based timescale for the Paleocene–Eocene thermal maximum (PETM) from Walvis Ridge, IODP Site 1266, *Geochim. Cosmochim. Ac.*, 74, 5098–5108, 2010.
- 25 Murray, J. W.: *Ecology and Palaeoecology of Benthic Foraminifera* Longman, Harlow, 397 pp., 1991.
- Murray, J. W.: *Ecology and Applications of Benthic Foraminifera*, Cambridge University Press, USA, 426 pp., 2006.
- 30 Murray, J. W. and Pudsey, C. J.: Living (stained) and dead foraminifera from the newly ice-free Larsen Ice Shelf, Weddell Sea, Antarctica: ecology and taphonomy, *Mar. Micropaleontol.*, 53, 67–81, 2004.

4250

- Nicolo, M. J., Dickens, G. R., and Hollis, C. J.: South Pacific intermediate water oxygen depletion at the onset of the Paleocene–Eocene thermal maximum as depicted in New Zealand margin sections, *Paleoceanography*, 25, PA4210, doi:10.1029/2009PA001904, 2010.
- Nomura, R.: Paleogene to Neogene deep-sea paleoceanography in the eastern Indian Ocean: benthic foraminifera from ODP Sites 747, 757 and 758, *Micropaleontology*, 41, 251–290, 1995.
- Ortiz, N.: Differential patterns of benthic foraminiferal extinctions near the Paleogene/Eocene boundary in the North Atlantic and western Tethys, *Mar. Micropaleontol.*, 26, 341–359, 1995.
- Ortiz, S., Alegret, L., Payros, A., Orue-Extebarria, X., Apellaniz, E., and Molina, E.: Distribution pattern of benthic foraminifera across Ypresian-Lutetian Gorrondatxe section, Northern Spain: response to sedimentary disturbance, *Mar. Micropaleontol.*, 78, 1–13, 2011.
- Pagani, M., Caldeira, K., Archer, D., and Zachos, J. C.: An ancient carbon mystery, *Science*, 314, 1556–1557, 2006a.
- Pagani, M., Pedentchouk, N., Huber, M., Sluijs, A., Schouten, S., Brinkhuis, H., Sinninghe Damsté, J. S., Dickens, G. R., and the Expedition 302 Scientists: Arctic hydrology during global warming at the Palaeocene/Eocene thermal maximum, *Nature*, 442, 671–675, 2006b.
- Pälike, C., Delaney, M. L., and Zachos, J. C.: Deep-sea redox across the Paleocene–Eocene thermal maximum, *Geochem. Geophys. Geosy.*, 15, 1038–1053, 2014.
- Panchuk, K., Ridgwell, A., and Kump, L. R.: Sedimentary response to Paleocene–Eocene thermal maximum carbon release: a model-data comparison, *Geology*, 36, 315–318, 2008.
- Panieri, G. and Sen Gupta, B. K.: Benthic foraminifera of the Blake Ridge hydrate mound, Western North Atlantic Ocean, *Mar. Micropaleontol.*, 66, 91–102, 2007.
- Paytan, A., Averyt, K., Faul, K., Gray, E., and Thomas, E.: Barite accumulation, ocean productivity, and Sr/Ba in barite across the Paleocene–Eocene thermal maximum, *Geology*, 35, 1139–1142, 2007.
- Pearson, P. N. and Thomas, E.: Drilling disturbance and constraints on the onset of the Paleocene–Eocene boundary carbon isotope excursion in New Jersey, *Clim. Past*, 11, 95–104, doi:10.5194/cp-11-95-2015, 2015.
- Penman, D. E., Hönisch, B., Zeebe, R. E., Thomas, E., and Zachos, J. C.: Rapid and sustained surface ocean acidification during the Paleocene–Eocene thermal maximum, *Paleoceanography*, 29, 357–369, doi:10.1002/2014PA002621, 2014.
- Pflum, C. E. and Frerichs, W. E.: Gulf of Mexico deep-water foraminifers, Cushman Foundation for Foraminiferal Research, Special Publication, 14, 125 pp., 1976.

4251

- Pierrehumbert, R. T.: The hydrologic cycle in deep-time climate problems, *Nature*, 419, 191–198, 2002.
- Post, J. E., Thomas, E., and Heaney, P. J.: Jianshuiite in oceanic manganese nodules at the Paleocene–Eocene boundary, *Am. Mineral.*, in press, 2015.
- Raymo, M. E., Ruddiman, F., and Froelich, P. N.: Influence of late Cenozoic mountain building on ocean geochemical cycles, *Geology*, 16, 649–653, 1988.
- Ravizza, G. E., Norris, R. N., Blusztajn, J., and Aubry, M.-P.: An osmium isotope excursion associated with the late Paleocene thermal maximum: evidence of intensified chemical weathering, *Paleoceanography*, 16, 155–163, 2001.
- Robert, C. and Chamley, H.: Development of early Eocene warm climates, as inferred from clay mineral variations in oceanic sediments, *Global Planet. Change*, 89, 315–331, 1991.
- Robert, C. and Kennett, J. P.: Antarctic subtropical humid episode at the Paleocene–Eocene boundary: clay–mineral evidence, *Geology*, 22, 211–214, 1994.
- Rodriguez-Tovar, F. J., Uchman, A., Alegret, L., and Molina, E.: Impact of the Paleocene–Eocene thermal maximum on the macrobenthic community: ichnological record from the Zumaia section, northern Spain, *Mar. Geol.*, 282, 178–187, 2011.
- Röhl, U., Westerhold, T., Bralower, T. J., and Zachos, J. C.: On the duration of the Paleocene–Eocene thermal maximum (PETM), *Geochem. Geophys. Geosy.*, 8, Q12002, doi:10.1029/2007GC001784, 2007.
- Sachse, D., Radke, J., and Gleixner, G.:  $\delta D$  values of individual *n*-alkanes from terrestrial plants along a climatic gradient—implications for the sedimentary biomarker record, *Org. Geochem.*, 37, 469–483, 2006.
- Schmiedl, G.: Late Quaternary benthic foraminiferal assemblages from the eastern South Atlantic: reconstruction of deep-water circulation and productivity changes, *Reports on Polar Research, Bremerhaven*, 160, 207 pp., (in German), 1995.
- Schmiedl, G. and Mackensen, A.: Late Quaternary paleoproductivity and deep water circulation in the eastern South Atlantic Ocean: evidence from benthic foraminifera, *Palaeogeogr. Palaeoclimatol.*, 130, 43–80, 1997.
- Schmiedl, G., De Bovee, F., Buscail, R., Charriere, B., Hemleben, C., Medernach, L., and Picon, P.: Trophic control of benthic foraminiferal abundance and microhabitat in the bathyal Gulf of Lions, western Mediterranean Sea, *Mar. Micropaleontol.*, 40, 167–188, 2000.

4252



- Schmitz, B. and Pujalte, V.: Sea-level, humidity, and land-erosion records across the initial Eocene thermal maximum from a continental-marine transect in northern Spain, *Geology*, 31, 689–692, 2003.
- Schmitz, B. and Pujalte, V.: Abrupt increase in seasonal extreme precipitation at the Paleocene–Eocene boundary, *Geology*, 35, 215–218, 2007.
- Schmitz, B., Pujalte, V., and Núñez-Betelu, K.: Climate and sea level perturbations during the initial Eocene thermal maximum: evidence from siliciclastic units in the Basque Basin (Ermua, Zumaia and Trabakua Pass), northern Spain, *Palaeogeogr. Palaeoecol.*, 165, 299–320, 2001.
- Schmitz, B., Asaro, F., Molina, E., Monechi, S., Von Salis, K., and Speijer, R.: High resolution iridium,  $\delta^{13}\text{C}$ ,  $\delta^{18}\text{O}$ , foraminifera and nannofossil profiles across the latest Paleocene benthic extinction event at Zumaya, *Palaeogeogr. Palaeoecol.*, 133, 49–68, 1997.
- Schoon, P. L., Heilmann-Clausen, C., Schultz, B. P., Sinninghe Damsté, J. S., and Schouten, S.: Warming and environmental changes in the eastern North Sea Basin during the Palaeocene–Eocene thermal maximum as revealed by biomarker lipids, *Org. Geochem.*, 78, 79–88, 2015.
- Secord, R., Gingerich, P. D., Lohmann, K. C., and MacLeod, K. G.: Continental warming preceding the Palaeocene–Eocene thermal maximum, *Nature*, 467, 955–958, 2010.
- Sgarrella, F., Sprovieri, F., Di Stefano, E., and Caruso, S.: Paleoceanography conditions at the base of the Pliocene in the Southern Mediterranean Basin, *Riv. Ital. Paleontol. S.*, 103, 207–220, 1997.
- Sing, R. K. and Gupta, A. K.: Late Oligocene–Miocene paleoceanographic evolution of the southeastern Indian Ocean: evidence from deep-sea benthic foraminifera (ODP Site 757), *Mar. Micropaleontol.*, 51, 153–170, 2004.
- Sluijs, A. and Brinkhuis, H.: A dynamic climate and ecosystem state during the Paleocene–Eocene Thermal Maximum: inferences from dinoflagellate cyst assemblages on the New Jersey Shelf, *Biogeosciences*, 6, 1755–1781, doi:10.5194/bg-6-1755-2009, 2009.
- Sluijs, A., Schouten, S., Pagani, M., Woltering, M., Brinkhuis, H., Sinninghe Damsté, J. S., Dickens, G. R., Huber, M., Reichart, G. J., and Stein, R.: Subtropical Arctic Ocean temperatures during the Palaeocene/Eocene thermal maximum, *Nature*, 441, 610–613, 2006.
- Sluijs, A., Bowen, G. J., Brinkhuis, H., Lourens, L. J., and Thomas, E.: The Paleocene–Eocene thermal maximum super greenhouse: biotic and geochemical signatures, age models and mechanisms of global change, in: *Deep-Time Perspectives on Climate Change: marrying*

4253

- the Signal From Computer Models and Biological Proxies, edited by: Williams, M., Haywood, A.M., Gregory, F. J., and Schmidt, D. N., *The Micropalaeontological Society Special Publication*, The Geological Society, London, 323–350, 2007a.
- Sluijs, A., Brinkhuis, H., Schouten, S., Bohaty, S. M., John, C. M., Zachos, J. C., Reichart, G.-J., Sinninghe Damsté, J. S., Crouch, E. M., and Dickens, G. R.: Environmental precursors to rapid light carbon injection at the Palaeocene/Eocene boundary, *Nature*, 450, 1218–1221, 2007b.
- Sluijs, A., Brinkhuis, H., Crouch, E. M., John, C. M., Handley, L., Munsterman, D., Bohaty, S. M., Zachos, J. C., Reichart, G., Schouten, S., Pancost, R. D., Sinninghe Damsté, J. S., Welters, N. L. D., Lotter, A. F., and Dickens, G. R.: Eustatic variations during the Paleocene–Eocene greenhouse world, *Paleoceanography*, 23, PA4216, doi:10.1029/2008PA001615, 2008.
- Sluijs, A., Bijl, P. K., Schouten, S., Röhl, U., Reichart, G.-J., and Brinkhuis, H.: Southern Ocean warming, sea level and hydrological change during the Paleocene–Eocene thermal maximum, *Clim. Past*, 7, 47–61, doi:10.5194/cp-7-47-2011, 2011.
- Smith, F. A. and Freeman, K. H.: Influence of physiology and climate on  $\delta\text{D}$  of leaf wax *n*-alkanes from C3 and C4 grasses, *Geochim. Cosmochim. Ac.*, 70, 1172–1187, 2006.
- Smith, F. A., Wing, S. L., and Freeman, K. H.: Magnitude of the carbon isotope excursion at the Paleocene–Eocene thermal maximum: the role of plant community change, *Earth Planet. Sc. Lett.*, 262, 50–65, 2007.
- Speijer, R. P., Schmitz, B., Aubry, M.-P., and Charisi, S. D.: The latest Paleocene benthic extinction event: punctuated turnover in outer neritic foraminiferal faunas from Gebel Aweina, Egypt, in: *Paleocene/Eocene Boundary Events in Space and Time*, edited by: Aubry, M.-P., and Benjamini, C., Israel, *J. Earth Sci.*, 44, 207–222, 1996.
- Speijer, R. P. and Schmitz, B.: A benthic foraminiferal record of Paleocene sea level and trophic/redox conditions at Gebel Aweina, Egypt, *Palaeogeogr. Palaeoecol.*, 137, 79–101, 1998.
- Speijer, R. P., Scheibner, C., Stassen, P., and Morsi, A.-M.: Response of marine ecosystems to deep-time global warming: a synthesis of biotic patterns across the Paleocene–Eocene thermal maximum (PETM), *Austrian Journal of Earth Sciences*, 105, 6–16, 2012.
- Stassen, P., Thomas, E., and Speijer, R. P.: The progression of environmental changes during the onset of the Paleocene–Eocene thermal maximum (New Jersey Coastal Plain), *Austrian Journal of Earth Sciences*, 105/1, 169–178, 2012a.

4254

- Stassen, P., Thomas, E., and Speijer, R. P.: Integrated stratigraphy of the Paleocene–Eocene thermal maximum in the New Jersey Coastal Plain: toward understanding the effects of global warming in a shelf environment, *Paleoceanography*, 27, PA4210, doi:10.1029/2012PA002323, 2012b.
- 5 Stassen, P., Thomas, E., and Speijer, R. P.: Paleocene–Eocene thermal maximum environmental change in the New Jersey Coastal Plain: benthic foraminiferal biotic events, *Mar. Micropaleontol.*, 115, 1–23, 2015.
- Stoll, H. M., Shimizu, N., Archer, D. E., and Ziveri, P.: Coccolithophore productivity response to greenhouse event of the Paleocene–Eocene thermal maximum, *Earth Planet. Sc. Lett.*, 258, 192–206, 2007.
- 10 Suhr, S. B., Pond, D. W., Gooday, A. J., and Smith, C. R.: Selective feeding by foraminifera on phytodetritus on the western Antarctic Peninsula shelf: evidence from fatty acid biomarker analysis, *Mar. Ecol.-Prog. Ser.*, 262, 153–162, 2003.
- Takata, H., Nomura, R., and Khim, B.-K.: Response to abyssal benthic foraminifera to mid-Oligocene glacial events in the eastern Equatorial Pacific Ocean (ODP leg 199), *Palaeogeogr. Palaeoclimatol.*, 292, 1–11, 2010.
- 15 Takeda, K. and Kaiho, K.: Faunal turnovers in central Pacific benthic foraminifera during the Paleocene–Eocene thermal maximum, *Palaeogeogr. Palaeoclimatol.*, 251, 175–197, 2007.
- Thiry, M.: Palaeoclimatic interpretation of clay minerals in marine deposits: an outlook from the continental origin, *Earth-Sci. Rev.*, 49, 201–221, doi:10.1016/S0012-8252(99)00054-9, 2000.
- 20 Thomas, D. J., Bralower, T. J., and Zachos, J. C.: New evidence for subtropical warming during the late Paleocene thermal maximum: stable isotopes from Deep Sea Drilling project site 527: Walvis Ridge, *Paleoceanography*, 14, 561–570, doi:10.1029/1999PA900031, 1999.
- 25 Thomas, D. J., Zachos, J. C., Bralower, T. J., Thomas, E., and Bohaty, S.: Warming the fuel for the fire: evidence for the thermal dissociation of methane hydrate during the Paleocene–Eocene thermal maximum, *Geology*, 30, 1067–1070, 2002.
- Thomas, E.: Late Eocene to Recent deep-sea benthic foraminifera from the central equatorial Pacific Ocean, in: *Initial Rep. Deep Sea*, edited by: Mayer, L., Theyer, F., Barron, J. A., Dunn, D. A., Handyside, T., Hills, S., Jarvis, I., Nigrini, C. A., Piasias, N. C., Pujos, A., Saito, T., Stout, P., Thomas, E., Weinreich, N., and Wilkens, R. H., 85, US Government Printing Office, Washington, 655–656, 1985.
- 30

4255

- Thomas, E.: Development of Cenozoic deep-sea benthic foraminiferal faunas in Antarctic waters, *Geol. Soc. Spec. Publ.*, 47, 283–296, 1989.
- Thomas, E.: Late Cretaceous through Neogene deep-sea benthic foraminifera (Maud Rise, Weddell Sea, Antarctica), in: *Proceedings of the Ocean Drilling Program, Scientific Results*, edited by: Barker, P. F., Kennett, J. P., O'Connell, S., Berkowitz, S., Bryant, W. R., Burckle, L. H., Egeberg, P. K., Fiitterer, D. K., Qersonde, R. E., Qolovchenko, X., Hamilton, N., Lawver, L., Lazarus, D. B., Lonsdale, M., Mohr, B., Nagao, T., Pereira, C. P. Q., Pudsey, C. J., Robert, C. M., Schandl, E., **Speijer, J. V.**, Stott, L. D., Thomas, E., Thompson, K. F. M., and Wise, S. W. Jr., 113, College Station, TX (Ocean Drilling Program), 571–594, 1990.
- 10 Thomas, E.: Biogeography of the late Paleocene benthic foraminiferal extinction, in: *Late Paleocene-Early Eocene Climatic and Biotic Events in the Marine and Terrestrial Records*, edited by: Aubry, M. P., Lucas, S., and Berggren, W., A., Columbia University Press, New York, 214–243, 1998.
- 15 Thomas, E.: Extinction and food at the seafloor: a high-resolution benthic foraminiferal record across the Initial Eocene thermal maximum, Southern Ocean site 690, in: *Causes and Consequences of Globally Warm Climates in the Early Paleogene*, edited by: Wing, S. L., Gingerich, P. D., Schmitz, B., and Thomas, E., *Geol. Soc. Am. S.*, Boulder, Colorado, The Geological Society of America, 369, 319–332, 2003.
- Thomas, E.: Cenozoic mass extinctions in the deep sea: What perturbs the largest habitat on Earth?, in: *Large Ecosystem Perturbations: Causes and Consequences*, edited by: Mon-echi, S., Coccioni, R., and Rampino, M., *Geol. Soc. Am. S.*, Boulder, Colorado, The Geological Society of America, 424, 1–23, 2007.
- 20 Thomas, E. and Gooday, A. W.: Cenozoic deep-sea benthic foraminifera: tracers for changes in oceanic productivity?, *Geology*, 24, 355–358, 1996.
- 25 Thomas, E. and Shackleton, N. J.: The Paleocene–Eocene benthic foraminiferal extinction and stable isotopes anomalies, *Geol. Soc. Spec. Publ.*, 101, 401–441, 1996.
- Thomas, E., Zachos, J. C., and Bralower, T. J.: Deep-Sea Environments on a Warm Earth: latest Paleocene-early Eocene, in: *Warm Climates in Earth History*, edited by: Huber, B., MacLeod, K., and Wing, S., Cambridge University Press, Cambridge, UK, 132–160, 2000.
- 30 Tipple, B. J., Pagani, M., Krishnan, S., Dirghangi, S. S., Galeotti, S., Agnini, C., Giusberti, L., and Rio, D.: Coupled high-resolution marine and terrestrial records of carbon and hydrologic cycles variations during the Paleocene–Eocene thermal maximum (PETM), *Earth Planet. Sc. Lett.*, 311, 82–92, 2011.

4256

- Tjalsma, R. C. and Lohmann, G. P.: Paleocene–Eocene bathyal and abyssal benthic foraminifera from the Atlantic Ocean, *Micropaleontology Special Publication*, 4, 1–90, 1983.
- Torrent, J., Barro, V., and Liu, Q.: Magnetic enhancement is linked to and precedes hematite formation in aerobic soil, *Geophys. Res. Lett.*, 33, L02401, doi:10.1029/2005GL024818, 2006.
- 5 Van Morkhoven, F. P. C. M., Berggren, W. A., and Edwards, A. S.: Cenozoic cosmopolitan deep-water benthic foraminifera, *B. Cent. Rech. Expl.*, 11, 1–421, 1986.
- Von Hillebrandt, A.: Das Paläozän und seine Foraminiferenfauna im Becken von Reichenhall und Salzburg, *Bayerische Akademie der Wissenschaften, Mathematisch-Naturwissenschaftliche Klasse, Abhandlungen, neue folge, München*, 108, 9–180, 1962.
- 10 Waškowska, A.: Response of early Eocene deep-water benthic foraminifera to volcanic ash falls in the Polish Outer Carpatians: palaeoecological implications, *Palaeogeogr. Palaeoecol.*, 305, 50–64, 2011.
- Wendler, I., Huber, B. T., MacLeod, K. G., and Wendler, J. E.: Stable oxygen and carbon isotope systematics of exquisitely preserved Turonian foraminifera from Tanzania – understanding isotopic signatures in fossils, *Mar. Micropaleontol.*, 102, 1–33, 2013.
- 15 Westerhold, T., Röhl, U., Laskar, J., Raffi, I., Bowles, J., Lourens, L. J., and Zachos, J. C.: On the duration of Magnetostratigraphic C24r and C25n, and the timing of early Eocene global warming events: implications from the ODP leg 208 Walvis Ridge depth transect, *Paleoceanography*, 22, PA2201, doi:10.1029/2006PA001322, 2007.
- 20 Wieczorek, R., Fantle, M. S., Kump, L. R., and Ravizza, G.: Geochemical evidence for volcanic activity prior to and enhanced terrestrial weathering during the Paleocene Eocene thermal maximum, *Geochim. Cosmochim. Ac.*, 119, 391–410, 2013.
- Wing, S. L., Harrington, G. J., Smith, F. A., Bloch, J. I., Boyer, D. M., and Freeman, K. H.: Transient floral change and rapid global warming at the Paleocene–Eocene boundary, *Science*, 310, 993–996, 2005.
- 25 Winguth, A. M. E., Shellito, C., Shields, C., and Winguth, C.: Climate response at the Paleocene–Eocene thermal maximum to greenhouse gas forcing – a model study with CCSM3, *J. Climate*, 23, 2562–2584, doi:10.1175/2009JCLI3113.1, 2010.
- Winguth, A. M. E., Thomas, E., and Winguth, C.: Global decline in ocean ventilation, oxygenation, and productivity during the Paleocene–Eocene thermal maximum: implications for the benthic extinction, *Geology*, 40, 263–266, 2012.
- 30 Zachos, J. C., Pagani, M., Sloan, L. C., Thomas, E., and Billups. K.: Trends, rhythms, and aberrations in global climate 65 Ma to present, *Science*, 292, 686–693, 2001.

4257

- Zachos, J. C., Schouten, S., Bohaty, S., Quattlebaum, T., Sluijs, A., Brinkhuis, H., Gibbs, S. J., and Bralower, T. J.: Extreme warming of mid latitude coastal ocean during the Paleocene–Eocene thermal maximum: inferences from TEX86 and isotope data, *Geology*, 34, 737–740, 2006.
- 5 Zachos, J. C., Röhl, U., Schellenberg, S. A., Sluijs, A., Hodell, D. A., Kelly, D. C., Thomas, E., Nicolo, M., Raffi, I., Lourens, L. J., Mccarren, H., and Kroon, D.: Rapid acidification of the ocean during the Paleocene–Eocene thermal maximum, *Science*, 308, 1611–1615, 2015.
- Zeebe, R. E., Zachos, J. C., and Dickens, G. R.: Carbon dioxide forcing alone insufficient to explain Paleocene–Eocene thermal maximum warming, *Nat. Geosci.*, 2, 576–580, 2009.
- 10 Zeebe, R. E., Dickens, G. R., Ridgwell, A., Sluijs, A., and Thomas, E.: Onset of carbon isotope excursion at the Paleocene–Eocene thermal maximum took millennia, not 13 years (Comment), *P. Natl. Acad. Sci. USA*, 111, E1062–E1063, doi:10.1073/pnas.1321177111, 2014.
- Zhang, Y., Ji, J., Balsam, W. L., Liu, L., and Chen, J.: High resolution hematite and goethite records from ODP 1143, South China Sea: co-evolution of monsoonal precipitation and El Niño over the past 600,000 years, *Earth Planet. Sc. Lett.*, 264, 136–150, 2007.
- 15 Zhou, X., Thomas, E., Rickaby, R. E. M., Winguth, A. M. E., and Lu, Z.: I/Ca evidence for global upper ocean deoxygenation during the Paleocene–Eocene thermal maximum (PETM), *Paleoceanography*, 29, 964–975, doi:10.1002/2014PA002702, 2014.

4258