

Drilled petit-spot basalts reveal asthenospheric mantle heterogeneity before subduction

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Summary

Submarine petit-spot volcanoes form where oceanic plates bend and flex before sinking into subduction zones, providing a rare opportunity to sample mantle-derived melts before subduction. Here we report results from the first scientific drilling of a sediment-buried petit-spot volcano during International Ocean Drilling Programme Expedition 502, recovering basalts from a previously inaccessible interior of a petit-spot magmatic system. The recovered basalts exhibit a distinctive geochemical signature among oceanic intraplate magmas, combining Ni-rich olivine phenocrysts with unusually low $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$, SiO_2 -rich bulk compositions, pronounced Ba enrichment and Th–U–Nb–Ta depletion, and the most enriched mantle 1 (EM1)-like Sr–Nd isotopic compositions yet recognized in petit-spot basalts. Thermodynamic modelling rules out fractional crystallization of dry or carbonated peridotite-derived parent melts and requires a contribution from enriched SiO_2 -excess pyroxenite. Fresh glasses further record CO_2 depletion and low vesicularity relative to exposed petit-spot basalts. These findings reveal the petrological complexity of known EM1-type mantle heterogeneity, with isotopic signatures that can mask diverse mantle lithologies and melting processes that remain hidden from conventional seafloor sampling.

Main text

Oceanic lithosphere is generated at mid-ocean ridges, progressively cools and thickens as it ages (Parsons and Sclater, 1977; Stein and Stein, 1992)^{1,2}, and is recycled into Earth’s mantle at subduction zones. During its evolution, the underlying asthenosphere may preserve chemical and lithological heterogeneities inherited from recycled mantle components (Machida et al., 2015, 2017; Matzen et al., 2017)^{3,4,5}, while magmatic and metasomatic processes further modify the lithosphere–asthenosphere system (Pilet et al., 2016; Warren et al., 2016)^{6,7}. Resolving this heterogeneity beneath mature oceanic lithosphere is important for understanding how distinct chemical and lithological components are preserved and extracted by melting before subduction. Yet, buried beneath kilometres of seawater and sediment, the mature lithosphere–asthenosphere system remains one of the least accessible components of

the solid Earth, and our current understanding of its nature is based largely on geophysical observations and thermal models (Kawakatsu and Utada, 2017; Richards et al., 2020)^{8,9}. Thus, the nature and extent of chemical heterogeneity of asthenospheric mantle before subduction remains poorly constrained.

Petit-spot volcanoes provide one of the few natural opportunities to directly characterize the asthenospheric mantle composition beneath mature oceanic lithosphere before subduction (Hirano et al., 2006; Machida et al., 2017)^{4,10}. These small-volume alkaline volcanoes erupt on the outer-rise of subduction zones, where small-scale mantle convection promotes decompression melting within the underlying asthenosphere, and plate flexure provides pathways for eruption (Hirano et al., 2006; Sato et al., 2018)^{10,11}. Melt fractions are exceptionally small (Okumura & Hirano, 2013)¹², so petit-spot magmas preserve geochemical signatures of the most fusible components within the heterogeneous asthenosphere that are often obscured during higher-degree melting beneath mid-ocean ridges, volcanic arcs, and ocean islands (Hirano & Machida, 2022)¹³. Geochemical studies have classified northwestern Pacific petit-spot basalts into three groups [Group 1 (G1), Group 2 (G2), and Group 3 (G3)] based on their trace-element characteristics (Machida et al., 2015; Hirano & Machida, 2022)^{3,13}. Existing models invoke variable contributions from carbonated peridotite, pyroxenitic lithologies, and recycled mantle components to explain their enriched geochemical characteristics (Hirano & Machida, 2022)¹³. Furthermore, xenolith studies suggest possible interaction between petit-spot magmas and the lithospheric mantle during ascent (Pilet et al., 2016)⁶. However, these models are based exclusively on basalts recovered by dredging or submersible sampling from seafloor-exposed volcanic edifices. Such sampling preferentially recovers exposed eruptive products, whereas volcanic units buried beneath sediments remain inaccessible, potentially leaving part of the compositional diversity of petit-spot magmatism unsampled. Thus, it remains uncertain whether existing geochemical models adequately represent the mantle source of petit-spot magmatism or instead reflect selective sampling of individual eruptive products. This sampling bias limits understanding of both the origin of petit-spot magmas and the chemical heterogeneity of the asthenosphere.

The first scientific drilling of petit-spot volcanic sequences on the incoming Pacific Plate seaward of the Japan Trench during International Ocean Drilling Programme (IODP³) Expedition 502 overcomes this sampling bias (Fig. 1a; Refs. 14, 15). Expedition 502 recovered petit-spot basalts together with exceptionally fresh volcanic glass from beneath the seafloor, providing a minimally altered record of sub-seafloor petit-spot magmatism. Here, we present integrated bulk-rock major- and trace-element geochemistry, mineral chemistry, volatile abundances, and Sr–Nd isotope data for these drilled petit-spot basalts. Our results resolve the petrological heterogeneity of asthenospheric mantle beneath mature Pacific Plate and demonstrate that petit-spot basalt drilling provides a key record of mantle source lithology and melting processes before subduction.

The first drilled record of petit-spot volcanism

Petit-spot volcanism on the incoming oceanic plate in the northwest Pacific Ocean has been documented at three locations offshore of Japan, referred to as Sites A, B, and C (Fig. 1a) (Hirano et al., 2006)¹⁰. IODP³ Expedition 502 drilled a petit-spot volcano at sediment-buried Site C0027 in the petit-spot Site C region, recovering the first sub-seafloor petit-spot volcanic succession from the ~135-Myr-old Pacific Plate at ~5.5 km water depth (Yamaguchi et al., 2026)¹⁴. Three holes (Holes C0027D, C0027E and C0027F) intersect a petit-spot volcanic section buried beneath ~60-m of pelagic sediment, recovering basalt from ~59 to ~106.5 metres below seafloor (mbsf) (Fig. 1b).

Based on groundmass crystallinity, the recovered basalts are classified into two lithological units: glassy basalt and cryptocrystalline basalt (Fig. 1b). Both units retain abundant volcanic glass together with skeletal to dendritic quench textures and fresh olivine phenocrysts (Supplementary Fig. S1). Glassy basalts contain sparse euhedral to subhedral olivine phenocrysts in a glass-rich groundmass, whereas cryptocrystalline basalts contain more abundant olivine phenocrysts and a more crystalline groundmass; both contain dendritic olivine and clinopyroxene microlites with Fe–Ti oxide grains. Clinopyroxene-bearing cryptocrystalline basalts are restricted to the deepest part of Hole C0027E (Fig. 1a).

Glassy basalts dominate the uppermost basalt sequence beneath the sediment cover, whereas cryptocrystalline basalts become progressively more abundant with depth. However, the glassy basalts appear repeatedly throughout Hole C0027E and alternate with the cryptocrystalline basalts. Repeated alternations in the two lithological units are inconsistent with progressive crystallization within a single cooling magma flow and instead records multiple magmatic or eruptive episodes. Recurrence of glass-rich basalts throughout the drilled sequence indicates repeated magma ascent to the seafloor, preserving a stratigraphically coherent record of successive petit-spot eruptions. At Site A, submersible observations document pillow basalts, providing direct evidence for submarine lava emplacement during petit-spot volcanism (Fig. 1c) (Akizawa et al., 2022a, b)^{16,17}.

Vesicularity is generally low throughout the drilled sequence (Fig. 1b). Compared to previously reported petit-spot basalts (~43 vol.%; Ref. 12), the drilled basalts are markedly less vesicular despite preserving abundant fresh glass (Fig. 1d, e).

Distinctive geochemical signatures of drilled petit-spot basalts

The drilled petit-spot basalts exhibit major- and trace-element contents distinct from published petit-spot basalts (Supplementary Tables S1 and S2). Bulk-rock major-element compositions show progressive SiO₂ enrichment with decreasing MgO observed across petit-spot sites, but extend its compositional range to the highest SiO₂ contents yet reported for petit-spot basalts (51.6–53.6 wt%) (Fig. 2a). The SiO₂ enrichment can be reproduced by high degrees of partial melting of either dry or carbonated peridotite (~50%, pink arrows in Fig. 2a) (Walter, 1998; Dasgupta et al., 2007)^{18,19}. Such high degrees of melting, however, may be difficult to reconcile with the elevated K₂O contents (~3.3 wt%) and high K₂O/Na₂O ratios (~1.1) of the drilled basalts (Supplementary Tables S1), given the incompatible behaviour of K during mantle melting.

Previous studies classified petit-spot basalts from the northwest Pacific Ocean into three geochemical groups (G1 to G3) based primarily on trace-element compositions as presented above

(Machida et al., 2015)³. Primitive mantle-normalized trace-element patterns of the drilled petit-spot basalts closely resemble those of the G1 petit-spot basalts, with enrichment in highly incompatible elements together with positive Ba and negative Th, U, Nb, and Ta anomalies (Fig. 2b). Compared to published G1 basalt data, however, the drilled basalts have modestly higher Ba together with more pronounced negative Th, U, Nb, and Ta anomalies, while retaining the overall G1 trace-element signature. In contrast, the G2 basalts have additional negative Zr–Hf and Pb anomalies, while the G3 basalts have Ba enrichment with pronounced Pb and Zr–Hf depletion (Fig. 2b). Directly ascending petit-spot basalts (DAP), which are interpreted to represent asthenosphere-derived melts that ascended through the lithosphere with limited modification, are strongly alkaline and silica-poor (Fig. 2a) and have pronounced Ba enrichment and negative Zr–Hf and Pb anomalies (Fig. 2b) (Sato et al., 2018)¹¹. None of these trace-element patterns resembles those of Pacific oceanic island basalts (OIBs) from Aitutaki, Tahiti, or Pitcairn, which generally lack the coupled Ba enrichment and negative Th, U, Nb, and Ta anomalies characteristic of the drilled petit-spot basalts.

The mineral chemistry of the drilled petit-spot basalts differs from that of previous petit-spot basalts and mantle xenoliths (Supplementary Table S3) (Hirano & Machida, 2022; Akizawa et al., 2022a, b)^{13,16,17}. Olivine phenocrysts extend to lower Mg/(Mg + Fe²⁺) atomic ratios (Mg# < 0.86) than those from known petit-spot basalts (Fig. 3a), consistent with the SiO₂-rich and relatively evolved bulk-rock compositions. Despite their lower Mg#, however, they retain unexpectedly high NiO contents (~0.43 wt%) and remain compositionally distinct from olivines in petit-spot mantle xenoliths, defining a trend distinct from the differentiation trend of other petit-spot basalts. Clinopyroxene compositions likewise differ from those in the petit-spot mantle xenoliths, although they broadly overlap the range of clinopyroxene phenocrysts in other petit-spot basalts (Fig. 3b). These mineralogical characteristics indicate crystallization from a chemically distinct melt rather than entrainment of mantle-derived xenocrysts or differentiation of previously recognized petit-spot magmas.

Drilled petit-spot basalts define the most EM1-like isotopic compositions

Isotopic compositions of Sr and Nd further distinguish the drilled petit-spot basalts from known petit-spot basalts (Fig. 4; Supplementary Table S4). The drilled basalts have a narrow isotopic range ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7052\text{--}0.7050$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.51235\text{--}0.51241$), overlapping those of known G1 petit-spot basalts. Also, the drilled basalt isotopic compositions trend systematically towards the enriched mantle 1 (EM1) component relative to reported petit-spot basalts. In contrast, G2 and G3 petit-spot basalts have progressively more depleted isotopic signatures, with higher $^{143}\text{Nd}/^{144}\text{Nd}$ at comparable $^{87}\text{Sr}/^{86}\text{Sr}$. Pitcairn basalts overlap the EM1-like isotopic compositions of the drilled petit-spot basalts, despite their distinct trace-element patterns compared to those of the drilled petit-spot basalts (Fig. 2b). Tahiti and Aitutaki basalts plot towards more depleted mantle compositions. The Sr–Nd isotopic compositions make the drilled petit-spot basalts the most isotopically enriched expression of G1 petit-spot magmatism recognized to date, and provide new constraints on the origin of the enriched mantle component beneath the mature Pacific Plate.

Drilled petit-spot basalts redefine the G1 geochemical signature

The drilled petit-spot basalts clearly belong to G1 (Fig. 2b) and also systematically extend the G1 compositional range towards more SiO_2 -rich major-element compositions (Fig. 2a), more pronounced G1 trace-element characteristics (Fig. 2b), and the most EM1-like Sr–Nd isotopic compositions (Fig. 4). These observations demonstrate that the drilled petit-spot basalts do not represent a previously unrecognized magma type but rather the most extreme expression of the G1 geochemical signature. The exceptional preservation of fresh volcanic glass, together with the stratigraphically constrained volcanic succession recovered by scientific drilling, indicates that this extreme composition is unlikely to reflect sampling bias, seawater alteration, or selective preservation of individual lava blocks. Instead, the drilled petit-spot basalts provide the first continuous record of G1 petit-spot magmatism, therefore revealing a more complete geochemical range of G1 petit-spot magmatism.

An enriched pyroxenitic component accounts for the extreme G1 signature

The geochemical diversity of petit-spot basalts has been explained using conceptual models involving variable mantle sources, carbonate–silicate melt immiscibility, and magmatic differentiation (Hirano et al., 2006; Machida et al., 2015; Hirano & Machida, 2022; Mikuni et al., 2024)^{3,10,13,20}. However, these hypotheses have not been evaluated using thermodynamic modelling. To assess whether the distinctive geochemical characteristics of the drilled petit-spot basalts can be reproduced within the existing petrogenetic framework, crystallization paths are modelled here for parent melts generated from both dry and carbonated peridotites.

High-pressure–temperature experimental studies demonstrate that partial melting of dry peridotite at 3 GPa and 1580 °C (Walter, 1998)¹⁸, and carbonated peridotite at 3 GPa and 1600 °C (Dasgupta et al., 2007)¹⁹, generates SiO₂-rich primary melts that can represent the parent magma of the petit-spot basalts (Fig. 2a). Whether subsequent fractional crystallization of these parental melts could reproduce the observed mineral composition of olivine phenocrysts was, therefore, evaluated using thermodynamic modelling (Supplementary Methods). Although progressive orthopyroxene crystallization successfully generates NiO-rich olivine phenocrysts from both melts, it produces a NiO–Mg# trajectory opposite to that defined by olivine phenocrysts in the drilled petit-spot basalts (Fig. 2c). Consequently, no plausible crystallization path from SiO₂-rich parental melts derived from either dry or carbonated peridotite reproduces the observed olivine chemistry (Fig. 2c). The inability of either melting model to reproduce the olivine phenocryst chemistry indicates that the discrepancy does not arise from crystallization processes alone. Instead, it reflects a more fundamental parent magma composition difference.

Our observations require an additional mantle lithology capable of generating SiO₂-rich melts while preserving the enriched trace-element and isotopic signatures of the drilled petit-spot basalts. Among plausible candidates, SiO₂-excess pyroxenite provides a consistent explanation. Mg-isotope studies of northwest Pacific Ocean petit-spot basalts suggest involvement of recycled oceanic crust

represented by eclogitic or pyroxenitic mantle source components (Liu et al., 2020)²¹. Our results provide independent petrological constraints on the nature of the recycled component. Experimental and theoretical studies indicate that partial pyroxenite melting can generate SiO₂-rich melts while retaining enriched geochemical signatures inherited from recycled oceanic lithologies (Sobolev et al., 2007; Lambart et al., 2013)^{22,23}. However, this mechanism alone is unlikely to explain the elevated K₂O contents and high K₂O/Na₂O ratios of these drilled basalts (Yamaguchi et al., 2026)¹⁴. Subsequent interaction with the lithospheric mantle during magma ascent may have further modified their compositions (Pilet et al., 2016)⁶. The coupled major-element, mineralogical, trace-element, and isotopic characteristics of the drilled petit-spot basalts, therefore, suggest a SiO₂-rich pyroxenitic contribution to the mantle source, with possible subsequent modification by melt–lithosphere interaction.

Volatile systematics of SiO₂-rich petit-spot magmas

Fresh groundmass glasses from the drilled cores (Samples C0027D-8XCC, 3–4 cm and C0027E-8K-1, 12–14 cm) contain 226–246 µg g⁻¹ CO₂ and 1.14 wt% H₂O, compared with 2313 µg g⁻¹ CO₂ and 2.07 wt% H₂O in fresh groundmass glass from the seafloor in the petit-spot Site C region (Sample KS-18-9-D05-001) (Supplementary Table S3). The drilled glasses are systematically depleted in CO₂, while retaining comparable H₂O contents (Fig. 5). Calculated volatile saturation pressures of ~600–700 bar closely match the present hydrostatic pressure in the petit-spot Site C region (~550 bar), which indicates that volatile exsolution continued until before quenching on the seafloor. The drilled basalts are also markedly less vesicular than the seafloor petit-spot basalts (Figs. 1d, e).

Preservation of comparable H₂O contents despite substantially lower CO₂ concentrations is consistent with preferential CO₂ loss during magma ascent, reflecting the much lower solubility of CO₂ relative to H₂O in silicate melts (Dixon et al., 1995; Wallace and Edmonds, 2011)^{24,25}. Moreover, fresh glass preservation indicates that the lower CO₂ contents are unlikely to result from post-eruptive alteration but instead record syn-eruptive degassing. The drilled basalts are also markedly less vesicular than the

seafloor petit-spot basalts (Figs. 1d, e). Coupled CO₂ depletion and low vesicularity suggest that exsolved CO₂ was separated efficiently from the melt before final quenching, leaving little gas preserved as vesicles.

The distinctive SiO₂-rich composition of the parent magma may have influenced this degassing behaviour. Melt composition influences magma viscosity (Giordano et al., 2008)²⁶, which in turn affects magma transport and degassing dynamics (Gonnermann and Manga, 2007)²⁷. The relatively SiO₂-rich parent melt may have experienced ascent and degassing dynamics that are different from those of recognized petit-spot magmas, potentially allowing more extensive CO₂ exsolution and gas–melt separation before seafloor emplacement. Volatile systematics indicate that substantial CO₂ loss can occur during deep submarine petit-spot magma emplacement, even under high hydrostatic pressures.

Scientific drilling reveals asthenospheric mantle heterogeneity before subduction

Models of petit-spot magmatism have been developed largely from basalts recovered from volcanic edifices exposed on the seafloor by dredging and submersible sampling (Hirano & Machida, 2022)¹³. IODP³ Expedition 502 provides the first stratigraphically constrained volcanic succession from a sediment-buried petit-spot volcano in the Site C region (Fig. 1a), revealing geochemical variability that may not be represented by exposed seafloor petit-spot basalts. The distinctive combination of SiO₂-rich major-element compositions, unusual mineral chemistry, amplified G1 trace-element characteristics, EM1-like isotopic signatures, and systematic volatile characteristics is preserved throughout the drilled succession. This demonstrates that the extreme expression of G1 petit-spot magmatism forms part of a coherent eruptive sequence and reflects a genuine mantle signature rather than selective sampling or preservation.

Recognition of the extreme G1 petit-spot geochemical end-member indicates that the asthenospheric mantle beneath mature Pacific Plate before subduction is more compositionally heterogeneous than previously inferred (Machida et al., 2015; Hirano & Machida, 2022)^{3,13}. While

previous studies primarily attribute this heterogeneity to mixing between depleted mantle and an EM1-like enriched component, our results reveal additional lithological and volatile complexity during the melt generation process. Although isotopic variations remain broadly consistent with mixing involving a common EM1-like component, the contrasting major-element, mineralogical, and volatile characteristics indicate that isotopically related melts can originate from different mantle lithologies and under different volatile regimes. The observed geochemical diversity may, therefore, reflect variation in the proportion of an enriched component and the mantle lithologies that contribute to melting and the role of volatiles in facilitating melt generation. The drilled G1 petit-spot basalts, therefore, do not contradict the recognized EM1-type mantle heterogeneity; instead, they reveal the petrological complexity underlying its geochemical expression.

Scientific drilling provides access to a hidden record of asthenospheric mantle heterogeneity by recovering volcanic products buried beneath the seafloor. Petit-spot drilling can, therefore, capture melts derived from mantle source lithologies and melting conditions that are poorly represented by exposed lava flows. This approach provides new constraints on the nature of asthenospheric mantle heterogeneity beneath mature oceanic lithosphere before subduction.

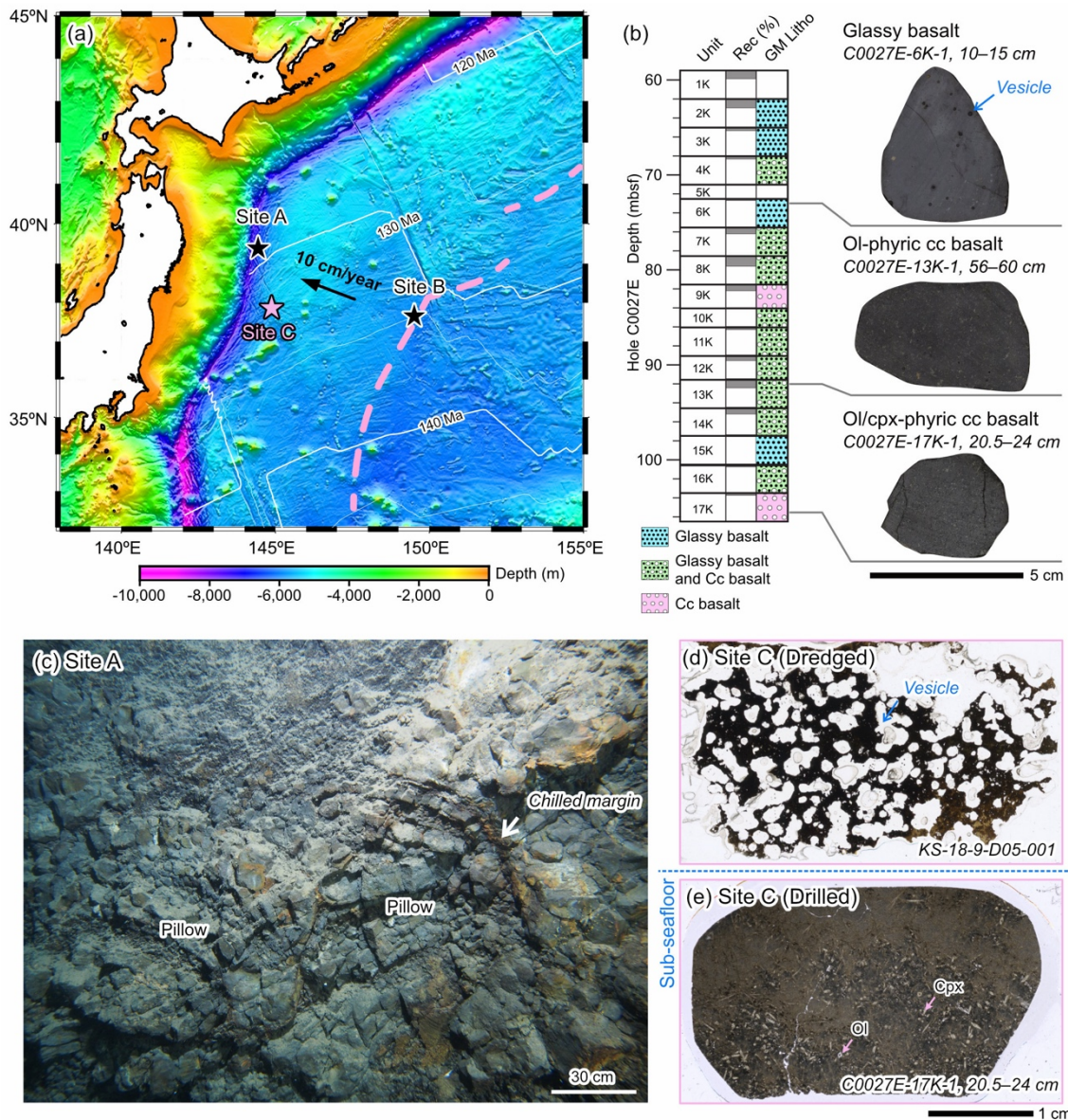


Fig. 1. Geological setting and drilled petit-spot basalts from the northwest Pacific Ocean. (a) Bathymetric map with locations of petit-spot Sites A, B, and C on the incoming Pacific Plate, which currently moves to the WNW at 10.3 cm yr⁻¹ (Gripp et al., 1990)²⁸. Seafloor age-gridded data are from Müller et al. (2019)²⁹. The eastern side of the outer-rise topography is delineated by the dashed pink line (Hirano & Machida, 2022)¹³. (b) Lithological succession recovered from IODP³ Hole C0027E, with representative drilled basalt samples. Groundmass lithologies are based on recovered basalt intervals and are assumed to represent the corresponding cores despite low recovery. (c) Seafloor photograph of pillow lavas and chilled margins taken during a dive of the Human Occupied Vehicle Shinkai 6500 at Site A (dive number 6K1565) during the YK20-14S cruise. (d, e) Representative thin-section scans of petit-spot basalts recovered from Site C by (d) dredging and (e) drilling. The dredged basalt is highly vesicular (~40 vol%), whereas the drilled basalt is nearly non-vesicular (<1 vol%), despite both being recovered from Site C. Abbreviations: Cc = cryptocrystalline, Cpx = clinopyroxene, Ol = olivine, Rec = recovery rate and GM litho = groundmass lithology.

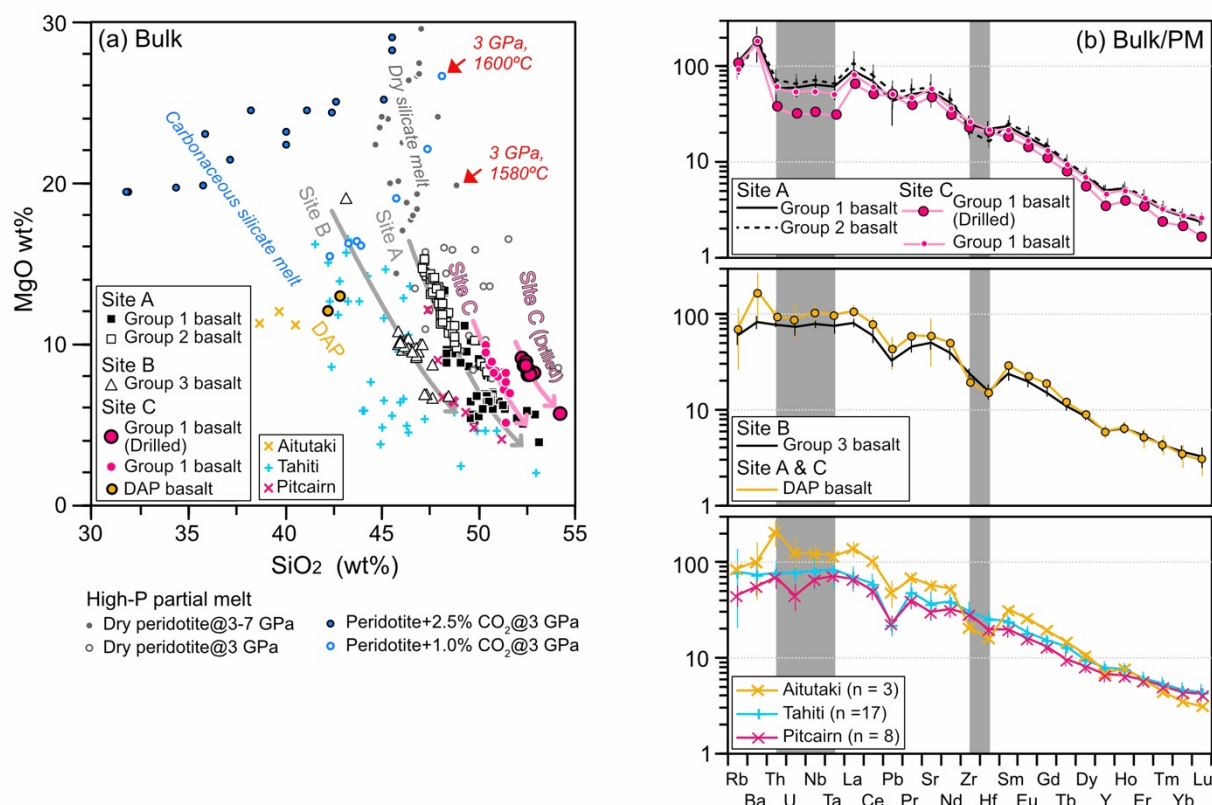


Fig. 2. Bulk-rock major- and trace-element compositions of basalts. (a) Bulk-rock MgO versus SiO₂ compositions of drilled petit-spot basalts from Site C, compared to petit-spot basalts from Sites A to C (Hirano & Machida, 2022)¹³, and ocean-island basalts from Aitutaki (Jackson et al., 2020)³⁰, Tahiti (Duncan et al., 1994)³¹, and Pitcairn (Eisele et al., 2002)³². Experimental partial melts of dry and CO₂-bearing peridotite are shown for comparison (Takahashi, 1986; Hirose & Kushiro, 1993; Hirose, 1997; Walter, 1998; Dasgupta et al., 2007)^{17,18,33,34,35}. The red arrows indicate starting compositions used for the thermodynamic modelling shown in Fig. 3a. (b) Averaged primitive-mantle-normalized trace-element patterns of petit-spot basalts from Sites A to C and ocean-island basalts from Aitutaki (Jackson et al., 2020)³⁰, Tahiti (Duncan et al., 1994; White & Duncan, 1995)^{31,36}, and Pitcairn (Eisele et al., 2002)³². Published data for petit-spot basalts are from Hirano & Machida (2022)¹³. Grey bands highlight characteristic Th–U, Nb–Ta, and Zr–Hf depletions. Error bars in (b) indicate ±1σ. Abbreviations: DAP = directly ascending petit-spot basalt, and PM = primitive mantle.

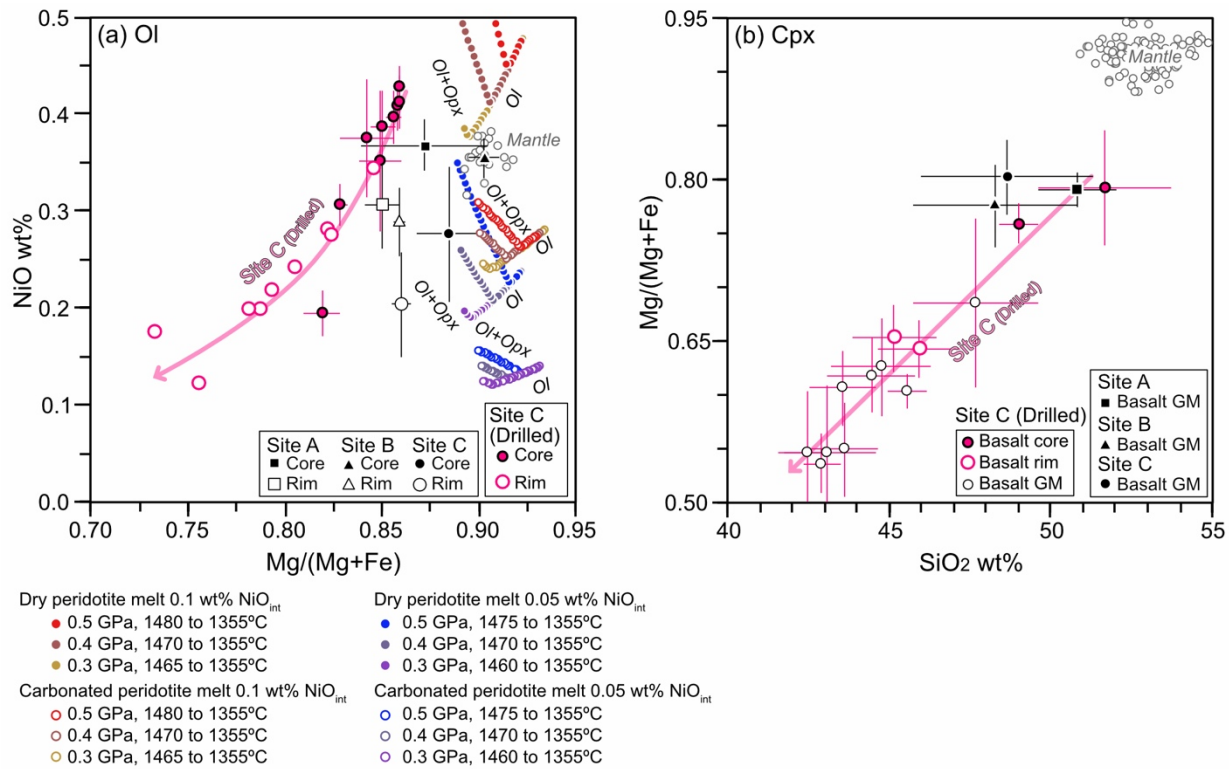


Fig. 3. Mineral major-element compositions of petit-spot samples. (a) NiO versus Mg/(Mg+Fe) compositions of olivine in petit-spot basalts from Sites A to C, compared to crystallization trends calculated using alphaMELTS (Smith & Asimow, 2005)³⁷ for dry and CO₂-bearing peridotite-derived melts. The starting composition of dry peridotite-derived melt was taken from a melt generated at 1580 °C and 3 GPa (Walter, 1998)¹⁸, whereas that of the CO₂-bearing peridotite-derived melt was taken from a melt generated at 1600 °C and 3 GPa (Dasgupta et al., 2007)¹⁹; compositions are indicated by the red arrows in Fig. 2a. The pink arrow indicates an inferred differentiation trend of drilled petit-spot basalts. (b) Mg/(Mg+Fe) versus SiO₂ compositions of clinopyroxene in petit-spot basalts from Sites A to C. The pink arrow indicates an inferred differentiation trend of drilled petit-spot basalts. Petit-spot mantle xenolith data are shown as gray circles with white centres in (a) and (b). Error bars indicate $\pm 1\sigma$. Abbreviations: Cpx = clinopyroxene, GM = ground mass, Int = initial, Ol = olivine, and Opx = orthopyroxene.

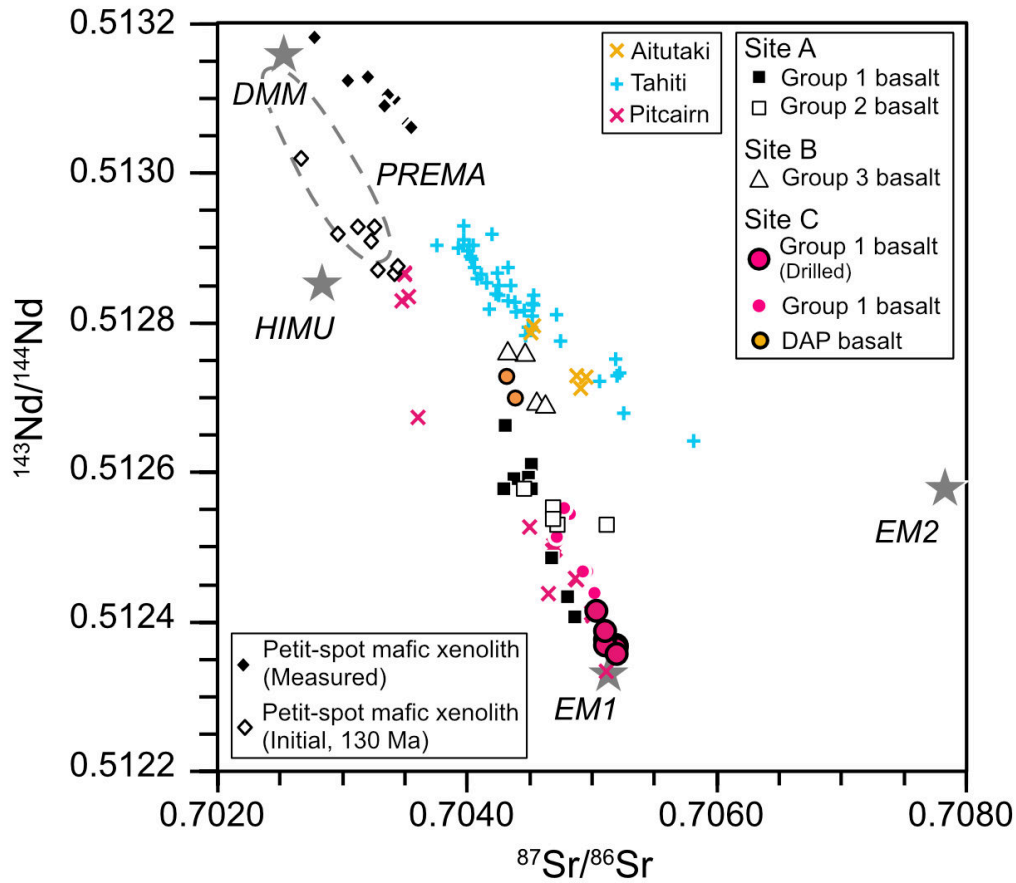


Fig. 4. Sr–Nd isotope compositions of petit-spot basalts. $^{143}\text{Nd}/^{144}\text{Nd}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ compositions of drilled petit-spot basalts from Site C, compared to seafloor petit-spot basalts from Sites A to C (Hirano & Machida, 2022)¹³, petit-spot mafic xenoliths (Mikuni et al., 2025)³⁸, and ocean-island basalts from Aitutaki (Jackson et al., 2020)³⁰, Tahiti (Duncan et al., 1994; White & Duncan, 1995)^{31,36}, and Pitcairn (Eisele et al., 2002)³². For the petit-spot mafic xenoliths, original measured isotope ratios and initial ratios age-corrected to 130 Ma are shown as filled and open diamonds, respectively. Reference mantle components (depleted MORB mantle = DMM, prevalent mantle = PREMA, high $^{238}\text{U}/^{204}\text{Pb}$ mantle = HIMU, enriched mantle I and II = EM1 and EM2) are shown for comparison (Hart et al., 1992; Workman & Hart, 2005; Stracke et al., 2012)^{39,40,41}. Abbreviations are the same as in Fig. 2.

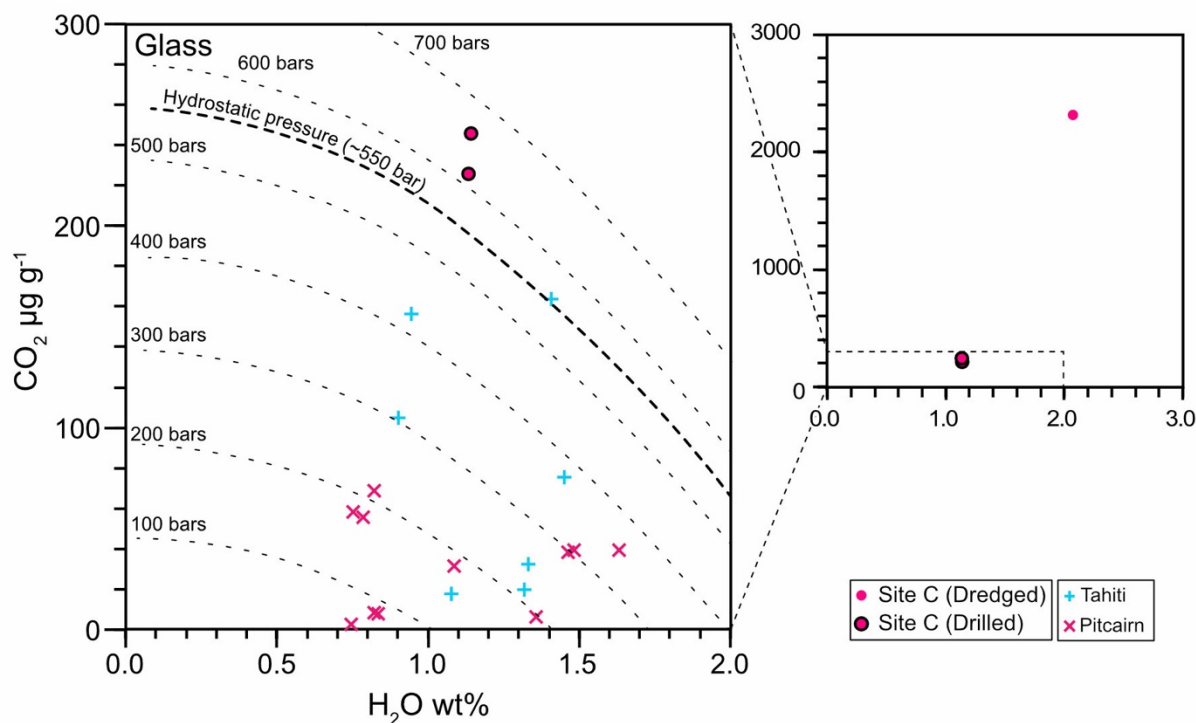


Fig. 5. H₂O and CO₂ contents of petit-spot volcanic glasses. CO₂ versus H₂O concentrations of fresh glasses from drilled and dredged petit-spot basalts, compared with glasses from ocean-island basalts from Tahiti and Pitcairn (Kendrick et al., 2014)⁴². The right-hand panel is an illustration of the full compositional range, including the CO₂-rich dredged Site C glass, whereas the low-CO₂ range is enlarged in the left-hand panel. Dashed curves in the left-hand panel are volatile saturation pressures calculated using VESICAL (Iacovino et al., 2021)⁴³ with the Dixon H₂O–CO₂ solubility model (Dixon et al., 1995)²⁴. Calculations were performed at 1200 °C using the averaged major-element composition of drilled petit-spot glass (Supplementary Table S3), normalized to 100 wt% on a volatile-free basis. The thick dashed curve is the present-day hydrostatic pressure at the Site C seafloor (~550 bar).

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Methods

Mineral-phase distribution map analysis

Whole-thin-section elemental maps were acquired using a Bruker AXS M4 TORNADO scanning X-ray analytical microscope at the Geological Survey of Japan (GSJ), National Institute of Advanced Industrial Science and Technology (AIST, Japan). Elemental mapping was performed at an accelerating voltage of 30 kV and a tube current of 200 μ A, using a 25- μ m beam spot and a scan speed of 20 mm s⁻¹. Results are shown in Supplementary Fig. S2.

Sample powder preparation

Basalt samples with ~2–8 cm³ volumes were cut from the core with a diamond saw blade. Saw marks and alteration rinds were removed from outer rock sample surfaces by grinding with a diamond-impregnated grinding wheel. Each sample was then sonicated for 15 min in Milli-Q water. Cleaned samples were dried under vacuum at room temperature for 24 h and then crushed to <1 mm using an agate mortar and pestle. A Fritsch P-5 ball mill equipped with agate grinding balls and bowls was then used to grind the fragments into a fine powder. These processes were conducted aboard the D/V *Chikyu*.

Loss on ignition and bulk-rock major-element analyses

Sample powders were weighed in an alumina crucible, heated to 100°C for 2 h to remove moisture, and re-weighed. They were then ignited at 1000°C for 3 h and re-weighed. Weight differences of samples between the two heating processes were used to calculate loss on ignition (LOI) as a weight percent (wt%) of the original sample mass (Supplementary Table S1). Ignited sample powders (0.8950–0.9040 g) were fused with 4.4950–4.504 g of Spectromelt® A12 flux (34 % LiBO₂ and 66 % Li₂B₄O₇) for 7 min at 1150°C using an internally rotating induction furnace (Bead Sampler NT-4100, Tokyo Kagaku)

aboard the D/V *Chikyu*. To prevent cooled glass beads from adhering to the crucible, 4 to 5 drops of 20 wt% aqueous LiBr solution were added to the mixture of flux and sample powder as a non-wetting agent.

Bulk-rock major-element composition (Na_2O , MgO , Al_2O_3 , SiO_2 , P_2O_5 , K_2O , CaO , TiO_2 , MnO , and Fe_2O_3) of fused-glass beads was measured using a Zetium (PaNalytical) wavelength dispersive X-ray fluorescence (XRF) spectrometer equipped with a 2400 W rhodium anode X-ray tube aboard the D/V *Chikyu*. The instrument was operated at 60 kV and 100 mA. Calibration curves were determined with geological reference materials of JA-1 (andesite), JA-2 (andesite), JB-2 (basalt), JB-3 (basalt), JF-1 (feldspar), JF-2 (feldspar), JG-1 (granodiorite), JG-1a (granodiorite), JG-2 (granite), JGb-1 (gabbro), JGb-2 (gabbro), JH-1 (hornblende), JR-2 (rhyolite), JR-3 (rhyolite), and JSy-1 (syenite) distributed by the GSJ. The results are shown in Supplementary Table S1.

Bulk-rock trace-element composition analysis

Bulk-rock trace-element analysis was conducted by inductively coupled plasma-mass spectrometry (ICP-MS) using a Thermo Fisher Scientific iCAP Q system at JAMSTEC (Japan). Sample digestion followed the method of [Chang et al. \(2003\)](#)⁴⁴. Approximately 50 mg of sample powder used for XRF analysis was dissolved in an HF – HClO_4 mixture, followed by sequential dissolution in HClO_4 and HNO_3 . Final solutions were diluted by a factor of 50,000 to 65,000 with 2% HNO_3 containing trace amounts of HF . Geological reference material JB-2 was analyzed alongside the samples to monitor analytical accuracy and precision. The results are presented in Supplementary Table S2.

Mineral and glass major-element composition analyses

Major-element compositions of minerals and volcanic glasses were determined by electron probe microanalysis (EPMA) using a JEOL JXA-iHP200F at the GSJ, AIST (Japan), and a JEOL JXA-

iSP100 at the Core Facility Management Center, Hiroshima University (Japan). All drilled samples were analyzed using the former instrument, whereas the other samples were analyzed using the latter instrument. The results are summarized in Supplementary Table S3.

For JEOL JXA-iHP200F analyses, minerals were analyzed at an accelerating voltage of 15 kV, beam current of 12 nA, and beam diameter of 2 μm . Volcanic glasses were analyzed at an accelerating voltage of 15 kV, beam current of 5 nA, and beam diameter of 30 μm . Peak and background counting times were 20 and 10 s, respectively, for all elements except Na and Ni, which were 15 and 30 s, and 2 and 5 s, respectively. Natural and synthetic standards include quartz (SiO_2), rutile (TiO_2), corundum (Al_2O_3), hematite (Fe_2O_3), manganosite (MnO), periclase (MgO), wollastonite (CaSiO_3), albite ($\text{NaAlSi}_3\text{O}_8$), K-feldspar (KAlSi_3O_8), potassium titanium phosphate (KTiOPO_4), eskolaite (Cr_2O_3), and nickel oxide (NiO). Raw data were corrected using a ZAF online correction program.

For analyses using the JEOL JXA-iSP100, minerals were analyzed at an accelerating voltage of 20 kV, beam current of 20 nA, and beam diameter of 2 μm . Volcanic glasses were analyzed at an accelerating voltage of 15 kV, beam current of 10 nA, and beam diameter of 30 μm . Peak and background counting times were 10 and 5 s, respectively, for all elements except Na and Ni, which were 5 and 20 s, and 2 and 10 s, respectively. Natural and synthetic standards include forsterite (Mg_2SiO_4), rutile (TiO_2), corundum (Al_2O_3), hematite (Fe_2O_3), manganosite (MnO), periclase (MgO), wollastonite (CaSiO_3), albite ($\text{NaAlSi}_3\text{O}_8$), K-feldspar (KAlSi_3O_8), potassium titanium phosphate (KTiOPO_4), eskolaite (Cr_2O_3), and nickel oxide (NiO). Raw data were corrected using a ZAF online correction program.

Volatile analyses of volcanic glasses

Concentrations of CO_2 , H_2O , F, Cl, and S in volcanic glasses were determined with secondary ion mass spectrometry (SIMS) using an AMETEK CAMECA IMS-1280HR installed at the Kochi Institute for Core Sample Research, JAMSTEC (Japan). A 20 kV (10 kV at the ion source and 10 kV at

the sample surface) Cs^+ primary ion beam of 300–500 pA was defocused to a spot size of $\sim 10\text{--}15\ \mu\text{m}$ in diameter. Secondary ions were accelerated at 10 kV, and transfer optics were operated at $\times 200$ magnification. An electron gun operated at -10 kV ($\sim 100\ \mu\text{m}$ in diameter) was applied for electrostatic charge compensation. The field aperture was set to $1 \times 1\ \text{mm}$, corresponding to a $5 \times 5\ \mu\text{m}$ field of view of the secondary ion image; only secondary ions transmitted through this field aperture were collected, thereby minimizing contributions from surface contamination and primary beam edges. A mass resolving power of ~ 6000 was used, which is sufficient to separate $^{17}\text{O}^-$, $^{29}\text{SiH}^-$, $^{30}\text{SiH}^-$, $^{31}\text{PH}^-$, and $^{34}\text{SH}^-$ from $^{16}\text{OH}^-$, $^{30}\text{Si}^-$, $^{31}\text{P}^-$, $^{32}\text{S}^-$, and $^{35}\text{Cl}^-$, respectively.

Negative secondary ions of $^{12}\text{C}^-$, $^{16}\text{OH}^-$, $^{19}\text{F}^-$, $^{30}\text{Si}^-$, $^{31}\text{P}^-$, $^{32}\text{S}^-$, and $^{35}\text{Cl}^-$, were measured in magnetic peak-switching mode. For volcanic glasses, all species were detected using an axial electron multiplier (EM). The counting time and waiting time per cycle were 1 s and 2 s for $^{12}\text{C}^-$, $^{16}\text{OH}^-$, $^{19}\text{F}^-$, $^{30}\text{Si}^-$, $^{31}\text{P}^-$, $^{32}\text{S}^-$, and $^{35}\text{Cl}^-$; and 0.5 s and 5 s for 11.9 amu. Each analysis consisted of 20 s of presputtering, ~ 120 s of automatic centering of secondary ions to the field aperture (X and Y directions) and contrast aperture (X direction), followed by 10 measurement cycles. The total measurement time per analysis was ~ 7 min.

Volatile concentrations in volcanic glasses were calibrated using 14 basaltic glass standards (natural and synthetic) with known compositions following Shimizu et al. (2017)⁴⁵. Calibration curves were constructed from secondary ion intensity ratios normalized to $^{30}\text{Si}^-$. CO_2 concentrations in volcanic glasses were determined from the basaltic-glass calibration curves. For H_2O in volcanic glasses, matrix effects were modified based on the glass major-element composition (Shimizu et al., 2022)⁴⁶, as shown in Supplementary Table S3.

Bulk-rock Sr and Nd isotope analyses

Rock powders were acid-leached with 6 M HCl and 1 M HF, rinsed with Milli-Q water, and dried. Sample digestion and chemical separation were performed following Miyazaki et al. (2018)⁴⁷,

using the fully automated COLUMNSPIDER system (Miyazaki et al., 2012)⁴⁸. Total procedural blanks for Sr and Nd were less than 275 and 9 pg, respectively. Sr and Nd isotope ratios were measured by thermal ionization mass spectrometry (TIMS) using a Thermo Fisher Scientific Triton TI. Measured ratios were normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. Analyses of NIST SRM-987 yielded $^{87}\text{Sr}/^{86}\text{Sr} = 0.710245 \pm 07$ (2 standard deviations, $n = 3$), while JNdi-1 yielded $^{143}\text{Nd}/^{144}\text{Nd} = 0.512106 \pm 28$ (2 standard deviations, $n = 6$). Reported $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of the samples in Supplementary Table S4 are presented as measured, without offset correction relative to standard values.

Thermodynamic modelling

Crystallization paths were modelled using alphaMELTS 2, which implements the MELTS thermodynamic framework of Ghiorso and Sack (1995)⁴⁹ through the alphaMELTS interface (Smith and Asimow, 2005)³⁷. Experimentally determined partial-melt compositions of dry peridotite at 3 GPa and 1580 °C (Walter, 1998)¹⁸ and carbonated peridotite at 3 GPa and 1600 °C (Dasgupta et al., 2007)¹⁹ were used as starting compositions (indicated by red arrows in Fig. 2a). These compositions were selected because they represent SiO₂-rich melts potentially relevant to the parent magmas of the drilled petit-spot basalts.

Crystallization was modelled at 0.3, 0.4, and 0.5 GPa, where olivine occurs as a liquidus phase in the SiO₂-rich starting melts, to evaluate whether subsequent crystallization, including orthopyroxene fractionation, could reproduce the observed NiO–Mg# trend of the olivine phenocrysts. To evaluate the effect of initial Ni concentration on calculated olivine compositions, initial melt NiO contents of 0.05 and 0.10 wt% were examined for both dry- and carbonated-peridotite-derived melts. Melts were cooled progressively from temperatures near their respective liquidus conditions to 1355 °C. Starting temperatures were 1465, 1470, and 1480 °C at 0.3, 0.4, and 0.5 GPa, respectively, for calculations with 0.10 wt% initial NiO, and 1460, 1470, and 1475 °C, respectively, for calculations with 0.05 wt% initial

584 NiO. Crystallizing olivine compositions were extracted from model outputs; their NiO contents and Mg#
585 $[\text{Mg}/(\text{Mg} + \text{Fe})]$ are compared with those of olivine phenocrysts in drilled petit-spot basalts (Fig. 2c).
586

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Author contributions

Conceptualization was carried out by N.A., K.Mi., T.M., A.Y., and H.K. Sample investigation and petrographic analyses were performed by N.A., K.Mi., J.M.L., C.Y., F.N., K.P., H.U., P.V., and L.A. Geochemical analyses were conducted by N.A., K.Mi., T.M., T.S., B.S.V., Q.C., Y.S., K.S., and T.U. Numerical modelling was completed by N.A. Shipboard data design and acquisition were undertaken by N.A., K.Mi., J.M.L., C.Y., T.M., F.N., T.K., A.Y., H.K., N.O., K.P., H.U., P.V., L.A., K.Ma., L.H.S.,

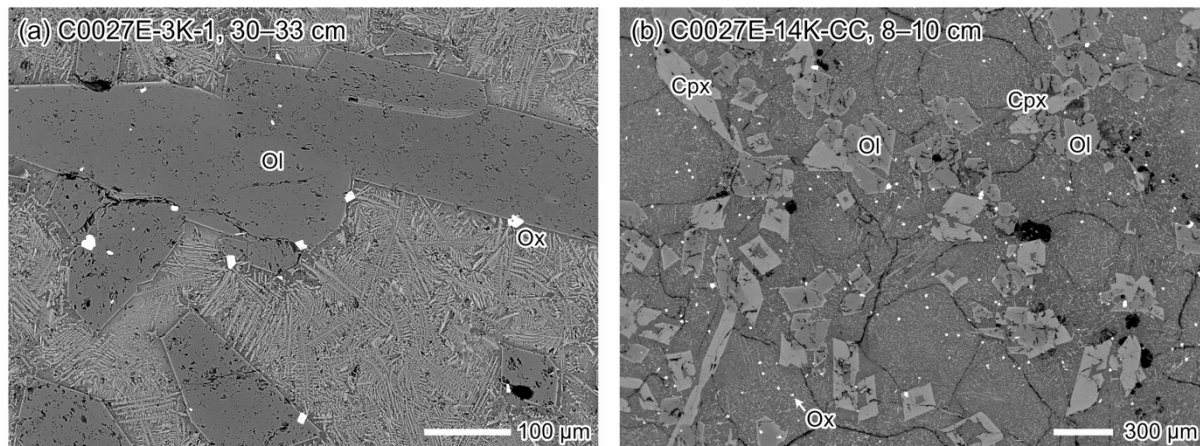
A.P.R., H.O., O.F., T.U., F.T., Y.N., A.M., Y.A., R.L., M.I., and T.K. Funding was secured by N.A. The original manuscript was written by N.A., K.Mi., T.M., A.Y., H.K., N.H., and S.M., and all authors contributed to reviewing and editing the final text.

Competing interests

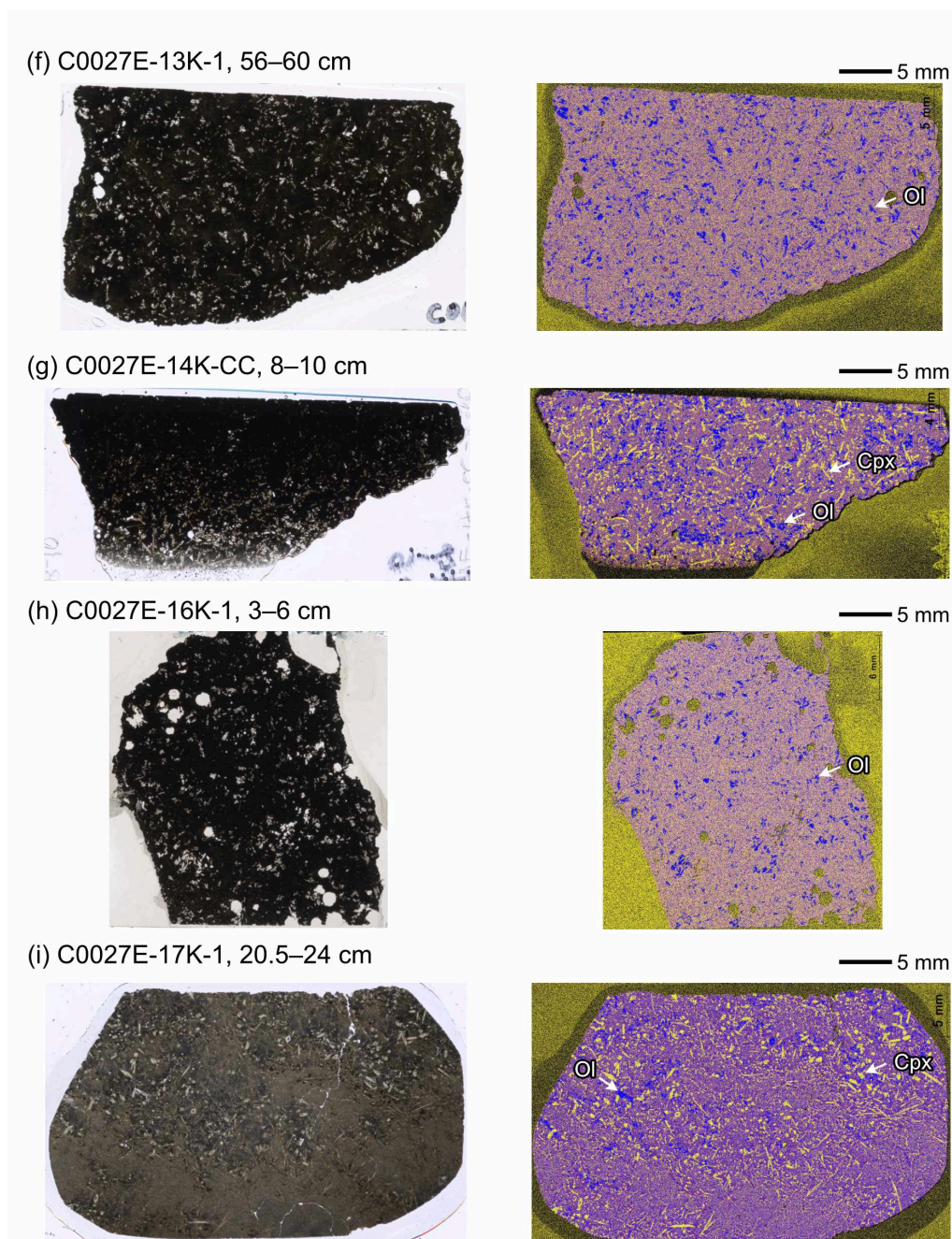
The authors declare no competing interests.

Supplementary Information

Figures



Supplementary Fig. S1. Representative backscattered-electron images of drilled petit-spot basalts from Hole C0027E. (a) Glassy basalt (C0027E-5K-1, 30–33 cm) with olivine phenocrysts in a glass-rich groundmass with acicular olivine and clinopyroxene microlites. (b) Cryptocrystalline basalt (C0027E-14K-CC, 8–10 cm) with olivine and clinopyroxene phenocrysts in a glass-rich groundmass with acicular olivine and clinopyroxene microlites. Abbreviations: Cpx = clinopyroxene, Ol = olivine, and Ox = oxide.



Supplementary Fig. S2. Thin-section images and elemental maps of drilled petit-spot basalts from Hole C0027E. Thin-section images (left) and corresponding composite μ XRF elemental maps (right) of drilled petit-spot basalt samples recovered from different intervals of Hole C0027E. In the μ XRF maps, Ca, Fe, and K are shown in yellow, blue, and pink, respectively. Olivine phenocrysts (Ol) and clinopyroxene phenocrysts (Cpx) are indicated by white arrows.

634 Tables

Table S1 Bulk-rock major-element composition of drilled petit-spot basalts (wt%).

Expedition	Hole	Core	Section	Section interval (cm)	Top depth (mbsf)	Bottom depth (mbsf)	Sample ID	SiO ₂	TiO ₂	Al ₂ O ₃	TFe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	LOI
502	C0027D	8X	CC	25.0–27.0	62.3	62.3	C0027D-8X-CC, 25–27 cm	51.9	2.30	12.5	10.0	0.12	7.94	6.74	3.12	3.27	0.66	98.5	1.31
		3K	1	26.0–28.0	65.3	65.3	C0027E-3K-1, 26–27 cm	51.9	2.28	12.4	10.0	0.12	8.36	6.69	3.07	3.20	0.66	98.7	1.19
		4K	1	0.0–4.0	68.0	68.0	C0027E-4K-1, 0–4 cm	52.7	2.30	12.6	10.0	0.12	8.13	6.72	3.11	3.20	0.66	99.5	0.13
		7K	1	26.5–28.0	75.8	75.8	C0027E-7K-1, 26.5–28 cm	52.1	2.30	12.5	10.1	0.12	8.22	6.74	3.07	3.27	0.66	99.0	1.82
		8K	1	63.0–66.0	79.1	79.2	C0027E-8K-1, 63–66 cm	51.6	2.24	12.2	10.2	0.12	8.89	6.58	3.03	3.15	0.64	98.6	1.89
		9K	1	48.0–50.0	82.0	82.0	C0027E-9K-1, 48–50 cm	52.3	2.32	12.5	10.2	0.12	8.23	6.85	3.09	3.14	0.63	99.4	1.43
		11K	CC	9.0–13.0	86.2	86.2	C0027E-11K-CC, 9–13 cm	51.9	2.29	12.4	10.3	0.13	8.44	6.77	3.03	3.14	0.62	98.9	2.15
		12K	1	21.0–25.0	89.2	89.3	C0027E-12K-1, 21–25 cm	51.9	2.30	12.4	10.1	0.12	8.15	6.85	3.19	3.03	0.62	98.7	0.75
		13K	1	56.0–60.0	92.1	92.1	C0027E-13K-1, 56–60 cm	51.7	2.27	12.4	10.1	0.12	8.12	6.87	3.14	2.83	0.57	98.1	1.17
		14K	CC	8.0–10.0	95.1	95.2	C0027E-14K-CC, 8–10 cm	51.8	2.23	12.3	10.3	0.13	8.73	6.78	3.14	2.72	0.57	98.7	1.08
C0027F	1K	16K	1	3.0–6.0	100.5	100.6	C0027E-16K-1, 3–6 cm	52.1	2.30	12.5	10.1	0.12	7.95	6.73	3.12	3.26	0.66	98.9	1.40
		17K	1	20.5–24.0	103.7	103.7	C0027E-17K-1, 20.5–24 cm	53.6	2.10	13.5	9.19	0.12	5.48	7.34	3.58	3.15	0.64	98.7	1.61
		1K	CC	14.0–16.0	57.5	57.5	C0027F-1K-CC, 14–16 cm	51.9	2.27	12.4	10.0	0.12	8.48	6.60	3.16	3.19	0.65	98.8	0.02

Total Fe is expressed as Fe₂O₃ (TFe₂O₃). LOI represents loss on ignition.

Table S2 Bulk-rock trace-element composition of drilled petit-spot basalts and JB-2 ($\mu\text{g g}^{-1}$).

Sample ID	Sc	Co	Cu	Rb	Sr	Y	Zr	Nb	Cs	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	Ti	Pb	Th	U
C0027E-3K-1, 26–28 cm	11.0	42.9	58.2	69.7	102.2	15.6	26.1	23.0	0.387	1240	47.5	95.6	11.2	43.9	8.06	2.40	6.45	0.858	4.02	0.629	1.61	0.166	1.01	0.113	6.57	1.28	0.120	9.68	3.15	0.662
C0027E-4K-1, 0–4 cm	11.6	41.4	59.5	71.5	105.6	16.1	27.0	23.7	0.413	1296	48.9	98.6	11.5	45.3	8.28	2.47	6.64	0.880	4.16	0.651	1.61	0.175	1.01	0.119	6.73	1.30	0.123	10.0	3.23	0.675
C0027E-8K-1, 63–66 cm	11.4	43.3	57.8	68.2	100.9	15.6	25.6	22.7	0.397	1220	46.6	93.5	10.9	43.3	8.01	2.37	6.37	0.853	3.96	0.640	1.62	0.167	1.01	0.119	6.45	1.27	0.122	9.58	3.10	0.644
C0027E-9K-1, 48–50 cm	11.6	42.1	58.9	65.3	97.8	15.8	24.5	23.0	0.395	1127	42.8	86.0	10.2	41.1	7.83	2.33	6.31	0.847	4.04	0.650	1.63	0.177	1.06	0.115	6.13	1.27	0.113	8.62	2.99	0.636
C0027E-11K-CC, 9–13 cm	10.9	42.8	57.9	63.9	96.0	15.6	24.1	22.9	0.412	1106	42.2	84.6	10.1	40.2	7.73	2.29	6.10	0.832	3.97	0.642	1.58	0.176	1.06	0.121	6.02	1.27	0.111	8.56	2.99	0.637
C0027E-12K-1, 21–25 cm	11.5	43.1	59.5	65.4	98.2	15.8	24.5	23.2	0.392	1129	42.4	86.0	10.2	40.7	7.87	2.34	6.40	0.851	4.04	0.646	1.65	0.175	1.03	0.121	6.14	1.29	0.105	8.52	3.00	0.642
C0027E-16K-1, 3–6 cm	10.7	40.5	58.9	69.8	102.5	15.8	26.2	23.1	0.399	1257	48.0	96.5	11.3	44.5	8.27	2.44	6.53	0.868	4.03	0.639	1.60	0.174	1.06	0.114	6.63	1.27	0.123	9.76	3.18	0.674
C0027E-17K-1, 20.5–24 cm	12.1	30.2	57.5	64.8	113.2	16.9	23.9	24.0	0.439	1115	42.5	85.5	10.2	41.6	8.24	2.52	6.70	0.898	4.27	0.697	1.70	0.186	1.13	0.127	5.83	1.32	0.105	9.04	3.52	0.812
JB-2 (This study)	51.4	35.0	210.39	6.33	171	21.1	44.8	0.452	0.771	208	2.18	6.42	1.11	6.25	2.25	0.812	3.22	0.581	3.96	0.861	2.62	0.375	2.52	0.383	1.50	0.032	0.031	5.06	0.257	0.154
	50.6	34.8	208.1	6.25	172	21.0	44.5	0.453	0.768	211	2.19	6.37	1.11	6.28	2.23	0.806	3.21	0.580	3.98	0.862	2.60	0.377	2.56	0.381	1.49	0.033	0.030	5.02	0.260	0.158
JB-2 (Jochum et al., 2016)	54.1	37.6	222.1	6.40	178	23.6	48.3	0.565	0.800	218	2.28	6.55	1.13	6.39	2.27	0.836	3.12	0.586	3.87	0.863	2.54	0.393	2.53	0.389	1.49	0.040	0.034	5.25	0.258	0.1528

Table S3 Mineral and glass major-element and volatile compositions of drilled petri-spot samples.

[illegible]

s.d. represents one standard deviation.

Table S4 Sr–Nd isotope compositions of drilled petit-spot basalts.

Sample ID	$^{87}\text{Sr}/^{86}\text{Sr}$	2 s.e.	$^{143}\text{Nd}/^{144}\text{Nd}$	2 s.e.
C0027E-3K-1, 26–28 cm	0.705186	0.000009	0.512364	0.000008
C0027E-4K-1, 0–4 cm	0.705185	0.000008	0.512362	0.000008
C0027E-8K-1, 63–66 cm	0.705169	0.000008	0.512357	0.000008
C0027E-9K-1, 48–50 cm	0.705083	0.000009	0.512370	0.000009
C0027E-11K-CC, 9–13 cm	0.705090	0.000008	0.512364	0.000009
C0027E-12K-1, 21–25 cm	0.705090	0.000008	0.512383	0.000009
C0027E-16K-1, 3–6 cm	0.705178	0.000008	0.512349	0.000008
C0027E-17K-1, 20.5–24 cm	0.705003	0.000009	0.512407	0.000010

2 s.e. represents 2 standard errors.