Volcanism in Response to Plate Flexure

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Volcanism on Earth is known to occur in three tectonic settings: divergent plate boundaries (such as mid-ocean ridges), convergent plate boundaries (such as island arcs), and hot spots. We report volcanism on the 135 million-year-old Pacific Plate not belonging to any of these categories. Small alkalic volcanoes form from small percent melts and originate in the asthenosphere, as implied by their trace element geochemistry and noble gas isotopic compositions. We propose that these small volcanoes erupt along lithospheric fractures in response to plate flexure during subduction. Minor extents of asthenospheric melting and the volcanoes' tectonic alignment and age progression in the direction opposite to that of plate motion provide evidence for the presence of a small percent melt in the asthenosphere.

The northwestern Pacific Plate is currently subducting beneath the Kuril and Japan trenches (*1*). This plate dates to the Early Cretaceous [150 to 120 million years ago (Ma) (*2*)] and is dotted with seamounts and oceanic plateaus, interpreted as having formed during Cretaceous times (*3*). The oceanic lithosphere cools as it ages (*4*) and moves away from the divergent plate boundary. Without the presence of a hot spot, new volcanism is not anticipated. During a dive (10K#56 in Fig. 1B) via the remotely operated vehicle *Kaiko*, the sampling of a young alkali basalt [5.95 ± 0.31 Ma (*5*)] near the Japan Trench was unexpected, because there are no known hot spots in the vicinity and recent volcanism has not been reported. In light of this finding, we decided to conduct extensive surveys of the area with the Japan Agency for Marine-Earth Science and Technology research ships *Kairei* (cruises KR03-07 and KR04-08 in Fig. 1B) and *Yokosuka* (cruise YK05-06), which is equipped with the submersible *Shinkai 6500* (dives 6K#877 to 6K#880 in Fig. 1, B and D). Ocean floor mapping was carried out with the use of the multibeam survey system SeaBeam 2112, in the direction of plate motion (Fig. 1A). Two

locations were investigated: site A (near the Japan Trench) and site B (located ~600 km to the southeast) (Fig. 1A). These investigations led to the discovery of volcanoes younger than 1 million years old, as well as the presence of a broad lava field. The age difference between the two sites, obtained from plate motion back-calculations, is estimated to be ~6 million years (*6*). The volcanoes proved to be very small (0.005 to 1 km³ each; exposure above the sea floor was estimated from bathymetric data), and we have given them the name "petit spot" volcanoes to convey both their size and their location far from known ridges and hot spots.

Volcanic cones and ridges in site A are distinct from the normal sea floor in bathymetric and sonar surveys (Fig. 1, B and C). Erosion of sediments by the strong bottom current in the trench (*7*) and local normal faulting has exposed the small volcanoes and ridges. These features are composed of moderately to highly vesicular lavas [~10 to 40 volume percent (volume %)], but lavas recovered along the fault outcrops are generally less vesicular (0 to 20 volume %). Previous $^{40}Ar/^{39}Ar$ dating of a lava sample produced an age of ~6 Ma (*5*), and new $^{40}Ar/^{39}Ar$ ages for additional petit spot volcanoes are 4.23 ± 0.19 and 8.53 ± 0.18 Ma (*8*) (table S1).

Approximately 600 km to the southeast of site A lies site B. This site is much farther from the trench and has not been eroded or faulted. Therefore, only the tops of the volcanic cones (<1 km in diameter) stand above the thick surrounding layer of abyssal sediment. Outcrops of young lava are, however, visible in side-scan sonar images because of their high reflectivity (Fig. 1E). Dredges and three *Shinkai 6500* submersible dives (6K#877, 6K#878, and 6K#879) were carried out at three young volcanoes at site B (Fig. 1, D and E). The sequences and lithologies exposed are typical of a single eruption and include highly vesicular (up to 60 volume %) pillow lava; water-

chilled bombs; and hyaloclastite, peperite, and contact-metamorphosed mud (*8*) (fig. S1, A and B). Glassy rock samples have 1- to 4-mm-thick palagonitic rims (fig. S1C); because the growth rate of palagonite in basaltic glass exposed to seawater is ~0.003 to 0.02 mm/year (*9*), the volcanic eruption should have occurred between 0.05 and 1 Ma.

Lavas and bombs from sites A and B contained xenocrysts and xenoliths (composed of basalt, dolerite, gabbro, or spinel peridotite), all of which are typical of the oceanic lithosphere (fig. S1C). The presence of xenoliths provides the following constraints on the origin of the lavas: (i) the eruptions must have taken place very rapidly to prevent the xenolith from being absorbed by the host magma; (ii) the magmas probably originated from the mantle, because they contain xenoliths representative of all lithosphere layers; and (iii) brittle lithospheric fractures must have been present to allow magmas to ascend. Finally, the occurrence and geochemistry of olivine xenocrysts from site A lavas imply a derivation from the oceanic lithosphere at depths of ~14 km (*10*); the depth to the base of the crust in this location is 7 to 8 km (*11*).

The lava samples were alkalic with steep primitive mantle–normalized rare earth element (REE) patterns (*8*) (fig. S2 and table S2). This suggests that they formed from small degrees of melting in the presence of garnet, which retains the heavy REEs (>90 km deep) (*12*). In the standard model of oceanic plates, the 135 million-year-old Pacific Plate would be ~95 km thick (*4*); thus, the melting probably took place in the asthenospheric mantle beneath the Pacific Plate. The high vesicularity of the rocks was probably caused by the presence of CO_2, because it is not very soluble in alkalic magmas, in contrast to H_2O (*8*, *13*).

The composition of the mantle source is important to determine in order to exclude a hot spot origin for the petit spot magmas. Mid-ocean ridge basalts (MORBs), presumed to be sourced from the upper, depleted asthenospheric mantle, have radiogenic noble gas isotopic compositions (for example, low $^3He/^4He$ ratios), whereas ocean island basalts (OIBs) have unradiogenic values. This is because nucleogenic, radiogenic, or fissiogenic isotopes of ^{21}Ne, ^{40}Ar, and $^{129,131–136}Xe$ are more abundant in the degassed MORB-source mantle than in the OIB-source mantle, which is generally less degassed and may even be undegassed (that is, primitive) (*14*, *15*). Our samples from site B are highly radiogenic in noble gas isotope compositions, suggesting a similar source to that of MORB (Fig. 2 and table S3) (*8*). The high $^{40}Ar/^{36}Ar$ ratios (>10,000) are higher than any reported for OIBs (*16*) and are convincing evidence for an upper mantle source.

A key question is whether the volcanoes represent a hot spot fed by a mantle plume. The presence of a tomographically imaged low-

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velocity region (a zone potentially representing a mantle plume) at a 410-km depth in this area was reported by Obayashi *et al.* (*17*); however, there is no evidence for a conduit or connection of any type between this low-velocity region and the shallower mantle. Our geochemical evidence strongly supports a depleted mantle (nonplume-like) source. Furthermore, the volume of magma produced at the petit spot volcanoes must have been several orders of magnitude less than those typical of hot spot volcanoes. We found 4.2 to 8.5 million-year-old volcanoes at site A, suggesting episodic eruption of magma over a distance of 400 km of plate motion. Accordingly, the petit spot volcanic province is characterized by several million years of small-volume magma production over a large area.

Temperatures of the asthenosphere beneath the Pacific Plate have been mapped precisely by means of surface wave tomography, showing that the thermal state of the asthenosphere is notably homogeneous throughout the Pacific Ocean (*18*). The temperature at a depth of 150 km is estimated to be between 1450° and 1480°C, which implies that the temperature just below the Pacific Plate is 50° to 150°C lower than the solidus of dry mantle materials (*19*). However, at this depth and temperature in the asthenosphere, a small percent melt should exist in the presence of small amounts (<1%) of H_2O or CO_2 (*20*), which lowers the melting temperature. The highly vesicular petit spot lavas probably represent incipient partial melts that formed in the asthenosphere in the presence of volatiles, most plausibly CO_2. If the magmas were supplied from the normal asthenosphere, with emplacement channels controlled by tectonic fracturing of the overlying lithospheric plate, the low volumes of magma output over a large area could easily be explained.

An old and cold lithospheric plate behaves elastically and may be flexed because of loading by an ocean island or seamount or by subduction-related plate flexure (*21*). In the area between sites A and B, the bathymetric high (or outer rise) is aligned parallel to the Japan Trench. The Pacific Plate flexes convexly here, as it subducts beneath Japan and yields a positive gravity anomaly (*22*). This flexed region is elevated >800 m above the normal ocean floor (~6000 m below sea level at site B). Large curvatures imposed on the preflexed lithosphere might instigate brittle fracturing (that is, bending-induced faults) (*23*). As for volcanic cones at site A, the volcanic features, aligned in a west-northwest to east-southeast direction, are essentially perpendicular to hinge lines on the bending plate (Fig. 1, A to C). Accordingly, it appears that magmas are brought to the surface along fractures parallel to the direction of the maximum horizontal compression. However, the surface compression is actually caused by extensional stresses on the base of the downwarping Pacific Plate (Fig. 3C).

Post–erosional-stage lavas on some of the Hawaiian Islands, as well as submarine lavas on the flexural Hawaiian Arch (because of loading on the plate), have chemical compositions and tectonic emplacement mechanisms (*24*) that are similar to those of the petit spot lavas. It has also been proposed that alkalic lavas in the western Samoan Islands (located on the opposite side of the main Samoan hot spot shield volcanoes) may be derived from the asthenosphere during tectonic faulting (*25*). If true, a similar style of volcanism may be present
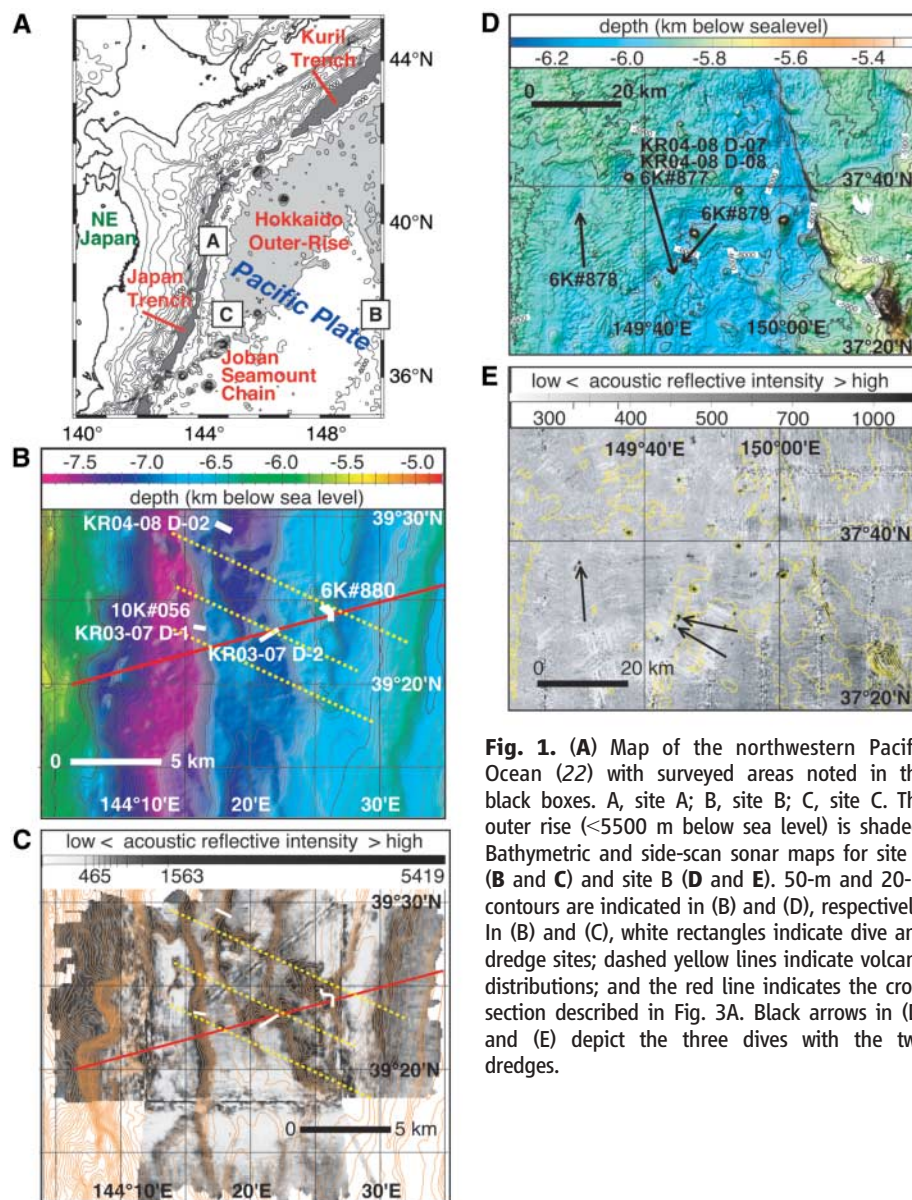

Fig. 1. (**A**) Map of the northwestern Pacific Ocean (*22*) with surveyed areas noted in the black boxes. A, site A; B, site B; C, site C. The outer rise (<5500 m below sea level) is shaded. Bathymetric and side-scan sonar maps for site A (**B** and **C**) and site B (**D** and **E**). 50-m and 20-m contours are indicated in (B) and (D), respectively. In (B) and (C), white rectangles indicate dive and dredge sites; dashed yellow lines indicate volcano distributions; and the red line indicates the cross section described in Fig. 3A. Black arrows in (D) and (E) depict the three dives with the two dredges.
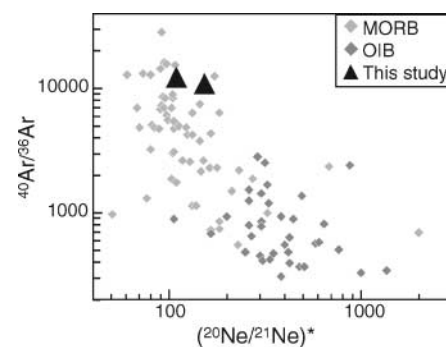

Fig. 2. Plot of Ne versus Ar isotopes. $(^{20}Ne/^{21}Ne)^*$ is equal to $[(^{20}Ne/^{22}Ne) - (^{20}Ne/^{22}Ne_{Air})]/[(^{21}Ne/^{22}Ne) - (^{21}Ne/^{22}Ne_{Air})]$, showing the slope of a mixing line on the conventional neon three-isotope plot $(^{20}Ne/^{22}Ne$ versus $^{21}Ne/^{22}Ne)$ (*8*). Data with $^{20}Ne/^{22}Ne$ ratios of less than 10 were not plotted (*8*). Literature and data for MORB and OIB may be found in the following online databases: Petrological Database of the Ocean Floor (www.petdb.org/) and Geochemistry of Rocks of the Oceans and Continents (http://georoc.mpch-mainz.gwdg.de/georoc/).

on other oceanic plates where extensive flexure and fracturing are taking place. Investigating these types of areas may prove to be a fruitful endeavor and result in the detection of other small volcanic features. For example, we have also observed volcanic cones and/or highly reflective sonar images, similar to those observed at the petit spot, elsewhere on the Pacific Plate (site C in Fig. 1A); these small cones will be examined further in the near future.

Early in the theory of plate tectonics, the presence of partial melts in the asthenosphere was considered to correspond to the solidus of Earth's mantle (1, 26). This hypothesis was supported by observations of a seismic low-velocity zone, a highly electric conductive layer, and an experimentally determined peridotite solidus in the presence of volatiles (27). More recently, the argument for the existence of partial melts in the asthenosphere has been weakened by studies, such as laboratory measurements of mantle material (28) and the predicted rheology of the mantle (29), that question its necessity. Therefore, this documentation of young alkali basalts on the old Pacific Plate provides new and strong support to the long-standing idea of the asthenosphere as a zone of partial melt.

References and Notes

1. D. P. McKenzie, R. L. Parker, *Nature* **216**, 1276 (1967).
2. M. Nakanishi, K. Tamaki, K. Kobayashi, *J. Geophys. Res.* **94**, 15437 (1989).
3. A. A. P. Koppers, H. Staudigel, R. A. Duncan, *Geochem. Geophys. Geosyst.* **4**, 8914 (2003).
4. C. A. Stein, S. Stein, *Nature* **359**, 123 (1992).
5. N. Hirano, K. Kawamura, M. Hattori, K. Saito, Y. Ogawa, *Geophys. Res. Lett.* **28**, 2719 (2001).
6. A. E. Gripp, R. G. Gordon, *Geophys. Res. Lett.* **17**, 1109 (1990).
7. W. B. Owens, B. A. Warren, *Deep-Sea Res. I* **48**, 959 (2001).
8. Materials and methods and detailed geochemical data are available as supporting material on *Science* Online.
9. J. G. Moore, D. J. Fornari, D. A. Clague, *U.S. Geol. Surv. Bull.* **1663**, 1 (1985).
10. N. Hirano, J. Yamamoto, H. Kagi, T. Ishii, *Contrib. Mineral. Petrol.* **148**, 47 (2004).
11. K. Suyehiro, A. Nishizawa, *J. Geophys. Res.* **99**, 22331 (1994).
12. J. G. Arth, *J. Res. U.S. Geol. Surv.* **4**, 41 (1976).
13. J. E. Dixon, *Am. Mineral.* **82**, 368 (1997).
14. M. Honda, I. McDougall, D. B. Patterson, A. Doulgeris, D. A. Clague, *Nature* **349**, 149 (1991).
15. T. Staudacher, C. J. Allégre, *Earth Planet. Sci. Lett.* **60**, 389 (1982).
16. J. Hopp, M. Trieloff, *Earth Planet. Sci. Lett.* **240**, 573 (2005).
17. M. Obayashi, H. Sugioka, J. Yoshimitsu, Y. Fukao, *Earth Planet. Sci. Lett.* **243**, 149 (2006).
18. K. Priestley, D. McKenzie, *Earth Planet. Sci. Lett.* **244**, 285 (2006).
19. M. M. Hirschmann, *Geochem. Geophys. Geosyst.* **1**, 10.1029/2000GC000070 (2000).
20. P. J. Wyllie, *J. Geodyn.* **20**, 429 (1995).
21. A. B. Watts, Ed., *Isostasy and Flexure of the Lithosphere* (Cambridge Univ. Press, Cambridge, 2001).
22. D. T. Sandwell, W. H. F. Smith, *J. Geophys. Res.* **102**, 10039 (1997).
23. H. O. Mofjeld, C. M. Symons, P. Lonsdale, F. I. Gonzalez, V. V. Titov, *Oceanography* **17**, 38 (2004).
24. D. A. Clague, R. T. Holcomb, J. M. Sinton, R. S. Detrick, M. E. Torresan, *Earth Planet. Sci. Lett.* **98**, 175 (1990).
25. J. H. Natland, *Am. J. Sci.* **280A**, 709 (1980).
26. W. J. Morgan, *J. Geophys. Res.* **73**, 1959 (1968).
27. P. J. Wyllie, *Rev. Geophys.* **26**, 370 (1988).
28. U. H. Faul, I. Jackson, *Earth Planet. Sci. Lett.* **234**, 119 (2005).
29. S. Karato, H. Jung, *Earth Planet. Sci. Lett.* **157**, 193 (1998).
30. We are extremely grateful for helpful comments and suggestions provided by J. Baker and two anonymous reviewers. We thank Captains S. Ishida, Y. Imai, O. Yukawa, and H. Tanaka, and the crews of the research vessels *Kairei*, *Yokosuka*, and *Shinkai 6500* for their help during the YK05-06, KR04-08, and KR03-07 cruises; K. Nagao, M. Nakanishi, T. Fujiwara, H. Kagi, S. Umino, M. Ichiki, S. Haraguchi, K. Baba, H. Sumino, K. Kawamura, A. Takahashi, and N. Takehara; and the International Research Center for Nuclear Materials Science, Institute for Materials Research, Tohoku University, for their assistance and discussions. This study was financially supported in part by the Research Fellowships of the Japan Society for the Promotion of Science for Young Scientists and by grants in aid for Scientific Research in Japan (numbers 12002006, 13304038, 14340147, 18204050, and 18740344).
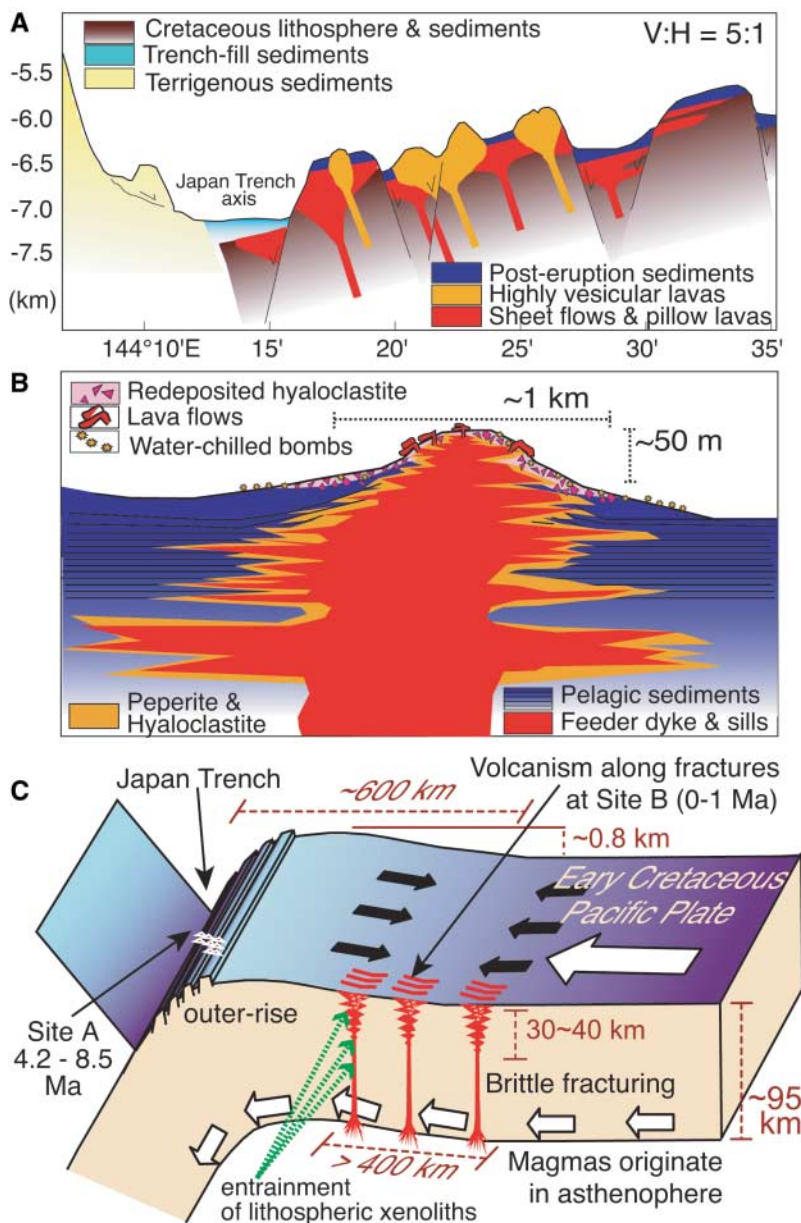
Fig. 3. Geologic interpretations of the lava fields. (**A**) Schematic cross section of site A (red line in Fig. 1, B and C). (**B**) A schematic cross section of a volcano at site B constructed from observations made during dives. (**C**) A conceptual model of petit spot volcanism. Magmas from the asthenosphere escape to the shallow depths because of the extensional environment of the lower lithosphere (*21*) and migrate up through the brittle compressed upper lithosphere by exploiting fractures created by flexure of the plate. Data for the plate and flexure framework are from previous studies (*6, 11, 21, 22*).