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DIFFERENCES IN THE MINOR ELEMENT COMPOSITION OF BERYL IN VARIOUS ENVIRONMENTS[1]

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ABSTRACT

The range in abundance of certain elements is different in beryls from different environments, and these differences are so large that the environment of most beryls can be determined from their composition. 33 minor elements were found in beryl by spectrographic analysis, but only 13 made up as much as 0.1 per cent of any beryl. Beryl from pegmatite contains relatively small amounts of Fe, Mg, Sc, Ti and V, and may contain relatively large amounts of Cs, Rb and Li. Beryl from wallrock adjacent to pegmatite generally has more Ti, Sc, V, Cr, Mg, Fe and Ni than beryl from pegmatite, and less Rb. Beryl comes from several types of veins and hence the amounts of the various elements may vary widely. Generally, however, beryl from veins contains only small amounts of Cs, Rb and Li. Some of the greater amounts of Mg, V, K, Fe, Cr and Ti occur in beryl from veins. Beryl from granite generally contains only minor amounts of Cs, Li, Rb, Cr, Ni, V and Zn, and large amounts of Fe. Beryl from rhyolite contains only small amounts of Li, Na, Mg and Sc, but has the largest amount of all the beryls analyzed of Rb, Fe, Ti, Zn, Zr, Mn, As, B, Ga, Nb, Sn, Y and Yb.

INTRODUCTION

The physical properties of beryl, especially its indices of refraction and specific gravity, have been correlated with its chemical composition (Winchell, 1947; Dorfman, 1952; Norton *et al.* 1958; Schaller *et al.*, 1962). These data have been valuable in the study of individual pegmatites, where the indices of refraction have been used to determine the BeO content of the beryl (Staatz and Trites, 1955; Sheridan, 1955; Thurston, 1955; Staatz, *et al.* 1963). The physical properties and the alkali metal and BeO content of beryl commonly vary from zone to zone in the same pegmatite (Page *et al.*, 1953; Staatz, *et al.*, 1963).

Beryl has been found in many pegmatites throughout the United States, and most of that described comes from this environment. Beryl, however, also occurs in the wallrock adjacent to pegmatite, in granite, in veins, and in rhyolite. Prior to the end of World War II, beryl had rarely been described in these other environments, although in the United States it had been reported from rhyolite in the Thomas Range, Utah (Hillebrand, 1905), and in veins on Mt. Antero, Colorado (Landes, 1935), at Boriana, Arizona (Hobbs, 1944), and at Irish Creek, Virginia (Koschmann *et al.*, 1942).

The generally accepted chemical formula for beryl is $3BeO \cdot Al_2O_3 \cdot 6SiO_2$. It is well known, however, that beryl varies in chemical composi-

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tion and that the alkali metal oxides Cs_2O, Li_2O, Na_2O, K_2O, and Rb_2O may total as much as 8 per cent of the mineral (Folinsbee, 1941; Winchell, 1947). As Be^{2+}, Si^{4+} and Al^{3+} have ionic radii of 0.34, 0.39 and 0.57 Å, respectively, and Na^+, K^+, Rb^+ and Cs^+ have ionic radii of 0.98, 1.33, 1.49, and 1.65 Å (Mason, 1952), respectively, it is doubtful that any of these alkali metal ions can substitute for beryllium, aluminum or silicon. Lithium, which has an atomic radius of 0.78 Å, may substitute for aluminum. A study of the atomic structure of beryl suggests the probable position of the other elements. This structure consists of a series of hexagonal rings formed by six silicon-oxygen tetrahedra (Bragg and West, 1926). These rings are connected by tetrahedrally surrounded beryllium and octahedrally surrounded aluminum and have open channels down the center of the rings. It is probable that most of the alkalies in beryl are located in these channels (Folinsbee, 1941). As Cs, which has the very large ionic radius of 1.65 Å, is evidently found in these channels, there is the possibility that a large number of other elements with atomic radii intermediate between Cs and Al may be similarly situated. The presence of other elements in the beryl structure is also dependent, however, on the charge requirements and the availability of the element.

For this study beryl was analyzed spectrographically and 68 elements were looked for. Thirty-three elements besides beryllium, aluminum, and silicon were found above the limit of detection. Of these 33, however, only 13 made up as much as 0.1 per cent of any beryl.

Beryls in granitic pegmatites occur in an environment rich in alkali metals and poor in iron, magnesium, titanium, nickel, chromium, and vanadium. Beryls from veins, granites, wallrock adjacent to pegmatites, and rhyolite occur in environments that are generally poorer in the alkali metals and richer in other elements. Beryl was studied from all five environments to see if the minor element content varied in the different environments.

Type of Material

A total of 47 beryl specimens was used in this study—19 came from pegmatites, 3 from country rock adjacent to pegmatites, 15 from veins, 9 from granite and 1 from a rhyolite. In two pegmatites one specimen of beryl came from the wall zone and one from the core and show the type of variation one might expect within a single pegmatite. Beryls collected from the granite not only include segregations of beryl within the granite but also beryl in aplite dikes within the granite and in veinlets made up almost entirely of beryl within the granite. In Table 1, beryls used in this study are grouped according to the environment, and the locality of each specimen is shown. Double numbers occur where two spectrographic

TABLE 1. LOCATIONS OF BERYLS USED IN THIS STUDY

Environment	Sample number or numbers	Locality	Remarks
Pegmatite	9	Helen Beryl pegmatite, Custer County, S. Dak.	From wall zone.
Pegmatite	5, B43	Helen Beryl pegmatite, Custer County, S. Dak.	From Core.
Pegmatite	8, B46	Bull Moose pegmatite, Custer County, S. Dak.	From wall zone.
Pegmatite	7	Ross pegmatite, Custer County, S. Dak.	From intermediate zone.
Pegmatite	B34	Scott rose quartz pegmatite, Custer County, S. Dak.	From core.
Pegmatite	B54	Dan Patch pegmatite, Pennington County, S. Dak.	
Pegmatite	B5	Pegmatite from Avon district, Idaho	From wall zone.
Pegmatite	B7	Pegmatite on Errington-Theil property, Ruby Range, Nev.	From unzoned pegmatite.
Pegmatite	B4	Pegmatite in Crystal Mountain district, Colo.	From small pod.
Pegmatite	B55	Apache pegmatite, Petaca district, N. Mex.	
Pegmatite	B40	Harding pegmatite, near Dixon, N. Mex.	From wall zone.
Pegmatite	B41	Harding pegmatite, near Dixon, N. Mex.	From core.
Pegmatite	B21, B48	Millard-Chandler pegmatite, Rockingham County, N. H.	Green beryl from core.
Pegmatite	B20, B47	Millard-Chandler pegmatite, Rockingham County, N. H.	Pink beryl from same crystals as B48.
Pegmatite	B1	Edwards pegmatite, Spruce Pine, N. C.	From intermediate zone.
Pegmatite	B2	Edwards pegmatite, Spruce Pine, N. C.	From replacement unit.
Pegmatite	B3	Ray pegmatite, Spruce Pine, B. C.	From unzoned pegmatite.
Pegmatite	B52	Patterson pegmatite, Shelby district, N. C.	
Pegmatite	B53	Pegmatite in Lincolnton quadrangle, N. C.	
Country rock adjacent to pegmatite	B6, B50	Avon district, Idaho	Near pegmatite yielding B5.
Country rock adjacent to pegmatite	B22, B49	Near Harding pegmatite, near Dixon, N. Mex.	Near pegmatite yielding B40.
Country rock adjacent to pegmatite	6, B42	Sunnyside mine, Petaca district, N. Mex.	
Vein	B14	Near Bagdad, Arix.	
Vein	B39	Boomer mine, Lake George, Colo.	
Vein	B18	Elfrida, Ariz.	Vug in vein.
Vein	B19	Elfrida, Ariz.	Beryl-muscovite mass in same vein as sample B19
Vein	B35	California mine, Mt. Antero, Colo.	
Vein	B37	Mohawk tin mine, near Hill City, S. Dak.	
Vein	B38	Emerald mine, Chivor district, Colombia.	
Vein	B13	Black Pearl wolframite mine, Bagdad, Ariz.	
Vein	B9	Windy claims, Ariz.	
Vein	B10	Scheelite mine, Oreana, Nev.	
Vein	B17	Lakeview Scheelite mine, Nev.	
Vein	B36	Lakeview Scheelite mine, Nev.	Margin of vein.
Vein	B32	Lakeview Scheelite mine, Nev.	Center of vein.
Vein	B8, B45	Wolframite vein, Victorio Mts., N. Mex.	
Vein	B33	Tungsten vein, El Karit, Morocco	
Granite	B16, B44	Near Bagdad, Ariz.	
Granite	4	Agua Verde, Pima County, Ariz.	Vein in granite.
Granite	2	Lone Pine, Calif.	Vein in granite
Granite	3	Sheeprock Mts., Tooele County, Utah.	
Granite	B12	Sheeprock Mts., Tooele County, Utah.	
Granite	B11	Sheeprock Mts., Tooele County, Utah.	Aplite dike in granite.
Granite	1	Mt. Antero, Colo.	
Granite	B30	Mt. Antero, Colo.	Aplite dike in granite.
Granite	B31	Mt. Antero, Colo.	
Rhyolite	MHS-84-55	Thomas Range, Juab County, Utah.	

analyses were made on different samples of the same specimen to check the precision of the method.

Coarse-grained beryl was separated by handpicking. Finer grained beryl was crushed and the heavy fraction from a bromoform separation was further purified by passing it through a Frantz Isodynamic Separator. The beryl was then handpicked under a binocular microscope from the beryl-rich nonmagnetic fraction. These samples contained no readily visible impurities. However, two beryls from veins in carbonate rocks (Lakeview, Nevada, and Victorio Mountains, New Mexico) had anomalously high values for Ca and one of these had anomalously high Mg. These samples were reseparated and, with all the samples analyzed in this lot (B30 to B55), were boiled in dilute HCl to remove all carbonate minerals.

Spectrographic Analyses

Both semiquantitative and quantitative spectrographic methods were used (Table 2). Results obtained by quantitative methods are italicized in Table 2. Barnett made all the spectrographic analyses except for samples MHS-84-55 and 1–9 which were done by J. C. Hamilton.

To check the analytical results both semiquantitative and quantitative methods were used on some specimens, and for nine specimens (5, 8, B20, B21, B16, B8, 6, B6 and B22) a second sample from the same material was given a new number (B43, B46, B47, B48, B44, B45, B42, B50 and B49) and resubmitted. In most specimens the difference in the analyses of the two samples is within the analytical limit of error, indicating that the method of sampling was quite precise. Semiquantitative results are grouped between the limiting values 1.0, 0.464, 0.0215, 0.01 per cent, etc., and are reported as 0.7, 0.3, 0.15 per cent, etc., which are the approximate mid-points of these groups. Except for Ca and Cr, the agreement between semiquantitative and quantitative results are good. Excluding these two elements, 62 per cent of the values obtained by the two different methods fall within the same group (Meyers *et al.*, 1961). For Ca and Cr there is a definite bias, with the quantitative results being higher by about a factor of two.

Elements that were not looked for are represented by a dash in Table 2. An element that was looked for but not found is listed as "$<$" followed by a value representing the approximate limit of detection. This minimum limit is not only different for various elements, but can vary for the same element. For example, the presence of moderate amounts of Na will in part mask the presence of Zn and makes its limit higher than if there are lesser amounts of Na. Likewise, the detection limits for the alkalies are

TABLE 2. SPECTROSCOPIC ANALYSES[1] OF THE MINOR ELEMENTS IN BERYL FROM DIFFERENT ENVIRONMENTS

(Analysts: P. R. Barnett and J. C. Hamilton)

Specimen No.	Environment	Cs	Rb	Na	K	Li	Ca	Fe	Mg	Ti	Cr	V	Mn	Sc	Zn	Ba	Cu	Ga
9	Pegmatite	—	—	0.3	—	—	<0.02	0.15	0.15	0.0007	<0.0001	<0.0005	0.003	<0.0005	0.015	0.003	0.0007	0.0015
9	Pegmatite	*0.08*	*<0.09*	—	*0.11*	*0.11*	—	—	—	—	—	—	—	—	—	—	—	—
5	Pegmatite	—	—	1.5	—	—	<.02	.15	.03	.003	<.0001	<.0005	.003	<.0005	.015	<.00015	.0007	.0007
5	Pegmatite	*1.0*	*.3*	—	*.23*	*.5*	—	—	—	—	—	—	—	—	—	—	—	—
B43[2]	Pegmatite	—	—	.7	<.7	.7	<.005	.15	.03	.0007	0.00015	<.0005	.0015	<.0005	.015	.00015	.0003	.0007
B43[2]	Pegmatite	*1.0*	*.3*	*1.0*	*.3*	*.6*	*.008*	*.24*	*.03*	—	*.0004*	*<0.0005*	*.002*	*0.002*	—	—	—	—
8	Pegmatite	—	—	.3	—	—	.03	.15	.015	.0007	<.0001	<.0005	.0015	<.0005	<.015	<.00015	.0007	.0003
8	Pegmatite	*.2*	*<.09*	—	*.14*	*.14*	—	—	—	—	—	—	—	—	—	—	—	—
B46[3]	Pegmatite	—	—	.3	<.7	.15	.03	.15	.015	.0003	<.0001	<.0005	.0015	.007	.015	.0003	.0007	.0003
B46[3]	Pegmatite	*.2*	*<.02*	*.4*	*.2*	*.2*	*.07*	*.26*	*.01*	—	*<.0002*	*.0005*	*.002*	*<.0005*	—	—	—	—
7	Pegmatite	—	—	.3	—	—	<.02	.15	.003	.0007	<.0001	<.0005	.003	<.0005	.03	<.00015	.0007	.0003
7	Pegmatite	*.2*	*<.09*	—	*.06*	*.11*	—	—	—	—	—	—	—	—	—	—	—	—
B34	Pegmatite	—	—	.7	<.7	.3	<.005	.15	.007	<.00015	.00015	<.0005	.0007	.0003	.015	.00015	.0003	.0003
B34	Pegmatite	*.4*	*.06*	*.9*	*.1*	*.3*	*.01*	*.29*	*.01*	—	*.0005*	*<.0005*	*.001*	*<.0005*	—	—	—	—
B54	Pegmatite	—	—	.7	<.7	.3	.15	.15	.015	.00015	<.0001	<.0005	.007	<.0005	.03	.00015	.0003	.0007
B54	Pegmatite	*.5*	*.2*	*.7*	*.3*	*.3*	*.24*	*.22*	*.01*	—	*.0002*	*<.0005*	*.006*	*<.0005*	—	—	—	—
B5	Pegmatite	*0.2*	*<0.04*	0.3	*0.2*	*0.05*	0.015	0.15	0.07	<0.00015	<0.0001	<0.0005	0.003	<0.0005	0.015	0.0007	0.007	0.00015
B7	Pegmatite	*.1*	*.04*	.3	*.4*	*.09*	.007	.3	.03	<.00015	<.0001	<.0005	.007	<.0005	.03	.0003	.015	.0007
B4	Pegmatite	*.2*	*.04*	.3	*.4*	*.1*	.007	.3	.03	.0015	<.0001	<.0005	.007	<.0005	.015	.0007	.007	.00015
B55	Pegmatite	—	—	.7	<.7	.3	<.005	.07	.003	.0003	.0003	<.0005	.015	<.0005	.015	.00015	.0015	.007
B55	Pegmatite	*.5*	*.2*	*.7*	*.2*	*.3*	*.01*	*.09*	*<.005*	—	*.0003*	*<0.0005*	*.019*	*<0.0005*	—	—	—	—
B40	Pegmatite	—	—	.7	<.7	.7	<.005	.15	.03	.00015	<.0001	.0015	.007	<.0005	.015	.00015	.0003	.0015
B40	Pegmatite	*1.0*	*.3*	*1.0*	*.3*	*.5*	*.01*	*.16*	*.03*	—	*<.0001*	*.002*	*.005*	*<.0005*	—	—	—	—
B41	Pegmatite	—	—	.7	<.7	.7	<.005	.015	.007	<.00015	<.0001	<.0005	.003	<.0005	<.015	.00015	.00015	.0003
B41	Pegmatite	*3.0*	*.3*	*1.0*	*.3*	*.6*	*.01*	*.03*	*.005*	—	*<.0001*	*<.0005*	*.003*	*.0009*	—	—	—	—

[1] Quantitative analyses are italicized; the remainder are semiquantitative analyses.

[2] Sample B43 is a repicked specimen of sample 5.

[3] Sample B46 is a repicked specimen of sample 8.

Other elements found in minor amounts in some samples:

Ag 0.00005 percent in samples B46, B55, B52, B22, B49, B42, B13, and B45; 0.00007 percent in samples B53, B35, B37, B32, B33, B44, B30, and B31; 0.00015 percent in sample B38.

As 0.26 percent in sample MHS-84-55.

B 0.003 percent in sample B14; and 0.02 percent in sample MHS-84-55.

Bi 0.0015 percent in samples B6, B7, and B12; 0.003 percent in sample B13; and 0.015 percent in sample B14.

Co 0.0003 percent in samples B22, B42, and B14.

Mo 0.0007 percent in sample B35.

Nb 0.01 percent in sample MHS-84-55.

Ni 0.0003 percent in sample 6; and 0.0007 percent in samples B22, B49, and B42.

Pb 0.0007 percent in sample 4; 0.0015 percent in samples 2, B30, and B31; and 0.003 percent in samples B2 and B14.

Sn 0.0007 percent in samples B20 and B18; 0.0015 percent in samples B14, B19, B33, and 1; 0.003 percent in samples B43, B37, and B45; and 0.08 percent in sample MHS-84-55.

Sr 0.00015 percent in samples B54 and B36; 0.0007 percent in samples 8, B46, B10, and 3.

W 0.015 percent in sample B16.

Y 0.003 percent in sample 3; and 0.009 percent in sample MHS-84-55.

Yb 0.00015 percent in sample 1; 0.0003 percent in sample 3; and 0.0008 percent in sample MHS-84-55.

Zr 0.0015 percent in samples B43 and B16; 0.003 percent in samples B14, B44, 3, and B12; 0.007 percent in sample B11; and 0.02 per cent in sample MHS-84-55.

Elements not found: P, Au, Cd, Ce, Dy, Er, Eu, Gd, Ge, Hf, Hg, Ho, In, Ir, La, Lu, Nd, Os, Pd, Pr, Pt, Re, Rh, Ru, Sb, Ta, Tb, Te, Th, Tl, Tm, and U.

TABLE 2.—(*continued*)

Specimen No.	Environment	Cs	Rb	Na	K	Li	Ca	Fe	Mg	Ti	Cr	V	Mn	Sc	Zn	Ba	Cu	Ga
B21	Pegmatite	.4	.05	.7	.15	.3	<.005	.15	.0015	<.00015	<.0001	<.0005	.007	<.0005	.03	.00015	.015	.003
B48[4]	Pegmatite	—	—	.7	<.7	.3	<.005	.15	.007	.00015	<.0001	<.0005	.007	<.0005	.015	.00015	.0007	.003
B48[4]	Pegmatite	.4	.2	1.0	.2	.4	.008	.18	.005	—	<.0001	<.0005	.005	.005	—	—	—	—
B20	Pegmatite	.8	.07	.7	.2	.5	<.005	.015	<.001	<.00015	<.0001	<.0005	.007	<.0005	<.015	.00015	.007	.003
B47[5]	Pegmatite	—	—	.7	<.7	.7	<.005	.015	<.001	<.00015	<.0001	<.0005	.007	<.0005	<.015	.00015	.0007	.003
B47[5]	Pegmatite	.8	.2	1.0	.2	.4	.005	.03	<.005	—	<.0001	<.0005	.005	<.0005	—	—	—	—
B1	Pegmatite	.2	<.04	.3	.15	.15	.007	.3	.07	/<.00015	.00015	<.0005	.03	<.0005	.07	.0003	.007	.0015
B2	Pegmatite	0.1	<0.04	0.3	0.07	0.15	0.007	0.3	0.03	<0.00015	<0.0001	<0.0005	0.07	<0.0005	0.07	0.0007	0.007	0.003
B3	Pegmatite	.2	.04	.3	.1	.15	<.005	.3	.03	<.00015	<.0001	<.0005	.015	<.0005	.03	.0003	.003	.0015
B52	Pegmatite	—	—	.3	<.7	.07	<.005	.15	.07	<.00015	.00015	<.0005	.0015	<.0005	.015	.00015	.0007	.00015
B52	Pegmatite	.3	.03	.5	.08	.1	.01	.30	.19	—	.0006	<.0005	.002	<.0005	—	—	—	—
B53	Pegmatite	—	—	.3	<.7	.15	<.005	.3	.03	<.00015	.0007	<.0005	.0015	<.0005	.015	.00015	.0007	.0003
B53	Pegmatite	.2	.05	.5	.1	.2	.01	.34	.11	—	.0002	<.0005	.002	<.0005	—	—	—	—
B6	Wallrock adjacent to pegmatites	.2	<.04	.3	.2	.05	.015	.3	.15	.003	.0007	.003	.007	.0015	.015	.0007	.007	.0003
B50[6]	Wallrock adjacent to pegmatite	—	—	.3	<.7	.07	<.005	.3	.07	.0015	.0007	.0015	.0015	.0007	.007	.00015	.0003	<.00015
B50[6]	Wallrock adjacent to pegmatites	.3	.02	.4	.2	.06	.02	.36	.25	—	.0014	.002	0.03	.002	—	—	—	—
B22	Wallrock adjacent to pegmantes	.8	<.04	1.5	.2	.5	.03	1.5	.7	.007	.003	.015	.015	.007	<.015	.0003	.003	<.00015
B49[7]	Wallrock adjacent to pegmatites	—	—	1.5	<.7	.7	.03	.7	.7	.003	.003	.097	.015	.003	<.015	.00015	.0007	<.00015
B49[7]	Wallrock adjacent to pegmatites	.8	.05	2.0	.3	.6	.037	1.3	.80	—	.0054	.01	.012	.01	—	—	—	—
6	Wallrock adjacent to pegmatites	—	—	.3	—	—	<.02	.7	.15	.0007	.0007	.0015	.007	.0007	.015	<.00015	.0007	<.00015
6	Wallrock adjacent to pegmatites	.1	<.09	—	.045	.042	—	—	—	—	—	—	—	—	—	—	—	—
B42[8]	Wallrock adjacent to pegmatites	—	—	0.3	<0.7	0.07	0.015	0.3	0.15	<0.00015	0.0007	0.0015	0.003	0.0007	0.015	0.00015	0.003	<0.00015
B42[8]	Wallrock adjacent to pegmatites	0.2	<0.02	.5	0.03	.08	.026	.75	.19	—	.0012	.0025	.004	.001	—	—	—	—
B14	Vein	.5	.07	.7	.6	.15	.07	1.5	.15	0.07	<.0001	.0007	.07	.003	.03	.0003	.015	.0015
B39	Vein	—	—	.15	<.7	.03	<.005	.15	.007	.0003	<.0001	<.0050	.0015	.015	.03	.0003	.0007	.0003
B39	Vein	<.1	<.02	.1	.2	.02	.01	.30	.005	—	.0001	<.0005	.002	.014	—	—	—	—
B18	Vein	.3	<.04	.3	.15	.02	<.005	1.5	.15	.015	<.0001	.007	.015	.03	<.015	.00015	.003	.0003
B19	Vein	.2	<.04	.3	.1	.02	.007	1.5	.15	.015	<.0001	.007	.015	.03	<.015	.00015	.015	.0007
B35	Vein	.1	.02	.1	.07	.02	<.005	.52	.02	—	.002	.002	.006	.017	—	—	—	—
B35	Vein	—	—	.07	<.7	<.02	<.005	.3	.03	.003	.0007	.0007	.007	.015	.007	.00015	.0007	.0003
B37	Vein	—	—	.15	<.7	.07	<.005	.07	.03	.00015	<.0001	<.0005	.0015	<.0005	.015	.0007	.0015	.00015
B37	Vein	.3	.04	.2	.3	.07	.02	.14	.06	—	<.0001	.0006	.002	<.0005	—	—	—	—

[4] Sample B48 is a repicked specimen of sample B21.
[5] Sample B47 is a repicked specimen of sample B20.
[6] Sample B50 is a repicked specimen of sample B6.
[7] Sample B49 is a repicked specimen of sample B22.
[8] Sample B42 is a repicked specimen of sample 6.

TABLE 2.—(*continued*)

Specimen No.	Environment	Cs	Rb	Na	K	Li	Ca	Fe	Mg	Ti	Cr	V	Mn	Sc	Zn	Ba	Cu	Ga
B38	Vein	—	—	.15	<.7	.015	<.005	.07	.15	<.00015	.07	.03	.0007	.015	.007	.00015	.00015	.00015
B38	Vein	*<.1*	*<.02*	*.2*	*.03*	*.02*	*.01*	*.12*	*.23*	—	*.14*	*.05*	*.001*	*.014*	—	—	—	—
B13	Vein	*<.1*	*<.04*	.15	*.06*	*.02*	.007	.7	.03	.003	<.0001	.0015	.007	<.0005	<.015	.0003	.007	.0003
B9	Vein	*0.3*	*0.04*	0.7	*0.2*	*0.06*	<0.005	0.7	0.7	0.003	0.0007	0.015	0.015	0.03	<0.015	0.0007	0.007	0.0003
B10	Vein	*.6*	*.04*	.7	*.2*	*.08*	.07	.3	.7	.0003	.007	.07	.03	.03	<.015	.0003	.007	.0015
B36	Vein	—	—	.7	.7	.07	.3	.15	.3	.0003	<.0001	<.0005	.015	<.0005	<.015	.0015	.0003	.00015
B36	Vein	*.3*	*.05*	*.4*	*.8*	*.03*	—	—	—	—	—	—	—	—	—	—	—	—
B32	Vein	—	—	.3	<.7	.07	<.005	.15	.07	<.00015	<.0001	<.0050	.003	<.0005	.007	.0003	.00015	<.00015
B32	Vein	*.2*	*<.02*	*.2*	*.2*	*.06*	*.008*	*.20*	*.21*	—	*<.0001*	*<.0005*	*.003*	*<.0005*	—	—	—	—
B45[9]	Vein	—	—	.15	<.7	.03	.15	.3	.07	.007	.00015	.003	.007	.007	.007	.00015	.0007	.0003
B45[9]	Vein	*.2*	*.04*	*.2*	*.09*	*.04*	*.26*	*.43*	*.19*	—	*.0003*	*.0045*	*.007*	*.01*	—	—	—	—
B33	Vein	—	—	.3	<.7	.07	<.005	.15	.03	.0015	<.0001	<.0005	.003	<.0005	.015	.0007	.0003	.00015
B33	Vein	*.3*	*.04*	*.3*	*.3*	*.1*	*.01*	*.24*	*.05*	—	*<.0001*	*<.0005*	*.004*	*.0006*	—	—	—	—
B16	Granite	*.4*	*.04*	.3	*.2*	*.1*	.03	.7	.07	.015	<.0001	.0015	.03	.003	.015	.00015	.0015	.0007
B44[10]	Granite	—	—	.3	<.7	.07	.015	.7	.07	.007	<.0001	.0015	.015	.0015	.007	.00015	.0003	.0003
B44[10]	Granite	*.3*	*.06*	*.5*	*.1*	*.1*	*.029*	*1.0*	*.13*	—	*.001*	*.001*	*.016*	*.005*	—	—	—	—
4	Granite	—	—	.7	<.7	.07	.07	1.5	.7	.003	<.0001	.007	.015	.03	<.015	.015	.0015	.003
2	Granite	*.8*	*.1*	.7	*.23*	*.04*	.07	1.5	.3	.007	<.0001	.007	.015	.07	<.015	.0015	.0007	.0015
3	Granite	*.23*	*.09*	.3	*.45*	*.03*	.7	1.5	.15	.007	.00015	.003	.015	.015	<.015	.0007	.0007	.003
B12	Granite	*0.1*	*<0.04*	0.15	*0.1*	*0.03*	0.015	0.7	0.03	0.0015	<0.0001	0.0015	0.007	0.015	<0.015	0.00015	0.03	0.0015
B11	Granite	*.1*	*.05*	.3	*.2*	*.04*	.03	1.5	.07	.007	.00015	.003	.015	.03	<.015	.00015	.003	.0015
1	Granite	*.4*	*.1*	.3	*.2*	*.035*	.03	1.5	.07	.03	.00015	.003	.03	.07	<.015	<.00015	.0007	.003
B30	Granite	—	—	.3	<.7	<02	<.005	.7	.07	.007	.00015	.003	.007	.015	.015	.0003	.0007	.0003
B30	Granite	*.1*	*.05*	*.5*	*.2*	*.05*	*.02*	*.84*	*.16*	—	*.0002*	*.003*	*.009*	*.015*	—	—	—	—
B31	Granite	—	—	.3	<.7	<.02	<.005	.7	.15	.003	.0003	.003	.007	.03	.007	.00015	.0007	.0007
B31	Granite	*.2*	*.05*	.7	*.06*	*.03*	*.01*	*1.0*	*.25*	—	*.0007*	*.004*	*.009*	*.022*	—	—	—	—
MHS-84 -55	Rhyolite	*.9*	*.35*	*.3*	*.5*	*.05*	.07	*1.6*	.007	*.2*	—	—	*.2*	*.001*	*.2*	*.0023*	*.007*	*.006*

[9] Sample B45 is a repicked specimen of sample B8.
[10] Sample B44 is a repicked specimen of sample B16.

lower by the quantitative than by the semiquantitative method because more sensitive analytical lines were used for the quantitative.

Variation of Composition in Different Environments

Variation in chemical composition of beryl from different environments can be seen by arranging the chemical analyses of some elements in groups according to their occurrence (Table 2). These variations are large enough so that beryls from pegmatites can generally be distinguished from those from granite and from wallrock adjacent to pegmatites. Beryls from some veins can be distinguished from those from other environments but beryls from other veins cannot. Actually, vein beryl represents several different types of veins and, as might be expected, the range in composition of these beryls is large. As only one beryl was obtained from rhyolite—from the only United States locality known to us—little can be said of the range of its minor elements. However, if beryl from other rhyolites is even somewhat similar in composition, it should be readily distinguishable from beryl formed in other environments. The beryl from the rhyolite will not be compared to the compositions of the other beryls, but will be discussed separately at the end of this section.

In order to give a better visual picture of the differences in composition found in different environments, the ranges in composition of the various beryls are shown graphically in Fig. 1 for the alkali metals and for certain other diagnostic metals. For a single beryl analyzed by both quantitative and semiquantitative methods, only the quantitative data were used in Fig. 1; where a quantitative analysis was not available, a semiquantitative analysis was used. The compositional range of beryl from a wallrock adjacent to pegmatite is based on only six specimens, and when more specimens become available the range may need to be lengthened for some elements. The compositional ranges for beryls from other types of environments may also have to be expanded. This expansion will include the probable increasing of the ranges for lithium, cesium, and rubidium content of beryls from pegmatites. We believe, however, that although details of these graphs may need modification, the general relation among the compositions of beryl from different environments will remain the same.

The alkali metals are generally the most common minor elements found in beryl. The ranges of the metal content of two of them, sodium and potassium, in beryl from different environments are not distinctive, as they overlap one another (Fig. 1). The range in lithium content in pegmatite beryl is similar to that in beryl from wallrock adjacent to pegmatite but is much greater than that from veins or granite. The ranges in content of the other two alkali metals (cesium and rubidium) in

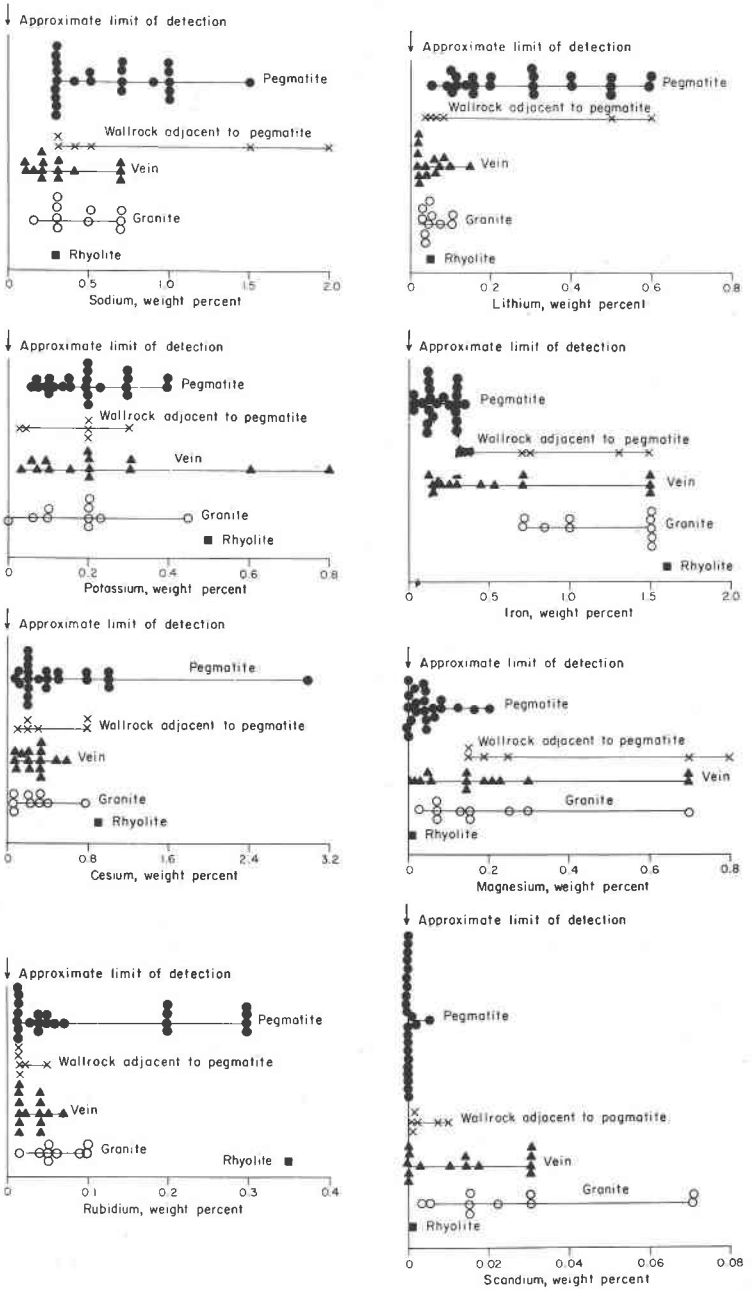

FIG. 1. Range in abundance of various minor elements in beryl from various environments.

pegmatite beryl are much greater than that found in beryl in other environments. Characteristically, beryl with high Li, Rb or Cs content comes from pegmatites rich in lithium minerals and generally from the inner zones, where the lithium minerals are ordinarily concentrated. In a few pegmatites, such as the Tin Mountain pegmatite in the Black Hills of South Dakota, cesium is concentrated enough to form pollucite ($Cs_4Al_4Si_9O_{26}\cdot H_2O$). In most pegmatites, however, both cesium and rubidium occur as minor elements in such minerals as lepidolite (Stevens, 1938) and beryl. Hence, the higher content of Li, Rb and Cs in beryl from the inner zones of a pegmatite reflects the general increase of these elements in the magma that formed this part of the pegmatite.

Two other elements, iron and magnesium, may make up more than 0.5 per cent of some beryl (Table 2 and Fig. 1). The range of the iron and magnesium content of beryl from pegmatites is smaller than that of beryl from other environments (Fig. 1). The range in iron content of beryl from pegmatites overlaps in part the range of beryl from veins and wallrock adjacent to pegmatite, but is less than that of any beryl from granite. The range of magnesium content of beryl from pegmatite also overlaps the lower part of the range of beryl from other environments; most pegmatite beryl contains little magnesium.

Scandium, although occurring in only minor amounts, has a progressive increase in its range from pegmatite to granite (Fig. 1). This element has a very small range in beryl from pegmatite, a little larger range in beryl in wallrock adjacent to pegmatite, and a much larger range in beryl from veins and granite. Almost all of the beryl from granite contains more Sc than that from pegmatite.

Vanadium and titanium occur in minor amounts, if at all, in beryl from pegmatite. The vanadium content of only a few beryls exceeds 0.005 per cent from other environments; in two veins (Chivor district, Colombia, and Oreana, Nevada), however, the beryl contained 0.05 and 0.07 per cent vanadium. The titanium content of beryl rarely exceeds 0.01 per cent, but is greater in a few beryls from veins and granite.

Minor amounts of zinc are found in many beryls including almost all of those from pegmatite. The range in zinc content in beryl from pegmatite is larger than that of beryl from any other environment. The overlap in the ranges of zinc content in beryl from different environments, however, is quite large, and, hence, the zinc content is not useful in separating beryls from different environments.

Some of the minor elements that are found in beryl in wallrock adjacent to pegmatite evidently came from the pegmatite, others were obtained from the wallrock. Our data were derived from two localities: the Harding pegmatite is represented by beryl samples from the core (B41), wall zone

(B40), and the adjacent wallrock (B49); the Avon pegmatite is represented by beryl from the wall zone (B5) and the adjacent wallrock (B50). From this small group of specimens the following trends were observed: (1) The amounts of Li, Cs and Zn in beryls in both the wallrock and adjacent pegmatite are similar, suggesting that these elements migrated from the pegmatite; (2) the amount of Rb in beryls in the wallrock is much less than that in the pegmatite, suggesting that only a little of this element migrated from the pegmatite; and (3) the amounts of Ti, Sc, V, Cr, Mg, Fe, Na, Ni and Co in beryls in the wallrock are greater than that in the pegmatite, suggesting that these elements are largely obtained from wallrock. Nickel is of special interest, although it occurs in only minor amounts, because the only beryls containing any of it came from wallrock adjacent to pegmatite. Two of the three specimens containing Co also came from wallrock; the other from a vein (B14).

Vein beryl is found associated with a variety of minerals, most of which are generally considered to be of high-temperature origin. It is commonly associated with tungsten minerals (scheelite or wolframite), and half of the beryl localities from which specimens were collected for this report contained tungsten. It is also commonly associated with cassiterite, molybdenite or just quartz. The emerald veins at Chivor (B38) are a rare type and consist of pyrite, albite, quartz and emerald (Mentzel, 1931). The ranges of some of the minor element contents in beryl from these various types of veins are, therefore, large. We thought that a significant difference might occur between the tungsten-bearing veins and the non-tungsten-bearing veins but examination of Table 2 shows that the range of most minor elements is similar in these two groups of veins. The biggest and perhaps the only significant difference was noted in the titanium content; the beryl in tungsten-bearing veins contained from 0.00015 to 0.007 per cent, that in non-tungsten-bearing veins contained from 0 to 0.07 per cent. As many veins are poor in most alkali metals, the beryl from veins have small ranges and low contents of Li, Cs, Na and Rb. In some places rock types similar to both vein and pegmatite are found, and in these gradational types the minor element content of beryl is similar to both.

Vein beryl is difficult to distinguish from that in wallrocks adjacent to pegmatite, as both types have a high and similar Fe and Mg content. The larger Li range in beryl from the wallrock adjacent to pegmatite may aid in distinguishing some of the beryl in these two groups.

Beryl from granite contains relatively minor amounts of Na, Li, Cs, Rb, Cr, Ni and Zn and the range of these elements is small. Probably the two most diagnostic minor elements are Fe and Sc. The Fe contents of beryls from granite are all relatively large as compared to those from

pegmatite (Fig. 1). Scandium has a very large range of values, with a mean of about 0.03 per cent Sc. Although this range is large it will undoubtedly have to be increased, as the mineral bazzite, which occurs in drusy cavities in granite near Baveno in the Alps (Spencer, 1916), is, according to Fleisher (1955), a scandian beryl. Beryl from granite, as noted above, can be easily distinguished from that in pegmatite but it is more difficult to distinguish from that occurring in veins and in wallrock adjacent to pegmatite. The presence of Ni or Cr and a high Li content may aid in distinguishing beryl adjacent to a pegmatite from that in a granite. A low Fe content in beryl from a vein might aid in distinguishing it from beryl in a granite.

The red beryl from the rhyolite is probably the most distinctive of all the beryls studied and its content of several minor elements is unique. This beryl has a relatively low Li, Na, Mg and Sc content; a relatively high Ba and Cs content, and the highest content, of any beryl analyzed, of Rb, Fe, Ti, Zn, Mn, As, B, Ga, Nb, Sn, Y, Yb and Zr (Table 2). Of the elements in this last group, As and Nb were detected only in this beryl. Because rhyolite and granite commonly are of similar composition, beryls from these two environments might be expected to be similar. Surprisingly, this is not so, and the minor element content of the beryl from rhyolite falls within the range of that found for granites only for Na, K, Li, Ca, Ba and Cu; for Mg and Sc it is less than this range; for all other minor elements for which we have data, it is greater. The beryl from the rhyolite has several other anomalous characteristics. In most beryls, if one of the alkali metals (Na, Li, Rb and Cs) except K is high, the others are also. In the beryl from the rhyolite, the Cs and Rb contents are high, Na is moderate and Li is low. Commonly beryls with high Fe content have a high Mg content, but this beryl has one of the lowest Mg contents and highest Fe contents of any beryl found.

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