Table 1. Chemical composition of surface facies, structural weathering crusts and sideritic carbonatites of the Seis Lagos deposit (wt.%) (Giovannini et al., 2013)

Component	Surface facies of KV					Structural KV		Siderite carbonatites
	1	2	3	4	5	6	7	8
SiO_2	0.56	0.53	0.31	0.16	0.42	0.48	1.04	0.66
Al_2O_3	1.95	1.70	2.51	0.47	0.40	0.33	0.46	1.17
Fe_2O_{3tot}	77.63	80.87	74.23	85.59	57.76	82.40	82.22	52.46
MgO	–	–	0.01	0.01	–	0.01	0.01	3.04
CaO	–	–	0.01	0.01	–	0.01	0.01	0.22
Na_2O	0.02	–	0.02	0.01	0.01	0.01	0.01	0.01
K_2O	0.01	–	0.01	–	0.02	0.03	0.01	0.06
TiO_2	5.52	1.08	6.63	4.99	0.45	2.69	0.91	0.18
P_2O_5	0.44	0.58	1.72	0.34	0.16	0.22	0.39	1.30
MnO	0.04	0.00	0.10	0.27	26.65	0.90	0.32	7.72
LOI	10.10	9.93	10.33	5.30	8.72	9.15	10.96	
CO_2								24.38
BaO	0.04	0.04	0.09	0.06	3.23	0.23	0.11	4.28
Nb_2O_5	1.59	0.89	1.76	0.99	0.22	1.97	1.34	0.15
La_2O_3	0.04	0.07	0.15	0.03	0.02	0.10	0.12	0.86
Ce_2O_3	0.15	0.19	0.35	0.26	0.74	0.48	1.16	
Total	98.07	95.90	98.24	98.46	98.80	98.99	99.07	96.48

Note. 1–5 – surface facies: 1 – pisolith crusts (average of 2 analyses), 2 – fragmental crusts (average of 3 analyses), 3 – spotted crusts (average of 3 analyses), 4 – oolitic crusts (average of 4 analyses), 5 – manganese crusts (average of 5 analyses); 6, 7 – structural crusts: 6 – red ochres (average of 2 analyses), 7 – brown ochres (average of 5 analyses); 8 – sideritic carbonatites (average of 4 analyses). *Here and below*: dash – not detected, empty cell – not determined.

Table 2. Chemical composition of lateritic ochres (analysis 1) and products of their epigenetic transformation: zone of ochre bleaching, rich ores (analysis 2); limonite-siderite rocks (analysis 3) (Tomtor, wt.%)

Component	1	2	3
SiO_2	3.82	8.70	3.92
TiO_2	1.42	7.30	1.40
Al_2O_3	1.66	15.25	2.55
Fe_2O_3	49.72	9.01	30.63
FeO	5.46	5.90	19.72
MnO	4.64	0.61	4.30
MgO	0.72	0.25	0.80
CaO	5.93	3.04	5.36

K_2O	0.05	0.31	0.12
Na_2O	0.17	0.20	0.14
P_2O_5	6.24	13.90	4.85
SO_3	0.25	0.63	0.28
CO_2	5.16	2.70	13.71
Nb_2O_5	1.54	4.70	1.22
TR_2O_3	4.50	10.72	
Total	91.28	83.22	88.99

Table 3. Results of microanalysis of the manganese-rich (hollandite) (analyses 9, 13) and iron-rich (goethite) (analysis 14) phases in liquid separation structures (Chuktukon,wt.%)

Component	Liquid Separation structures Mn- and Fe-phases in brown ironstone		
	3*a**		3*c*
	13	14	9
Na_2O			<0.05
BaO	12.64	0.19	13.10
PbO			0.19
SLn_2O_3	0.20		
Nb_2O_3	0.27	0.26	
ZrO_2			0.13
Fe_2O_3	4.93	78.04	0.12
MnO_2	82.63	3.39	86.39
Al_2O_3	0.07	2.88	0.05
V_2O_3			0.04
P_2O_5	0.07	0.17	
SiO_2	0.07	2.14	
Total	100.87	87.08	100.03

Note. * – analyzed areas of aggregates shown in Fig. 3*a*, *c*; analysis numbers correspond to point numbers in Fig. 3*a*, *c*.

Table 4. Chemical composition of hollandite from manganese horizon of the weathering crust of sideritic carbonatites from the Seis Lagos deposit (Giovannini et al., 2017) (wt.%)

Component	13.01	13.02	15.01	15.02	15.03	15.04	15.05	17.01
K_2O	0.07	0.05	0.01	0.11	0.07	0.08	0.16	0.19
BaO	17.22	14.66	17.59	16.88	16.43	15.94	16.52	14.62
PbO	0.03	0.20	□	0.04	□	□	□	0.13
MnO	6.46	6.50	2.72	7.15	7.05	6.53	7.35	6.66

MnO_2	70.99	75.89	67.47	73.24	73.30	73.73	73.51	75.74
Al_2O_3	1.10	0.43	2.22	0.72	0.46	0.50	0.40	0.17
Fe_2O_3	1.82	0.18	8.72	0.58	0.62	1.24	0.31	0.38
Total	97.69	97.91	98.73	98.72	97.93	98.02	98.24	97.89

Table 5. Chemical analyses of carbonated (siderite) laterite weathering crusts based on 10-m group samples of borehole 3665 (Tomtor ore field)

Analysis No.	SiO_2	TiO_2	Al_2O_3	FeO	Fe_2O_3	MnO	MgO	CaO	K_2O	Na_2O	P_2O_5	SO_3	CO_2	LOI	**Total**
1	0.80	0.67	7.00	4.75	25.87	15.80	0.50	3.00	0.05	0.08	2.98	7.10	19.15	9.70	**97.45**
2	1.60	0.16	0.10	12.29	3.52	30.30	1.75	9.12	0.05	0.08	2.58	0.01	27.88	4.09	**93.53**
3	3.60	0.67	0.10	14.09	3.88	21.60	1.87	1.00	0.05	0.08	3.75	0.01	22.72	8.49	**81.91**

Table 6. Results of microanalysis of Nb-rutile of the first generation (an. 2–9) and the second generation (an. 1, 10–12) Tomtor array (wt.%)

Component	1	2	3	4	5	6	7	8	9	10	11	12
Al_2O_3	0.16	0.05	0.06	0.06	н.о.	0.21	0.88	1.58	0.12	0.17	0.20	0.20
SiO_2	0.53	0.42	0.54	0.29	0.40	0.53	0.24	0.45	0.41	1.12	0.98	0.90
TiO_2	60.14	78.66	80.69	81.90	79.29	69.24	74.60	60.80	66.41	53.41	47.16	47.36
V_2O_3	1.29	1.28	0.84	1.44	1.06	1.51	0.97	1.27	2.50	1.64	1.58	2.03
Fe_2O_3	6.61	4.78	4.84	3.55	4.82	3.91	3.07	3.10	4.45	7.15	9.03	8.10
Nb_2O_5	28.96	14.59	13.59	13.49	15.34	17.01	10.38	12.19	17.64	30.17	37.12	30.21
Total	97.66	99.78	100.52	100.72	100.91	92.41	90.15	79.39	93.06	93.67	96.07	89.80

Note. The amounts of some analyses (8–10) are significantly lower than 100%, since minerals contain additional Na_2O – 0.21, CaO – 0.17, P_2O_5 – 0.33, MnO – 0.09, BaO – 0.30, Y_2O_3 – 0.34, Sc_2O_3 – 0.09 wt.%; SrO, Ta_2O_5 – not detected.

Table 7. Chemical composition of Nb-rich rutile from the weathering crusts of sideritic carbonatites from the Seis Lagos deposit (Giovannini et al., 2017) (wt.%)

Component	4.1	6.1	6.2	6.3	6.4	6.5	12.1	34.1	34.2	34.3	34.4	34.5
Fe_2O_3	8.96	12.18	13.94	11.12	14.95	10.52	17.78	14.92	11.64	11.67	11.18	12.43
SiO_2	□	1.09	0.45	0.63	0.62	0.52	1.00	0.33	0.27	0.34	0.30	0.28
TiO_2	80.92	70.73	68.92	72.45	66.26	74.08	57.84	58.26	67.34	68.66	66.92	57.86
Nb_2O_5	11.26	16.59	19.08	16.71	18.89	14.89	22.23	25.46	19.16	17.47	20.28	27.61
WO_3	0.16	0.35	0.31	0.70	0.33	0.64	1.27	0.20	0.33	0.19	0.85	0.62
Total	101.30	100.94	102.70	101.61	101.05	100.65	100.12	99.17	98.74	98.33	99.53	98.80

Table 8. Chemical composition of Nb-rich brookite from the weathering crusts of sideritic carbonatites from the Seis Lagos deposit (Giovannini et al., 2017)

Component	10.1	10.2	10.3	12.1	12.2
Fe_2O_3	12.08	12.53	9.86	10.89	10.69
SiO_2	0.97	1.24	0.64	0.72	0.78
TiO_2	69.60	73.45	76.68	76.93	78.02
Nb_2O_5	16.03	12.09	11.77	10.75	10.43
WO_3	0.69	0.32	0.74	1.10	0.80
Total	99.37	99.63	99.69	100.39	100.72

Table 9. Chemical composition (EPMA) of vanadium compounds (Tomtor, wt.%)

Component	1	2	3	4	5
V_2O_5	19.08				
V_2O_3		10.93	11.14	15.39	15.85
PbO	49.67			0.19	0.05
Fe_2O_{3tot}		54.95	53.28	51.54	49.18
FeO	4.51				
Nb_2O_5	0.55	8.24	5.34	3.41	5.19
Al_2O_3	2.4	1.86	2.10	2.76	1.93
SiO_2	4.47	3.03	3.21	3.82	3.40
TiO_2	2.38	3.32	4.05	3.84	3.36
BaO	0.49	0.50	0.20		
SrO	0.57				
P_2O_5	1.42				
SO_3	4.85	3.88	3.88	1.54	1.91
Total	90.39	86.68	83.21	82.49	80.37

Table 10. Distribution of manganese in the hypergenic complex by wells of the Severny part of Tomtor ore field

Drilling well No.	Thickness, m	Average content MnO, %
101	28.4	11.71
105	110	13.75
108	40	10.58
111	13	12.25
3665	30	22.57
4465	70	12.72
Average by wells	48.6	12.83

Table 11. Forecast resources of manganese oxide in laterite weathering crusts of the Severny section of the Tomtor ore field

The area of the ore-bearing site, thous. m^2	Average ore capacity, m	Ore volume, mln m^3	Volume weight of ore, t/m^3	Ore volume, mln t.	Average content of MnO in ore, %	Ore resources, mln t.
1550.6	23	35.7	3.8	135.5	12.83	17.4

Table 12. Weathering crust deposits of carbonatites

Deposit	Type of deposit; substrate*	Type of ore	Ore component	Average component content, %
Beloziminskoe, Russia	Hydrosluidic crust; K, AK	Apatite-pyrochlore in hydrosluidic ochres and loose particles	Nb_2O_5 P_2O_5	0.5 6.4–11.74
Novopoltavskoe, Ukraine	The same; K, D, DC	The same	Nb_2O_5 P_2O_5	0.32 9.0
Tatarskoe I, Russia	The same; A	The same	Nb_2O_5 P_2O_5 vermiculite, hydrosluda	0.61 8.2 30.0
Anjico, Brazil	The same; K	Apatite with vermiculite in hydrosluidic ochres	P_2O_5	15.4
Tatarskoe II, Russia	Laterite crust; A	Pyrochlore in laterite ochres Francolites in limonite-francolite rocks	Nb_2O_5 P_2O_5	1.2–2.5 23.7
Chuktukon, Russia	The same; K, AK	Pyrochlore-monazite-florencite in laterite ochres Francolites in limonite-francolite rocks	Nb_2O_5 P_2O_5 Y_2O_3 P_2O_5	1.0-1.48 5.0 0.23–0.34 13.75
Kovdor, Russia	Laterite crust; K	Apatite-francolite	P_2O_5	15-20
Arasha (Bareiro), Brazil	The same; D	Pyrochlore with barite in laterite ochres Monazite in laterite ochres Francolites in limonite-francolite rocks	Nb_2O_5; $BaSO_4$ TR_2O_3 P_2O_5	2.5; 20.67 13.5 15.01
Catalan I, Brazil	The same; K, D	Pyrochlore in laterite ochres Phosphate Rare earths Titanium	Nb_2O_5 P_2O_5 TR_2O_3 TiO_2	1.51 7.96 12.2 19.9
Catalan II, Brazil	The same; K, D	Pyrochlore in laterite ochres	Nb_2O_5	2.18
Ceish Lagos, Brazil	The same; A	Ti–Nb-ores with Nb-rutile and Nb-brookite in ochres	Nb_2O_5 TiO_2	2.81 12.0
		Hollandite in the surface facies of the crust including the rich	MnO_2	26.0 61.6
		Ferruginous oxide in ochres	Fe_2O_3	80.0
Moro do Cerrote (Brazil)	The same; K	Apatite-francolite	P_2O_5	29
Bingo, Zaire	The same; K	Pyrochlore in laterite ochres	Nb_2O_5	2.86
Luesh, Zaire	The same; K, CK	Pyrochlorite in ochre-clay weathering products	Nb_2O_5	1.34
Mrima, Kenya	The same; K, D	Pyrochlore-monazite in laterite ochres	Nb_2O_5 TR_2O_3	0.7 5.0

Mabouni, Gabon	The same; K, D	Pyrochlore in laterite ochres	Nb_2O_5	1.5
Sokli, Finland	The same; K	Francolite with pyrochlore in limonite-francolite rocks	P_2O_5 Nb_2O_5 TR_2O_3	17.8 0.46 0.35–0.94
Mount Weld, Australia	The same; K	Pyrochlore in laterite ochres	Nb_2O_5 Ta_2O_5	1.86 0.034
	The same; A	Monazite in laterite ochres	TR_2O_3 including the rich TR_2O_3 Y_2O_3	11.2 23.6 0.33
Tomtor, Russia	Epigenetically altered laterite cortex (Buranny site); LO	Crandallite-monazite pyrochlorite in epigenetically altered ochres	Nb_2O_5 TR_2O_3 Y_2O_3 Sc_2O_3 V_2O_5 SrO TiO_2	4.93 12.8 0.87 0.06 1.0 3.9 7.0
	Laterite crusts (deposit as a whole); K, AK, A	Monazite-pyrochlorite in laterite ochres Pyrochlore-francolite in limonite-francolite rocks	Nb_2O_5 TR_2O_3 Nb_2O_5 P_2O_5	0.7–1.4 4.4 0.6 14–20

Note. *Rocks undergoing weathering or reductive epigenesis: K – calcitic, A – ankeritic, AK – ankerite-calcitic, D – dolomitic, DK – dolomite-calcite carbonatite, F – sideritic ferrocarbonatite, SK – syenite-carbonatite, LO – lateritic ochres. The table uses overview summary works "Deposits of carbonatite weathering crust" (Lapin and Tolstov 1995). "Mineralgeny of the weathering crust of carbonatites" (Lapin and Tolstov 2011), as well as original sources on individual deposits given in these summary works.