

ON THE GEOCHEMISTRY OF KAATIALA PEGMATITE, WESTERN FINLAND

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Spark source mass spectrometry with electrical detection was used for determining 36 elements in 25 individual mineral samples, bulk samples and country rock samples from the Kaatiala pegmatite deposit in Finland. Also determined were the sum of the REE in all the samples, and the distribution pattern in the samples with higher REE contents.

The mineralogical and chemical balance of the whole pegmatite was estimated on the basis of the analytical data.

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History

The Kaatiala pegmatite, located in the parish of Kuortane, W. Finland (Fig. 1) was first mentioned by Holmberg (1857). The first detailed geological description was given by Laitakari (1914).

The exploitation of the pegmatite started in 1942. Before then only quartz had been temporarily quarried at the end of the last century. However, the needs of the steel-making industry during the Second World War made it feasible to reopen the mine. Soon afterwards, the production of feldspar for the domestic ceramics industry was also started up. Quarrying was initially directed at the quartz and feldspar core of the deposit.

Wartime conditions meant that there was an acute shortage of all kinds of equipment. Both drilling and the sorting of blasted rock

were done by hand. The sorted products were carried on stretchers from the bottom of the quarry to stock piles at the edge of the pit.

When enough material had been produced, an application was made to the Ministry of Trade and Industry for a special licence to transport the products by truck to Niinimaa railway station, 10 km to the west.

The quarrying was gradually modernized. In 1943, the stretchers were replaced by a hand windlass. In 1945—1947 a steam winch, donkey pumps and a locomotive-driven compressor were installed. In 1950—1951 the steam engines were replaced by electric motors, and in 1951 the first sorting plant was built. This consisted of a wooden silo from which the rock ran on to sorting tables arranged radially around the silo. On the tables pure feldspar and quartz were sorted

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Fig. 1. Location of the Kaatiala pegmatite.

out from the gangue. Rock fragments consisting of several minerals were hammered down in size until monomineralic feldspar or quartz was obtained.

The last version of the sorting plant was

built in 1956 (Fig. 2). The rock was crushed by jaw crusher under 75 mm and screened into three fractions: 75—50 mm, 50—25 mm, and minus 25 mm. The minus 25 mm fraction went directly to waste. The coarse fractions proceeded to the sorting belts where the monomineralic quartz, feldspar and other mineral products were picked out and dropped each into their own silo.

With the modernization of the quarrying and sorting, however, it became increasingly more difficult to recover the valuable minerals. Quarrying operations had first centered on the core zone, which consisted of huge quartz and potassium feldspar crystals. Sorting was easy and produced no waste at all. Over the years, however, it became necessary to mine more and more heterogeneous zones with small crystal size and ever larger amounts of tourmaline and other impurities.

To obtain first class products but with low recovery, all lumps containing tourmaline or quartz had to be discarded, no matter how low the content of these minerals was, or else a more impure product with higher recovery had to be accepted. A compromise was reached and in addition to the first-class lump product, a second-class product with some tourmaline and quartz inclusions was also accepted. This product was further milled and cleaned by a high intensity

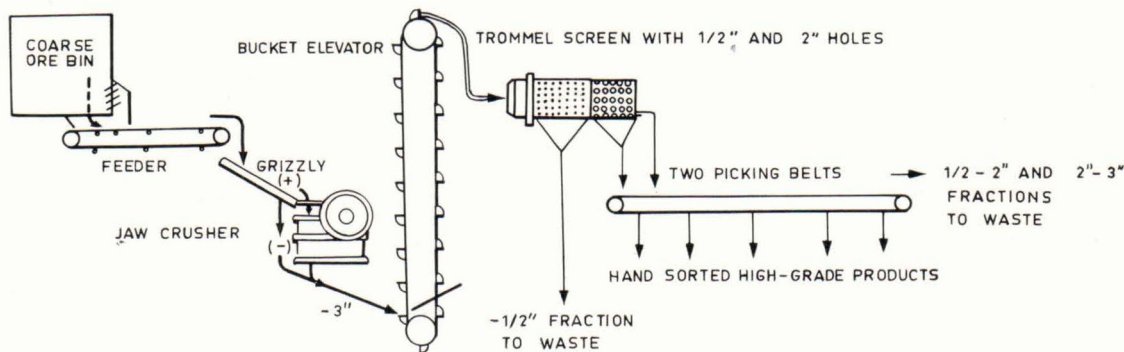


Fig. 2. Flowsheet of the Kaatiala sorting plant.

Table 1. Production statistics of Kaatiala pegmatite from 1942 to 1969.

Quarried	
Pegmatite	516.000 tons
Gangue	136.000 tons
Produced	
Potassium feldspar	160.000 tons
Quartz	30.000 tons
Mica	700 tons
Beryl	18 tons
Columbite	5 tons
Löllingite	5 tons
Wasted	
0—25 mm fraction	134.000 tons
> 25 mm waste	193.000 tons

gangue to pegmatite exceeded 1. Mining became unprofitable and in 1968 was stopped altogether. A total of 516 000 tons of pegmatite and 136 000 tons of gangue had been mined. Statistics of the production are presented in Table 1.

Geology and mineralogy

The geology of Kaatiala deposit, based mainly on the works of Tavela (1949), Volborth (1952), Neuvonen (1960), and on the author's own observations during the quarrying period, is presented in Fig. 3. The pegmatite lens dips about 15 degrees to NE through granodioritic country rock. The border zone closest to the footwall was characterized by sodium feldspar, whereas the border zone on the hanging wall was an

magnetic separator in the Tapanila feldspar mill near Helsinki. It also became expedient to mine the gangue on the hanging wall to an ever increasing extent.

In the final operational years the ratio of

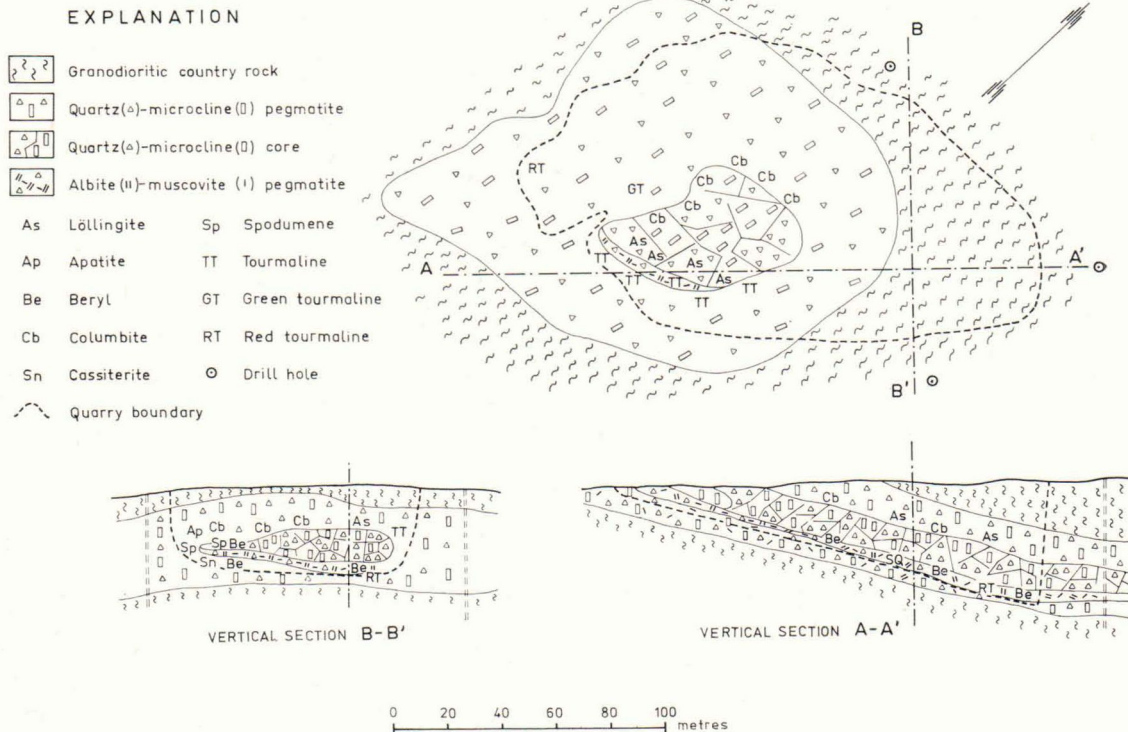


Fig. 3. Geology of the Kaatiala feldspar quarry. SQ = smoky quartz.

aplitic variety of pegmatite, which after 2 to 5 metres graded into medium- or coarse-grained microcline-quartz-muscovite pegmatite with black tourmaline. On the south-western side, nearest to the centrally located intermediate and core zones, there was a nearly vertical, roughly 5 m wide zone with very abundant tourmaline. The central parts were underlain by muscovite-rich zones with beryl. Löllingite, columbite and spodumene occurred mainly above the central part.

The central part consisted of large microcline crystals and discrete quartz cores, with some rose quartz and smoke quartz crystals. Cavities with transparent green and red tourmalines, water-clear beryls and lepidolite were encountered near the narrow northwestern margin. This same zone also contained spodumene, and the only cassiterite specimen found in the deposit.

Feldspars occurred in Kaatiala as microcline with 15 to 22 mole-% albite, and as plagioclase with 12 mole-% anorthite. No transitional forms in larger quantities were met with. The two feldspar varieties differed conspicuously in appearance. The potassium feldspar crystals were grey in colour with clear lustrous faces, whereas the sodium feldspar was white in colour with mat and dull surfaces. Thus, even hand sorting could produce relatively pure products in terms of the ratio of potassium to sodium.

Chemical analyses

The chemical composition of Kaatiala pegmatite was investigated by supplementing the analyses made during the operational period with new multi-element analyses of the various minerals, of the representative bulk samples, and of the country rock.

Analyses of the main components for pure microcline and albite specimens from the operational period as well as partial analyses

Table 2. Composition of pure feldspar lumps.

	Microcline 1	Microcline 2	Oligoclase
	Chemical analyses ^a		
	%	%	%
SiO ₂	65.31	63.73	64.79
TiO ₂	0.00	0.00	0.00
Al ₂ O ₃	18.81	18.99	21.80
Fe ₂ O ₃	0.04	0.07	0.11
MnO	0.00	0.00	0.01
MgO	0.03	0.01	0.02
CaO	0.04	0.07	2.51
Li ₂ O	0.02	0.02	0.02
Na ₂ O	2.46	1.70	9.66
K ₂ O	12.99	14.02	0.69
Rb ₂ O	0.12	0.33	0.00
Cs ₂ O	0.03	0.20	0.00
P ₂ O ₅	0.13	0.70	0.04
H ₂ O+	0.23	0.14	0.28
H ₂ O—	0.05	0.12	0.05
Totals	100.26	100.10	99.98
Norms ^b			
Q	0.7	0.0	0.5
Or	76.2	83.8	3.9
Ab	21.9	15.2	82.9
An	0.2	0.4	11.9
Totals	99.0	99.4	99.2

^a Analyst: P. Ojanperä, Geological Survey of Finland.

^b Method after Hutchison (1974).

for feldspar concentrates with norm values for quartz, ortoclase, albite and anorthite are presented in Tables 2 and 3.

The minerals selected for multi-element analysis were typical pure specimens of the most common types. The bulk samples were taken from stock piles of the minus 25 mm fraction, obtained by screening the crushed pegmatite before hand sorting. Its chemical composition closely approximates the composition of the whole pegmatite body.

The first country rock sample was taken from the E side and the second from N side of the pegmatite at a distance of 25 metres from the contact.

The analyses were performed mainly with an MS 702 double focusing spark source mass spectrometer using electrical detection. The

Table 3. Composition of Kaatiala feldspar concentrates.

	Partial chemical analyses (% by weight) ^a													
	K-feldspar										Na-feldspar			
	1953	1954	1959	1962	1963	1964	1965	1966	1967	1968	Average	1958	1963	Average
K ₂ O	10.75	10.81	9.24	12.05	11.50	11.10	11.30	10.85	10.30	11.10	10.90	0.40	0.62	0.51
Na ₂ O	2.59	2.74	2.52	3.10	3.10	2.85	2.60	3.20	3.11	3.22	2.90	8.73	8.34	8.54
CaO	0.26	0.22	0.45	0.31	0.30	0.32	0.61	0.49	0.45	0.40	0.38	1.08	4.07	2.58
Fe ₂ O ₃	0.07	0.12	0.06	0.05	0.10	0.07	0.08	0.07	0.05	0.04	0.06	0.05	0.11	0.08
Norms														
Or	63.70	64.06	54.76	71.41	68.15	65.78	66.96	64.30	61.04	65.78	64.59	2.37	3.67	3.02
Ab	21.97	23.25	21.38	26.30	26.30	24.18	22.06	27.15	26.39	27.32	24.63	74.07	70.76	72.41
An	1.29	1.09	2.24	1.54	1.49	1.59	3.03	2.44	2.24	1.99	1.89	5.37	20.24	12.81
Q	13.04	11.60	21.62	0.75	4.06	8.45	7.95	6.11	10.33	4.91	8.89	18.19	5.33	11.76

^a Each sample represents a carload (16.5 tons) milled and analysed at Tapanila feldspar mill.

analytical procedure has been described by Nieminen and Yliruokanen (1974). In addition to the ratios peak height/content ppm in weight, which constituted the basis for calculating the contents of certain elements, some additional values were calculated with the aid of a third standard, a Limestone ZG1-KH (Flanagan 1973). The new ratios are presented in Table 4.

Table 4. The ratios peak height/content ppm by weight in ZG1-KH

Isotope	
³³ S+	0.4
⁵³ Cr++	0.14
⁶¹ Ni+	0.40
⁶² Ni+	1.15
⁶⁷ Zn+	0.82
⁶⁷ Zn++	0.10
⁷¹ Ga+	3.38
⁷¹ Ga++	0.15
⁷³ Ge+	0.63
⁷⁵ As+	4.42
⁷⁷ Se+	27.4
⁸⁸ Sr+	3.0
⁹² Zr+	0.26
¹²¹ Sb+	1.21
¹²³ Sb+	1.35
¹⁸² W+	0.93
¹⁸⁴ W+	1.08
²⁰⁹ Bi++	0.37

Because the contents of lanthanoids and barium were low, it was possible in this work to use the following isotopes: ⁶⁷Zn, ⁷¹Ga, ⁷³Ge, and ⁷⁵As for the calculations. Further, the standard ZG1-KH is also more convenient for determining the isotopes ³³S, ⁶¹Ni, ⁶²Ni, ⁷⁵As, ⁷⁷Se, ⁸⁸Sr, ⁹²Zr, ¹¹⁴In, ¹²³Sb, ¹⁸³W, ¹⁸⁴W, and ²⁰⁹Bi than the standards USGS-G-1 and USGS-W-1. AAS replaced mass spectrometry (Bernas 1968) in those cases where high contents of alkalis and beryllium were present.

Three chemical analyses of beryl have already been published by Erämetsä *et al.* (1973). The new chemical analyses are presented in Tables 5a and 5b.

Mineralogical and chemical balance

With the aid of the production figures (Table 1) and of the analyses, Tables 2, 3, 5a, and 5b an attempt was made to calculate the total amounts of the various minerals of the Kaatiala pegmatite, Table 6. In calculations, the chemical composition of the bulk sample of the minus 25 mm fraction was taken to represent the whole pegmatite body. The

Table 5 a. Multielement analyses of Kaatiala minerals and rocks. The contents are given as ppm.

— Not determined < below detection limit

No. Sample	Group 1		Group 2								Group 3						Group 4			
	Be	B	Li	Na	K	Rb	Cs	Ca	Sr	Ba	Cu	Zn	Ga	Ge	As	Tl	Pb	Y	REE	
28	Microcline perthite	2	3	20	15000	91500	300	35	1500	50	120	1.0	25	15	1.0	1.0	2.2	100	<	<
2	Microcline perthite	3	5	50	17000	105000	800	20	2000	6	10	6	15	20	1.0	5	5	50	<	<
16	Na-rich microcline	7	4.5	25	70000	56000	450	45	1800	20	50	22	20	12	4.7	1.7	3.8	90	<	<
33	Microcline, transp.	—	7	700	4000	125000	2500	800	1300	5	40	7	20	20	10	30	20	30	<	4
15	Black microcline	4	4	40	16000	95000	900	50	2000	12	60	30	30	25	4.6	410	7	450	1.2	14
18	Oligoclase	1	0.8	2.1	98000	600	2	0.5	6700	45	<	1.9	55	30	4.0	1.8	<	11	<	<
20	Green albite	5	7	14	117000	7200	14	3.2	11000	20	6	2.1	4.8	30	3.4	60	0.2	40	18	11
1	Quartz, regular	0.1	1.0	5	5	40	0.2	0.2	110	1.0	<	0.5	0.6	—	1.7	0.1	<	<	<	<
38	Rose quartz	0.5	1.0	40	30	125	0.1	0.5	50	0.8	<	0.5	1.0	—	1.1	0.3	<	<	<	<
37	Smoky quartz	0.4	1.0	35	15	130	0.1	—	60	0.5	<	1.0	2.5	0.4	3.0	0.5	<	<	<	<
6	Muscovite	10	70	1500	5000	70000	1500	120	1000	<	1.5	5	30	65	5	10	5	5	1.2	<
7	Li-rich mica	50	70	7000	2000	49000	3000	2000	1000	11	—	3	50	100	10	1.5	15	<	6	<
4	Tourmaline, schorl.	2	28000	50	12000	1200	5	2	1000	2.5	<	3.3	700	130	3.4	65	<	7	3.7	<
34	Green tourmaline	15	28000	800	21000	2300	25	120	1500	6	<	3.7	300	100	9	1.8	0.3	125	<	<
35	Red tourmaline	11	30000	1000	18000	140	1.2	8	1200	5	<	2.5	25	350	8	2.0	<	30	<	<
41	Apatite	9	4.7	15	6200	4300	35	8	400000	85	1.5	350	50	35	8	30	<	9	12700	15500
40	Beryl, regular	42000	3	1400	17000	1200	180	2300	500	<	<	<	100	35	1.0	<	<	<	<	<
39	Beryl, heliodor	41000	9	1500	9100	600	180	2900	150	<	<	<	180	30	3.0	<	<	<	<	<
50	Beryl, vorobyevite	39000	1	2400	6800	400	90	24500	85	2	1	<	11	60	2.0	5	1.0	1.0	<	<
11	Columbite	3	3	12	300	500	1.0	0.8	20000	20	35	200	100	10	15	30	0.9	550	1000	430
12	Löllingite	—	—	7	250	250	8	5	230	5	<	8	1.3	1	3.2	700000	1.0	20	<	<
10	Cassiterite	20	5	120	150	2500	20	11	500	1.7	75	1.5	15	10	3.0	3.0	12	25	13	140
8	Spodumene	3.0	30	16000	1600	2000	15	7	300	13	—	10	3	30	10	12	<	<	<	<
23	Pegmatite	6	1200	150	35000	45000	300	30	3700	30	30	10	30	25	2.5	30	1.5	30	5	14
26	Country rock	2	3	30	25000	37500	130	4.0	20500	280	240	30	30	25	3.0	3	1.0	25	35	240
	Granite average	5	15	30	27700	33400	145	5	15800	285	600	10	40	20	1.5	1.5	1.0	30	40	184

Table 5 b. Multielement analyses of Kaatiala minerals and rocks. The contents are given as ppm.

— Not determined < below detection limit

No. Sample	Group 5				Group 6							Group 7						
	F	P	S	Cl	Sc	V	Cr	Mn	Fe	Co	Ni	Ti	Zr	Nb	Sn	Ta	Th	U
28 Microcline perthite	215	200	16	18	16	5.3	49	19	340	0.1	45	27	<	1.1	3.4	0.4	<	<
2 Microcline perthite	40	175	15	55	15	4	85	30	500	0.5	42	60	<	0.2	24	<	<	<
16 Na-rich microcline	50	350	21	60	23	48	50	31	200	0.4	23	33	1.8	20	7.3	<	<	<
33 Microcline, trans.	1900	125	75	20	5	4	55	15	800	0.6	125	20	5.6	10	6.5	5	<	7
15 Black microcline	450	500	480	60	12	7	50	65	4700	1.0	37	32	12	4.5	7.3	1.3	7	18
18 Oligoclase	110	250	13	20	10	1.5	17	4.6	430	0.1	21	17	<	1.3	—	2.1	<	<
20 Green albite	50	250	150	23	76	1.4	30	65	2300	0.4	13	18	5.8	1.9	3.0	<	45	20
1 Quartz, regular	17	14	15	11	1.7	0.2	40	1.6	280	0.1	1.4	17	<	1.5	0.6	4.2	5	<
38 Rose quartz	9	18	12	7.5	5	0.4	52	5.4	590	0.1	9.2	—	<	—	—	<	25	0.7
37 Smoky quartz	15	12	15	5.6	5.7	0.4	59	6.0	1250	0.2	15	58	<	—	—	<	<	<
6 Muscovite	8500	40	30	35	50	3.7	20	550	2150	1.8	14	1000	6.2	150	160	30	<	1.1
7 Li-rich mica	22500	55	650	90	75	6.7	35	95	1250	1.2	2.3	820	3.3	250	220	70	<	<
4 Tourmaline, schorl.	3900	40	45	42	13	37	69	2500	58700	0.2	60	620	10	40	19	1.4	1.8	1.4
34 Green tourmaline	25000	26	41	16	2	13	64	5000	32000	10	80	100	10	40	120	5.3	<	<
35 Red tourmaline	7500	67	24	20	1	8	61	3800	4600	8	50	400	15	4.9	100	75	5.9	<
41 Apatite	12500	—	55	36	—	3.7	7.5	6200	1260	<	2500	100	20	—	11	—	49	12
40 Beryl, regular	42	15	34	14	4	1.5	86	30	1800	—	2	25	—	47	2	—	—	—
39 Beryl, heliodor	7	1.2	16	14	12	—	160	160	800	—	<	40	—	—	2	—	—	—
50 Beryl, vorobyevite	—	110	—	—	25	1	85	50	660	—	6	25	—	—	45	—	—	—
11 Columbite	90	18	175	52	420	0.7	1.1	47000	150000	9	75	16700	—	500000	1700	41000	24	1300
12 Löllingite	150	7.5	5000	15	0.2	1.2	1.6	10	200000	4.6	42	30	1.8	4.6	42	70	<	<
10 Cassiterite	12	75	19	11	8.7	1.5	1.1	1500	9300	930	25000	2050	1350	—	—	—	<	3.8
8 Spodumene	120	20	12	30	—	13	30	720	8300	1.2	2.3	40	0.4	1.5	110	8.3	<	<
23 Pegmatite	1000	250	30	30	4	4	40	30	7000	5	30	500	13	60	12	4.3	3.2	3.3
26 Couuntry rock	500	200	50	30	10	50	50	300	30000	20	7	3000	40	23	1.5	1.2	6	2.3
Granite average	850	700	270	200	6	40	10	400	27000	2	4	2300	180	20	3	3.5	17	4.8

Table 6. Bulk composition of the Kaatiala pegmatite.

	Main components of bulk sample ^a % by weight	Tourmaline and micas deducted ^b % by weight	Calculated mode for bulk sample ^c	
SiO ₂	71.41	73.71	Quartz	21.2
Al ₂ O ₃	15.41	14.68	Microcline	35.6
Fe ₂ O ₃	0.81	0.17	Albite	32.5
MgO	0.28	0.09	Micas	6.0
CaO	0.52	0.52	Tourmaline	4.0
Na ₂ O	4.60	4.91	Others	0.7
K ₂ O	5.40	5.33		100.0
Rest	1.24			

	Trace elements forming own specific mineral ppm	Disperced in the other minerals ^d %	Modal composition of specific minerals %	
Be	6	40	Beryl	0.01
B	1200	0.5	Tourmaline	4.0
P	250	50	Apatite	0.06
As	30	5	Löllingite	0.004
Nb	35	30	Columbite	0.005

^a Analyst: v. Weymarn, P-O, Partek Oy.

^b Approximative chemical analyses for micas and tourmaline in weight per cent: SiO₂ 62 and 42, Al₂O₃ 20 and 25, Fe₂O₃ 1 and 15, MgO 2 and 2, CaO 0.5 and 0.5, Na₂O 1 and 3, and K₂O 10 and 0.

^c Quartz=SiO₂, Microcline Or₈₀ Ab₂₀, Albite Ab₉₄ An₆, Micas: approx. 75 per cent muscovite+25 per cent lithia mica.

^d Estimates base on the mode of the main minerals and their typical analyses.

amounts of micas were obtained from the flotation tests, and the amount of tourmaline from the boron content (1200 ppm) of the bulk sample. Oxides bound in micas and tourmaline were deducted from the bulk chemical analysis, and the amounts of other minerals were calculated from the residual. Owing to the varying chemical compositions of both tourmaline and micas, the deduction was based on approximate chemical analyses.

The content of micas (6 wt-%) corresponds well to the values of zoned pegmatites, e.g. the Hugo pegmatite, Keystone, USA, whose weighted mica content is also 6 per cent (Norton *et al.*, 1962). In unzoned pegmatites, on the other hand, the mica content is mostly below 4 per cent (Norton 1970).

Like the percentage of tourmaline, the percentages of beryl, apatite, löllingite and columbite were calculated from the contents of Be, P, As, and Nb in the bulk sample.

Tin and lithium are dispersed to such a high degree, especially in micas, that it was not possible with the aid of trace element analyses to calculate the amounts of their minerals proper, cassiterite and spodumene. According to mineralogical observations made during the operational period, their quantities are without significance and have no influence on chemical balance.

Table 7 gives the total chemical and mineralogical balance of the whole Kaatiala pegmatite, estimated on the basis of the amounts of minerals and their chemical analyses. For

Table 7. The chemical and mineralogical balance of the Kaatiala pegmatite

Mineral	Percent of total	K- feldspar 36	Na- feldspar 33	Quartz 21	Mica 6	Tour- maline 4	Apatite 0.06	Beryl 0.01	Colum- bite 0.005	Löll- ingite 0.004	Peg- matite 100
Quantity, tons		180 000	165 000	105 000	30 000	20 000	300	50	25	20	500 000
Be	ppm tons	2.0 0.36	1.0 0.17	0.3 0.03	10—50 0.3—1.5	2.0 0.04	9 —	36 000 1.8	— —	— —	6 3
B	ppm tons	5 0.9	0.7 0.12	3 0.3	70 2.1	30 000 600	5 —	3 —	3 —	— —	1 200 600
Li	ppm tons	50 9.0	2 0.3	5 0.5	1500—7000 45—210	50 1	15 —	1400 0.1	12 —	7 —	150 75
Rb	ppm tons	300—800 54—144	2 0.3	0.2 0.02	1500—3000 45—90	5 0.1	35 —	180 0.01	1 —	8 —	300 150
Cs	ppm tons	20—35 3.6—6.3	0.5 0.1	0.2 —	120—2200 3.6—66	2 0.1	7.5 —	2300 0.1	0.8 —	5 —	30 15
Ca	ppm tons	1500—2000 270—360	6700 1140	110 11	1000 30	950 19	400000 120	500 —	20000 0.5	230 —	3700 1850
Sr	ppm tons	9—50 1.6—9	45 7.4	1 0.1	11 0.1	2.5 —	85 —	— —	20 —	5 —	30 15
Ba	ppm tons	10—20 1.8—21.6	— —	— —	1.5 —	— —	15 —	— —	35 —	— —	30 15
Ga	ppm tons	15—20 2.7—3.6	25 4.1	— —	65—100 2—3	130 2.6	35 —	35 —	10 —	1 —	25 12.5
Ge	ppm tons	1 0.18	4 0.66	1.7 0.17	5—10 0.15—0.30	3.4 0.06	8 —	1 —	15 —	3.2 —	2.5 1.3
As	ppm tons	1.0 0.18	1.8 0.29	0.1 0.10	10—15 0.30—0.45	65 1.3	30 —	— —	30 —	700000 14	30 15
Tl	ppm tons	2.2—5 0.40—0.90	— —	— —	5—15 0.15—0.45	— —	— —	— —	0.9 —	1 —	1.5 0.75
Pb	ppm tons	50—100 9—18	11 1.8	— —	6 0.18	7 0.14	9 —	— —	550 0.03	20 —	30 15
F	ppm tons	40—215 7.2—38.7	110 18.0	17 1.7	8500—22500 255—675	3900 68	12500 3.8	42 —	90 —	150 —	1000 500
P	ppm tons	175—200 31.5—36.0	250 41.3	14 1.4	40—55 1.2—1.7	40 0.8	180000 54.0	15 —	18 —	7.5 —	250 125
Nb	ppm tons	0.2—1.1 0.04—0.2	1.3 0.2	1.5 0.15	150—250 4.5—7.5	4.0 0.1	— —	4.7 —	500000 12.5	4.6 —	35 17.5
Sn	ppm tons	2.4—3.4 0.4—0.6	— —	0.6 0.1	160—220 4.8—6.6	19 0.3	11 —	2 —	1700 —	42 —	12 6
Ta	ppm tons	0.4 0.07	2.1 0.35	4.2 0.42	30—70 0.9—2.1	1.4 —	— —	— —	41000 1.03	6.7 —	4.3 2.15
Th	ppm tons	0—7 0—1.26	0—45 0—7.4	— —	— —	1.8 0.03	49 0.01	— —	24 —	— —	3.2 1.60
U	ppm tons	0—18 0—3.2	0—20 0—3.3	— —	1.1—2.8 0.03—0.08	1.4 0.02	12 —	— —	1300 0.03	— —	3.3 1.65
REE	ppm tons	0—14 0—2.52	0—11 0—1.85	— —	— —	— —	15500 4.65	— —	430 0.01	— —	13 6.50

convenience, the total amount of the quarried pegmatite is rounded from 516 000 to 500 000 tons.

Discussion

The analytical data are presented in the manner proposed by Taylor (1965), this being

a convenient way of arranging trace element data for many elements. This arrangement is based largely on geochemical association.

Within each group of elements of similar geochemical behaviour, the arrangement is not in the order of decreasing radius as Taylor has advised but in the order of atomic

numbers. The values for the granite average proposed by Taylor (1964) are used for comparison. The enrichment factor is the ratio of the content of any element in the pegmatite body to that of the granite average. The concentration coefficients for an element were calculated according to the equation $\frac{k \cdot 100}{k + p}$, where k is the amount of the element in its minerals proper and p is the amount of the disseminated element in the pegmatite except in its own minerals (Beus 1966).

The small cations Be and B.

Table 5a, group 1

The beryllium enrichment factor is only 1.2. Despite the low beryllium content, beryl was formed, although its abundance is only 0.01 %. The coefficient of beryllium concentration is 60 %. The highest contents of disseminated beryllium are in lithium-rich mica, 50 ppm and in coloured tourmalines, 11–15 ppm. The relatively high degree of dissemination is typical of granitic pegmatites containing rare metals and small amounts of beryllium (Beus 1966).

The enrichment factor for boron in the Kaatiala pegmatite is 80. This is the highest enrichment factor of any element in the pegmatite determined in this work. The country rock, on the other hand, shows a negative boron anomaly, *i.e.* only 6 ppm. The granite average for boron is 15 ppm.

Boron is concentrated in tourmaline, the coefficient of concentration exceeding 99 per cent. The content of boron in all the other minerals except micas is remarkably low, that is, below 10 ppm.

According to Oftedal (1964), pegmatite minerals containing rare earths are often relatively rich in boron, up to several tenths of a per cent; nevertheless, columbite and apatite, the only rare earth element carriers, contain only 4.7 and 3.0 ppm B, respectively.

The mobile complexes, in which form boron is transported, are probably borontrihalides or even CsBF_4 as proposed by Stavorov *et al.* (1962). The relatively high content of fluorine and cesium in the pegmatite corroborates this theory.

Bräuer (1970), too, points to the marked influence of fluorine on the formation of tourmaline. He suggests that the BF_4^- complex gets concentrated into the last granitic melts and forms, during the progress of autometasomatism, independent tourmaline crystals.

The large cations including alkalis Li, Na, K, Rb, and Cs and alkaline earths Ca, Sr and Ba. Table 5 a, group 2

All these elements, except Li, occur in eight to twelvefold coordination with oxygen in silicates. Lithium generally occurs in sixfold coordination, isomorphously replacing Mg, Fe^{2+} and Al. They all form dominantly ionic bonds.

The alkalis are all enriched in the pegmatite body compared with the granite average. The enrichment factor for lithium is 5.0, for sodium 1.2, for potassium 1.3, for rubidium 2.1 and for cesium 6.0.

If all micas are regarded as Li-bearing minerals, the coefficient of lithium concentration is 82. The proper Li-mineral, spodumene, is so rare, that its Li-content is without significance in this calculation. Except in Li-specific minerals, the Li-content varies as follows: Vorobyevite (Cs-rich beryl) contains 2400 ppm lithium, other beryl varieties 1500–1400 ppm, coloured tourmaline 800–1000 ppm, black tourmaline 50 ppm, rose and smoky quartz 35–40 ppm, normal quartz 5 ppm, K-feldspars from 20 ppm to 700 ppm in the last crystallization forms and Na-feldspars from 2.1 ppm to 14 ppm.

Sodium and potassium do not show any

marked tendency to enrichment except in their minerals proper, Na- and K-feldspars and micas. Normal quartz contained about 5 ppm Na and 40 ppm K. The tenors in the coloured varieties were slightly higher.

Tourmalines are all relatively poor in K, from 140 ppm to 2300 ppm, but richer in Na, 12 000—21 000 ppm. No big differences were observed in the K + Na contents between coloured and black tourmalines. Spodumene is relatively poor in both Na, 1600 ppm and K, 2000 ppm.

The enrichment factor for Rb, 2.1, is too low, especially regarding the marked abundance of K in pegmatite, to form its own minerals; it is, therefore, completely dispersed in K-feldspar and micas (Povarennykh 1972). All the other minerals are very poor in Rb, mostly below 25 ppm, except beryls with 90—180 ppm.

The cesium content of the whole pegmatite is 30 ppm. It has been concentrated in the cesium beryl vorobyevite, which contained 34 500 ppm Cs.

Lithium-rich mica is another mineral with high cesium content, 2000 ppm. The tenor of cesium in muscovite is much lower, only 120 ppm. Like rubidium, the bulk of the cesium is dispersed in K-feldspar, which normally contains 20—50 ppm Cs. Nevertheless, the transparent K-feldspar variety found in the cavity representing the last stage of crystallization contained as much as 800 ppm Cs and 2500 ppm Rb. Lappalainen and Neuvonen (1968) found at Kaatiala a specimen of K-feldspar which contained 490 ppm Cs and 9400 ppm Rb.

Unlike the alkalis, the alkaline earths show a clear deficiency compared with the granite average, calcium 0.23, strontium 0.11 and barium 0.05. Calcium occurs in its own minerals, plagioclase and apatite. These minerals also contain most of the dispersed strontium. Barium, on the other hand, is dispersed into K-feldspar, the highest content

being 120 ppm in the early crystallization forms.

The chalcophile elements Cu, Zn, Ga, Ge, As, Tl, and Pb. Table 5 a group 3

Copper is concentrated into apatite and columbite, and zinc and gallium into tourmalines. Germanium is almost ubiquitous in all minerals, and shows a low degree of concentration in micas, columbite and last-stage K-feldspar.

The contents of Cu, Zn, Ga and Ge are almost identical with the average granitic values of these elements. The enrichment factor of arsenic compared with the granite average is 20. It forms its own mineral, löllingite, which contains nearly 95 per cent of the total arsenic.

Thallium is mainly concentrated into last-stage K-feldspar and lithia mica, whereas lead is most abundant in early stage K-feldspar, columbite and green tourmaline.

The rare earth elements La-Lu and Y. Table 5c, group 4

The rare earth elements in Kaatiala pegmatite show the highest contents in apatite, which assays 15500 ppm lanthanoids and 12700 ppm Y. Columbite is another concentrator of rare earths although the abundances in it are clearly lower, only 430 ppm lanthanoids and 1000 ppm Y. Together these minerals contain about 70 per cent of the rare earth elements in the whole pegmatite. The remaining 30 per cent are to be found in feldspars.

The mean content of lanthanoids in the Kaatiala pegmatite is 14 ppm and that of yttrium 5 ppm. These contents are much lower, only 7.5 and 12.5 per cent, respectively, of those of the same elements in the average

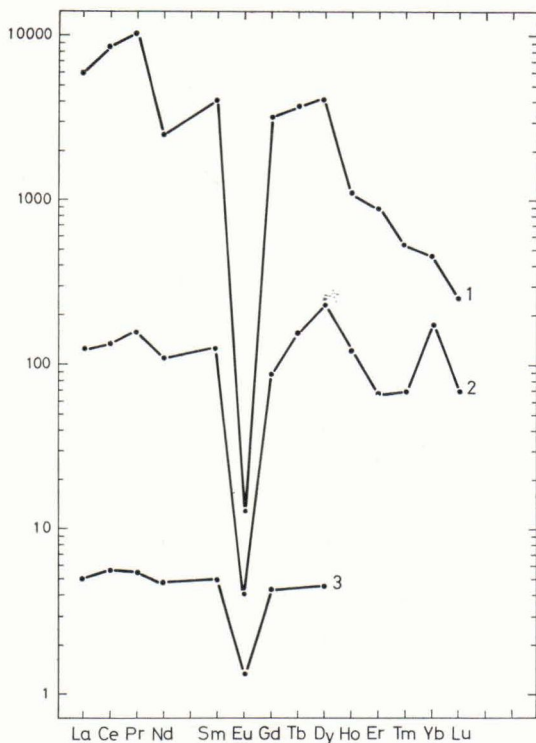


Fig. 4. Distribution patterns of the lanthanoids in Kaatiala apatite (1), columbite (2) and the total pegmatite (3) normalized against chondrite.

granite, which are 184 ppm for lanthanoids and 40 ppm for yttrium (Taylor 1968).

The distribution patterns of the lanthanoids in Kaatiala apatite, columbite, and the whole pegmatite normalized against chondrite, (Nance *et al.* 1976) are shown in Fig. 4. Typical of all are the pronounced deficiency of europium and neodymium, and the elevated value of dysprosium. Columbite also shows an elevated value for ytterbium, which is consistent with its high yttrium content.

The anions of F, P, S and Cl. Table 5 b, group 5

Kaatiala pegmatite averages 1000 ppm fluorine. Most of the fluorine, about 80 %, is found in micas. In these minerals fluorine ion

substitutes for hydroxyl. The content of fluorine is lowest in all varieties of quartz, 9–17 ppm; in other minerals it is as follows: 7–42 ppm in beryls, 40–1900 ppm in K-feldspar, 50–110 ppm in Na-feldspar, 3900–25000 ppm in tourmalines and 12500 ppm in apatite.

The average content of phosphorus in the pegmatite is 250 ppm, which is about one third of that of the average granite. Nevertheless, despite this low value, small amounts of apatite have formed, mostly on the border zone. Apatite contains about 50 per cent of the total phosphorus. The remaining 50 per cent is mainly in Na- and K-feldspars.

The average content of sulphur in the whole pegmatite is only 30 ppm, which is one ninth of the granite average. In addition to löllingite, only lithium-rich mica, biotite and columbite concentrate sulphur to some degree.

In spite of relatively high fluorine tenor, the Kaatiala pegmatite is poor in chlorine. The average content is 30 ppm, which is only one sixth of that in the average granite. Chlorine exhibits almost constant abundances in all minerals, ranging from 5.6–60 ppm in quartz and feldspars to 90 ppm in lithium-rich mica. Even in apatite the chlorine content is as low as 36 ppm.

The trivalent and divalent cations Sc, V, Cr, Mn, Fe, Co and Ni. Table 5 b, group 6

Scandium is an ubiquitous element in all the Kaatiala minerals. The only significant scandium carrier, however, is columbite, which contains 420 ppm scandium. Haapala *et al.* (1967) have found that a variety of columbite of Haapaluoma pegmatite, about 16 km southwest of Kaatiala, contained 0.90 per cent Sc_2O_3 .

Owing to the small amount of columbite and its low scandium content, the overall

scandium tenor in Kaatiala pegmatite is 4 ppm, which is slightly less than in the average granite, 6 ppm.

Vanadium is concentrated into black tourmaline. Its mean content is 10 per cent of the granite average.

Chromium is a disperse element without any significant accumulation tendency. Its enrichment factor is 4 in the whole pegmatite.

Manganese shows the highest concentration in columbite, iron in löllingite and columbite, cobalt and nickel in cassiterite. The manganese and iron contents are distinctly lower and the abundances of cobalt and nickel higher than those of the granite averages.

It is of great practical importance that all these elements occur in negligible amounts in feldspars and quartz. They all have a colouring effect on silicate melts; thus, elevated abundances of these elements are harmful in ceramic raw materials.

The large highly charged cations with valencies 4, 5 or 6 including Ti, Zr, Nb, Sn, Ta, Th and U. Table 5 b, group 7

These elements do not readily enter common rock-forming minerals owing to valency difficulties. They therefore occur in the last hydrous fluids that migrate through the fractures formed after consolidation of

the main pegmatite body. Albite, micas, spodumene, cassiterite, coloured tourmalines, columbite and löllingite crystallize from these fluids directly or through hydrothermal processes. Thus, these minerals are the main carriers of elements of this subgroup.

Columbite and micas contain over 95 per cent of the total of niobium and tantalum. Cassiterite is the main concentrator of tin and zirconium, although the bulk of the tin is found in micas. Löllingite is the only concentrator of arsenic and columbite that of titanium.

The zirconium content in the pegmatite is far below, and the niobium, tin and tantalum contents distinctly higher than in the average granite.

The mean contents of thorium and uranium are also below the granite average. Thorium is concentrated in apatite, and uranium in columbite. The bulk of the thorium and uranium are, however, in feldspars of the fracture and replacement zones. Uranium-rich black microcline contained 18 ppm U and 7 ppm Th, and green albite 20 ppm U and 45 ppm Th. These minerals exhibit black submicroscopic powder in their microfractures. According to Leonova *et al.* (1958), uranium occurs in quartz and feldspars as discrete submicroscopic uranium minerals or as scattered uranium molecules, which are absorbed by crystal planes or deformed crystal lattices.

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