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Supporting online material for:

Fracturing of the Panamanian Isthmus during initial collision with South America

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Methods and supporting material

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References

1. Geochemical methods

The geochemical data presented in this paper is derived from instrumental neutron activation analysis (INAA). The one exception is Nb, which was determined using x-ray fluorescence spectrometry (XRF). INAA was conducted at the University of Missouri Research Reactor, whereas the XRF analyses were conducted at the Smithsonian Museum Conservation Institute in Washington D.C. Both analytical techniques were conducted on powdered whole rock samples. To reduce contamination powdering was done using an agate mill. INAA analytical precision varies depending on the element and sample matrix, but for most elements the coefficient of variation (C.V.) is less than 5%. The number of decimal places reported in Table S1 reflects the relative precision for each element.

NAA Sample Preparation

Two analytical samples were prepared from each sample. Portions of approximately 150 mg of powder were weighed into clean high-density polyethylene vials used for short irradiations at MURR. At the same time, 200 mg of each sample was weighed into clean high-purity quartz vials used for long irradiations. Individual sample weights were recorded to the nearest 0.01 mg using an analytical balance. Both vials were sealed prior to irradiation. Along with the unknown samples, standards made from National Institute of Standards and Technology (NIST) certified standard reference materials of SRM-1633a (coal fly ash) and SRM-688 (basalt rock) were similarly prepared, as were quality control samples (e.g., standards treated as unknowns) of SRM-278 (obsidian rock) and Ohio Red Clay (a standard developed for in-house applications).

Irradiation and gamma-ray spectroscopy

Neutron activation analysis of ceramics at MURR, which consists of two irradiations and a total of three gamma counts, constitutes a superset of the procedures used at most other NAA laboratories (Glasscock 1992; Neff 1992, 2000). As discussed in detail by Glasscock (1992), a short irradiation is carried out through the pneumatic tube irradiation system. Samples in the polyvials are sequentially irradiated, two at a time, for five seconds by a neutron flux of $8 \times 10^{13} \text{ n cm}^{-2} \text{ s}^{-1}$. The 720-second count yields gamma spectra containing peaks for 10 short-lived elements aluminum (Al), barium (Ba), calcium (Ca), dysprosium (Dy), potassium (K), magnesium (Mg),

manganese (Mn), sodium (Na), titanium (Ti), and vanadium (V). The samples are encapsulated in quartz vials and are subjected to a 24-hour irradiation at a neutron flux of $5 \times 10^{13} \text{ n cm}^{-2} \text{ s}^{-1}$. This long irradiation is analogous to the single irradiation utilized at most other laboratories. After the long irradiation, samples decay for seven days, and then are counted for 1,800 seconds (the "middle count") on a high-resolution germanium detector coupled to an automatic sample changer. The middle count yields determinations of seven medium half-life elements, namely arsenic (As), lanthanum (La), lutetium (Lu), neodymium (Nd), samarium (Sm), uranium (U), and ytterbium (Yb). After an additional three- or four-week decay, a final count of 8,500 seconds is carried out on each sample. The latter measurement yields the following 17 long half-life elements: cerium (Ce), cobalt (Co), chromium (Cr), cesium (Cs), europium (Eu), iron (Fe), hafnium (Hf), nickel (Ni), rubidium (Rb), antimony (Sb), scandium (Sc), strontium (Sr), tantalum (Ta), terbium (Tb), thorium (Th), zinc (Zn), and zirconium (Zr).

Element concentrations were determined using the standard-comparator method in which the elemental abundances of the unknown samples (i.e., the rocks) were determined by ratioing the measured activities per unit weight of the unknown sample to those measured for a reference standard with known concentrations (SRM-1633a, SRM-278, SRM-688). The element concentration data from the three measurements were tabulated in parts per million using the EXCEL spreadsheet program. Descriptive data for the sample were appended to the concentration spreadsheet and are archived in the MURR INAA ceramic database.

XRF methods

XRF analyses of the rocks permitted quantification of the following elements: potassium (K), gallium (Ga), rubidium (Rb), strontium (Sr), yttrium (Y), zirconium (Zr), niobium (Nb). All samples were analyzed as pressed powdered pellets. The XRF instrument is equipped with a rhodium tube and a SiPIN detector with a resolution of ca. 170 eV FWHM for 5.9 keV X-rays (at 1000 counts per second) in an area 7 mm². All analyses were conducted at 40 keV, 15 μA , using a 0.127 mm copper filter in the X-ray path for a 200-second live-time count. Peak intensities for the above listed elements were calculated as ratios to the Compton peak of rhodium, and converted to parts-per-million (ppm) using linear regressions derived from the analysis of 15 well-characterized rock standards. SRM-278 (obsidian rock) was included in the analysis as a QC.

Table DR1. Averaged trace-element geochemistry shown in Fig. 2A. Note the analytical limit for Nb is approximately 1 ppm and a number samples from the Paleocene-Oligocene arc have values that are near or below this limit.

Element	Method		Paleocene-Olig. Arc (n=96)	Miocene Canal Zone (n=92)	Bocas del Toro (n=14)	Miocene and younger Western Panama (n=42)
Cs	INAA	ppm	0.33	0.27	1.28	0.48
Rb	INAA	ppm	12.8	13.2	86.8	39.5
Ba	INAA	ppm	290	406	1207	654
Th	INAA	ppm	0.83	1.25	7.19	2.83
Nb	XRF	ppm	5	13	22	9
Ta	INAA	ppm	0.115	0.418	0.939	0.329
K	INAA	ppm	5941	6365	29485	13898
La	INAA	ppm	6.39	12.40	39.23	14.95
Ce	INAA	ppm	13.28	26.06	75.91	27.55
Sr	INAA	ppm	244.0	409.6	622.7	617.8
Nd	INAA	ppm	9.67	15.24	36.91	12.45
Zr	XRF	ppm	80.5	167.1	213.1	135.4
Hf	INAA	ppm	1.79	3.46	5.93	2.82
Sm	INAA	ppm	2.63	4.34	7.83	2.70
Eu	INAA	ppm	0.875	1.423	1.957	0.837
Ti	INAA	ppm	3517	6778	5847	2577
Tb	INAA	ppm	0.600	0.818	0.867	0.366
Dy	INAA	ppm	3.13	5.01	4.61	2.08
Yb	INAA	ppm	2.26	2.92	3.47	1.26
Lu	INAA	ppm	0.282	0.399	0.499	0.188

Table DR2. Welch two sample t-test results of trace element ratios shown in Fig. 2B and 2C. This indicates that the extensional zone volcanic rocks (the Canal Zone and Bocas del Toro) have significantly different trace element ratios than either older arc rocks or similarly aged and younger arc rocks located outside of the extensional zones. The one exception is that the extensional zone rocks have Ba/Yb ratios that are not significantly different than the older arc, however they exhibit significantly higher Ta/Yb and La/Yb ratios and so have a significantly different overall signature. In general, the Ba/Yb ratio increases over time, but in extensional zones it is significantly lower than equivalently aged rocks outside of such zones. Finally, the Western Panama group have Ta/Yb, La/Yb and Ba/Yb ratios that are all significantly higher than those in the extensional and early arc groups.

A.

Paleocene-Oligocene Arc vs. Extensional Zone (Canal and Bocas del Toro) volcanic rocks

	Paleocene-Oligocene arc mean	Extensional Zone mean	t	df	p-value	Interpretation
Ta/Yb	0.059	0.159	-14.4803	206.417	2.20E-16	Paleocene-Olig. Arc Ta/Yb ratio is significantly lower
La/Yb	2.93	5.09	-6.8515	190.523	9.83E-11	Paleocene-Olig. Arc La/Yb ratio is significantly lower
Ba/Yb	162.43	163.12	-0.0313	197.357	0.975	Paleocene-Olig. Arc Ba/Yb ratio is not significantly different

B.

Western Panama (Miocene and younger arc rocks outside of the extensional zones) vs. Extensional Zone (Canal and Bocas del Toro)

	Western Panama mean	Extensional Zone mean	t	df	p-value	Interpretation
Ta/Yb	0.394	0.159	4.2315	40.69	0.000129	Western Panama Ta/Yb ratio is significantly higher
La/Yb	19.28	5.09	4.5614	40.54	4.63E-05	Western Panama La/Yb ratio is significantly higher
Ba/Yb	842.29	163.12	5.2933	41.479	4.22E-06	Western Panama Ba/Yb ratio is significantly higher

2. Low-Temperature thermochronology

Apatite and zircon (U-Th)/He analyses in the Panamanian arc were conducted on samples collected on two separate elevation profiles: Mamoni River and Petaquilla Region. Elevation intervals of ~70 m were used for sample collection, trying to cover the largest possible range of paleocrustal depths available in the relatively limited relief of the study site. The Petaquilla profile included samples recovered from drill cores. Apatite and zircon concentrates were obtained through the conventional method of heavy liquid-magnetic susceptibility separation. From a non-magnetic mineral fraction, apatite and zircon crystals were hand-picked using a high-power (180x), stereozoom, petrographic microscope with cross-polarization that allows for inclusion screening under reflected and transmitted light. When possible, typical grain morphologies for apatite (hexagonal prisms with pincoidal terminations) and for zircon (tetragonal prisms with bipyramidal terminations) were chosen. Mostly transparent, inclusion-free, euhedral, unfractured grains with similar shape and size were selected (average prism width $\sim 80 \pm 10 \mu\text{m}$, length/width ratios of less than 1.5). Uniform grain size minimizes differences in He diffusion behavior (Farley 2000; Farley 2002; Hourigan et al., 2005). Sizes $>60\text{-}70 \mu\text{m}$ require low correction factors for He ages and increase accuracy (Farley 2002). Selected grains were digitally photographed and geometrically characterized by measuring each grain for its prism length (parallel to the c axis) and prism width in at least two different orientations (perpendicular

to the c axis). Measurements were used to perform alpha ejection corrections (Ft) (Farley, 2002). Seven samples yielded suitable grains of apatite and zircon for He dating according to previously established criteria (Reiners, 2005; Ehlers and Farley, 2003; Farley, 2002).

All (U-Th)/He analytical procedures were performed at the University of Arizona Radiogenic Helium Laboratory following a protocol based on methods reported for apatite (House et al., 1999; Stockli, 2000; Farley et al., 2000; Farley 2002) and for zircon (Reiners, 2005; Farley, 2002). Helium isotopic measurements were made by degassing each sample replicate through laser heating and evaluating ^4He by isotope-dilution gas source mass spectrometry. Radiogenic He was analyzed using a fully-automated mass spectrometry system consisting of a Nd:YAG laser for total He laser extraction, an all-metal, ultra-high-vacuum extraction line, a precise volume aliquot systems for ^4He standard and ^3He tracer for isotope, a cryogenic gas purification system, and a Blazers Prisma QMS-200 quadrupole mass spectrometer for measuring $^3\text{He}/^4\text{He}$ ratios. Two single-grain aliquots per sample were prepared following the standard protocol available at the University of Arizona. Determination of U, Th, and Sm were performed on the same crystals by isotope-dilution ICP-MS on a Thermo Element 2 ICP-MS also at the University of Arizona. Mean (U-Th)/He ages were calculated on the basis of 2 apatite and zircon replicate analyses.

Apatite He dating methods

Single-grain aliquots were prepared and two replicate analyses were performed for each sample. After careful optical screening, apatite crystals were placed into 0.8 mm Nb packets, which were then loaded into stainless steel sample planchets. Each sample replicate was degassed via laser heating for 3 minutes utilizing a Nd-YAG laser at 1.5 W to attain temperatures of $\sim 1050^\circ\text{C}$ and then analyzed for ^4He , followed by a second extraction (He re-extraction) to ensure complete degassing and to monitor He release from more retentive U- and Th-bearing inclusions in analyzed apatite. Helium blanks (0.05-0.1 fmol ^4He) were determined by heating empty Nb foil packets using the same procedure. Gas extracted from samples was processed by: 1) spiking with ~ 4 pmol of ^3He ; 2) concentrating in a cryogenic system at 16°K on a charcoal trap, and purification by release at 37°K; and 3) measuring $^4\text{He}/^3\text{He}$ ratios (corrected for HD and H₃ by monitoring H⁺) on a quadrupole mass spectrometer. All ratios were referenced to multiple same-day measured ratios and known volumes of ^4He standards processed in a similar fashion.

Once ^4He measurements were completed, samples were retrieved from the laser cell, placed in Teflon® vials, dissolved in $\sim 30\%$ HNO_3 , and spiked with mixed ^{230}Th - ^{235}U - ^{149}Sm tracer for isotope dilution ICP-MS analysis of U, Th, and Sm. Each batch of samples was prepared with a series of acid blanks and spiked normals to monitor the purity and calibration of reagents and spikes. Spiked samples were analyzed as 0.5 mL of ~ 1.5 ppb U-Th solutions by isotope dilution on a Thermo Element 2 ICP-MS. Precision and sensitivity of the instrument allow isotopic analyses with RSD $< 1\%$. Concentrations of ^{147}Sm were close to zero for all samples. Th/U ratios were used to monitor for the presence of Th rich phases such as monazite (House 2001). Normal Th/U ratios for monazite are between 5-20 (Stern and Berman 2001). The mean Th/U for all of the replicates combined is 0.9 and most values are below 1 so none of the analysis had to be excluded.

Alpha ejection was corrected for apatite He ages using the method of Farley et al (1996, 2002) et al. (1996) and Farley (2002). Durango apatite standards were run during each batch of

unknown samples (every 9 unknowns) to monitor system performance and check analytical accuracy. Durango is a well-characterized apatite from Durango Mexico with a reference Ar-Ar age of 31.44 ± 0.18 Ma (2σ) and a (U-Th)/He age of 31.13 ± 1.01 Ma (± 1 S.E.=0.21) (McDowell et al., 2005). Replicate analyses of Durango apatite in our study yielded a mean age of 31.02 ± 1.01 Ma (1σ), with a standard error (S.E.) of ± 0.22 Ma. Analytical uncertainties for the University of Arizona (U-Th)/He facility are assessed $\sim 6\%$ (2σ) which incorporates noble gas analysis and ICP-MS uncertainties. Propagated errors for apatite He ages based on the analytical uncertainty associated with U, Th, and He measurements are 4% (2σ) for laser samples. A 6% (2σ) uncertainty for all samples is reported based on the reproducibility of replicate analysis of laboratory standard samples (Reiners, 2005).

Zircon He dating methods

Measurements of parent and daughter nuclides in zircon grains were performed on two single-grain aliquots per sample following the protocol presented in Reiners (2005). To minimize potential zonation effects, grains without obvious inclusions were chosen. Clear, non-magnetic, tetragonal crystals with prism widths of at least 75–100 μm were preferred while grains with prism widths < 60 μm were avoided. Morphologies most similar to a tetragonal prism with bipyramidal terminations were selected because alpha-ejection corrections entail the assumption of this characteristic grain morphology (Reiners, 2005; Hourigan et al., 2005). Irregular morphologies, elongated grains, or crystals with fractured surfaces at low angles relative to the c -axis were rejected. Selected crystals were photographed and their dimensions measured in two perpendicular perspectives parallel to the a_1 and a_2 crystallographic axes. Measured dimensions and an assigned morphology were used to calculate the alpha-ejection correction following the Ft correction scheme of Farley (2002).

He extraction involved placement of a single crystal into a ~ 1 mm Nb foil packet that was then slightly closed and placed on a Cu planchet with another few dozen sample slots in a high-vacuum sample chamber connected to the He purification/measurement line. Each foil packet was directly heated using a 10 μm focused laser beam of a 1064-nm Nd:YAG laser to ~ 1100 – 1250 $^{\circ}\text{C}$ for 15 minute extraction intervals. All samples were then subjected to at least two re-extractions and He measurements, to assess the extent of degassing of the crystal (typical re-extracts yielded less than 0.5% of previous ^4He values). Helium extracted from zircons was spiked with ~ 0.1 – 1.0 pmol ^3He , cryogenically concentrated and purified, and expanded into a small volume with a gas-source quadrupole mass spectrometer. Ratios of $^4\text{He}/^3\text{He}$ were measured for about ten seconds following gas release and nominal equilibration time. Measured ratios were corrected for background and interferences on mass 3 (HD+ and H3+), and compared with $^4\text{He}/^3\text{He}$ measured on pipetted aliquots of a manometrically calibrated ^4He standard processed by the same methods. ^4He in the unknown zircon is assumed to be the product of the ^4He content of the standard with the ratio of the $^4\text{He}/^3\text{He}$ measurements on the unknown and the standard.

Uranium and Thorium nuclides in degassed zircons were measured by isotope dilution and solution ICP-MS. The approach required spiking with isotopically distinctive U-Th spike, sample-spike equilibration, and dissolution to a final solution suitable for ICP-MS. Zircon dissolution was carried out using HF-HNO₃ mixtures that permit dissolving the entire Nb foil and zircon content in Parr Parr bombs at higher than ambient temperatures and pressures. Ratios of $^{238}\text{U}/^{233}\text{U}$ and $^{232}\text{Th}/^{229}\text{Th}$ were quantified by 2000 measurements of the average intensities in the middle 10% of peak widths in low resolution mode on an Element2 high-resolution ICP-MS.

$^{238}\text{U}/^{235}\text{U}$ was also measured to check for Pt contamination and mass fractionation. U and Th contents of zircons were calculated from multiple determinations of isotope ratios on pure spike and spiked normals containing 1–4 ng of isotopically normal U and Th.

In zircon He dating alpha ejection was corrected using the method of Farley et al (1996) and Farley (2002). Analyzed standard included zircons from the Fish Canyon Tuff with two standard analysis per sample batch. This standard has been routinely calibrated, yielding a (U-Th)/He age of 28.29 ± 0.26 Ma in one hundred fourteen grains (95%; 2s external error of 2.6 Ma or 9.3%, MSWD = 20). Propagated errors for zircon He ages based on the analytical uncertainty associated with U, Th, and He measurements are $\sim 4\%$ (2σ) for laser samples (Reners, 2005; Farley, 2002). Nevertheless a 6% (2σ) uncertainty for all samples is reported based on the reproducibility of replicate analysis of laboratory standard samples (Reiners, 2005).

Table DR3. Low temperature thermochronology data shown in Figure 3

Sample	Age (Ma)	\pm (Ma)	Elevation (m)	Latitude	Longitude	Location	Author	System
<i>SR41-Ap</i>	25.06	1.25	1380	6.41	-75.41	Central Cordillera	Restrepo et al. (2009)	A-He
<i>SR-CC-003-Ap</i>	24.23	1.21	1070	6.76	-75.12	Central Cordillera	Restrepo et al. (2009)	A-He
<i>SR-CC-002-Ap</i>	23.93	1.20	1000	6.8	-75.14	Central Cordillera	Restrepo et al. (2009)	A-He
<i>SR-CC-001-Ap</i>	22.85	1.14	760	6.86	-75.18	Central Cordillera	Restrepo et al. (2009)	A-He
<i>SR44-Ap</i>	26.59	1.33	1640	6.34	-75.58	Central Cordillera	Restrepo et al. (2009)	A-He
<i>SR-42 b</i>	25.90	1.70	1400	6.41	-75.41	Central Cordillera	Restrepo et al. (2009)	A-He
<i>SR-42</i>	25.90	1.70	1480	6.41	-75.41	Central Cordillera	Restrepo et al. (2009)	A-He
<i>60022 (avg.)</i>	28.97	5.09	164	9.28511	-79.1329	Mamoni	Unpublished	A-He
<i>60034 (avg.)</i>	21.79	2.38	143	9.29007	-79.133	Mamoni	Unpublished	A-He
<i>60059 (avg.)</i>	25.00	2.02	162	9.28564	-79.1379	Mamoni	Unpublished	A-He
<i>60062 (avg.)</i>	19.55	1.11	182	9.28817	-79.1354	Mamoni	Unpublished	A-He
<i>AC060120B</i>	22.33	0.70	0	8.8320	-80.6631	Petaquilla	Unpublished	Zr-He
<i>AC060121 (avg.)</i>	22.08	1.36	-100	8.8320	-80.6631	Petaquilla	Unpublished	Zr-He
<i>AC060118A</i>	19.52	0.08	112	8.8320	-80.6631	Petaquilla	Unpublished	Zr-He
<i>EAM-18-72</i>	21.71	0.68	130	10.5954	-74.0952	Sierra Nevada de Santa Marta	Cardona et al. (in-press)	Zr-He
<i>EAM-11-43</i>	21.44	0.57	189	10.6083	-74.0928	Sierra Nevada de Santa Marta	Cardona et al. (in-press)	Zr-He
<i>EAM-11-42</i>	23.18	0.55	252	10.6066	-74.0915	Sierra Nevada de Santa Marta	Cardona et al. (in-press)	Zr-He
<i>JRG-11-15</i>	22.67	0.47	617	10.6042	-74.0903	Sierra Nevada de Santa Marta	Cardona et al. (in-press)	Zr-He
<i>EAM-11-50</i>	24.19	0.57	943	10.6031	-74.0885	Sierra Nevada de Santa Marta	Cardona et al. (in-press)	Zr-He
<i>EAM-19-59</i>	24.34	0.46	1602	10.5984	-74.0536	Sierra Nevada de Santa Marta	Cardona et al. (in-press)	Zr-He
<i>FT-583</i>	23.20	3.10	2890			Eastern Cordillera	Mora et al. (2010)	AFT
<i>AM-10</i>	19.80	2.00	2542			Eastern Cordillera	Mora et al. (2010)	AFT
<i>RG-04</i>	19.90	2.10	3619	5.9250	-73.0882	Eastern Cordillera	Mora et al. (2010)	AFT
<i>FT-627</i>	20.00	2.00	3186			Eastern Cordillera	Mora et al. (2010)	AFT
<i>MP-72</i>	22.80	3.40	486	5.6674	-72.2283	Eastern Cordillera	Mora et al. (2010)	AFT
<i>FT-79C</i>	20.00	3.30	2355			Eastern Cordillera	Mora et al. (2010)	AFT
<i>Z14</i>	18.50	1.00	1451	4.3705	-73.9007	Eastern Cordillera	Parra et al. (2009)	ZFT
<i>Z03</i>	19.50	1.00	1114			Eastern Cordillera	Parra et al. (2009)	ZFT
<i>Z02</i>	24.00	1.40	737	5.1183	-74.4121	Eastern Cordillera	Parra et al. (2009)	ZFT
<i>Z04</i>	19.40	1.10	1085			Eastern Cordillera	Parra et al. (2009)	ZFT

Table DR4. Detailed data for (U-Th)/He ages from Panama (Fig. 3)

Sample No.	Age (Ma)	\pm (Ma)	Mass (μ g)	U (ppm)	Th (ppm)	Sm (ppm)	4He (nmol/g)	Ft	Elevation (m)	Lat. (Deg.)	Long. (Deg.)	Profile
06-0022A	34.06	0.70	1.47	11.25	16.55	109.40	1.89	0.67	164	9.28511	-79.1329	Mamoni A-He
06-0022B	23.87	0.47	3.22	22.81	12.06	135.62	2.47	0.74	164	9.28511	-79.1329	Mamoni A-He
060034A	24.18	1.78	0.72	3.96	12.38	74.61	0.50	0.55	143	9.29007	-79.133	Mamoni A-He
060034B	19.41	0.90	1.12	8.53	16.16	110.77	0.80	0.61	143	9.29007	-79.133	Mamoni A-He
060059A	27.01	0.60	1.35	14.06	24.44	107.27	1.84	0.63	162	9.28564	-79.1379	Mamoni A-He
060059B	22.98	0.92	0.73	15.41	24.22	104.20	1.47	0.56	162	9.28564	-79.1379	Mamoni A-He
060062A	20.67	0.75	2.69	3.43	13.02	388.40	0.56	0.73	182	9.28817	-79.1354	Mamoni A-He
060062B	18.44	0.64	1.80	6.02	24.34	599.65	0.86	0.69	162	9.28817	-79.1354	Mamoni A-He
AC060120B	22.33	0.43	4.94	316.63	176.09		32.83	0.76	-93	8.8320	-80.6631	Petaquilla Zr-He
AC060121B	20.72	0.39	22.16	128.53	71.31		13.91	0.86	-219	8.8320	-80.6631	Petaquilla Zr-He
AC060121A	23.44	0.46	15.14	151.21	67.53		17.61	0.83	-219	8.8320	-80.6631	Petaquilla Zr-He
AC060118A	19.52	0.38	13.19	137.17	68.39		13.36	0.83	-302.5	8.8320	-80.6631	Petaquilla Zr-He

Ft=Correction for alpha ejection loss (Farley, 2002, Reiners, 2005)

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