Depleted mantle wedge and sediment fingerprint in unusual basalts from the Manihiki Plateau, central Pacific Ocean

Stephanie Ingle* Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Tokyo 152-8551, Japan
John J. Mahoney School of Ocean and Earth Science and Technology, University of Hawaii, Honolulu, Hawaii 96822, USA
Hiroshi Sato School of Business Administration, Senshu University, Kanagawa 214-8580, Japan
Millard F. Coffin Ocean Research Institute, University of Tokyo, Tokyo 164-8639, Japan
Jun-Ichi Kimura Department of Geoscience, Shimane University, Matsue 690-8504, Japan
Naoto Hirano Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Tokyo 152-8551, Japan
Masao Nakanishi Graduate School of Science and Technology, Chiba University, Chiba 263-8522, Japan

ABSTRACT

Numerous large igneous provinces formed in the Pacific Ocean during Early Cretaceous time, but their origins and relations are poorly understood. We present new geochronological and geochemical data on rocks from the Manihiki Plateau and compare these results to those for other Cretaceous Pacific plateaus. A dredged Manihiki basalt gives an ^{40}Ar-^{39}Ar age of 117.9 ± 3.5 Ma (2σ), essentially contemporaneous with the Ontong Java Plateau ~2500 km to the west, and the possibly related Hikurangi Plateau ~3000 km to the south. Drilled Manihiki lavas are tholeiitic with incompatible trace element abundances similar to those of Ontong Java basalts. These lavas may result from high degrees of partial melting during the main eruptive phase of plateau formation. There are two categories of dredged lavas from the Danger Islands Troughs, which bisect the plateau. The first is alkalic lavas having strong enrichments in light rare earth and large-ion lithophile elements; these lavas may represent late-stage activity, as one sample yields an ^{40}Ar-^{39}Ar age of 99.5 ± 0.7 Ma. The second category consists of tholeiitic basalts with U-shaped incompatible element patterns and unusually low abundances of several elements; these basalts record a mantle component not previously observed in Manihiki, Ontong Java, or Hikurangi lavas. Their trace element characteristics may result from extensive melting of depleted mantle wedge material mixed with small amounts of volcaniclastic sediment. We are unaware of comparable basalts elsewhere.

Keywords: large igneous provinces, Early Cretaceous, Manihiki Plateau, Pacific Ocean, geochemistry, geochronology.

INTRODUCTION

Early Cretaceous time was marked by the formation of numerous large igneous provinces (LIPs) in amounts vastly exceeding their formation in Cenozoic time, perhaps reflecting a fundamentally different mode of mantle dynamics. Cretaceous Pacific LIPs include Hess, Magellan, and Shatsky Rises and the Ontong Java, Manihiki, and Hikurangi Plateaus (Fig. 1). LIPs are commonly believed to form by impingement of a mantle plume head on the base of the lithosphere, where the plume then decompresses and melts extensively (e.g., Richards et al., 1989). Several Cretaceous Pacific LIPs have been suggested to be products of a single superplume (e.g., Larson, 1991), and workers have discussed whether three of these features (Ontong Java, Manihiki, and Hikurangi) formed as a single LIP, despite their current separation by thousands of kilometers (Taylor, 2006; Worthington et al., 2006). If true, the area affected covered >1% of Earth's surface.

The Manihiki Plateau covers an area of 0.77×10^6 km^2 (Coffin and Eldholm, 1994), has a crustal thickness of up to 25 km (Viso et al., 2005), and is bisected by the Danger Islands Troughs (Fig. 1; Winterer et al., 1974). It is interpreted as having formed during active rifting (Winterer et al., 1974), from arrival of a large mantle plume head (Mahoney and Spencer, 1991), or a combination of the two (Larson, 1997). Biostratigraphy suggests that its minimum age is late Aptian (Bukry, 1976). Igneous rocks have been sampled from Deep Sea Drilling Project Site 317 (24.5 m of cored basalt; Jackson et al., 1976), a few dredge locations in the Danger Island Troughs (herein referred to as "Troughs") (Clague, 1976), and two seamounts on the eastern flank of the plateau (Beiersdorf et al., 1995; Fig. 1B). Previous workers have noted geochemical similarities between Site 317 and Ontong Java rocks, but values for the Troughs rocks are distinct (Mahoney and Spencer, 1991). Most published incompatible trace element data are not of modern quality.

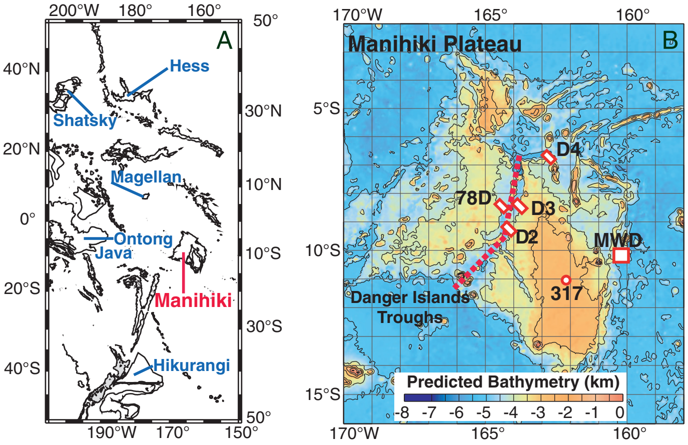

Figure 1. A: Locations of large western Pacific plateaus and rises. B: Bathymetric map with locations of Site 317 and KH03–01 Leg 5 (D2–D4), SOTW (78D), and seamount (MWD) dredges. Strikes of Danger Islands Troughs are indicated.

Additional sampling and data are needed to understand the origin of the plateau and its relationship to other LIPs, particularly Hikurangi and Ontong Java. We dredged four locations in the Troughs during the R/V *Hakuho Maru* cruise KH03–01 Leg 5 in August 2003. Three dredges (D2–D4) returned igneous rocks (GSA Data Repository Table DR1[1]). Sample volumes were small, limiting the types of analyses we could perform (Methods and Fig. DR1). Here we present geochemical and ^{40}Ar-^{39}Ar data (Tables DR2–DR5). We also analyzed incompatible trace element contents in two previously sampled Troughs rocks (referred to here as SOTW samples) and four samples from Site 317.

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*Current address: School of Ocean and Earth Science and Technology, University Hawaii at Manoa, Honolulu, Hawaii 96822, USA; e-mail: ingle@hawaii.edu.

[1] GSA Data Repository item 2007150, methods, Figure DR1 (photomicrographs), and Tables DR1–DR5 (location, age, and geochemical data), is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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RESULTS

Holocrystalline portions of six samples were selected for ^{40}Ar-^{39}Ar analysis. Two yielded plateaus and concordant isochron ages (Fig. 2; Table DR2). Sample D2–1 produced a 5-step plateau age of 117.9 ± 3.5 Ma (2σ). This age is consistent with previous Site 317 age estimates, including a basement ^{40}Ar-^{39}Ar age of 123 ± 3 Ma (data of R.A. Duncan, reported in Mahoney et al., 1993) and an Aptian microfossil assemblage in near-basement sediments (Bukry, 1976). In contrast, sample D3–1 gave a 4-step plateau age of 99.5 ± 0.7 Ma.

One sample each from D2 and D4, and two samples from D3, were analyzed for major elements (Table DR3; see footnote 1). The D2 sample is a low-K, low-Ti tholeiitic basalt, like the Site 317 and SOTW lavas. The D4 sample is altered with elevated K_2O, but it is probably a tholeiitic basalt because it has low TiO_2. Lavas from D3 are trachybasalts (MgO = 1.2–1.5 wt%).

Site 317 basalts have incompatible element patterns similar to those of the Ontong Java Singgalo magma–type rocks (Fig. 3A; Table DR4). D2, D4, and SOTW basalts exhibit unusual U-shaped patterns, with lower abundances of many alteration-resistant elements, including light and middle rare earth elements (REE), Hf and Zr (e.g., Zr = 17–30 ppm; Fig. 3B). In contrast, concentrations of Nb and Ta are equivalent to, or greater than, those of Site 317 (Nb/La to 3.3). D3 lavas have higher abundances of large-ion lithophile elements and light REEs, and low Nb/Ta (~8–11 versus 13–15 in Troughs basalts). Site 317 and SOTW rocks appear unaltered, in contrast to many D2, D3, and D4 basalts that have incompatible element patterns with anomalies in Rb, Pb, and/or Ba, and Ce.

The D2 tholeiites have age-corrected Sr and Nd isotope compositions comparable to those of the SOTW rocks [e.g., $\varepsilon_{Nd}(t)$ = ~6.0; Figs. 3C, 3D; Table DR5]. Age-corrected Pb isotope ratios are slightly elevated in the D2 rocks compared to the SOTW samples, except for $(^{206}Pb/^{204}Pb)_t$ in sample D2–2. D3 and D4 lavas have lower $\varepsilon_{Nd}(t)$ and much higher $(^{87}Sr/^{86}Sr)_t$, $(^{206}Pb/^{204}Pb)_t$, and $(^{208}Pb/^{204}Pb)_t$ than D2 or SOTW basalts. All Troughs rocks have less radiogenic $(^{87}Sr/^{86}Sr)_t$, more radiogenic $(^{206}Pb/^{204}Pb)_t$ and $(^{208}Pb/^{204}Pb)_t$, and are confined to a narrower range of $\varepsilon_{Nd}(t)$ than the Site 317 basalts.

ORIGIN OF UNUSUAL BASALTIC COMPOSITIONS AND THEIR RELATIONSHIP TO OTHER MANIHIKI LAVAS

Incompatible element patterns of the Troughs basalts appear to be unique among oceanic plateau, island, ridge, and arc basalts, implying a source with an atypical history. Low abundances of light to middle REEs in the Troughs basalts indicate high degrees of partial melting of an already melt-depleted mantle source; this is consistent with the previous interpretation of the SOTW rocks by Clague (1976; Fig. 3B). The positive slope from the middle to heavy REEs suggests that the depletion occurred in the garnet stability zone. The elevation in the most incompatible elements (Rb, Th, Nb, Ta) requires re-enrichment of this source, possibly by a small amount of sediment or sediment-derived fluid; elevations in Nb and Ta relative to Th and La may be commensurate with this re-enrichment. Few sediment types have elevated Nb/La or Ta/Th; e.g., continent-derived or pelagic sediments typically have trace element patterns with Nb-Ta troughs (e.g., Plank and Langmuir, 1998). A possible alternative might be sediment shed from ocean islands: volcaniclastic sediment with slightly elevated Nb/La and Ta/La (~1.2 and ~1.5, respectively) has been recovered from the East Mariana Basin at Ocean Drilling Program Site 801 (Plank and Langmuir, 1998). This type of sediment could be added to a mantle source via transportation atop subducting lithosphere, which would refertilize a highly depleted mantle wedge. A mantle wedge origin for the depleted source seems reasonable, because mantle there may undergo extensive melting and dehydration in the garnet stability zone.

We propose the following model for the mantle source of these unusual basalts (Fig. 4). (1) In a subduction-zone setting, mantle wedge material dehydrates and melts extensively (as much as 15%) in the garnet stability zone. (2) A small amount (~2%) of subducted volcaniclastic sediment is then added to this residue. (3) At a later time, this modified mantle is melted to high degrees, on average, from 15% to 20% in the spinel peridotite stability zone to produce magmas having the U-shaped element patterns observed for SOTW and D2 rocks (Fig. 4). Although the solution is nonunique (lower melting extents during step 1 may permit addition of less sediment in step 2 and less melting in step 3, or vice versa), the components and melting conditions used provide the best fit to the available data. The length of time between steps 2 and 3 may be roughly estimated from the Sm/Nd and Rb/Sr of the modeled source and the ε_{Nd} and $^{87}Sr/^{86}Sr$ of a 98:2 mix of average ocean-ridge–type mantle and Site 801 volcaniclastic turbidites. This yields a time of source enrichment (mixing) of ~230 Ma and a relatively short mantle isolation time of ~110 m.y. to develop the age-corrected ε_{Nd} and $^{87}Sr/^{86}Sr$ of the SOTW samples.

Geochemical differences between the Troughs and Site 317 basalts require two distinct mantle sources. The rock ages, however, must be considered essentially identical because the Site 317 age is not published and cannot be assessed for potential ^{39}Ar recoil effects, and D2 basalt data show no low-temperature Ar loss (Fig. 2). Thus, we must base the relative ages on stratigraphy and the timing of events during formation and deformation of the Manihiki Plateau. Site 317 basalts cap the plateau, and therefore should represent the final eruptive stages. Troughs basalts, in contrast, were recovered from steep scarps (to 4 km of relief) that likely formed shortly after the plateau (e.g., Coffin et al., 2004; Winterer et al., 1974). The relative ages depend on whether Troughs basalts are stratigraphically lower than those at Site 317, or whether they represent lavas erupted during formation of the Troughs. The latter seems unlikely because it requires extensive melting of a very depleted source during limited extension. Conversely, high degrees of melting occurred during the main plateau-building phase (Mahoney et al., 1993), and it is more plausible that large degrees of melting of a very depleted mantle source would have occurred at this time. As such, we tentatively favor a pre-deformational origin for the SOTW, D2, and D4 tholeiites.

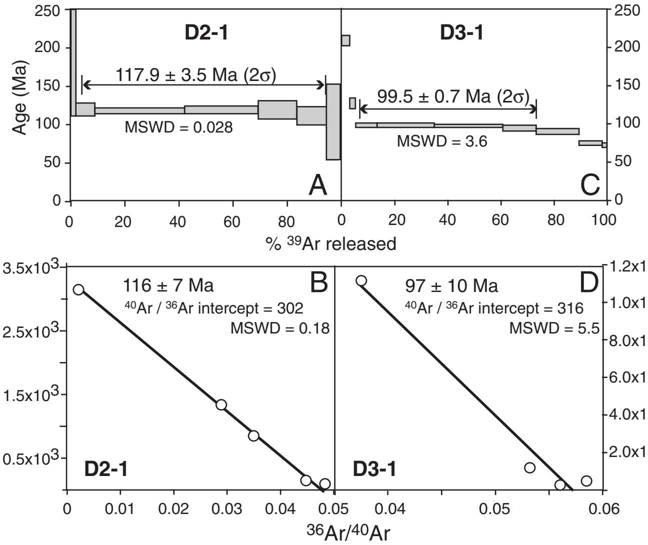

Figure 2. A, C: Apparent age vs. mole% of ^{39}Ar released during successive incremental heating steps of 100 °C. Width of horizontal bars represents 2σ error on measurement; arrow signifies steps used in plateau-age calculation. B, D: Inverse isochrons for same samples as in A and C; circles correspond to sequential steps used in plateau and isochron age calculations. MSWD—mean square of weighted deviates.

The age of D3–1 (99.5 ± 0.7 Ma) suggests that it formed well after the tholeiites. The alkalic nature of the D3 rocks and their steep trace element patterns are consistent with an origin by small degrees of melting. Their trace element patterns mimic some features found in the tholeiites, such as high Nb/La, but isotopic compositions differ, D3 (and D4) having higher $(^{206}Pb/^{204}Pb)_t$ and lower $\varepsilon_{Nd}(t)$ than D2 or SOTW rocks. Therefore, the derivation of the D3 lavas from the same ultimate mantle source as the D2 and SOTW basalts requires an isotopically heterogeneous source subjected to late-stage, small extents of melting.

RELATIONSHIP TO THE ONTONG JAVA AND HIKURANGI PLATEAUS

Despite the physical separation of the Manihiki, Hikurangi, and Ontong Java Plateaus, a relationship between two or all of these has been proposed by several authors on the basis of age, geophysical, and geochemical arguments (e.g., Billen and Stock, 2000; Mahoney and Spencer, 1991; Mortimer and Parkinson, 1996; Taylor, 2006). Our data add new evidence in favor of temporal and petrogenetic connections among the three plateaus; however, they also complicate this story.

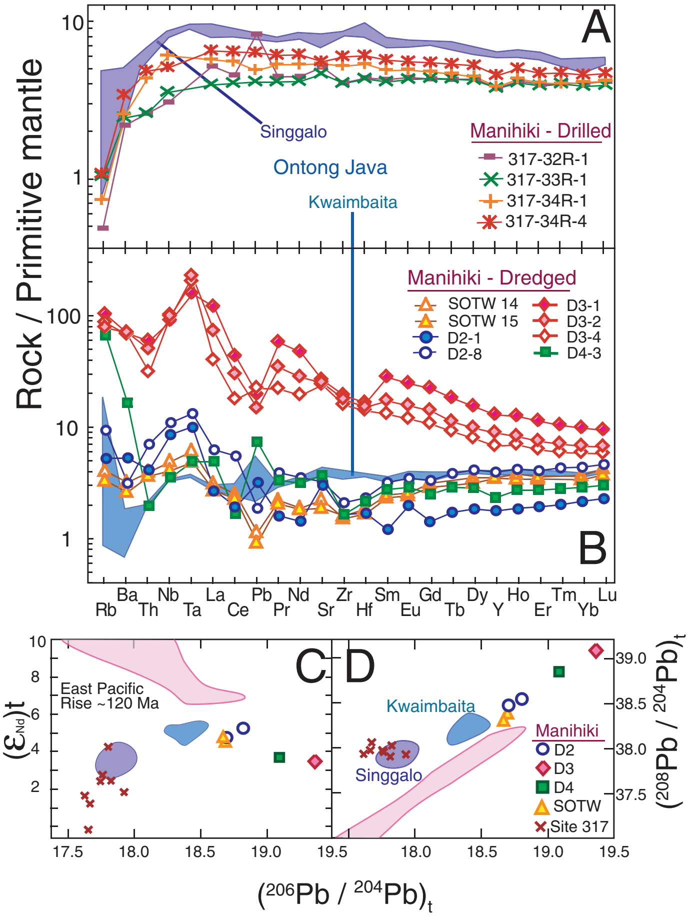

Figure 3. A, B: Primitive mantle-normalized (Sun and McDonough, 1989) incompatible element patterns of Site 317, SOTW, and selected D2–D4 samples compared to Ontong Java's Kwaimbaita (blue; Kroenke type; Fitton and Godard, 2004) and Singgalo (purple; Tejada et al., 1996) lavas. C, D: ε_{Nd}(t) vs. $(^{206}Pb/^{204}Pb)_t$ and $(^{206}Pb/^{204}Pb)_t$ for D2–D4, SOTW, Site 317, and Ontong Java rocks (Mahoney, 1987; Mahoney and Spencer, 1991; Mahoney et al., 1993; Tejada et al., 2004, 1996, 2002), and southern East Pacific Rise (pink; Mahoney et al., 1994).

Manihiki tholeiites have ^{40}Ar-^{39}Ar ages (117.9 ± 3.5 Ma and 123.1 ± 3 Ma) similar to those of rocks from both Ontong Java (ca. 120 ± 5 Ma for the main volcanic phase; Mahoney et al., 1993; Tejada et al., 2002) and Hikurangi (as old as 118 Ma; Hoernle et al., 2005). Relatively minor, late-stage volcanism also occurred on all three plateaus between 100 Ma and 88 Ma (this study; Hoernle et al., 2005; Mahoney et al., 1993; Tejada et al., 1996).

Previous geophysical observations coupled with plate tectonic reconstructions suggest that Manihiki and Hikurangi separated after forming as a single plateau, as evidenced by the Osbourn Trough, an interpreted relict spreading center located midway between the two (Billen and Stock, 2000). The Nova Canton Trough in the Ellice Basin has been proposed as either a remnant spreading center (e.g., Larson, 1997) or one of several E-W fracture zones (Taylor, 2006) between the Ontong Java and Manihiki Plateaus. Taylor (2006) argued for a combined Ontong Java–Manihiki–Hikurangi Plateau forming in Early Cretaceous time and separating shortly afterward. Radiometric ages for the eastern Nova Canton Trough should help to test this tectonic model (Pyle and Mahoney, 2006).

Major and trace element and/or isotopic data for the Manihiki and Ontong Java basalts have been compared and contrasted in several studies (e.g., Castillo, 2004; Mahoney et al., 1993). Mortimer and Parkinson (1996) and Hoernle et al. (2005) reported trace element and isotopic data for Hikurangi lavas that are comparable to those of rocks from both Ontong Java and Manihiki. Site 317 tholeiites cap Manihiki basement, just as Singgalo-type rocks are found stratigraphically above Ontong Java's Kwaimbata basalts (e.g., Tejada et al., 1996). Our data for Site 317 basalts strongly support previous suggestions of a genetic relationship with the Singgalo-type lavas (e.g., Castillo, 2004; Mahoney and Spencer, 1991). However, although Troughs tholeiites have ε_{Nd}(t) within the range of Ontong Java Kwaimbata-type rocks, $(^{87}Sr/^{86}Sr)_t$ is lower and $(^{206}Pb/^{204}Pb)_t$ is notably higher in Troughs basalts. Troughs tholeiites also have some similarities with Hikurangi rocks, including comparable ε_{Nd}(t) and $(^{87}Sr/^{86}Sr)_t$, but age-corrected Pb isotope data are not yet available for Hikurangi rocks. Late-stage events (after ca. 100 Ma) on the three plateaus vary in age and magma type, but proposed rifting between the three plateaus would have occurred before any of these events (Billen and Stock, 2000; Taylor, 2006); therefore, it is uncertain whether any relationship among these events should exist.

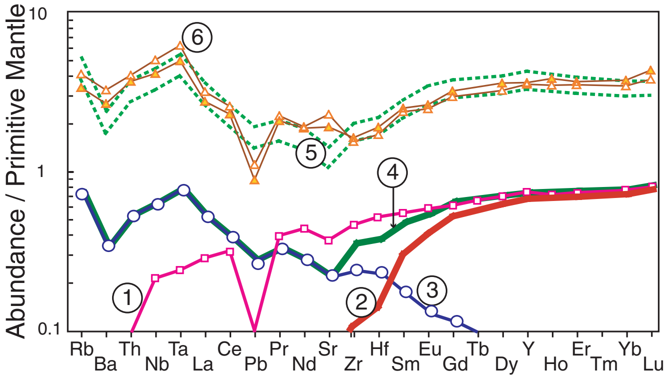

Figure 4. Model of possible melting and re-enrichment events leading to formation of Danger Island Troughs tholeiites. 1: Starting depleted mantle (wedge) composition (Workman and Hart, 2005). 2: Residue after 15% fractional melting in garnet stability zone. 3: Average composition of volcaniclastic turbidites at Site 801 (Plank and Langmuir, 1998), multiplied by 0.02. 4: Addition of 2% of Site 801 turbidites to mantle residue. 5: Model patterns generated by 15% (upper) to 20% (lower) batch melting of mixed source in spinel stability zone. 6: Data for sample SOTW-11–78D-14, SOTW-11–78D-15. Concentrations are normalized as in Figures 3A and 3B. Further details can be found in the Data Repository (see footnote 1).

CONCLUSIONS

Marked geochemical differences in drilled and dredged Manihiki Plateau tholeiites require distinct petrogenetic histories and mantle sources. Whereas drilled lavas strongly resemble the Ontong Java Singgalo-type basalt, basalts exposed along the Danger Islands Troughs represent a mantle component not identified from Ontong Java, Hikurangi, or elsewhere. The unusual incompatible element characteristics of these samples appear to require a multistage source history. We propose a model incorporating extensive melting in a depleted mantle wedge below the garnet stability zone, followed by slight re-enrichment of the residue in highly incompatible elements through addition of subducted, possibly ocean-island–derived, volcaniclastic sediment, and eventual high-degree melting of this hybrid source to produce key features of Troughs tholeiites.

The main volcanic events on Ontong Java, Manihiki, and Hikurangi appear to have been contemporaneous ca. 120 Ma, consistent with their proposed formation as a single immense feature. The overlap in incompatible element characteristics and isotopic compositions is significant, but far from complete. If these three plateaus did form as one, then the mantle source was either heterogeneous on a very large scale, resulting in sampling of distinct source components in different areas, or some mantle components remain to be sampled at each plateau.

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