Supplementary material

Pervasive contamination of the remote open ocean with anthropogenic zinc

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Table S1: Aerosol enrichment factors (EF) during the GP21 cruise. Each aerosol sampling interval (48 – 72 h) ranged over 2 – 5 stations. Sample names and station range correspond to air mass back trajectory simulations depicted in Extended Data Figure 3.

Sample name	Stations	Zn EF	Pb EF
BC1	1-5	19	12
BC2	5-8	7	2
BC3	9-10	1380	51
BC4	12-14	783	45
49	14-16	3667	78
50	16-19	1893	44
B14	19-22	-	-
51	22-25	6153	55
52	25-27	1428	-
53	28-31	4770	77
BA7	31-33	-	94
BB4	40-44	683	24

Table S2: Evaluation of the long-term Zn and Pb isotope composition of aerosols deposited in the South Pacific. The range of possible Zn isotope compositions in Australian-sourced aerosols is estimated by the upper and lower limits of $\delta^{66}Zn$ measured in marine aerosols east of Australia since no direct observations of $\delta^{66}Zn$ in Australian emissions exist. The range of possible Australian-source Pb isotope compositions is estimated from $^{206}Pb/^{207}Pb$ ratio of aerosols sampled adjacent to Australian Pb mines and in eastern Australia. The isotopic range of South American aerosols is estimated from urban aerosols from Brazil and Chile.

Aerosol source	**Upper $\delta^{66}Zn$ (‰)**	**Lower $\delta^{66}Zn$ (‰)**	**Upper $^{206}Pb/^{207}Pb$**	**Lower $^{206}Pb/^{207}Pb$**	**References**
Australia	0.21	-0.35	1.102	1.049	(this study; Bollhöfer & Rosman, 2000; Bunnell et al., 2025; Mackay et al., 2013)
South America	-0.12	< -0.8	1.251	1.063	(this study; Bollhöfer & Rosman, 2000; Souto-Oliveira et al., 2018)

Table S3: Concentrations of Zn, Pb, Al, Mn, and P (µg g^{-1}) in measured certified reference materials (BCR-414 and BCR-2) compared to certified and literature values. For BCR-2, both the combined labile and refractory fractions and bulk (total) digestions are presented.

		Zn	**Pb**	**Al**	**Mn**	**P**
BCR-414	This study (n = 13)	114.6 ± 12.7	3.93 ± 0.88	2654 ± 298	299 ± 33	14480 ± 1562
	Certified	111.6 ± 2.5	3.97 ± 0.19		299 ± 13	
	Ohnemus et al. (2014) [a]			2742 ± 256 [2618 ± 21]		14316 ± 1299 [12300 ± 600]
BCR-2	This study Labile + refractory (n = 4)	136.2 ± 4.6	10.18 ± 0.43	71588 ± 1007	1557 ± 15	1573 ± 64
	This study Bulk (n = 4)	134.1 ± 3.3	10.59 ± 0.78	72383 ± 2181	1589 ± 18	1473 ± 46
	Certified	129.5 ± 1.8	10.59 ± 0.17	71340 ± 635	1523 ± 23	1568 ± 41

a presented are the average ± 1SD values from an interlaboratory study with the informational (non-certified) values in brackets.

Table S4: Procedural blank contributions and isotope composition. Elemental abundances in marine particles and aerosols were corrected for filter blank contributions. The Zn and Pb isotope composition of the procedural blank (sum of filter and column blanks) was used to correct for isotopic shifts induced by the blank. The uncertainty in the procedural blank is propagated from those of the filter and column blanks.

		Filter blank (ng)	**Column blank (ng)**	**Procedural blank (ng)**	**Procedural blank $\delta^{66}Zn$ (‰)**	**Procedural blank $^{208}Pb/^{206}Pb$**	**Procedural blank $^{206}Pb/^{207}Pb$**
Marine particulates	Zn labile	4.0 ± 1.4	0.4 ± 0.2	4.4 ± 1.4	0.49 ± 0.05		
	Zn refractory	3.7 ± 0.9	0.4 ± 0.2	4.1 ± 0.9	0.10 ± 0.05		
	Pb labile	0.009 ± 0.005	0.0012 ± 0.0007	0.01 ± 0.01		2.0742 ± 0.0003	1.1747 ± 0.0003
	Pb refractory	0.04 ± 0.04	0.0012 ± 0.0007	0.04 ± 0.04		2.0853 ± 0.0001	1.1674 ± 0.0001
Aerosols	Zn labile	37.0 ± 8.5	0.4 ± 0.2	37.4 ± 8.5	0.21 ± 0.01		
	Zn refractory	14.2 ± 6.5	0.4 ± 0.2	14.6 ± 6.5	0.16 ± 0.02		
	Pb labile	0.23 ± 0.09	0.0012 ± 0.0007	0.23 ± 0.09		1.9534 ± 0.0001	1.2472 ± 0.0001
	Pb refractory	0.28 ± 0.10	0.0012 ± 0.0007	0.28 ± 0.10		1.9532 ± 0.0001	1.2500 ± 0.0001

Table S5: Pb isotope ratios of NIST SRM 981 analyzed at varying concentrations. Relative uncertainties (ppm) are calculated from the uncertainty (2 standard error) produced by the instrumental analysis.

NIST SRM 981 (ppb)	**$^{208}Pb/^{206}Pb$**	**Relative uncertainty (ppm)**	**$^{206}Pb/^{207}Pb$**	**Relative uncertainty (ppm)**
25	2.16776 ± 0.00003	13.5	1.09301 ± 0.00001	12.9
5	2.16787 ± 0.00002	11.0	1.09300 ± 0.00002	14.5
1	2.16771 ± 0.00006	25.8	1.09305 ± 0.00006	58.8
0.5	2.16761 ± 0.00012	54.4	1.09310 ± 0.00003	25.3
0.1	2.16755 ± 0.00062	287.1	1.09316 ± 0.00048	442.4
Baker et al. (2004)	2.16775		1.09302	

Table S6: Isotope compositions of Zn ($\delta^{66}Zn$, relative to JMC-Lyon) and Pb measured in certified reference materials (BCR-414 and BCR-2) compared to literature values.

		δ^{66}Zn (‰)	**$^{206}Pb/^{204}Pb$**	**$^{206}Pb/^{207}Pb$**	**$^{208}Pb/^{206}Pb$**	**$^{208}Pb/^{207}Pb$**
BCR-414	This study (*n* = 16)	0.28 ± 0.04	18.382 ± 0.012	1.1746 ± 0.0006	2.0900 ± 0.0011	2.4549 ± 0.0006
	Druce et al. (2020)	0.32 ± 0.03				
	Jeong et al. (2021)	0.29 ± 0.04				
	Takano et al. (2020)	0.31 ± 0.03				
	Grun et al. (2023)	0.33 ± 0.07				
	Takano et al. (2024)	0.30 ± 0.02	18.382 ± 0.003	1.1730 ± 0.0002		2.4544 ± 0.0003
BCR-2	This study Labile + refractory (*n* = 3)	0.28 ± 0.04	18.769 ± 0.007	1.2009 ± 0.0005	2.0652 ± 0.0001	2.480 ± 0.001
	This study Bulk (*n* = 3)	0.27 ± 0.02	18.766 ± 0.002	1.2006 ± 0.0003	2.0649 ± 0.0011	2.479 ± 0.002
	Druce et al. (2020)	0.28 ± 0.02				
	Druce et al. (2020) [a]	0.26 ± 0.08				
	Liao et al. (2021)	0.28 ± 0.07				
	Souto-Oliveira et al. (2019)	0.29 ± 0.07	18.742 ± 0.008	1.2011 ± 0.0004	2.0631 ± 0.0014	2.478 ± 0.001
	Baker et al. (2004)		18.765 ± 0.011	1.2007 ± 0.0007	2.0651 ± 0.0006	2.480 ± 0.001
	Bridgestock et al. (2016)		18.760 ± 0.009	1.2006 ± 0.0001		2.469 ± 0.003
	Weis et al. (2006)		18.753 ± 0.020	1.2002 ± 0.0013	2.0649 ± 0.0004	2.478 ± 0.003

a recommended value after an average of 20 studies

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