Petit-spot as definitive evidence for partial melting in the asthenosphere caused by CO₂

Shiki Machida¹,², Tetsu Kogiso³ & Naoto Hirano⁴

The deep carbon cycle plays an important role on the chemical differentiation and physical properties of the Earth’s mantle. Especially in the asthenosphere, seismic low-velocity and high electrical conductivity due to carbon dioxide (CO₂)-induced partial melting are expected but not directly observed. Here we discuss the experimental results relevant to the genesis of primitive CO₂-rich alkali magma forming petit-spot volcanoes at the deformation front of the outer rise of the northwestern Pacific plate. The results suggest that primitive melt last equilibrated with depleted peridotite at 1.8–2.1 GPa and 1,280–1,290 °C. Although the equilibration pressure corresponds to the pressure of the lower lithosphere, by considering an equilibration temperature higher than the solidus in the volatile–peridotite system along with the temperature of the lower lithosphere, we conclude that CO₂-rich silicate melt is always produced in the asthenosphere. The melt subsequently ascends into and equilibrates with the lower lithosphere before eruption.

¹Research and Development Center for Submarine Resources, Japan Agency for Marine-Earth Science and Technology, Natsushima-cho 2-15, Yokosuka, Kanagawa 237-0061, Japan. ²School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-8654, Japan. ³Graduate School of Human and Environmental Studies, Kyoto University, Yoshida-nihonmatsu, Sakyo, Kyoto 606-8501, Japan. ⁴Center for Northeast Asian Studies, Tohoku University, Kawauchi 41, Aoba-ku, Sendai 980-8576, Japan. Correspondence and requests for materials should be addressed to S.M. (email: m-shikit@jamstec.go.jp).
he nature of the seismic low-velocity zone in the upper mantle, the asthenosphere, is a matter of debate. Hirschmann showed that the peridotite–CO₂–H₂O system melts and produces carbonatite or CO₂-rich silicate melt at the asthenosphere under normal thermal gradient. Subsequently, the existence of CO₂- and H₂O-rich melt in the asthenosphere was suggested by experimental determination of electrical conductivity of such melt; however, we have no direct observations or evidence of melt yet. Petit-spot volcanism, which is plate deformation-induced eruption of alkali magma forming diminutive volcanoes on the oceanic plate, is expected as the evidence for melt in the asthenosphere because of the following observations. No upwelling of hot, deep mantle was observed by seismic tomography, indicating that petit-spot did not originated from an active mantle plume. Okumura and Hirano determined 10% of CO₂ and 1% of H₂O in the primary petit-spot magma on the basis of measurement of CO₂ and H₂O content in the glassy rinds of lavas using infrared spectroscopy and back calculations of primary content considering magma degassing along the path of ascending magma and the vesicularity of lava. In addition, several petit-spot volcanic fields have been reported in the northwestern Pacific, the ocean-ward slope of the Tonga Trench, the Chile Trench and the Sunda Trench, the Basin and Range Province of North America, offshore southern Greenland and the Santa Rosa accretionary complex in Costa Rica. These observations suggest that petit-spot volcanism is ubiquitous phenomenon in the regions of plate flexure owing to oceanic plate subduction and glacial melting. Therefore, if magma originates in the asthenosphere, as originally proposed by Hirano et al., petit-spot volcanism should provide critical insight into melt production in the asthenosphere based on the high amount of CO₂ in the melt and the ubiquitous distribution of volcanic fields. Obviously, a comprehensive model for petit-spot volcanism from magma genesis to eruption is desirable.

A model for the eruption of petit-spot volcanoes was first proposed by Hirano et al. The authors proposed that a petit-spot volcano forms by exuding magma that originates in the upper asthenosphere and passes through the lithosphere in response to plate flexure during the formation of the outer rise. In addition to this basic model, Yamamoto et al., based on peridotite xenoliths, suggested that the formation of melt ponds before eruption at the lithosphere–asthenosphere boundary (LAB) is needed to explain the localized hot geotherm of the petit-spot volcanoes. The ponding is caused by the horizontal melt migration against the plate motion beneath the LAB owing to the pressure gradient that is induced by the excess topography of the outer rise, which is the difference in depth between the shallow seafloor at the top of the outer rise and deep normal seafloor. Machida further ascertained that the position of the eruption of magma in a petit-spot volcanic field temporally migrates opposite to the direction of the movement of the Pacific plate, accompanying gradual change of the erupted lava geochemistry. These observations were explained by a new eruption model that considered a petit-spot volcanic field to correspond to an isolated melt pond at the LAB defined by Yamamoto et al. The melt pond is dragged by the plate motion, while it is being constantly supplied with new magma (magma mixing) and moves slightly slower than the plate and repeatedly induces melt eruption owing to plate flexure.

Nevertheless, three critical problems need to be understood in petit-spot genesis. First, the ‘plate-flexure model’ explains the eruption mechanism reasonably well. However, the model requires the existence of melt in the asthenosphere. On the viewpoint, second, if petit-spot genesis is attributed to the formation of the outer rise based on the ‘plate-flexure model’, volcanoes should be commonly distributed along the outer rise. However, they are not. For example, Hirano et al. and Machida et al. showed that the three petit-spot volcanic fields in the northwestern Pacific are not continuous along the outer rise. This observation suggests that the melting processes, not only plate-flexure, constrain the locus of petit-spot magmatism. Third, to understand the melting processes, our previous geochemical studies have shown that alkali lava from petit-spot volcanoes have high concentrations of incompatible trace elements indicating
extreme enrichment in highly incompatible elements, (for example, Rb, Ba, U, Th and Nb) and light rare earth elements\textsuperscript{3,7}, and have extreme enriched mantle 1-like Sr–Nd–Pb isotope compositions\textsuperscript{8,15}. Machida et al.\textsuperscript{15} thus proposed that melting of small blobs of recycled ancient plate materials (small-scale heterogeneity) in the upper mantle produces petit-spot magmas. This model is critical but the melting conditions and lithology of the source material are debated. Because all of the previous models that demonstrate the origin of petit-spot volcanism\textsuperscript{3,7,14,15} do not constrain the melting processes in the asthenosphere, we clarify whether or not the petit-spot melt is generated in the asthenosphere in this study.

To define the magma genesis of petit-spot volcanoes, the independent determination of temperature and pressure conditions for magma production is required. We thus performed melting experiments to define the melting phase relations of petit-spot primary magmas. We report the results of high-pressure melting experiments for basalts from the two youngest knolls (erupted between 0.05 and 1 Ma\textsuperscript{3}) situated in the flexed region of the northwestern Pacific plate, while considering the phase relations of the CCO (graphite–carbon dioxide) buffer or 1.4 log units below the IW (iron–wu¨stite) buffer, which is lower than the actual melting conditions in the mantle (+ 2 ΔIW log units)\textsuperscript{17}. In the reduced conditions of the Pt–graphite capsule, the Mg\# likely decreases because Fe\textsuperscript{3+} in the starting materials (FeO) reduced to Fe\textsuperscript{2+} (FeO). Therefore, the lower FeO concentration likely causes the lower olivine Mg\# that is higher than that of peridotite. However, the phase relations depend more on the SiO\textsubscript{2} activity in the melt than the Fe–Mg exchange\textsuperscript{18}. We thus consider that the differences in olivine Mg\# to minimally affect our results.

### Results

#### Accuracy evaluation of experiments. We conducted high pressure and temperature experiments for primary basalts from the two youngest knolls of petit-spot in the northwestern Pacific plate (Fig. 1). The H\textsubscript{2}O content of the starting materials (3.0–4.2 wt\%; Table 1) is higher than the estimated initial H\textsubscript{2}O content of petit-spot magmas. This model is critical but the melting conditions and lithology of the source material are debated. Because all of the previous models that demonstrate the origin of petit-spot volcanism\textsuperscript{3,7,14,15} do not constrain the melting processes in the asthenosphere, we clarify whether or not the petit-spot melt is generated in the asthenosphere in this study.

**Table 1 | Compositions of starting materials.**

|          | SiO\textsubscript{2} (wt.%)| TiO\textsubscript{2} (wt.%)| Al\textsubscript{2}O\textsubscript{3} (wt.%)| FeO* (wt.%)| MnO (wt.%)| MgO (wt.%)| CaO (wt.%)| Na\textsubscript{2}O (wt.%)| K\textsubscript{2}O (wt.%)| P\textsubscript{2}O\textsubscript{5} (wt.%)| H\textsubscript{2}O (wt.%)| CO\textsubscript{2} (wt.%)| FeO*/MgO (p.p.m.)| Cr (p.p.m.)| Ni (p.p.m.) |
|----------|-----------------|-----------------|-----------------|-------------|----------|----------|----------|----------------|-------------|----------------|----------------|-------------|---------------|----------------|----------|
| **KR04-08 D08-002** | | | | | | | | | | | | | | | |
| Original* | 45.41 | 2.80 | 11.54 | 12.33 | 0.35 | 10.61 | 9.54 | 2.60 | 2.90 | 0.89 | 1.05 | 371 | 352 |
| Primary† | 41.26 | 2.24 | 9.39 | 10.91 | 0.23 | 13.55 | 8.13 | 2.42 | 2.55 | 0.22 | 4.22 | 10.88 | 0.81 |
| **YK05-06 6K#879-R3A** | | | | | | | | | | | | | | | |
| Original* | 47.61 | 2.65 | 13.62 | 11.23 | 0.29 | 6.60 | 11.33 | 3.05 | 2.84 | 0.72 | 1.53 | 165 | 93 |
| Primary† | 41.39 | 1.94 | 9.97 | 10.01 | 0.22 | 12.35 | 8.29 | 2.24 | 2.08 | 0.52 | 2.96 | 7.33 | 0.81 |

FeO*: total iron as FeO.

Original composition data are from Machida et al.\textsuperscript{7}.

Primary indicates compositions of primary melt equilibrated with Fo = 90 olivine. Data are estimated from original composition (see Methods in detail).

The P–T phase relations for primitive magma. D08-002 has olivine (ol) on the liquidus at pressures lower than 2.1 GPa, whereas orthopyroxene (opx) is the liquidus phase at higher pressures (Fig. 3). Liquidus temperatures of approximately 1,270, 1,280 and 1,290 °C were respectively estimated on the basis of the change in the proportions of ol and opx with increasing temperature on experiments at 1.8 GPa, 2.0 GPa and 2.3 GPa. The melt is co-saturated with ol and opx at 2.1 GPa and 1,250 and 1,220 °C. Olivine disappears at lower than approximately 1,210 °C at 2.1 GPa. Clinopyroxene (cpx) is found only at 2.0 GPa and 1,200 °C with melt and ol. We thus conclude that D08-002 liquid is multiply saturated with ol and opx at 2.1 GPa and 1,280 °C, and cpx joins in at approximately 80 °C below the liquidus.

Ox or opx is respectively the liquidus phase at pressures ≤ 1.8 GPa or ≥ 1.9 GPa for 6K#879-R3A (Fig. 3). The melt is co-saturated with Ol, cpx, and opx at between 1.7 GPa and 1.8 GPa and 1,260 °C or lower. In the case of the experiment at 2.5 GPa and 1,320 °C, mass balance calculations using the compositions of the observed melt phases (glass and the quenched crystals on polished section of the run product) shows high \( \sum R^2 \). However, recalculation adding opx (composition same as the opx observed in the experiment at 2.5 GPa and 1,300 °C) to the solid phases decreased \( \sum R^2 \) to less than 1 (Supplementary Data 1). Therefore, we consider that opx was present at 2.5 GPa and 1,320 °C even though it was
not observed in the polished section. Although ol was not observed in the experiments at 1.5 GPa and 1,280 °C, 1.6 GPa and 1,270 °C and 1.8 GPa and 1,280 °C, the calculation after adding ol (same composition as the ol observed in the experiment at 1.6 GPa and 1,250 °C for the first two experiments and ol observed in the experiment at 1.8 GPa and 1,260 °C for the latter) to solid phase decreased the $\sum R^2$ to < 1 (Supplementary Data 1). Thus, 6K#879-R3A liquid is multiply saturated with ol and opx at 1.8 GPa and 1,290 °C, and cpx joins in at approximately 20 °C below the liquidus. Two phase stability fields, ol–cpx at low pressure and two pyroxenes at high pressure, were also observed.

**Discussion**

On the basis of our experiments, the multiple saturation point of the primary petit-spot melt is at 1.8–2.1 GPa and 1,280–1,290 °C (Fig. 4), indicating that the petit-spot magma last equilibrated with harzburgite ~60 km deep under slightly lower temperature than the adiabat of the mantle potential temperature (MPT) of 1,250 °C (ref. 19). This is shallower than the depth of the LAB for the northwest Pacific (82 km depth at WP2 (ref. 20)), suggesting that the last equilibrium depth of the petit-spot magma is within the lower lithosphere. If the estimated last equilibration pressure suggests segregation depth of the primary petit-spot melt from the solid phases at the lower...
respectively, proposed by Dalton green and orange lines are adiabats corresponding to the given mantle marks the depth of the lithosphere–asthenosphere boundary (LAB) for the ridge19. Variation of the mantle potential temperature beneath the mid-ocean ridge if CO2 or carbonate exists in the asthenosphere, melt migration horizontally owing to the pressure gradient induced by the introduction, the accumulated melt at the LAB further migrates horizontally owing to the pressure gradient induced by the formation of the outer rise14, forming isolated melt ponds7. Therefore, we propose the following model for the processes of CO2–H2O (refs 23,24) system. The green thick line and dashed line respectively denote the thermal structure of the 130 Ma plate estimated on calculations by Hirschmann1, the CO2-rich silicate melt is likely to be produced in the asthenosphere because of the existence of CO2–rich fluid or carbonate. However, our experiments also suggest that the melt segregation from solid phases may occur at the lower lithosphere. Therefore, we have to connect the melt pond at the LAB7,14 and the melt that equilibrated in the lower lithosphere. At the deformation front of the outer rise (examined in this study), the lower lithosphere experiences extensional stress owing to the concave bending of the plate11. Then, it is reasonable to argue that ascending occurs faster than the cooling of melt by the ambient lithologies. Moreover, the stress field changes from extensional to compressional at midlithospheric depths11, probably corresponding to the slightly shallower than the last equilibration depth (approximately 60 km, equivalent to 2 GPa) of the primary petit-spot magma obtained in this study. Therefore, we interpret the last equilibration depth as the depth where melt ascending stops or slows owing to the stress rotation in the lithosphere11. We thus conclude that the original eruption model for petit-spot7, considering direct exuding of the melt through the lithosphere, needs to be slightly modified; that is, (a) CO2– and H2O–rich melt ponding at the LAB ascends the overlying lithosphere owing to plate flexure, (b) the ascending melt equilibrates with harzburgite at approximately 1,280 °C and 60 km depth that corresponds to the base of the elastic lithosphere and finally (c) melt erupts on the seafloor. As the support for b, melt entrapment at the lower lithosphere can explain the localized anomalies of high electrical conductivity at ~60 km in the lithosphere27 and the extremely high geotherm14 just beneath the petit-spot volcanoes. To constrain c, rapid lava eruption is suggested from the presence of xenocrysts and xenoliths, which represent lithospheric lithologies in petit-spot lavas2. The deepest peridotitic xenolith (from ~45 km depth (1.3 GPa)22) suggests that melt ascends from the lower lithosphere before eruption on the seafloor. Detailed melt ascending processes through the lithosphere will be investigated in the future.

The principal constraint on the petit-spot origin revealed in this report and our previous studies7,14 is the role of CO2-fluid or carbonate in partial melting in the asthenosphere. Melting of small blobs of recycled ancient plate materials (small-scale heterogeneities) in the upper mantle produces petit-spot magmas15, thus, recycled plate materials could be the source of the CO2-fluid or carbonate in the asthenosphere. Hence, blobs of
CO₂-fluid- or carbonate-rich material in the asthenosphere is expected to constrain the loci of Petit-spot magmatism (the second critical problem in Petit-spot genesis, as pointed out in the introduction). Future detailed geochemical and petrological investigations of Petit-spot lavas will provide insights of the linkage between the lithology of the seismic low-velocity layer and global carbon recycling.

**Methods**

**Sample selection.** Samples D08-002 and 6K#879-R3A were selected as representative of Petit-spot basalts. They were collected from two isolated knobs during cruises KR04-08 of RV Kairei (by dredge) and YK06-05 of RV Yokosuka (by dive of the Shinkai 6500 submersible) (Fig. 1). These knobs are situated in a Petit-spot volcanic field ~600 km ESE of the Japan Trench and correspond to the deformation front of the outer rise formation (Fig. 1). These volcanoes on the Cretaceous Pacific plate formed approximately 136 Ma.

**Preparation of starting materials.** The original bulk-rock compositions of samples D08-002 and 6K#879-R3A (Table 1) equilibrates with Fo (that is, 100MgO + FeO in molar percent) = 86 and 81, respectively. This observation indicates that composition of Petit-spot magma was changed from primary Mg-rich magma, which equilibrates with mantle, owing to crystal fractionation before eruption. Therefore, for the precise experiment, the primary composition of starting material has to be reconstructed from the original composition by taking into account olivine fractionation. We consider that olivine-bearing lithology should exist in the source, even if contributions of recycled materials are expected. Furthermore, involvement of recycled materials into the magma source would not significantly affect the Fo content of olivine in the source. Thus, the major element compositions of primary melt equilibrated with Fo = 90 olivine (Table 1) have been reconstructed from the original compositions of samples D08-002 and 6K#879-R3A using the olivine maximum-fractionation model.

**Preparation of starting materials.** The original bulk-rock compositions of samples D08-002 and 6K#879-R3A (Table 1) equilibrates with Fo (that is, 100MgO + FeO in molar percent) = 86 and 81, respectively. This observation indicates that composition of Petit-spot magma was changed from primary Mg-rich magma, which equilibrates with mantle, owing to crystal fractionation before eruption. Therefore, for the precise experiment, the primary composition of starting material has to be reconstructed from the original composition by taking into account olivine fractionation. We consider that olivine-bearing lithology should exist in the source, even if contributions of recycled materials are expected. Furthermore, involvement of recycled materials into the magma source would not significantly affect the Fo content of olivine in the source. Thus, the major element compositions of primary melt equilibrated with Fo = 90 olivine (Table 1) have been reconstructed from the original compositions of samples D08-002 and 6K#879-R3A using the olivine maximum-fractionation model.

**Preparation of starting materials.** The original bulk-rock compositions of samples D08-002 and 6K#879-R3A (Table 1) equilibrates with Fo (that is, 100MgO + FeO in molar percent) = 86 and 81, respectively. This observation indicates that composition of Petit-spot magma was changed from primary Mg-rich magma, which equilibrates with mantle, owing to crystal fractionation before eruption. Therefore, for the precise experiment, the primary composition of starting material has to be reconstructed from the original composition by taking into account olivine fractionation. We consider that olivine-bearing lithology should exist in the source, even if contributions of recycled materials are expected. Furthermore, involvement of recycled materials into the magma source would not significantly affect the Fo content of olivine in the source. Thus, the major element compositions of primary melt equilibrated with Fo = 90 olivine (Table 1) have been reconstructed from the original compositions of samples D08-002 and 6K#879-R3A using the olivine maximum-fractionation model.

**Preparation of starting materials.** The original bulk-rock compositions of samples D08-002 and 6K#879-R3A (Table 1) equilibrates with Fo (that is, 100MgO + FeO in molar percent) = 86 and 81, respectively. This observation indicates that composition of Petit-spot magma was changed from primary Mg-rich magma, which equilibrates with mantle, owing to crystal fractionation before eruption. Therefore, for the precise experiment, the primary composition of starting material has to be reconstructed from the original composition by taking into account olivine fractionation. We consider that olivine-bearing lithology should exist in the source, even if contributions of recycled materials are expected. Furthermore, involvement of recycled materials into the magma source would not significantly affect the Fo content of olivine in the source. Thus, the major element compositions of primary melt equilibrated with Fo = 90 olivine (Table 1) have been reconstructed from the original compositions of samples D08-002 and 6K#879-R3A using the olivine maximum-fractionation model.

**Preparation of starting materials.** The original bulk-rock compositions of samples D08-002 and 6K#879-R3A (Table 1) equilibrates with Fo (that is, 100MgO + FeO in molar percent) = 86 and 81, respectively. This observation indicates that composition of Petit-spot magma was changed from primary Mg-rich magma, which equilibrates with mantle, owing to crystal fractionation before eruption. Therefore, for the precise experiment, the primary composition of starting material has to be reconstructed from the original composition by taking into account olivine fractionation. We consider that olivine-bearing lithology should exist in the source, even if contributions of recycled materials are expected. Furthermore, involvement of recycled materials into the magma source would not significantly affect the Fo content of olivine in the source. Thus, the major element compositions of primary melt equilibrated with Fo = 90 olivine (Table 1) have been reconstructed from the original compositions of samples D08-002 and 6K#879-R3A using the olivine maximum-fractionation model.

**Preparation of starting materials.** The original bulk-rock compositions of samples D08-002 and 6K#879-R3A (Table 1) equilibrates with Fo (that is, 100MgO + FeO in molar percent) = 86 and 81, respectively. This observation indicates that composition of Petit-spot magma was changed from primary Mg-rich magma, which equilibrates with mantle, owing to crystal fractionation before eruption. Therefore, for the precise experiment, the primary composition of starting material has to be reconstructed from the original composition by taking into account olivine fractionation. We consider that olivine-bearing lithology should exist in the source, even if contributions of recycled materials are expected. Furthermore, involvement of recycled materials into the magma source would not significantly affect the Fo content of olivine in the source. Thus, the major element compositions of primary melt equilibrated with Fo = 90 olivine (Table 1) have been reconstructed from the original compositions of samples D08-002 and 6K#879-R3A using the olivine maximum-fractionation model.

**Preparation of starting materials.** The original bulk-rock compositions of samples D08-002 and 6K#879-R3A (Table 1) equilibrates with Fo (that is, 100MgO + FeO in molar percent) = 86 and 81, respectively. This observation indicates that composition of Petit-spot magma was changed from primary Mg-rich magma, which equilibrates with mantle, owing to crystal fractionation before eruption. Therefore, for the precise experiment, the primary composition of starting material has to be reconstructed from the original composition by taking into account olivine fractionation. We consider that olivine-bearing lithology should exist in the source, even if contributions of recycled materials are expected. Furthermore, involvement of recycled materials into the magma source would not significantly affect the Fo content of olivine in the source. Thus, the major element compositions of primary melt equilibrated with Fo = 90 olivine (Table 1) have been reconstructed from the original compositions of samples D08-002 and 6K#879-R3A using the olivine maximum-fractionation model.
14. Yamamoto, J., Korenaga, J., Hirano, N. & Kagi, H. Melt-rich lithosphere-asthenosphere boundary inferred from petit-spot volcanoes. Geology 42, 967–970 (2014).
15. Machida, S., Hirano, N. & Kimura, J.-I. Evidence for recycled plate material in Pacific upper mantle unrelated to plumes. Geochim. Cosmochim. Acta 73, 3028–3037 (2009).
16. Méard, E., McCammon, Barr, J. A. & Grove, T. L. Oxygen fugacity, temperature reproducibility, and H2O contents of nominally anhydrous piston-cylinder experiments using graphite capsules. Am. Mineral. 93, 1838–1844 (2008).
17. Green, D. H. & Falloon, T. J. in The Earth’s Mantle. (ed. Jackson, L.) 311–378 (Cambridge University Press, 1998).
18. Ghiroso, M. S., Carmichael, I. S. E., Rivers, M. L. & Sack, R. O. The Gibbs free-energy of mixing of natural silicate liquids — an expanded regular solution approximation for the calculation of migmatic intensive variables. Contrib. Mineral. Petrol. 84, 107–145 (1983).
19. Dalton, C. A., Langmuir, C. H. & Gale, A. Geophysical and geochemical evidence for deep temperature variations beneath mid-ocean ridges. Science 344, 80–83 (2014).
20. Kawakatsu, H. et al. Seismic evidence for sharp lithosphere-asthenosphere boundaries of oceanic plates. Science 324, 449–502 (2009).
21. Schmerr, N. The Gutenberg discontinuity: melt at the lithosphere-asthenosphere boundary. Science 335, 1480–1483 (2012).
22. Stein, C. A. & Stein, S. A model for the global variation in oceanic depth and heat flow with lithospheric age. Nature 359, 123–129 (1992).
23. Wallace, M. E. & Green, D. H. An experimental determination of primary carbonatite magma composition. Nature 335, 343–346 (1988).
24. Falloon, T. J. & Green, D. H. Solidus of carbonated fertile peridotite under fluid-saturated conditions. Geology 18, 195–199 (1990).
25. Sakamaki, T. et al. Ponded melt at the boundary between the lithosphere and asthenosphere. Nat. Geosci. 6, 1041–1044 (2013).
26. Dasgupta, R. et al. Carbon-dioxide-rich silicate melt in the Earth’s upper mantle. Nature 493, 211–215 (2013).
27. Baba, K., Abe, N., Hirano, N. & Ichiki, M. Three-dimensional inversion analysis of seafloor magnetotelluric data collected in the northwestern Pacific and implications for the source of petit-spot volcanoes. 5th International Symposium on Three-Dimensional Electromagnetics Sapporo, Japan, May 7–9 (2013).
28. Harigane, Y. et al. Direct evidence for upper mantle structure in the NW Pacific plate: microstructural analysis of a petit-spot peridotite xenolith. Earth. Planet. Sci. Lett. 302, 194–202 (2011).
29. Nakarishi, M., Tamaki, K. & Kobayashi, K. Mesozoic magnetic anomaly lineations and seafloor spreading history of the Northwestern Pacific. J. Geophys. Res. 94, 15437–15462 (1989).
30. Müller, R. D., Sdrolias, M., Gaima, C. & Roest, W. R. Age, spreading rates, and spreading asymmetry of the world’s ocean crust. Geochim. Geophys. Geosyst. 9, Q04006 (2008).
31. Sobolev, A. V. et al. The amount of recycled crust in source of mantle-derived melts. Science 316, 412–417 (2007).
32. Stooper, E., Sherman, S., Garcia, M., Baker, M. & Seaman, C. Glass in the submarine section of the HSDP2 drill core, Hilo, Hawaii. Geochim. Geophys. Geosyst. 5, Q07G15 (2004).
33. Herzberg, C. Identification of source lithology in the Hawaiian and Canary Islands: Implications for origins. J. Petrol. 52, 113–146 (2011).
34. Takahashi, E. Origin of basaltic magmas-Implications from peridotite melting experiments and an olivine fractionation model. Bull. Volcanol. Soc. Jpn 30, S17–S40 (1986).
35. Machida, S., Ishii, T., Kimura, J.-I., Awaji, S. & Kato, Y. Petrology and geochemistry of cross-chains in the Izu-Bonin back arc: Three mantle components with contributions of hydrous liquids from a deeply subducted slab. Geochim. Geophys. Geosyst. 9, Q05002 (2008).
36. Bose, K. & Ganguly, J. Quartz-coesite transition revisited: reversed experimental determination at 500–1200 °C and retrieved thermochemical properties. Am. Mineral. 80, 231–238 (1995).
37. Öh, S., Miyake, A. & Yashima, M. Stability field of the high-temperature orthorhombic phase in the enstatite-diopside system. Am. Mineral. 95, 1267–1275 (2010).
38. Putirka, K. D. Thermometers and barometers for volcanic systems. Rev. Mineral. Geochem. 69, 61–120 (2008).
39. Toplis, M. J. The thermodynamics of iron and magnesium partitioning between olivine and liquid: criteria for assessing and predicting equilibrium in natural and experimental systems. Contrib. Mineral. Petrol. 149, 22–39 (2005).
40. Green, D. H. & Ringwood, A. E. Mineralogy of peridotitic compositions under upper mantle conditions. Phys. Earth Planet. Int. 3, 359–371 (1970).
41. Hirschmann, M. M. Mantle solidus: experimental constraints and the effects of peridotite composition. Geochim. Geophys. Geosyst. 1, 2000GC000070 (2000).
42. Green, D. H. Experimental melting studies on a model upper mantle composition at high pressure under water-saturated and water-undersaturated conditions. Earth Planet. Sci. Lett. 19, 37–53 (1973).
43. Grove, T. L., Chatterjee, N., Parman, S. W. & Mèlard, E. The influence of H2O on mantle wedge melting. Earth Planet. Sci. Lett. 249, 74–89 (2006).
44. Till, C. B., Grove, T. L. & Withers, A. C. The beginnings of hydrous mantle wedge melting. Contrib. Mineral. Petrol. 163, 669–688 (2012).
45. Green, D. H., Hibberson, W. O., Kovács, I. & Rosenthal, A. Water and its influence on the lithosphere–asthenosphere boundary. Nature 467, 448–451 (2013).
46. Falloon, T. J. & Green, D. H. The solidus of carbonated, fertile peridotite. Earth Planet. Sci. Lett. 94, 364–370 (1989).
47. Dasgupta, R. & Hirschmann, M. M. The deep carbon cycle and melting in Earth’s interior. Earth Planet. Sci. Lett. 298, 1–13 (2010).

Acknowledgements
This study was supported by the Cooperative Program (2012, No. 127, and 2013, No. 132) of AORI. S.M. thanks K. Okino and N. Ogawa for help with the microprobe work at AORI. K. Baba and K. Yasukawa for their invaluable assistance with the calculation of the thermal structure of the lithosphere. S.M. and T.K. are indebted to K. Mibe for his help in the determining the H2O composition of the starting materials, and N. Kawamura for her help with the CO2 composition of the starting materials. This study was financially supported by the Japan Society for the Promotion of Science (JSPS) Grant-in-Aid for Young Scientists (B) No. 20740293 and No. 23740379 (S.M.), and a Grant-in-Aid for Challenging Exploratory Research No. 24654180 (N.H.), and a Toray Science and Technology grant No. 11-5208 (conceded to N.H. and S.M.).

Author contributions
S.M. and T.K. designed the project and performed the experiments and sample analysis. N.H. led and supervised researches on petit-spot volcanism. All authors contributed equally to writing of the article and producing figures.

Additional information
Supplementary Information accompanies this paper at http://www.nature.com/naturecommunications

Competing financial interests: The authors declare no competing financial interests.

Reprints and permission information is available online at http://npg.nature.com/reprintsandpermissions/

How to cite this article: Machida, S. et al. Petit-spot as definitive evidence for partial melting in the asthenosphere caused by CO2. Nat. Commun. 8, 14302 doi: 10.1038/ncomms14302 (2017).

Publisher’s note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© The Author(s) 2017