Supplementary material

Mineral Phase-element Associations Based on Sequential Leaching of Ferromanganese Crusts, Amerasia Basin Arctic Ocean

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Table S1. Correlation coefficient matrix for the ferromanganese mineral association.

	N	Na	Mg	Al	Si	P	S	Cl	K	Ca	Sc	Ti	Mn	Fe	Co	Ni
Na	113	1	-0.21	0	-0.22	-0.3	0.1	-0.14	0.04	0.32	0.29	-0.42	0.29	-0.4	-0.5	0.02
Mg	121	-0.21	1	-0.14	-0.24	-0.36	0.62	-0.26	-0.16	-0.14	-0.26	0.45	0.35	-0.48	0.61	0.15
Al	121	0	-0.14	1	0.51	0.44	-0.23	-0.02	0.26	-0.2	0.09	-0.4	-0.27	0.05	0.36	-0.47
Si	121	-0.22	-0.24	0.51	1	0.37	-0.3	0.06	0.75	-0.37	-0.08	-0.1	-0.48	0.26	0.13	0.02
P	118	-0.3	-0.36	0.44	0.37	1	-0.29	0.19	0.04	-0.51	0.09	0.03	-0.71	0.74	-0.09	-0.38
S	109	0.1	0.62	-0.23	-0.3	-0.29	1	-0.32	-0.1	0.15	-0.08	0.31	0.33	-0.42	0.47	-0.04
Cl	121	-0.14	-0.26	-0.02	0.06	0.19	-0.32	1	-0.12	0.04	-0.16	-0.01	-0.2	0.26	0.4	0.24
K	92	0.04	-0.16	0.26	0.75	0.04	-0.1	-0.12	1	-0.11	0.08	-0.05	-0.09	0	-0.25	0.31
Ca	121	0.32	-0.14	-0.2	-0.37	-0.51	0.15	0.04	-0.11	1	0.06	-0.24	0.64	-0.37	0.27	0.08
Sc	91	0.29	-0.26	0.09	-0.08	0.09	-0.08	-0.16	0.08	0.06	1	-0.10	-0.01	0.05	0.66	0.05
Ti	80	-0.42	0.45	-0.4	-0.1	0.03	0.31	-0.01	-0.05	-0.24	-0.10	1	-0.02	0.17	0.23	-0.01
Mn	121	0.29	0.35	-0.27	-0.48	-0.71	0.33	-0.2	-0.09	0.64	-0.01	-0.02	1	-0.75	0.35	0.63
Fe	121	-0.4	-0.48	0.05	0.26	0.74	-0.42	0.26	0	-0.37	0.05	0.17	-0.75	1	-0.08	-0.37
Co	10	-0.5	0.61	0.36	0.13	-0.09	0.47	0.4	-0.25	0.27	0.66	0.23	0.35	-0.08	1	0.13
Ni	28	0.02	0.15	-0.47	0.02	-0.38	-0.04	0.24	0.31	0.08	0.05	-0.01	0.63	-0.37	0.13	1

N — number of samples. Bolded red values reflect values above zero point of correlation at the 99% confident level.

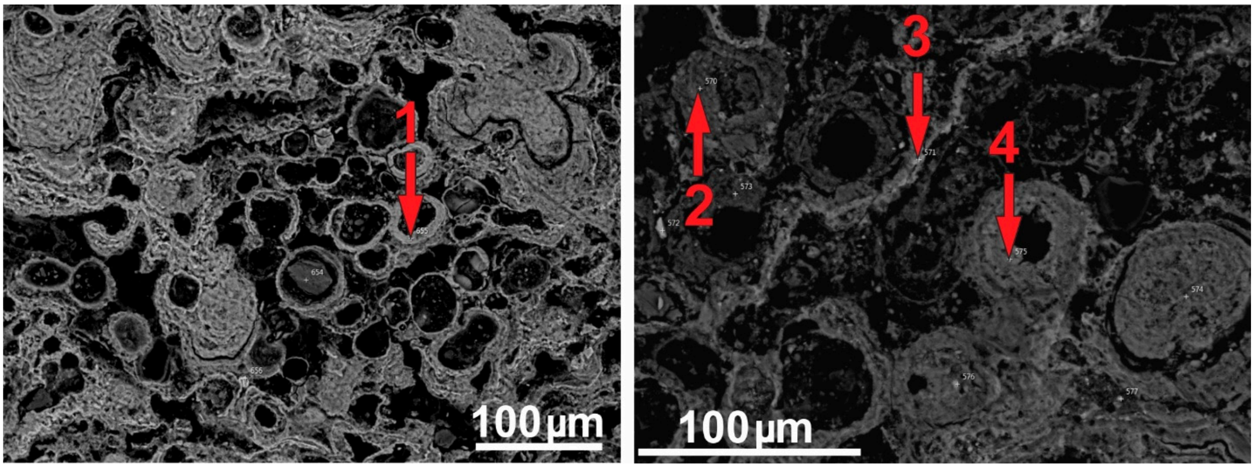

Figure S1. Back-scatter photomicrographs of organic relicts replaced by iron minerals. Chemical composition (SEM-EDS) for spots 1-4 presented in Table S2.

Table S2. Chemical composition (SEM-EDS) of points in Figure S1.

	Na	Mg	Al	Si	P	S	Cl	K	Ca	Sc	Ti	V	Mn	Fe
1	BD	1.18	2.64	4.41	0.84	BD	1.34	BD	0.54	BD	0.41	BD	BD	57.1
2	0.57	2.34	10.9	13.8	0.94	0.19	0.89	1.75	0.49	BD	0.31	BD	0.71	31.1
3	1.67	1.96	5.24	2.13	1.46	0.34	0.6	0.18	1.17	BD	0.48	BD	5.37	45.5
4	0.99	2.18	5.27	4.22	1.46	0.31	1.33	0.26	0.91	0.07	0.28	0.14	0.98	49.2

BD=below detection.

Table S3. Correlation coefficient matrix for the iron mineral association.

	N	Na	Mg	Al	Si	P	S	Cl	K	Ca	Sc	Ti	V	Mn	Fe
Na	32	1	-0.07	-0.15	0.35	-0.07	0.12	0.1	-0.14	0.28	0.08	0.33	-0.35	0.33	-0.3
Mg	54	-0.07	1	0.52	-0.24	0.4	-0.05	0.04	-0.29	0	0.27	0.25	-0.23	0.18	-0.53
Al	54	-0.15	0.52	1	0.36	0.37	-0.37	0.17	0.15	-0.27	-0.17	-0.12	-0.52	-0.04	-0.45
Si	54	0.35	-0.24	0.36	1	-0.33	-0.41	0.1	0.79	-0.29	-0.30	0.04	-0.43	-0.27	-0.21
P	54	-0.07	0.4	0.37	-0.33	1	0.26	0.17	-0.25	-0.02	0.51	0.11	0.29	-0.18	-0.02
S	29	0.12	-0.05	-0.37	-0.41	0.26	1	0.12	-0.07	0.68	0.62	0.36	0.07	0.23	-0.03
Cl	46	0.1	0.04	0.17	0.1	0.17	0.12	1	-0.19	0.04	-0.10	-0.08	-0.25	0.01	0.26
K	36	-0.14	-0.29	0.15	0.79	-0.25	-0.07	-0.19	1	-0.49	-0.05	-0.02	-0.33	-0.26	-0.3
Ca	54	0.28	0	-0.27	-0.29	-0.02	0.68	0.04	-0.49	1	0.05	0.36	-0.1	0.52	0.03
Sc	44	0.08	0.27	-0.17	-0.30	0.51	0.62	-0.10	-0.05	0.05	1.00	0.59	-0.05	-0.34	0.10
Ti	40	0.33	0.25	-0.12	0.04	0.11	0.36	-0.08	-0.02	0.36	0.59	1	0.44	-0.02	-0.28
V	17	-0.35	-0.23	-0.52	-0.43	0.29	0.07	-0.25	-0.33	-0.1	-0.05	0.44	1	-0.33	0.62
Mn	45	0.33	0.18	-0.04	-0.27	-0.18	0.23	0.01	-0.26	0.52	-0.34	-0.02	-0.33	1	-0.31
Fe	54	-0.3	-0.53	-0.45	-0.21	-0.02	-0.03	0.26	-0.3	0.03	0.10	-0.28	0.62	-0.31	1

N = number of samples. Bolded red values reflect values above zero point of correlation at the 95% confident level.

Table S4. Leach phase mass percentages for 13 samples.

%	L1	L2	L3	L4	Total
DR5-D-A	16.2	27.1	19.5	34.8	97.6
DS5-042/1	11.7	26.7	23.4	34	95.8
DS5-042/2	11.3	28.5	26.1	28.6	94.5
DS1-001/A	21.1	21.9	20.5	33.5	97
DS1-001/B	10.4	26.3	30.6	28.6	95.9
DS1-001C	7.7	16.9	30.5	38.8	93.9
DS1-001D	24.2	15	18.9	40.2	98.3
DR4-003A	6.6	39.9	21.3	27.7	95.5
09-648/1	19.8	33.2	25.8	18.3	97.1
09-648/2	12.2	30.6	33.4	19.7	95.9
09-648/3	14.2	20.1	29.6	31.4	95.3
10/1	9.7	31.9	23.5	30.6	95.7
D07-33	12.6	44.3	29.5	7.5	93.9

L1-L4 - four sequential leaching fractions.

Table S5. Complete set of sequential leaching results for 13 FeMn crust samples from the Arctic Ocean and two from the Pacific Ocean.

	DR5-D-A				DS5-042/1				DS5-042/2				DS1-001/A				DS1-001/B				DS1-001/C				DS1-001D			
	L1	L2	L3	L4	L1	L2	L3	L4	L1	L2	L3	L4	L1	L2	L3	L4	L1	L2	L3	L4	L1	L2	L3	L4	L1	L2	L3	L4
Li	10.1	51.4	3.9	34.7	10.3	44.2	5.7	39.8	9.4	51.6	4.2	34.8	14.4	46.6	5.2	33.8	10.2	53.4	5.4	31.0	7.9	42.3	5.2	44.6	8.1	36.6	5.2	50.0
Mg	40.6	24.7	14.9	19.8	42.7	23.4	14.9	19.0	45.5	19.8	15.8	18.8	46.5	18.7	15.2	19.6	43.7	17.5	19.3	19.5	39.7	13.8	20.0	26.6	40.6	12.3	17.2	29.9
K	-	-	-	-	16.6	4.2	1.8	77.4	17.4	4.7	1.5	76.4	-	-	-	-	18.8	4.5	2.1	74.6	14.1	3.5	1.4	81.0	-	-	-	-
Ca	62.5	28.7	1.0	7.8	65.2	24.5	1.6	8.7	66.4	25.6	1.2	6.7	65.5	21.9	1.4	11.1	68.3	22.6	2.3	6.9	62.5	20.7	0.9	15.9	61.9	18.4	0.6	19.2
Sr	50.7	37.2	2.2	10.0	50.3	39.3	1.9	8.6	47.0	44.7	1.8	6.4	54.5	29.9	2.1	13.5	51.3	37.8	2.7	8.2	49.9	29.5	3.3	17.3	52.5	23.9	2.7	20.9
Cs	0.2	0.8	3.2	95.8	0.5	1.3	4.8	93.4	0.3	1.1	4.3	94.4	0.4	1.8	5.6	92.2	0.6	2.1	5.0	92.3	0.2	1.5	5.1	93.2	-	-	-	-
Ba	0.0	39.4	6.7	53.9	0.0	42.6	6.6	50.7	0.0	50.2	7.3	42.4	0.0	34.9	4.7	60.4	0.2	46.0	8.3	45.5	0.0	29.8	5.7	64.5	0.0	24.5	3.1	72.4
Mn	0.0	97.9	2.0	0.1	0.0	97.8	2.1	0.1	0.0	97.4	2.6	0.1	0.0	98.0	1.8	0.2	0.0	96.0	3.8	0.2	0.0	96.1	3.7	0.2	0.0	97.1	2.7	0.2
Co	0.0	98.7	1.1	0.2	0.0	98.7	1.1	0.2	0.0	98.4	1.4	0.2	0.0	98.8	0.8	0.3	0.1	98.3	1.3	0.3	0.1	97.1	2.0	0.8	0.1	97.5	1.6	0.9
Ni	0.2	96.3	2.7	0.8	0.5	95.1	3.8	0.7	0.3	94.6	4.2	0.9	0.7	95.6	2.7	0.9	0.8	92.4	5.5	1.3	0.5	89.8	6.6	3.1	0.7	91.8	4.5	3.0
Zn	0.0	47.4	34.0	18.7	0.0	49.4	35.5	15.1	0.0	45.7	37.5	16.8	0.0	44.9	36.9	18.1	0.0	37.4	42.6	20.0	-	-	-	-	0.0	29.7	41.0	29.4
Cu	1.5	48.2	39.3	11.0	-	-	-	-	-	-	-	-	2.5	48.2	40.1	9.3	1.4	38.3	47.8	12.5	-	-	-	-	3.0	34.9	47.6	14.5
Y	0.0	69.3	23.3	7.4	0.0	72.1	22.7	5.2	0.0	74.7	20.5	4.9	0.0	68.0	24.1	7.9	0.0	72.1	22.2	5.8	0.0	63.3	27.4	9.3	0.0	64.3	25.1	10.6
La	0.0	66.2	18.7	15.1	0.0	71.9	18.4	9.7	0.0	74.2	17.6	8.2	0.0	63.5	20.0	16.5	0.0	71.3	19.1	9.6	0.0	58.0	22.9	19.0	0.0	54.0	21.8	24.2
Ce	0.0	77.0	18.6	4.4	0.0	76.8	20.2	3.0	0.0	81.9	16.0	2.1	0.0	77.4	17.6	5.1	0.0	79.5	18.4	2.1	0.0	74.4	20.8	4.9	0.0	74.1	18.7	7.2
Pr	0.0	62.9	22.0	15.0	0.0	68.2	23.6	8.2	0.0	69.7	21.5	8.7	0.0	60.1	23.3	16.6	0.0	68.4	21.7	9.9	0.0	56.5	25.7	17.8	0.0	54.0	24.5	21.5
Nd	-	-	-	-	-	-	-	-	0.0	80.6	14.8	4.6	-	-	-	-	0.0	78.4	15.7	5.9	-	-	-	-	-	-	-	-
Gd	0.0	77.7	18.2	4.1	0.0	76.6	20.6	2.8	0.0	80.8	17.3	2.0	0.0	78.6	17.0	4.3	0.0	79.9	17.6	2.5	0.0	73.6	22.2	4.1	-	-	-	-
Dy	0.0	69.9	25.4	4.7	0.0	70.1	26.0	3.9	0.0	73.1	23.8	3.0	0.0	70.0	25.1	4.8	0.0	72.5	23.9	3.6	0.0	65.8	28.4	5.8	0.0	67.9	25.8	6.3

Tm	0.0	46.5	40.1	13.4	0.0	49.5	41.8	8.6	0.0	48.9	40.5	10.6	0.0	45.5	41.2	13.3	0.0	48.5	40.3	11.1	0.0	43.7	40.7	15.6	0.0	43.4	40.7	15.9
Pb	0.0	26.7	70.2	3.2	0.0	27.3	69.8	2.9	0.0	18.9	78.3	2.9	0.0	31.7	64.9	3.4	0.0	24.6	72.5	2.9	0.0	19.2	75.3	5.5	0.0	28.1	65.7	6.1
U	15.2	9.3	66.2	9.3	18.6	8.2	65.6	7.6	12.3	6.7	74.4	6.6	24.7	11.3	53.7	10.3	16.4	12.4	63.4	7.9	10.2	11.8	66.4	11.6	18.3	13.5	54.7	13.4
Cd	0.9	83.3	13.5	2.2	1.0	83.0	14.6	1.4	0.9	85.8	12.2	1.1	2.2	80.2	14.9	2.7	2.0	81.2	15.4	1.4	-	-	-	-	2.3	75.9	17.2	4.6
Al	0.1	20.3	22.0	57.6	0.1	21.8	23.3	54.8	0.1	21.9	25.9	52.1	0.3	20.2	21.3	58.2	0.2	20.0	28.6	51.3	0.0	12.4	24.9	62.6	-	-	-	-
Ti	0.0	0.2	43.9	55.9	0.0	0.2	50.3	49.5	0.0	0.3	49.2	50.5	-	-	-	-	0.0	0.2	50.4	49.4	0.0	0.1	36.6	63.3	-	-	-	-
Fe	0.0	18.0	62.4	19.6	0.0	20.1	61.6	18.2	0.0	18.4	62.7	18.9	0.0	18.3	63.8	17.9	0.0	14.5	67.3	18.2	0.0	11.9	67.5	20.6	0.0	15.3	62.3	22.4
Th	-	-	-	-	0.0	0.1	93.5	6.4	0.0	0.6	92.0	7.4	0.0	0.1	87.7	12.2	0.0	0.2	92.8	7.0	0.0	0.2	88.0	11.9	0.0	0.2	84.0	15.9
V	0.0	28.2	50.1	21.7	0.0	30.6	48.2	21.2	0.0	29.4	49.5	21.1	0.0	27.0	51.8	21.2	0.1	23.1	57.0	19.9	0.0	21.9	55.8	22.3	0.0	24.9	47.9	27.2
Cr	11.2	0.0	33.1	55.7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	11.3	0.0	26.3	62.3
As	0.1	0.8	73.6	25.5	0.1	0.9	74.8	24.3	0.1	1.1	76.8	22.0	0.1	0.8	76.0	23.1	0.1	0.6	74.6	24.7	0.1	0.5	73.9	25.5	0.1	0.7	74.4	24.9

Continue Table S5

	DR4-003				**09-648/1**				**09-648/2**				**09-648/3**				**10/1**				**D07-33 (Pacific)**				**Govorov Guyot (Pacific)**			
	L1	L2	L3	L4	L1	L2	L3	L4	L1	L2	L3	L4	L1	L2	L3	L4	L1	L2	L3	L4	L1	L2	L3	L4	L1	L2	L3	L4
Li	15.4	73.3	2.2	9.0	-	-	-	-	13.3	53.0	4.2	29.6	9.4	41.4	4.7	44.4	5.9	78.5	5.6	10.0	18.2	47.0	13.6	21.2	-	-	-	-
Mg	35.1	45.9	10.0	9.0	53.4	23.2	13.3	10.1	51.3	20.8	16.6	11.3	46.9	15.6	18.4	19.1	44.4	28.8	14.5	12.4	66.4	25.3	4.3	4.0	64.8	25.7	3.9	5.5
K	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	57.7	24.3	1.1	16.9	61.6	21.9	0.0	16.6
Ca	55.7	34.6	1.3	8.4	67.5	20.7	0.3	11.5	71.4	23.0	0.7	5.0	65.3	19.2	1.5	14.0	67.5	20.7	0.3	11.5	60.5	33.0	0.1	6.4	56.3	39.9	0.6	3.3
Sr	41.4	48.8	1.9	7.8	48.5	41.6	1.5	8.3	50.2	44.7	1.7	3.4	51.3	34.1	2.3	12.3	48.5	41.6	1.5	8.3	34.4	63.4	1.0	1.2	30.4	68.3	0.8	0.5

Cs	1.2	1.4	3.2	94.3	0.4	1.4	5.6	92.7	0.4	2.3	5.0	92.2	0.5	1.5	4.0	93.9	0.4	1.4	5.6	92.7	-	-	-	-	-	-	-	-
Ba	0.0	47.4	9.6	43.0	0.0	60.5	6.5	33.1	0.0	59.6	13.4	27.1	6.6	38.1	5.7	49.6	0.0	60.5	6.5	33.1	-	-	-	-	0.1	89.5	9.0	1.4
Mn	0.0	97.5	2.4	0.1	0.0	96.5	3.5	0.0	0.0	95.5	4.4	0.1	0.0	96.4	3.4	0.2	0.0	95.9	4.0	0.1	0.0	97.6	2.4	0.0	0.0	97.3	2.6	0.0
Co	0.0	97.0	2.9	0.1	0.0	98.3	1.7	0.1	0.0	97.8	2.0	0.2	0.0	97.8	1.7	0.5	0.0	97.7	1.9	0.3	0.0	98.2	1.8	0.0	0.0	89.6	10.3	0.1
Ni	0.2	95.3	4.3	0.2	-	-	-	-	0.5	90.3	8.5	0.6	0.7	91.0	6.5	1.7	0.5	92.2	6.0	1.3	0.2	93.3	6.3	0.1	1.1	83.2	15.6	0.1
Zn	0.0	65.5	26.5	8.0	0.0	52.3	36.4	11.3	-	-	-	-	0.0	35.7	44.9	19.5	0.0	41.5	45.5	12.9	0.3	67.2	30.3	2.1	3.2	66.5	28.8	1.4
Cu	-	-	-	-	1.5	47.6	41.4	9.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Y	0.0	70.9	24.0	5.1	0.0	77.5	19.8	2.7	0.0	78.5	18.9	2.6	0.0	71.3	22.4	6.3	0.0	66.7	27.6	5.7	0.0	77.7	20.9	1.4	30.4	68.3	0.8	0.5
La	0.0	68.2	18.8	13.0	0.0	81.9	15.4	2.7	0.0	81.7	14.8	3.5	0.0	71.6	17.7	10.7	0.0	69.6	21.0	9.4	0.0	83.6	15.7	0.7	0.5	64.5	10.2	24.8
Ce	0.0	71.5	23.9	4.6	0.0	79.7	19.5	0.9	0.0	83.2	15.9	0.9	0.0	79.4	17.3	3.4	0.0	76.9	19.7	3.4	0.0	80.6	19.2	0.2	0.0	48.3	14.2	37.5
Pr	0.0	64.5	24.4	11.2	0.0	76.8	19.7	3.5	0.0	77.2	18.7	4.0	0.0	67.3	21.2	11.5	0.0	64.6	25.5	9.8	0.0	76.9	21.2	1.9	0.7	43.9	13.7	41.8
Nd	-	-	-	-	0.0	82.6	15.7	1.6	0.0	84.8	13.4	1.8	-	-	-	-	-	-	-	-	0.0	85.4	14.6	0.0	0.9	41.4	13.1	44.6
Gd	0.0	71.6	24.0	4.4	0.0	81.1	18.0	0.9	0.0	82.9	16.4	0.7	0.0	79.6	17.7	2.7	0.0	77.3	21.5	1.2	0.0	83.5	16.5	0.0	1.5	37.6	17.2	43.7
Dy	0.0	66.7	29.3	4.0	0.0	76.0	22.4	1.6	0.0	76.7	21.9	1.4	0.0	71.9	24.5	3.6	0.0	67.5	29.7	2.8	0.0	77.0	22.5	0.5	1.4	37.4	30.4	30.8
Tm	0.0	50.2	42.4	7.4	0.0	53.4	40.0	6.6	0.0	52.6	40.3	7.1	0.0	47.7	40.1	12.3	0.0	45.5	42.4	12.1	0.0	52.5	43.2	4.2	1.1	37.0	47.7	14.3
Pb	-	-	-	-	-	-	-	-	-	-	-	-	0.0	24.3	72.7	3.0	0.0	17.7	79.7	2.6	-	-	-	-	-	-	-	-
U	-	-	-	-	25.4	10.7	60.1	3.8	-	-	-	-	11.2	13.1	65.7	10.0	10.5	7.1	75.6	6.8	-	-	-	-	29.5	8.9	61.0	0.5
Cd	0.8	83.6	14.1	1.4	2.1	80.9	15.9	1.2	-	-	-	-	1.7	79.2	17.4	1.7	1.6	79.8	17.4	1.1	1.6	77.1	21.0	0.4	4.2	76.9	18.6	0.3

Al	0.1	27.6	30.2	42.1	-	-	-	-	0.1	24.6	34.2	41.1	0.0	15.5	25.5	59.0	0.0	21.8	29.0	49.1	0.1	29.9	29.0	41.0	-	-	-	-
Ti	0.0	0.6	54.8	44.5	0.0	0.4	72.8	26.9	0.0	1.4	67.1	31.5	0.0	0.2	42.9	56.9	0.0	0.1	53.4	46.4	0.0	0.5	94.7	4.8	0.0	0.8	96.2	3.0
Fe	0.0	21.4	65.3	13.3	-	-	-	-	0.0	18.2	73.7	8.0	0.0	16.5	68.9	14.6	0.0	17.0	73.6	9.4	0.0	31.3	63.7	4.9	0.0	14.6	81.8	3.6
Th	0.0	1.1	89.6	9.3	-	-	-	-	0.0	2.3	94.3	3.4	0.0	0.3	90.1	9.6	0.0	0.1	93.2	6.7	-	-	-	-	0.1	0.0	93.2	6.7
V	0.0	36.2	47.5	16.3	-	-	-	-	0.0	29.9	61.6	8.5	0.0	30.6	53.8	15.5	0.0	38.7	52.3	9.0	0.0	42.5	52.9	4.7	0.0	75.8	22.7	1.5
Cr	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
As	0.1	2.2	77.0	20.8	0.1	0.9	80.8	18.2	-	-	-	-	0.1	0.7	83.0	16.2	0.1	0.6	88.3	10.9	0.2	3.7	85.3	10.8	-	-	-	-

- analytical data with poor recovery through the leaching steps with respect to the bulk analyses using a cutoff of 100%±20% recovery.