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“Grand” petit-spot volcanism off the Japan Trench

Asuka Yamaguchi^{1*}, Hiroko Kitajima², Norikatsu Akizawa³, Olivier Fabbri⁴, Matt J. Ikari⁵, Kenji M. Matsuzaki¹, Takashi Miyazaki⁶, Yasuyuki Nakamura⁶, Andrew P. Roberts⁷, Paola Vannucchi⁸, Naoto Hirano⁹, Gou Fujie⁶, Hanaya Okuda¹⁰, Ayumu Miyakawa¹¹, Natsumi Okutsu⁶, Yuya Akamatsu⁶, Lottie Atton¹², Takanori Kagoshima¹³, Taro Kido¹⁴, Rachel Lauer¹⁵, Jennifer M. Lington¹⁶, Kazuto Mikuni^{11&17}, Francesco Narduzzi¹⁸, Katie Preece¹⁹, Louisa H. Stokes²⁰, Fuka Takuwa¹, Taizo Uchida²¹, Hayato Ueda²², Christopher Yen²³, Erwan Le Ber²⁴, Adam Wspanialy⁶, Edoardo Barbero²⁵, Chin-Yeh Chen²⁶, Jose-Abel Flores²⁷, Mila Huebasch²⁸, Yuji Kato²⁹, Eun Young Lee³⁰, Jason Phipps Morgan³¹ and Sebastien Pilet²³

¹Atmosphere and Ocean Research Institute, The University of Tokyo, Chiba 277-8564, Japan

²Department of Geology and Geophysics, Texas A&M University, TX 77843-3115, USA

³Earth and Planetary System Science, Hiroshima University, Hiroshima 739-8526, Japan

⁴UMR Chrono-environnement, University Marie and Louis Pasteur, Besançon 25000, France

⁵MARUM – Center for Marine Environmental Sciences, University of Bremen, Bremen D28359, Germany

⁶Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokosuka, Kanagawa 237-0061, Japan

⁷Research School of Earth Sciences, Australian National University, Canberra, ACT 2601, Australia

⁸Department of Earth Sciences, University of Florence, Florence 50121, Italy

⁹Center for Northeast Asian Studies, Tohoku University, Sendai, Miyagi 980-8576, Japan

¹⁰Kochi Institute for Core Sample Research, JAMSTEC, Nankoku, Kochi 783-8502, Japan

¹¹Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology, Ibaraki 305-8567, Japan

¹²School of Geography, Earth and Environmental Sciences, University of Plymouth, Plymouth PL4 8AA, United Kingdom

¹³Graduate School of Science and Engineering, University of Toyama, Toyama 930-8555, Japan

¹⁴Department of Earth and Planetary Science, The University of Tokyo; Tokyo 113-8654, Japan

¹⁵Earth, Energy, and Environment, University of Calgary, Calgary T2N1N4, Canada

¹⁶School of Ocean and Earth Science, National Oceanography Centre Southampton, University of Southampton, Southampton SO14 3ZH, United Kingdom

¹⁷Department of Earth and Planetary Sciences, Institute of Science Tokyo, Tokyo 152-8551, Japan

¹⁸Department of Earth and Environmental Sciences, University of Pavia, Pavia 27100, Italy

¹⁹Department of Geography, Swansea University, Swansea SA2 8PP, United Kingdom

²⁰Earth Dynamics Research Group, School of Earth and Planetary Sciences, Curtin University, Perth, 6102, Australia

²¹Graduate School of Integrated Arts and Sciences, Kochi University, Kochi 780-8520, Japan

²²Department of Geology, Faculty of Science, Niigata University, Niigata 950-2181, Japan

²³Institute of Earth Sciences, University of Lausanne, Lausanne 1015, Switzerland

²⁴Géosciences Montpellier, Université de Montpellier, Montpellier 34095, France

²⁵Institute of Geoscience, CNR - National Research Council, Torino 10125, Italy

²⁶Institute of GeoEnergy Engineering, Heriot-Watt University, Edinburgh EH14 4AS, United Kingdom

²⁷Department of Geology, University of Salamanca, Plaza de la Merced, Salamanca 37008, Spain

²⁸School of Environment, University of Auckland, Auckland 1142, New Zealand

²⁹Marine Core Research Institute, Kochi University, Kochi 783-8502, Japan

³⁰Department of Geology, University of Vienna, Josef-Holaubek-Platz 2, 1090 Vienna, Austria

³¹Institut de Ciències del Mar (ICM-CSIC), Passeig Marítim de la Barceloneta 37–49, 08003 Barcelona, Spain

*Corresponding author: Asuka Yamaguchi

Atmosphere and Ocean Research Institute, The University of Tokyo

5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8564 Japan

Email: asuka@aori.u-tokyo.ac.jp

Abstract

Petit-spot volcanoes are a recently discovered type of small intraplate volcanoes that erupt on the outer rise of subducting plates. At petit-spot regions on the outer rise of the Japan Trench, an anomalously shallow acoustic basement reflector is widely distributed, leading to the hypothesis that it corresponds to sills or sheet-like lava flows and is associated with petit-spot magmatism. Here we report discoveries from the first drilling into the shallow acoustic basement off the Japan Trench. The basement is composed of petit-spot basalt, which is less altered with fewer vesicles than those exposed on the seafloor, resulting in higher bulk density and P-wave velocity. The lack of baked margins at the sediment-basalt boundary suggests that the basalt erupted as a lava onto the seafloor and was covered subsequently by 60 metres of sediment deposited over the past 3.6 Ma. Similar basalt ages and compositions at the drill site and an adjacent petit-spot knoll exposed on the seafloor, together with regional distribution of acoustic basement, suggest that the petit-spot volcanic base extends horizontally for at least 18 kilometres and potentially for hundreds of kilometres. Consequently, petit-spot volcanoes may have a greater impact on geochemical cycling and seismogenesis than previously thought.

Introduction

Petit-spot volcanoes are clusters of small, monogenetic intra-plate volcanoes that occur on the trench outer rise¹. Petrologically, they are composed of highly alkaline ($\text{Na}_2\text{O}+\text{K}_2\text{O} = 2.7\text{--}11.2 \text{ wt}\%$) and vesicular basalts originated from high carbon dioxide (CO_2) melts generated around the lithosphere-asthenosphere boundary³. First recognized on the ~130–140-Myr-old Pacific Plate off the Japan Trench¹, petit-spot volcanism has since been identified in other subduction-related settings, including offshore of Tonga, Chile, Java and in the Mariana Trench^{2,4}. In addition to previously recognized volcanism styles at mid-ocean ridges, volcanic arcs and hotspots, petit-spot volcanism occurs in and around trench outer rises of mature oceanic plates, and is associated with flexural bending of the oceanic plate before subduction. Petit-spot volcanism, therefore, offers valuable insight into the lithospheric and asthenospheric processes operating beneath oceanic plates immediately before they enter a subduction zone. Individual petit-spot volcanoes are generally thought to be small, with diameters of a few kilometres and heights of less than 300 metres, and so have been regarded as volumetrically minor volcanic features^{1,2,5}.

At petit-spot regions on the outer rise of the Japan Trench, seismic reflection surveys reveal a widespread distribution of anomalously shallow acoustic basement⁶ (Fig. 1). This has led to the hypothesis that the shallow acoustic basement corresponds to sills or sheet-like lava flows within

or above the pelagic sedimentary sequence, respectively, associated with petit-spot magmatism. If correct, the abundance and volume of petit-spot magmatism based solely on seafloor morphology may be substantially underestimated. However, direct evidence for the nature and origin of the shallow acoustic basement has been lacking because petit-spot volcanic rocks were so far recovered by submersible dives and dredging at the seafloor.

Here we present initial results from the International Ocean Drilling Programme (IODP³) Expedition 502: Impact of petit-spot magmatism on subduction zone seismicity and global geochemical cycles⁷ (T-Petit), conducted at Site C0027 on the outer rise of the Japan Trench (Fig. 1). Site C0027 is located in the petit-spot Site C region¹, where shallow acoustic basement is recognized pervasively⁶ (Fig. 1b; Supplementary Table S1). Expedition 502 achieved the first sampling across the shallow acoustic basement in a petit-spot province through coring and downhole logging to explore the nature of the basement in relation to petit-spot magmatism and to assess the impacts of such volcanism on carbon cycling and subduction zone seismogenesis.

Lithologies and physical properties at IODP³ Site C0027

Coring operations at Site C0027 recovered sediments from the seafloor (5477.0–5479.5 m water depths) down to ~60 metres below seafloor (mbsf) and igneous rocks between ~60 mbsf and the bottom of the hole at ~106.5 mbsf⁸ (Figure 2; Fig. S1, Table S1). The sediments recovered mainly from Hole C0027D are divided into Lithological Unit 1 (0–25.07 mbsf; early middle Pleistocene to Holocene siliceous mud) and Unit 2 (25.07–62.12 mbsf; late Pliocene to early middle Pleistocene siliceous mud with ash layers). Unit 1 consists of dark olive-grey siliceous mud with rare, thin volcanic ash layers. The mud comprises clay- to silt-sized siliciclastic grains, abundant siliceous microfossils including diatoms and sponge spicules, and common volcanic glass shards, with minor pumice and accessory minerals. Unit 2 comprises siliceous mud interbedded with frequent volcanic ash layers. The ash layers exhibit light to dark color variations and sedimentary structures such as normal grading, sharp basal contacts and variable laminations, indicating derivation from multiple distal volcanic sources and partial reworking. Unit 2 is subdivided into Subunits 2A (25.07–53.09 mbsf) and 2B (53.09–62.12 mbsf) in Hole C0027D based on a marked contrast in mud colour between olive-grey and yellowish-brown, respectively, across a sharp boundary at 53.09 mbsf (Fig. 2). No apparent sedimentological differences are observed between Subunits 2A and 2B, other than colour. Bioturbation of the sediments is pervasive and locally obscures primary sedimentary structures. Deformation is generally weak, with only minor normal faulting and soft-sediment deformation structures observed. Bedding is predominantly horizontal to subhorizontal (Fig. 2).

Basic volcanic rocks of Lithological Unit 3 were recovered from ~62 to 106.5 mbsf, the bottom of Hole C0027E (Fig. 2). Retrieved rocks were fragmented and rounded into small pieces with lengths of < 10 cm (mainly < 5 cm). Despite limited core recovery (average ~18 % core recovery), some of the volcanic rock pieces contain planar to curvilinear joint surfaces (Fig. 2; maximum ~23 joints per 1 m core), probably associated with columnar jointing during cooling. Based on core-scale observations, the volcanic rocks consist mainly of fresh glassy to cryptocrystalline basalt, containing olivine and minor clinopyroxene phenocrysts within a groundmass of acicular to dendritic crystals and glass (Fig. 2). No feldspar phenocrysts are observed and very small (~2 mm in diameter) xenoliths and xenocrysts of olivine occur in several cores. Downhole alternations of glassy basalt, glassy-cryptocrystalline basalt, and cryptocrystalline basalt are observed. Based on whole-rock compositions from X-ray fluorescence (XRF) analysis, volcanic rocks from Site C0027 have a high-alkali (> 6 wt % Na₂O + K₂O) basaltic trachyandesite composition on a total alkali–silica (TAS) diagram (Fig. 3a; after ref. ⁹). Basaltic rocks from Site C0027 overlap with the alkali and silica content range for seafloor samples from the petit-spot Site C region, closest to Site C0027, and other northwest Pacific petit-spot sites^{1,2,4,10}, although further detailed petrological analyses on major and trace elements confirm the unique petrological characteristics of the Site C0027 basalts different from seafloor samples¹¹.

The sediment-basalt boundary occurs at ~60 mbsf in all three coring holes (Supplementary Table S1). None of these boundaries have a well-developed baked margin on the sediment side, except for several millimetre-scale patches of sediments with mineral zonation on the basalt side. The absence of baked margins suggests that the basalt was not intruded into unconsolidated sediment as a sill but instead erupted onto the seafloor as lava and was covered subsequently by sediments. The colour change in Subunit 2B is interpreted as a low-temperature alteration zone that developed following petit-spot basalt eruption.

Downhole logging at Hole C0027C shows a sharp electrical resistivity increase from ~1.5 to ~20 Ω m at 63.5 mbsf, corresponding to the sediment-basalt boundary (Fig. 2). Sediments from Lithological Units 1 and 2 have bulk densities of 1.37–1.66 g cm⁻³, porosities of 57–80%, P-wave velocities of 1.49–1.81 km s⁻¹ and electrical resistivities of 0.4–0.56 Ω m, except for ash layers, which have higher resistivities of approximately 0.9 Ω m (Fig. 2). In contrast, basalt from Lithological Unit 3 has bulk densities of 2.72–2.86 g cm⁻³, porosities of 0.03–3%, P-wave velocities of 4.77–6.56 km s⁻¹ and electrical resistivities of 67–2261 Ω m. Such distinct physical property differences across the sediment-basalt boundary result in a sharp acoustic impedance contrast, consistent with the acoustic basement reflector with a large amplitude (Fig. 1c; Fujie et al., 2020).

The original target depth for logging at Site C0027 was 225 mbsf⁷. However, drilling of a logging hole (Hole C0027C) was challenging, and the penetration decreased to ~1 m/hour with the torque on bit increasing up to 17 kN m in the basalt unit (Fig 2.; Supplementary Figure S1). Efforts to deepen the hole were abandoned after 98 mbsf; the drill bit was completely worn and the hole was enlarged (See details in methods; Supplementary Figure S1). Basalt coring at Hole C0027E was also challenging, and recovered material was limited and fragmented. Poor recovery and planar fractures observed on recovered basalt fragments and hole enlargement suggest that the petit-spot basalt lava was fractured pervasively, contributing to cooling and hydrothermal circulation immediately after the petit-spot basalt emplacement. The basal part of the volcanic sequence and the underlying lithology could not be determined because coring was abandoned at 106.5 mbsf.

Age of eruption

The basalt at Site C0027 is interpreted as an extrusive lava, so its eruption age can be constrained from the age of the deepest overlying sediments. An integrated age model for sediments at Site C0027 was constructed using radiolarian biostratigraphy and magnetostratigraphy (Fig. 3b). Radiolarian bioevents and palaeomagnetic reversal datums are consistent within their respective uncertainties. The basal sediments show a depositional age of ~3.6 Ma. All five analyzed basalt samples have negative palaeomagnetic inclinations (Fig. 2), suggesting that the basalt erupted during a reversed magnetic polarity interval at 4.18–3.58 Ma (Fig. 3b). These estimated ages are consistent with a reported 3.77 ± 0.15 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ age for petit-spot basalt (7KII#392; ref. ⁴) in the petit-spot Site C region, sampled by remotely operated vehicle from a knoll ~18 km NNE of Site C0027 (Fig. 1). The age coincidence (4.18–3.58 Ma and ~3.77 Ma) and similar alkali and silica contents of basalts at Site C0027 and 7KII#392 suggest that the petit-spot lava spreads across the seafloor, perhaps due to a series of large-scale eruptions occurred at ~3.8–3.6 Ma (Fig. 4). By contrast, basalt samples from several knolls in the petit-spot Site C region, including those from two knolls located ~10 km E from Site C0027 (6K#1393a and 6K#1393b), yield younger ages of 1.85–0.02 Ma, estimated from the thickness of hydrated palagonite rims on chilled-margin glasses, and slightly different alkali and silica contents¹⁰. The duration of eruptions and whether the eruptions were continuous or episodic over the period is unknown at this moment, and requires further investigation to fully understand the petit-spot volcanism.

Extent of “grand” petit-spot volcanism

Drilling results at Site C0027 reveal that the anomalously shallow acoustic basement is composed of petit-spot basalts, implying that petit-spot knolls exposed on the seafloor represent only a small fraction of the entire volcanic system. Assuming that the petit-spot lavas erupted from the knoll at 7KII#392 and covered the seafloor to form a thin disk with 18 km radius and ~50 m thickness, the total volume of lavas are estimated to be ~50 km³. Seismic reflection profiles indicate that the thin-sediment section extends for ~90 km in the E–W direction and ~120 km in the N–S direction⁶. In a more extreme case, assuming a lava-covered area with 90–120 km diameter and ~50 m thickness, the overall erupted volume would be ~320–570 km³. Estimated volumes of the petit-spot volcanism in the Site C region range from 50 to 570 km³, which is 1–5 orders of magnitude larger than previously estimates (~10⁻³–10⁰ km³) for individual petit-spot volcanoes based on topographical information^{5,12}.

This total volume estimate of the petit-spot volcanism could be several times to an order of magnitude larger because the base of the lava sequence was not reached during Expedition 502, and several sills at greater depths are suggested to be present based on P-wave to S-wave (P-S) conversion interfaces detected below the acoustic basement by receiver-function analysis⁶ (Fig. 4). Although the estimated volume of this “grand” petit-spot volcanism is much smaller than that of a large igneous province (LIP)¹³, it is comparable to that of the North Arch volcanic field off Hawaii (1,000–1,250 km³; ref. ¹⁴). Future grid surveys of seismic reflection profiles, and further drilling beneath the shallowest petit-spot lava flow, will allow further understanding of both anatomy of petit-spot volcanoes and petit-spot magmatism.

The role of “grand” petit-spots for the global carbon cycle

The subseafloor petit-spot lava recovered at Site C0027 has few vesicles and low porosity, in contrast to highly vesicular petit-spot basalts sampled from seafloor knolls¹. This implies that CO₂ could be exsolved from the magma during eruption before emplacement and solidification of lava on the seafloor. The initial petit-spot magma is estimated to contain 5–10 wt% CO₂¹⁵. If this amount of CO₂ was released from the petit-spot lava body (2.8 g/cm³ bulk density) with an estimated ~50–570 km³ volume, the total CO₂ released from such “grand” petit-spot volcanism would correspond to ~2–43 × 10⁹ tonnes of carbon. Because the petit-spot eruptions occurred at a ~5 km water depth, the high hydrostatic pressure (~50 MPa) would have promoted dissolution of the CO₂ released into deep seawater. Thus, a substantial fraction of the CO₂ released by petit-spot volcanism may have been transferred directly to the deep ocean rather than the atmosphere, potentially contributing to its CO₂ saturation state and to deep seawater acidification, largely depending on the duration of eruptions and CO₂ release. The estimated CO₂ contribution equals ~0.03–0.12% of the carbon currently dissolved in the intermediate to deep ocean (37,100 × 10⁹

tonnes; ref. ¹⁶). Although this is small relative to the total amount of dissolved oceanic carbon, the cumulative contribution of similar “grand” petit-spot eruptions, if they occur along subduction zones worldwide, could be significant.

The role of “grand” petit-spots in subduction zone seismogenesis

At the Japan Trench, the plate-boundary fault is localized within a smectite-rich pelagic clay layer overlying chert, with exceptionally low coseismic friction^{17,18}. This layer is distributed widely across the northwest Pacific and is, therefore, an important component of the incoming plate that influences shallow megathrust slip^{19,20}. Petit-spot magmatism may disrupt its continuity, as suggested by the presence of basalts mixed with sediments²¹.

The physical property range of petit-spot basalts at Site C0027 is significantly different from that of typical Pacific plate oceanic basalts. Compared to basalts and dolerites from the subducting Pacific plate in the Japan Trench at Site C0019, located ~100 km west of Site C0027 (Fig. 1; ref. ²²), basaltic rocks at Site C0027 have lower porosity, higher bulk density, P-wave velocity and electric resistivity (Fig. 2). In addition, challenging drilling with higher torque and lower rate of penetration and recovery of limited and fragmented cores at Site C0027 contrast with relatively smooth drilling and continuous core recovery of intact basalts and dolerites at Site C0019²² (Fig. 2 and Supplementary Figure S1). Differences in physical properties are likely attributed to alteration differences of basalt; basalt at Site C0027 is little altered whereas basalt at Site C0019 has experienced various degree of low-temperature alteration²². Collectively, these findings suggest the petit-spot basalt formation at Site C0027 likely has greater strength compared to typical Pacific plate oceanic basalt.

The presence of such basalt could not only disrupt the continuity of the low-friction pelagic clay layer but also introduce substantial heterogeneity in the mechanical properties of the incoming plate and potentially create exceptionally strong patches along the subduction plate interface. Such mechanical heterogeneity in the subducting plates created by petit-spots should be evaluated not only in the Japan Trench but also in other subduction zones where petit-spots have been observed². Strong patches due to petit-spot volcanics have 10³–10⁴ km² area, and could influence the nucleation and rupture propagation of megathrust earthquakes. If a patch with 10³–10⁴ km² area is fully ruptured, it could produce a $M_w \sim 7.5$ –8.5 earthquake²³. Measurements of the strength and frictional properties of petit-spot basalt from Site C0027 samples, combined with numerical modelling, will help to clarify its potential role in subduction-zone seismogenesis.

Methods

Drilling, logging, and coring operations at Site C0027

IODP³ Expedition 502 was conducted using the Drilling Vessel *Chikyu*. At Site C0027, four boreholes were drilled at water depths of 5477–5479.5 m⁸ (Fig. 1; Supplementary Table S1); Holes C0027C, C0027D and C0027E are ~30 metres apart from each other and Hole C0027F is located ~400 metres away from other three holes.

In Hole C0027C, after drilling to 98.0 mbsf with an 8.5-inch bit, logging data were acquired between 26 and 80 mbsf while tripping the bit out of the drillhole over three runs using a tool suite measuring natural gamma radiation, spectral gamma radiation, electrical resistivity, sonic velocity, and resistivity imaging. Sonic and resistivity imaging data are of poor quality owing to borehole enlargement (> 10 inches based on caliper measurements). By contrast, gamma-ray and resistivity logs remain within their respective depths of investigation and provide reliable measurements.

Coring operations were conducted in Holes C0027D, C0027E, and C0027F (Fig. 2). At Hole C0027D, nine cores were collected primarily from sediments using a Hydraulic Piston Coring System (HPCS)/Extended Shoe Coring System (ESCS) from the seafloor to 67.5 mbsf. In Holes C0027E and C0027F, cores were collected using the Small Diameter Rotary Core Barrel (SD-RCB). Seventeen cores, consisting primarily of igneous rock, were collected from the 59–106.5 mbsf interval in Hole C0027E. A core that contains the sediment-basalt boundary was recovered in an interval from 56.2 to 63 mbsf at Hole C0027F. Drilling parameters, including weight and torque on bit, drilling fluid pumping rate, and bit depth, were measured, monitored, and recorded at 1 Hz during all the drilling operations, and were analyzed when the bit advanced to cut the formation.

Shipboard core descriptions and analyses

Shipboard core handling, description, and data processing during Exp. 502 followed the procedures established during previous International Ocean Discovery Program (IODP) expeditions conducted by D/V *Chikyu* (e.g., ref. ²⁷). Recovered cores were cut into ~1.4-m-long sections. Core sections were scanned using X-ray computed tomography (X-CT), and non-destructive physical property measurements were performed by the Core Measurement Track (COMET; NS Design). Each section was split into working and archive halves. The archive half was subjected to non-destructive measurements and observations, including lithological visual core description (VCD), smear-slide analysis, and digital photographic imaging. The working half

was used for destructive measurements and analyses, including physical property measurements (porosity, density, and resistivity), bulk geochemical analyses, including X-ray diffraction (XRD) and X-ray fluorescence (XRF), palaeomagnetic analyses, and structural VCD. Sediments were classified based on composition, colour, grain size, and sedimentary structures, with support from smear-slide observations and X-CT, XRD, and XRF analyses. Igneous rocks were described based on mineral composition, texture, and colour, with support from thin-section observations and X-CT, XRD, and XRF analyses.

Moisture and density index properties (e.g., bulk density, porosity, and grain density) for discrete samples taken from the working halves were determined from mass measurements on wet and dry specimens, volume measurements of dry specimens, and corrected for salinity. Mass and solid volume of the samples were measured using an Ocean High Technology Institute custom-built motion-compensated shipboard balance system and a Quantachrome helium gas pycnometer, respectively. Dry mass and volume were measured after the samples were dried in a convection oven at 105 ± 5 °C for at least 24 hours. With this method, the measured porosity is connected porosity. Electrical resistivity was measured using a Keysight E4990A Impedance Analyzer with the bridge method. For unconsolidated sediment, a four-pin Wenner array consisting of four 1 cm-long electrodes spaced 7.5 mm apart was inserted into the working halves of split cores. For consolidated sediments and hard rocks, discrete cube samples (2 cm × 2 cm × 2 cm) were prepared, and the specimen cube was positioned between two stainless steel electrodes lined with seawater-saturated filter paper and measured in three orthogonal directions. For consolidated sediments and hard rocks, *P*-wave velocity (V_P) and *S*-wave velocity (V_S) were also measured on the same cubic samples used for electrical resistivity. Wave velocities along a given direction were measured using an Elastic Wave Velocity for Discrete analysis apparatus (D-EWVEL) equipped with two sets of 1 MHz transducers, one for V_P measurements and one for V_S measurements, along with the sample length between the transducers determined with a laser distance sensor.

For sediment age estimation, micropalaeontological samples for radiolarian biostratigraphy were collected routinely from the core catcher of each core and also from selected intervals of split cores (Supplementary Table S2). Palaeomagnetic analyses were conducted on discrete samples collected from the working halves of cores. Stepwise alternating-field demagnetization of the natural remanent magnetization was performed at room temperature. Demagnetization data were analyzed to determine the characteristic remanent magnetization components, including declination, inclination, and maximum angular deviation, for samples with stable remanence. Biostratigraphic age determination is based on regional radiolarian biostratigraphic zonations established for the Pleistocene and Mio-Pliocene in northwest Pacific²⁸. Palaeomagnetic age

324 assignments were based on the Geological Time Scale 2020²⁹.

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326 Figures

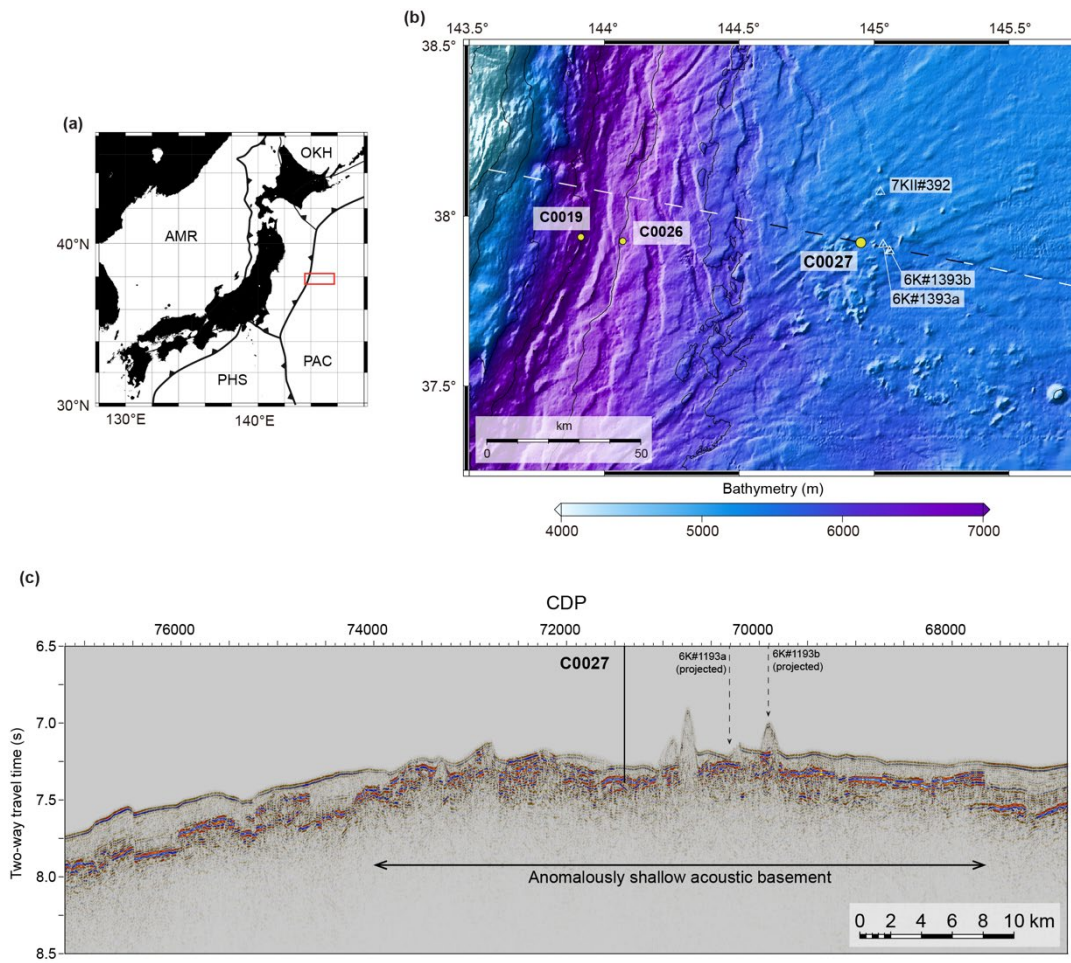


Figure 1. Geological setting of the study area on the outer rise of the Japan Trench. a) and b) Map of the study area and IODP³ Site C0027, respectively, and c, seismic reflection profiles near Site C0027. The red box in a indicates the location of the more detailed map in b. In b, adjacent petit-spot sampling locations (7KII#392, 6K#1393a and 6K#1393b; ref. ^{4,10}) as well as IODP Sites C0019 and C0026 (ref.²⁴) are shown. Furthermore, the white dashed line is location of seismic reflection lines TH03²⁵ and A4²⁶; the black dashed line indicates the seismic profile along the seismic reflection line A4 shown in c. In c, the projected locations of 6K#1393a and 6K#1393b are shown. Anomalously shallow acoustic basement is observed near Site C0027^{6,7}. PAC, Pacific plate; PHS, Philippine Sea plate; OKH, Okhotsk plate; AMR, Amur plate.

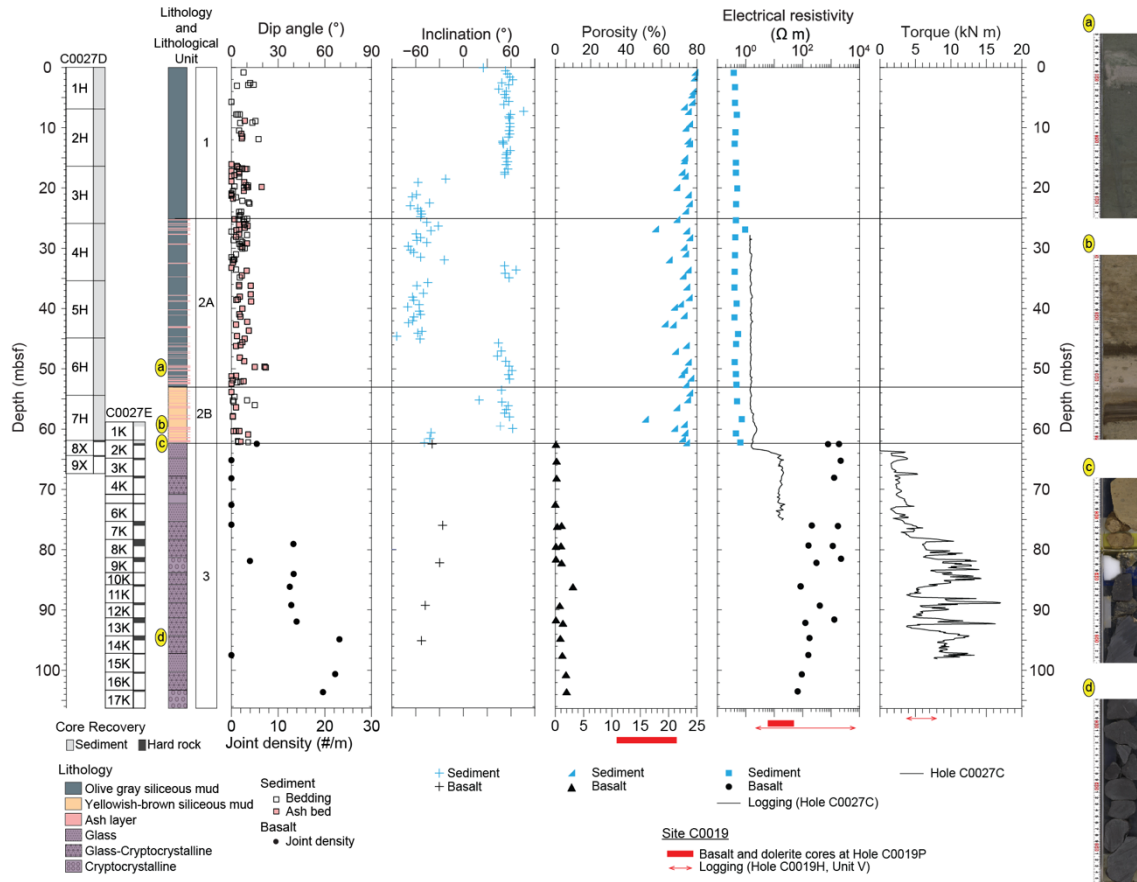


Figure 2. Composite summary of Site C0027, IODP³ Expedition 502. Coring, logging, and drilling data with depth at Site C0027, including coring, lithology and lithological units, dip angle of bedding in sedimentary units (Lithological Units 1, 2A, and 2B) and joint density in basalt (Lithological Unit 3), palaeomagnetic inclination, porosity, electrical resistivity measured on discrete samples (blue squares for sediments and black circles for basalt) collected from Holes C0027D and C0027E, electrical resistivity log at Hole C0027C, and, torque on bit (8.5” diameter) measured drilling of the logging hole (Hole C0027C) (Modified from ref. ⁸). Measured ranges of porosity (10.8–21.4%), electrical resistivity (6–50 Ω m in discrete samples and 2–8,000 Ω m in log), and torque on 8.5” diameter bit (4–8 kN m) at Site C0019 for Lithologic Unit P3 consisting of basalt and dolerite at 940.46–946.61 mbsf (Hole C0019P) and logging Unit V at 926.5–980 mbsf (Hole C0019 H) are shown for comparison (Regalla et al., 2025). Representative core photos of (a) Lithological Unit 2A (C0027D-6H-4, 53–83 cm; 50 mbsf) and (b) Lithological Unit 2B (C0027D-7H-4, 40–70 cm; 59 mbsf); (c) sediment-basalt boundary (C0027E-2K-1, 24–54 cm; 62.5 mbsf); and (d) Lithological Unit 3 (C0027E-14K-1, 26–56 cm; 95 mbsf) are shown on the right.

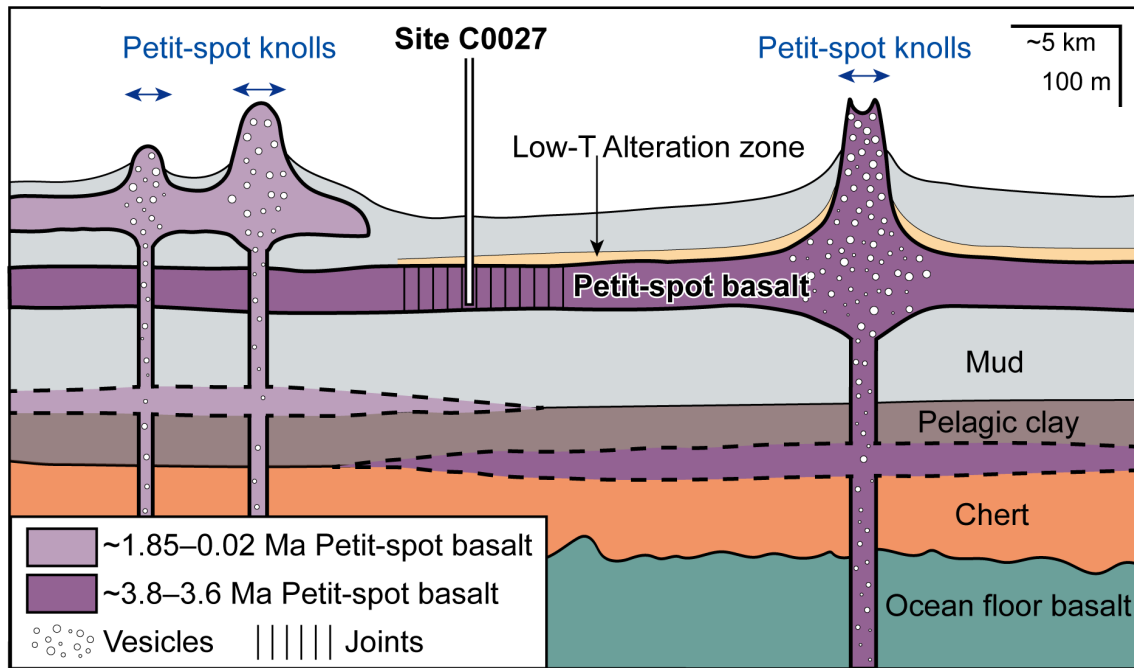
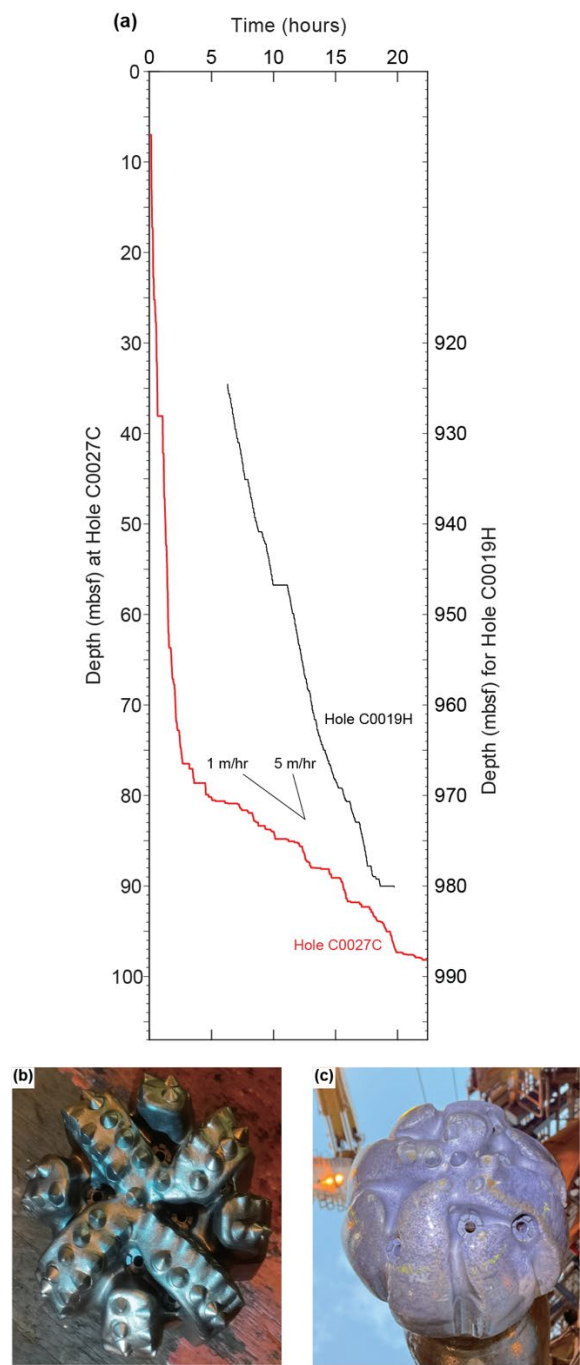


Figure 4. Schematic diagram of “grand” petit-spot volcanism revealed by subseafloor drilling. Petit-spot basalts recovered at Site C0027 likely originated from a widespread lava flow erupted on the seafloor at least over 18 km at ~3.8–3.6 Ma, which is buried by sediments deposited after the eruption. The buried lava flow has low porosity and is fractured possibly by columnar jointing in contrast to vesicular basalt forming the knolls. Younger petit-spot volcanoes (1.85–0.02 Ma; ref. ¹⁰) also erupted onto the seafloor by magma penetrating through the 3.8–3.6 Ma petit-spot lava basalts. Note that the presence and distribution of sills beneath the lava flow remain highly uncertain, and follows the conceptual models presented in ref. ^{6,21}. Vesicles and joints in the figure are not to scale.



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379 **Figure S1: Drilling challenges at Site C0027.** (a) Drill bit depth as a function of time since spud-
380 in. (b and c) Photos of an 8.5” drill bit (b) before and (c) after drilling operations at Hole C0027C.
381 In a, drill bit depth while drilling logging Unit V (basalt) from 925–980 mbsf at Hole C0019H is
382 shown for comparison (time is in a relative scale)²².

Supplementary Tables captions

Table S1. Summary of hole locations and operations at Site C0027.

Table S2. Summary of the biostratigraphic events identified at Holes C0027D and C0027E.

Data availability

All data acquired during the offshore operations are available in J-SODD:

<https://www.jamstec.go.jp/jsodd/chikyu/datasearch/>. Seismic data used in this study is available upon request in the JAMSTEC seismic survey database, <https://doi.org/10.17596/0002069>.

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Author Contributions

A.Y., H.K. and N.O. developed the scientific objectives and operational plan of IODP³ Expedition 502. A.Y., H.K., N.O., Y.A., N.A., L.A., O.F., M.J.I., T.Ka., T.Ki., R.L., J.M.L, K.M.M., K.M., A.M., T.M., Y.N., F.N., H.O., K.P., A.P.R., L.H.S., F.T., T.U., H.U., P.V., C.Y., E.L.B. and A.W. contributed to data collection, analysis, and quality assurance on *Chikyu* during IODP³ Expedition 502. A.Y. and H.K. prepared the original draft based on the shipboard data collection and analysis. All co-authors contributed to review and edit the manuscript.

Competing interests

The authors declare no competing interests.

Supplementary Table S1. Summary of Expedition 502 operations and hole locations (Kitajima et al., submitted) and submersible sampling locations (Machida et al., 2015; Sato et al., 2018). mbsl = metres below sea level and mbsf =metres below sea floor.

Site	Hole	Latitude	Longitude	Water depth (mbsl)	Total penetration (m)	Drilled interval (mbsf)	Operation	Cored interval (mbsf)	Core recovered (m)	Recovery (%)	Total cores (n)
C0027	C	37°55.3351'N	144°57.0339'E	5477.5	98.0	0-98.0	Logging	-	-	-	-
	D	37°55.3436'N	144°57.0129'E	5477.0	67.5	-	Coring	0-67.5	64.8	96.0	9
	E	37°55.3436'N	144°57.0514'E	5477.5	106.5	0-59.0	Coring	59.0-106.5	8.60	18.1	17
	F	37°55.3002'N	144°57.3128'E	5479.5	63.0	0-56.2	Coring	56.2-63.0	1.33	19.6	1
	Expedition Total:				335.0			121.8	73.4	60.3	27

7KII#392		38°04.40'N	145°01.61'E	5450	(Machida et al., 2015)
6K#1393a		37° 55.0020'N	145° 1.9736'E	5398	(Sato et al., 2018)
6K#1393b		37° 53.8543'N	145° 3.4159'E	5189	(Sato et al., 2018)

Supplementary Table S2. Summary of the biostratigraphic events identified at Holes C0027D and C0027E. LO: Last Occurrence; FO: First Occurrence.

Event species	top (sample)	bottom (sample)	Top depth (m)	Bottom depth (m)	Middle depth (m)	Age (Ma)	Age error (Ma)
LO <i>Lychnocanoma sakaii</i>	-	C0027D-1H-3, 50–52 cm	0.00	3.32	1.66	0.03	0.05
LO <i>Amphimelissa setosa</i>	C0027D-1H-3, 50–52 cm	C0027D-1H-CC, 20–25.5 cm	3.32	6.98	5.15	0.08	0.05
LO <i>Schizodiscus japonicus</i>	C0027D-1H-CC, 20–25.5 cm	C0027D-2H-3, 67–68 cm	6.98	10.42	8.70	0.29	0.05
LO <i>Axoprunum acquilonium</i>	C0027D-2H-3, 67–68 cm	C0027D-2H-CC, 45.5–50.5 cm	10.42	16.48	13.45	0.36	0.01
LO <i>Stylatractus universus</i>	C0027D-2H-3, 67–68 cm	C0027D-2H-CC, 45.5–50.5 cm	10.42	16.48	13.45	0.43	0.01
LO <i>Lamprocyrtis neoheteroporus</i>	C0027D-3H-3, 68–69 cm	C0027D-3H-CC, 38.5–43.5 cm	19.97	26.32	23.15	0.77	0.10
LO <i>Eucyrtidium matuyamai</i>	C0027D-3H-CC, 38.5–43.5 cm	C0027D-4H-3, 55–56 cm	26.32	29.37	27.85	0.95	0.05
FO <i>Amphimelissa setosa</i>	C0027D-4H-3, 55–56 cm	C0027D-4H-CC, 44.5–49.5 cm	29.37	35.89	32.63	0.99	0.05
FO <i>Schizodiscus japonicus</i>	C0027D-4H-3, 55–56 cm	C0027D-4H-CC, 44.5–49.5 cm	29.37	35.89	32.63	0.99	0.05
LO <i>Lamprocyrtis heteroporus</i>	C0027D-4H-CC, 44.5–49.5 cm	C0027D-5H-3, 82–83 cm	35.10	39.10	37.10	1.55	0.10
LO <i>Actinomma robusta</i>	C0027D-4H-CC, 44.5–49.5 cm	C0027D-5H-3, 82–83 cm	35.10	39.10	37.10	1.45	0.10
FO <i>Eucyrtidium matuyamai</i>	C0027D-5H-3, 82–83 cm	C0027D-5H-CC, 28.5–33.5 cm	39.10	45.55	42.33	1.80	0.10
LO <i>Cycladophora sphaeris</i>	C0027D-5H-CC, 28.5–33.5 cm	C0027D-6H-3, 125–126 cm	45.55	49.09	47.32	2.30	0.10
FO <i>Cycladophora davisiana</i>	C0027D-6H-9, 95–96 cm	C0027D-6H-CC, 21.5–26.5	53.4	54.4	53.90	2.61	0.10
LO <i>Hexaconthium parviakitaensis</i>	C0027D-6H-CC, 21.5–26.5 cm	C0027D-7H-3, 68–69 cm	54.4	57.99	56.20	2.71	0.05
FO <i>Botryostrobus aquilonaris</i>	C0027D-7H-3, 68–69 cm	C0027D-7H-5, 105–106 cm	57.99	60.71	59.35	2.80	0.10
LO <i>Stichocorys peregrina</i>	C0027D-6H-3, 125–126 cm	C0027D-6H-4, 64–65 cm	49.09	50.30	49.70	2.70	0.10
LO <i>Haliomma pseudojaponica</i>	C0027D-7H-5, 105–106 cm	C0027D-7H-6, 53–54 cm	60.70	61.70	61.20	3.30	0.10
LO <i>Anthicyrtidium pliocenica</i>	C0027D-7H-CC, 0–5 cm	C0027E-2K-2, 29–31 cm	61.94	62.29	62.12	3.40	0.20