

LETTERS

Subtropical Arctic Ocean temperatures during the Palaeocene/Eocene thermal maximum

Appy Sluijs^{1*}, Stefan Schouten^{2*}, Mark Pagani³, Martijn Woltering², Henk Brinkhuis¹, Jaap S. Sinninghe Damsté^{2,4}, Gerald R. Dickens⁵, Matthew Huber⁶, Gert-Jan Reichert⁴, Ruediger Stein⁷, Jens Matthiessen⁷, Lucas J. Lourens⁴, Nikolai Pedentchouk³, Jan Backman⁸, Kathryn Moran⁹ & the Expedition 302 Scientists†

The Palaeocene/Eocene thermal maximum, ~55 million years ago, was a brief period of widespread, extreme climatic warming^{1–3}, that was associated with massive atmospheric greenhouse gas input⁴. Although aspects of the resulting environmental changes are well documented at low latitudes, no data were available to quantify simultaneous changes in the Arctic region. Here we identify the Palaeocene/Eocene thermal maximum in a marine sedimentary sequence obtained during the Arctic Coring Expedition⁵. We show that sea surface temperatures near the North Pole increased from ~18 °C to over 23 °C during this event. Such warm values imply the absence of ice and thus exclude the influence of ice-albedo feedbacks on this Arctic warming. At the same time, sea level rose while anoxic and euxinic conditions developed in the ocean's bottom waters and photic zone, respectively. Increasing temperature and sea level match expectations based on palaeoclimate model simulations⁶, but the absolute polar temperatures that we derive before, during and after the event are more than 10 °C warmer than those model-predicted. This suggests that higher-than-modern greenhouse gas concentrations must have operated in conjunction with other feedback mechanisms—perhaps polar stratospheric clouds⁷ or hurricane-induced ocean mixing⁸—to amplify early Palaeogene polar temperatures.

Stable carbon isotope ($\delta^{13}\text{C}$) records of carbonate and organic carbon from numerous sites show a prominent negative carbon isotope excursion across the Palaeocene/Eocene thermal maximum (PETM)^{2,9}. The carbon isotope excursion is expressed as a >2.5‰ drop in $\delta^{13}\text{C}$, which signifies an input of at least 1.5×10^{18} g of ^{13}C -depleted carbon, somewhat analogous in magnitude and composition to current and expected fossil fuel emissions. The PETM captures ~200 kyr (ref. 10) and is associated with profound environmental changes that are well-documented at low- to mid-latitudes (<60°), including a 4–8 °C temperature rise of surface and deep ocean waters^{1–3} and major terrestrial and marine biotic changes^{11–13}. Terrestrial mammal turnovers are consistent with mass migrations across Arctic regions resulting from high-latitude warming¹⁴, but no Arctic data have existed to evaluate this hypothesis.

The Integrated Ocean Drilling Program Expedition (IODP) 302 (or the Arctic Coring Expedition) recently recovered a Palaeogene marine sedimentary record from Hole 4A (~87° 52.00' N; 136° 10.64' E; 1,288 m water depth), on the Lomonosov ridge in

the central Arctic Ocean⁵. This ridge represents a fragment of continental crust that rifted from the Eurasian shelf margin at high latitudes (>85°; Fig. 1) during the latest part of the Palaeocene epoch and subsided to present depths after the Palaeocene. Upper Palaeocene and Lower Eocene sediments between approximately 406 and 263 m composite depth below sea floor (m.c.d.) at Hole 4A consist of organic-rich (~2% total organic carbon (TOC) by mass on average) siliciclastic claystone⁵. Shipboard observations showed that this interval is barren of calcareous and siliceous microfossils but yields rich assemblages of palynomorphs, notably organic-walled dinoflagellate cysts (dinocysts) and terrestrial pollen and spores⁵.

The PETM was identified from the top of Core 32X to within Core

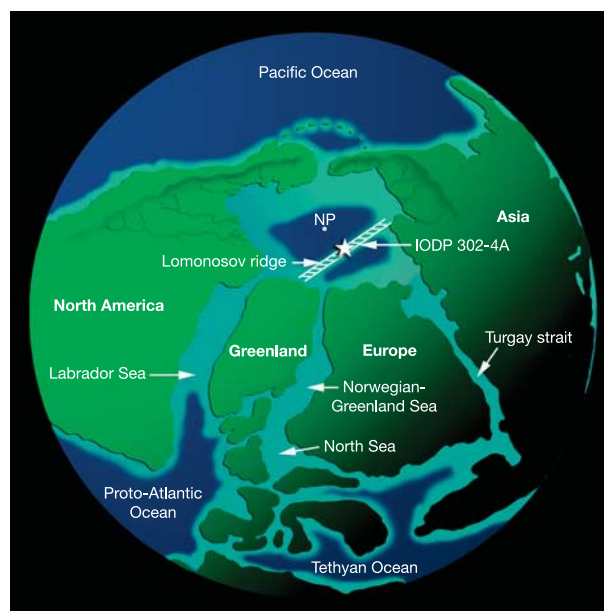


Figure 1 | Location of IODP Hole 302-4A within the palaeogeographic reconstruction of the Arctic Basin at late Palaeocene-early Eocene times. The figure is modified from ref. 24. NP, North Pole.

¹Palaeoecology, Institute of Environmental Biology, Utrecht University, Laboratory of Palaeobotany and Palynology, Budapestlaan 4, 3584 CD Utrecht, The Netherlands. ²Royal Netherlands Institute for Sea Research (NIOZ), Department of Marine Biogeochemistry and Toxicology, PO Box 59, 1790 AB, Den Burg, Texel, The Netherlands. ³Department of Geology and Geophysics, Yale University, PO Box 208109, New Haven, Connecticut 06520, USA. ⁴Department of Earth Sciences, Utrecht University, Budapestlaan 4, 3584 CD Utrecht, The Netherlands. ⁵Department of Earth Sciences, Rice University, 6100 Main Street, Houston, Texas 77005, USA. ⁶Earth and Atmospheric Sciences Department and the Purdue Climate Change Research Center, Purdue University, 550 Stadium Mall Drive, West Lafayette, Indiana 47906, USA. ⁷Alfred-Wegener-Institute for Polar and Marine Research, Columbusstrasse, 27568 Bremerhaven, Germany. ⁸Department of Geology and Geochemistry, Stockholm University, Stockholm, SE-106 91, Sweden. ⁹University of Rhode Island, Bay Campus, Narragansett, Rhode Island 02882, USA.

*These authors contributed equally to this work.

†A list of authors and affiliations appears at the end of the paper.

29X (~387–378.5 m.c.d.) by the occurrence of the dinocyst species *Apectodinium augustum*, which is diagnostic of the PETM¹⁵ (Fig. 2; Supplementary Fig. S-1a). The lower bound is somewhat problematic, though, because the upper 50 cm of Core 32X has been disturbed by drilling and various proxies suggests that the sediment from this interval represents a mixture of uppermost Palaeocene and PETM material¹⁶. Moreover, only 55 cm of section was recovered of the critical Core 31X, which has an uncertain stratigraphic position relative to Cores 30X and 32X (see error bars in Fig. 2 and Supplementary Information). Stable carbon isotopes of bulk organic carbon ($\delta^{13}\text{C}_{\text{TOC}}$) show a prominent ~6‰ drop between the top of Core 32X (388 m.c.d.) and 31X (~386 m.c.d.), apart from one value from the disturbed zone, followed by a gradual recovery through Cores 30X and 29X to ~378.5 m.c.d. (Fig. 2). The $\delta^{13}\text{C}_{\text{TOC}}$ pattern is generally reproduced in the carbon isotope record of the C_{27} and C_{29} *n*-alkanes, which are biomarkers derived from the leaf waxes of terrestrial higher plants¹⁶. Despite the core gaps, the magnitude and shape of the $\delta^{13}\text{C}_{\text{TOC}}$ excursion resembles other shallow marine PETM sections, such as Doel in Belgium¹⁷, confidently correlating this interval to the Palaeocene/Eocene boundary event.

Before the PETM, *Apectodinium* was a subtropical dinoflagellate restricted to low latitudes^{11,15}. Thus, the sudden influx of *Apectodinium* spp. dinocysts across the PETM at Hole 4A (Fig. 2) suggests a substantial rise in Arctic sea surface temperature (SST) to subtropical or tropical levels. Angiosperm pollen becomes more abundant at the expense of spores and gymnosperm pollen (Fig. 2), suggesting an expanded growing season. The lack of calcareous microfossils prohibits the use of the common techniques for quantifying past SSTs. Instead, we employed the newly developed palaeothermometer TEX_{86}' (see Supplementary Information), which is based on the distribution of crenarchaeotal membrane lipids¹⁸. This distribution is independent of surface water parameters such as nutrient availability or salinity^{18,19}, and shows a highly significant linear correlation with present-day mean annual SST in the range of 10 to 28 °C (Supplementary Fig. S-2B). Because the export of crenarchaeotal lipids to the sea floor predominantly occurs during the season with

highest phytoplankton productivity, which in the Arctic Ocean is summer, our TEX_{86}' record is probably skewed towards summer temperatures (see also Supplementary Information).

Arctic SSTs rose from ~18 °C in the latest Palaeocene, to over 23 °C during the PETM, and subsequently decreased to ~17 °C by the end of the event (Fig. 2). Background SSTs from the latest Palaeocene and early Eocene are generally consistent with the few other proxy data estimates from Arctic locations with late Cretaceous and early Palaeogene strata^{20–22}. The significantly lower terrestrial temperature estimates from Ellesmere Island at 73°N palaeolatitude²³ are derived from upper Lower Eocene strata and are similar to TEX_{86} -derived SSTs in the Arctic Ocean for that time period²⁴; these estimates are thus not in disagreement with our data. Maximum SSTs coincide with minimum $\delta^{13}\text{C}$ values during the PETM, while the cooling trend mirrors the recovery pattern in $\delta^{13}\text{C}$ and a decrease of angiosperm pollen.

Several lines of evidence (Fig. 2) suggest that the location of Hole 4A was proximal to the coast and strongly influenced by fluvial inputs in the latest Palaeocene. For example, palynomorph assemblages from upper Palaeocene strata are dominated by terrestrial spores and pollen (~90%). Those samples with sufficient dinocysts yield abundant *Senegalinium* spp. and *Cerodinium* spp. (Supplementary Fig. S-1), which probably come from dinoflagellates that tolerated low surface-water salinities²⁴ and required nutrient-rich conditions²⁵. Sediments from this interval also contain abundant amorphous organic matter, presumably of terrestrial origin. Moreover, values of the Branched and Isoprenoid Tetraether (BIT) index—a measure for the amount of river-derived terrestrial organic matter relative to marine organic matter²⁶—are relatively high.

In contrast to uppermost Palaeocene sediments, palynomorph assemblages from the PETM interval are characterized by abundant dinocysts (60%) and substantially lower BIT indices (Fig. 2), indicating a relative decrease of riverine-derived organic carbon. Also, the increase in the Rock Eval hydrogen index suggests a relative increase in aquatic versus terrestrial organic matter (Supplementary Fig. S-3A). We attribute the enhanced influence of marine conditions during the

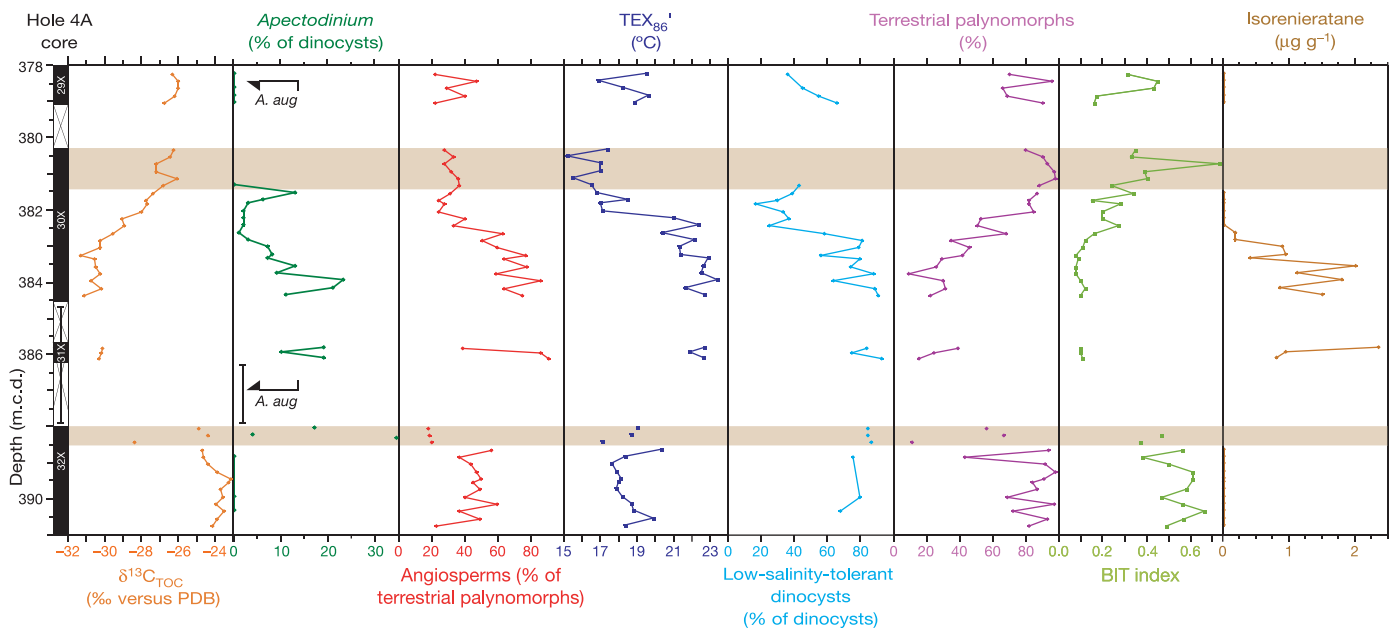


Figure 2 | Core recovery and palynological and geochemical results across the PETM of IODP Hole 302-4A. Core 31X was plotted 100 cm lower than m.c.d.⁵ for illustration purposes. Error bars connected to Core 31X in the recovery column indicate the uncertainty of its stratigraphic position (see Supplementary Information). Orange bars indicate intervals affected by drilling disturbance. Stable carbon isotopes are expressed relative to the

PeeDee Belemnite standard. Low-salinity-tolerant dinocysts comprise *Senegalinium* spp., *Cerodinium* spp., and *Polysphaeridium* spp., while *Membranosphaera* spp., *Spiniferites ramosus* complex, and *Areoligera-Glaphyrocysta* cpx. represent the typical normal marine species²⁵ (Supplementary Fig. S-1). Arrows and *A. aug* indicate the first and last occurrences of dinocyst *Apectodinium augustum*.

PETM to a sea level rise, an interpretation consistent with evidence from other neritic locations²⁷. The gradual return to more terrestrial influence later in the event probably results from subsequent regression. Despite the transgression, low-salinity-tolerant dinocysts remain dominant (Fig. 2), showing that brackish surface waters persisted during the PETM. If the earliest Palaeogene greenhouse world was continental-ice-free, a mechanism for the sea-level rise may comprise the ~5 m thermal expansion of sea water expected from a 5–8 °C (refs 2, 3) increase in deep ocean temperatures.

The occurrence of laminated sediments from the onset of the PETM (although hardly visible in Core 31X due to its disturbed state) up to 382.5 m.c.d., and the absence of benthic foraminiferal linings (Supplementary Fig. S–3A) suggest that bottom waters became anoxic during the PETM. Within the laminated interval, derivatives of the characteristic pigment isorenieratene are recorded in concentrations of up to 2 µg g⁻¹ sediment; they are below the detection limit outside this interval (Fig. 2; Supplementary Fig. S–3). These compounds are derived from the brown strain of photosynthetic green sulphur bacteria, which requires euxinic (anoxic and sulphidic) conditions to thrive²⁸. Accordingly, at the PETM photic zone euxinia developed at the drill site coincident with bottom water anoxia, which gradually disappeared during the recovery of SST and δ¹³C excursion (Fig. 2).

We can exclude selective preservation as a mechanism to explain the marked changes in organic biomarkers and palynomorph assemblages that occur in coincidence with water column anoxia. First, the preservation of organic matter is also excellent outside the laminated interval (>2% TOC on average; Supplementary Fig. S–3A) and second, most of our proxies compare the relative abundance of structurally similar organic compounds that are equally susceptible to oxidation (see Supplementary Information).

The euxinic conditions were potentially caused by several factors. For example, increased freshwater input, greater nutrient load and warmer temperatures would all conspire to reduce dissolved O₂ in the water column. However, given the shallow water depth of the site, an important factor was probably intense stratification due to the influence of a brackish surface-water lid. Although several mechanisms could drive such stratification, given that low-salinity-tolerant dinocysts remain dominant despite the more distal position of the site, and given the data presented in a companion paper¹⁶, the simplest explanation is that decreased mixing resulted from increased SSTs and enhanced fluvial runoff, with the latter also supplying extra nutrients to increase production and saturate photic zone respiration. The termination of euxinic conditions coincides with increasing surface salinities¹⁶ (Fig. 2) and cooling, suggesting an increase of mixing with more-saline deeper waters.

Even if we assume that our TEX₈₆' temperatures represent summer values (see Supplementary Information), palaeoclimate models simulating the early Palaeogene world with 2,000 p.p.m.v. of CO₂ in the atmosphere⁶ underestimate Arctic Ocean summer SSTs by at least 15 °C for the PETM and 10 °C for the surrounding late Palaeocene and early Eocene. This discrepancy may be even larger because the initial part of the PETM, and potentially also the strata formed under maximum temperatures, were possibly not recovered (Fig. 2). On the other hand, the magnitude of the carbon isotope excursion is comparable to previous studies and peak PETM temperatures lagged the onset of the carbon isotope excursion by ~40 kyr (ref. 1), indicating that optimum Arctic SSTs are probably covered in our record.

The models consistently predict pole-to-Equator temperature gradients of ~30 °C (ref. 29). Such gradients represent significant overestimates because they would imply unrealistically warm tropical SSTs considering our polar temperatures. The high polar temperatures and reduced pole-to-Equator temperature gradients cannot be explained by invoking even greater greenhouse gas concentrations because this would elevate tropical SSTs, which in existing model predictions already match or exceed those determined from proxy

records at low-latitude locations⁶. Also, ocean heat transport is unlikely to be the cause because this requires a threefold increase, which cannot be simulated in the current generation of fully coupled ocean–atmosphere climate models²⁹. Similarly, atmospheric general circulation models do not support strong enough positive feedbacks in atmospheric heat transport³⁰. Consequently, we surmise that physical processes that are not yet incorporated in the models operated in conjunction with high greenhouse gas concentrations to enhance polar warmth and reduce the pole-to-Equator temperature gradient during the early Palaeogene. These processes could include high-latitude warming and tropical cooling through the enhancement of polar stratospheric clouds⁷, and hurricane-induced ocean mixing⁸, respectively.

With latest Palaeocene SSTs of 18 °C it is not likely that ice was present in the Arctic. This implies that the PETM at Hole 4A allows us to examine the Arctic environment and the nature of polar amplification during a time of massive greenhouse gas emissions and extreme global warming in the absence of ice-albedo feedbacks. Interestingly, polar amplification of temperature rise at the PETM appears to have been minor (Fig. 2; refs 1–3), suggesting that the strengthening of the mechanism that caused above early Palaeogene polar temperature amplification was small at the PETM. Our extremely warm polar temperatures indicate that, despite much recent progress, feedbacks responsible for early Palaeogene mid- to high-latitude warmth remain poorly understood and are not implemented in existing climate models.

METHODS

Palynology. Sediments were oven-dried at 60 °C. To ~2 g of sediment, a known amount of *Lycopodium* spores were added, after which the sample was treated with 30% HCl and twice with 30% HF for carbonate and silicate removal, respectively. After sieving over a 15-µm nylon mesh sieve, residues were analysed at 500 × magnification until a minimum of 200 dinocysts had been recorded per sample. Absolute quantitative numbers were calculated using the relative number of *Lycopodium*.

Organic geochemistry. Powdered and freeze-dried sediments were analysed for %TOC and δ¹³C_{TOC} with a Fison NA 1500 CNS analyser, connected to a Finnigan Delta Plus mass spectrometer. Analytical precision and accuracy were determined by replicate analyses and by comparison with international and in-house standards, and were better than 0.1% and 0.1‰ for %TOC and δ¹³C_{TOC}, respectively.

Powdered and freeze-dried sediments (1–3 g dry mass) were extracted with dichloromethane (DCM)/methanol (2:1) by using the Dionex accelerated solvent extraction technique. The extracts were separated by Al₂O₃ column chromatography using hexane/DCM (9:1) and DCM/methanol (1:1) to yield the apolar and polar fractions, respectively. The apolar fractions were analysed for isorenieratene derivatives by gas chromatography and gas chromatography/mass spectrometry, while the polar fractions were analysed for tetraether lipids and used to calculate TEX₈₆' (see Supplementary Information; reproducibility was within ~1 °C) and BIT (see ref. 26 for method description) indices.

Received 7 July 2005; accepted 21 February 2006.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements A.S. thanks the Utrecht Biogeology Centre for funding. H.B. thanks the Netherlands Organization for Scientific Research, and Utrecht University for enabling participation in the ACEX expedition. M.H. thanks the Purdue Climate Change Research Center, ITaP and the Purdue Research Foundation for their continued support. This research used samples and data provided by the IODP. We thank L. Bik, J. van Tongeren, N. Welters and A. van Dijk for technical support, and C. E. Stickley for discussions.

Author Contributions A.S. and H.B. carried out the palynology, A.S. & G.-J.R. the $\delta^{13}\text{C}_{\text{TOC}}$, S.S., M.W. and J.S.D. the TEX₈₆, BIT and isorenieratane analyses. R.S. generated the hydrogen index data. J.B. and K.M. were the co-chiefs of the ACEX expedition. N.P., J.M. and the Expedition 302 Scientists were involved in generating shipboard and shore-based ACEX data. A.S., S.S., M.P., H.B., J.S.D., G.R.D., M.H. and L.J.L. contributed to interpreting the data and writing the paper.

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Expedition 302 Scientists (those not listed above): Steve Clemens¹, Thomas Cronin², Frédérique Eynaud³, Jérôme Gattacceca⁴, Martin Jakobsson⁵, Ric Jordan⁶, Michael Kaminski⁷, John King⁸, Nalán Koc⁹, Nahysa C. Martinez¹⁰, David McInroy¹¹, Theodore C. Moore Jr¹², Matthew O'Regan⁸, Jonaotaro Onodera¹³, Heiko Pälike¹⁴, Brice Rea¹⁵, Domenico Rio¹⁶, Tatsuhiko Sakamoto¹⁷, David C. Smith⁸, Kristen E. K. St John¹⁸, Itsuki Suto¹⁹, Noritoshi Suzuki²⁰, Kozo Takahashi¹³, Mahito Watanabe²¹ & Masanobu Yamamoto²²

¹Geological Sciences, Brown University, 324 Brook Street, PO Box 1846, Providence, Rhode Island 02912-1846, USA. ²US Geological Survey, Eastern Earth Surface Processes Team, 926A USGS National Center, Reston, Virginia 20192, USA. ³Department de Géologie et Océanographie, Université Bordeaux 1, Avenue des facultés, c/o Bernei Housen, 33405 Talence Cedex, France. ⁴Department of Geophysics, CEREGE (CNRS)/University of Aix-Marseille 3, BP 80, 13545 Aix-en-Provence Cedex 4, France. ⁵Department of Geology and Geochemistry, Stockholm University, 106 91 Stockholm, Sweden. ⁶Department of Earth and Environmental Sciences, Faculty of Science, Yamagata University, 1-4-12 Kojirakawa-machi, Yamagata 990-8560, Japan. ⁷Department of Earth Sciences, University College London, Gower Street, London WC1E 6BT, UK. ⁸Graduate School of Oceanography, University of Rhode Island, Narragansett Bay Campus, South Ferry Road, Narragansett, Rhode Island 02882, USA. ⁹Norwegian Polar Institute, Polar Environmental Center, N-9296 Tromsø, Norway. ¹⁰Department of Earth Sciences, Boston University, 685 Commonwealth Avenue, Boston, Massachusetts 02215, USA. ¹¹British Geological Survey, Murchison House, West Mains Road, Edinburgh, EH9 3LA, UK. ¹²Geological Sciences, University of Michigan, Ann Arbor, Michigan 48109-1063, USA. ¹³Department of Earth and Planetary Sciences, Graduate School of Sciences, Kyushu University, Hakozaki 6-10-1, Higashi-ku, Fukuoka 812-8581, Japan. ¹⁴School of Ocean and Earth Science, University of Southampton, Southampton Oceanography Center, European Way, Southampton SO14 3ZH, UK. ¹⁵Department of Geography and Environment, School of Geosciences, University of Aberdeen, Elphinstone Road, Aberdeen AB24 3UF, UK. ¹⁶Department of Geology, Paleontology and Geophysics, University of Padova, Via Giotto 1 I-35137 Padova, Italy. ¹⁷Institute for Research on Earth Evolution (IFREE), Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Natsushima-cho 2-15, Yokosuka 237-0061, Japan. ¹⁸Department of Geology and Environmental Science, MSC 7703, James Madison University, Harrisonburg, Virginia 22807, USA. ¹⁹Institute of Life and Environmental Science, University of Tsukuba, Tennoudai 1-1-1, Tsukuba, Ibaraki 305-8572, Japan. ²⁰Institute of Geology and Paleontology, Graduate School of Science, Tohoku University, Aramaki, Aoba, Aoba-ku, Sendai City 980-8578, Japan. ²¹Institute of Geoscience, National Institute of Advanced Industrial Science, and Technology (Geological Survey of Japan) AIST Tsukuba Central 7, Higashi-1-1-1, Tsukuba, Ibaraki 305-8567, Japan. ²²Graduate School of Environmental Earth Science, Hokkaido University, Kita-10, Nishi-5, Kita-ku, Sapporo 060-0810, Japan