An abyssal carbonate compensation depth overshoot in the aftermath of the Paleocene-Eocene Thermal Maximum

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During the Paleocene-Eocene Thermal Maximum (PETM) about 56 million years ago, thousands of petagrams of carbon were released into the atmosphere and ocean in just a few thousand years, followed by a gradual sequestration over approximately 200,000 years. If silicate weathering is one of the key negative feedbacks that removed this carbon, a period of seawater calcium carbonate saturation greater than pre-event levels is expected during the event's recovery phase. In marine sediments, this could be recorded as a temporary deepening of the depth below which no calcite is preserved - the calcite compensation depth (CCD). Previous and new sedimentary records from sites that were above the pre-PETM calcite compensation depth show enhanced carbonate accumulation following the PETM. A new record from an abyssal site in the North Atlantic that lies below the pre-PETM calcite compensation depth shows a period of carbonate preservation beginning about 70,000 years after the onset of the PETM, providing the first direct evidence for an over-deepening of the calcite compensation depth. This record confirms an overshoot in ocean carbonate saturation during the PETM recovery.

Simulations with two earth system models support scenarios for the PETM that involve both a large initial carbon release followed by prolonged low-level emissions, consistent with the timing of CCD deepening in our record. Sequestration of these emissions was most likely the result of both globally enhanced calcite burial above the calcite compensation depth and, at least in the North Atlantic, by a temporary over-deepening of the calcite compensation depth.

The Paleocene-Eocene Thermal Maximum (PETM; ~56 Ma) represents one of the largest and most abrupt greenhouse warming events in Earth history. Marine and terrestrial records document a global >2.5‰ negative carbon isotope excursion (CIE)[1-3] coincident with global mean surface ocean warming of >4°C[4] and geochemical and sedimentological evidence for ocean acidification[5,6]. Collectively, these lines of evidence suggest a rapid (10^3-10^4 years) and massive (~3,000-10,000 PgC) release of ^{13}C-depleted carbon into the ocean-atmosphere system[7-9]. The PETM thus offers the opportunity to examine the response and recovery of the global carbon cycle and seawater carbonate chemistry to an ancient CO_2 release similar in magnitude to ongoing anthropogenic fossil fuel combustion[10].

Current understanding of long-term carbon cycle processes predicts that rapid carbon injection should cause a short-term (0-10^4 years) period of ocean acidification featuring reduced seawater carbonate saturation (Ω), followed by a longer-term (10^4-10^5.years) period of carbonate oversaturation due to elevated terrestrial silicate weathering rates (see Box 1). This carbonate saturation overshoot manifests itself in several carbon cycle model simulations of the PETM[9,11] as an over-deepening of the CCD

relative to its pre-event depth. Yet no records exist from abyssal sites below the pre-PETM CCD with which to detect possible CCD over-deepening. Sedimentary records from above the CCD (Southern Ocean Site 690 [12-15] at ~1900m paleodepth and South Atlantic Sites 1263[5,14,15] at ~1500m paleodepth and 1266[5,16] at ~2500m paleodepth) show increases in $CaCO_3$ content and accumulation rate during and after the PETM recovery[13-15]. These supra-CCD records are consistent with weathering feedbacks prompting increased carbonate burial during the PETM recovery, and provide important constraints because the long-term requirement to balance the elevated weathering flux only requires carbonate burial to increase globally (not necessarily buried at deeper depths). It is thus theoretically possible to accommodate such elevated global carbonate burial without substantial deepening of the CCD[17]. Nonetheless, some models[9-11] predict that a testable facet of the recovery process from massive carbon cycle perturbation involves an over-deepening of the CCD, and the location of these sites above the pre-PETM CCD means that they cannot directly test for this predicted CCD over-deepening. Direct observational evidence from sites sufficiently deep to test for a post-PETM CCD overshoot has thus far remained elusive.

New records from the North Atlantic

Here we present lithology, $CaCO_3$ content, and carbon isotope ($\delta^{13}C$) records from recently recovered sediment cores in the North Atlantic (IODP Sites U1403, PETM paleodepth ~4374m and U1409, paleodepth ~2913m[18]) that provide important constraints on the evolution of the CCD through the PETM, including the first evidence for CCD over-deepening during the PETM recovery. To explore the broader implications of these records for PETM carbon emissions scenarios, we present new carbon release

experiments using two carbon cycle models – LOSCAR[9,19] and cGENIE[20,21] and discuss uncertainties in the representation of geological carbon cycling in current models.

At Site U1409, the PETM CIE occurs in an interval of variously silicified sediments (siliceous claystones, siliceous limestones and cherts) at 178.9-179.2 mcd (Figure 1A), contrasting with the nannofossil chalk that characterizes much of the Paleogene at this site[18]. Although likely somewhat condensed, the $\delta^{13}C_{carb}$ record bears the typical[15] PETM CIE pattern of an abrupt decrease (here of ~2‰) followed by a plateau of low values and then gradual recovery (Fig. 1). Bulk $\delta^{13}C_{carb}$ over the PETM CIE interval sampled a heterogeneous mixture of lithology (clay, carbonate-rich burrows within that clay, and siliceous sediments), with all three lithologies revealing significantly lower $\delta^{13}C$ within the CIE than pre-event values. The integrity of the bulk $\delta^{13}C_{carb}$ record is also supported by the close structural similarity between it and the equivalent bulk $\delta^{13}C_{carb}$ records from the Southern Ocean and Walvis Ridge (Fig. 1, 2A). The Site U1409 $\delta^{13}C$ record from benthic foraminifera is discontinuous owing to silicification across the onset and initial recovery, but minimum values within the CIE show a large (~3‰) excursion, similar to that seen in benthic records from the Southern Ocean[22] and South Atlantic[23]. Below the CIE, carbonate content is between 60-70 wt%, decreases to a minimum of ~40 wt% at the CIE onset, and rebounds to ~70% following the CIE. This pattern is similar to other pelagic PETM sections[24] and implies that the local CCD was always deeper than the paleodepth of Site U1409, while the decrease in carbonate during the PETM can be interpreted as a transient decrease in the calcite saturation state, Ω, consistent with shoaling of the CCD. The absence of near-0 wt% $CaCO_3$ sediment at Site U1409 contrasts with records from the South Atlantic Ocean[5] where cores even shallower

than U1409 are barren of carbonate within the CIE. Although this observation could imply that CCD shoaling in the North Atlantic was less dramatic than that in the South Atlantic, hiatuses, bioturbation by burrowing, or incomplete recovery of this silicified interval could have obscured or resulted in the loss of the interval containing the lowest wt% $CaCO_3$ values. Regardless, carbonate content and accumulation rate at Site U1409 were higher during the PETM recovery than before the event, similar to other sites at mid-ocean depths or shallower[5,12-14,16], thus providing support for elevated saturation states and increased carbonate burial above the CCD during the recovery phase.

Lower abyssal Site U1403 features a prominent transition (over ~5 cm) from carbonate-poor (<0.5 wt%) claystone in the Upper Paleocene (extending from the P-E boundary to at least ~61 Ma[18]) to carbonate-bearing (~20-30 wt%) nannofossil claystone in the lower Eocene (Figure 1B). This carbonate-rich interval contains calcareous nannofossils of zone NP9B, including PETM excursion taxa *Discoaster araneus* and *Rhomboaster* spp[18]. Bulk $\delta^{13}C_{org}$ reveals a negative CIE between 200.7 and 201.5 mcd that is superimposed on comparatively high amplitude orbital timescale variability in the late Paleocene. The $\delta^{13}C_{carb}$ record necessarily begins at the onset of carbonate sedimentation with low values of ~0.6‰, followed by a gradual 1.4‰ increase over the next ~1.6 m, parallel to the recovery in $\delta^{13}C_{org}$. Given the simultaneous trends to higher values in both $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ within zone NP9B, this $\delta^{13}C$ increase can be unambiguously assigned to the PETM CIE recovery. The magnitude of the $\delta^{13}C_{carb}$ increase (1.4‰) is close to the full amplitude of the PETM CIE recovery observed in bulk carbonates globally[15] and at Site U1409 (Figure 2A), so we confidently assign the onset of carbonate sedimentation at Site U1403 to early in the PETM recovery phase.

We construct age models by correlating the $\delta^{13}C_{carb}$ records to a compilation of bulk and fine-fraction $\delta^{13}C_{carb}$ on an orbitally calibrated age model[15] (Figure 2A and 2C). This age model, based on several PETM sites, produces a shorter duration of the PETM CIE than extraterrestrial ^{3}He-based estimates,[12,16] so durations here may represent minima. On this timescale, carbonate sedimentation begins at Site U1403 ~70kyr after the PETM onset and is followed by a period of elevated (20-40) wt% $CaCO_3$ that persists for a further ~150kyr. Fluctuations between 5 and 25 wt% $CaCO_3$ continue throughout the lower Eocene. Although the CIE onset at Site U1403 (as defined by the somewhat noisy $\delta^{13}C_{org}$ record) introduces some uncertainty around the placement of the P-E boundary, this does not affect the relative timing of the initial appearance of carbonate at this lower abyssal site, which is unambiguously assigned to the PETM recovery interval based on $\delta^{13}C_{carb}$ and the occurrence of PETM excursion-interval calcareous nannofossils.

The pattern of carbonate sedimentation at Site U1403 (carbonate-barren in the Paleocene with carbonate appearing during the PETM recovery) has not previously been observed in sediments spanning the PETM. The absence of carbonate in the Upper Paleocene and into the earliest Eocene indicates the CCD lay shallower than Site U1403 before the PETM and through the CIE onset and body. The onset of carbonate sedimentation ~70kyr after the PETM onset indicates that the CCD over-deepened to below the ~4400 m lower abyssal paleo-water depth of Site U1403 during the early phase of PETM recovery – direct evidence for a post-PETM CCD overshoot. The ~150kyr period of elevated carbonate deposition at Site U1403 represents the main phase of the CCD over-deepening, and is coeval with enhanced carbonate accumulation and

preservation at shallower paleodepths documented here at Site U1409 and elsewhere[5,13,14,16] (Figure 2D). These observations strongly implicate elevated whole-ocean saturation state as the cause of enhanced carbonate burial at all water depths and from the North Atlantic to the Southern Ocean.

Implications of a CCD overshoot explored with carbon cycle models

To explore the implications of a CCD overshoot and its timing, and the CCD over-deepening at U1403 in particular, we tested a variety of PETM carbon emissions scenarios using the models LOSCAR and cGENIE. Rather than carry out an extensive sweep of all combinations of plausible size and duration of carbon release, our emissions scenarios are based on ref. [9], characterized by an initial C input ($\delta^{13}C$ = -50‰) of 3000 PgC over 5 kyr, followed by 1480 PgC over 50 kyr, and originally developed to best match records of carbonate dissolution (particularly in the South Atlantic[5]). However, we explored a number of variations on this basic emissions trajectory (Figs. S4-S15) such as doubling the total mass with half the isotopic composition ($\delta^{13}C$ = -25‰). In order to isolate the response of carbonate burial dynamics from circulation effects that might diverge in the two models, we ran cGENIE with radiative forcing (and thus ocean circulation) fixed, and for direct comparison with cGENIE (Figure 3) we omitted the prescribed circulation changes of ref. 9 in LOSCAR. We tracked the evolution of global sedimentary wt% $CaCO_3$ preserved, and simulated the expected marine sediment record in modeled 'cores' at North Atlantic depths approximating Sites U1409 and U1403.

The configurations of both LOSCAR and cGENIE models used here include a CO_2-dependent silicate weathering feedback (see methods). Both models simulate a global CCD and wt% $CaCO_3$ overshoot which occurs between 20 and 45 kyr after the

onset of carbon emissions and peaks between 65 and 97 kyr after the onset, depending on the emissions schedule and model (Figure 3 and Figure S3)[9,11]. The carbonate overshoot begins earlier when the carbon pulse occurs over a shorter interval of time (Figures S6, S12). The long delay (~70kyr) in the onset of carbonate sedimentation at Site U1403 that we infer from our age model is hence difficult to reconcile with only a short "spike" of carbon released at the onset of the PETM. Rather, the delay is better explained by a sustained release of carbon lasting many tens of kyr after an initial spike (Figure 3, S1), consistent with the conclusions of refs. [9] and [6]. Such sustained carbon release might arise as a feedback response to initial warming[25,26] or represent prolonged North Atlantic volcanism. Our experiments also demonstrate that the timing of the overshoot is not particularly sensitive to the mass of carbon released – doubling the mass of carbon results in < 2 kyr delay in overshoot timing (e.g. Figure S4 vs. Figure S5).

While both models generate a whole-ocean carbonate burial overshoot during the recovery interval, the spatial distribution of $CaCO_3$ content in sediments shows differences both between the models and in comparison to Sites U1403 and U1409 (Figure 3). Because LOSCAR has much coarser spatial resolution (e.g. it represents the deep Atlantic as a single box), regional patterns need to be interpreted with greater caution. Nevertheless, LOSCAR generates a deep (4500m) $\%CaCO_3$ overshoot comparable to that seen at Site U1403, but in shallow sediments (3000m) generates a larger $\%CaCO_3$ decrease (to near-zero) and smaller overshoot than seen at Site U1409. In contrast, cGENIE closely matches the Site U1409 record, but at 5000m, sediments overshoot their pre-event $\%CaCO_3$ levels by only ~1%. It appears that in response to enhanced weathering-driven elevated saturation states, LOSCAR accommodates greater

194 global carbonate burial with higher %$CaCO_3$ in deep sediments (an over-deepening of the
195 CCD), whereas cGENIE accommodates greater global carbonate burial predominantly
196 within and above the lysocline. Observational evidence (in the form of new and previous
197 carbonate accumulation rate records) suggest that in the real world (at least in the case of
198 the PETM), both of these processes may operate.

199 The differences between the models' predictions for the locus of intensified
200 carbonate burial result from of how the models represent sedimentary processes. In
201 cGENIE, the respiration of organic carbon in sediments reduces porewater saturation
202 state and dissolves $CaCO_3$ even in shallow sediments well above the carbonate saturation
203 horizon. Because of this, those shallow sediments have greater potential to accommodate
204 an increase in $CaCO_3$ content in response to higher bottom water saturation state such as
205 that seen in the aftermath of the PETM. cGENIE thus balances enhanced weathering flux
206 via elevated carbonate burial mostly in shallow sediments (within and above the
207 lysocline)[17]. Conversely, %$CaCO_3$ in sediments above the lysocline in LOSCAR is set by
208 the ratio of clay to $CaCO_3$ in the sediment rain (81% $CaCO_3$ in the present
209 configuration)[19], so when saturation state increases those shallow sediments cannot
210 accommodate higher $CaCO_3$ contents (they are already at a maximum). Hence, LOSCAR
211 balances an increase in weathering flux via enhanced carbonate burial within the
212 lysocline and below the (pre-event) CCD.

213 A notable aspect of the Site U1403 carbonate record is that following the main
214 phase of the CCD over-deepening featuring the highest carbonate contents, wt% $CaCO_3$
215 does not return to 0% (its pre-event level) before the next major hyperthermal (ETM-2,
216 ~2Myr later[18]) (Fig. 1, 2). Hence, the North Atlantic CCD did not return to its pre-PETM

state. Two possible explanations exist for this observation. First, negative feedbacks on carbonate undersaturation could have been very slow to re-establish equilibrium. This is unlikely, given that all other records of environmental and carbon-cycle perturbation during the PETM (such as temperature[4], pH[27], and the CIE[15]) recovered in hundreds of thousands of years, not millions. Second, the carbon cycle might have transitioned to a new equilibrium state featuring a deeper CCD. Several mechanisms may help explain a deeper post-PETM equilibrium CCD in the North Atlantic. Importantly, the PETM CCD evolution may have been superimposed on a long-term (multi-million year) global CCD deepening trend[28-31]. Increasing pCO_2 on multi-million year timescales across the Late Paleocene-Early Eocene from greater volcanic CO_2 release or an imbalance between terrestrial C_{org} oxidation and marine C_{org} burial could have strengthened weathering rates, thus increasing seawater carbonate saturation and driving a gradual CCD deepening from ~58 to ~52Ma, independently of the PETM[28]. Indeed, LOSCAR simulations of carbon release superimposed on gradual long-term CCD deepening (Figure S2) agree well with observations from Site U1403, including the persistence of the overshoot.

Changing ocean circulation or regional carbonate export across the PETM might have also affected the regional North Atlantic CCD (i.e. the observed CCD over-deepening was not necessarily global). Weakened North Atlantic-sourced overturning during the acidification phase followed by strengthened overturning during the oversaturation phase could have produced the initial large CCD shoal documented at Walvis Ridge[5] (South Atlantic) and the later CCD over-deepening at Site U1403 (North Atlantic). If such circulation changes persisted for several Myr, they could have produced a persistently deeper post-PETM North Atlantic CCD. Spatial benthic $\delta^{13}C$ gradients can

shed light on circulation changes[22], because the accumulation of respired C_{org} reduces the $\delta^{13}C$ of deep water DIC as it ages. Owing to its location in the lower abyss, Site U1403 is unfortunately nearly barren of benthic foraminifera throughout the PETM and its recovery. However, Site U1409 benthic $\delta^{13}C$ values overlap with those of South Atlantic[23] and Southern Ocean[22] during intervals immediately prior to the PETM and during the later stages of the recovery, including the time interval (>110kyr after the event) during which Site U1403 documents a CCD overshoot (Figure 2). Benthic gradients between the South and North Atlantic therefore do not show any evidence for large-scale changes in Atlantic overturning circulation during the PETM recovery that could have contributed to a localized CCD over-deepening.

Other processes could have also contributed to CCD over-deepening during the PETM recovery, specifically those processes that could have removed carbon from the ocean/atmosphere and increase seawater pH and saturation state (in a sense, the opposite of the PETM acidification phase), and hence influence the CCD. In particular, studies have suggested that the pace of the CIE recovery, which is complete within ~150kyr[12,16], is too rapid to be explained by enhanced weathering and carbonate burial alone. Instead, the preferential removal of ^{12}C via enhanced burial of organic carbon (C_{org}) has been proposed to explain the CIE recovery timing[32]. This is consistent with evidence of increased marine productivity during the PETM from elevated biogenic barium accumulation rates[33,34] and coccolith Sr/Ca[35]. Our model experiments focus on the long-term inorganic carbon cycle and silicate weathering and hence cannot exclude a role for enhanced organic carbon burial.

In summary, our finding of a post-PETM CCD overshoot in the North Atlantic Ocean constitutes the first evidence for post-PETM variations in carbonate burial from sediments deeper than the pre-PETM CCD. It thus represents an important constraint on the vertical extent of the CCD's response to carbon release during the PETM and consequently, the processes responsible for restoring the carbon cycle to steady state. It is tempting to use this constraint to directly calculate the mass of carbon released during the PETM because the excess carbonate burial should scale with the mass of carbon released. However, we recognize that one site does not fully constrain the global extent of the overshoot, nor its absolute magnitude. Further constraints on the CCD over-deepening from even deeper water depths and additional ocean basins are therefore an essential target for future scientific drilling. Additionally, uncertainty in the strength of the silicate weathering feedback (Figure S2)[36] as well as the potential influences of initial carbon cycle conditions, circulation changes, C_{org} burial, and changing clay flux preclude explicit calculation of the total carbon release[10]. Indeed, the differing responses of the two different global carbon cycle models we have tested against the observations underscore the lack of consensus on how the marine carbonate carbon sink responds in detail (and particularly in the depth distribution of $CaCO_3$ burial) to perturbation. Multiple combinations of mass and rate of carbon release, weathering feedback strength, and C_{org} burial are consistent with the new observations described here. Our findings nevertheless provide an important constraint on how carbon was sequestered in the aftermath of the PETM, an event that continues to guide our understanding of Earth system processes and feedbacks during large-scale carbon cycle perturbations.

Author Contributions: DEP, SKT, PFS, RDN, and SB conceived the study and participated in IODP Expedition 342 that recovered and described the sediments used here. DEP generated carbonate stable isotope analyses in the lab of JCZ, and AJD generated organic carbon stable isotope and Coulormat %$CaCO_3$ analyses. XRF scanning records were generated by SKT at Scripps, and AC, PFS, TW, and UR at MARUM. DEP and SKT performed the carbon cycle modeling with guidance from REZ and AR. DEP wrote the manuscript with help from SKT and PFS, and all authors edited the manuscript.

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METHODS

Geochemical analyses

During IODP Expedition 342, drilling operations penetrated the P-E boundary at Sites U1403 (39°56.5997N, 51°48.1998W, 4946m depth) and U1409 (41°17.7501N, 49°13.9996W, 3502m depth). Shipboard investigation described lithology, identified the approximate positions of the P-E boundary by nannofossil biostratigraphy, and provided coarse-resolution records of wt% $CaCO_3$. The surface of core archive halves spanning the PETM were scanned at 1-2 cm-resolution at the MARUM – Center for Marine Environmental Sciences, University of Bremen and at Scripps Institution of Oceanography using Avaatech X-ray fluorescence (XRF) core scanners. Estimates of the total abundance of calcium (Ca) and iron (Fe) were obtained by scanning cores at an energy level of 10kV, current of 500 uA, count time of 20 sec, and measurement area of

10 x 12 mm. Estimated wt% $CaCO_3$ records were generated by regressing shipboard wt% $CaCO_3$ measurements[18] against the natural logarithm of XRF-derived Ca/Fe ratios. For stable isotope analyses, samples were collected at ~5cm resolution from Site U1409 and 10cm resolution from Site U1403, freeze dried, homogenized with mortar and pestle, and analyzed for $\delta^{13}C_{carb}$ on a ThermoFisher MAT 253 stable isotope mass spectrometer coupled to a Kiel IV carbonate device using standard dual-inlet techniques (typical long-term $\delta^{13}C_{carb}$ reproducibility of carbonate standards is < ±0.05‰, 1 S.D.) In addition, samples from Site U1409 were washed and sieved, and specimens of the benthic foraminifera *Nuttalides truempyi* were picked from the 150-200 and 212-300μm size fraction. Where possible, 3-8 of these specimens from each sample were run using the $\delta^{13}C_{carb}$ methods described above. For $\delta^{13}C_{org}$ analysis of Site U1403, homogenized sample powders were de-carbonated in 1M HCL and washed in de-ionized water. $\delta^{13}C_{org}$ was measured using a Thermo-Finnegan MAT 253 mass spectrometer coupled to a Thermo Scientific 2000 HT elemental analyzer via a Conflo IV interface optimized for the measurement of samples with low organic carbon abundances. Analytical reproducibility was monitored using analyses of IAEA CH-6 sucrose and was < ±0.1‰ (1 S.D). All $\delta^{13}C$ data are expressed relative to V-PDB. Additional Site U1403 wt. % $CaCO_3$ was measured using a Strohlein Coulormat.

Carbon cycle modeling

LOSCAR is a numerically-efficient geochemical box model of the marine carbon cycle with realistic interaction with sediments, capable of multi-million year simulations of carbon cycle processes including CCD depth. All runs use Paleogene LOSCAR setup[19]. Code availability: the C code for the LOSCAR model can be obtained from

author REZ upon request (zeebe@hawaii.edu). cGENIE is an intermediate-complexity Earth system model including a 3-D dynamic ocean model with biogeochemical cycling of key elements and isotopes and a spatially resolved sediment model capable of generating virtual sediment cores – synthetic stacks of deep-sea sediments[20,21,37]. We use the late Paleocene/early Eocene configuration of ref. [38]. For this study, we evaluate virtual sediment core results from a depth transect in the North Atlantic ranging from 5000-3000 m water depth and at locations corresponding to Expedition 342 sites.

Both models include carbonate and silicate weathering feedbacks. In LOSCAR, weathering is parameterized as $F_w = F_{eq} * ([CO_2]_{atm} / [CO_2]_{eq})^{Nsi}$, where F_{eq} and $[CO_2]_{eq}$ are equilibrium weathering flux and atmospheric pCO_2 at which volcanic carbon emissions are perfectly balanced by silicate weathering and carbonate burial[19]. N_{Si} sets the strength of the silicate weathering feedback (default $N_{Si} = 0.2$). We implement the same formulation for a CO_2-dependent carbonate and silicate weathering feedback in cGENIE using a model for terrestrial rock weathering[39]. Following ref. [40], we assume carbonate weathering proportional to the square root of $[CO_2]_{atm} / [CO_2]_{eq}$ and silicate weathering proportional to $[CO_2]_{atm} / [CO_2]_{eq}$ raised to the power of 0.3. We assume a 50:50 split between carbonate and silicate weathering in order to match total carbonate burial, and balance silicate weathering with volcanic outgassing. We utilize the cGENIE and LOSCAR models in this study in order to qualitatively demonstrate what mechanisms are consistent with the new data, not in an attempt to reconstruct exactly a PETM scenario.

Data: Accompanying data can be found at [PANGEA web address forthcoming]

FIGURE CAPTIONS

Figure 1: Lithology and $\delta^{13}C$ over the PETM at Sites U1409 (A) and U1403 (B) plotted against composite depth (mcd). Each panel shows core photo (Site U1403 vertically compressed), lithologic description, calcareous nannofossil biostratigraphy, wt. %$CaCO_3$ estimated by XRF scanning data (black line), and bulk $\delta^{13}C_{carb}$ (blue line). Lithology codes for Site U1409: NC = nannofossil chalk, CNC = clayey nannofossil chalk, SL = siliceous limestone, Cl = claystone, SC = siliceous claystone, Ch = chert. Bulk $\delta^{13}C_{org}$ (green line) and wt. % $CaCO_3$ measured with a Coulormat device (black X's) are also shown for Site U1403, and benthic foraminifer *Nuttalides truempyi* $\delta^{13}C$ (red squares) is shown for Site U1409. The heterogeneous mixture of clay- and carbonate-rich facies within the CIE at Site U1409 is interpreted as carbonate-rich burrows within clay-rich sediments, with both recording low (<0.5‰) bulk $\delta^{13}C$. Depth intervals representing the Paleocene, CIE, Recovery, and post-PETM based on $\delta^{13}C$ stratigraphy are highlighted with grey, red, orange, and white shaded bars, respectively. PETM phases nomenclature from ref. 15.

Figure 2: Age models and PETM isotopic and sedimentological records from new and previous sites. A: Bulk $\delta^{13}C_{carb}$ records from Sites 690[13], 1263[15], U1403, and U1409 plotted on the age model used in this study. B: Weight %$CaCO_3$ of Sites U1403 and U1409 (this study), 690[13], and 1263[5]. C: Linear sedimentation rates used in age models constructed by this study for Sites U1403 and U1409, and Sites 690 and 1263 from Röhl, et al. [15] D: Carbonate mass accumulation rate calculated from dry bulk density, sedimentation rates (C), wt. % $CaCO_3$ (B). E: Comparison of benthic foraminifer $\delta^{13}C$

from South Atlantic Site 1263,[23] Southern Ocean Site 690,[22] and U1409 demonstrating small and constant North-South aging gradient during the CCD overshoot. Green bars indicate silicified intervals at Site U1409 which precluded measurement of benthic foraminifers. In (B), (D) and (E), the silicified interval of U1409 is marked with a dashed line to reflect potential hiatuses or incomplete recovery which may have resulted in an incomplete %$CaCO_3$ record (see text).

Figure 3: Comparison of LOSCAR and cGENIE C release experiments using the Emissions scenario of ref. 9 with radiative forcing (and thus circulation) fixed in cGENIE, and no circulation changes in LOSCAR. Top panel: Emissions scenario. Middle panel: modeled 3000m sediment core-top %$CaCO_3$ compared with Site U1409 %CaCO3 record. Bottom panel: modeled 4500m (LOSCAR) and 5000m (cGENIE) sediment core-top %$CaCO_3$ compared with Site U1403 %CaCO3 record. In middle and bottom panels, thin, opaque traces mark pre-event %$CaCO_3$ for cGENIE and LOSCAR.

Box 1: The ocean's two-phase response to rapid carbon injection

Current understanding of long-term carbon cycle processes suggests that large-scale carbon injection into the ocean-atmosphere should induce a two-phase response in ocean carbonate saturation. Initially, rapid invasion of CO_2 into the ocean lowers pH and carbonate saturation state (Ω) in tandem[6,38,41], resulting in dissolution of both newly deposited and pre-existing carbonate sediments[5]. The result is a dramatic reduction in $CaCO_3$ burial in marine sediments globally and, in places, evidence for a shoaling of the

399 calcite compensation depth (CCD, the depth below which no calcium carbonate, in the
400 form of calcite, is preserved).[5,24,42].

401 A second phase of carbonate saturation and burial response arises from elevated
402 atmospheric pCO_2 and increased global temperatures that are thought to drive an increase
403 in the rate of terrestrial carbonate and silicate rock chemical weathering[43,44], which can be
404 generalized:

405 $$CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^- \quad (1)$$

406 $$CaSiO_3 + 2CO_2 + 3H_2O \rightarrow Ca^{2+} + 2HCO_3^- + H_4SiO_4 \quad (2)$$

407 Accelerating these reactions increases the delivery of Ca^{2+} (and thus total alkalinity, TA)
408 and dissolved inorganic carbon (DIC) to the oceans, elevating Ω. An intensification of
409 continental weathering during the PETM is supported by a pronounced increase in the
410 $^{187}Os/^{188}Os$ of seawater[45,46] and an increase in kaolinite in marine sediments[47]. However,
411 although the silicate weathering rate responds quickly to increased temperature/CO_2, the
412 rate of CO_2 drawdown from global weathering (~ 0.1 PgC/yr[41]) is small in comparison to
413 estimates of initial carbon release (thousands of PgC)[7-9], meaning that this feedback
414 should take $>10^4$ years to gradually overcome the undersaturation associated with the
415 initial acidification phase[11,48,49]. On longer timescales ($>10^5$ years)[49], this increased
416 weathering-derived flux of TA and DIC to the oceans must be balanced by carbonate
417 production and burial to balance the ocean's alkalinity budget:

418 $$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O \quad (3)$$

419 The long-term balance of carbonate weathering with carbonate burial has no permanent
420 effect on the ocean's TA or DIC budgets (Equation 1 is simply the reverse of Equation 3).
421 However, the long-term balance of silicate weathering (Equation 2) with carbonate burial

(Equation 3) gives rise to a net consumption of CO_2 that is buried as $CaCO_3$ sediment – the long-term fate of carbon released during the PETM.

The assumption that net CO_2 consumption via elevated silicate weathering and carbonate burial (Equation 2+3) is responsive to perturbations in climate forms the basis of a proposed long-term negative (stabilizing) feedback on climate, hypothesized to have been important in maintaining a habitable climate throughout Earth history[43,44] and specifically during the PETM recovery[11]. One way in which global carbonate burial could respond to changing weathering flux is through fluctuations of the global sea-floor area of carbonate-free sediments (i.e. the CCD). In other words, during the initial acidification phase, carbonate undersaturation leads to a reduced $CaCO_3$ sink and a short-term shoaling of the CCD, whereas on longer timescales (>10^5 years), faster weathering rates lead to carbonate oversaturation and increased carbonate burial, which might be reflected in an over-deepening of the CCD[10,11,50]. The interval of excess (compared to pre-PETM) $CaCO_3$ burial primarily reflects the removal of carbon released at the onset of the PETM by enhanced silicate weathering, together with the quantity of $CaCO_3$ dissolved during the initial carbonate undersaturation phase and additional terrestrial weathering of carbonate rocks under warmer temperatures (both of which will be some function of CO_2 release). The characteristics of any post-PETM CCD overshoot hence potentially hold key information regarding the magnitude of carbon release and the processes involved in the recovery from an abrupt carbon cycle perturbation.

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