Supporting Information

A Stable Method for Ionic Rare Earth Elements Extraction and Quantitative Analysis of Total Quantity and Composition of Batch Samples

Feng Tian [a, b], Mingli Wu [a, b], Guoyun Yang [c, *],

a. *Guangdong Institute of Mineral Applications, Shaoguan City, 512026, Guangdong Province, China.*

b. *Key Laboratory of Radioactive and Rare Scattered Minerals, Ministry of Natural Resources, Shaoguan City, 512026, Guangdong Province, China.*

c. *Geology & Mineral Analysis & Test Research Centre of Guangxi Zhuang Autonomous Region, Nan Ning, 530023, Guangxi Zhuang Autonomous Region, China.*

Correspondence (c): 731757094@qq.com (Guoyun Yang)

Detailed list

S1 Table 1 Conversion factor between rare earth elements and their oxides.

Elements	*k*	Elements	*k*
^{89}Y	1.2699	^{159}Tb	1.1764
^{139}La	1.1728	^{163}Dy	1.1477
^{140}Ce	1.2284	^{165}Ho	1.1455
^{141}Pr	1.2082	^{166}Er	1.1435
^{146}Nd	1.1664	^{169}Tm	1.1421
^{147}Sm	1.1596	^{172}Yb	1.1387
^{153}Eu	1.1579	^{175}Lu	1.1372
^{157}Gd	1.1526	/	/

S2 Table 2 Standard series of rare earth elements.

standard series	Mass(μg)														
	Y	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1000	1000	10	500	1000	10	5	10	5	10	5	5	2.5	5	2.5
3	500	500	25	250	500	25	12.5	25	12.5	25	12.5	12.5	6.25	12.5	6.25
4	250	250	50	125	250	50	25	50	25	50	25	25	12.5	25	12.5
5	100	100	100	62.5	125	100	50	100	50	100	50	50	25	50	25
6	50	50	250	25	50	250	125	250	125	250	125	125	62.5	125	62.5
7	4000	4000	1000	2000	4000	600	500	1000	500	600	500	500	250	500	250

S3 Detection interference between rare earths in different helium flow collision modes.

Table Ce interference to Gd under different measurement modes and collision gas flow.

Detection modes	140Ce	157Gd	Ce interference to 157Gd	Interference multiple	coefficient of distrubancy
STD	55664828	12713390	75136	169	0.001349793
KED-4.9	6573692	1752728	4431	396	0.00067405
KED-5.5	4407623	1383753	1946	711	0.000441508
KED-6.0	2769241	1060995	877	1210	0.000316693
KED-6.5	1895681	730319	331	2206	0.000174607
KED-7.0	1026938	461849	180	2566	0.000175278
KED-7.25	755250	366669	84	4365	0.000111221
KED-7.5	465278	269479	96	2807	0.000206328

Table Pr interference to Gd under different measurement modes and collision gas flow.

Detection modes	141Pr	157Gd	Pr interference to 157Gd	Interference multiple	coefficient of distrubancy
STD	74799281	12713390	1677444	8	0.022426
KED-4.9	6059750	1752728	81653	21	0.013475
KED-5.5	3645985	1383753	33012	42	0.009054
KED-6.0	2049961	1060995	12594	84	0.006144
KED-6.5	1221207	730319	4649	157	0.003807
KED-7.0	585594	461849	1511	306	0.00258
KED-7.25	391083	366669	902	407	0.002306
KED-7.5	233503	269479	493	547	0.002111

Table Nd interference to Tb under different measurement modes and collision gas flow.

Detection modes	146Nd	159Tb	Nd interference to 159Tb	Interference multiple	coefficient of distrubancy
STD	13586216	87734905	203950	430	0.015012
KED-4.9	1318592	8170130	10981	744	0.008328
KED-5.5	779578	5778109	4280	1350	0.00549
KED-6.0	449863	3925908	1804	2176	0.00401
KED-6.5	242359	2325815	667	3487	0.002752
KED-7.0	117464	1534189	280	5479	0.002384
KED-7.25	79367	1078385	122	8839	0.001537
KED-7.5	48078	691228	66	10473	0.001373

Table Nd interference to Er under different measurement modes and collision gas flow.

Detection modes	146Nd	166Er	Nd interference to 166Er	Interference multiple	coefficient of distrubancy

STD	13586216	31039730	99557	312	0.007328
KED-4.9	1318592	2908067	5965	488	0.004524
KED-5.5	779578	2168780	2651	818	0.003401
KED-6.0	449863	1648068	1191	1384	0.002647
KED-6.5	242359	998816	407	2454	0.001679
KED-7.0	117464	604347	112	5396	0.000953
KED-7.25	79367	445806	56	7961	0.000706
KED-7.5	48078	288299	42	6864	0.000874

Table Gd interference to Yb under different measurement modes and collision gas flow.

Detection modes	157Gd	172Yb	Gd interference to 172Yb	Interference multiple	coefficient of distrubancy
STD	12713390	22424542	174142	129	0.013698
KED-4.9	1752728	2395108	8176	293	0.004665
KED-5.5	1383753	1887288	3884	486	0.002807
KED-6.0	1060995	1373629	2019	680	0.001903
KED-6.5	730319	854127	853	1001	0.001168
KED-7.0	461849	554050	347	1597	0.000751
KED-7.25	366669	425778	231	1843	0.00063
KED-7.5	269479	271582	181	1500	0.000672

Table Tb interference to Lu under different measurement modes and collision gas flow.

Detection modes	159Tb	175Lu	Tb interference to 175Lu	Interference multiple	coefficient of distrubancy
STD	87734905	99936221	977014	102	0.011136
KED-4.9	8170130	5504056	43837	126	0.005366
KED-5.5	5778109	3248508	22085	147	0.003822
KED-6.0	3925908	1760820	10769	164	0.002743
KED-6.5	2325815	850202	4880	174	0.002098
KED-7.0	1534189	367284	2049	179	0.001336
KED-7.25	1078385	226585	1223	185	0.001134
KED-7.5	691228	116467	674	173	0.000975

Table Tm interference to Re under different measurement modes and collision gas flow.

Detection modes	169Tm	185Re	Tm interference to 185Re	Interference multiple	coefficient of distrubancy
STD	99339204	33313219	231823	144	0.002334
KED-4.9	9088861	3462201	7925	437	0.000872
KED-5.5	6978811	3100230	4356	712	0.000624
KED-6.0	4894903	2386811	2256	1058	0.000461
KED-6.5	3233129	1891940	1050	1802	0.000325
KED-7.0	1994552	1291120	453	2850	0.000227

KED-7.25	1596620	1100616	321	3429	0.000201
KED-7.5	1082314	724532	188	3854	0.000174

S4 mineral composition and physicochemical characterizations of samples.

Considering that samples GD1-5 and GX1-4 come from two mining areas, respectively, we selected GD1, GD2, GX1, GX2 as representatives for research.

The following tables show the semi-quantitative spectral results of GD1, GD2, GX1 and GX2, respectively.

GD1					
Elements	ω（*B*）/(10^{-2})	Elements	ω（*B*）/(10^{-2})	Elements	ω（*B*）/(10^{-2})
Ag	ND	Li	0.0042	Tb	0.0002
Al	9.87	Lu	ND	Th	0.0044
As	ND	Mg	0.35	Ti	0.39
Ba	0.11	Mn	0.033	Tl	ND
Be	0.0006	Na	0.12	U	ND
Bi	ND	Nb	0.0023	V	0.0047
Ca	0.031	Nd	0.0036	Y	0.0032
Cd	ND	Ni	0.0012	Zn	ND
Ce	0.0050	P	0.042	Zr	0.0058
Co	0.0012	Pb	0.0067	Se	ND
Cr	0.0014	Rb	0.059	Ge	ND
Cu	0.0083	Sb	ND	Sn	ND
Fe	3.56	Sc	0.0008	Mo	ND
Ga	0.0026	Sm	0.0014	W	ND
K	2.35	Sr	0.010	Si	31.82
La	0.0056	Ta	ND	In	ND

GD2					
Elements	ω（*B*）/(10^{-2})	Elements	ω（*B*）/(10^{-2})	Elements	ω（*B*）/(10^{-2})
Ag	ND	Li	0.010	Tb	0.0004
Al	8.42	Lu	ND	Th	0.0032
As	ND	Mg	0.31	Ti	0.23
Ba	0.072	Mn	0.030	Tl	ND
Be	0.0006	Na	0.064	U	ND
Bi	ND	Nb	0.0044	V	0.0038

Ca	0.020	Nd	0.0040	Y	0.0051
Cd	ND	Ni	0.0007	Zn	ND
Ce	0.0080	P	0.023	Zr	0.011
Co	0.0010	Pb	0.0055	Se	ND
Cr	0.0004	Rb	0.052	Ge	ND
Cu	0.0008	Sb	ND	Sn	ND
Fe	2.54	Sc	0.0004	Mo	ND
Ga	0.0020	Sm	0.0061	W	ND
K	4.31	Sr	0.0057	Si	32.12
La	0.0049	Ta	ND	In	ND

GX1					
Elements	ω（*B*）/(10^{-2})	Elements	ω（*B*）/(10^{-2})	Elements	ω（*B*）/(10^{-2})
Ag	ND	Li	0.0040	Tb	0.0002
Al	13.86	Lu	ND	Th	0.0061
As	ND	Mg	0.26	Ti	0.41
Ba	0.27	Mn	0.039	Tl	ND
Be	0.0006	Na	0.032	U	ND
Bi	ND	Nb	0.0080	V	0.0077
Ca	0.023	Nd	0.0078	Y	0.0065
Cd	ND	Ni	0.0013	Zn	ND
Ce	0.020	P	0.057	Zr	0.0080
Co	0.0015	Pb	0.0058	Se	ND
Cr	0.0017	Rb	0.051	Ge	ND
Cu	0.0017	Sb	ND	Sn	ND
Fe	3.98	Sc	0.010	Mo	ND
Ga	0.0030	Sm	0.0014	W	ND
K	1.81	Sr	0.016	Si	29.60
La	0.013	Ta	ND	In	ND

GX2					
Elements	ω（*B*）/(10^{-2})	Elements	ω（*B*）/(10^{-2})	Elements	ω（*B*）/(10^{-2})
Ag	ND	Li	0.0078	Tb	0.00027
Al	13.97	Lu	ND	Th	0.0054
As	ND	Mg	0.34	Ti	0.47
Ba	0.087	Mn	0.067	Tl	ND
Be	0.00027	Na	0.0030	U	ND
Bi	ND	Nb	0.010	V	0.0067

Ca	0.0079	Nd	0.013	Y	0.014
Cd	ND	Ni	0.0026	Zn	ND
Ce	0.025	P	0.064	Zr	0.0043
Co	0.0038	Pb	0.018	Se	ND
Cr	0.0025	Rb	0.018	Ge	ND
Cu	0.0016	Sb	0.00031	Sn	ND
Fe	3.54	Sc	0.0012	Mo	ND
Ga	0.0026	Sm	0.0063	W	ND
K	1.60	Sr	0.011	Si	30.40
La	0.045	Ta	ND	In	ND

The following tables show the phase analysis results of GD1, GD2, GX1, and GX2, respectively.

GX1			
NO.	Phase name	Molecular formula	Analysis result
1	Kaolinite	$Al_2Si_2O_5(OH)_4$	44±2
2	Quartz	SiO_2	8±1
3	Sericite	$(K,Na)(Al,Mg,Fe)_2(Si_{3.1}Al_{0.9})O_{10}(OH)_2$	19±1
4	Illite mica	$(K, H_3O)\ Al_2Si_3AlO_{10}(OH)_2$	1±0.5
5	Muscovite	$KAl_2Si_3AlO_{10}(OH)_2$	1±0.5
6	Potassium orthoclase	$KAlSi_3O_8$	4±1
7	Albite	$NaAlSi_3O_8$	0.5
8	Clinochlorite	$(Mg, Fe, Al)_6(Si, Al)_4O_{10}(OH)_8$	3±1
9	Hematite	Fe2O3	3±1
10	Magnetic chlorite	$(Fe^{+2}, Fe^{+3}, Al)_3(Si, Al)_2O_5(OH)_4$	3±1
11	Anatase	TiO_2	0.7
12	Amorphous phase and others		13±2

GX2			
NO.	Phase name	Molecular formula	Analysis result
1	Kaolinite	$Al_2Si_2O_5(OH)_4$	47±2
2	Quartz	SiO_2	7±1
3	Sericite	$(K,Na)(Al,Mg,Fe)_2(Si_{3.1}Al_{0.9})O_{10}(OH)_2$	19±1
4	Illite mica	$(K, H_3O)\ Al_2Si_3AlO_{10}(OH)_2$	1±0.5
5	Muscovite	$KAl_2Si_3AlO_{10}(OH)_2$	1±0.5
6	Potassium orthoclase	$KAlSi_3O_8$	4±1

7	Albite	$NaAlSi_3O_8$	3±1
8	Clinochlorite	$(Mg, Fe, Al)_6(Si, Al)_4O_{10}(OH)_8$	3±1
9	Hematite	Fe2O3	3±1
10	Magnetic chlorite	$(Fe^{+2}, Fe^{+3}, Al)_3(Si, Al)_2O_5(OH)_4$	3±1
11	Anatase	TiO_2	0.8
12	Amorphous phase and others		11±2

GD1			
NO.	Phase name	Molecular formula	Analysis result
1	Kaolinite	$Al_2Si_2O_5(OH)_4$	39±2
2	Quartz	SiO_2	11±1
3	Sericite	$(K,Na)(Al,Mg,Fe)_2(Si_{3.1}Al_{0.9})O_{10}(OH)_2$	18±1
4	Illite mica	$(K, H_3O) Al_2Si_3AlO_{10}(OH)_2$	1±0.5
5	Muscovite	$KAl_2Si_3AlO_{10}(OH)_2$	1±0.5
6	Potassium orthoclase	$KAlSi_3O_8$	5±1
7	Albite	$NaAlSi_3O_8$	3±1
8	Clinochlorite	$(Mg, Fe, Al)_6(Si, Al)_4O_{10}(OH)_8$	2±1
9	Hematite	Fe2O3	3±1
10	Magnetic chlorite	$(Fe^{+2}, Fe^{+3}, Al)_3(Si, Al)_2O_5(OH)_4$	3±1
11	Anatase	TiO_2	0.3
12	Amorphous phase and others		14±2

GD2			
NO.	Phase name	Molecular formula	Analysis result
1	Kaolinite	$Al_2Si_2O_5(OH)_4$	37±2
2	Quartz	SiO_2	13±1
3	Sericite	$(K,Na)(Al,Mg,Fe)_2(Si_{3.1}Al_{0.9})O_{10}(OH)_2$	17±1
4	Illite mica	$(K, H_3O) Al_2Si_3AlO_{10}(OH)_2$	1±0.5
5	Muscovite	$KAl_2Si_3AlO_{10}(OH)_2$	1±0.5
6	Potassium orthoclase	$KAlSi_3O_8$	6±1
7	Albite	$NaAlSi_3O_8$	3±1
8	Clinochlorite	$(Mg, Fe, Al)_6(Si, Al)_4O_{10}(OH)_8$	2±1
9	Hematite	Fe2O3	3±1
10	Magnetic chlorite	$(Fe^{+2}, Fe^{+3}, Al)_3(Si, Al)_2O_5(OH)_4$	3±1
11	Anatase	TiO_2	0.4
12	Amorphous phase and others		14±2