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Melt re-injection into large magma reservoir after giant caldera eruption at Kikai Caldera Volcano



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Melt re-injection after a giant caldera eruption was quantitatively investigated for the Kikai Caldera Volcano in Japan, which erupted 7300 years ago (Kikai-Akahoya eruption). Our seismic refraction survey revealed a low-velocity anomaly directly beneath the Kikai Caldera Volcano, indicating the existence of a large magma reservoir at a shallow depth of 2.5–6 km. The reservoir can be approximated by a trapezoidal shape in this 2D section, with its width being at least the same as the width of the inner caldera, and its melt fraction was estimated as 3–6%, but could be limited to 10% at most. We propose a melt re-injection model in which new melt is re-injected into this large magma reservoir at the shallow depth just beneath the caldera, which is the same magma reservoir for the Kikai-Akahoya eruption. This model may demonstrate a common feature of volcanoes that have experienced a giant caldera eruption.

Giant caldera eruptions eject large amounts of magma in a short period, creating a caldera topography. Based on the statistical characteristics of the magnitude M ($M = \log_{10}(m) - 7.0$, where m is the erupted mass in kg¹) and frequency of volcanic eruptions on the Japanese Islands, giant caldera eruptions that eject 10^{14} kg of magma (equivalent to 40 km^3 when the bulk density of the deposit is 2500 kg m^{-3}), or more ($M > 7$) are considered to have different magma generation, accumulation, and eruption processes from small-scale mountain eruptions ($M < 5.7$) that occur at a high frequency². To advance our understanding of magma generation, accumulation, and eruptive processes of giant caldera volcanoes, eruption cycle models have been proposed by estimating the eruptive volumes of past eruptions through geological surveys³. Quantifying the extent of melt re-injection following giant caldera eruptions, the timing and magnitude of which are well known, can provide a clearer picture of magma generation and accumulation at giant caldera volcanoes, and lead to an understanding of the processes that result in eruptions.

Investigations to image the seismic crustal structure beneath caldera volcanoes after giant caldera eruptions have been conducted using seismic methods with natural sources, such as seismic tomography, including the recent ambient noise tomography method. These methods are useful for studying large-scale magma reservoirs because of their resolution. One example is the study of the Yellowstone volcanic system, which had the last giant caldera eruption that formed the Yellowstone caldera at 631 ka and ejected $>1000 \text{ km}^3$ of rhyolite that composes the Lava Creek Tuff^{4,5}. Tomographic images based on the full waveform inversion of ambient noise

correlations revealed reductions in the shear wave speed of over 30% associated with Yellowstone's silicic magma reservoir⁶. Their results showed that the slowest seismic wave speeds, which estimated a partial melt fraction of 16–20%, were present at depths between 3 and 8 km just beneath the Yellowstone caldera. Another example is the study of the Toba caldera volcanic system, which had the last giant caldera eruption at 74 ka, widely regarded as the largest terrestrial volcanic eruption of the Pleistocene^{7,8}. The total volume of the material erupted was $\sim 5300 \text{ km}^3$ DRE (Dense Rock Equivalent)⁹. A multiparameter ambient noise adjoint tomography method revealed over 30% S-wave velocity reductions beneath the Toba caldera, with its peak located at depths of 5–11 km just beneath the caldera, and estimated a melt fraction ranging from 14.5% to 18.5%¹⁰. An important aspect is that both caldera volcanoes have a large magma reservoir at a shallow depth just beneath the caldera.

The study of the Santorini Volcano in Greece is the only previous study to carry out a large-scale detailed seismic refraction survey after a recent large caldera-forming eruption: the Late Bronze Age (LBA or Minoan) eruption occurred 3600 years ago¹¹, with a DRE of $34.5 \pm 6.8 \text{ km}^3$ ¹², although the ejected magma was slightly smaller than 40 km^3 . The results of the seismic refraction surveys imaged low-velocity anomalies that are interpreted as two distinct parts. One is a high-porosity column created by collapse of a limited area of the caldera floor below the northern caldera basin centred at 1.6 km depth¹³. The other is a magma body from 2.8 km to 5 km depth localized below the northern caldera basin, suggesting that the

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shallow crust remains conducive to melt storage shortly after the LBA eruption¹⁴.

We chose the Kikai Caldera Volcano (Fig. 1a) as the target for our quantitative study of melt re-injection after a giant caldera eruption. This is because this volcano experienced a giant caldera eruption, the Kikai-Akahoya (K-Ah) eruption, 7300 years ago¹⁵ with a DRE of 133–183 km³, which is probably the largest eruption of the Holocene¹⁶. The existence of a post-caldera central lava dome within the inner caldera, caused by a different magma source than the K-Ah eruption, is known to be the largest worldwide, with a volume of over 32 km³¹⁷. In addition, a petrological study¹⁸ proposed a model of the magma reservoirs after the K-Ah eruption, suggesting that the central lava dome was formed by volcanic activity from a different magma 3900 years ago. To determine the current state of the magma reservoir beneath the Kikai Caldera Volcano, we conducted a seismic refraction survey using 39 ocean bottom seismometers and an air-gun array from the R/V Kaimei along a 175 km survey line across the volcano (survey overview in Methods).

Results and discussion

Four regions showing different characteristic velocity structures

Two-dimensional P-wave velocity structures were estimated just below the survey line crossing the Kikai Caldera Volcano (velocity modelling in

Methods). The results show that the velocity structure varies horizontally and can be classified into four regions with characteristic velocity structures based on vertical P-wave velocity profiles (Figs. 1 and 2). That is, the velocity gradient from the surface, which has a steep gradient, changes to a gentle gradient at a faster velocity in the order of regions A to D (Fig. 2). Except for Region A where the Kikai Caldera Volcano is located, the velocity gradients are spatially aligned from slowest to fastest from Region B to Region D, suggesting a transition from Region B on the Ryukyu Trench side, which shows a velocity structure considered to be island arc crust¹⁹, to Region D on the Okinawa Trough side, which shows a velocity structure similar to oceanic crust^{20,21}. Region C can therefore be interpreted as representing the transition process from Region B to Region D. These results suggest that the Kikai Caldera Volcano is located in this transition, Region C, and its activity modified the P-wave velocity structure as Region A.

Low velocity anomaly, temperature and melt fraction below the Kikai Caldera Volcano

Region A, where the Kikai Caldera Volcano is located, has a lower mean P-wave velocity than the surrounding Region C at depths of 2–12 km (Fig. 2). To quantify the spatial extent of this low-velocity region, we calculated the velocity anomaly as the difference from the background velocity structure. The one-dimensional background velocity structure was

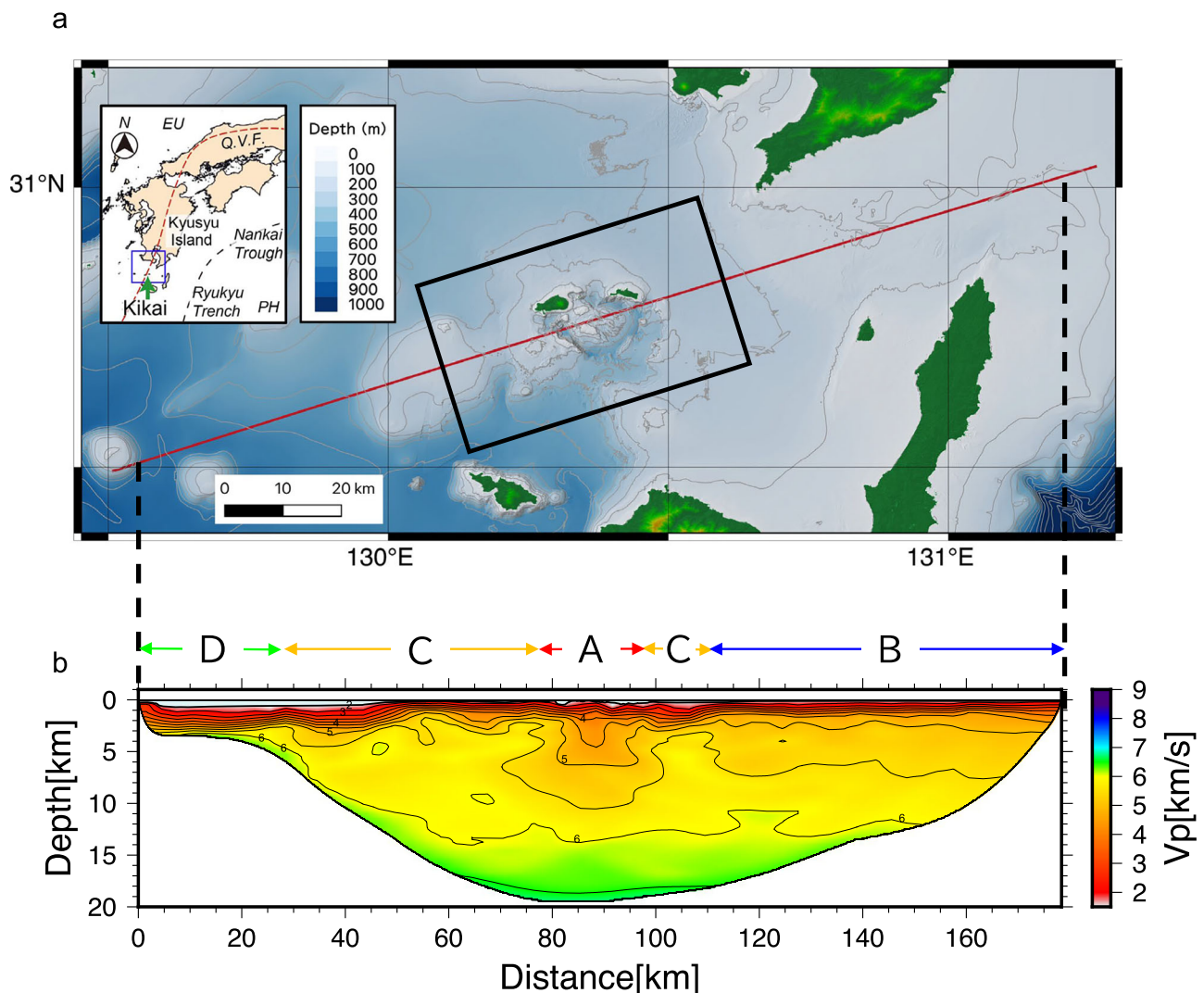
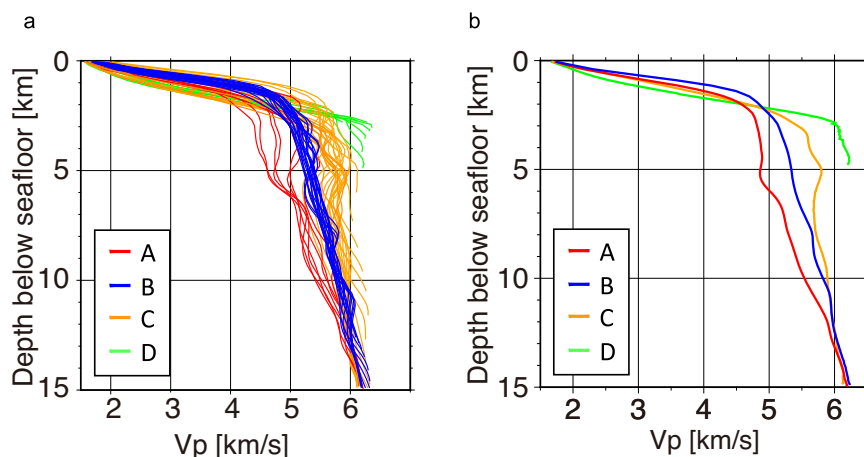


Fig. 1 | Study area and P-wave velocity model. **a** Bathymetric map of the study area (inset). The solid red line represents the seismic refraction survey line. The Kikai Caldera Volcano is located within the quadrangle, and its enlarged view is shown in Fig. 3a. **b** P-wave velocity model along the survey line determined using first-arrival

tomography. The contour interval is 0.5 km s⁻¹ and is annotated every 1.0 km s⁻¹. Areas deeper than the ray path coverage were masked. Four regions with characteristic velocity structures are shown in regions A, B, C, and D at the top of the figure.

Fig. 2 | Vertical P-wave velocity profiles. The vertical P-wave velocity profiles were extracted from the 2D P-wave velocity structure, where the vertical axis is the depth from the seafloor and the horizontal axis is the P-wave velocity. Different regions are shown in different colours. **a** Vertical P-wave velocity profile for every 3 km horizontal distance. **b** Vertical P-wave velocity profile averaged over each region.



generated by averaging the one-dimensional velocity profiles at 1 km intervals along the survey line in the western (60–77 km horizontal distance) and eastern (100–110 km horizontal distance) parts of Region C. The cross section of the velocity anomaly (Fig. 3b) shows that the area of the pronounced low-velocity anomaly with a velocity reduction rate of more than 15% (maximum velocity reduction of 22%) was trapezoidal in shape. We excluded areas shallower than 2 km to calculate the velocity anomaly because these areas show steep velocity gradients with depth (Fig. 2) and these gradients cause large uncertainties in the velocity anomaly estimate, as even a small depth difference results in a large velocity anomaly.

The low-velocity anomaly beneath the Kikai Caldera Volcano (Fig. 3b) allows us to estimate the temperature and the melt zone with its melt fraction. The low-velocity anomaly beneath the volcano can be interpreted as a high-porosity column created by collapse or melt with high temperature as suggested for the Santorini Volcano^{13,14}, but we assumed that the low-velocity anomaly beneath the Kikai Caldera Volcano, which is deeper than 2 km, is due only to temperature up to the solidus temperature and only to melt above the solidus temperature. Our assumption is based on a petrological study of rhyolite dredged from the large central lava dome of the post-caldera, which estimated magma depths of 2–4 km beneath the Kikai Caldera Volcano¹⁸. A high-porosity column created by collapse may exist in the shallower part than 2 km, as occurs in the northern caldera basin of the Santorini Volcano¹³, but the Kikai Caldera Volcano may be different as it has the large central lava dome covering the whole area within the inner caldera without a basin.

We calculated the temperature (Fig. 3c), assuming that the background geothermal gradient is 40 K km^{-1} and the low-velocity anomaly is caused only by the temperature increase. It should be noted that the temperature above the solidus temperature is not real, as the velocity decrease there is caused mainly by the melt fraction rather than by the temperature increase. The calculation is based on the empirical relationship between changes in P-wave velocity and temperature with velocity anomalies being proportional to temperature anomalies. We used the value of -0.00018 K^{-1} for the temperature derivative term of velocity, as this value is based on the average value obtained in laboratory experiments on granite up to 500°C ²².

The melt zone, where melting occurs, is an area with a temperature above the solidus temperature, which we assumed to be 750°C (dashed red line in Fig. 3c and dashed green line in Fig. 3d). The melt fraction in the melt zone (Fig. 3d) was estimated by assuming that any further seismic velocity reduction in the low-velocity anomaly above the solidus temperature was equivalent to the melt fraction. The velocity reduction by raising the temperature to the solidus temperature was 5–10%, depending on the depth. And the further velocity reduction in P-wave velocity was used to estimate the melt fraction by applying it to the formula for seismic velocities in solid-liquid mixed systems²³, assuming an aspect ratio of the melt based on experimental studies. Specifically, we refer to experimental studies showing that the maximum grain boundary dihedral angle in basalt-peridotite is

10° ²⁴, and assuming a maximum dihedral angle of 10° for rhyolite, the product of the magma here, the melt aspect ratio is estimated to be 0.09 from the relationship between the dihedral angle and the equivalent aspect ratio in a solid-liquid mixed system²³. We then estimated the melt fraction (Fig. 3d) from the velocity reduction rate with a melt aspect ratio of 0.09. For example, the melt fractions corresponding to velocity reduction rates of 6% and 13% were estimated to be 3% and 7%, respectively (Fig. 4), which shows that the melt fraction is approximately half of that of the velocity reduction rates.

Identification of magma reservoir

The melt fraction in the melt zone (Fig. 3d) indicates the existence of a region with a high melt concentration directly beneath the central lava dome of the Kikai Caldera Volcano. We identified the region with a melt fraction greater than 3% (up to 6%) as a magma reservoir (outlined by the solid green line in Fig. 3d). This corresponds to an area of 15% or more reduction in velocity, since a 10% reduction is equivalent to a temperature increase to the solidus temperature located at a shallow depth, and a 5% reduction is equivalent to a 3% melt fraction. The magma reservoir is located at a shallow depth of 2.5–6 km and can be approximated by a trapezoidal shape in this 2D cross section, with an upper base of 4 km, a lower base of 13 km, and a height of 3.5 km. Assuming that this magma reservoir is an axial object, its volume can be calculated as 220 km^3 , indicating the large size of the magma reservoir.

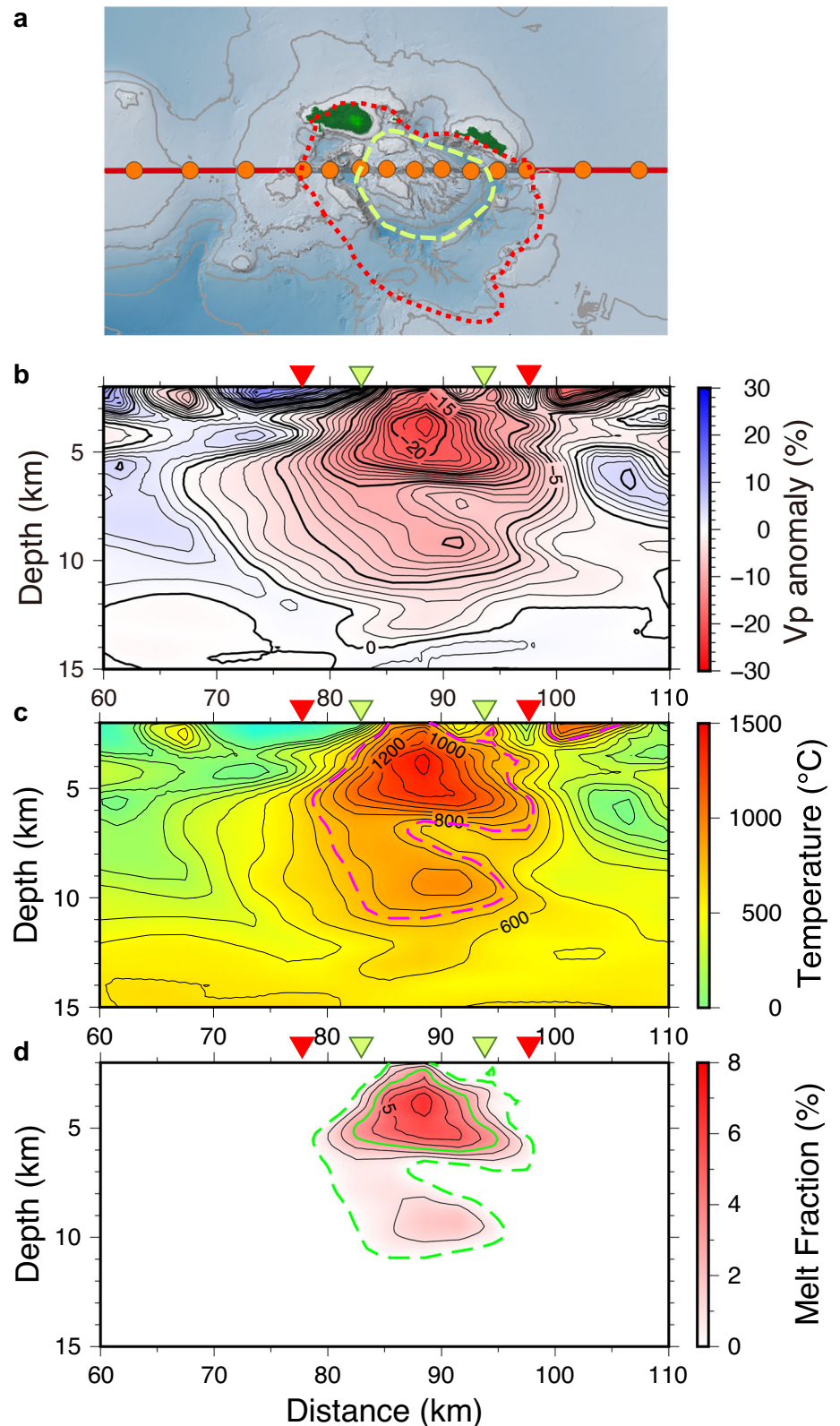
The validity of the velocity structure model for the magma reservoir, which corresponds to the area of velocity reduction of 15% or more, was confirmed by checkerboard resolution tests and Monte Carlo uncertainty analysis (velocity modelling in Methods). Furthermore, we performed a synthetic recovery test (velocity modelling in Methods) to assess the extent to which the area of velocity reduction of 15% or more could be reproduced by applying a corresponding velocity anomaly. The results (Fig. 5) indicate that the area of velocity reduction of 15% can be generally reproduced by applying a lower velocity anomaly to a broader region than that identified in the velocity structure model, suggesting that the actual magma reservoir is larger and has a greater melt fraction than those of the magma reservoir as we estimated.

We identified the magma reservoir at a shallow depth of 2.5–6 km directly beneath the central lava dome of the Kikai Caldera Volcano, but its size and melt fraction may vary depending on the choice of the parameter values we assumed, such as the background geothermal gradient, the solidus temperature, and the temperature derivative term of P-wave velocity. As the background geothermal gradient was expected to vary widely from region to region, we used a general gradient ranging from 30 K km^{-1} to 50 K km^{-1} , but found no notable differences due to the background geothermal gradient. We examined the solidus temperature dependence (Supplementary Fig. 1a) because the solidus temperature is known to vary depending on the composition of rhyolite, especially its water content. The results show that the size and melt fraction of the magma reservoir increase as the solidus temperature decreases, but its dependence is slight. However, the dependence of

Fig. 3 | Velocity anomaly, temperature, and melt fraction beneath the Kikai Caldera Volcano.

a Bathymetric map around the Kikai Caldera Volcano, showing the location of the outer caldera (red dotted line) and post-caldera central lava dome (yellow dashed line), and the location of the ocean bottom seismometers (orange circles) along the seismic refraction survey line (brown solid line).

b Cross-section of velocity anomaly below the seismic refraction survey line. This velocity anomaly does not include the area shallower than 2 km. The reason for this is that the area shows a steep velocity gradient with depth (Fig. 2), so that even a small depth difference results in a large velocity anomaly, leading to a large uncertainty in the estimate of the velocity anomaly. **c** Cross-section of the temperature below the same survey line. The melt zone, where melting occurs, is an area with a temperature above the solidus temperature, which is shown by the red dashed line. It should be noted that the temperature in the melt zone is not real, as the velocity decrease there is caused mainly by the melt fraction rather than by the temperature increase. **d** Cross-section of the melt fraction in the melt zone below the same survey line. The melt zone shown by the green dashed line is the same as **c**, and the area of the magma reservoir identified in this study is shown by the green solid line. The positions of the outer caldera and the two ends of the central lava dome are indicated by red and yellow-green inverted triangles, respectively.



the temperature derivative term is much greater, as shown in our calculations (Supplementary Fig. 1b). This large dependence on this value may prevent us from determining the exact size and total melt volume of the magma reservoir, even though we chose the value of the temperature derivative term based on results from laboratory experiments. Despite this limitation, our results of the low-velocity anomaly clearly indicate the existence of a large magma reservoir at a shallow depth of 2.5–6 km, directly

beneath the central lava dome of the Kikai Caldera Volcano, and the shape of this reservoir can be approximated by a trapezoidal shape in the 2D section. Even when potential variations are considered, the width of the magma reservoir is at least the same as the width of the inner caldera, and our estimate of its melt fraction (3–6%) is a robust number that could be limited to 10% at most, as the melt fraction is approximately half that of the velocity reduction rates.

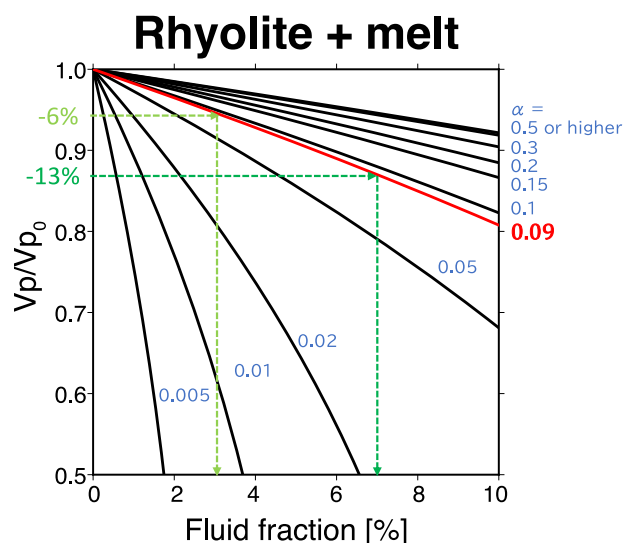


Fig. 4 | Normalised P-wave velocity (V_p/V_{p0}) and melt volume fraction for different aspect ratios. This plot represents for a composite of rhyolite and its melt is based on the formula for seismic velocities in solid-liquid mixed systems²³. Bulk and shear moduli and density are taken to be $K = 39.8$ GPa, $G = 30.2$ GPa, $\rho = 2371$ kg m⁻³ for rhyolite³⁷ and $k_f = 13$ GPa, $G_f = 0$ GPa, $\rho_f = 2290$ kg m⁻³ for rhyolite melt³⁸. This plot allows us to estimate the melt fraction from the velocity reduction rate at a melt aspect ratio of 0.09 (red line), for example the melt fractions corresponding to 6% and 13% velocity reduction were estimated to be 3% (light green dashed lines with arrows) and 7% (dark green dashed lines with arrows) respectively.

Melt re-injection model and its implications

Our identification of the large magma reservoir at a shallow depth, together with the results of the previous study (Fig. 6a), led us to propose a melt re-injection model (Fig. 6b) with two main assumptions: 1) the large magma reservoir for the K-Ah eruption was at the same location as the present large magma reservoir found in this study, and 2) a new melt was re-injected into the same magma reservoir, indicating the current state of the Kikai Caldera Volcano. The reason for proposing assumption 1) is based on the following. First, the present large magma reservoir is at least as wide as the inner caldera and is located beneath it, which explains why caldera subsidence was the result of the K-Ah eruption when magma was removed from the large magma reservoir. In addition, our results indicate that the depth of the large magma reservoir is 2.5–6 km, whereas petrographic magma depth estimates for the K-Ah eruption are 3–7 km^{25,26}, and petrographic magma depth estimates for the central lava dome are 2–4 km¹⁸ (Fig. 6a), indicating that the magma reservoir since the K-Ah eruption has been at approximately the same depth as today. Furthermore, the volume of the K-Ah eruption was so large, with a DRE of ~160 km³ (133–183 km³)¹⁶, that another large magma reservoir for this eruption could not have existed separately in the vicinity of the present large magma reservoir. Thus, we propose that the large magma reservoir for the K-Ah eruption was located at the same location as the present large magma reservoir (Fig. 6b). The reason for proposing assumption 2) that the new melt was re-injected into the same magma reservoir is based on the following: the rock composition of the volcanic rocks of the K-Ah eruption is different from that of the later volcanism (e.g. central lava dome), except for a small eruption of the old Iwo-dake volcanic stage (5.2–3.9 ka), suggesting a different magma source for the later volcanism^{17,18}. Therefore, since 3,900 years ago, a new melt has been re-injected into the magma reservoir for later volcanism.

The melt re-injection scenario (Fig. 6b) was as follows: the K-Ah eruption occurred at 7.3 ka¹⁵ with a volume of ~160 km³ (133–183 km³)¹⁶ (phase (1)). Then, caldera collapse started during the eruption¹⁵, and the mountain subsided by a volume equal to the amount of magma ejected from the reservoir, forming a caldera (phase (2)). The Kikai Caldera Volcano exhibits a topographical double-caldera structure¹⁷, which is likely to be

present in phase (2). The state of the magma reservoir was uncertain at this stage. During phase (3), a central lava dome with a volume of more than 32 km³ was formed within the inner caldera by different magma¹⁷. The composition of the rock suggests that this magma formed after 3900 years ago¹⁸. Therefore, at least 32 km³ of different melts have been re-injected into the same large magma reservoir over the last 3900 years. The melt re-injection leads to the results that the melt was stored by increasing the melt fraction in the large magma reservoir (phase (4)), and that the central lava dome formed as the melt pushed up the volcanic body and was ejected onto the surface to solidify as lava. The melt injection rate is estimated to be more than 8.2 km³ kyr⁻¹, as this melt injection rate is an average: this melt injection was continuous over the last 3900 years, or episodic at some time during the last 3900 years to reach the current large magma reservoir.

The melt re-injection into the same large magma reservoir at a shallow depth just beneath the caldera, as we suggested for the Kikai Caldera Volcano, may be a common feature of volcanoes that have experienced a large or giant caldera eruption. Our estimate for the current magma reservoir of the Kikai Caldera Volcano is a depth of 2.5–6 km, which matches the estimated magma depths of 3–7 km for the K-Ah eruption^{25,26} and 2–4 km for the central lava dome¹⁸. This match is used as evidence of melt re-injection into the same magma reservoir as that of previous volcanism. Similar matches are suggested for other volcanoes that have experienced large or giant caldera eruptions. Large magma reservoirs are present at depths of 3–8 km with a melt fraction of 16–20% just beneath the Yellowstone caldera⁶, and its depth overlaps with petrological estimates of the assembly depth of erupted rhyolite bodies (3–6 km depth)^{27,28}. A petrological study of the 74 ka Toba Tuff suggested that the Toba Tuff magma resided at nearly water-saturated pressures of 100–150 MPa (4–6 km depth)²⁹. This depth might match the depth of over 30% S-wave velocity reduction beneath the Toba caldera (5–11 km depth), as the S-wave velocity reduction was estimated by a multiparameter ambient noise adjoint tomography method¹⁰. The Santorini Volcano, after a recent large caldera-forming eruption, shows a magma body at 2.8–5 km depth localized below the northern caldera basin¹⁴, which is at the same depth as that constrained for pre-eruptive storage of Kameni Island lavas by a melt inclusion study³⁰. These melt re-injection processes in a magma reservoir at a shallow depth just beneath the caldera could be a step towards the next giant caldera eruption, and then observations of the seismic wave velocity reduction rate and information on these changes are important indicators of subsequent giant caldera eruptions.

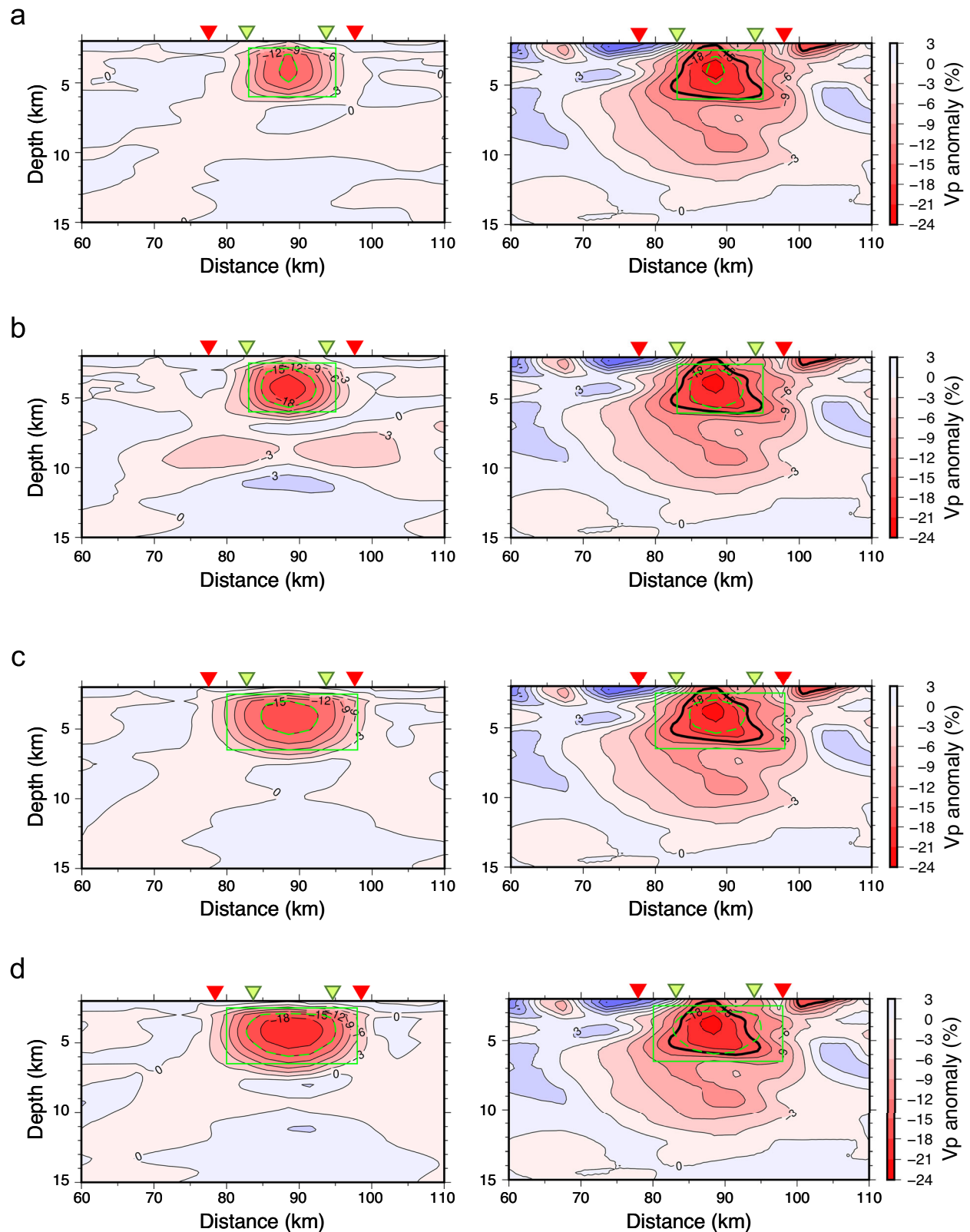
Methods

Survey overview

We conducted a seismic refraction survey using 39 ocean bottom seismometers (OBS) and an airgun array from the R/V Kaimei along a 175 km survey line across the Kikai Caldera Volcano. Nine OBS were deployed at 2.5 km intervals just above the caldera volcano and 30 OBS were deployed at 5 km intervals outside the caldera. The airgun array generated seismic pulses approximately every 200 m, except inside the caldera where no seismic pulses were generated at a distance of 78–98 km from the western end of the survey line. The airgun array consisted of 24 airguns with a total capacity of 10,600 inch³ and an air pressure of 2000 psi, towed at a depth of 10 m.

Velocity modelling

First, we manually picked approximately 12,300 first arrivals from 38 OBS record sections. We then applied first-arrival tomography³¹ as a similar procedure to that used in the previous work^{32–34}. The P-wave velocity model consists of two layers, water and sub-seafloor, separated by the seafloor topography. The seafloor topography was derived from the bathymetric data along the survey line obtained during the seismic survey. The acoustic velocity within the water layer was set to 1.520 km s⁻¹ based on XBT observations during the survey and remained constant during the inversion. The P-wave velocity below the seafloor of the starting model was based on the P-wave velocity model along the ECr11 line, which obliquely crossed the survey line²⁰. By applying the first-arrival tomography, the RMS of the travel



time misfit (differences between observed and synthetic travel times) was 64 msec in the final model and 632 msec in the starting model. The chi-squared, RMS misfit divided by the given uncertainty of each pick data, was 0.87 in the final model, indicating that the final model (Fig. 1b and Supplementary Fig. 2b) explained the data well. The travel-time misfit for each pick data from OBSs is shown in Supplementary Fig. 2d.

To investigate the spatial resolution of the tomographic results, checkerboard resolution tests were performed using two sizes of checkerboard patterns with $\pm 5\%$ velocity perturbation (Supplementary Fig. 3). To investigate the dependence of the final model on the starting model, we applied a Monte Carlo type uncertainty analysis (Supplementary Fig. 4). The results of both the checkerboard and uncertainty tests indicate that the low-

Fig. 5 | Results of synthetic recovery test. The left figure shows the velocity anomaly beneath the Kikai Caldera Volcano, which was reproduced by applying a corresponding velocity anomaly to the region indicated by the green square. The -15% velocity anomaly is indicated by the green dashed line. The right figure shows the velocity anomaly revealed by our seismic refraction survey. The -15% velocity anomaly is indicated by the thick solid line, and the same green square and the green dashed line in the left figure are also indicated for comparison. **a** The case where the low velocity anomaly is -15% in a region with a width of 12 km and a depth of 2.5–6.0 km. The recovered region with a velocity anomaly of -15% is notably smaller than the region identified in the survey, even though a corresponding velocity anomaly of -15% was applied to a region of roughly the same size as the base

of the region with a velocity anomaly of -15% identified in the survey. **b** The case where the low velocity anomaly was -30% , with the same region as in **a**. **c** The case where the low velocity anomaly was -15% , with a larger region than the case **a**, i.e. a width of 18 km and a depth of 2.5–6.5 km. **d** The case where the low velocity anomaly was -20% , with the same region as in **c**. In cases **b** and **c**, the recovered region with a velocity anomaly of -15% is smaller than the region identified in the survey, but in case **d**, the recovered region is similar to the region identified in the survey. These results indicate that the low velocity anomaly identified in the survey can be generally reproduced by applying a lower velocity anomaly to a broader region than those identified in the survey.

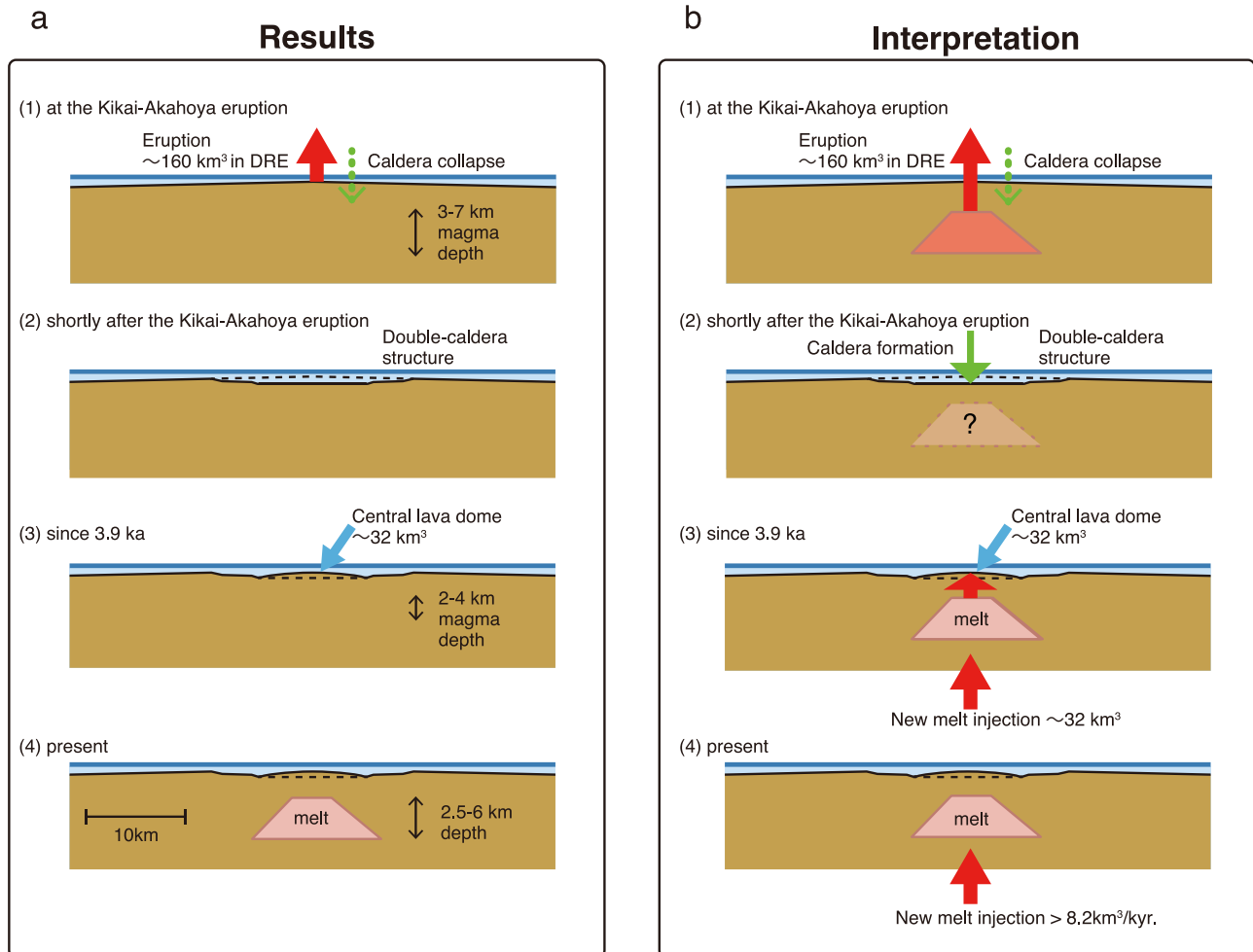


Fig. 6 | All available results and conceptual diagram of the melt re-injection model. **a** Results of this study, together with the results of the previous study, in four distinct phases from top to bottom: (1) at the Kikai-Akahoya eruption, (2) shortly after the Kikai-Akahoya eruption, (3) since 3.9 ka, and (4) present. In phase (1), the volume of $\sim 160 \text{ km}^3$ ($133\text{--}183 \text{ km}^3$) in DRE was erupted¹⁶, and both arrows indicate petrographic estimates of 3–7 km magma depth^{25,26}. The caldera collapse started during the eruption¹⁵. The Kikai Caldera Volcano exhibits a topographical double-caldera structure¹⁷, which is likely to be present in phase (2). The

post-caldera central lava dome, with a volume of 32 km^3 , was formed¹⁷, and it occurred in phase (3) with petrographic estimates of 2–4 km magma depth shown by both arrows¹⁸. The results of this study show the existence of a magma reservoir in the present (phase (4)) with a depth of 2.5–6 km (both arrows). The dotted line indicates that this part of the process occurred in the previous phase. The scale is drawn with the same aspect ratio. **b** Conceptual diagram of the melt re-injection model in the same four distinct phases. See main text for details.

velocity anomaly for the magma reservoir imaged beneath the Kikai Caldera Volcano is reliable.

Synthetic recovery tests were performed to assess the extent to which the low-velocity anomaly beneath the Kikai Caldera Volcano, as revealed by our seismic refraction survey, could be reproduced by applying a corresponding velocity anomaly in four different cases (Supplementary Fig. 5). This closely replicated the conditions of our seismic refraction survey data processing. The results are summarised as follows: The zone of low-velocity anomalies obtained by inversion basically matches the zone incorporated as

a low-velocity anomaly (Supplementary Figs. 5a(4), 5b(4), 5c(4), and 5d(4)). However, the degrees of the velocity anomaly are much reduced compared to those of the incorporated low-velocity anomaly. A clear example is case **a** (Fig. 5a and Supplementary Fig. 5a), which shows that the recovered region with a velocity anomaly of -15% is notably smaller than the region identified in the survey, even though a corresponding velocity anomaly of -15% was applied to a region of approximately the same size as the lower base of the trapezoidal shape with a velocity anomaly of -15% identified in the survey. The velocity anomaly region identified in the survey could be

generally reproduced by applying a lower velocity anomaly to a broader region than those identified in the survey, as in case **d** (Fig. 5d and Supplementary Fig. 5d). In other cases, the recovered region with a velocity anomaly of -15% is smaller than the region identified in the survey, even when only a lower velocity anomaly is applied as in case **b** (Fig. 5b and Supplementary Fig. 5b), or when it is applied to a broader region as in case **c** (Fig. 5c and Supplementary Fig. 5c).

Figure creation

We used GMT software³⁵ to create nearly all the figures. The map data was compiled primarily from our own bathymetric dataset¹⁷, as well as two others. One is bathymetric data from the J-EGG500 500 m gridded bathymetry dataset, which was provided by the Japan Oceanographic Data Center (JODC), and the other is land topography data from Digital Elevation Models, which were provided by the Geospatial Information Authority of Japan (GSI).

Data availability

The minimal dataset supporting the findings of this study³⁶ is available in the Zenodo repository (<https://doi.org/10.5281/zenodo.18628660>). This includes the processed data used to generate the figures presented in the study. All the seismic data are available upon request from the JAMSTEC seismic survey database (<https://www.jamstec.go.jp/datadoi/doi/10.17596/0002069.html>).

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Author contributions

NS, HS, and SK led this study as part of the Kikai Caldera project. ST was the chief scientist on the R/V Kaimei KM21-05 research cruise, and AN, NS, GF, ST, and SK collected data during the cruise. AN performed the data analysis, with GF, SK, and NS supervising. GF and NS performed future data analysis and additional calculations. AN wrote some of the manuscript in Japanese, and NS completed the paper with comments and input from GF, SK, and HS for the seismic part, and from ST for the melt interpretation part. All authors have reviewed the manuscript and approved the final version.

Competing interests

The authors declare no competing interests.

Additional information

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