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**The interdependence of the chemical compositions and the
physical properties of non-pegmatite beryl from the
Snake Range of eastern Nevada**

by

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ABSTRACT

Chemical and physical properties are given for five genetically related samples of non-pegmatite beryl from the Snake Range of eastern Nevada. Two of the five samples are homogeneous, and a third non-homogeneous sample was split into three magnetic fractions. Content of Fe_2O_3 ranges from 0.86 to 2.57 wt. percent, FeO ranges from 0.09 to 0.87, MgO ranges from 0.23 to 2.19, and Na_2O ranges from 0.44 to 2.13. Minor amounts of K_2O , Li_2O , and Cs_2O are present. The presence of these elements results in systematic variation of the unit cell parameters, density, refractive indices, color, and magnetic susceptibility of the beryl.

INTRODUCTION

Beryl occurs about 50 miles southeast of Ely, Nev., in the Snake Range of eastern Nevada. It is hosted by quartz veins in Cambrian sedimentary rocks and by Jurassic aplites that transect granitoid rock. In the early 1950's beryllium-bearing rock was discovered in the Mount Wheeler tungsten mine on the west side of the Snake Range (fig. 1); the beryllium-bearing minerals were found to be phenakite, beryl, and bertrandite (Stager, 1960). Lee and Erd (1963) and Whitebread and Lee (1961) reported on other beryl occurrences in the Mount Wheeler area. Later, Lee and Van Loenen (1971) reported another beryl occurrence about 8.5 mi northeast of the Mount Wheeler mine.

Chemical and physical properties were determined for beryl from three of the localities that include two quartz veins and one aplite dike. Beryl from one of the quartz veins was found to be quite heterogeneous, in contrast to that from the other quartz vein and the aplite dike. The heterogeneous beryl is variably zoned and euhedral; it varies widely in chemical composition and physical properties. This variation occurs in beryl from a small sample of quartz vein material about the size of a hand specimen. No similar variation occurs in the beryl from the other quartz vein and the aplite dike. Three separates of the heterogeneous beryl were made on the basis of magnetic susceptibilities, and these and the two homogeneous beryl samples were analyzed for major and minor elements. The effects of these elements on the physical and X-ray properties of the beryls were determined. There have been many papers written on the effects of the composition of beryl on its physical properties (many are cited by Deer and others (1986)), but little has been written on magnetic properties of beryl. Data in Deer and others (1986) are, however, mostly for beryl from pegmatites. In this study the beryl is of a non-pegmatite origin. All five samples are genetically related and contain the same non-essential elements (Fe^{++} , Fe^{+++} , Na, and Mg) that vary widely in content.

GEOLOGIC SETTING

A thick sequence of folded Cambrian sedimentary strata is exposed in this area of the Snake Creek Range. The lowermost exposed sedimentary unit of this sequence is the Prospect Mountain Quartzite, which is overlain by about 450 ft of Pioche Shale. The contact between the two is

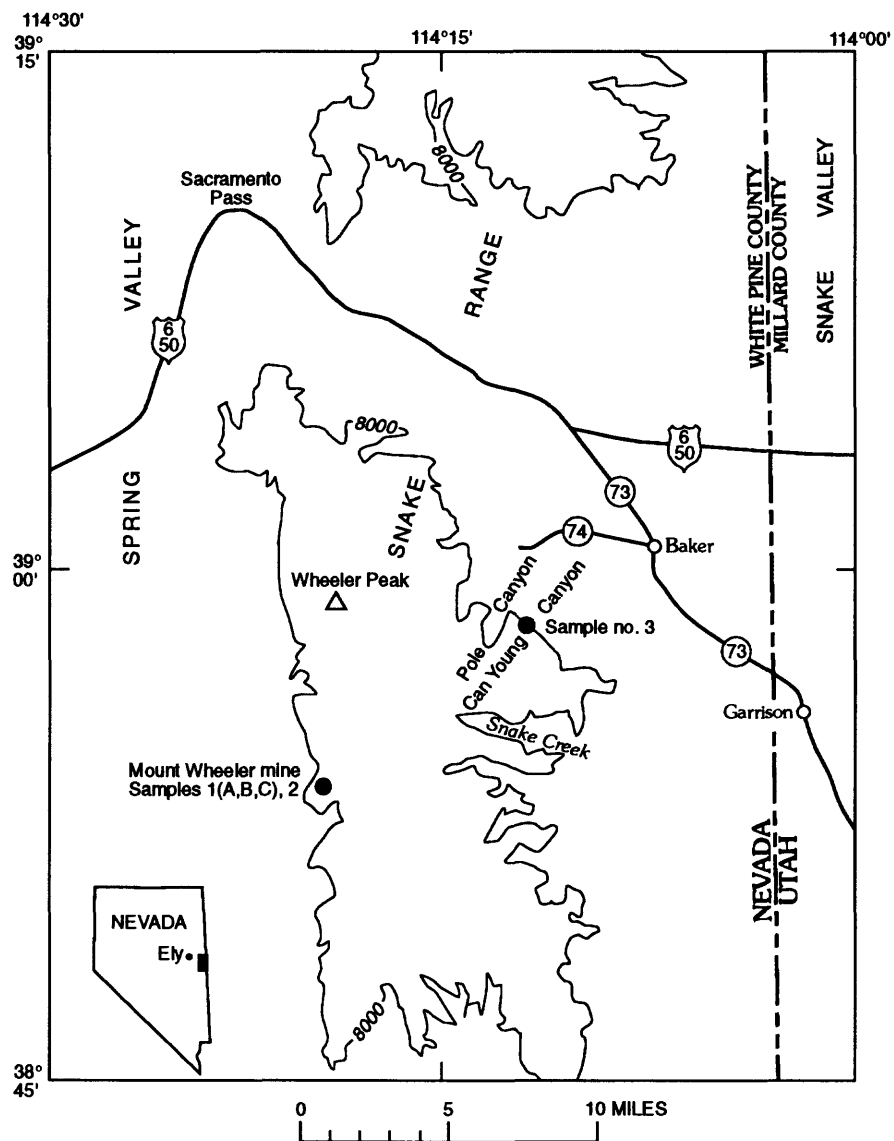


Figure 1. Index map showing location of the Mount Wheeler mine and the Pole Canyon-Can Young Canyon areas of beryllium mineralization.

considered to be at the top of the uppermost light-gray, resistant quartzite. From about 10 ft to as much as 65 ft above the contact is a medium-gray to dark-bluish-gray, thin- to thick-bedded limestone known locally as the Wheeler limestone (Whitebread and Lee, 1961). This limestone is known to be the primary host of the tungsten and beryllium deposits of the area (Stager, 1960). The Wheeler limestone averages about 20 ft thick. Conformably overlying the Pioche Shale is the Pole Canyon Limestone, which is a massive to thick-bedded limestone that is distinguished by its saccharoidal texture. All three formations are intruded by a Jurassic age granitoid body. Although the nearest outcrop of the intrusive is more than 3 mi to the north of the Mount Wheeler mine, the intrusive is thought to occur at depth beneath the mine. An increase in metamorphic grade in the Wheeler limestone in the headwall was noted by Stager (1960). Regionally, the intrusive body has distinct chemical and mineralogical differences that were primarily caused by assimilation of the host rocks, yielding a range of composition from granodiorite (within the Pole Canyon Limestone) to quartz monzonite (within Prospect Mountain Quartzite) (Lee and Van Loenen, 1971). Aplite dikes are common in the granitoid intrusive.

Quartz veins containing beryllium minerals are found within the fault zones in the Wheeler limestone and the upper part of the Prospect Mountain Quartzite. In the vicinity of the Mount Wheeler mine the veins are a few inches to as much as 5 ft wide (Stager, 1960). Beryl was also found in just one aplite dike about 8.5 mi northeast of the Mount Wheeler mine (Lee and Van Loenen, 1971, p. 41). The beryllium mineralization of the quartz veins and of the aplite dike probably are genetically related, with the source of the beryllium for both being the Jurassic intrusive (Whitebread and Lee, 1961; Lee and Van Loenen, 1971).

SAMPLE DESCRIPTIONS

Beryl sample 1 (separated into 1A, 1B, and 1C) was collected outside of, but near, the adit of the Mount Wheeler mine (fig. 1), where a fault-controlled quartz vein is exposed in the upper part of the Prospect Mountain Quartzite near its stratigraphic contact with the overlying Pioche Shale. The beryl is present in the quartz vein as small, less than 0.5 cm, very light blue clusters of euhedral crystals. Only beryl and quartz occur in this quartz vein.

Beryl sample 2 was collected in the Mount Wheeler mine about 1,200 m from the adit from a quartz vein in the Wheeler limestone (Lee and Erd, 1963) (fig. 1). The beryl is pale blue and occurs in 2- to 10-cm-wide veinlets within the quartz vein. Minerals associated with beryl in the veinlet are scheelite, pyrite, calcite, muscovite, fluorite, and phenakite. The phenakite was discussed by Lee and Erd (1963).

Beryl sample 3 is from an aplite dike in the granitoid rocks in the Can Young Canyon area, about 8.5 mi northeast of the Mount Wheeler mine (Lee and Van Loenen, 1971, p. 41). Aplite dikes are common in the granitoid rocks, but beryl is known to occur in only this particular one. The beryl occurs in veinlets up to 10 cm wide. No other ore minerals are present. The veinlets consist of pale-blue, subhedral to euhedral beryl crystals up to 1 cm long.

ANALYTICAL DATA AND PHYSICAL PROPERTIES

Beryl-rich rock samples, about fist size, from each of the three occurrences were crushed and ground to less than 120 mesh (125 microns). The samples were washed and material smaller than 40 microns was discarded. Beryl was then separated from quartz and other minerals by centrifuging in heavy liquids (bromoform diluted with acetone) that were slightly heavier than beryl and again in liquid slightly lighter than beryl. Beryl concentrates were more than 95 percent pure after the heavy liquid separation. The density of the beryl separates (table 1) was determined by measuring the specific gravity of the heavy liquids that held beryl in suspension.

Table 1.—*Physical properties of beryl from the Mount Wheeler, Nevada, area.*

Sample No.	1A	2	1B	1C	3
Non-essential elements, wt. percent	7.45	6.23	6.11	3.50	1.82
Indices of refraction					
ϵ (± 0.002)	1.589	1.584	1.582	1.574	1.570
ω (± 0.002)	1.595	1.592	1.588	1.582	1.576
δ	.006	.006	.006	.008	.006
Density					
Measured (± 0.005)	2.790	2.750	2.740	2.710	2.672
Cell parameters (angstroms Å)					
a (± 0.002)	9.256	9.251	9.250	9.232	9.224
c (± 0.002)	9.187	9.193	9.193	9.197	9.188
Vol. (± 0.2) Å ³	681.6	681.2	681.2	678.9	677.0
c/a	.9925	.9937	.9938	.9962	.9961
Magnetic susceptibility (e.m.u./g) $\times 10^6$					
(± 0.3)	5.8	2.1	2.4	.68	.72
Color					
	Light blue	Very pale blue	Light greenish gray	Yellowish gray	Bluish white
Munsel color codes	5B 7/6	5B 7/6	5GY B/1	5/Y B/1	5B 9/1

For further purification, the beryl-rich concentrates were then passed repeatedly through a Frantz magnetic separator at increasing magnetic field strength. It became evident at this stage of the purification that beryl of sample 1 from the quartz vein in the Prospect Mountain Quartzite varied considerably in magnetic properties. Some beryl in the sample was unaffected by the magnet, whereas other beryl had a relatively strong attraction to the magnet. Furthermore, a number of beryl splits could be made between the non-magnetic and the magnetic fractions by altering the magnetic field strength of the separator. Only three splits were selected, based on magnetic properties, for further analysis. These splits include the most magnetic (sample 1A), an intermediate (sample 1B), and the least or non-magnetic (sample 1C). The magnetic susceptibilities (table 1) were determined for each of the beryl splits with the Frantz isodynamic separator using the method described by McAndrew (1957). Corresponding changes of chemical composition and the physical properties of these three separates accompany the changing magnetic properties.

Beryl samples from the quartz vein in the Pioche Shale (sample 2) and from the aplite dike in granitoid rock (sample 3) were also purified by heavy liquids. The magnetic susceptibilities (table 1) of these two beryls are relatively constant; they could not be further fractionated by their magnetic properties.

All five beryl samples appeared to be pure except for a few very tiny inclusions of zircon, apatite, and muscovite. The purified beryl samples ranged from about 0.1 to 0.5 mm in size. The colors (table 1) were determined by comparing this size fraction to Munsell color charts.

Optical Properties

The indices of refraction were determined by the immersion method, by use of a spindle stage (Wilcox, 1959) and the focal masking technique (Wilcox, 1962). Several measurements were made for the ϵ and ω index of beryl from each of the five samples. Each sample contained beryl whose indices varied slightly. An average index, which represents a range of values, is given in table 1.

Samples from the first beryl locality have a wide range of refractive indices; the ω index varies systematically from 1.582 for separate 1C, the non-magnetic beryl, to a maximum of 1.600 for the magnetic phase separate 1A. The magnetic separate 1A is light blue. It has an average ω index of 1.595; pleochroism is colorless to pale blue; and zoning within individual crystals is quite pronounced. The index of refraction varies slightly from zone to zone. Separate 1C, the non-magnetic beryl, is yellowish gray and has an ω index of 1.582. It is also zoned, but the index of refraction does not vary as much between zones as with the magnetic separate 1A. The intermediate beryl separate 1B is light greenish gray. Its indices of refraction are about midway between separates 1A and 1C (table 1). Other magnetic splits of sample 1 were examined, and their refractive indices were found to vary according to their magnetic properties; that is, the more magnetic the sample the higher the indices of refraction.

Sample 2 is a homogeneous very pale blue beryl with optical and physical properties similar to separate 1B. Sample 2 is zoned, but the optical properties vary only slightly between zones.

Sample 3 is a homogeneous bluish-white beryl with an ω index of refraction of 1.576, the lowest of the 5 samples. Zoning is absent.

Fluid inclusions are common in all of the samples; some beryl crystals or fragments were estimated to contain as much as 0.5 percent inclusions that contain as much as 30 percent fluid. Solid inclusions include zircon, apatite, and muscovite. These mineral inclusions are usually aligned parallel to the long dimension (*c*-axis) of beryl.

Unit-Cell Measurements

The unit cell parameters (table 1) for the five beryl samples were calculated by least-squares refinement of the X-ray powder data using a computer program developed by Evans and others, (1963). Fluorite ($a = 5.4540\text{\AA}$) was added to the samples for use as an internal standard. Refinements of the d-spacings, using both fixed and non-fixed indexing of the X-ray powder data, were made to insure the accuracy of the cell parameters obtained. Radcliffe and Bailey (1972) suggested that, due to the similarities of the a and c parameters for beryl, X-ray reflections could be mis-indexed, thus generating ambiguous cell parameters.

Chemical Analysis

Several analytical methods were employed in determining the chemical composition of the beryl samples (tables 2 and 3). The analyses, by personnel in the U.S. Geological Survey laboratories, were as follows: SiO_2 X-ray fluorescence analyses by M. Solt; K_2O , Li_2O , and Cs_2O quantitative spectrographic analyses by A. Sutton; FeO volumetric analyses by G. Burrow; Al_2O_3 , Fe_2O_3 , MgO , Na_2O , and BeO atomic absorption analyses by W. Mountjoy; TiO_2 , CaO , and trace elements (table 3) semiquantitative 6-step spectrographic analyses by H. Neiman; and total H_2O analyses by the Penfield method by E. Brandt.

Structural formulas (table 2) were calculated on the basis of 36 oxygens (the theoretical unit cell contents of beryl is $2\text{Be}_3\text{Al}_2(\text{Si}_6\text{O}_{18})$), using a computer program described by Jackson and others (1967). The formulas were calculated on a water-free basis.

DISCUSSION

The study of these beryl samples, particularly the separates from sample 1, allows the changes in chemistry and the effects of the changes to be assessed for several varieties of beryl that formed together in a hydrothermal environment. Beryl from the quartz vein (sample 1) must have formed from hydrothermal fluids that had wide fluctuations in their compositions. The other two genetically related beryl samples, containing the same oxides but in varying amounts, complement as well as extend the range of composition found in the separates of sample 1.

Element substitutions are common in the mineral beryl, and many of the substitutions and the effects of the substitutions on the physical properties of beryl are widely discussed in the literature. Common substitutions are in the octahedral Al sites or in the Be tetrahedral sites, while alkalis enter open channel sites in the honeycomb-like structure of beryl. The channel sites can also be occupied by water or iron (Deer and others, 1986). It is not the scope of this paper to speculate on individual element substitutions that take place but only to show how the physical properties of beryl are affected by the presence of varying amounts of non-essential elements. These non-essential elements include the oxides of all elements listed in table 2 except H_2O and those elements that are essential in beryl [$\text{Be}_3\text{Al}_2(\text{Si}_6\text{O}_{18})$]. The weight percent of the oxides of the non-essential elements ranges from 1.82 to 7.45 percent with the bulk of this weight due to Fe^{++} , Fe^{+++} , Na, and Mg.

The presence of the non-essential elements in the five beryl samples and their effect on the cell parameters (particularly a), indices of refraction, density, and magnetic susceptibilities are shown on figure 2.

The most significant difference in the cell parameters of the beryl is in the length of the a axis. Increasing amounts of Fe, Na, and Mg correspond linearly with an increase in the a dimension, but there is little change in the c dimension. The a parameter ranges from 9.256\AA for separate 1A to 9.224\AA for sample 3, and, as shown on figure 2A, this increase of 0.032\AA is in direct

Table 2.—*Chemical analyses of beryl from the Mount Wheeler, Nevada, area.*

[In weight percent; --, indicates oxide not found]

Sample No.	1A	2	1B	1C	3
SiO ₂	64.0	64.0	65.0	67.0	67.0
TiO ₂* .....	.05	.12	.02	.03	tr.
Al ₂ O ₃	13.7	13.8	14.2	14.2	17.0
Fe ₂ O ₃ *	2.57	1.36	1.77	.90	.86
FeO* .....	.87	.22	.60	--	.09
BeO	12.96	13.18	12.49	12.38	13.24
MgO*	1.69	2.19	1.53	.99	.23
CaO*	--	.07	--	.01	.03
Na ₂ O*	2.13	2.00	1.89	1.31	.44
K ₂ O* .....	.03	.10	.15	.10	.13
Li ₂ O* .....	.04	.08	.09	.13	.02
Cs ₂ O* .....	.07	.09	.06	.03	.02
H ₂ O total	2.64	2.77	2.65	2.60	1.49
Total	100.75	99.98	100.45	99.68	100.55
Wt. percent of non-essential elements*	7.45	6.23	6.11	3.50	1.82
Number of atoms on the basis of 36 oxygen; excluding H ₂ O					
Si	12.015	12.037	12.185	12.498	12.193
Ti .....	.007	.017	.003	.004	--
Al	3.031	3.059	3.137	3.122	3.646
Fe ³⁺363	.193	.250	.126	.118
Be	5.845	5.955	5.625	5.548	5.789
Mg .....	.473	.614	.428	.275	.062
Li .....	.030	.060	.068	.098	.017
Fe ²⁺137	.035	.094	--	.014
Na .....	.775	.729	.687	.474	.155
Ca	--	.014	--	.002	.007
K .....	.008	.024	.036	.024	.031
Cs .....	.006	.007	.005	.002	.002
ΣMe	10.675	10.707	10.333	9.675	9.841
Sum of metal ions except Si					

Table 3.—*Semiquantitative spectrographic analyses of minor elements in beryls from the Mount Wheeler, Nevada, area.*

[In parts per million. 0, not found; L, detected but below limit of determination]

Sample No.	1A	2	1B	1C	3
B	0	0	0	0	L
Ba	7	20	30	20	100
Cr	1	2	3	5	L
Cu	15	5	20	15	10
Ga	0	0	0	0	20
Mn	500	150	150	50	50
Rb	50	100	30	30	20
Sc	30	30	150	10	0
Sr	0	0	0	5	0
V	10	15	15	15	7
Zr	0	10	0	15	0

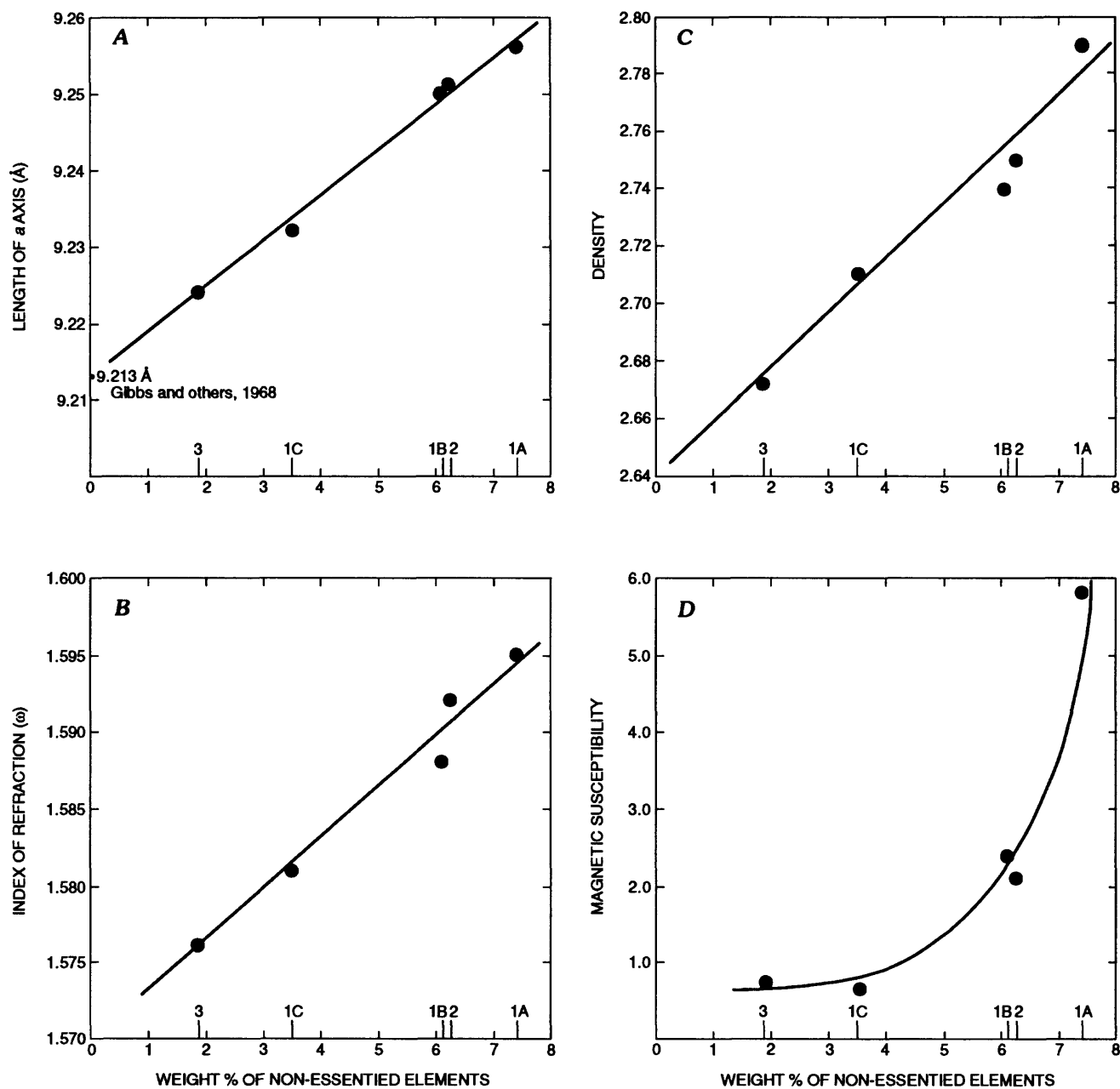


Figure 2. Plots showing the effects of the sum of the non-essential elements on the length of the a crystallographic axis (A), index of refraction (B), density (C), and magnetic susceptibilities (D). The five beryls are plotted along the x-axis according to their respective contents of the non-essential elements as shown in table 2. Data shown along the x-axis are the same in all four plots.

relationship to the presence of non-essential elements. The length of the a axis for pure beryl, as discerned from the plot on figure 2A, would be near 9.214Å. Gibbs and others (1968) determined the a parameter for synthetic hydrous beryl (pure) to be 9.213Å (fig. 2), which is in very close agreement with the plot. Schaller and others (1962) reported a beryl from Arizona that contained 15.6 percent non-essential elements, and its a parameter was determined to be 9.30Å. Although not shown on figure 2A, if the plot were extended to 15.6 percent non-essential elements, the Arizona beryl would fall very near the linear plot.

The indices of refraction (fig. 2B) of the beryl samples also show a positive correlation with the presence of the non-essential elements. Alkalis and iron are known to increase the indices of refraction in beryl (Deer and others, 1986), and this correlation is clearly shown in these five related beryl samples. Extrapolating from figure 2B, the intersection of the index line with the ordinate shows pure beryl to have an ω index of 1.570. Gibbs and others (1968) did not give the indices for their pure synthetic hydrous beryl.

The density of the beryl samples also has a positive correlation with the non-essential elements; increasing amounts of the non-essential elements increase the density. The density plot intersects the ordinate at 2.64, the location on the abscissa for pure beryl. The density of the very impure Arizona beryl (Schaller and others, 1962) is 2.918, and it plots on an extension of the measured density plot on figure 2C.

Beryl is known to have a wide range of magnetic susceptibilities (Sam Rosenblum, U.S. Geological Survey, written commun., 1991). Magnetic susceptibility, shown on figure 2D, shows a positive relationship to the proportion of non-essential elements in this beryl, although it is not a straight line relationship as seen in the other plots. The higher the concentration of non-essential elements the stronger the attraction in the magnetic field. The non-linear plot on figure 2D may be caused by several different factors such as grain size and shape and inclusions; however, the major response must be due to the presence of the ferric ion. A plot of the ferric ion content and mass susceptibilities gives a similar non-linear relationship.

SUMMARY

The purpose of this report is to present chemical and physical data and to relate the collective effects of increasing amounts of all the non-essential elements (ranging from 1.82 to 7.45 percent) to the physical properties of the five non-pegmatite beryls. The proportions of these elements in this suite of genetically related beryls clearly show positive correlation to the unit cell size, indices of refraction, density, and mass magnetic susceptibilities. The major elements contributing to these changes in physical properties are Fe, Na, and Mg. Given the high quality of the chemical determinations and measurements of the physical properties, the linear nature of the plots on figure 2 must be more than a mere coincidence. Pure beryl probably never occurs naturally; however, theoretical values for some of the physical properties of beryl that contains little or no non-essential elements may be extrapolated from the linear plots on figure 2. The extrapolations indicate that, for pure beryl, the a axis of the unit cell is 9.213Å, the ω index of refraction is 1.570, the density is 2.64, and the mass magnetic-susceptibility will be less than 1 (e.m.u./g) $\times 10^6$.

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