The magnitude of ocean warming across the Paleocene-Eocene Boundary

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Acknowledgements:
Steven Bohaty, Clay Kelly, Appy Sluijs, Cedric John, Heather McCarren,
Stephen Schellenberg, Tina Nielsen, Henk Brinkhuis,
Stefan Schouten, Samantha Gibbs, Thomas Quattlebaum
Greenhouse Climate Sensitivity?

- $pCO_2 > 800$ ppm
Carbon Dioxide and Climate (0-65 Mya)

IPCC Report, 2007
Deep-sea (Benthic Foram.) Isotope Record

Epochs
Paleocene
Eocene

Chrons
50
52
54
56
58
60

$\delta^{13}C$

$\delta^{18}O$

PETM

higher org. carbon burial
Cold
Warm

5 pt running mean
P-E Deep-sea Isotope Excursion

$\Delta \delta^{13}C = 3.0\%o$

$\Delta T = +5^\circ C$
Paleocene-Eocene Thermal Maximum (PETM) ~ 55 Mya

Characterized by:

- Extreme and rapid (~10-20 kyr) warming;
  - ~5 to 9°C Tropic/Polar SST, +4-5°C deep sea

Temperature anomalies estimated from $\delta^{18}$O, Mg/Ca, and TEX$_{86}$ Proxies
PETM Continental Climate Response

- Bighorn Basin, WY
Transient Floral Change and Rapid Global Warming at the Paleocene-Eocene Boundary

Scott L. Wing¹*, Guy J. Harrington², Francesca A. Smith¹,³, Jonathan I. Bloch⁴, Douglas M. Boyer⁵, Katherine H. Freeman³
Transient Mega-Flora of the Paleocene-Eocene Thermal Maximum

Lower PETM Flora
- Increased Aridity

Upper PETM Flora
- Increased Humidity “Sub-tropical”
P-E Deep-sea Isotope Excursion

$\Delta^{13}C = 3.0\%$

$\Delta T = +5^\circ C$
Massive Release of Carbon: Sources?

- **Decomposition of Methane Hydrate** - (Dickens et al., 1996)
  - bacteria, $\delta^{13}C = -60\%$
  - 2000-3000 PgC (Archer & Buffet, 2004)

- **Mantle Plume/Mid-ocean Ridge Volcanism** - CH$_4$/CO$_2$
  - (Svensen et al., 2004)
  - Thermal Corg decomposition, $\delta^{13}C = -7$ to $-25\%$
  - 0.1-0.5 PgC/y

- **Dessication & Oxidation of Corg (soils/sediments)** - CO$_2$
  - Forest peats/bogs/swamps/other? - $\delta^{13}C = -20\%$
  - 5000-10,000 PgC
Theoretical Carbon Inputs for Rapid, Global Negative $\delta^{13}$C Excursions

Ocean Acidification

nannofossil ooze

dusky-red clay

nannofossil ooze

Zachos, Kroon, Blum et al. (2004)
Key Questions:

• The total mass of carbon released?
• How fast?
• Trigger?
• Climatic response (sensitivity) - Ocean Temperature
Key Questions:

• **Climatic response (sensitivity)?**

• **Open Ocean SST**
  – Oxygen Isotopes
  – Mg/Ca

• **Coastal SST**
  – Oxygen Isotopes
  – Mg/Ca
  – TEX$^{86}$
Late Paleocene (~55 Mya)

ODP Site 690, Maud Rise
ODP Site 690

Kennett & Stott, 1991; Kelly et al, 2005

$\delta^{13}C$ (‰)  $\delta^{18}O$ (‰)

~180 kyr

Mbsf

benthic foram.

thermocline planktonic foram.

mixed-layer planktonic foram.

+9°C
Mixed layer
Thermocline
Benthic

Site 690 (~2000 m), Maud Rise

Depth (Mbsf)

Single shell isotopes
• Mixed Layer Plank.
• Thermocline Plank.
• Benthic Foraminifera

Source: Thomas et al., Geology, 2002
Single shell isotopes
- Mixed Layer Plank.
- Thermocline Plank.
- Benthic Foraminifera

Nielsen et al. (submitted)
1. Gradual warming triggers methane hydrate dissociation (~ $10^2$ Gt in $10^2$ yr, ~ $10^3$ Gt in $10^3$ - $10^4$ yr)
2. Oxidation and mixing (atmosphere and mixed layer)
3. Deep mixing (~$10^3$ y)
Climate Sensitivity: Quantifying the change in SST
PETM SST Anomaly (°C)

Temperature anomalies estimated from oxygen isotope, Mg/Ca, and TEX$_{86}$ Proxies
PETM: California and New Jersey

A) The Late Paleocene world

B) Paleogeography and location of Panoche Hills in the Paleocene

C) New Jersey Coastal Plains (Bass River and Wilson Lake)

John et al., submitted
PETM: Shelf vs. Pelagic

John et al., submitted
Wilson Lake, NJ

- USGS Core (*T. Gibson, 2000*)
- Inner Shelf Facies; unconsolidated siliciclastic sands & clay
  - Kaolinite rich
- P-E boundary is conformable
- Unconformity in the lower Eocene truncates upper portion of CIE
- Dinoflagellate blooms
- Foraminifera - scarce, but well preserved
Distributional variations in marine crenarchaeotal membrane lipids: a new tool for reconstructing ancient sea water temperatures?

Stefan Schouten *, Ellen C. Hopmans, Enno Schefuß, Jaap S. Sinninghe Damsté

Royal Netherlands Institute for Sea Research, Department of Marine Biogeochemistry and Toxicology, P.O. Box 59, 1790 AB Den Burg, Texel, The Netherlands

![Graph showing correlation of TEX86 with annual mean SST](image)

**correlation of TEX86 from surface sediments with annual mean SST**
TEX$_{86}$/SST Calibration Curve

Correlation of TEX86 from surface sediments with annual mean SST:

- Linear or non-linear at high T?
- Regression between 20-28°C (Schouten et al., 2003)
δ\(^{18}\)O	TEX

SST\(^{\text{Paleoc}}\) 23°	25°

SST\(^{\text{Eocen}}\) 33°	33°

ΔSST 10°	8°

Zachos et al., 2006
Bass River, NJ

Caption:

- Cibicidoides spp.
- Subbotina triangularis
- Acarinina spp.
- Morozavella group
- Bulk rock
- Bulk

John et al., submitted
Bass River, NJ

- Siliciclastic Shelf Sequence
- Multiple δ^{13}C Records
  - Foraminifera
  - Bulk CaCO_3
  - Bulk Organic
  - Dinoflagellates
- Multiple SST Proxies
  - Oxygen Isotope
  - TEX_{86}

Sluijs et al., submitted
• Multiple/Single Shell Isotope Data

Zachos et al. (in press)
P-E Single Shell Isotope Data

Zachos et al. (in press)
Bass River, NJ

Sluijs et al., in prep.

Initial Warming Leads the CIE!?!
QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.
PETM: California and New Jersey

Figure 1

John et al., submitted
Lodo Gulch, CA
Toomey Gulch, CA
Sluijs et al. (2006)
Arctic Core (ACEX)

Sluijs et al. (2006)
Paleocene-Eocene Thermal Maximum (PETM) ~ 55 Mya

Temperature anomalies estimated from $\delta^{18}O$, Mg/Ca, and TEX$_{86}$ Proxies
PETM: California

C. John et al, in prep
Surface Temperature Response to Greenhouse Forcing

- Coupled atmosphere/ocean climate model (NCAR CSM (v.1.2))
- Warming at all latitudes in response to a rise in atmospheric $p$CO$_2$
- Polar amplification?
- Tropical SST?
- Annual (model) vs. Seasonal (data)?
PETM Summary

- SST anomaly of 5 to 9°C
- Peak SST
  - Mid latitudes ~ 28-33°C
  - Arctic ~ >20°C
  - Southern Ocean - >20°C
  - Tropics - ?
- Couple ocean/atmosphere models
  - Higher sensitivity?
Enhanced Climate Sensitivity?

- Biogeochemical feedbacks & trace gasses
Process Based Climate Models

- Sources and sinks of traces gasses

Climate Model
Hadley Centre HadSM3

Vegetation/Carbon Cycle Model
Sheffield Dynamic Veg. Model

Temperature Precipitation etc.

Trace gas biogeochemistry emissions models
CH$_4$ $f$(water table, tmp, veg. activ.) (Cao et al., 1996)
VOCs $f$(foliage dens., tmp, veg. type, PAR) (Guenther et al., 1995)
NO$_x$ $f$(tmp, ppt, veg. type) (Yienger & Levy, 1995)
NO$_x$ Lightning production $f$(conv. ppt)

Three dimensional atmospheric chemistry model
STOCHEM

Equilibrium chemical state of the atmosphere

Courtesy P. Valdes & D. Beerling
Modelled Net Primary Productivity

Pre-industrial: 53 Gt C yr\(^{-1}\)

Eocene: 114 Gt C yr\(^{-1}\)

Valdes & Beerling (2006);
Also see A42B-04
Eocene
Trace Gas Emissions
Simulated sources of trace gases

<table>
<thead>
<tr>
<th>Trace gas</th>
<th>Cool-SSTs</th>
<th>Warm-SSTs</th>
<th>Pre-industrial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total CH$_4$ emissions</td>
<td>616</td>
<td>795</td>
<td>159</td>
</tr>
<tr>
<td>(Tg CH$_4$ yr$^{-1}$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Isoprene</td>
<td>1605</td>
<td>2561</td>
<td>199</td>
</tr>
<tr>
<td>Monoterpene (Tg C yr$^{-1}$)</td>
<td>213</td>
<td>144</td>
<td>591</td>
</tr>
<tr>
<td>Soil NO$_x$</td>
<td>6.9</td>
<td>10.8</td>
<td>5.0</td>
</tr>
<tr>
<td>Lightning NO$_x$ (Tg N yr$^{-1}$)</td>
<td>6.3</td>
<td>7.4</td>
<td>4.2</td>
</tr>
</tbody>
</table>

Valdes & Beerling (2006);
Also see A42B-04
CO$_2$ induced warming impacts N$_2$O and tropospheric O$_3$

N$_2$O increases from 277 to 453 ppbv

Ozone increases by ~20%

Global warming of ~4.5$^\circ$C
Regional warming up to ~10$^\circ$C

*Valdes & Beerling (2006)*; *Also see A42B-04*
N. Atlantic Volcanism & C-outgassing

• Greenland Rifts from Europe (51-59 Ma)
• Iceland Plume/Rapid Rift Propagation

\[ \sim 55.4 \text{ Ma} \]

Storey, Duncan, & Swisher (in press)
Atmosphere/Surface Ocean $\delta^{13}C$
1350-2000 A.D.

$\delta^{13}C = -20\%$

Ocean Uptake
$\sim 123$ PgC

Böhm et al., 2002
The Next 1000 years?
Emissions, $pCO_2$, & Ocean pH

Consequences?

- Transient, Extreme Global Warming
- Increased dissolution of carbonate in the water column & on the seafloor
- Extinction of calcifying organisms??

Caldeira & Wickett, 2003
Paleocene-Eocene Thermal Maximum (PETM) ~ 55 Mya

Characterized by:

- Extreme and rapid (~10-20 kyr) warming;
  - ~5 to 10°C tropic/Polar SST, +4-5°C deep sea
- Elevated humidity/precipitation in mid- to high latitudes
- Changes in the diversity and distribution of marine and terrestrial biota
  - Expansion of tropical/subtropical fauna/flora into high latitudes
  - Mammalian dispersal/faunal reorganization
  - Mass extinction - calcareous benthic foraminifera
- Evidence of a “Large” perturbation to the global carbon cycle
  - Carbon isotope excursion (CIE)
Reconstructing Ocean History with Stable Isotopes of Microfossils in Deep-sea Sediments

Foraminifera shells ~ calcite (CaCO₃)

Mass Spectrometers

CO₂

Isotopes:

Notation:

\[ \delta^{13}C, \delta^{18}O \]

\[ \frac{^{13}C}{^{12}C}, \frac{^{18}O}{^{16}O} \]

\[ \delta^{13}C\text{ (‰)}, \delta^{18}O\text{ (‰)} \]

\[ \Delta \text{Ocean Temperature} \]

As T increases, \( \delta^{18}O \) decreases 1‰ ~ 4°C

Dissolved inorganic carbon (DIC) of seawater. Mean \( \delta^{13}C_{DIC} \) of the ocean varies with changes in the input and output of reduced and oxidized carbon

Mixed layer planktonic foraminifera

Benthic foraminifera
ODP Leg 198
*Shatsky Rise*

ODP Leg 208
*Walvis Ridge*
PETM Section
Hole 1209B - Shatsky Rise

• Lithology
  - nannofossil ooze
• paleodepth (55 Ma): ~2000 m
• paleolatitude (55 Ma): 15-20°N
• Sampling

*M. velascoensis*  *A. soldadoensis*
Shatsky Rise, Western Pacific
ODP Leg 198 Sites
The Paleocene-Eocene Thermal Maximum on Shatsky Rise

_Hole A_ Hole B

Site 1209 2387 m

Site 1211 2907 m

Site 1212 2681 m

Site 1210 2573 m

Site 1208 3346 m

_Bralower, Premoli-Silva, Malone, et al. (2002)_

**ODP Leg 198, Shatsky Rise PE Boundary Depth Transect**
Hole 1209B, Shatsky Rise

- M. velascoensis
- A. soldadoensis

Source: Zachos et al., Science, 2003
Carbon Mass & Climate Sensitivity (CO₂ doubling)

- Is the climate (T) response consistent with the mass of carbon released?
ODP Leg 208, Walvis Ridge
PE Boundary Depth Transect

Zachos, Kroon, Blum et al. (2004)
Modern Ocean - %CF (>63µm) / Carbonate Ion [CO₃] Relationship

Broecker et al., 1999

Increasing dissolution

Less Plankton Shells

More Plankton Shells
CO$_3$ Supersaturation: “Coccolith Deluge”

Kelly, Zachos et al. (in prep)
CO₂ Absorption and Ocean Acidification

Archer, 2004

No CaCO₃ deposition

Archer, 2004
Deep Sea Sediments:
Archive of Ocean History

Microfossil shell chemistry provides information on ocean temperature & carbon chemistry

Foraminifera tests ~ calcite (CaCO₃)
### Paleocene-Eocene Boundary (55 Mya)

<table>
<thead>
<tr>
<th>EON</th>
<th>ERA</th>
<th>PERIOD</th>
<th>MILLIONS OF YEARS AGO</th>
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<tr>
<td></td>
<td>Cenozoic</td>
<td>Quaternary</td>
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<td>Tertiary</td>
<td>66</td>
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<td>Mesozoic</td>
<td>Cretaceous</td>
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<td>Permian</td>
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<td>Mississippian</td>
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<td>Cambrian</td>
<td>570</td>
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<tr>
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<td>Proterozoic</td>
<td>Late Proterozoic</td>
<td>2500</td>
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<td>Early Proterozoic</td>
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</tr>
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<td>Archean</td>
<td>Late Archean</td>
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<td>Middle Archean</td>
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</tr>
<tr>
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<td>Early Archean</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pre-Archean</td>
<td></td>
<td>3800?</td>
</tr>
</tbody>
</table>

- **Quaternary**: 1.6 Mya
- **Eocene**: 55 Mya
- **Oligocene**: 33 Mya
- **Miocene**: 23 Mya
- **Pliocene**: 5 Mya
- **Pleistocene**: 1.8 Mya
- **Cenozoic**: 66 Mya

**Millions of years ago**
Are there other data that can be used to constrain changes in deep sea carbonate ion concentration?
An Ancient Carbon Mystery

Mark Pagani, Ken Caldeira, David Archer, James C. Zachos

Sudden global warming 55 million years ago provides evidence for high climate sensitivity to atmospheric CO₂, but the source of the carbon remains enigmatic.

About 55 million years ago, Earth experienced a period of global warming that lasted ~170,000 years (1). This climate event—the Paleocene-Eocene Thermal Maximum (PETM)—may be the best ancient analog for future increases in atmospheric CO₂. But how well do we understand this event?

Temperature records from the tropics to the poles indicate that at the start of the PETM, global temperatures increased by at least 5°C in less than 10,000 years (2). The rise in surface temperature was associated with changes in the global hydrological cycle (3) and a large decrease in the ¹³C/¹²C ratio of marine (4) and terrestrial carbonates.
Atmospheric CO\(_2\): the last 1006 years

Anthropogenic CO\(_2\) flux (+380 PgC; \(\delta^{13}C=-20\%\))
CO₂ Absorption and Ocean Acidification

Archer, 2004

No CaCO₃ deposition

Archer, 2004
Bass River, NJ
• Salisbury Embayment
• Middle Shelf Facies; unconsolidated siliciclastic silts & clay
  • Kaolinite rich
• ~30 m/m.y.
• P-E boundary is conformable
• CIE
• Foraminifera - scarce, but well preserved
Surface Ocean $[\text{CO}_3^{2-}]$ Saturation State

Orr et al. (2005)
Calcareous (Algae) Nannofossil Abundances

ODP 1263

Raffi et al. (in prep)
Shatsky Rise, Western Pacific
ODP Leg 198 Sites
PETM Section
Hole 1209B - Shatsky Rise

- Lithology
  - nannofossil ooze
- paleodepth (55 Ma): ~2000 m
- paleolatitude (55 Ma): 15-20°N
- Mixed-layer foraminifera

\[ M. \text{velascoensis} \quad A. \text{soldadoensis} \]
Mass Extinction of Calcifying Benthic Foraminifera

ODP Site 1209, Shatsky Rise, Pacific

P-E Boundary

(Takeda, Kahio, et al. in prep)
Lysocline and CCD Variations Across the P-E Boundary: Inferences From Leg 208 Sites

- Bulk Sediment Carbon Isotope Stratigraphies
  - Site to Site Correlation
- Age Model
  - Site 690: Orbital vs. Helium
- % CaCO$_3$
- % Coarse Fraction

Photo Courtesy: K.C. Lohmann
Methane Hydrate Contribution to Anthropogenic CO$_2$

Graphs showing the impact of different carbon releases on pCO$_2$ and ocean temperature change:

- **Graph a:**
  - 300 Gton C Anthropogenic Release
  - pCO$_2$ over time
  - Two scenarios: Clathrates and No Clathrates

- **Graph b:**
  - 2000 Gton C Anthropogenic Release
  - pCO$_2$ over time
  - Two scenarios: Clathrates and No Clathrates

- **Graph c:**
  - Ocean T Change, °C
  - Two scenarios: Clathrates and No Clathrates

- **Graph d:**
  - Ocean T Change, °C
  - Two scenarios: Clathrates and No Clathrates

Time from Present, kyr
The Paleocene-Eocene Thermal Maximum on Shatsky Rise

Site 690 and Leg 198 Sites

Source: Kahio et al., 2006
ODP Leg 208, Walvis Ridge
PE Boundary Depth Transect

Zachos, Kroon, Blum et al. (2004)
CO₂ Absorption and Ocean Acidification

Archer, 2004

No CaCO₃ deposition

Archer, 2004
Late Paleocene (~55 Mya)

ODP Site 690, Maud Rise
At 5000 PgC
Loss of sea-floor carbonate increases atmospheric load

Archer, 2004
PETM: Source of Carbon?

1. Pattern & rate of ocean carbonate changes consistent with absorption of large mass of carbon 55 Mya
   - >4500 Gt in 20 ky

2. Marine $\delta^{13}C$ excursion ~4‰

3. Excludes hydrates as sole source of carbon

4. Positive feedbacks
   - Dessication/soil organics/swamps
   - Hydrates