BERYL FROM BIRCH PORTAGE, SASKATCHEWAN

DENNIS RADCLIFFE AND FINLEY A. CAMPBELL
Department of Geological Sciences, Queen's University, Kingston, Ontario
Department of Geology, University of Alberta, Calgary, Canada

ABSTRACT

Yellow beryl from Birch Portage has a composition expressed by $(Be_{2.77}Al_{.12}Fe_{.05})_{2.94}Al_{2.00}(Si_{5.86}Al_{.14})_{6.00}O_{18}Na_{.04}K_{.01}$, and the following properties; unit cell parameters $a = 9.201$ Å, $c = 9.187$ Å, specific gravity 2.722, refractive indices $\epsilon = 1.567$, $\omega = 1.573$. Green beryl has a composition expressed by $(Be_{2.27}Al_{.23}Fe_{.43})_{2.93}Al_{2.00}Si_{6.00}O_{18}Na_{.05}K_{.01})$ and the following properties; unit cell parameters $a = 9.255$ Å, $c = 9.189$ Å, specific gravity 2.791, refractive indices $\epsilon = 1.575$, $\omega = 1.579$.

An x-ray diffraction pattern of beryl has been indexed and the observed reflections agree with the space group $P/6mcc$. Chemical analysis of 3 beryl crystals and 12 pegmatitic and aplitic rocks are reported.

The chemical, physical, and optical properties of yellow and green beryl from Birch Portage are correlated, and compared with previously published data. This leads to the conclusion that the colouration may be associated with R_2O components. If these components occupy structural positions, the lattice may be expanded in the direction of c, and if they reside in the open channels of beryl, the lattice may be expanded in the direction of a. The terms 'C' type and 'A' type beryl are proposed. Birch Portage beryl falls in the latter category.

The location of Birch Portage is shown in Figure 1 (see also National Topographic Map, Sheet Number 63L/15 Birch Portage, East Half). The country rocks of a 4.3 square mile area immediately west of the Birch Portage Indian Reservation consist of medium grade Precambrian Kisseynew hornblende and/or biotite gneisses, arranged in a series of north-south striking bands with a general easterly dip of 50°. Simple statistical analysis (Radcliffe, 1964) of the various structural elements has shown a northeasterly plunging antiform whose eastern limb has been truncated by a north-south wrench fault (Sturgeon Weir Fault System). In the 4.3 square mile area immediately west of this wrench fault, 335 dykes have been located and these are mainly of granitic composition (beryl has been identified in 61 dykes). They have a general southwesterly dip, and statistical analysis on the variation of the dip of the dykes, suggests a fan-like fracture system, the beryl pegmatites occupying intermediate dips (37°) and aplitic dykes high and low angle dips (85° and 28°).

Beryl occurs only in dyke-like bodies, that are usually less than 24 inches wide and 600 feet long. These dykes usually taper out over a distance of 30 feet and they may be pictured as elongated lenticular

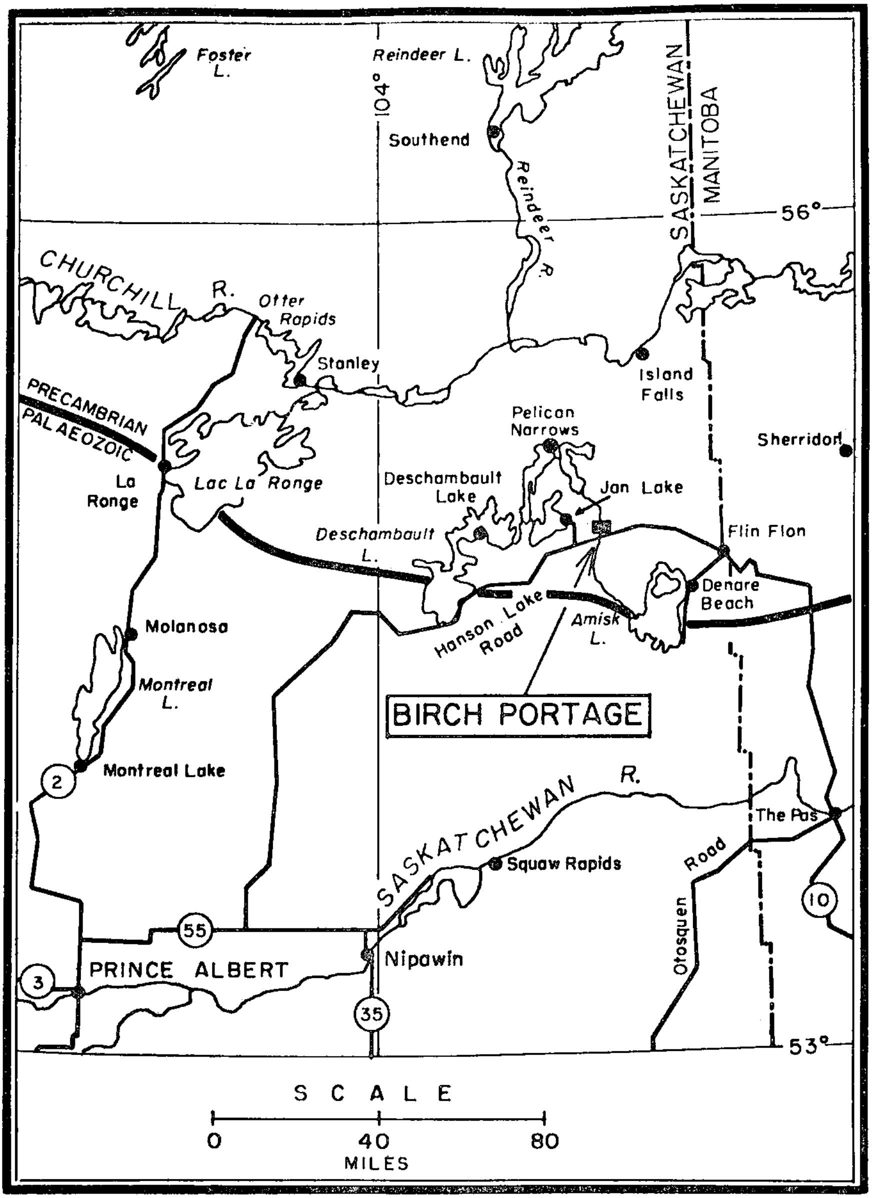

FIG. 1. Location map for Birch Portage, Saskatchewan.

envelopes. Detailed mapping has shown approximately 90 per cent of the beryl bearing pegmatites restricted to a zone extending no further than 2,600 feet west of the wrench fault. No dykes have been identified east of this fault, strongly suggesting that the factors responsible for producing the wrench fault, were also instrumental in opening up a series of shear and extension fractures, now occupied by igneous rocks. This same type of fold-fracture-fault control system for certain types of beryl pegmatites has been described by Beus (1962) for unspecified localities in the USSR.

PETROLOGY

Birch Portage beryl occurs in small pockets averaging approximately twelve inches square by one inch thick, and the greatest dimensions of these lenses parallels the plane of the dykes. In this plane the highest concentration of beryl observed was twelve-one-inch crystals in a square foot. The largest beryl crystal observed was one inch in diameter and of indeterminate length. Commonly crystals are 1/2 inch to 1 inch long and 1/4 inch to 1/2 inch in width. The beryls are always opaque and green to yellow-green in colour. They are occasionally zoned from green to yellow toward the outside of the crystal, and this zoning is particularly evident where the beryl is in close association with alkali feldspar.

The beryl pegmatites are mineralogically simple, consisting of quartz, feldspar and beryl, with accessory spessartite, muscovite, biotite, apatite and magnetite. A simple zonation can be frequently recognized in dykes, where a central zone of coarsely crystalline quartz is surrounded by co-precipitated quartz and feldspar. Beryl may be located at the junction of these two zones, while in other dykes in which coarsely crystalline quartz is absent, beryl and feldspar occupy the central zone. Beryl is found with any combination of quartz, K-feldspar, and albite (Table 1).

Beryl occurs in coarse grained dykes (1 inch feldspars), dominantly

TABLE 1. MODAL ANALYSES OF FOUR BERYL PEGMATITES (VOLUME %)*

	512	521	522	601	No. Dykes
Quartz	38.3	18.7	30.1	24.2	61
K-feldspar	3.7	41.7	28.1	30.9	61
Albite	55.4	34.5	39.7	42.8	61
Biotite	2.0	—	0.9	—	6
Muscovite	—	—	Trace	Trace	8
Garnet	Trace	5.2	—	—	6
Apatite	Trace	—	—	—	2
Magnetite	0.7	—	1.2	—	4
Beryl	Trace	Trace	Trace	2.1	61
grid (sq. cm.)	12.5	18.0	30.0	30.0	

*These specimens are 2 inches wide, sampled from the margins to the centres of 4 inch wide dykes.

fine grained dykes (1/8 inch feldspars), wide dykes (36 inches) or narrow dykes (4 inches), and in dykes with red, pink, or cream coloured feldspars. Macroscopic examination of 61 beryl pegmatites indicates the mineral frequencies shown in Table 1.

The following two mineralogical structures occur frequently in the dykes.

(1) Coarse K-feldspar, albite, and quartz may grow perpendicular to the dyke walls in discrete subparallel crystals, and occasionally the central phase of such dykes may grow in the plane parallel with the dyke walls (Figure 2A).

(2) Rhythmic alternation of mineralogical bands parallel with the dyke walls consist essentially of fine albite and quartz followed by K-feldspar and quartz (Figure 2B). The following bands were recognized:

(i) Fine, feldspathic contact marginal phase.
(ii) Coarse, K-feldspar + quartz + albite.
(iii) Fine, albite + quartz + minor K-feldspar.
(iv) Coarse, K-feldspar + quartz + minor albite.
(v) Fine, albite + quartz + minor K-feldspar + beryl.

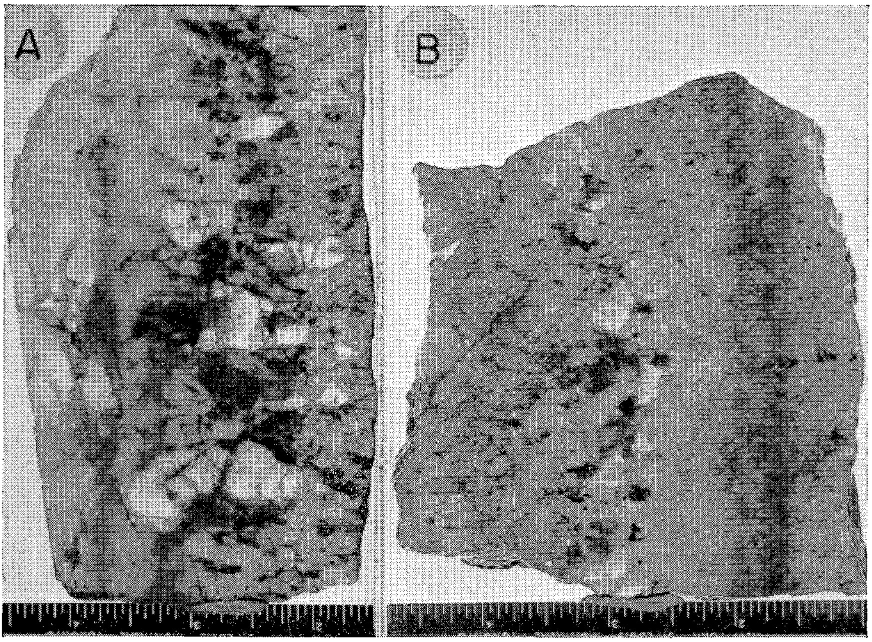

FIG. 2. Mineralogical structures of Birch Portage pegmatites (right margin of photographs A and B are the dyke walls, left side are central phases). A. Beryl pegmatite. D. R. 549–63. Illustrating parallelism of crystal growth from the margins of the dyke and non-parallel, but rather planar, growth in the central phase. Note narrow chilled margin. B. Beryl pegmatite. D. R. 601A–63. Two phase dyke illustrating the rhythmic banding of coarse and fine phases. Note hexagonal beryl crystal in central phase.

These two features can be explained by crystallization in an open system e.g. the mineralogical compositions of successive rhythmically banded units are incompatible in a closed system, either under equilibrium or disequilibrium crystallization (Tuttle & Bowen, 1958).

It is suggested that beryllium was concentrated into a beryllium rich residual phase which precipitated beryl at a late stage in widely separated small pockets, probably loci of low pressures.

CHEMICAL VARIATIONS OF BIRCH PORTAGE BERYL

Two selected Birch Portage beryl crystals, one green and the other yellow, have been analyzed chemically and compared in Table 2 with an aquamarine from Mt. Antero, Colorado. It is possible that the colour variation of the beryls is influenced by the R_2O components and this suggestion is supported by association of zoned beryl crystals with co-precipitated alkali feldspars and general absence of zoned crystals in the presence of abundant quartz. Sosedko (1957) has related colour changes with increasing Cs_2O content.

UNIT CELL PARAMETERS OF BERYL

Beryl was structurally analyzed by Bragg & West (1926) who gave the unit cell dimensions as $a = 9.21 \pm 0.01$ Å, $c = 9.17$A $\pm$ 0.01 Å. They gave the cell content as $2[Be_3Al_2Si_6O_{18}]$ with a calculated density of 2.661, and derived the space group as $P6/mcc$ (No. 192).

One of the main problems in determining accurate unit cell dimensions of beryl from powder data (see Table 3) arises from the fact that a and c may be virtually the same length, thus many combination peaks appear on the pattern as there are often several *hkl* planes with the same *d* spacing. It is therefore desirable to use uniquely indexed reflections when deriving the cell parameters. In this study the following reflections were used:

(100) odd orders only, as (200) is coincident with (102)

(112) to determine c knowing a, as (002) is coincident with (110).

The results obtained using this method are given in Table 4, and are compared with previously published results.

The accuracy of cell parameters may be examined by calculating the density from the chemical analysis and cell volume and comparing with the measured density. The results of this procedure are given in Table 5. In all cases the calculated density was lower than the measured density and this may be due to one of three main causes.

TABLE 2. CHEMICAL ANALYSES OF APLITES, BARREN PEGMATITES, BERYL PEGMATITES, AND BERYL

	501	510	519	533	531	539	540	556	512	521	522	601	Be 609	Be 522	Be 551
SiO_2	75.01	74.02	74.40	74.08	72.98	76.28	77.40	75.32	71.08	71.34	74.36	73.26	66.00	63.66	63.94
TiO_2	0.05	0.08	0.04	0.03	0.01	0.02	0.01	0.01	0.02	0.02	0.04	0.01	0.03	—	0.01
Al_2O_3	13.97	13.10	14.47	13.92	15.17	13.61	13.73	14.08	15.65	15.09	14.35	14.51	19.34	20.89	20.98
Fe_2O_3	1.39	2.41	0.73	1.40	0.48	1.25	0.68	0.83	1.28	1.80	1.23	0.45	2.04	0.83	2.04
MnO	0.03	0.03	0.03	0.11	0.06	0.39	0.12	0.04	0.19	0.78	0.09	0.07	0.02	0.01	0.02
MgO	—	—	—	0.96	—	—	—	—	—	—	—	—	—	—	—
CaO	0.75	1.60	0.98	0.76	0.65	0.48	0.26	0.51	1.04	0.62	0.63	0.54	—	0.01	—
Na_2O	3.62	4.06	2.87	4.44	5.39	4.68	3.82	4.28	7.72	3.60	4.02	3.63	0.04	0.24	0.32
K_2O	4.93	4.22	6.42	3.89	3.29	3.31	3.72	3.68	0.77	6.07	3.81	6.13	0.03	0.05	0.09
BeO	—	—	—	—	—	—	—	—	—	—	—	—	10.75	12.49	10.08
H_2O^+	?	?	0.04	0.26	—	?	—	?	0.22	0.47	?	?	0.59	0.74	1.15
H_2O^-	?	?	0.53	0.28	0.30	?	0.35	?	0.23	0.46	?	?	0.38	0.38	0.47
Others	0.04	0.05	0.05	0.05	0.04	0.04	0.06	0.05	0.02	0.08	0.05	0.08	—	—	0.01
Total	99.79	99.57	100.56	100.18	98.37	100.06	100.15	98.80	98.22	100.33	98.38	98.68	99.22	99.30	99.11
Trace Elements (ppm)															
SrO	43	216	85	61	35	24	19	41	72	54	65	57	7	8	11
Li_2O	24	29	43	37	31	108	29	13	16	39	28	26	7	23	4
Rb_2O	210	113	204	277	188	191	359	325	55	469	315	515	16	12	98
Cs_2O	126	107	147	159	181	110	172	123	73	238	135	233	4	2	30

Aplites: 501, 510, 519, 533. Barren Pegmatites: 531, 539, 540, 556. Beryl Pegmatites: 512, 521, 522, 601. Be 609: Aquamarine, Mt. Antero, Colorado. Be 522: Yellow Beryl, Birch Portage. Be 551: Green Beryl, Birch Portage.

ANALYST: Dennis Radcliffe.

TABLE 3. *X*-RAY DIFFRACTION DATA FOR YELLOW BERYL (*D. R. 522*)

I	*d*Å	*hkl*	*I*	*d*Å	*hkl*
100	7.94	100	2	1.3686	216, 512
31	4.567	002, 110	1	1.3273	306, 600
32	3.810	200, 102	7	1.2772	520, 226
62	3.251	112	7	1.2653	521, 424
19	3.011	202, 210	4	1.2056	217, 433
50	2.8624	211	1	1.1768	523
3	2.6611	300	1	1.1515	440, 604
16	2.5183	212	2	1.1491	008, 434
7	2.3007	004, 220	1	1.1390	700
7	2.2097	310, 104	10	1.1163	208, 442
11	2.1493	213, 311	1	1.0845	336, 702
3	2.0575	222, 114	1	1.0750	426, 218
16	1.9897	400, 204	1	1.0676	533, 435
2	1.8305	320, 214	1	1.0493	516, 525
14	1.7937	321, 313	1	1.0479	444, 228
14	1.7378	410, 304	1	0.9989	630, 606
9	1.7104	322, 411	1	0.9974	408
12	1.6261	224, 412	1	0.9947	800
5	1.5946	500, 314	1	0.9269	550
3	1.5730	215, 702	1	0.9209	00.10
2	1.5315	006, 330	2	0.9158	640, 428
8	1.5136	404, 413	1	0.9011	522
10	1.4505	116, 332	2	0.8936	545, 900
9	1.4320	422, 206	1	0.8542	22.10

Cu $K\alpha_1$, radiation. λ = 1.54050.

TABLE 4. CELL DIMENSIONS OF BERYL

	a Å	*c* Å		*a* Å	*c* Å
609. Aquamarine	9.2121*	9.1853*	Huttenlocher (1954)	9.22	9.18
522. Yellow	9.2006*	9.1868*	Sosedko (1957)	9.221	9.202
551. Green	9.2545*	9.1892*	Sosedko (1957)	9.221	9.228
			Sosedko (1957)	9.219	9.246
Bragg (1926)	9.23	9.19	N.B.S. (1960)	9.215	9.192
Schiebold (1935)	9.235	9.203	Schaller (1962)	9.30	9.20
Schiebold (1935)	9.415	9.226	Grubb (1964)	9.15	9.21
Schiebold (1935)	9.231	9.188	Grubb (1964)	9.19	9.17
Norrish (1950)	9.188	9.189	Grubb (1964)	9.20	9.21

*This study ±0.001 Å.

TABLE 5. MEASURED AND CALCULATED DENSITIES

	S.G. measured	S.G. calc.	diff.		S.G. measured	S.G. calc	diff.
609 Aquamarine	2.715	2.686	0.029	Sosedko (1957)	2.72	2.62	0.10
522 Yellow	2.722	2.681	0.041	Sosedko (1957)	2.75	2.63	0.12
551 Green	2.791	2.739	0.052	Sosedko (1957)	2.78	2.73	0.05
Norrish (1950)	2.73	2.64	0.09	Schaller (1962)	2.92	2.84	0.08

MODIFIED SOSEDKO VALUES

	a Å	*c* Å	S.G. meas.	S.G. calc.	Difference
Sample 1	9.2370	9.2048	2.72	2.66	0.06
Sample 2	9.2294	9.2322	2.75	2.67	0.07
Sample 3	9.2353	9.2460	2.78	2.79	0.01

Firstly, the measured density could be inaccurate but the method used (silica glass pycnometer) gives a precision of ±0.001. Secondly, the chemical analysis could be inaccurate but the change of mass required to raise the calculated density to the measured value, assuming the volume to be correct, is outside the limits of experimental error, e.g. for D.R. 522 the change of mass required would be equivalent to +2.40 per cent Fe_2O_3 the heaviest oxide, +3.76 per cent Al_2O_3 or +6.38 per cent SiO_2. Thirdly, the cell dimensions could be inaccurate but the change required is too large for this to be a decisive factor. In D.R. 522 assuming c to be correct, a would have to be changed from 9.200 Å to 9.121 Å, a change of 0.079 Å, whereas the method gives an accuracy of at least +0.01 Å.

The reason for this discrepancy is, at present, unknown. Other authors have found this same discrepancy (see Table 5). In most cases the difference obtained by previous investigations is higher than those obtained in this study. This may be due, in part, to less accurate determination of unit cell parameters, e.g. if the technique used to determine cell parameters in this study is applied to Sosedko's (1957) data, then the difference in densities is greatly reduced (see Table 5). Clearly a superior value of a and c has been obtained and it is suggested that the values obtained for the cell parameters of beryl should only be accepted when the difference between measured and calculated density is less than 0.05.

CRYSTAL CHEMISTRY

A brief review of the two main characteristics of the crystal structure of beryl is given so that the problems of crystal chemistry can be appreciated.

(1) In the planes perpendicular to the c axis the structures consist of hexagonal rings of six SiO_4 tetrahedra which envelop a channel that is continuous down the length of the structure parallel to c. According to Bragg (1926) no atom is nearer than 2.55 Å to the centres of these channels which form hexad axes.

(2) In any plane parallel with the c axis, the silicon and shared oxygens lie within the same planes which are repeated at intervals of $c/2$. In between these planes is a single plane of cations containing Al and Be atoms, each Al being co-ordinated with an octahedral group of six oxygen atoms and each Be atom surrounded by four oxygen atoms in a distorted tetrahedron.

POSITION OF ALKALIS

The formulae for the three beryls of Table 2 are given in Table 6. These formulae are calculated on the basis of 18 oxygen atoms per formula unit.

TABLE 6. FORMULAE OF BERYL (THIS STUDY)

609	$(Be_{2.39}Si_{.11}Al_{.11}Fe_{.14})_{2.75}Al_{2.00}Si_{6.00}O_{18}Na_{.01}$
522	$(Be_{2.77}Al_{.12}Fe_{.05})_{2.94}Al_{2.00}(Si_{5.86}Al_{.14})_{6.00}O_{18}Na_{.04}K_{.01}$
551	$(Be_{2.27}Al_{.23}Fe_{.43})_{2.93}Al_{2.00}Si_{6.00}O_{18}Na_{.05}K_{.01}$

In two of the three cases the Si tetrahedral positions are completely filled with Si, but in D.R. 522 some Al may enter these sites. The 6 co-ordinated Al positions are in all cases completely filled with Al. The situation regarding Be is noteworthy as in all cases there is insufficient Be to completely fill all the available sites. This fact has given rise to much speculation, especially among Russian authors, as to whether or not these positions can be filled with alkalis or if the alkalis are located only in the channels. In any case it is probable that Al^{+3} and perhaps Fe^{+3} could enter the 4 co-ordinated sites of Be^{+2}.

The most probable positions of the alkalis is in the channels of beryl where they can play a small part in the electrical neutrality of the system. Water occupies these channels as its exit upon heating occurs without any endothermic effects or change in unit cell dimensions. This indicates that the water in beryl is "zeolitic." However, Ginzburg (1955) has shown that the water is not expelled at temperatures less than 800° C. and Damon (1958) has shown that as little as 60 per cent of the gases are expelled by 1,200° C. and 100 per cent expulsion is not obtained at temperatures less than 1,475° C. At this temperature beryl melts incongruently into liquid and phenakite, Be_2SiO_4 (Van Valkenburg, 1957).

The high temperatures needed to expel water from the beryl structure may be explained in one of two ways:

(1) It plays a small part in the electrical neutrality of the system. The non-stoichiometric quantities of Be in beryl may give rise to a slight residual positive charge when higher valency cations, e.g. Al enter the (divalent) tetrahedral Be sites, and/or the presence of monovalent alkalis especially Li and Na in the channels may give rise to unbalanced charges.

(2) The presence of alkalis in the channels blocks the exit of water at low temperatures.

Bakakin (1962) suggests that the R_2O members occupy definite positions in the channels with the HOH molecules situated opposite the Si-O rings and alkalis opposite the Be-Al cation rings. The proposal is that since the Si atoms lie closest to the centre of the channels the alkalis will thus be midway between the Si-O rings due to mutual repulsion and consequently the HOH group has to be in the Si-O planes.

Perhaps the best guide to the positioning and possible substitutions is obtained by studying the variation of cell parameters. Since the Si-O ring is a strong unit any substitution within the structure will most probably cause an increase in the *c* direction i.e. the introduction of ions of larger radius than Be into the Be-Al plane can be more easily accommodated by interplanar expansion parallel to *c*. If on the other hand these atoms reside in the open channels, the lattice would be expanded in the direction of *a* by mutual repulsion of cations.

It is interesting to compare the work of Sosedko (1957) and Schaller (1962) on cesium beryl. Schaller showed that the *a* lattice parameter was expanded in a cesium rich beryl while Sosedko described an increase in the *c* parameter (Table 7).

TABLE 7. BERYL: THE EFFECT OF CESIUM ON CELL DIMENSIONS

	Cs_2O (%)	*c*Å	*a*Å	*c*/*a*
Sosedko				
Sample 1	0.27	9.202	9.221	.998
Sample 2	0.67	9.228	9.221	1.001
Sample 3	4.13	9.246	9.219	1.003
Schaller				
No. 54	6.32	9.20	9.30	.989

It appears that these are two fundamentally different types of beryl which could be explained by the location of the alkalis either in the structure proper or in the channels.

An examination of the lattice parameters of this study shows that the *c* parameter may be expanded slightly in relation to Al and Fe^{+3} in tetrahedral co-ordination. However, the *a* dimension is greatly expanded in relation to total R_2O components. This and other trends are shown in Figure 3, and it appears that a threshold value exists at about 2.5 mol per cent R_2O when any further introduction expands the lattice in the suggested manner.

The actual nature of the substitution of alkalis in the beryl structure has been debated by various authors. It is most probable that substitution takes place for most part, within the Be-Al cationic layer. Folinsbee (1941) suggests the nature of substitution is: 3 $\text{alkalis}^{+1} + 1\ Al^{+3} = 3\ Be^{+2}$. Deer (1962) modified this into: 2 $\text{alkalis}^{+1} = 1\ Be^{+2}$. Another relationship may be suggested: 1 $\text{alkali}^{+1} + 1\ (Al, Fe)^{+3} = 2\ Be^{+2}$ whereby the trivalent ions enter the beryllium sites while the alkalis may either reside in the open channels or enter the structure proper.

CONCLUSIONS

It is possible to predict the theoretical existance of at least two distinct types of beryl. These are determined for the most part by R_2O components which may occupy either the open channels or the tetrahedrally

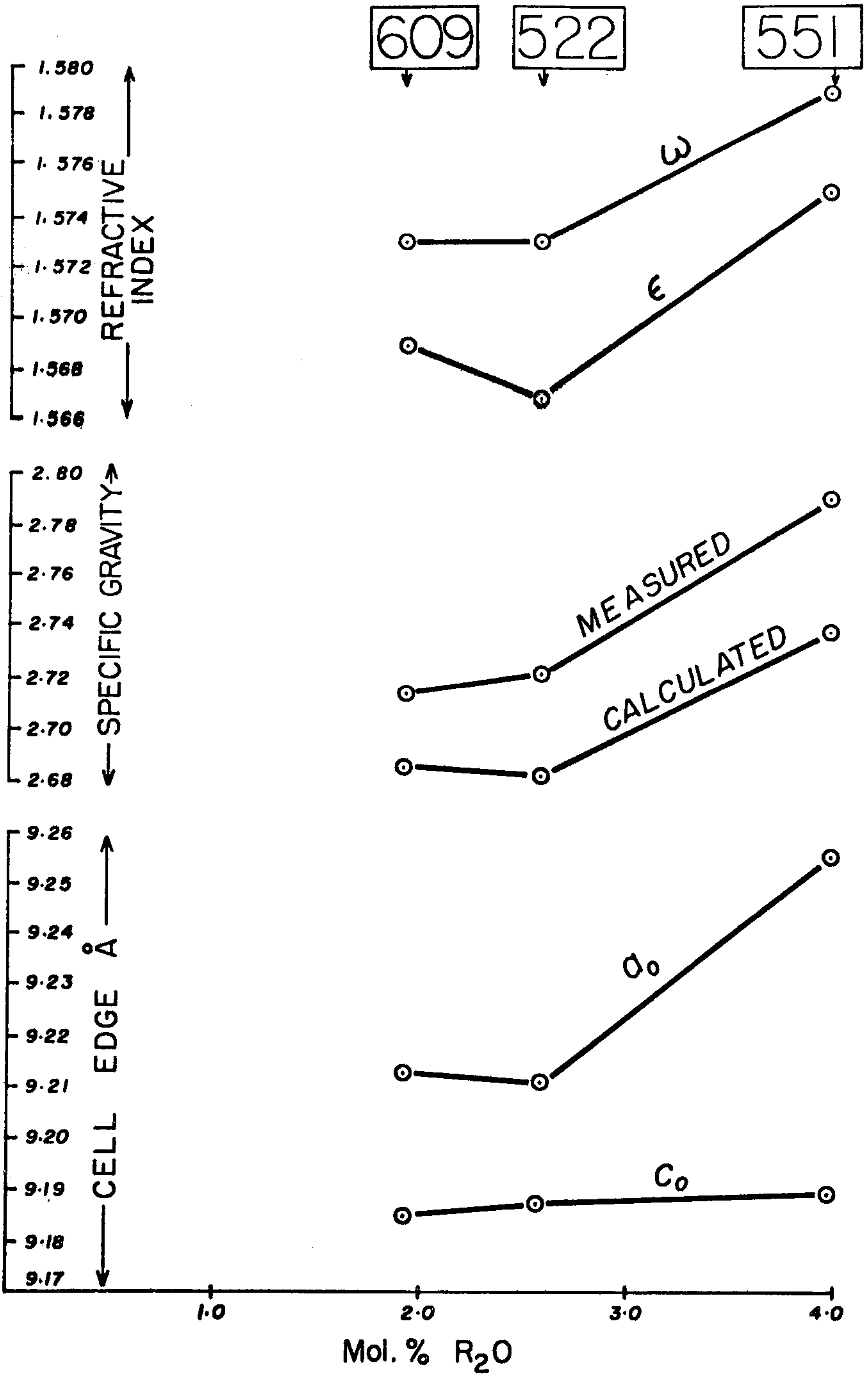

FIG. 3. The effect of increasing R_2O content on the physical properties of beryl.

co-ordinated beryllium structural positions. The different types of beryl can be detected experimentally by studying the departure of lattice parameters *a* and *c* from a dimension of approximately 9.19 Å.

This present experimental study and a literature survey indicates that two and perhaps three distinct classes of beryl probably exist.

These are as follows:

(1) '*C*' type beryl where substitution proper occurs and since this is generally by cations of larger ionic radii an expansion of the lattice occurs in the direction of *c*.

(2) '*A*' type beryl where R_2O types and perhaps higher valence cations reside in the open channels. Once a (possible) threshold value of about 2.5 mol. per cent R_2O has been exceeded then the lattice expands in the direction of *a*.

(3) '*A*-*C*' type beryls could exist and these would involve an expansion in both directions.

The non-recognition of these fundamental types of beryl is the main reason for the confusion and debate in the geological literature on beryl to date. These different types of beryl can be explained in terms of, firstly, supply and demand of component elements, and secondly, varying physico-chemical conditions at the time of crystallization.

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