Supplementary Materials:

Table S1. The samples and methods used in the research.

Samples	Optical microscopy	Raman spectroscopy	WDS EMPA	EDXRF	ICP-MS	LA-ICP-MS	UV-Vis-NIR spectroscopy
1-K	+						
2-K	+						
3-K	+			+	+		
4-K	+						
5-K	+						
6-K	+			+	+		
7-K	+						
8-K	+	+	+	+		+	+
9-K	+						
10-K	+						
11-K	+						
12-K	+	+	+	+		+	
13-PY	+		+	+	+		
14-cont.	+			+	+		
15-y/o	+		+	+	+		
16-K+Cl	+		+	+			

Sample 1-K-13PY, 16K+Cl – kyshtymites, 14-cont. - reaction rim between kyshymites and meta-ultramafic host rock, 15 y/o –meta-ultramafic host rocks.

Table S2. Minerals identified in association with the sapphire

Mineral Groups	Major Minerals	Minor Mineral	Accessory Minerals (Syngenetic Inclusions)
Silicates	Plagioclase	Muscovite	Zircon
		Clinochlore	
		Clinozoisite	
Phosphates			Apatite
			Churchite-(Y)
			Monazite-(Ce)

Table S3. Representative compositions (wt. %) of major minerals found in association with sapphire.

Element	Plagioclase n=12		Clinozoisite n=4		Muscovite n=2		Clinochlore n=9	
	range	mean	range	mean	range	mean	range	Mean
SiO_2	43.62-57.17	49.04	37.48-39.2	38.41	44.23-46.5	45.37	33.59-38.25	36.19
TiO_2	0.00-0.06	0.02	0.06-0.14	0.09	0.00-0.38	0.19	0.31-.045	0.36
Al_2O_3	27.24-36.21	32.64	31.58-32.77	32.25	36.97-37.46	37.22	20.47-22.91	21.33
FeO	0.00-0.06	0.04	0.39-2.07	1.59	0.36-0.55	0.46	4.83-8.04	6.27
MnO	0.00-0.07	0.02	0.01-0.06	0.04	n.d.	0.01	0.03-0.08	0.05
MgO	0.00-0.04	0.02	0.02-0.18	0.13	1.37-1.71	1.54	18.3-24.19	20.48
CaO	9.13-19.43	0.02	23.57-24.25	23.88	0.48-0.95	0.72	0.01-0.38	0.10
Na_2O	0.33-6.39	2.86	0.02-0.03	0.03	0.71-0.87	0.79	0.35-2.01	1.33
K_2O	0.00-0.06	0.02	—	0.03	8.92-9.4	9.16	3.1-7.87	6.74
V_2O_5	0.00-0.03	0.02	0.07-0.09	0.08	n.a	—	0.00-0.12	0.07

Cr_2O_3	0.00-0.05	0.02	—	0.06	0.04-0.05	0.05	0.00-0.08	0.03
Ga_2O_3	0.01-0.07	0.05	—	0.03	n.a	—	0.04-0.07	0.03
Total	97.25-101.44	99.43	95.49-98.38	96.52	96.22-94.74	95.48	90.10-95.78	92.91
Formula coefficients								
Si	2.07-2.37	2.19	2.91-3.00	2.96	2.93-3.05	2.99	2.83-3.10	2.99
Ti	—	—	—		—		0.02-0.03	0.02
Al	1.64-1.86	1.82	2.89-3.00	2.93	2.89-2.90	2.89	1.982.2.22	2.08
Fe	—	—	0.03-0.13	0.10	0.02-0.03	0.03	0.32-0.55	0.44
Mg	—	—	0.01-0.02	0.02	0.13-0.17	0.15	2.34-2.96	2.53
Ca	0.62-0.86	0.79	1.96-1.98	1.97	0.03-0.07	0.05	0.00-0.03	0.01
Na	0.10-0.38	0.21	—		0.09-0.11	0.10	0.06-0.32	0.21
K	—	—	—		0.75-0.80	0.77	0.32-0.81	0.71

n.a. — not analyzed, n.d. — not detected. Plagioclase calculated on the basis of - 8 O, clinozoisite - 8 cations *pfu*, muscovite – 10 O, clinochlore – 9 cations *pfu*.

Table S4. Representative compositions (wt. %) of minor minerals found in association with sapphire.

Element	Churchite-(Y)			Monazite-(Ce)		Zircon	
SiO_2	0.14	n.d.	0.31	0.32	32.18	31.89	32.15
Al_2O_3	n.d.	n.d.	n.d.	0.47	n.d.	n.d.	0.12
FeO	0.03	0.16	0.17	n.d.	n.d.	n.d.	n.d.
CaO	0.11	0.07	0.35	0.17	0.06	0.07	0.09
ZrO_2	n.d.	n.d.	n.d.	0.65	64.81	65	62.76
P_2O_5	35.9	36.84	35.84	32.27	0.62	0.44	0.58
F	n.d.	n.d.	n.d.	0.86	0.22	0.18	0.02
PbO	0.48	0.12	0.44	n.d.	0.03	0.15	n.d.
Gd_2O_3	1.8	2.15	2.19	4.27	0.05	0.09	0.06
Pr_2O_3	0.1	0.17	0.12	n.d.	n.d.	0.2	n.d.
Sm_2O_3	0.91	0.93	1.05	2.74	0.43	0.75	0.51
Y_2O_3	42.09	43.02	41.3	2.08	n.d.	0.04	0.16
HfO_2	n.d.	n.d.	n.d.	n.d.	2.45	0.97	1.98
La_2O_3	0.12	0.09	n.d.	17.56	n.d.	0.02	0.02
Ce_2O_3	0.14	n.d.	n.d.	29.89	0.08	0.25	0.16
Nd_2O_3	0.52	0.16	0.14	9.78	n.d.	0.09	0.26
ThO_2	0.72	0.55	0.69	0.7	0.15	n.d.	0.4
U_2O_3	1.77	n.d.	2.14	n.d.	n.d.	n.d.	n.d.
Total	84.81	84.11	84.58	101.81	101.13	100.33	99.48
O=F	—	—	—	0.36	0.09	0.08	0.01
Total	84.81	84.11	84.58	101.45	101.04	100.25	99.47
Formula coefficients							
Si	—	—	—	—	0.98	0.98	0.99
Al	—	—	—	0.02	—	—	—
Ca	—	—	0.01	0.01	—	—	—
Y	0.80	0.80	0.78	0.04	—	—	—
Zr	—	—	—	—	0.96	0.97	0.95
P	1.08	1.09	1.08	1.03	0.02	0.01	0.02
Gd	0.02	0.02	0.03	0.05	—	—	—
Sm	0.01	0.01	0.01	0.04	—	0.01	0.01
Hf	—	—	—	—	0.02	0.01	0.02
La	—	—	—	0.24	—	—	—
Ce	—	—	—	0.41	—	—	—
Zr	—	—	—	0.01	—	—	—
Nd	—	—	—	0.13	—	—	—
Th	0.01	—	0.01	0.01	—	—	—

n.d. — not detected. Churchite-(Y), Monazite-(Ce), and zircon were calculated on the basis of 4 oxygen atoms.

Table S5. Representative compositions (wt. %) of the zircon inclusions in sapphire.

Element	1	2	3	4	5
SiO_2	29.75	28.95	28.11	30.26	30.16
TiO_2	0.02	n.d.	0.07	n.d.	n.d.
Al_2O_3	0.09	0.38	0.18	0.35	0.13
FeO	0.05	0.08	0.04	0.02	0.07
MnO	0.00	0.01	0.04	0.03	0.08
MgO	0.02	0.02	0.03	0.01	0.04
CaO	0.01	0.06	n.d.	n.d.	0.01
K_2O	0.02	0.01	n.d.	n.d.	n.d.
ZrO_2	64.40	61.79	60.27	63.30	64.69
HfO_2	1.51	3.00	5.38	0.72	0.59
Cr_2O_3	n.d.	n.d.	0.07	0.04	0.03
V_2O_3	n.d.	0.12	0.05	0.12	0.14
Ga_2O_3	n.d.	0.03	n.d.	n.d.	n.d.
Total	95.88	94.45	94.23	94.85	95.94
Formula coefficients					
Si	0.96	0.96	0.95	0.98	0.97
Al	—	0.01	0.01	0.01	—
Zr	1.02	1.00	0.99	1.00	1.02
Hf	0.01	0.03	0.05	0.01	0.01

Table S6. Chemical composition of sapphires from Ilmen Mountains and sapphire occurrence with possible anorthositic-syenitic origin.

	Kysh-tymites	Ilmen syenite pegmatites [2]	Ilmen metaso-matites within meta-ultramafic rocks [3]	Yogo Gulch lamprophyre dike [39]	Gortva syenite/ anortho-clasite xenoliths [38]	Montana (USA) [37]	Pailin (Cambodia) [35, 56]
Fe in μg/g	1010 – 5209	2614-3235	686-1128	2026-6631	2073-3415	2191-7687	320–640
Mg in μg/g	47-335	1-7.5	11-106	89-172	16-148	9.4-394	80 - 200
Ti in μg/g	101-940	5.9-167	92-279	135-301	174-2385	23-142	120-270
Ga in μg/g	30-61	36-221	9-35	31-80	71-97	38-65	0-70
V in μg/g	4 -9	13-19	0.92-2.46	4-84	40-94	9-15	5 -20
Gr in μg/g	0 -12	3.5-16	0-520	2-12590	0-6.8	0-100	—
Ga/Mg	0.11-0.80	36-221	0.43-2.72	0.20-0.57	0.9-4.8	0.65-4.43	0.35
Fe/Mg	6.15-43.32	429-2628	7.23-74.34	22.76-38.55	31-137	23.07-129.56	3.2-4
Cr/Ga	0.01-0.32	0.018-0.074	1.29-9.45	0.06-307.88	0.002-0.088	0.07	—
Fe/Ti	1.08-22.95	19-366	3.21-16.11	8.6-28.2	1.2-16.3	1.43-11.91	2.37-2.66
10000Ga/Al	0.60-0.80	0.68-4.18	0.17-0.66	0.59-1.51	1.34-1.83	0.72-1.23	1.32

Table S7. Representative analyses of corundum-blue sapphire anorthosites-kyshtymites, meta-ultramafic host rocks, and reaction rim.

Sample	6K	8K	12K	16KC4	13PY	14-cont.	15 y/o
SiO_2 (wt.%)	42.37	42.72	40.84	41.56	41.24	45.09	69.72
TiO_2	0.04	0.10	0.07	0.08	0.13	0.21	0.00
Al_2O_3	34.76	36.77	42.94	35.33	42.77	4.29	1.18
Fe2O3*	0.38	1.32	0.12	0.62	0.51	6.72	6.22
MnO	0.01	0.01	n.d.	n.d.	0.01	0.05	0.18
MgO	1.61	2.52	0.60	2.86	1.11	28.08	17.97
CaO	15.79	11.23	7.46	13.82	5.89	0.42	0.25
Na_2O	1.08	2.17	4.01	0.82	3.98	0.09	0.19
K_2O	0.50	0.99	0.98	1.29	1.05	0.05	0.05
P_2O_5	0.06	0.07	0.04	0.04	0.04	0.02	0.02
S	0.03	0.02	0.02	0.02	0.02	0.01	0.05
LOI	2.51	1.44	2.42	2.96	2.71	14.67	3.91
Total	99.15	99.37	99.51	99.40	99.46	85.03	95.83
Li (μg/g)	17	—	—	—	102	17	8.9
Be	3.6	—	—	—	17	1.3	0.40
Ti	243	—	—	—	319	1008	35
V	7.3	—	—	—	4.9	25	13
Cr	78	—	—	—	36	1515	656
Mn	147	—	—	—	79	352	1327
Co	7.8	—	—	—	2.6	30	53
Ni	219	—	—	—	45	843	1316
Cu	6.3	—	—	—	4.5	1.7	16
Rb	18	—	—	—	19	34	532
Sr	4391	—	—	—	2690	1.9	1.4
Y	38	—	—	—	14	8.4	13
Zr	143	—	—	—	260	0.19	0.56
Nb	4.5	—	—	—	9.9	8.8	3.8
Mo	0.25	—	—	—	b.d.l.	9.6	1.5
Ba	226	—	—	—	644		1.3
La	13	—	—	—	23	40	47
Ce	21	—	—	—	42	1.1	1.3
Pr	2.09	—	—	—	4.6	2.6	2.8
Nd	7.2	—	—	—	15.54	0.30	0.37
Sm	2.4	—	—	—	4.0	0.92	1.3
Eu	3.1	—	—	—	2.2	0.35	0.37
Gd	3.1	—	—	—	3.8	0.11	0.13
Tb	0.79	—	—	—	0.52	0.21	0.28
Dy	5.3	—	—	—	2.7	0.031	0.037
Ho	1.2	—	—	—	0.60	0.17	0.25
Er	3.3	—	—	—	1.8	0.036	0.063
Tm	0.52	—	—	—	0.25	0.12	0.22
Yb	3.1	—	—	—	1.8	0.022	0.040
Lu	0.44	—	—	—	0.25	0.21	0.29
Hf	11	—	—	—	13	0.042	0.043
Ta	0.92	—	—	—	0.77	0.25	1.0
W	2.8	—	—	—	0.11	0.35	0.21
Pb	42	—	—	—	48	114	
Th	90	—	—	—	17	7.5	1.5
U	119	—	—	—	13	3.1	0.89
Zr/Hf	12.42	—	—	—	20.72	34.86	3.71
Sr/Ba	19.39	—	—	—	4.18	0.21	0.27
Nb/Ta	4.94	—	—	—	12.83	27.09	7.15

3-K, 6-K, 8-K, 12-k, 16-KC4, 13-PY – kyshtymites, 14-cont. - reaction rim, 15 y/o - meta-ultramafic host rocks. Data on major elements are from Filina et. al. 2019. Fe was measured as Fe_2O_3 total; n.d. — not detected. b.d.l. — below the detection limit.

Table S8. LA-ICP-MS trace-elements measurements of zircons from sampel 8-K (in μg/g).

Sample	1-1	1-2	1-3	2-1	2-2	3-1	3-2	3-3	4-1	4-2	5-1	5-2	6-1	6-2
^{43}Ca	699	b.d.l.	8226	16894	8338	b.d.l.	823	1562	16366	972	884	3974	5793	392
^{49}Ti	b.d.l.	b.d.l.	43.5	182.1	b.d.l.	53.9	55.3	2523.3	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.
^{51}V	b.d.l.	b.d.l.	b.d.l.	7.15	2.2	b.d.l.	2.43	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	1.74
^{53}Cr	b.d.l.	b.d.l.	b.d.l.	46.7	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.
^{89}Y	727	512	1332	497	654	1501	988	2370	1082	381	666	1180	429	522
^{93}Nb	1.83	2.32	4.96	7.14	5.66	5.74	21.6	426	5.62	4.76	2.53	10.3	2.57	3.28
^{95}Mo	2.14	2.42	2.15	1.45	1.75	2.47	2.31	2.37	3.18	3.00	2.39	2.57	2.08	4.26
^{118}Sn	b.d.l.	b.d.l.	b.d.l.	1.10	1.26	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.
^{121}Sb	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.18	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.
^{139}La	0.23	b.d.l.	0.66	3.12	1.53	1.14	1.48	4.60	1.90	0.75	0.60	12.28	0.36	0.19
^{140}Ce	30.1	13.3	66.1	14.3	29.4	73.7	13.8	88.0	48.5	10.4	24.9	87.3	22.9	22.8
^{141}Pr	0.26	0.15	0.94	0.69	0.52	0.70	0.49	5.38	0.66	0.21	0.29	3.96	0.20	0.192
^{146}Nd	3.94	1.94	13.6	5.17	4.47	8.95	3.06	42.8	7.44	1.95	3.95	19.0	1.83	2.17
^{147}Sm	6.21	3.11	20.4	3.72	5.04	13.9	4.63	43.6	13.5	3.77	4.93	14.5	3.96	3.93
^{153}Eu	2.96	1.38	9.5	1.69	2.57	6.52	1.46	15.3	5.25	1.26	2.56	6.23	3.81	2.93
^{157}Gd	26.0	14.2	74.8	12.2	21.9	60.6	16.9	120	43.6	10.9	22.8	49.0	15.1	17.2
^{159}Tb	7.11	4.27	18.1	3.93	6.21	16.0	5.87	33.5	11.4	3.25	6.01	12.5	4.35	4.86
^{163}Dy	70.5	45.7	160	42.0	63.0	163	74.8	296	109	35.6	65.0	121	41.2	49.4
^{165}Ho	24.7	16.8	48.8	14.9	21.2	52.7	30.7	80.4	37.9	13.0	22.0	40.6	14.1	17.1
^{166}Er	112	80.3	194	74.5	92.7	232	159	297	161	57.1	99.4	176	63.5	78.9
^{169}Tm	22.2	17.6	35.9	17.0	18.5	43.8	38.3	52.6	32.7	12.2	20.2	34.6	12.8	16.1
^{172}Yb	209	169	303	174	171	407	424	448	297	123	197	312	133	153
^{175}Lu	41.8	34.7	58.2	35.4	32.1	79.6	82.9	80.6	58.0	24.4	39.4	61.7	23.3	30.3
^{178}Hf	8850	9812	9284	6936	8027	9438	17483	9971	12048	11398	10328	9784	6845	10060
^{181}Ta	0.54	0.42	0.77	13.2	2.53	3.55	26.8	66.5	1.54	0.83	0.95	0.96	0.42	1.56
^{182}W	b.d.l.	b.d.l.	0.69	b.d.l.	0.46	0.19	1.97	30.4	0.65	b.d.l.	0.24	0.35	b.d.l.	b.d.l.
^{208}Pb	5.38	2.18	15.5	21.3	16.3	16.6	10.5	29.5	14.7	4.93	4.84	12.0	3.76	4.49
^{232}Th	181	83.4	551	81.9	187	557	104	507	348	55	141	395	105	113
^{238}U	503	436	884	774	508	1145	2154	1105	946	504	505	866	288	382

Table S9. In situ LA-ICP-MS geochronology of zircons from sample 8-K.

	Ratios				Rho	Ratios		Ages (Ma)					Common Pb
	$^{207}Pb/^{235}U$	±2σ	$^{206}Pb/^{238}U$	±2σ		$^{207}Pb/^{206}Pb$	±2σ	$^{207}Pb/^{235}U$	±2σ	±2σ%	$^{206}Pb/^{238}U$	±2σ	$^{206}Pb/^{204}Pb$
1-1	0.35087	0.01232	0.04869	0.00112	0.66	0.05227	0.00138	305.4	9.3	3.0	306.5	6.9	
1-2	0.34681	0.01299	0.04832	0.00112	0.62	0.05206	0.00153	302.3	9.8	3.2	304.2	6.9	1805
1-3	0.40919	0.01260	0.05693	0.00125	0.71	0.05213	0.00113	348.3	9.1	2.6	356.9	7.6	
1-4	0.37836	0.01264	0.05205	0.00087	0.50	0.05272	0.00152	325.8	9.3	2.9	327.1	5.3	
1-5	0.37111	0.01633	0.04660	0.00078	0.38	0.05776	0.00235	320.5	12.1	3.8	293.6	4.8	
1-6	0.35599	0.02133	0.05122	0.00117	0.38	0.05040	0.00279	309.2	16.0	5.2	322.0	7.2	488
1-7	0.32687	0.01228	0.04549	0.00083	0.49	0.05211	0.00171	287.2	9.4	3.3	286.8	5.1	1948
2-1	0.37850	0.01374	0.05177	0.00114	0.61	0.05303	0.00153	325.9	10.1	3.1	325.4	7.0	1137
3-1	0.34958	0.01426	0.04828	0.00088	0.45	0.05251	0.00191	304.4	10.7	3.5	304.0	5.4	1198
3-2	0.32427	0.01269	0.04627	0.00130	0.72	0.05083	0.00138	285.2	9.7	3.4	291.5	8.0	1185
3-3	0.34030	0.01234	0.04593	0.00105	0.63	0.05374	0.00151	297.4	9.3	3.1	289.5	6.5	1337
3-5	0.30824	0.01249	0.04421	0.00145	0.81	0.05056	0.00120	272.8	9.7	3.6	278.9	8.9	1010
3-7	0.32184	0.01157	0.04304	0.00133	0.86	0.05423	0.00100	283.3	8.9	3.1	271.7	8.2	14173
4-1	0.35583	0.01733	0.04745	0.00168	0.73	0.05439	0.00182	309.1	13.0	4.2	298.8	10.3	
4-2	0.43799	0.01872	0.05746	0.00188	0.77	0.05528	0.00152	368.8	13.2	3.6	360.2	11.5	2213
4-3	0.40243	0.01533	0.05339	0.00169	0.83	0.05466	0.00115	343.4	11.1	3.2	335.3	10.4	2331
4-4	0.40219	0.01524	0.04938	0.00159	0.85	0.05907	0.00119	343.2	11.0	3.2	310.7	9.8	2113
5-3	0.46492	0.02520	0.05206	0.00173	0.61	0.06477	0.00278	387.7	17.5	4.5	327.2	10.6	2461
5-5	0.39586	0.02054	0.05023	0.00190	0.73	0.05716	0.00203	338.6	14.9	4.4	315.9	11.6	14986
6-1	0.46051	0.02136	0.05349	0.00178	0.72	0.06244	0.00202	384.6	14.9	3.9	335.9	10.9	2262

Table S10. Frequently detected solid inclusions and common minerals found in association with sapphires from Ilmen Mountains and sapphires occurrence with possible anorthositic-syenitic origin.

	Kysh-tymites	Ilmen syenite pegmatites [2]	Ilmen metasomatites within meta-ultramafic rocks [3]	Yogo Gulch lamprophyre dike [39]	Gortva syenite/anorthoclasite xenoliths [38]	Montana (USA) [37]	Pailin (Cambodia) [35,56]
Plagioclase	+			+	+	+	+
Alkali feldspar		+	+		+	+	
Zircon	+	+	+	+	+		+
Xenotime-(Y)	+				+		
Columbite-(Fe)		+					+
Monazite-(Ce)	+	+			+	+	+
Churchite-(Y)	+						
Uraninite		+					
Muscovite	+	+	+			+	
Ilmenite		+			+	+	
Spinel			+		+	+	
Clinoclore	+		+				
Pb- Ni-bearing minerals			+				
Apatite group minerals	+		+			+	
Rutile	+					+	+
Anatase						+	+

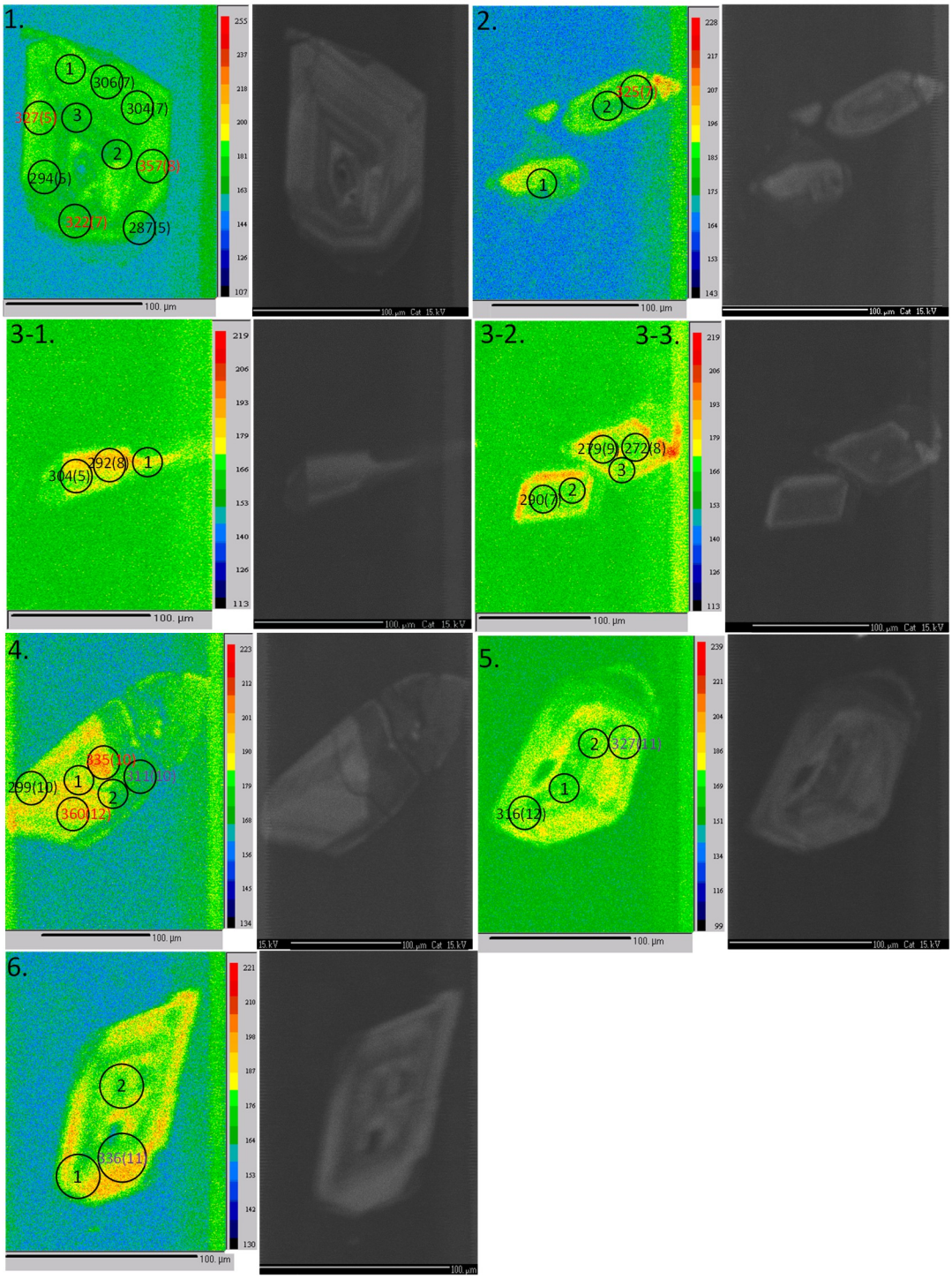

Figure S1. Zircon CL images and maps in average weighted atomic numbers with the spots positions for trace-elements (No of spots inside of circles) and U-Pb geochronological measurements (U-Pb ages inside of circles). Black – Concordia kyshtymite age, red – 6 Concordia elder ages, purple – 3 ages in Discordia.

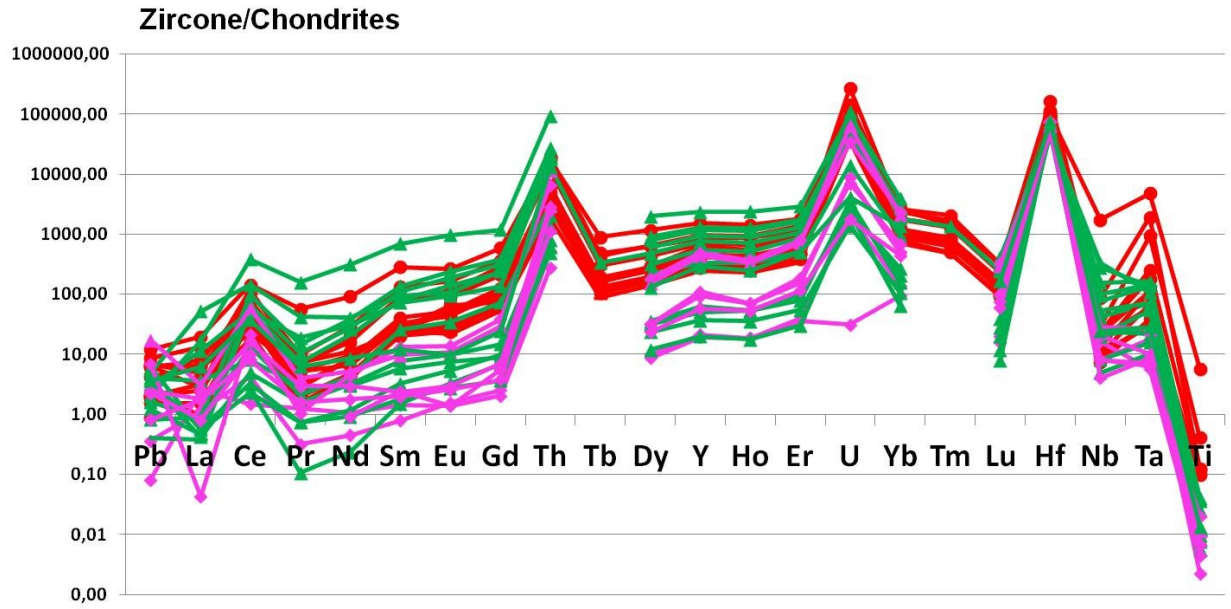

Figure S2. Chondrite-normalized concentration of REE and trace elements in studied zircons from kyshtymites (red circle), miascites (purple diamond), and carbonatites (green triangle), of the Ilmensky-Vishnevogorsky complex modified after [45]. Data on REE and trace elements in chondrite are after [41].

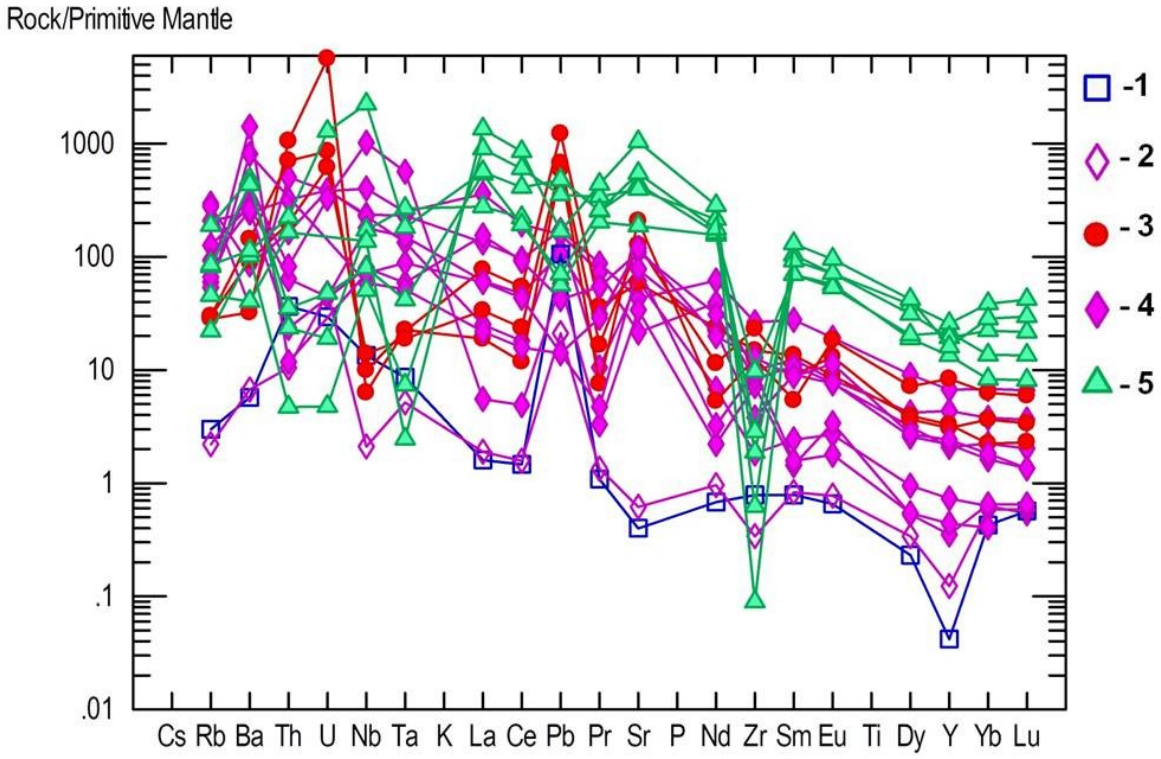

Figure S3. Trace-elements and REE distribution normalized to primitive mantle (the data on REE and trace-elements in primitive mantle are from [41]) in reaction rim (1) between kyshymites and meta-ultramafic host rock, meta-ultramafic host rocks (2), kyshtymites (3), miascites (4), and carbonatites (5) of the Ilmenogorsky-Vishnevogorsky complex modified after [18] and Medvedeva E.V (unpublished data).

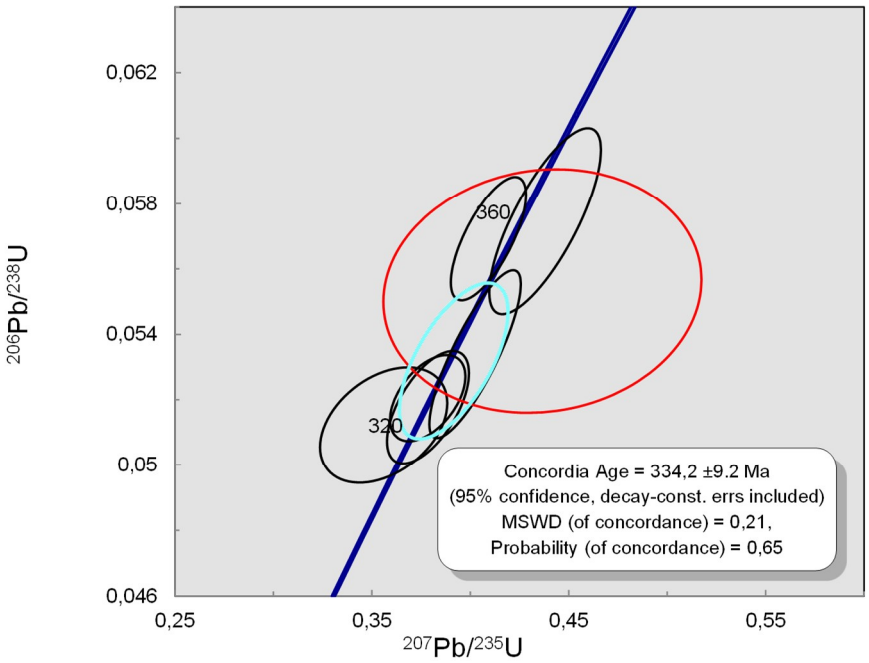

Figure S4. Concordia diagram for zircons from kyshtymite sample 8-K and carbonatites of Vishnevogorsky complex (sample 354 by Nedosekova [50]).

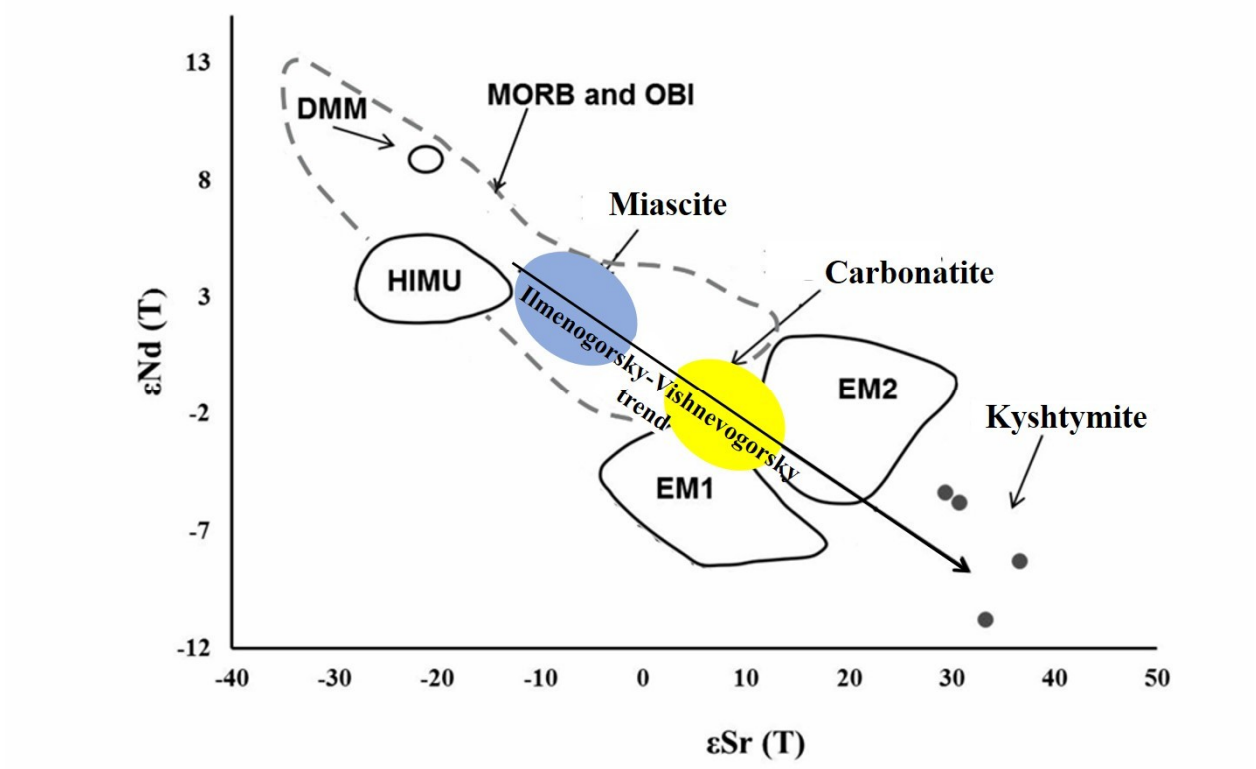

Figure S5. Diagram εSr (T) *vs* εNd (T) for kyshtymite, miascite and carbonatite of the Ilmenogorsky-Vishnevogorsky complex modified after [18,25], the diagram shows mantle reservoirs DMM, HIMU, EM1, EM2, MORB and OBI by [65].