THE AMERICAN MINERALOGIST, VOL. 47, MAY-JUNE, 1962

# AN UNUSUAL BERYL FROM ARIZONA[1]

WALDEMAR T. SCHALLER, ROLLIN E. STEVENS AND RICHARD H. JAHNS, *U. S. Geological Survey, Washington 25, D. C., and Menlo Park, California and The Pennsylvania State University, University Park, Pennsylvania.*

## ABSTRACT

A bluish beryl from a pegmatite dike in Mohave County, Arizona, differs distinctly from other known beryls in physical properties and chemical composition. The highest measured value of $\omega$ for this beryl is 1.610, and the analyzed sample has $\omega = 1.608$, $\epsilon = 1.599$. Only four published analyses of beryls with an $\omega$ index higher than 1.592 are known, and the highest index heretofore recorded for any beryl, recognized as such, is 1.602. $G = 2.921$.

In composition, this mineral differs markedly from other beryls. It has the lowest percentage of $SiO_2$ and of $Al_2O_3$ of any known beryl. It contains 4.69 per cent of oxides of bivalent elements other than beryllium, chiefly ferrous iron and magnesium. Its content of $Cs_2O$, 6.68 per cent, is much greater than that of nearly all other known beryls. On the other hand, its content of $Li_2O$, 0.23 per cent, is only about one-tenth of what would be expected for an alkali-rich beryl.

The composition and physical properties are incompatible with distinctive compositional trends determined for beryls by Schaller and Stevens. In general the $\omega$ index of refraction ranges from 1.570 for low-alkali beryls to 1.592 for high-alkali beryls. Low-alkali beryls are close to the composition indicated by the standard beryl formula $Be_3 \cdot Al_2 \cdot Si_6O_{18}$. The high-index beryls can be interpreted in terms of the standard beryl formula combined with the sodium-lithium beryl formula $Na \cdot Be_2Al \cdot AlLi \cdot Si_6O_{18}$ and its cesium-lithium analogue. In various solid solutions of these end-members the atomic ratios of Si and Al do not vary, but increases in Li are accompanied by equal increases in Na or Cs and by equal decreases in Be.

In contrast to the compositional trends for most beryls, the Arizona beryl is deficient in Al; it is high in Na and Cs but low in Li, and its Be content is abnormally high for a high-index, high-alkali beryl. These relationships are attributed to the presence of another end-member represented by the generalized formula $(Na, Cs) \cdot Be_3 \cdot Al(Fe^{2+}, Mg) \cdot Si_6O_{18}$. The Arizona beryl contains more than 50 per cent of this femag end-member.

Most of the Arizona beryl with the highest indices of refraction occurs in the fine-grained border zone of an irregular pegmatite dike, where it typically forms small podlike masses. Each mass is a single skeletal crystal of beryl that contains numerous inclusions of quartz, microcline, albite, fluorite and sphene. More euhedral and prismatic crystals of beryl, considerably less crowded with inclusions, in the inner parts of the dike also have high indices of refraction and unusual chemical composition.

The composition seems to be a direct reflection of a relatively high iron and magnesium content of the pegmatite fluid during its crystallization. These elements probably were derived in large part from digestion of mafic country rock. The incorporation of bivalent iron and magnesium into the beryl structure, in place of some trivalent aluminum, probably resulted in the strong attraction of large monovalent cations, chiefly $Cs^+$ and $Na^+$, into the tubular channels of the structure during formation of the crystals.

## INTRODUCTION

For many years mineralogists have attributed variations in certain physical properties of beryl to variations in its chemical composition, but

---

[1] Publication authorized by the Director, U. S. Geological Survey.

few serious attempts have been made to correlate specific differences in these properties with specific differences in composition. In an effort to define and attack this broad problem in a quantitative manner, Schaller and Stevens (report in preparation) have studied the properties of about 100 different beryl samples for which data on composition are available. They were able to measure many of the effects of compositional variation and to construct variation curves for G versus $\omega$, and for $\omega$ versus percentages of all major chemical constituents. As a result of this investigation, it is now possible to correlate indices of refraction and specific gravity with the percentages of major constituents in nearly all beryls. However, the properties of the bluish beryl from Arizona, described in this paper, do not agree with these variation curves. This beryl is the only one so far chemically analyzed for which these relationships do not apply, and hence it is considered to be unusual.

Preliminary data on correlations between physical properties and chemical composition were furnished by Schaller to several geologists who were investigating deposits of pegmatite minerals, mainly under the aegis of the U. S. Geological Survey, and these data were found to be especially useful in two general ways. In the first place, it became possible to appraise the composition of a given beryl solely from its $\omega$ index of refraction, which is readily determined under the microscope. Estimates of beryllium content thus can be made quickly, reliably, and without recourse to expensive chemical analyses. And second, the checking of indices of refraction for hundreds of beryls by geologists in the field greatly improved the chances for finding and recognizing varieties of this mineral that could best be used to fill gaps in the data already assembled by Schaller and Stevens.

The $\omega$ index of refraction for most beryls is within the range 1.570 to 1.592, and any variety with $\omega$ index above or below this range is unusual and merits further study. The low-index beryls have a very small total alkali content, and approach closely the composition indicated by the standard beryl formula, $Be_3 \cdot Al_2 \cdot Si_6O_{18}$ (or $3BeO \cdot Al_2O_3 \cdot 6SiO_2$). The high-index beryls, in contrast, are richer in total alkalies and have a much more complex composition. The published record at the present time includes only four analyses of beryls whose $\omega$ index is greater than 1.592, although Stevens recently has analyzed five other beryls whose index is similarly high. The highest $\omega$ value of any beryl whose analysis has been published is 1.600.

An unusual deposit of bluish and bluish-green beryl in Mohave County, Arizona, was examined by Jahns early in 1942, and subsequently was mapped and studied in detail. Some of the beryl was found to have an $\omega$ index greater than 1.590 and was sent to Schaller for further investigation. Schaller found that the index varied somewhat from one specimen to another, but the maximum determined value, 1.610, is considerably higher that the previously recorded maximum ω index of 1.602, reported by Lacroix (1913) for an unanalyzed beryl from Madagascar. Subsequent laboratory studies revealed other properties that establish this Arizona beryl as unusual among known varieties, and later a large suite of specimens was collected from the original locality for more complete and detailed investigations.

This paper presents the results and interpretations of the studies that were made on this beryl from Arizona. Schaller and Stevens are primarily responsible for the laboratory work and Jahns for the field work. All three authors share jointly in the responsibility for the structural and geological interpretations that are advanced to account for the origin of this beryl.

## General Features

In their general study of beryl, Schaller and Stevens were able to construct a variation curve correlating the specific gravity and index of refraction of about 180 beryls. About 100 chemical analyses have permitted correlation of the ω index with the percentages of the major constituents of beryl, namely, $SiO_2$, BeO, $Al_2O_3$, $Li_2O$, $Na_2O$, $Cs_2O$, and $H_2O$. In the unusual beryl from Arizona, which has the highest specific gravity (2.921) and the highest ω index of refraction (1.608 for the analyzed sample) recorded for any analyzed beryl, only the percentage for $SiO_2$ is compatible with these variation curves. The percentages for BeO, $Al_2O_3$, $Li_2O$, $Na_2O$, $Cs_2O$, and $H_2O$ show considerable discordances.

The Arizona beryl contains the lowest percentage of $SiO_2$ (59.52) recorded for any beryl except one whose analysis has been shown to be in error (Schaller and Stevens). Only six other beryl analyses indicate $SiO_2$ contents almost as low (60.39 to 60.70). Most beryls contain from 62 to 67 per cent of $SiO_2$.

The percentage of beryllia is unusual for a low-silica and high-alkali beryl. In all other analyzed beryls the percentage of BeO decreases as the proportion of total alkali oxides increases. According to the variation curve for beryllia versus ω index of refraction, a beryl with ω index of 1.600 should contain about 10 per cent of BeO, and extrapolation of this curve suggests that a beryl with ω index of 1.608 should contain only a little more than 8 per cent of BeO. Yet the Arizona beryl, with ω index of 1.608, contains 12.47 per cent of BeO, or about half again as much as the expected amount.

An even greater divergence is shown by the $Al_2O_3$ content, which in beryls normally ranges from 17 to 19 per cent. The Arizona mineral contains only 10.73 per cent of $Al_2O_3$, little more than half the usual amount. All the other published analyses of beryl, as well as analyses made by Stevens but not yet published, indicate a fixed ratio of 2 aluminum atoms to 6 silicon atoms in the crystal structure. In this unusual beryl, however, the ratio is only 1.26 aluminum atoms to 6 silicon atoms, or 1.44 aluminum+ferric iron+chromium atoms to 6 silicon atoms.

This beryl also contains 2.08 per cent of $Fe_2O_3$, which is in the mineral and is not due to limonitic stain, as the crushed sample was carefully cleaned with oxalic acid before analysis. The 4.32 per cent of total iron oxides ($Fe_2O_3+FeO$) is the highest recorded amount where purity of analyzed sample is assured.

The content of the bivalent elements Fe, Mn, and Mg, herein referred to as the femag elements, also exceeds that reported for any other beryl. Expressed as oxides, the content of total femags is 4.69 per cent.

Unlike all other high-cesium beryls, this unusual beryl contains very little lithium. On the basis of the appropriate variation curve, its index of refraction indicates a $Li_2O$ content of about 2.5 per cent, but it actually contains only a tenth as much, namely 0.23 per cent. Further, there is only 0.17 lithium atom to one atom of sodium+potassium+cesium, whereas other beryls studied by Schaller and Stevens show a more even balance between lithium atoms and total atoms of the other alkalies.

Like all beryls with high specific gravity and high indices of refraction, this Arizona beryl is alkali-rich. It contains the highest percentages of total alkali oxides (including $Li_2O$), namely 8.23 per cent, and of cesia, 6.68 per cent, for any beryl whose analysis has been previously published. Unpublished analyses (by Stevens) of three beryls from Madagascar show similar high percentages of total alkalies and of cesia. The maximum content of $Cs_2O$ in any previously published analysis of beryl is 4.56 per cent, in a beryl from Madagascar described by Lacroix and Rengade (1911).

The specific gravity and indices of refraction are distinctly higher for the Arizona beryl than for the three recently analyzed Madagascar beryls just mentioned, even though all four beryls have similar contents of cesia and of total alkalies. The higher G and $\omega$ index of the Arizona beryl are due mainly to the 4 per cent of iron oxides present.

Other high-alkali beryls contain about 2.0 to 2.5 per cent of water, but the water content of this Arizona beryl is only 1.62 per cent, a value characteristic of beryls with the much lower $\omega$ index of refraction of approximately 1.575.

## OCCURRENCE

*Geologic setting.* Beryl occurs in several irregular pegmatite dikes of Precambrian age that crop out in a small area of low hills and ridges about 15 miles south of Peach Springs in eastern Mohave County, Arizona. This pegmatite area can be reached over the road that extends southeastward to Wright Creek Ranch from a point on U. S. Highway 66 that is 13 miles west-southwest of Peach Springs. From a point near Wright Creek a poor side road provides access to the principal beryl-bearing dikes, which are exposed on the south slope of a low ridge about 4 miles east-southeast of the Wright Creek Ranch. The beryl described in this paper was obtained from an unusual deposit, known as the Bountiful Beryl prospect and also as the Bluebird prospect, that was briefly described by Moore (1936) and later mapped by Jahns (Cameron *et al.*, 1949, p. 26).

The principal rock type in the area is a coarse-grained, dark greenish gray quartz-mica-amphibole schist that is markedly chloritic. Coarse-grained, light gray to pinkish gneissic granite forms dikes and pods in the foliated rocks, and a distinctly finer-grained pinkish granite forms numerous sills and larger, cross-cutting masses. Both granites are transected by the pegmatite dikes, and all these rocks are overlain locally by gently dipping sandstone beds of Cambrian age.

The pegmatite bodies of principal interest are very irregular in form, and they range in thickness from a few inches to 25 feet. Their emplacement appears to have been controlled by fractures, and to a lesser degree by foliation in the country rock. Contacts between pegmatite and granite typically are sharp, whereas those between pegmatite and schist are gradational over widths of a few inches to as much as 6 feet. The hybrid rock is mainly biotite-bearing schist and gneiss that is spotted with tabular to nearly equant metacrysts of microcline, and much of it also is impregnated with numerous smaller anhedral crystals of microcline and albite along with locally abundant schorl and sphene. A large part of the biotite in the hybrid rock plainly was developed by alteration of amphiboles, and fine-grained pseudomorphs of biotite after hornblende are common.

### *Bountiful Beryl dike*

#### a. General features

The Bountiful Beryl dike is enclosed by schists and gneisses, and it also transects several sills and dikes of fine- to medium-grained granite. Like other pegmatite bodies in the area, this dike is highly irregular in form and has several thick, elongate branches. It is broadly sinuous in outcrop plan, pinches and swells markedly as traced along the strike, and ranges in thickness from 2 feet to 23 feet. In general it trends northeast and dips gently to moderately southwest.

The dike has a well-defined zonal structure and is composed of five readily distinguishable rock types:

1. Fine-grained microcline-albite-quartz pegmatite (border zone).
2. Medium- to coarse-grained microcline-quartz-albite pegmatite (wall zone).
3. Very coarse-grained graphic granite (intermediate zone).

4. Very coarse-grained quartz-euhedral perthite pegmatite (core).
5. Albite-quartz-microcline-garnet aplite (mainly within core).

The principal accessory minerals are fluorite, schorl, sphene, beryl and garnet. None of the pegmatite contains more than a trace of muscovite or biotite. No lithium mineral was observed.

b. Border-zone pegmatite

The border zone forms a discontinuous fringe about 2 feet in average thickness and nearly 6 feet in maximum thickness. The modal composition of this rock, as determined under the microscope from 10 specimens, is as follows:

Major constituents

| | *Per cent* |
|---|---|
| Microcline (including some albite in perthitic intergrowths) | 60 |
| Albite | 13 |
| Quartz | 20 |
| Total feldspar and quartz | 93 |

Minor constituents, 7 per cent of the rock, recalculated to 100 per cent

| | *Per cent* |
|---|---|
| Fluorite | 34 |
| Schorl | 25 |
| Sphene | 16 |
| Garnet | 9 |
| Beryl | 8 |
| Biotite | 3 |
| Hornblende | 2 |
| Muscovite | 2 |
| Apatite | 1 |
| Allanite | Trace |
| Magnetite | Trace |
| Microlite | Trace |
| Total | 100 |

In a sense the border zone is a fine-grained representative of the dike as a whole. It contains the same minerals and shows the same paragenetic sequence of minerals, and many of its textural features are duplicated on a larger scale in other parts of the dike. Restricted to this zone, however, is a crude but locally distinct planar structure that in most places is conformable with the walls of the dike; elsewhere this structure is parallel to the foliation of the adjacent schist and gneiss (Figs. 1, 2) and appears to be a relict feature in a transition zone of hybrid rock.

The border-zone pegmatite is a fine-grained aggregate of microcline,[1]

---

[1] Much of the potash feldspar in the dike is microperthitic, but in this paper it is referred to simply as microcline.

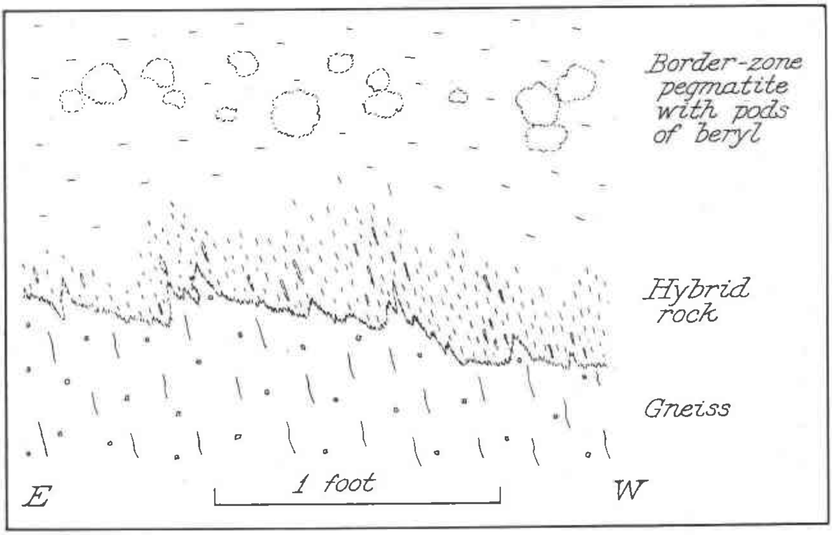

FIG. 1. Sketch of structural relations between border zone of Bountiful Beryl dike, Mohave County, Ariz., and the adjacent wall-rock gneiss, as exposed in wall of prospect pit.

albite, and quartz, through which are scattered numerous subhedral to anhedral crystals of quartz and flesh-colored microcline 0.5 to 1.5 cm in maximum dimension. The planar structure noted above results both from a preferred orientation of the largest and most rectangular crystals of microcline and a somewhat undulatory streaky layering (Fig. 2) caused by systematic variations in relative amounts of the finer-grained constituents.

The prevailing fabric of the border zone is interrupted here and there by large, podlike masses of schorl and by similar but less abundant masses of blue-green beryl. Though very irregular in detail, most of these pods are nearly equidimensional, and range in diameter from 0.5 cm to about 14 cm. They appear as prominent blotches that are randomly scattered through the finer-grained host rock (Fig. 3). Both the schorl and the beryl enclose many diversely oriented crystals of microcline, quartz, albite, fluorite, and sphene, and thus the pods are distinctly cellular in appearance (Fig. 4). The beryl in their central parts commonly contains sparsely scattered shreds of biotite and muscovite (Fig. 3).

The specimen shown in Fig. 4 was first polished and then partly etched with HF. The polish on the feldspars was completely obliterated and that on the quartz was largely but not completely destroyed, whereas the polish on the beryl was almost untouched. The specimen was then so

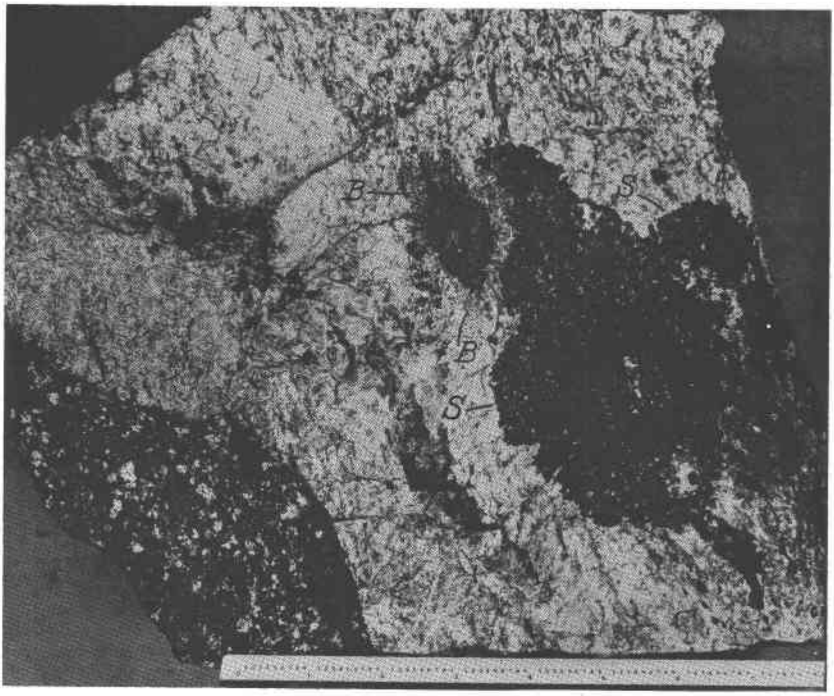

FIG. 2. Specimen of border-zone pegmatite from Bountiful Beryl dike, Mohave County, Ariz., showing sharp contact with biotite-rich country rock (black) at lower left. Large, irregular pod of schorl (S) appears in pegmatite at right, and smaller, beryl-rich pod (B) adjoins it above the center of the specimen. The blue beryl (B) appears dark in this infrared photograph. Note the distinct planar structure in the pegmatite (*cf.* Fig. 1).

oriented in photographing that the brightly polished surfaces of the beryl reflected straight into the camera, according to the photographic technique described by Schaller (1953). It was not possible completely to depolish all of the quartz, but its brightness was greatly reduced; the less brightly reflecting surfaces in the left center of the photograph are quartz.

Each pod of beryl is a single skeletal crystal, and some of those that contain relatively few inclusions of other minerals have rough crystal outlines. The beryl also shows internal crystal faces against numerous poikilitically enclosed masses of quartz and some crystals of schorl. The crystals of feldspar that fringe the pods are markedly euhedral, in contrast to their form elsewhere in the border zone, and they project into the beryl as if they were fringing the coarse, anhedral quartz of a typical miarolitic pod in a granite.

The pods of schorl contain even larger amounts of poikilitically enclosed quartz and other minerals, and some of them are spotted by rough crystals of microcline as much as 1 cm long. The schorl is extremely dark and strongly pleochroic, with $\omega$ = very dark greenish brown and $\epsilon$ = medium brownish olive. The $\epsilon$ index of refraction is 1.645 ± 0.003, and the total iron content of the mineral, determined as $Fe_2O_3$, is 15.6 per cent.

Fluorite is scattered through the border-zone pegmatite as pinkish, white, and very pale yellow-green crystals about 2 mm in average diameter. Sphene is also widely distributed, and is most abundant in and near the pods of beryl and schorl. It also is associated with flakes of biotite in those parts of the border zone that contain included country-rock material. It occurs as the characteristic diamond-shaped crystals, most of them 0.3 mm to 0.5 mm long.

Small crystals of salmon-pink to wine-red spessartite occur mainly in the quartz- and beryl-rich parts of the rock, and commonly are associated with fine-grained, sugary albite. Tiny prismatic crystals of apatite

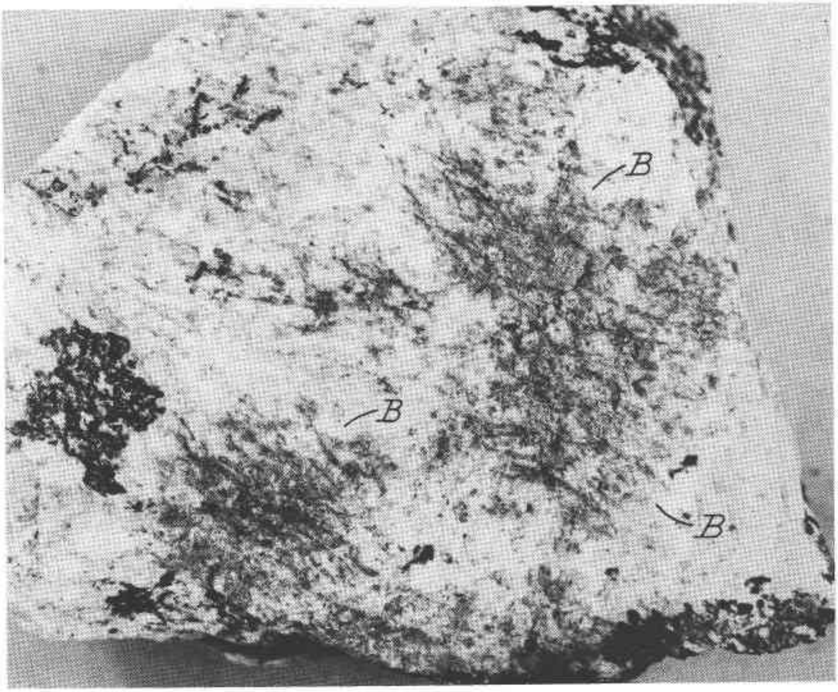

FIG. 3. Specimen of border-zone pegmatite from Bountiful Beryl dike, Mohave County, Ariz., showing irregular podlike masses of beryl (B). The blue beryl appears medium gray in this infrared photograph. The dark mass at the left is mainly schorl.

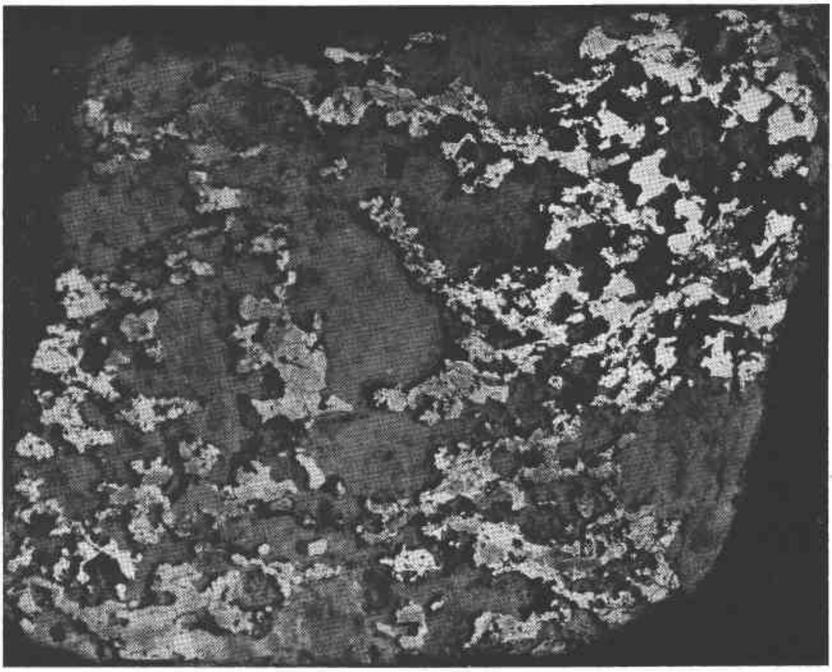

FIG. 4. Polished specimen of border-zone pegmatite, Bountiful Beryl dike, Mohave County, Ariz., showing parts of two beryl-rich pods. The polished surface has been partly etched with HF. The beryl, in the right-hand half and in the lower left-hand part of the specimen, is marked by the brightly reflecting surfaces.

are widespread, and are most abundant as inclusions in schorl. Fine-grained magnetite, hornblende, and allanite occur in the outer parts of the border zone, where they seem to have developed, at least in part, through reaction of pegmatite fluid with wall-rock material.

### C. Other pegmatite

The wall-zone pegmatite, which is distinctly coarser than that of the border zone, contains lesser amounts of beryl and garnet. The crystals of beryl are more euhedral and prismatic in form, and are considerably less crowded with inclusions of other minerals. This rock forms the full thickness of the dike in many places, and elsewhere it grades into a much coarser-grained rock that consists mainly of subhedral to euhedral crystals of coarsely perthitic microcline and subordinate amounts of anhedral quartz. The masses of this very coarse-grained pegmatite, interpreted as segments of a discontinuous core, locally are separated from the more granitoid pegmatite of the wall zone by irregular lenses of crudely formed graphic granite, which may constitute a discontinuous intermediate zone.

Both beryl and schorl are abundant in the perthite-quartz pegmatite of the core, in which they form well-faced prismatic crystals that are relatively free from inclusions of other minerals. Most of these crystals are surrounded by coarse-grained anhedral quartz, and the others lie along contacts between crystals of potash feldspar and quartz. Despite the textural differences between these prismatic crystals of beryl and the blotchy pods of beryl in the border-zone pegmatite, the beryl in both zones has the unusual blue color and high indices of refraction, although that with deepest color and extreme $\omega$ index of refraction occurs only in the border zone. Zoned crystals are common in both parts of the dike, and the beryl of deepest color consistently appears to have been formed earlier than that with lighter colors.

Relative ages of the several pegmatite zones are clearly demonstrated by the cross-cutting relations of numerous apophyses. The inner zones are successively younger than the zones nearer the margins of the dike, although there may well have been considerable overlap in the periods of their formation. Fine-grained, sugary aggregates of albite, quartz, microcline, and garnet, with minor amounts of beryl, fluorite, schorl, and other accessory minerals, form stringers and highly irregular masses in all parts of the dike, but are most abundant in its central parts. Their distribution does not wholly reflect the zonal structure described above, and in places they cut across boundaries between adjacent zones.

## Description of the Unusual Beryl

*Preparation of sample for analysis.* The preparation of a uniform sample of the beryl for analysis was a tedious operation, owing chiefly to the many inclusions of other pegmatitic minerals in the beryl grains, to the small size of the individual grains of fairly pure beryl, and to their variability in specific gravity.

A total weight of 750 grams of beryl-rich border-zone pegmatite was selected and coarsely crushed, and most of its black tourmaline was then removed by hand picking. The remaining material consisted of beryl (5 per cent), fluorite (11 per cent), sphene (13 per cent), and quartz and feldspars (71 per cent), the indicated amounts representing estimates. Tourmaline was present to the extent of less than 1 per cent.

This material was then further crushed to pass a 100-mesh screen, the dust washed out, and the heaviest beryl fraction removed in a mixture of methylene iodide and bromoform. Many repeated separations with heavy solutions, treatment of the recovered beryl fraction with oxalic acid to remove limonitic stain, and further purification with the Franz isodynamic separator finally yielded a 12.5-gram sample (Beryl No. 54, Schaller and Stevens) ready for analysis. This material was found to have a specific gravity of 2.918 and an $\omega$ index of refraction of 1.608.

Later, when it became desirable to repeat the chemical determinations of alkali percentages and no further material of sample No. 54 was available, a second sample (referred to as Beryl No. 55) was prepared from additional border-zone pegmatite. A gross weight of 442 grams of rock was used, and this material was purified as before. The final concentrate of pure beryl (No. 55) weighed 5 grams, had a specific gravity of 2.923 and $\omega$ index of refraction of 1.608, and thus was essentially the same as the first purified sample (No. 54) that was completely analyzed by Stevens. The alkalies in this second sample (Beryl No. 55) were determined gravimetrically by M. K. Carron and with the flame photometer by W. W. Brannock.

*X-ray patterns.* The *x*-ray diffraction pattern of the unusual beryl from Arizona is like the patterns of other beryls but with a slightly larger unit cell. Beryls, both synthetic and natural, that have the lowest indices of refraction and whose chemical compositions are most closely represented by the standard beryl formula, $Be_3 \cdot Al_2 \cdot Si_6O_{18}$, have the smallest unit cell with average values of $a=9.20$ and $c=9.19$. These include the synthetic beryls with $\omega=1.560$ to 1.567, a beryl of very low alkali content from Quebec with $\omega=1.569$, the Colombian emeralds, a beryl from Australia with $\omega=1.583$, and others. The unit cell becomes larger with increase in alkali content, $a$ increasing in length whereas $c$ remains essentially constant. The Arizona beryl has $a=9.30$ and $c=9.20$.

Like other beryls, the strongly ignited Arizona beryl (with loss of 1.62 per cent of $H_2O$) gives the same pattern as the unignited sample, with only slight intensity differences.

*Optical properties and specific gravity.* The beryl is optically uniaxial, negative and pleochroic in crushed grains, $\epsilon$ being decidedly bluish and $\omega$ colorless. The bluish color of $\epsilon$ is strong enough to show faintly in a thin section. The color of the 100-mesh sample that was analyzed corresponds to Ridgway's Light Glaucous Blue, Plate XXXIV 43″ GB.

The following indices of refraction were determined for grains of the analyzed beryl:

| | | | |
|---|---|---|---|
| Beryl No. 54 (Schaller): | $\omega=1.608$, | $\epsilon=1.599$, | B=0.009 |
| Beryl No. 54 (Glass): | $\omega=1.608$, | $\epsilon=1.599$, | B=0.009 |
| Beryl No. 55 (Schaller): | $\omega=1.608$, | $\epsilon=1.600$, | B=0.008 |
| Beryl No. 55 (Stevens): | $\omega=1.609$. | | |
| Beryl No. 55 (Erd): | $\omega=1.608$, 1.607–1.608 | | |

The values[1] $\omega=1.608$ and $\epsilon=1.599$ are the ones taken for this beryl.

The preliminary determination of the $\omega$ index of refraction for the original material yielded an extremely high value close to 1.605, and further study showed that the $\omega$ index for different fragments ranges from 1.595 to 1.610. Corresponding to this, the specific gravity ranges from about 2.80 to 2.92, as observed during preparation of the sample for analysis. Obviously the beryl with maximum indices of refraction ($\omega=1.610$) would be most desirable for chemical analysis, but not nearly enough of this material was available for such investigation. However, a considerable amount of beryl with $\omega$ very close to the maximum value was obtained, and the sample finally analyzed has an $\omega$ index of refraction of 1.608 and a specific gravity of 2.921 (average of 2.918 for Beryl No. 54 and 2.923 for Beryl No. 55).

Pale yellowish green to nearly colorless beryl of the original sample floated in a heavy solution of G 2.80. This material has an $\omega$ index of 1.595±, the minimum value observed for the border-zone beryl. Some greenish beryl from the quartz-rich core of the same pegmatite body has an $\omega$ index as low as 1.586, but this material was not studied further.

Almost identical values of $\omega$ were obtained independently by Jahns, who determined a range of 1.598 to 1.605 for the more greenish border-zone beryl, a range of 1.607 to 1.610 for the more bluish beryl, and a range of 1.608 to 1.610 for the deepest blue beryl. The more greenish beryl with $\omega=1.598$ to 1.600 is nonpleochroic to very faintly pleochroic in crushed fragments. Appreciably lower indices of refraction characterize the coarse-grained beryl from quartz-perthite-albite-garnet pegmatite in the central part of the main pegmatite dike. The average value of $\omega$ for this material is about 1.590 to 1.592. Some have an index slightly lower than 1.590, and all have an index lower than 1.595.

During the operation of the Franz isodynamic separator the beryl with $\omega=1.609$ to 1.610 was found to be the most magnetic, whereas that with $\omega=1.599$ to 1.601 was found to be the least magnetic. This suggests that the very high indices of this beryl are due in large part to its total iron content and not solely to its contained cesium.

When strongly ignited (blasted) the bluish beryl No. 54 becomes brownish gray in color, and its fragments are almost opaque as observed in immersion oils under the microscope. The ignited material has a mean $\omega$ index of about 1.575. This represents a decrease of about 2 per cent in the index of refraction, which is about twice as great as the decreases reported for several beryls by Gavrusevich and Sarapulov (1941).

---

[1] We thank our colleagues, Miss J. J. Glass and Mr. R. C. Erd, for their contribution in establishing these values.

*Chemical analysis.* Because of the refractory nature of beryl and the presence of such uncommon constituents as Be, Li, and Cs, the conventional methods of rock analysis were of necessity much modified.

One of the difficulties encountered in the analysis of beryl stems from failure of the usual procedures to effect complete decomposition of the sample, which must be accomplished before the analysis can proceed. Numerous failures of this type made considerable inroads on the limited quantity of Beryl No. 54 available for analysis. In decomposing the beryl for the determination of the major constituents, it was necessary to flux the sample as usual with five times its weight of $Na_2CO_3$, to leach the product with water, filter, and ignite the residue, and to repeat the sodium carbonate fusion on the residue, using half as much $Na_2CO_3$ as in the first fusion. Difficulties also were encountered in decomposing samples with HF and $H_2SO_4$, preparatory to titration of ferrous oxide with permanganate, as well as in the J. Lawrence Smith decomposition with $NH_4Cl$ and $CaCO_3$ for determination of alkalies, and in the modification of this method using $BaCl_2$ (Stevens, 1940).

Beryllium was determined, after its collection in the $R_2O_3$ group at pH 7, according to the method described by Stevens and Carron (1946).

Alkalies were determined by a modification of the procedures described by Wells and Stevens (1934). Cesium and potassium were weighed as chloroplatinates, and these were fractionally precipitated in order to separate the bulk of the less soluble $Cs_2PtCl_6$ from the more soluble $K_2PtCl_6$, after which the procedure outlined in the foregoing reference was followed on the soluble fraction. As a check, the alkali determinations on Beryl No. 55 were twice made gravimetrically by M. K. Carron, and once made with the flame photometer by W. W. Brannock. All results are in essential accord.

Results of analyses of Beryl No. 54, and of the essentially identical Beryl No. 55, are shown in Table 1.

## STRUCTURAL INTERPRETATION

*The beryl structure.* Beryl has a fundamentally columnar, honeycomb-like structure (Bragg and West, 1926). Each column is hollow, and consists of stacked hexagonal rings that are formed by linked silicon-oxygen tetrahedra. As indicated in Fig. 5, the columns are arranged in a hexagonal pattern, and their long axes are parallel to the *c*-axis of the crystal. Each ring, or cyclic $Si_6O_{18}^{12-}$ ion, is bonded by means of beryllium and aluminum ions to the rings above and below it in the column, and to other rings in adjacent columns, as well.

Each beryllium ion occupies a position of tetrahedral coordination between two columns and is surrounded by four oxygen ions from four different rings. Each aluminum ion occupies a position of octahedral coordination between three columns and is surrounded by six oxygen ions from six different rings (Fig. 5). The silicon ions are in tetrahedral

TABLE 1. ANALYSIS OF UNUSUAL BLUISH BERYL FROM THE BOUNTIFUL BERYL PEGMATITE, WRIGHT CREEK RANCH, NEAR PEACH SPRINGS, MOHAVE COUNTY, ARIZONA

| Beryl No.[1] | 54 | | 55 | | | Average |
|---|---|---|---|---|---|---|
| Analyst | Stevens[2] | | Carron[2] | | Brannock[3] | |
| $SiO_2$ | 59.54 | 59.50 | — | — | — | 59.52 |
| $BeO$ | 12.41 | 12.56 | — | — | — | 12.49 |
| $Al_2O_3$ | 10.73[4] | 10.53[4] | — | — | — | 10.63 |
| $Fe_2O_3$ | 2.11 | 2.04 | — | — | — | 2.08 |
| $Cr_2O_3$ | 0.09 | — | — | — | — | 0.09 |
| $Sc_2O_3$ | 0.10[5] | — | — | — | — | 0.10 |
| $FeO$ | 2.24 | — | — | — | — | 2.24 |
| $MnO$ | 0.29 | 0.28 | — | — | — | 0.29 |
| $MgO$ | 2.17 | 2.15 | — | — | — | 2.16 |
| $TiO_2$ | 0.05 | — | — | — | — | 0.05 |
| $Li_2O$ | 0.21 | — | 0.22[6] | 0.33 | 0.17 | 0.23 |
| $Na_2O$ | 1.23 | 1.12 | 1.05[6] | 1.16 | 1.24 | 1.16 |
| $K_2O$ | 0.21[7] | — | 0.17 | 0.16 | 0.11 | 0.16 |
| $Cs_2O$ | 6.32 | — | 6.70 | 6.80 | 6.90 | 6.68 |
| $CaO$ | 0.12 | 0.09 | — | — | — | 0.11 |
| $BaO$ | None | — | — | — | — | — |
| $H_2O$ | 1.59 | — | 1.65[8] | — | — | 1.62 |
| $P_2O_1$ | 0.27 | — | — | — | — | 0.27 |
| | | | | | | 99.88 |
| G | 2.918 | — | 2.923[9] | — | — | 2.921 |

[1] The beryl numbers refer to the numbers assigned to the different beryls discussed by Schaller and Stevens.

[2] The alkalies were determined gravimetrically. The first column gives the results obtained on sample twice sintered with $NH_4Cl$ and $CaCO_3$, the second column on sample twice sintered with $BaCl_2$ and $CaCO_3$.

[3] The alkalies were determined by the flame photometer on sample sintered with $NH_4Cl$ and $CaCO_3$.

[4] After deduction of 0.10 per cent $Sc_2O_3$ from the values first reported as $Al_2O_3$.

[5] Determined spectrographically by H. J. Rose, Jr., under the supervision of K. J. Murata, on a second sample of Beryl No. 55 with a specific gravity range of 2.89 to 2.92.

[6] Brannock obtained, by flame photometer on Carron's solutions, $Li_2O=0.17$, $Na_2O=1.10$.

[7] Includes any $Rb_2O$ present.

[8] Determined by Penfield tube method, using PbO as flux, in a furnace designed by Lee C. Peck of the U. S. Geological Survey.

[9] Determined by J. J. Fahey.

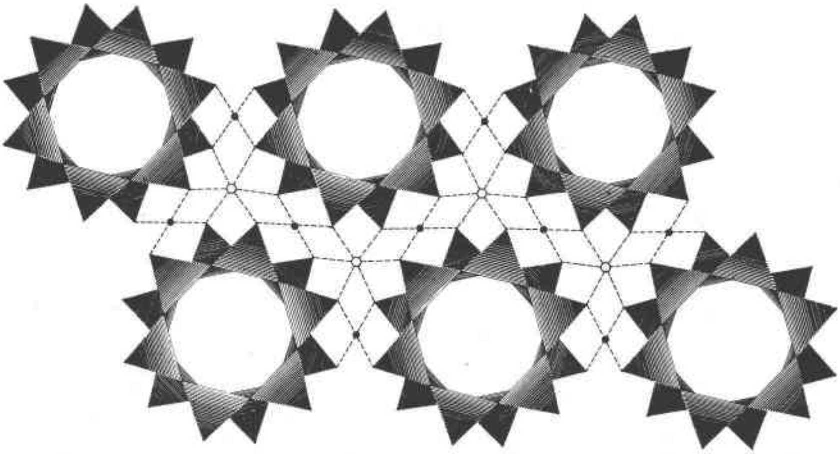

FIG. 5. The structure of beryl, $Be_3Al_2Si_6O_{18}$, projected on a plane normal to the *c*-axis. Each ring of shaded tetrahedra represents a cyclic $Si_6O_{18}^{12-}$ ion, and the corners of the tetrahedra represent the centers of $O^{2-}$ ions. The solid black circles represent the centers of $Be^{2+}$ ions, and the open circles and centers of $Al^{3+}$ ions. Modified from Evans (1948).

positions that surround the large tubular channels in the centers of the columns (Fig. 6). The structure is nicely adjusted to the radius-ratio requirements of the various cation-oxygen combinations and fully satifies Pauling's valency-bond rule. Each oxygen ion not involved in linkage of the silicon-oxygen tetrahedra is bonded to one $Be^{2+}$ ion, one $Al^{3+}$ ion, and one $Si^{4+}$ ion.

Without regard to the alkalies and other minor constituents that enter into the structure of natural beryls, the standard formula for beryl is written $Be_3 \cdot Al_2 \cdot Si_6O_{18}$, the different structural positions in the expression being separated by dots. Complexities arise, however, when consideration is given to the other elements that are present in most beryls. In particular, the alkali ions are too large to occupy the positions of tetrahedral and octahedral coordination within the structure, and it is apparent that these cations must occupy the only spaces that are large enough to accommodate them—the otherwise vacant channels that lie parallel to the *c*-axis (Figs. 5, 6). The positive charges contributed by these large ions must be balanced by cation substitutions elsewhere in the structure.

Some investigators have held that no ions can be placed in the channels, as the valences of the nearest oxygen ions are used wholly in the linking of the silicon-oxygen tetrahedra. This argument, however, holds only for the case of an ideal crystal, whereas in this instance it seems necessary to recognize the existence of a defect structure in order to

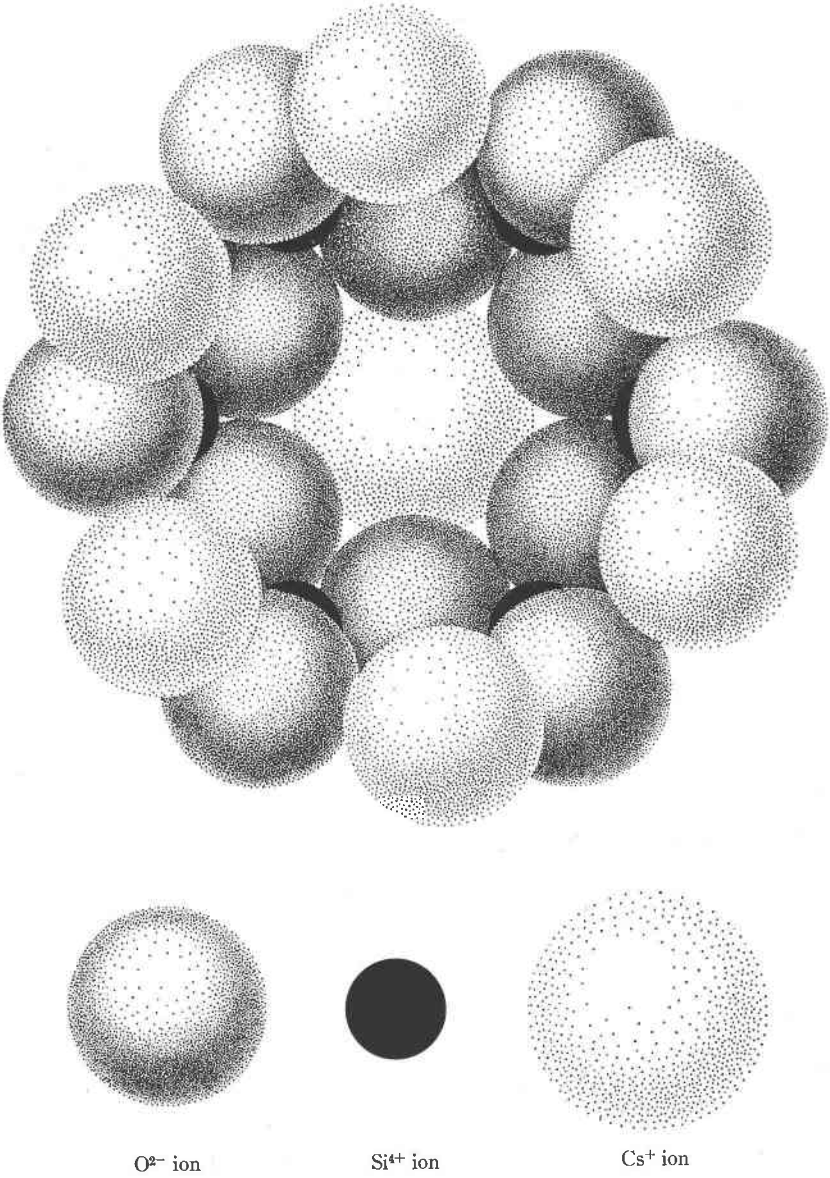

FIG. 6. Ring-like arrangement of linked $SiO^4$ tetrahedra around channel in the beryl structure, projected on to (0001). Adapted from Bragg and West (1926). Owing to stacking of these $Si_6O_{18}$ rings, each channel contains relatively open "pockets" that are regularly spaced like beads on a string. Each "pocket" is sufficiently large to accommodate the $Cs^+$ ion, one of which is shown in the center of the diagram.

account for the alkali ions that are know to occur in nearly all natural beryls, and in substantial amounts in many of them. Introduction of these large cations in the channels, where they can occur in proper 6-fold and 12-fold coordination, and concomitant substitution of smaller ions of appropriate charge in cation positions between the columns, yields a reasonably stable defect structure. Although it does not satisfy the valency-bond rule in detail, this structure does meet the radius-ratio requirements of the constituent ions and achieves gross electrical neutrality. As will be shown in the following paragraphs, it also provides a logical explanation for the occurrence and quantitative proportions of most minor constituents in the mineral.

*Calculation of atomic ratios.* The simple standard formula for beryl, $Be_3 \cdot Al_2 \cdot Si_6O_{18}$, contains 18 oxygen atoms to give 36 negative charges or hydrogen equivalents. These 36 equivalents of oxygen must be balanced by the same number of cation equivalents in order to develop a neutral structure, the various cations being assigned to positions within the structure according to their respective sizes.

Sodium, potassium and cesium are by far the largest of the cations. The lithium ion is much smaller and can replace the aluminum ion in octahedral coordination. The aluminum ion in turn is sufficiently small to replace the beryllium ion in tetrahedral coordination. Substitutions of these and other ions are discussed later on.

In the calculation of atomic ratios (Table 2), the percentages found in the analysis are first calculated to equivalents, $e$, by dividing the percentage of each constituent by its equivalent weight (the molecular weight divided by the total positive valence in the formula of the constituent). These are summed ($\sum e$) and are recalculated to make their sum ($\sum e'$) equal to 36, in accord with the standard unsubstituted beryl formula. The atomic ratios are then obtained by dividing each of these equivalents ($e'$) by the valence of the particular metal.

In the Arizona beryl the 6.00 equivalents of the aluminum in the unsubstituted formula, $Be_3Al_2Si_6O_{18}$, are reduced to 5.47 (from column $e'$) by lithium, bivalent iron, manganese, and magnesium, and the difference 0.53 ($6.00-5.47$) is essentially balanced by 0.56 equivalent in the large-cation positions in the open channels.

*Interpretation of Analysis.* In their general study of beryl, Schaller and Stevens considered nearly 100 published analyses (excluding several obviously poor and incomplete old analyses in which no alkalies were reported), as well as 15 new, unpublished analyses by Stevens. Comparison of these analyses indicates that the lithium substitutes for aluminum in octahedral positions, the displaced aluminum being shifted to take the place of beryllium in tetrahedral positions. The additional positive charge needed for balance is supplied by the large alkali cations (Na and Cs) in the channels of the structure. Thus the formula for the cesium-lithium beryl end-member is $Cs \cdot Be_2Al \cdot AlLi \cdot Si_6O_{18}$. These analyses show atomic ratios of Si and Al essentially the same as that in the unsubstituted beryl formula, $Be_3Al_2Si_6O_{18}$; they also show, through the derived formulas, that increases in Li are balanced by equal decreases in Be with equal increases in large alkali cations.

Because so many analyses have been found by Schaller and Stevens approximately to represent an isomorphous series between $Be_3 \cdot Al_2 \cdot Si_6O_{18}$ and $(Na, Cs) \cdot Be_2Al \cdot AlLi \cdot Si_6O_{18}$, this isomorphous series can be taken as adequately defining the composition of most beryls. Thus, the physical and optical properties of most beryls can be considered as resulting from various proportions of these two end-members in solid solution, with

TABLE 2. CALCULATION OF ATOMIC RATIOS, BERYL NO. 54

| Coordination | Analysis | | Equivalent ratios | | Atomic ratios | | | |
|---|---|---|---|---|---|---|---|---|
| | | | e | e′ = 6.0424 e | | | | |
| Tetrahedral | $SiO_2$ | 59.52 | 3.9627 | 23.944 | Si | 5.986 | | |
| | BeO | 12.49 | 0.9984 | 6.033 | Be | 3.017 | | |
| | | | | Σ Tet. | | | 9.003 | 9.00 |
| Octahedral | $Al_2O_3$ | 10.63 | 0.6257 | 3.781 | Al | 1.260 | | |
| | $Fe_2O_3$ | 2.08 | 0.0781 | 0.472 | $Fe^{3+}$ | 0.157 | | |
| | $Cr_2O_3$ | 0.09 | 0.0036 | 0.022 | Cr | 0.007 | | |
| | $Sc_2O_3$ | 0.10 | 0.0043 | 0.026 | Sc | 0.009 | | |
| | | | | Σ Triv. | | | 1.433 | |
| | FeO | 2.24 | 0.0623 | 0.376 | $Fe^{2+}$ | 0.188 | | |
| | MnO | 0.29 | 0.0082 | 0.050 | Mn | 0.025 | | |
| | MgO | 2.16 | 0.1071 | 0.647 | Mg | 0.324 | | |
| | | | | Σ Femags | | | 0.537 | |
| | $Li_2O$ | 0.23 | 0.0154 | Li 0.093 | Li | 0.093 | 0.093 | |
| | | | | Σ Oct. 5.467 | | 2.063 | | 2.06 |
| Large cations | $Na_2O$ | 1.16 | 0.0374 | 0.226 | Na | 0.226 | | |
| | $K_2O$ | 0.16 | 0.0034 | 0.020 | K | 0.020 | | |
| | $Cs_2O$ | 6.68 | 0.0474 | 0.286 | Cs | 0.286 | | |
| | CaO | 0.11 | 0.0039 | 0.024 | Ca | 0.012 | | |
| | | | | Σ L.c. 0.556 | | | 0.544 | 0.54 |
| | | | Σe 5.9579 | Σe′ 36.000 | | | | |

Factor used to convert e to $e' = \frac{36}{5.9579}$ or 6.0424.

minor substitution of other elements for those in the formulas.

Brief study of the atomic ratios in Table 2 shows that the unusual beryl from Arizona does not conform to this isomorphous series. Its beryllium content is not decreased in atomic proportion corresponding to its content of large alkali ions, but instead remains in essentially the same proportion with respect to silica as in the unsubstituted formula, $Be_3\cdot Al_2\cdot Si_6O_{18}$. In further contrast with most beryls, its atomic ratio of Si to Al is not near 6 to 2, but is closer to 6 to 1.

The close approach to a ratio of 6 Si to 3 Be in the Arizona beryl (Table 2) at first suggests that only end-members formulas having this ratio of Si to Be can be used to express the composition. Such formulas are $(Na_2,Ca)\cdot Be_3\cdot AlLi\cdot Si_6O_{18}$, $(Na, Cs)\cdot Be_3AlR^{2+}$, $Si_6O_{18}$, and $Be_3Al_2\cdot Si_6O_{18}$. However, use of the lithium beryl formula, $(Na_2Ca)\cdot Be_3\cdot AlLi\cdot Si_6O_{18}$, results in a serious deficiency of large cations; 0.72 large cation equivalent is thereby required, whereas only 0.56 equivalent is shown in Table 2. A much better fit of the analysis to a combination of end-member formulas is obtained by assigning a different lithium beryl formula, $(Na, Cs)\cdot Be_2Al\cdot AlLi\cdot Si_6O_{18}$, to one end-member, as was done by Schaller and Stevens to explain the composition of most beryls.

The ferromagnesian constituents of the Arizona beryl (Table 2) cannot be reconciled with any combination of standard beryl and lithium beryl formulas. A third end-member, represented by the femag beryl formula $(Na, K, Cs)\cdot Be_3\cdot R^{3+}R^{2+}\cdot Si_6O_{18}$, is required to account for the total composition. The atomic ratios in Table 2 indicate that the Arizona beryl can be regarded as the following combination of end-members:

| *End-member* | *Formula* | *Formula Per cent* |
|---|---|---|
| Standard beryl | $Be_3\cdot R^{3+}\cdot Si_6O_{18}$ | 36 |
| Lithium beryl | $(Na, Cs)\cdot Be_2Al\cdot AlLi\cdot Si_6O_{18}$ | 9 |
| Femag beryl | $(Na, K, Cs)\cdot Be_3\cdot R^{3+}R^{2+}\cdot Si_6O_{18}$ | 55 |
| | | 100 |

In these formulas $R^{3+}$ represents Al, $Fe^{3+}$, Cr, and Sc, and $R^{2+}$ represents $Fe^{2+}$, Mn, and Mg. These type formulas can be resolved into formulas representing the individual ions, as shown below. Calculated weight percentages of the individual formulas have been modified slightly in accord with combination of ions in the formulation and attendant adjustments for balance.

| *Standard beryl formulas* | *Weight per cent* | *Weight per cent* |
|---|---|---|
| $Be_3\cdot Al_2\cdot Si_6O_{18}$ | 29 | — |
| $Be_3\cdot Fe_2^{3+}\cdot Si_6O_{18}$ | 9 | — |
| Total per cent of general standard beryl formula.................. | | 38 |

| | | |
|---|---|---|
| *Lithium beryl formulas* | | |
| $Na\cdot Be_2Al\cdot AlLi\cdot Si_6O_{18}$ | 5 | — |
| $Cs\cdot Be_2Al\cdot AlLi\cdot Si_6O_{18}$ | 0 | — |
| Total per cent of general lithium beryl formula | | 5 |
| *Femag beryl formulas* | | |
| $Na\cdot Be_3\cdot AlFe^{2+}\cdot Si_6O_{18}$ | 21 | — |
| $K\cdot Be_3\cdot AlMg\cdot Si_6O_{18}$ | 3 | — |
| $Cs\cdot Be_3\cdot AlMg\cdot Si_6O_{18}$ | 33 | — |
| Total per cent of general femag beryl formula | | 57 |
| | 100 | 100 |

The two methods yield percentages of formula types that are in good agreement, considering the several adjustments that must be made in such calculations. Clearly the composition of the Arizona beryl is dominated by that of the femag end-member.

In Table 3 the composition calculated from the percentages of the end-members, above, is compared with that shown by the original analysis. The values are in fairly close agreement, which indicates that the formulation is essentially correct.[1]

Water is not included in any of the end-member formulas, as the water in natural beryls evidently occurs within the open channels as molecules that are not essentially bound to the structure. The *x*-ray diffraction pattern of strongly ignited beryls, with all the water driven off, do not differ from the patterns of the unignited material. That the water is uncombined, although given off at temperatures far above 100° C. (about 800°), is indicated by the infrared absorption studies of Lyon and Kinsey (1942). Thus the position of this occluded water in the structure appears to be similar to that of helium, small quantities of which are known to be accommodated in the tubular channels of many beryls.

---

[1] After the basic substitutional relationships had been worked out for the beryl structure, it was found that Machatschki, and later Schiebold, had previously suggested the same relationships. In his "Noten" (pp. 103–104) to his paper on the structure and constitution of the feldspars, Machatschki (1928) raised the question as to the role played by the alkalies and bivalent elements other than beryllium (our femags) in beryl and suggested that Al (but not the large alkali cations) could substitute for Be, that the large cations (the alkalies) could be placed in the channels of the beryl structure, and that necessary compensation of charges could be obtained through substitution of $O^{2-}$ by $(OH)^{1-}$. Three years later, in his abstract of the paper on beryls by Zambonini and Caglioti (1928), Machatschki (1931) added his own comments on the substitutions in beryl and stated that Li, as well as Mg, Fe, and Mn, could substitute for Al (our lithium beryl and femag beryl formulas), and that the large alkali cations, as well as $H_2O$, can be accommodated in the otherwise unoccupied channels of Bragg's beryl structure. Similar views, with some additional suggestions of possible substitutions in beryl, subsequently were advanced by Schiebold (1935).

TABLE 3. CALCULATED COMPOSITION OF THE ARIZONA BERYL (BERYL NO. 54)

| | 1 Analysis | 2 Adjusted analysis | 3 Col. 2 recalculated to 100 per cent | 4 Composition calculated from percentages of end-members | 5 Differences between cols. 3 and 4 |
|---|---|---|---|---|---|
| $SiO_2$ | 59.52 | 59.52 | 60.84 | 60.67 | −0.17 |
| BeO | 12.49 | 12.49 | 12.76 | 12.41 | −0.35 |
| $Al_2O_3$ | 10.63 | 10.63 | 10.86 | 11.01 | +0.15 |
| $Fe_2O_3$ | 2.08 | 2.27 | 2.32 | 2.42 | +0.10 |
| $Cr_2O_3$ | 0.09 | | | | |
| $Sc_2O_3$ | 0.10 | | | | |
| FeO | 2.24 | 2.53 | 2.59 | 2.56 | −0.03 |
| MnO | 0.29 | | | | |
| MgO | 2.16 | 2.16 | 2.21 | 2.20 | −0.01 |
| $TiO_2$ | 0.05 | — | — | — | — |
| $Li_2O$ | 0.23 | 0.23 | 0.24 | 0.13 | −0.11 |
| $Na_2O$ | 1.16 | 1.16 | 1.19 | 1.38 | +0.19 |
| $K_2O$ | 0.16 | 0.16 | 0.16 | 0.25 | +0.09 |
| $Cs_2O$ | 6.68 | 6.68 | 6.83 | 6.97 | +0.14 |
| CaO | 0.11 | — | — | — | — |
| $H_2O$ | 1.62 | — | — | — | — |
| $P_2O_5$ | 0.27 | — | — | — | — |
| Total | 99.88 | 97.83 | 100.00 | 100.00 | |

The function of the small amount of $P_2O_5$ present in the Arizona beryl is not known. It cannot all be referred to apatite, as not enough CaO is present. If the P ions are considered as substitutes for Si ions in the structure, and hence in the formula, it makes little difference in the atomic ratios noted above. No $P_2O_5$ was found in an $HNO_3$ extract of a crushed sample of the Arizona beryl. Apatite, if present, is probably enclosed in the beryl and hence not susceptible to acid extraction.

The 0.05 per cent of $TiO_2$ in the analyzed sample may well be due to admixed sphene or leucoxene abundantly present in the pegmatite host of the beryl. One tenth of 1 per cent of sphene would account for the $TiO_2$ found. Similarly, the 0.11 per cent of CaO may well be due to admixed other minerals, such as sphene, fluorite, and apatite. A small fraction of 1 per cent of any of these three minerals would account for the CaO found. The 0.16 per cent of $K_2O$ is taken as belonging to the beryl, although traces of microcline may have contributed a little. Slightly more than half the analyses of other beryls report small amounts of $K_2O$, but it is possible that some of the reported $K_2O$ might actually be $Cs_2O$.

*X-ray data and physical properties.* *X*-ray data for the Arizona beryl reveal small but distinct structural differences with respect to other beryls. A comparison of the *x*-ray diffraction patterns of colorless synthetic beryl[1] and the Arizona beryl (Table 4) shows that the unit cell of the latter is larger, *a* for the synthetic beryl being 9.21 whereas that for the Arizona beryl is 9.30. The data recorded in Table 4 are only for that part of the patterns up to $2\theta$(Cu)35°, which includes the six strongest lines of each pattern in addition to other weaker lines. Beyond this limit, correlation of lines cannot be conveniently made, as would be expected from the differences in the chemical composition of the two beryls. Measurements on the films were made by Fred A. Hildebrand with a detached millimeter scale and are considered by him to be accurate to at least ±0.05 mm ($2\theta$). We are greatly indebted to Mr. Hildebrand for his *x*-ray data on these beryls, for his calculations of the unit cells, and for his constant assistance and advice in interpreting the obtained values.

TABLE 4. COMPARISON OF *X*-RAY POWDER DIFFRACTION PATTERNS[1] AND VALUES OF THE UNIT CELLS OF TWO BERYLS

| | Synthetic Beryl No. 169 *X*-ray film 7989 | | | Arizona Beryl No. 54 *X*-ray film 7988 | | |
|---|---|---|---|---|---|---|
| hkl | *d*(Å) | *a* | *c* | *d*(Å) | *a* | *c* |
| (100) | 7.97 | 9.20 | — | 8.04 | 9.28 | — |
| (002) | 4.60 | — | 9.20 | 4.60 | — | 9.20 |
| (200) | 3.98 | 9.21 | — | 4.00 | 9.25 | — |
| (112) | 3.26 | 9.21 | — | 3.27 | 9.31 | — |
| (210) | 3.01 | 9.21 | — | 3.04 | 9.30 | — |
| (211) | 2.88 | 9.21 | — | 2.89 | 9.33 | — |
| (300) | 2.66 | 9.21 | — | 2.68 | 9.30 | — |
| (212) | 2.52 | 9.20 | — | 2.54 | 9.31 | — |
| (004) | 2.30 | — | 9.20 | 2.30 | — | 9.20 |
| | Av. | 9.21 | 9.20 | | 9.30 | 9.20 |

[1] CuK$\alpha$ (Ni filter), $\lambda = 1.5418$ Å.

Physical properties of nine beryls are shown in Table 5. Three discordant values are present. In Beryl No. 108, emerald from Muzo, the value of 9.396 given for *a* by Schiebold (1935) seems too high for a beryl with low specific gravity of 2.690. Could 9.396 be a misprint for 9.196? The values given by Villalba (1953) for both *a* and *c* seem to be considerably

---

[1] Beryl No. 169, Schaller and Stevens, made by C. F. Chatham of San Francisco and presumably free from any constituents other than $SiO_2$, BeO, and $Al_2O_3$.

TABLE 5. CORRELATION OF SIZE OF UNIT CELL WITH OTHER PROPERTIES FOR DIFFERENT BERYLS

| Beryl No. | Material | Reference | G | $\omega$ | B | $a$ | $c$ | $c/a$ |
|---|---|---|---|---|---|---|---|---|
| 169 | Synthetic, colorless | This paper | 2.635 | 1.560 | 0.003 | 9.21 | 9.20 | 0.999 |
| 57 | Synthetic, Igmerald | Schiebold (1935) | 2.651 | 1.566 | .007 | 9.185 | 9.216 | 1.003 |
| 60 | Calculated values | Bragg and West (1926) | 2.661 | (1.567) | — | 9.21 | 9.17 | .996 |
| 107 | Emerald, El Chivor | Schiebold (1935) | 2.694 | 1.575 | .006 | 9.207 | 9.170 | .996 |
| 108 | Emerald, Muzo | Schiebold (1935) | 2.690 | 1.578 | .007 | 9.396 | 9.212 | .980 |
|  | Misprint in $a$? |  |  |  |  | 9.196 | 9.212 | 1.002 |
| 59K | South Dakota | Huttenlocher (1954) | 2.713 | (1.581) | — | 9.22 | 9.18 | .996 |
| 46 | Australia | Norrish (1950) | 2.714 | 1.583 | .006 | 9.188 | 9.189 | 1.000 |
| — | Emerald, Muzo | Villalba (1953) | — | — | — | 9.51 | 9.36 | .984 |
| 54 | Arizona | This paper | 2.921 | 1.608 | .009 | 9.30 | 9.20 | .989 |

out of line. He indicates $a=9.5077$ and $c=4.681$ ($2X=9.362$). His figures are rounded off to $a=9.51$ and $c=9.36$, and differ appreciably from previous values, possibly because the too low (for an emerald) specific gravity of 2.66 was used in his calculations.

The values given in Table 5 seem to indicate that in the unit cell of beryl, it is only the $a$ direction that shifts with changes in the chemical composition, the $c$ direction remaining constant in length. The beryl numbers listed in the first column of this table refer to the identifying numbers used by Schaller and Stevens, and the values of $\omega$ that are enclosed by parentheses are derived from the specific gravity versus omega index variation curve established by the same investigators.

Increases in the values of the indices of refraction, the birefringence, and the specific gravity, as constituents other than $SiO_2$, BeO, and $Al_2O_3$ enter into the composition of beryls, are shown by the data in Table 6. It is clear that the unusual composition of the Arizona beryl results in extremely high values for these physical properties.

TABLE 6. VARIATION IN PROPERTIES OF BERYLS

| Beryls | Percentage of constituents other than $SiO_2$, BeO, and $Al_2O_3$[1] | $\epsilon$ | $\omega$ | B | G |
|---|---|---|---|---|---|
| Colorless synthetic | 0 | 1.557 | 1.560 | 0.003 | 2.635 |
| Synthetic emerald | 3 | 1.563 | 1.567 | 0.004 | 2.67 |
| Common | 1–5 | 1.564–1.584 | 1.570–1.590 | 0.006± | 2.67–2.76 |
| High cesium | 7–10 | 1.590 | 1.599 | 0.009 | 2.86± |
| Arizona | 15 | 1.599 | 1.608 | 0.009 | 2.92 |

[1] Excluding $H_2O$.

## ORIGIN

The detailed studies of this Arizona beryl indicate that it differs fundamentally in composition from the other beryls investigated by Schaller and Stevens. It is a high-alkali variety with unusually low lithium, low aluminum, high beryllium, and high bivalent Fe and Mg content. Further, it exhibits an unusual type of isomorphous replacement with respect to other beryls. These features bespeak special conditions of formation, for which strong supporting evidence is provided by the rocks in which the beryl occurs.

The geological factors that bear on the genesis of the beryl are best considered in terms of relationships within the Bountiful Beryl dike, the most fully studied of the pegmatite bodies in the area. This dike has a roughly symmetrical internal zoning characterized by a progressive increase in general grain size from the margins of the dike inward to its center. Irregular masses of fine-grained albite and quartz, most abundant in the central parts of the dike, constitute the only major exception to this textural trend.

The structural relations between each pair of zones indicate that the dike was consolidated inward from its margins, although there may well have been much temporal overlap in the development of adjacent zones. It also should be noted that the border zone consists in part of hybrid rock, the composition of which reflects considerable digestion of wall-rock schist and gneiss.

Beryl is present in all of the zones, but it is most abundant in the fine- to medium-grained border zone and in the coarse- to very coarse-grained core. The earliest-formed beryl in each zone contains the highest percentages of cesium, iron, and magnesium, as shown by the zonal relations within individual crystals, and in general the beryl in the border zone of the dike is richer in these elements than the beryl in the core of the dike. This is quite the reverse of the relations ordinarily observed in the beryls of zoned pegmatites, where cesium tends to be concentrated in the latest-formed crystals (*e.g.*, Landes, 1925; Fersman, 1931; Cameron *et al.*, 1949, pp. 69, 99; Jahns and Wright, 1951; Heinrich, 1952; Jahns and Adams, 1953), and hence requires an explanation.

The pegmatite fluid plainly contained sufficient beryllium to permit crystallization of beryl at a relatively early stage in the development of the dike. As indicated by the quartz, feldspar, and other minerals of the border zone, both silicon and aluminum were present in abundance, which evidently favored the formation of beryl rather than chrysoberyl or phenakite. The chrysoberyl structure is fundamentally similar to the olivine structure (Bragg and Brown, 1926) and his high thermal stability, but probably it would be developed at an early stage of crystallization only if the Al:Si ratio in the pegmatite fluid were exceptionally high. Similarly, the phenakite structure probably would be developed at an early stage only if the Al:Si ratio were very low and the Be content of the fluid were extremely high. Thus, where both beryl and phenakite occur in the same pegmatite body, the phenakite is at least in part younger than the beryl (Lemke *et al.* 1952; Adams, 1953) and presumably reflects a progressively increasing concentration of beryllium in the system. On the basis of known occurrences in Colorado and elsewhere, Adams 1953, pp. 100–101) concludes that "it is more probable that the formation of phenakite instead of beryl is a result of differences in the chemical environment, not lower-temperature conditions."

With development of the beryl structure early in the crystallization of the Bountiful Beryl dike, it seems likely that the unusual composition of the mineral is a direct reflection of the relatively high iron and magnesium content of the pegmatite fluid at that state. These elements evidently were derived in large part from digestion of country rock that contained abundant biotite and other mafic minerals, and their high concentrations led to development of numerous crystals of iron-rich tourmaline in the border zone of the dike. However, not all of the iron and magnesium was used up in the formation of tourmaline, and the concentrations of these elements in the pegmatite fluid seemingly remained high enough to permit incorporation of both into the growing crystals of beryl.

Ordinarily the principal iron-bearing mineral in the outer zones of pegmatites is biotite, but this mineral is relatively uncommon in the Bountiful Beryl dike, despite its widespread occurrence in the adjacent wall rock. It is suggested that the amount of water in the pegmatite fluid was too small to permit development of much biotite during crystallization of the beryl-bearing zones, and that the presumably low viscosity of the fluid was due more to fluorine than to water. This is fully compatible with the known mineralogic features of the dike, and especially with the relative abundance of fluorite and relative scarcity of muscovite and biotite.

The incorporation of bivalent iron and magnesium into the beryl structure, in place of some trivalent aluminum, was not accompanied by substitution of aluminum for beryllium, presumably because of a relatively high ratio of Be to Al in the system. The substitution of iron and magnesium therefore must have imposed an electrostatic gradient that resulted in the strong attraction of large monovalent cations, chiefly $Cs^+$ and $Na^+$, into the tubular channels of the structure, in order to achieve gross electrical neutrality. Thus the distribution of beryl that is richest in cesium does not appear to have been dependent upon variations in the concentration of $Cs^+$ ions in the fluid, as is thought to be the case in most pegmatite bodies; instead, it seems best explained in terms of the amounts of iron and magnesium that entered the structure at a given stage of crystallization, with attendant and necessary "sucking in" of cesium and sodium ions in order to balance the charges within the structure. The concentration of lithium in the system seems to have been very low during all stages of crystallization.

## References

ADAMS, J. W. (1953), Beryllium deposits of the Mount Antero region, Chaffee County, Colorado. *U. S. Geol. Survey Bull.* **982-D,** 95–119.

BRAGG, W. L. AND G. B. BROWN (1926), The crystalline structure of chrysoberyl, $BeAl_2O_4$. *Proc. Roy. Soc. London*, Ser. A, **110,** 34–63; *Zeit. Krist.*, **63,** 122–143.

——— AND J. WEST (1926), The structure of beryl, $Be_3Al_2Si_6O_{18}$. *Proc. Roy. Soc. London*, Ser. A, **111,** 691–714.

CAMERON, E. N., R. H. JAHNS, A. H. MCNAIR, AND L. R. PAGE (1949), Internal structure of granitic pegmatites. *Econ. Geol.*, Mon. **2.**

EVANS, R. C. (1948), An Introduction to Crystal Chemistry, 229–230, Cambridge Univ. Press.

FERSMAN, A. E. (1931), The pegmatites. *Acad. Sci. U.R.S.S.;* Translated from the Russian into French under the direction of R. du Trien de Terdonck and J. Thoreau, 422–423, 535–536, 556, Univ. of Louvain, Belgium, 1951.

GAVRUSEVICH, B. A. AND TH. J. SARAPULOV (1941), On the change of color and optical properties of beryls on heating. *C. R. Acad. Sci., U.R.S.S.*, **31,** 775–778.

HEINRICH, E. W. (1952), Chemical differentiation of multi-generation pegmatite minerals (abs.). *Geol. Soc. Am. Bull.*, **62,** 1261.

HUTTENLOCHER, H., TH. HUGI, AND W. NOWACKI (1954), Röntgenographische und spektrographische Untersuchungen am Bazzit vom Val Strem (Kt. Graubunden, Schweiz). *Experientia*, **10,** 366–367. Röntgenographische und spektrographische Untersuchungen am Bazzit. *Schweiz. Mineral. Petrogr. Mitt.*, **34,** 501–504.

JAHNS, R. H. AND J. W. ADAMS (1953), Beryl deposits in the Harding pegmatites, Taos County, New Mexico (abs.). *Econ. Geol.*, **48,** 328–329.

——— and L. A. WRIGHT (1951), Gem- and lithium-bearing pegmatites of the Pala district, San Diego County, California. *Calif. Div. Mines, Spec. Rept.* **7-A,** 37–38.

LACROIX, ALFRED (1913), Mineralogie de la France, **5,** 13.

——— AND RENGADE (1911), Sur les proprietes optiques des beryls roses de Madagascar. *Soc. Franc. Mineral., Bull.* **34,** 124.

LANDES, K. K. (1925), The paragenesis of the granite pegmatites of central Maine. *Am. Mineral.*, **10,** 374.

LEMKE, R. W., R. H. JAHNS, AND W. R. GRIFFITTS (1952), Mica deposits of the Southeastern Piedmont. Part 2. Amelia district, Virginia: U. S. Geol. Survey Prof. Paper 248-B, 128–131.

LYON, WALDO AND E. L. KINSEY (1942), Infra-red absorption spectra of water moelcules in crystals. *Phys. Rev.*, **61,** 482–489.

MACHATSCHKI, FELIX (1928), Zur Frage der Struktur und Konstitution der Feldspate. Noten. *Central. Mineral.* **Abt. A,** 103–104.

——— (1931), (Abstract of paper by Zambonini and Caglioti (1928). *Neues Jahrb. Mineral., Referate.* **1,** 356–359.

MOORE, B. N. (1936), Arizona beryl, *in* HEWETT, D. F. and others, Mineral Resources of the region around Boulder Dam. *U. S. Geol. Survey Bull.* **871,** 162.

Norrish, Keith (1950), An *X*-ray study of West Australian beryl. *Jour. Royal Soc. West. Australia,* **34** (1947–1948), 1–16.

Schaller, W. T. (1953), A photographic technique for showing some mineral relations. *U. S. Geol. Survey Bull.* **992,** 83–94.

———, and R. E. Stevens, A study of beryl (in preparation).

Schiebold, E. (1935), Vergleichende Untersuchungen an natürlichen und synthetischen Smaragdkristallen. *Zeit. Krist.*, **92,** 454–456.

Stevens, R. E. (1940), Extraction of alkalies in rocks. *Ind. Eng. Chem., Anal. Ed.*, **12,** 413–415.

——— and M. K. Carron (1946), Determination of beryllium in ores. Contributions to Geochemistry, 1942–1945: *U. S. Geol. Survey Bull.* **950,** 94–100.

Villalba, A. M. B. (1953), Estructura de las esmeraldas de Muzo. *Rev. Acad. Colombiana,* **9,** 37–43.

Wells, R. C. and R. E. Stevens (1934), Determination of the common and rare alkalies in mineral analysis. *Ind. Eng. Chem., Anal. Ed.*, **6,** 439–442.

Zambonini, Ferrucio and Vincenzo Caglioti (1928), Ricerche chimiche sulla rosterite di San Piero in Campo (Isola d'Elba) e sui berilli in generale. *Gazz. Chim. Ital.*, **58,** 131–152.

*Manuscript received, September 27, 1961.*