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Kenneth D. Collerson, *et al.*

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Stone Adze Compositions and the Extent of Ancient Polynesian Voyaging and Trade

Kenneth D. Collerson[1]* and Marshall I. Weisler[2]

The last region on Earth settled by humans during prehistory was East Polynesia. Hawaiian oral histories mention voyaging from Hawaiʻi to Tahiti and back via the Tuamotus, an open ocean journey of several thousands of kilometers. The trace element and isotope chemistries of a stone adze recovered from the Tuamotu Archipelago are unlike those of sources in central Polynesia but are similar to the Kahoʻolawe Island hawaiite, in the Hawaiian Islands, supporting the oral histories. Other adzes collected from the low coral islands of the northwest Tuamotus have sources in the Marquesas, Austral and Society Islands, and the Pitcairn Group, confirming that trade was widespread within East Polynesia.

The greatest maritime migration in human history culminated in the settlement of the eastern margins of the Pacific Ocean, delimited by Hawaiʻi, New Zealand, and Easter Island, the last region on Earth to be settled by humans. Some researchers have suggested that settlement was accidental or by drift voyages (*1*). However, computer simulations (*2*, *3*), sailing experimental canoes using traditional navigational techniques (*4*), and review of voyaging strategies (*2*) indicate that East Polynesian colonization was purposeful, perhaps taking about six human generations to colonize most archipelagoes before 900 CE (*5*).

In the eastern Pacific, the decreasing island size and isolation of archipelagoes across Polynesia made it difficult to maintain external relations among them, and the frequency of long-distance voyaging is thought to have diminished (*6*). However, two-way postcolonization voyaging between Hawaiʻi and Tahiti is well supported by Hawaiian oral histories (*7*).

To evaluate the extent of trade in eastern Polynesia, we studied the trace element compositions and isotope chemistry of exotic stone adzes collected from nine coral atolls in the Tuamotus: the navigational crossroads of East Polynesia (*2*) (Fig. 1, A and B). These adzes are made of basalt, for which there is no local source on the coral atolls. Thus, their provenance can be used to trace Polynesian travel and trade. To evaluate sources, we developed a database containing major, trace element,

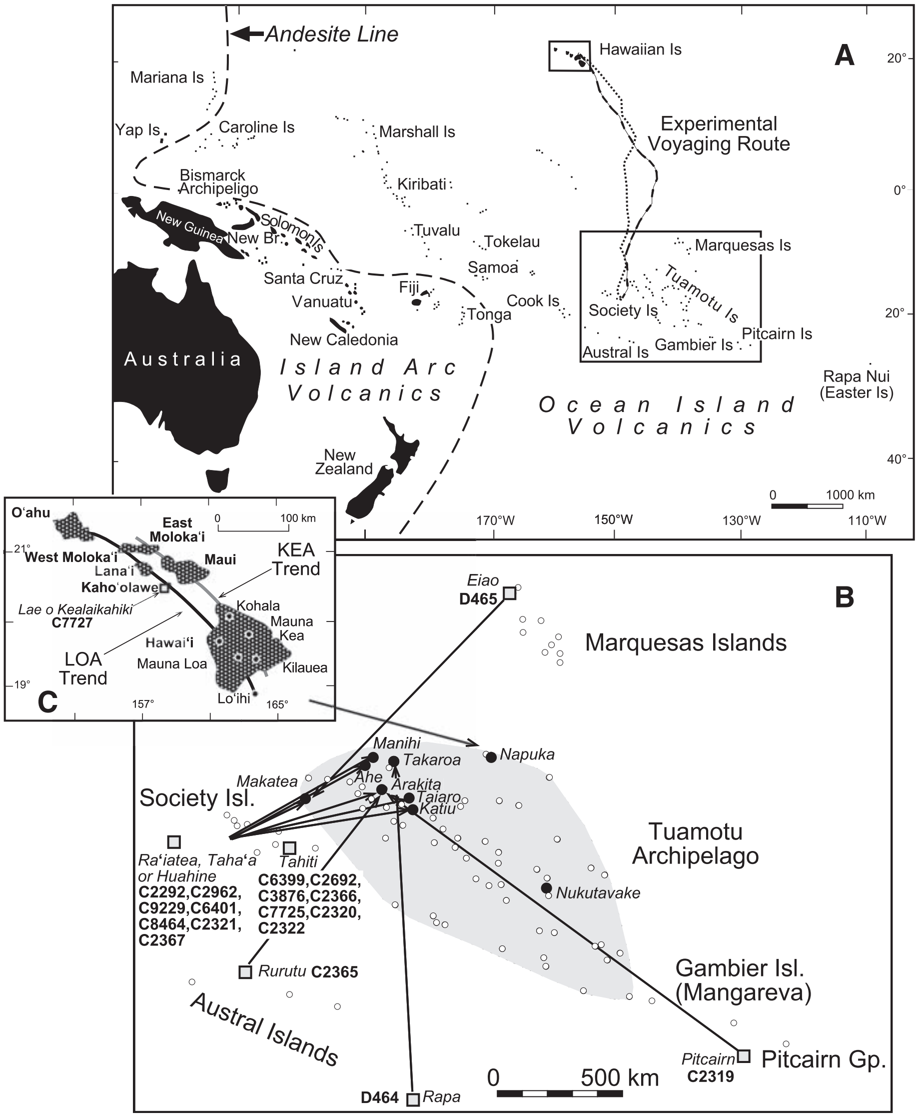

Fig. 1. (**A**) Pacific islands showing OIBs (east of the Andesite Line), IAVs, and the route between Hawaiʻi and Tahiti within the Society Islands established experimentally (*4*). (**B**) The distribution of adzes investigated in our study. Arrows link adze locations (solid circles) to their sources (gray squares) in the Marquesas, Society, Austral, Tuamotu, Gambier, and Pitcairn Island groups. (**C**) The Hawaiian Islands, with contemporary vents on Hawaiʻi and Loʻihi designated with black circles. The two linear trends (Loa and Kea) define distinctive chemical and isotopic differences within the Hawaiian mantle plume (*27*).

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[1] School of Physical Sciences–Earth Sciences, The University of Queensland, St. Lucia, QLD 4072, Australia. [2] School of Social Science–Archaeology, The University of Queensland, St. Lucia, QLD 4072, Australia.

*To whom correspondence should be addressed. E-mail: k.collerson@mailbox.uq.edu.au

Table 1. Major element compositions (in weight %), selected trace element ratios, and isotopic compositions of adzes and source basalts.

	Artifact	Rurutu	A/S*	Artifact	Eiao	A/S	Artifact	Pitcairn	A/S	Artifact	Societies	A/S	Societies	A/S	Artifact	Kaho'olawe	A/S
	C2365	KC-05-1		D465	KC-05-11		C2319	KC-05-13		C2367	Taha'a 1Ta-2V‖		Ra'iatea KC-05-21		C7727¶	H-1440#	
SiO_2	43.23	46.98	0.92	45.23	47.83	0.95	49.85	51.27	0.97	46.53	44.72	1.04	45.38	1.03	46.76	50.34	0.93
TiO_2	4.29	3.15	1.36	3.90	3.96	0.98	2.84	2.73	1.04	3.26	3.12	1.05	4.64	0.70	4.65	3.08	1.51
Al_2O_3	14.73	16.16	0.91	15.66	15.44	1.01	15.88	15.41	1.03	12.70	12.96	0.98	16.02	0.79	14.75	16.62	0.89
FeO	15.42	13.27	1.16	13.12	12.06	1.09	12.30	11.99	1.03	11.56	11.87	0.97	11.24	1.03	12.00	10.81	1.11
MnO	0.23	0.22	1.06	0.21	0.17	1.28	0.21	0.21	1.01	0.18	0.20	0.90	0.17	1.08	0.18	0.17	1.01
MgO	6.11	4.45	1.37	5.04	6.41	0.79	3.62	3.50	1.03	8.17	9.97	0.82	5.83	1.40	4.90	4.70	1.04
CaO	8.35	7.37	1.13	10.82	9.22	1.17	7.25	7.04	1.03	13.21	12.14	1.09	10.15	1.30	10.44	6.82	1.53
Na_2O	4.57	5.56	0.82	3.35	3.33	1.01	4.62	4.57	1.01	2.62	3.66	0.71	3.32	0.79	3.11	4.74	0.66
K_2O	1.78	1.67	1.07	1.89	1.05	1.80	2.07	1.99	1.04	1.28	0.76	1.68	2.22	0.58	2.43	1.86	1.30
P_2O_5	1.31	1.17	1.11	0.77	0.54	1.44	1.36	1.30	1.05	0.49	0.60	0.81	1.0	0.48	0.79	0.86	0.92
Total	100.0	100.0		100.0	100.0		100.0	100.0		100.0	100.0		100.00		100.0	100.00	
Rb/Sr	0.036	0.029	1.25	0.040	0.037	1.10	0.080	0.066	1.22	0.050	0.067	0.75	0.050	1.02	0.051	0.050	1.06
Sm/Nd	0.188	0.186	1.01	0.243	0.249	0.98	0.214	0.214	1.00	0.220	0.210	1.05	0.208	1.06	0.216	0.229	0.94
U/Pb	0.59	0.65	0.91	0.41	0.43	0.95	0.34	0.37	0.92	0.36	0.55	0.65	0.26	1.37	0.27		
Th/Pb	2.08	2.28	0.91	1.35	1.42	0.95	1.36	1.52	0.89	1.15	2.20	0.52	0.91	1.27	0.90		
Ba/Th	53.8	51.8	1.04	64.7	66.2	0.98	73.7	74.3	0.99	106.1	105.5	1.01	101.6	1.04	108.5	125.1	0.87
Zr/Hf	47.8	46.8	1.02	42.5	42.3	1.00	44.0	42.5	1.04	41.4	43.0	0.96	45.0	0.92	42.7	43.4	0.98
Nb/Ta	16.9	17.4	0.97	15.7	15.8	0.99	16.6	16.6	1.00	16.2	17.4	0.94	16.9	0.96	16.2	15.8	1.02
Nb/Th	14.4	11.5	1.25	9.9	9.8	1.00	11.6	11.6	1.00	13.4	10.5	1.28	10.2	1.31	13.1	11.9	1.10
$^{87}Sr/^{86}Sr$†	0.70330	0.70352		0.70400	0.70394		0.70360	0.70357		0.70414	0.70374		0.70440		0.704069	0.70426	
$^{143}Nd/^{144}Nd$‡	0.512933	0.512937		0.512943	0.512953		0.512820	0.512826		0.512896	0.512890		0.512894		0.512897	0.512864	
$^{206}Pb/^{204}Pb$	20.289 ± 0.018	20.332 ± 0.015		19.133 ± 0.014	19.132 ± 0.019		18.437 ± 0.026	18.455 ± 0.009		18.792 ± 0.010	18.766		18.873 ± 0.011		18.060 ± 0.004	18.005	
$^{207}Pb/^{204}Pb$	15.674 ± 0.014	15.718 ± 0.013		15.552 ± 0.011	15.576 ± 0.017		15.488 ± 0.021	15.497 ± 0.007		15.563 ± 0.009	15.480		15.602 ± 0.009		15.495 ± 0.003	15.447	
$^{208}Pb/^{204}Pb$	39.760 ± 0.036	39.912 ± 0.036		38.852 ± 0.029	38.915 ± 0.041		38.948 ± 0.054	38.996 ± 0.019		38.496 ± 0.029	38.301		38.699 ± 0.025		37.698 ± 0.011	37.817	
$^{207}Pb/^{206}Pb$	0.7726 ± 0.0001	0.7731 ± 0.0001		0.8128 ± 0.0001	0.8141 ± 0.0002		0.8401 ± 0.0002	0.8397 ± 0.0001		0.8291 ± 0.0001	0.8249		0.8267 ± 0.0001		0.8580 ± 0.0001	0.8579	
$^{208}Pb/^{206}Pb$	1.9597 ± 0.0003	1.9630 ± 0.0005		2.0306 ± 0.0004	2.0340 ± 0.0005		2.1127 ± 0.0004	2.1130 ± 0.0002		2.0508 ± 0.0003	2.0410		2.0505 ± 0.0002		2.0875 ± 0.0002	2.1004	
$^{208}Pb^*/^{206}Pb^*$§	0.936	0.947		0.954	0.961		1.038	1.041		0.951	0.933		0.964		0.939	0.959	
$^{207}Pb^*/^{206}Pb^*$§	0.490	0.492		0.535	0.538		0.569	0.569		0.556	0.548		0.555		0.594	0.593	

*The similarity of major and trace element data is shown by dividing artifact values by source compositions (A/S). †External reproducability in $^{87}Sr/^{86}Sr = 0.000025$ (2σ). ‡External reproducability in $^{143}Nd/^{144}Nd = 0.000016$ (2σ). §The $^{207}Pb^*/^{206}Pb^*$ and $^{208}Pb^*/^{206}Pb^*$ radiogenic Pb isotopic compositions were calculated by subtracting the following initial Pb isotope ratios: $^{206}Pb/^{204}Pb = 9.3066$, $^{207}Pb/^{204}Pb = 10.293$, and $^{208}Pb/^{204}Pb = 29.475$ (*39*). ‖Basanite from Taha'a expresses as anhydrous composition (*40*, *41*). ¶Single analysis of C7727 with 5-V ^{208}Pb beam. The mean given in table S4 was determined using this data as well as two new mass spectrometer determinations using separate and progressively smaller Pb loads from the same chemistry. Mass spectrometer run no. 2 with a 1-V beam and no. 3 with a 100-mv beam yielded the following isotopic compositions: $^{206}Pb/^{204}Pb = 18.020 \pm 0.009$ and 17.913 ± 0.048; $^{207}Pb/^{204}Pb = 15.940 \pm 0.028$ and 15.450 ± 0.043; $^{208}Pb/^{204}Pb = 37.708 \pm 0.028$ and 37.594 ± 0.101; $^{207}Pb/^{206}Pb = 0.8573 \pm 0.0002$ and 0.8580 ± 0.0022; $^{208}Pb/^{206}Pb = 2.0855 \pm 0.0004$ and 2.0918 ± 0.0045; $^{208}Pb^*/^{206}Pb^* = 0.945$ and 0.943; and $^{207}Pb^*/^{206}Pb^* = 0.597$ and 0.595. #Post-caldera hawaiite (*24*). The Ba/Th ratios for Kaho'olawe lavas range from 60 to 450, mean = 136 ± 89 ($n = 36$ analyses) (*42*).

and isotopic compositions of 28 volcanic sources from all Polynesian archipelagos, augmented by data (*8*) for oceanic island basalts (OIBs). Fine-grained basalt adzes and their resulting manufacturing debris occur throughout Polynesia, and this common woodworking tool has been used to identify prehistoric interaction between island groups (*9*, *10*).

Island arc volcanics (IAVs) and OIBs are chemically distinct because of differences in mantle sources and melting processes (*11*). The IAVs west of the Andesite Line (Fig. 1A) comprise volcanic rocks that range with increasing silica from basalt to andesite, dacite, and rhyolite. These IAVs form by melting of the hydrated mantle wedge above subduction zones (*12*). The range of silica in these magmas reflects fractional crystallization within high-level magma chambers and the assimilation of overlying felsic crust (*13*). By contrast, tholeiitic and alkalic OIBs and associated silica-undersaturated alkaline lavas (*8*) (fig. S1) form by partial melting in mantle away from subduction zones (*14*). The movement of overlying oceanic lithospheric plates across mantle upwellings or loci of melting explains the generation of lines of OIB volcanoes, with ages increasing in the direction of plate movement away from the hot spot (*15*), as at Hawai‘i (*16*). In eastern Polynesia, the Tuamotus, Marquesas, Society Islands, and Cook-Austral Islands, (Fig. 1B) are interpreted to have formed by this process (*17*).

Because of differences in mantle sources and melting processes, IAVs are chemically distinct from OIBs (*18*), and this difference provides a robust constraint for identifying the provenance of Polynesian basalt adzes. In addition, OIB lavas from different archipelagos exhibit different trace element and radiogenic isotope chemistries (*19*); such data can also be used to determine artifact sources. Major element chemistries may often not be diagnostic because similar basalt chemistries can be produced during the fractional crystallization of similar mineral phase sequences during cooling in high-level magma chambers.

OIBs are characterized by superchondritic Zr/Hf ratios (chondritic ratio 34.3 ± 0.3) and subchondritic Nb/Ta ratios [chondritic ratio 19.9 ± 0.6 (*20*)]. Furthermore, OIBs exhibit low and distinctive superchondritic Zr/Hf ratios of 35.5 to 43.5 [chondritic ratio 34.3 ± 0.3 (*20*)]. An additional method for discriminating between basalts is provided by radiogenic Sr, Nd, and Pb isotope compositions, for which there are extensive data for Polynesian volcanoes (*8*, *21*). Initial isotopic compositions of OIBs are diverse (*8*). In view of the marked trace element and isotopic differences between different OIB archipelagos, sources of basalt used in adze manufacture can be determined without requiring knowledge of specific locations of sources or quarries.

We analyzed 19 adzes collected by Emory between 1929 and 1934 (*8*, *22*) (table S1) from nine low coral atolls (Arakita, Makatea, Napuka, Takaroa, Katiu, Manihi, Ahe, Taiaroa, and Nukutavake) (Fig. 1, A and B). They are typical East Polynesian adze forms (Duff types 1A, 1E, 3A, 3B, 4A, and 5B) (*23*), with types 3A and 4A representing late prehistoric forms (fig. S1). These artifacts, analyzed by inductively coupled plasma mass spectrometry and with radiogenic isotope ratios analyzed by thermal ionization mass spectrometry, required <100 mg of sample (*8*) (table S2).

The radiogenic isotopic data (Table 1 and Fig. 2) allow three adzes to be assigned to their sources; C2365 from Rurutu, C2319 from Pitcairn, and C7727 with an isotopic composition indicating derivation from Kaho‘olawe, Hawai‘i. C7727 is a phenocryst-free aphanitic rock (fine-grained, where mineral phases are not discernable with the naked eye) that is typical of rocks selected for adze making. The unradiogenic Pb isotopic composition of C7727 is distinct from those of all other

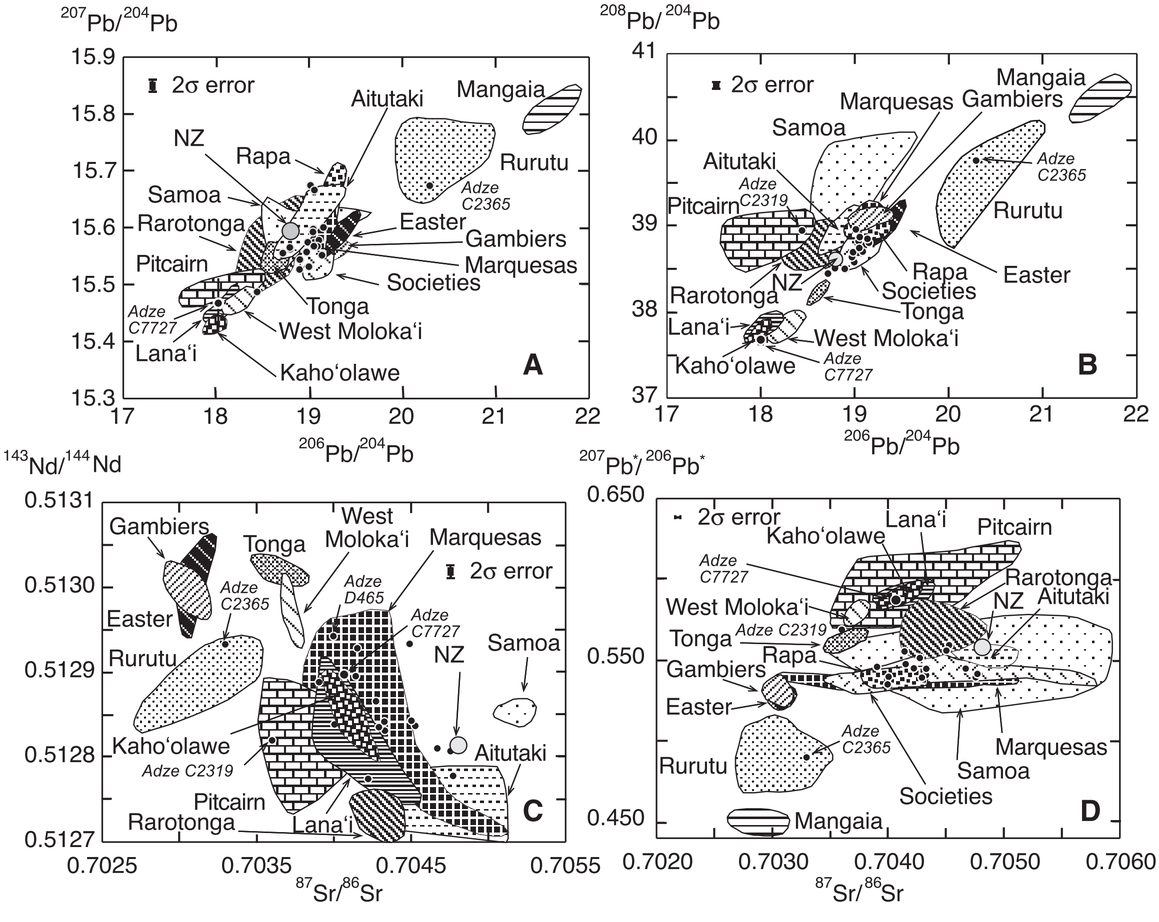

Fig. 2. (**A** to **D**) Isotopic compositions of adzes (solid circles) and compositional fields for different Polynesian OIBs. Source fields are defined by data in table S5 and studies cited in (*8*). Variations in isotopic composition define the nature and scale of chemical heterogeneity within mantle sources of OIBs (*11*). Radiogenic Pb isotopic compositions of adzes shown in Fig. 3, A and B, reflect variation in U/Pb (^{206}Pb/^{204}Pb and ^{207}Pb/^{204}Pb) ratios and also in Th/Pb (^{208}Pb/^{204}Pb) ratios. Figure 3C shows covariation between Sr isotopic composition and Nd isotopic compositions. Figure 3D shows covariation between ^{207}Pb*/^{206}Pb* and ^{87}Sr/^{86}Sr ratios. Based on isotopic composition, three adzes can be assigned to their sources: C2365, Rurutu; C2319, Pitcairn; and C7727, Hawai‘i [using the average of three Pb isotope determinations given in Table 1 and the sixth footnote of Table 1 (designated by ¶]). The unradiogenic Pb isotopic composition of C7727 is distinctive from that of all other eastern Polynesian OIBs and is similar to Loa trend basalts (Fig. 1C). Although isotopically similar, Lana‘i basalts are tholeiitic, whereas C7727, a hawaiite (fig. S1), is from Kaho‘olawe. Error bars show 2σ analytical uncertainties in each diagram.

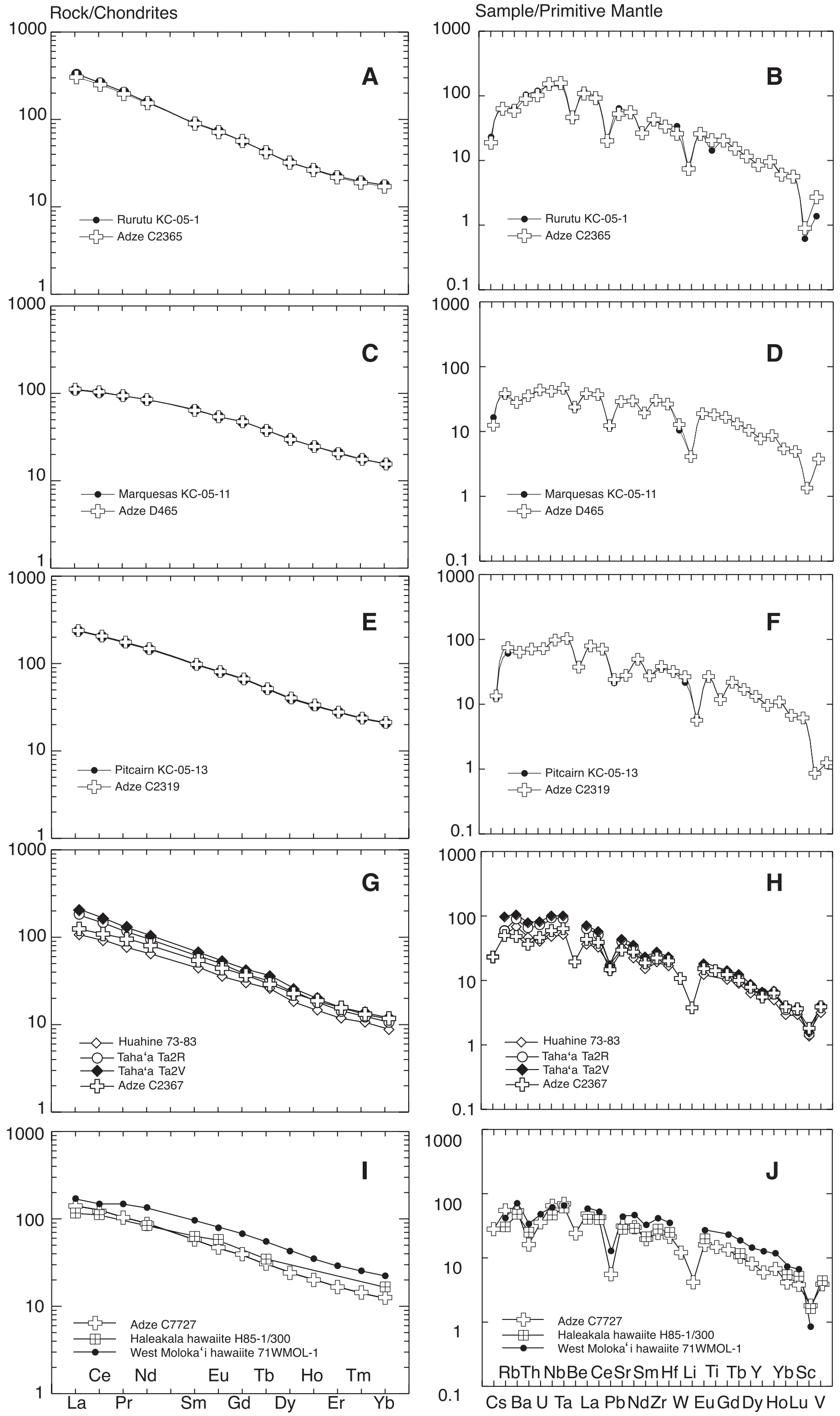

Fig. 3. Geochemical comparisons. (**A** and **B**) Similarity between C2365 and Rurutu basalts. (**C** and **D**) Similarity between D465 and the Eiao source, Marquesas. (**E** and **F**) Similarity between C2319 and Tautama basalt, Pitcairn Island. (**G** and **H**) Similarity between C2367 and basalts from Huahine and Taha'a in the Society Islands with high Ba/Th ratios. (**I** and **J**) Comparison between adze C7727 and hawaiites with similar SiO_2 composition from West Moloka'i (71WMOL-4) (*28*) and Haleakala, Maui (H85-1) (*29*). The similarity between C7727 and Haleakala hawaiite indicates that they had a common petrogenetic evolution.

eastern Polynesian OIBs but is similar to either Kahoʻolawe or Lanaʻi (*24*–*26*). Both of these islands lie in the Hawaiian Loa trend (*27*) (Fig. 1C). Although Lanaʻi basalts are isotopically similar to those on Kahoʻolawe, they are tholeiitic, whereas C7727, a hawaiite, is alkalic (fig. S2). Adze C7727 (table S4) has similar SiO_2, Al_2O_3, MgO, TiO_2, Fe_2O_3, and P_2O_5 compositions to hawaiites from West Molokaʻi and Haleakala, Maui (*28*, *29*) (table S5). Fig. S3A shows that hawaiites from Haleakala and West Molokaʻi have considerable variation in CaO (5.4 to ~10 weight %).

Adze C7727 has similar CaO and TiO_2 compositions to Ca-rich hawaiites from Haleakala, confirming a common petrogenetic evolution, different from hawaiites from Mauna Kea and West Molokaʻi. Adze C7727 falls within the field of covariation exhibited by other hawaiites from Hawaiʻi in plots of MgO with Nb, Sr, and Th (fig. S4) and with CaO/Na_2O, Nb/Th, Th/Ta, and Nb/Ta ratios (fig. S5). The adze has a similar CaO/Na_2O ratio to high-Ca hawaiites from Haleakala, Maui (fig. S5). However, its Pb isotopic composition excludes West Molokaʻi (*28*) or Maui (*30*) hawaiite as a source for this adze.

In Sr/Ce versus P_2O_5 space, adze C7727 plots within the distinctive range of compositions exhibited by hawaiites from Kahoʻolawe (fig. S6). Such variation reflects both shallow low-pressure fractionation of plagioclase (as in Haleakala, Maui hawaiites) and moderate-pressure fractionation of clinopyroxene (as in West Molokaʻi and Mauna Kea hawaiites) (*29*). Furthermore, Kahoʻolawe hawaiites are also characterized by higher Ni contents (range 54 to 226, 143 ± 71 μg/g) (*24*, *31*) than hawaiites from West Molokaʻi (1 to 40 μg/g) (*28*), Haleakala (4.5 to 51 μg/g) (*29*), and Mauna Kea (4 to 9 μg/g) (*32*). With 115 μg of Ni/g, adze C7727 is consistent with derivation from a hawaiite source on Kahoʻolawe.

Further support for the idea that C7727 originated from Hawaiʻi is provided by trace element ratios and by Sr and Nd isotope ratios given in Table 1, tables S4 and S5, Fig. 3, and fig S7. OIBs from Hawaiʻi and almost all basalts from the Emperor Seamont chain, which represents Hawaiian magmatism ranging in age from 85 to 42 million years ago, have Ba/Th ratios >100 (*33*). In East Polynesia, basalts from Raʻiatea (table S5) and Tahaʻa (*34*) in the Society Islands, shown in Fig. 3, G and H, also have Ba/Th ratios >100; however, basalts from the Society Islands have significantly higher radiogenic Pb isotopic compositions than those from Hawaiʻi (Fig. 2B, Table 1, and table S5). Although the La/Yb ratio of C7727 (16.5) (table S4) is higher than published values for Kahoʻolawe lavas, the rare earth elements are especially mobile because of alteration in some post-shield alkalic lavas (*31*). The La/Yb ratio is also affected by the degree of partial melting; thus, the higher ratio of C7727 reflects a lower degree of melting. In $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ space (fig. S7), adze C7727 plots within the Kahoʻolawe field on a mixing trend (correlation coefficient $R = 0.97$) defined by hawaiites from Kahoʻolawe, West Molokaʻi, and Haleakala (Maui). This indicates that a common petrogenetic process was involved in hawaiite formation. This most likely involved interaction between an enriched component with a high Rb/Sr ratio and low Sm/Nd ratio and a depleted component with a lower Rb/Sr ratio and higher Sm/Nd ratio.

We used the same methodology (Table 1 and Figs. 2 and 3) to identify the sources of all 19 adzes. In addition to the adzes from Kahoʻolawe, Hawaiʻi ($n = 1$); the Pitcairn Group ($n = 1$), and Rurutu ($n = 1$), adzes were also identified that were manufactured from basalt sources on Eiao in the Marquesas ($n = 1$); Rapa in the Australs ($n = 1$); the Society Islands with Ba/Th ratios >100, such as Raʻiatea, Tahaʻa, or Huahine ($n = 7$); and the Society Islands with Ba/Th ratios <100, such as Tahiti ($n = 7$).

Because adze C7727 was collected from Napuka, a low coral atoll in the western Tuamotus in central East Polynesia (Fig. 1B), the rock from which it was made was transported a minimum distance of 4040 km from its source on Kahoʻolawe in the Hawaiian chain (Fig. 1A). The likely route between Hawaiʻi and Tahiti via the Tuamotus (*35*) (Fig. 1A) has favorable winds and currents for two-way voyages. Experimental canoes using non-instrumental navigation made such a journey in 32 days (*36*).

There is much traditional ceremony in preparation for long-distance voyaging, and today, as possibly in the ancient past, canoeists often stop at the westernmost tip of Kahoʻolawe Island, Lae o Kealaikahiki (literally, "cape or headland of the way to Tahiti") (Fig. 1C) before beginning their voyage south. Sample C7727, a Duff type 3A adze, is made from rock that is consistent with hawaiite deposits found at only a few places along the coast of this island, one of which is close to Lae o Kealaikahiki. This adze type is unknown from Hawaiʻi but is common in the Tuamotus. Rock from Kahoʻolawe may thus have been taken as a gift or memento (as is done today by modern traditional voyagers) or used as ballast, and fashioned into adzes in the Tuamotus.

The Tuamotus, along with the Society Islands, could be approached from all quarters and was thus probably important in Polynesian trade (*2*). Our data show that Tuamotu adzes originate from the Marquesas, Pitcairn, Austral, and Society Islands; that is, most of the island groups surrounding the atoll archipelago. Furthermore, because the low coral atolls of the Tuamotus emerged after 1200 CE (*37*), and the surrounding island groups were colonized well before then, all imported adzes recovered in the Tuamotus relate to postcolonization interaction with adjacent archipelagoes. We therefore agree with Irwin (*2*) that postcolonization voyaging must have been common enough for voyaging knowledge to be passed across generations and that it continued until about 1450 CE when most voyaging ceased in East Polynesia (*38*).

References and Notes

1. A. Sharp, *Ancient Voyages in Polynesia* (Univ. of California Press, Berkeley, CA, 1964).
2. G. Irwin, *The Prehistoric Exploration and Colonisation of the Pacific* (Cambridge Univ. Press, Cambridge, 1992).
3. M. Levison, R. Ward, J. Webb, *The Settlement of Polynesia: A Computer Simulation* (Univ. of Minnesota Press, Minneapolis, MN, 1973).
4. B. R. Finney, *Science* **196**, 1277 (1977).
5. P. V. Kirch, *On the Road of the Winds: An Archaeological History of the Pacific Islands before European Contact* (Univ. of California Press, Berkeley, CA, 2000).
6. G. Irwin, *J. Polynesian Soc.* **107**, 111 (1998).
7. C. K. Cachola-Abad, *N. Z. Archaeol. Assoc. Mon.* **19**, 13 (1993).
8. Details are found in the supporting material on *Science* Online.
9. S. Best, P. Sheppard, R. Green, R. Parker, *J. Polynesian Soc.* **101**, 45 (1992).
10. M. I. Weisler, *N. Z. Archaeol. Assoc. Mon.* **21** (1997).
11. A. W. Hofmann, *Nature* **385**, 219 (1997).
12. T. L. Grove, N. Chatterjee, S. W. Parman, E. Medard, *Earth Planet. Sci. Lett.* **249**, 74 (2006).
13. T. L. Grove *et al.*, *Contrib. Mineral. Petrol.* **145**, 515 (2003).
14. Y. L. Niu, M. J. O'Hara, *J. Geophys. Res. Solid Earth* **108**, 2209 (2003).
15. W. J. Morgan, *Am. Assoc. Petrol. Geol. Bull.* **56**, 203 (1972).
16. J. A. Tarduno *et al.*, *Science* **301**, 1064 (2003).
17. A. Bonneville, L. Dosso, A. Hildenbrand, *Earth Planet. Sci. Lett.* **244**, 251 (2006).
18. J. A. Pearce, J. R. Cann, *Earth Planet. Sci. Lett.* **19**, 290 (1973).
19. C. Hemond, C. W. Devey, C. Chauvel, *Chem. Geol.* **115**, 7 (1994).
20. J. A. Pfander, C. Munker, A. Stracke, K. Mezger, *Earth Planet. Sci. Lett.* **254**, 158 (2007).
21. A. Zindler, S. Hart, *Annu. Rev. Earth Planet. Sci.* **14**, 493 (1986).
22. K. P. Emory, *Material Culture of the Tuamotu Archipelago* (Pacific Anthropological Records 22, Bishop Museum, Honolulu, HI, 1975).
23. R. Duff, in *Anthropology in the South Seas*, J. D. Freeman, W. R. Geddes, Eds. (Thomas Avery & Sons, New Plymouth, New Zealand, 1959), pp. 121–147.
24. W. P. Leeman, D. C. Gerlach, M. O. Garcia, H. B. West, *Contrib. Mineral. Petrol.* **116**, 62 (1994).
25. A. R. Basu, B. E. J. Faggart, in *Earth Processes: Reading the Isotopic Code*, A. Basu, S. Hart, Eds. (American Geophysical Union, Washington, DC, 1996), pp. 149–159.
26. S. C. Huang *et al.*, *Geochem. Geophys. Geosyst.* **6**, Q01L06 (2005).
27. W. Abouchami *et al.*, *Nature* **434**, 851 (2005).
28. G. Xu *et al.*, *Geochem. Geophys. Geosyst.* **8**, 10.1029/2006GC001554 (2007).
29. C. Y. Chen, F. A. Frey, M. O. Garcia, *Contrib. Mineral. Petrol.* **105**, 197 (1990).
30. H. B. West, W. P. Leeman, *Earth Planet. Sci. Lett.* **84**, 211 (1987).
31. R. V. Fodor, F. A. Frey, G. R. Bauer, D. A. Clague, *Contrib. Mineral. Petrol.* **110**, 442 (1992).
32. F. A. Frey *et al.*, *J. Geophys. Res. Solid Earth* **95**, 1271 (1990).
33. A. W. Hofmann, K. P. Jochum, *J. Geophys. Res. Solid Earth* **101**, 11831 (1996).
34. W. M. White, R. A. Duncan, in *Earth Processes: Reading the Isotopic Code*, A. Basu, S. Hart, Eds. (American Geophysical Union, Washington, DC, 1996), pp. 183–206.
35. B. R. Finney, in *Polynesian Culture History, Essays in Honor of Kenneth P. Emory*, G. A. Highland, R. W. Force, A. Howard, M. Kelly, Y. H. Sinoto, Eds. (Bishop Museum Press, Honolulu, HI, 1967), pp. 141–166.
36. B. R. Finney, *Voyage of Discovery, A Cultural Odyssey through Polynesia* (Univ. of California Press, Berkeley, CA, 1994).
37. W. R. Dickinson, *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **213**, 251 (2004).
38. M. I. Weisler, in *Geochemical Evidence for Long-Distance Exchange*, M. D. Glascock, Ed. (Bergin & Garvey, London, 2002), pp. 257–273.
39. J. H. Chen, G. J. Wasserburg, *Conf. Abstr. Lunar Planet. Inst.* **1**, 103 (1983).
40. R. Brousse, T. Gisbert, C. Leotot, *C. R. Acad. Sci. Ser. 11* **303**, 247 (1986).
41. W. White, personal communication.
42. Unpublished data are from Rice University, MPI Mainz, and Washington State University (W. P. Leeman, personal communication).

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Supporting Online Material

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Synchrony Dynamics During Initiation, Failure, and Rescue of the Segmentation Clock

Ingmar H. Riedel-Kruse,*† Claudia Müller, Andrew C. Oates†

The "segmentation clock" is thought to coordinate sequential segmentation of the body axis in vertebrate embryos. This clock comprises a multicellular genetic network of synchronized oscillators, coupled by intercellular Delta-Notch signaling. How this synchrony is established and how its loss determines the position of segmentation defects in Delta and Notch mutants are unknown. We analyzed the clock's synchrony dynamics by varying strength and timing of Notch coupling in zebrafish embryos with techniques for quantitative perturbation of gene function. We developed a physical theory based on coupled phase oscillators explaining the observed onset and rescue of segmentation defects, the clock's robustness against developmental noise, and a critical point beyond which synchrony decays. We conclude that synchrony among these genetic oscillators can be established by simultaneous initiation and self-organization and that the segmentation defect position is determined by the difference between coupling strength and noise.

The periodic and sequential segmentation of the vertebrate embryo along its anterior-posterior axis into blocks of cells called somites, the precursors of axial bone and muscle, is thought to be driven by the segmentation clock (Fig. 1A) (*1*, *2*). This clock com-