# *Plagioclases from the Juvinas meteorite and from allivalite from the Isle of Rhum.*

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*Summary.* The optical properties and specific gravity, and the variations in these properties, of analysed plagioclases separated from the meteorite (eucrite) from Juvinas, France, are compared with the corresponding values for a terrestrial plagioclase of almost identical composition from an allivalite from Rhum. The range in properties for the Juvinas plagioclase indicates a compositional range from about $Ab_{35}An_{65}$ to $Ab_{15}An_{85}$, but the great majority of grains are bytownite with approximately 83 % (molecular) anorthite.

The frequency of occurrence of the twin-laws of the Juvinas plagioclase resembles that of plagioclase from basalts and allied rocks.

The variable changes and, in some grains, absence of change in the optical properties shown by the Juvinas plagioclase crystals, after heating to 1100° C. for 48 hours followed by rapid cooling, contrasts with the small but constant optical changes shown by the allivalite plagioclase (for which geological evidence indicates slow cooling) after identical heat treatment. It is inferred that the meteoritic plagioclase grains have had differing thermal histories, and that some grains have been subjected to previous natural quenching.

THE main object of this investigation was to collect precise optical data (including optical changes on heating) for the calcic plagioclases of the eucritic meteorites, and to compare the results with those obtained from terrestrial plagioclases.

It was hoped that such information might give further clues to the geological history of this type of meteorite. It was also hoped that the optical data might complement the recent X-ray data of Gay and others as a guide to structural changes produced by heating plagioclases of this composition. Of the stony meteorites, the eucrites and howardites, though few in numbers, offer the most promising field for a study of meteoritic plagioclases. The eucrite from Juvinas, France (B.M. 90262), was chosen for this investigation because of the relative abundance of material and because some X-ray work has already been done upon its felspar. Much briefer examinations were made of the plagioclases from the Pasamonte and Vaca Muerta stones.

The intended comparison of meteoritic felspars with their earthly counterparts required the use of a terrestrial plagioclase as a 'control' upon the investigation. For this purpose the bytownite from the banded allivalite of Barkeval Pass, Rhum (B.M. 1923, 476 [21]), was chosen because of its suitable composition, freshness, and ease of separation.

Determinations were made of the refractive index, the optic axial angle, and the orientation of the indicatrix; the last two properties were also remeasured after heat treatment. Studies were also made of the twin-laws, the specific gravity, and the chemical composition.

## *Methods.*

*Separation.* The first separation of felspar from Juvinas was done by S. W. F. Patching and L. D. Muller of the Atomic Energy Research Establishment at Harwell using an induced roll magnetic separator followed by a Frantz magnetic separator. Subsequent separations (of additional material) and all separations of plagioclase from the allivalite were made in the Department of Mineralogy, British Museum (Natural History), using the Cook magnetic separator. After suitable sizing, the material was repeatedly fed into the separator, the current being progressively increased and the non-magnetic fraction being collected on each occasion until quite free of foreign material. This gave pure samples, uncontaminated by heavy liquids, which were used for the chemical analysis, and for the determinations of specific gravity and refractive index.

*Refractive indices.* The $\beta$ index was determined by the immersion method, using mixtures of eugenol and cinnamic aldehyde. The index of grains showing the central emergence of an optic axis was matched against that of the liquid in sodium light. The refractive index of the liquid was then determined on a Bellingham and Stanley refractometer, which had previously been calibrated against two test pieces of glass having indices close to that of the plagioclase.

*Optic axial angle.* 2V was measured on a Leitz 4-axis universal stage, which had previously been checked with a test piece of topaz of known optic axial angle.[1] Each optic axis was measured ten times in the 45° orientation and ten times in the 135° orientation. The data for 2V are based upon crystals in which both optic axes were directly observable.

*The orientation and 'twin-angle' values* were also determined on the calibrated universal stage. The crystallographic directions were obtained as the twin axes of the various twin-laws and not from cleavages or crystal boundaries, since these latter have been shown by previous investigators to give greater scatter of poles than do the twin-axes.[2] In

[1] Kindly sent by H. W. Fairbairn of the Massachusetts Institute of Technology.

[2] See, for example, H. Tertsch, Tschermaks Min. Petr. Mitt. 1941, vol. 53, p. 56.

general eight to ten measurements were made of each optic vector. It was found that grains so oriented that the three indicatrix axes were about equally inclined to the section normal usually gave less accurate right-angled triangles than grains having one axis near the normal. The accuracy of the stereographic net was checked before beginning the measurements, and the same net was used throughout.

*The twin-laws* (Juvinas plagioclase only) were obtained directly from the twin-angle values, which have now been published for the majority of twin-laws and plagioclase compositions. A rapid plot, constructed from a single measurement of each observable optic vector, usually sufficed to establish the twin-law. The few remaining ambiguous instances were resolved by locating the twin-axis and transposing in the usual way. In order to ensure a random sample, traverses were made across the section at equal intervals and grains equally spaced in each traverse were chosen for determination of the twin-law.

*The specific gravities* were determined in a diffusion column, which was prepared by the careful addition of a bromoform-benzene mixture to a lower bromoform layer in a graduated cylinder; from about 24 to 48 hours after the liquid addition an approximately linear relationship existed between height in the column and specific gravity. The column was calibrated by the insertion of mineral grains the specific gravities of which were determined by suspension in heavy liquid mixtures.

*Heating technique.* The method used was that described by H. G. Owen,[1] the section being mounted on a slide of vitreous silica, and heated in a tube furnace with a platinum–platinum-rhodium thermocouple to a temperature of 1100° C. for a period of 48 hours. Rapid quenches were not attempted owing to risk of fracture. By this means it proved possible to remeasure after heating the same crystals as had been measured before heating, and to detect small optical changes with greater certainty than is possible from determinations on different grains.

*Chemical analysis.* The four major constituents were each determined by at least two independent methods to eliminate, as far as possible, systematic errors. A direct colorimetric comparison was made of the $SiO_2$ percentages of the two felspars in order to confirm the virtual identity of their composition.

## *Results.*

*Refractive index.* The histogram (fig. 1) shows the results of thirty-three determinations of $\beta$ on the plagioclase of the allivalite and the same

[1] Min. Mag. 1957, vol. 31, p. 426.

number on the Juvinas plagioclase. The allivalite felspar measurements form a symmetrical distribution; the mean value of $\beta$ is 1·5760 with a standard deviation[1] of $\pm$0·0010 (equivalent to a range of 1·9 % in anorthite).

By contrast the Juvinas plagioclase measurements form a slightly

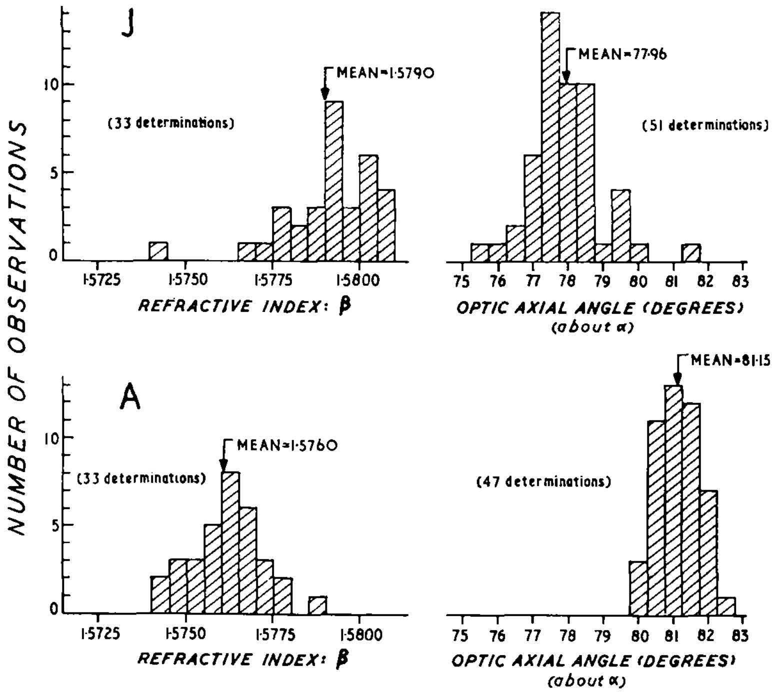


FIG. 1. Refractive index and optic axial angle ranges: $A$ = allivalite; J = Juvinas. The difference between the refractive index mean values corresponds to a 5¾ % anorthite difference. The difference between the optic axial angle mean values corresponds to a 6¾ % anorthite difference.

'skew' distribution with one abnormally low value. Proof of the validity of this low result and corroboration of the asymmetry of the distribution is given by the subsequent discovery, during the diffusion column experiments, of grains with an even lower refractive index (lowest value of $\beta$ = 1·5710). The refractive index distribution for Juvinas consists, essentially, of a 'main group' with limits of 1·577 to 1·581 and a 'tail' extending from 1·577 to 1·571. The overall mean is 1·5790$\pm$0·0013.

[1] In this and all subsequent standard deviations, the small sample correction has been applied.

*Optic axial angle.* The histogram (fig. 1) shows the results of forty-seven determinations of 2V on the allivalite and fifty-one on the Juvinas felspars. The distribution for the allivalite plagioclase is symmetrical; the mean value of 2V about $\alpha$ is $81{\cdot}1°\pm0{\cdot}60°$ (equivalent to a range of 0·9 % in anorthite).

The distribution for the Juvinas plagioclase is approximately symmetrical at its centre. There is, however, a much greater lateral spread than for the allivalite felspar and there is a suggestion in the histogram of a small subsidiary peak towards the higher angular values. The mean value of 2V is $78{\cdot}0°\pm1{\cdot}03°$.

*Orientation of indicatrix.* The crystal directions $\perp$ (010), [001], and $\perp$ [001] in (010) were determined in relation to a fixed indicatrix with $\beta$ at its centre and are shown, superimposed on W. Nikitin's migration curves,[1] in fig. 2. The mean positions of the three poles for the allivalite plagioclase lie on or very close to the curves at points representing 87 to 89 % anorthite. The alignment of the three directions with M. Reinhard's curves[2] is poorer. The (010) pole, for example, lies 3 mm. to the right of its curve.[3] For the Juvinas plagioclase the mean positions indicate a composition of 91 to 93 % anorthite; with the exception of the [001] pole, which falls about 2 mm. to the right (on the 20 cm. scale), the points again lie very close to the Nikitin curves. The scatter of points representing the (010) and [001] directions is considerably greater for the Juvinas than for the allivalite plagioclase. The scatter for $\perp$ [001] in (010) is similar for both felspars.

A more sensitive test of orientation than the plotting of crystal directions is afforded by the values of the 'twin-angles'. These are the angles between each axis of the indicatrix of one twin-member and the corresponding axis of the indicatrix of the other member, viz. the angles $\alpha\alpha_1$, $\beta\beta_1$, and $\gamma\gamma_1$, where $\alpha\,\beta\,\gamma$ are the indicatrix axes for one member and $\alpha_1\,\beta_1\,\gamma_1$ for the other of the twin-pair. The change in these angles with changing orientation is twice the change in the angles between $\alpha$, $\beta$, or $\gamma$ and the twin-axis. Moreover the twin-angles are obtained directly from the stereogram without transposal or location of the twin-axis; they are therefore not subject to the possible small plotting errors arising from these operations.

Additional twin-angle values can be obtained if the optic axes have been located for each twin-member. Thus if *A* and *B* be the two optic

[1] Die Fedorow-Methode. Berlin, 1936, fig. vi.
[2] Universaldrehtischmethoden. Basel, 1931.
[3] These curves are drawn on a stereographic projection of radius 10 cm.

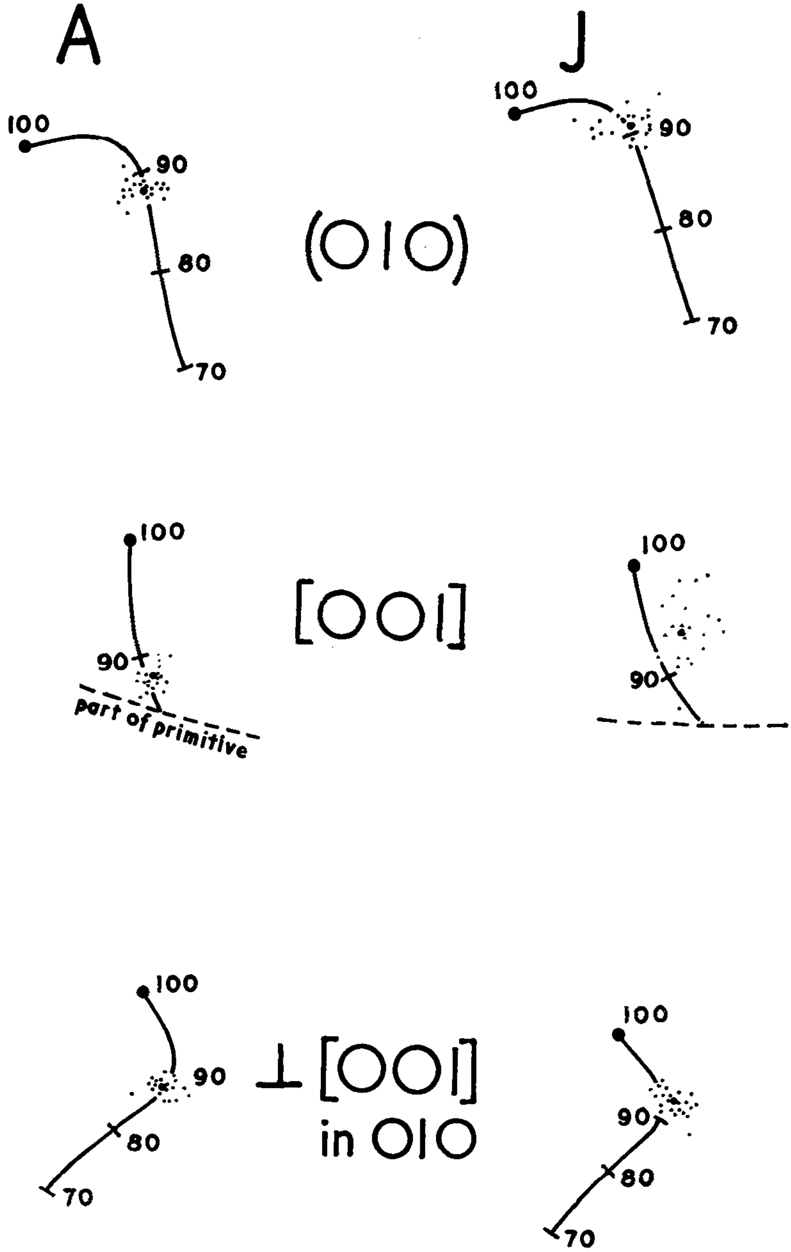


FIG. 2. Migration curves (Nikitin) of the poles of (010), [001], and ⊥ [001] in (010), showing the plotted positions of the poles for the allivalite and Juvinas plagioclases: A = allivalite; J = Juvinas.

axes for one member and $A_1$ and $B_1$ be the optic axes for the other, four angles can be measured, namely $AA_1$, $BB_1$, $AB_1$, and $BA_1$. It was found, however, that of these four angles only $BB_1$ is of practical use in the present investigation. Therefore the twin-angles to which reference is made are $\alpha\alpha_1$, $\beta\beta_1$, $\gamma\gamma_1$, and $BB_1$, measured over the twin-axis.

The values of these angles, and the standard deviations (expressing

TABLE I. Twin-angle values $\alpha\alpha_1$, $\beta\beta_1$, $\gamma\gamma_1$, and $BB_1$ (see text) for allivalite and Juvinas plagioclases. Each figure is the mean of determinations on ten crystals and the standard deviation* $\hat{\sigma}$ for each group is cited. The percentages of anorthite given are deduced from the values of $\alpha\alpha_1$, $\beta\beta_1$, and $BB_1$, for albite twins only (see text).

| Twin-law. | Albite. | | Carlsbad. | | Albite-Carlsbad. | | % Anorthite (albite law only). | |
|---|---|---|---|---|---|---|---|---|
| | Angle. | $\hat{\sigma}$. | Angle. | $\hat{\sigma}$. | Angle. | $\hat{\sigma}$. | | |
| Allivalite $\alpha\alpha_1$ | $63\frac{1}{2}$ | 1·0 | $107\frac{1}{2}$ | 1·4 | 31 | 0·8 | 85 | mean 87 |
| $\beta\beta_1$ | 58 | 1·4 | 177 | 1·6 | $57\frac{1}{2}$ | 1·4 | — | |
| $\gamma\gamma_1$ | $91\frac{1}{4}$ | 1·1 | $72\frac{1}{4}$ | 1·4 | 47 | 0·8 | 90 | |
| $BB_1$ | $6\frac{3}{4}$ | 0·9 | 9 | 1·0 | $6\frac{1}{2}$ | 0·5 | $86\frac{1}{2}$ | |
| Juvinas $\alpha\alpha_1$ | $66\frac{3}{4}$ | 1·6 | $106\frac{1}{2}$ | 1·2 | $28\frac{1}{2}$ | 1·6 | 90 | mean 93 |
| $\beta\beta_1$ | 57 | 2·4 | $172\frac{1}{2}$ | 2·5 | $58\frac{1}{4}$ | 1·7 | — | |
| $\gamma\gamma_1$ | $93\frac{2}{3}$ | 1·9 | 73 | 1·2 | $49\frac{3}{4}$ | 1·4 | 98 | |
| $BB_1$ | $1\frac{1}{4}$ | 0·7 | $9\frac{3}{4}$ | 2·5 | 9 | 1·2 | 92 | |

* The small sample correction $\sqrt{n}/(n—1)$ has been applied.

the scatter of these values) are given in table I for albite, Carlsbad, and albite-Carlsbad twins of the allivalite and Juvinas plagioclases. It is seen that, for most angles, the standard deviations are considerably greater for the Juvinas than for the allivalite felspars. Derivation of the plagioclase composition from these angular values can only be approximate on account of the uncertainty, at this composition, of the published curves. However, the curves for $\alpha\alpha_1$, $\gamma\gamma_1$, and $BB_1$ for albite twins have a sufficiently steep and uniform slope to make it possible at least to estimate the compositional difference between the two felspars, and the result[1] (table I) indicates a 6 % higher anorthite content for the plagioclase from Juvinas.

*Zoning.* No zoned plagioclases were seen in the allivalite sections and zoning is not conspicuous in the Juvinas plagioclase, although a few grains show 'patchy' extinction suggestive of some granulation and stress. In those rare Juvinas crystals in which zoning does occur it is

[1] Composition derived from the curves by H. Tertsch, Tschermaks Min. Petr. Mitt., 1942, vol. 54, figs. 4*a* and 6*a*. The An percentages are based on the high temperature curves because of the greater consistency in the values interpolated on these curves rather than on the low temperature curves.

of normal type: a relatively narrow outer zone of more sodic plagioclase, rather sharply separated from the 'core'. No measured difference between outer and inner zones exceeded 5 % anorthite. Compositional differences of this order were found to result in 5 to 6° triangles of error for the twin-axis, as located from the indicatrix for the inner zone of one twin-lamella coupled with the indicatrix for the outer zone of the other lamella. This is of interest because similar triangles of error were obtained for many unzoned Juvinas crystals (though they were never observed in the allivalite felspars). It must therefore be assumed that composition differences of this magnitude (5 % anorthite content) frequently occur between the paired lamellae of the Juvinas twinned crystals. On heating to 1100° C. (see p. 666) these differences are removed and the crystals become homogeneous.

*Results of heat treatment.* The aim of these experiments was to measure the effect of heat upon the optic axial angle and the orientation. Since the changes were expected to be small it was considered necessary, before heating, to determine the precision with which both 2V and the twin-angle values can be measured. Pairs of measurements were, therefore, made upon sufficient grains to evaluate the probable error of a determination. Fifteen measurements of 2V gave a standard deviation of 0·4°. Fifty-five measurements of twin-angle values gave a standard deviation of just under $1\frac{1}{4}$°.

Differences exceeding twice the value of the standard deviation are usually accounted significant. It may therefore be reckoned that differences in 2V measurements of 0·8° and in twin-angle values of $2\frac{1}{2}$° are significant differences.

*Effect of heat on the optic axial angle. Plagioclase from allivalite.* Re-measurement of 2V in eighteen crystals after heating at 1100° C. for 48 hours gave the results shown in table II. The smallest increase of angle after heating is well above the significance level. A small increase in 2V is thus established beyond doubt. The consistency of the figures for increase is a feature of the table. More than half the individual results are within $\frac{1}{3}$° of the mean value of increase, viz. $2\frac{3}{4}$°.

*Plagioclase from Juvinas.* The small proportion of suitable felspars in thin sections of the meteorite and the experimental difficulties limited the size of the sample to fourteen grains, the results for which are also given in table II. The inference from these figures is of both a smaller and a more variable increase in 2V for the meteoritic than for the terrestrial plagioclase. Two Juvinas crystals actually gave a smaller 2V after heating (though neither of these changes is statistically significant). Only two crystals showed increases comparable with the mean increase shown by the allivalite felspar.

*Effect of heat on twin-angle values. Plagioclase from allivalite.* The changes on heating in the values of $\alpha\alpha_1$, $\beta\beta_1$, $\gamma\gamma_1$, and $BB_1$ were measured for seven grains showing albite twins and for six grains twinned on the

TABLE II. Effect of heat treatment (48 hours at 1100° C.) upon the optic axial angle of allivalite and Juvinas plagioclases.

| 2V before heating. | 2V after heating. | Change in 2V. | 2V before heating. | 2V after heating. | Change in 2V. |
|---|---|---|---|---|---|
| | | *Allivalite.* | | | |
| 81·45 | 82·60 | +1·15 | 81·40 | 84·05 | +2·65 |
| 81·20 | 83·60 | +2·40 | 80·80 | 83·30 | +2·50 |
| 80·35 | 84·05 | +3·70 | 81·20 | 83·70 | +2·50 |
| 80·35 | 83·45 | +3·10 | 80·40 | 82·75 | +2·35 |
| 80·35 | 83·70 | +3·35 | 81·10 | 83·70 | +2·60 |
| 81·70 | 84·20 | +2·50 | 80·85 | 83·30 | +2·45 |
| 80·50 | 83·55 | +3·05 | 80·70 | 82·95 | +2·25 |
| 81·20 | 84·50 | +3·30 | 81·10 | 82·95 | +1·85 |
| 81·30 | 84·15 | +2·85 | 81·20 | 85·70 | +4·50 |
| | | Means | 80·95 | 83·68 | +2·73±0·73* |
| | | *Juvinas.* | | | |
| 77·50 | 79·70 | +2·20 | 76·85 | 78·15 | +1·30 |
| 77·65 | 78·75 | +1·10 | 77·50 | 79·35 | +1·85 |
| 78·30 | 79·50 | +1·20 | 77·60 | 78·80 | +1·20 |
| 79·50 | 82·05 | +2·55 | 78·30 | 80·45 | +2·15 |
| 78·40 | 78·30 | −0·10 | 77·70 | 79·25 | +1·55 |
| 78·00 | 80·05 | +2·05 | 78·05 | 77·40 | −0·65 |
| 76·40 | 78·65 | +2·25 | 78·75 | 81·80 | +3·05 |
| | | Means | 77·89 | 79·44 | +1·55±1·00* |

* Standard deviation; the small sample correction has been applied.

Carlsbad law. Only one crystal with an albite-Carlsbad twin could be remeasured after heating; it was not therefore possible to get significant results for albite-Carlsbad crystals. In order to save space only the changes in the angular values (and not the values themselves) are given in table III. The changes in $\beta\beta_1$ for both twin-laws are below the significance level. The changes in $\alpha\alpha_1$ and $\gamma\gamma_1$, though only just statistically significant, undoubtedly reflect an actual shift in the indicatrix, for the individual values have the same sign throughout. The change in $BB_1$ is quite marked. As a trial showed, one measurement made from a single setting of each $B$ optic axis would have sufficed to measure $BB_1$ with sufficient accuracy to detect the change after heating.

TABLE III. Effect of heat treatment (48 hours at 1100° C.) upon the twin-angle values (see text) for allivalite and Juvinas plagioclases (value before minus value after heating).

Allivalite.

| | $\alpha\alpha_1$. | $\beta\beta_1$. | $\gamma\gamma_1$. | $BB_1$. |
|---|---|---|---|---|
| Albite twins | −3½ | −2¾ | −5¾ | +5 |
| | −½ | −1½ | −2½ | +3 |
| | −½ | −2½ | −1¾ | +5 |
| | −2¼ | −1½ | −3 | +3½ |
| | −2½ | +½ | −1½ | +5 |
| | −2 | −½ | −1½ | +3¾ |
| | −3¼ | −1¼ | −3½ | +5¼ |
| Means | −2 | −1¼ | −2¾ | +4½ |
| Carlsbad twins | −2½ | 0 | +3 | +4¾ |
| | −½ | +3¾ | +1 | +4½ |
| | −3 | +¾ | +2½ | +5¼ |
| | −2¼ | 0 | +2¼ | +4¼ |
| | −2¼ | 0 | +2 | +3¾ |
| | −2¼ | 0 | +1½ | +4 |
| Means | −2¼ | +¾ | +2 | +4½ |

Juvinas.

| | $\alpha\alpha_1$. | $\beta\beta_1$. | $\gamma\gamma_1$. | $BB_1$. |
|---|---|---|---|---|
| Albite twins | 0 | −1½ | −2 | +1¼ |
| | −¼ | −¼ | 0 | 0 |
| | −½ | −2½ | −½ | — |
| | −2½ | +4½ | +2½ | — |
| | −4½ | +2½ | −3¼ | −½ |
| | −½ | −1½ | −2½ | +3½ |
| | −2¾ | +½ | −2½ | +½ |
| | −2 | −½ | −1½ | — |
| | −2¼ | +3¾ | +½ | +5 |
| | +2½ | −3½ | −1 | −2 |
| Means | −1¼ | 0 | −1 | +1 |
| Carlsbad twins | −3½ | +1 | +2½ | — |
| | −4 | 0 | +3½ | +¼ |
| Means | −3¾ | +½ | +3 | +¼ |

The interpretation of these angular changes is shown diagrammatically in fig. 3. The diagram combines the angular changes shown by both the albite and the Carlsbad twinned crystals. It shows that there is a rotation of about 2° of the indicatrix about $\beta$ (i.e. a rotation in the plane of the optic axes). This rotation, combined with an increase in 2V of about 2¾°, keeps the position of the $A$ optic axis almost unchanged, while the $B$ optic axis moves about 4½°.

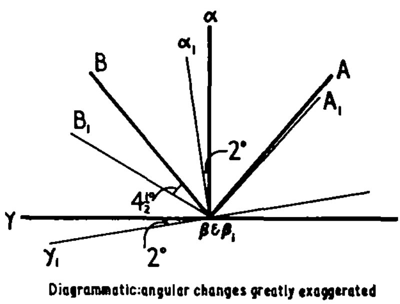


FIG. 3. Allivalite plagioclase: movement of indicatrix and of optic axes on heating. $\alpha$ and $\gamma$ = indicatrix axes, $A$ and $B$ = optic axes before heating; $\alpha_1$ and $\gamma_1$ = indicatrix axes, $A_1$ and $B_1$ = optic axes after heating.

*Plagioclase from Juvinas.* Table III also shows the changes, after heating, in the twin-angle values; unfortunately only two grains with Carlsbad twins could be remeasured. The measurements made on grains with albite-Carlsbad twins have been omitted since no comparison with the allivalite plagioclase is possible. The changes that occur on heating are more variable than those that took place in the allivalite plagioclase. Some crystals show virtually no change after heating (e.g. grain 2 of the albite twins and one grain having an albite-Carlsbad twin). Others show changes comparable with those which occurred in the allivalite plagioclase (e.g. grain 7 of the albite twins). The much reduced mean change in $BB_1$ is, of course, mainly due to the generally smaller increase in 2V compared with its increase in the allivalite felspar.

Owing to the smallness of the sample it is not possible to determine which crystals are unaffected by heating and which are most affected; in other words it is impossible to relate the change to the composition of the crystal (as indicated by the value of 2V). Different crystals belonging to the 'main group' (p. 659) showed both maximum and minimum change. Such as it is, the evidence does not point to a correlation. Unfortunately none of the crystals belonging to the much smaller, more sodic 'tail' (p. 659) could be measured both before and after heat treatment.

Finally, under the results of heat treatment, reference must be made to the homogenizing effect on twinned Juvinas plagioclases, in which the two twin-members, before heating, were of presumably different composition. Evidence for this is given by the prevalence of triangles of error in the location of the twin-axes at the intersection of great circles through $\alpha\alpha_1$, $\beta\beta_1$, and $\gamma\gamma_1$. Thus nine of the ten albite twinned Juvinas crystals listed in table III, before heating, gave triangles of error. After heating the triangles were, in every instance, reduced in size—in five instances almost to vanishing point. The allivalite plagioclases seldom gave triangles of error for the twin-axes before heating. The few exceptions (small triangles) were unaffected by the heat treatment.

*Twin-law frequencies for Juvinas plagioclases.* Determination of the twin-laws on 111 crystals (randomly located in two thin sections) gave the following percentage frequencies: albite 33 %, Carlsbad 18 %, albite-Carlsbad 25 %, pericline (and acline) 11 %, Manebach 9 %, Baveno 3 % (2 % 'right', 1 % 'left'), albite-Ala 1 %, Ala $<$ 1 %. Virtually all types of twinning are, therefore, present in Juvinas plagioclases, but albite, Carlsbad, and albite-Carlsbad twins represent more than three-quarters of the total.

Of ten 'threelings' which were measured, five showed combinations of albite and Manebach or Carlsbad and Manebach twins. The remaining five showed combinations of albite and Carlsbad, albite and pericline, Carlsbad and pericline, and albite-Carlsbad and pericline twins. One of two 'fourlings' showed an albite-Ala association; the other showed a combined albite, Carlsbad, and albite-Carlsbad twin.

*Specific gravities.* A sample of approximately 3 000 grains of each plagioclase was placed in the diffusion column during the period in which a linear relationship existed between height and specific gravity.

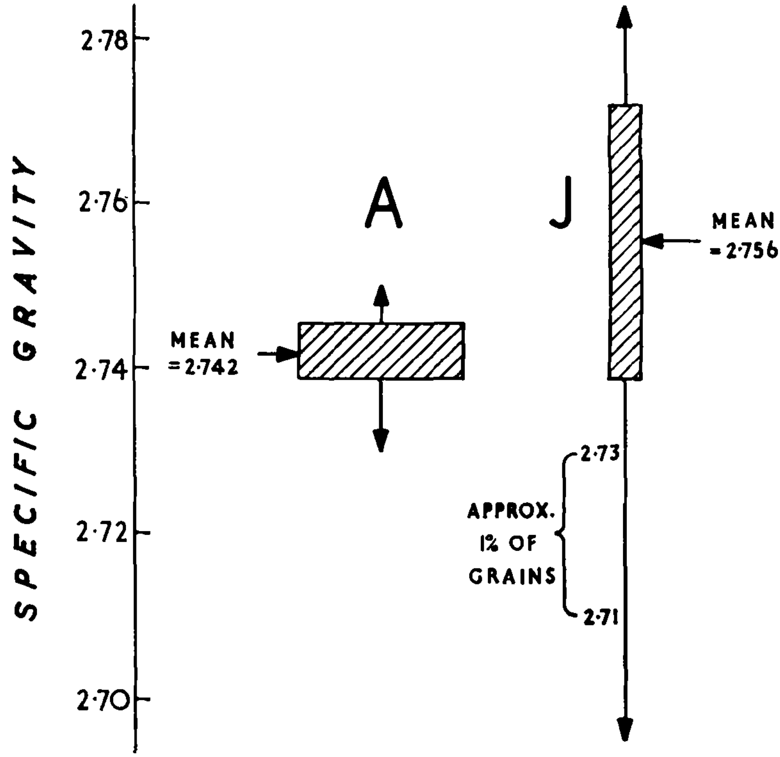


FIG. 4. Specific gravity ranges: A = allivalite; J = Juvinas. The main layer is shown shaded. The arrows indicate the extensions of the scattered grains above and below the main layer. The rectangles are of equal area, denoting approximately equal numbers of grains. The difference between the means corresponds to a 7¾ % anorthite difference.

The allivalite felspar then formed a narrow, compact layer with scarcely any noticeable 'fringe'.

The Juvinas plagioclase, by contrast, formed a main layer five times as broad as the allivalite felspar layer and divided into coalescing zones. This 'main' layer showed 'fringes' of scattered grains, particularly on the upper side (lower sp.gr.). The specific gravity limits of the main layer and of the extensions above and below it are shown diagrammatically in fig. 4.

Optical examination of several of the plagioclases of abnormally low gravity showed no inclusions, bubbles, &c., that could account for these values. It was also found that their refractive indices were abnormally low (see p. 659). These results show that some plagioclase grains from Juvinas are as sodic as $Ab_{35}An_{65}$, but the proportion of such grains having a composition markedly different from the main mass is small and probably does not exceed 1 %.

TABLE IV. Chemical analyses of plagioclases from allivalite (B.M. 1923, 476, [21]) and from the Juvinas meteorite (B.M. 90262); analyst: P. M. Game.

| | 1. | 2. | | 1a. | | 2a. | |
|---|---|---|---|---|---|---|---|
| $SiO_2$ ... | 46·66 | 46·59 | Si ... | 8·643 | 16·02 | 8·662 | 15·98 |
| $Al_2O_3$ ... | 33·40 | 33·42 | Al ... | 7·290 | | 7·322 | |
| $Fe_2O_3$ ... | 0·62 | — | $Fe^{\cdot\cdot\cdot}$ ... | 0·087 | | | |
| FeO ... | — | 0·80 | $Fe^{\cdot\cdot}$ ... | — | | 0·124 | 4·17 |
| CaO ... | 16·50 | 16·40 | Ca ... | 3·273 | 4·02 | 3·265 | |
| $Na_2O$ ... | 1·98 | 2·04 | Na ... | 0·711 | | 0·735 | |
| $K_2O$ ... | 0·16 | 0·20 | K ... | 0·038 | | 0·047 | |
| $H_2O+$ ... | 0·49 | 0·43 | O ... | | 32·00 | | 32·09 |
| | 99·81 | 99·88 | | | | | |
| Sp. gr. | 2·742 | 2·756 | | | | | |

Molecular composition (see text):
1. An 82·5, Ab 16·6, Or 0·9.
2. An 82·6, Ab 16·3, Or 1·1.

1. Plagioclase from allivalite.
2. Plagioclase from Juvinas.

*1a, 2a.* Empirical unit-cell contents, calculated using the determined specific gravities and cell volumes interpolated from values given by W. F. Cole, H. Sörum, and W. H. Taylor: Acta Cryst. 1951, vol. 4, pp. 22 and 23 [M.A. 11–427].

*Composition.* The results of the analyses of both plagioclases are given in table IV, and the unit-cell contents, derived therefrom, are also shown. The 4 % excess of alkalis in the unit cell of the Juvinas plagioclase mainly results from the inclusion of the FeO. No better balance can be obtained in the lattice, however, by substituting this Fe″ for Al. It seems possible that part of this ferrous iron derives from minute pyroxene inclusions in the Juvinas felspar and should be regarded as an impurity. Subsequent microscopic examination with a magnification of about ×400 confirms the presence of numerous rod-like inclusions, width 1 to 4 $\mu$, length 10 to 40 $\mu$, often showing parallel orientation.

Since it was considered that $SiO_2$ was the most reliably determined oxide (three independent determinations for each plagioclase differed by only 0·1 %) the molecular compositions were derived as the means of the values obtained, on the one hand, from the $SiO_2$ percentages, and, on the other, from the ratio of CaO to total alkalis. A direct colorimetric comparison of the $SiO_2$ contents of the two plagioclases gave: $SiO_2$ (allivalite plagioclase) : $SiO_2$ (Juvinas plagioclase) = 1·000 : 1·003. The difference is within the limits of experimental error. From this result and from the complete analyses the composition of the two plagioclases can thus be considered to be virtually identical. It is therefore surprising to find that independent optical properties and specific gravity values consistently indicate an anorthite content for the Juvinas plagioclase higher by 6 to 7 % than that for the plagioclase of the allivalite.

In table V the mean values, the difference in these means, and the

TABLE V. Compositional differences in Juvinas and allivalite plagioclases inferred from optical and specific gravity values.

| | | Mean value. Allivalite. | Mean value. Juvinas. | Difference between means. | Corresponding difference in anorthite percentage. |
|---|---|---|---|---|---|
| Refr. index ($\beta$) | ... | 1·5760 | 1·5790 | 0·0030 | 5¾ % |
| $2V_{\alpha}$ ... ... | ... | 81·1° | 78·0° | 3·1° | 6¾ % |
| Twin-angle (albite twins) $\alpha\alpha_1$ | ... | 63½ | 66¾ | 3¼° | 6% (mean) |
| Twin-angle (albite twins) $\gamma\gamma_1$ | ... | 91¼ | 93¾ | 2½° | |
| Twin-angle (albite twins) $BB_1$ | ... | 6¾ | 1¼ | 5½° | |
| Sp. gr. ... ... | ... | 2·742 | 2·756 | 0·014 | 7¾ % |

corresponding anorthite percentage differences are given for three independent optical parameters and for the specific gravity. The anorthite differences were obtained by taking, from recently published data[1] relating optics and specific gravity to anorthite content, a mean figure for the rate of change at this composition.

A fraction of the indicated difference in anorthite content may be due to the greater range in composition of the Juvinas felspar, which, as shown on p. 668, includes a small percentage of plagioclase as sodic as $Ab_{35}An_{65}$. Optical determinations on somewhat limited samples might not have accorded true representation to this small proportion of grains of a different composition. Also the possible substitution, in the Juvinas plagioclase, of Ca atoms by about 4 % of Fe″ atoms, of smaller ionic radius and greater mass, might be expected to have some influence on the lattice, and to raise the specific gravity and possibly the refractive

[1] G. C. Kennedy, Amer. Min., 1947, vol. 32, p. 562, fig. 1 [M.A. 10-267]; F. Chayes, Amer. Journ. Sci., 1952, Bowen vol., pt. 1, p. 96, table 5 [M.A. 12-134]; R. M. Crump and K. B. Ketner, Mem. Geol. Soc. Amer., 1953, no. 52, p. 31, fig. 6; A. N. Winchell and H. Winchell, Elements of Optical Mineralogy, 4th edn, 1951, pt. 2, p. 316; E. Wenk, Schweiz. Min. Petr. Mitt., 1945, vol. 25, p. 369, fig. 1; A. Poldervaart, Amer. Min., 1950, vol. 35, p. 1069, fig. 1 [M.A. 11-389]; H. Tertsch, Tschermaks Min. Petr. Mitt., 1942, vol. 54, p. 206, fig. 4a, and p. 208, fig. 5a [M.A. 9-270].

indices. However, X-ray powder photographs of the two felspars, recorded with a camera of 11·46 cm. radius, showed no differences.

## *Discussion.*

*Twinning and composition.* The twinning of the Juvinas plagioclase quite closely resembles that of the plagioclases of terrestrial basalts and allied types. Thus twin-law frequencies for the Juvinas plagioclase compare as follows with the frequencies (in parentheses) for the plagioclases of 'basaltic' rocks, calculated from about 2 400 determinations made by six investigators:[1] albite, Carlsbad, and albite-Carlsbad 76 % (79·4 %), pericline and acline 11 % (11·8 %), Manebach 9 % (5·1 %), Baveno 3 % (1·4 %), albite-Ala 1 % (1·6 %), Ala $<$ 1 % (0·7 %).

It is not easy to account for the frequent differences between contiguous twin lamellae of the Juvinas plagioclase. Although such differences have often been noted in the intermediate plagioclases, their presence in bytownites and anorthites is rare. In such calcic plagioclase, according to R. C. Emmons and V. Mann,[2] a very small or negligible compositional difference is the rule. It is possible that these differences (derived from optical measurements) are caused by strain and have no chemical foundation. Strains have certainly affected the meteorite, as shown by the discontinuous twinning and 'patchy' extinction of some of the felspars.

An alternative explanation is that the twinning may have replaced original zoning so that, as Emmons and Mann believe, 'the difference in composition of contiguous twin lamellae, in part at least, substitutes for the difference in composition between zones'. In view of the compositional range recorded in the Juvinas plagioclase, the likelihood of original zoning seems high; indeed, traces of it still remain. The elimination of these differences on heating is probably due to the greater molecular diffusion at these relatively high temperatures.

The compositional range supports a theory of formation by crystal settling in a differentiating magma.

*Cooling conditions.* Inferences on the thermal history of the Juvinas

[1] C. T. Barber, Mem. Geol. Surv. India, 1936, vol. 68, pt. 2, p. 224, table 6 [M.A. 7-21]; M. Gorai, Amer. Min., 1951, vol. 36, p. 885, table 1 [M.A. 11-489]; W. Larsson, Bull. Geol. Inst. Univ. Upsala, 1941, vol. 28, p. 373 [M.A. 9-177]; G. Paliuc, Schweiz. Min. Petr. Mitt., 1932, vol. 12, p. 428 [M.A. 5-436]; W. R. Chapman, Amer. Min., 1936, vol. 21, p. 39, table 2 [M.A. 6-293]; A. Vendl, Tschermaks Min. Petr. Mitt., 1931, vol. 42, pp. 491-550; Vendl's results summarized by H. Wieseneder, ibid., 1933, vol. 44, p. 203.

[2] Mem. Geol. Soc. Amer., 1953, vol. 52, p. 42.

plagioclase must depend upon a comparison between the results of the heating experiments on this felspar on the one hand and on the plagioclase from the Rhum allivalite on the other.

The bytownite from the Rhum allivalite can be assumed to have crystallized from the magma at a high temperature and to have cooled extremely slowly. In fact, G. M. Brown[1] has shown that there was little decrease of temperature during the lengthy period of deposition of 2600 feet of the 'layered series'.

Although P. Gay[2] was unable to detect any difference in the X-ray powder pattern of this plagioclase after 3 days' heat treatment at 1100° C. it has been shown that 2 days' heating at 1100° C. did, in fact, produce small but significant optical changes which showed considerable constancy in size and direction; these optical changes are probably caused by movement in the calcium (and sodium) ions only; the X-ray evidence suggests that higher temperatures (about 1300° C.) are needed to bring about disordering of the Si-Al distribution. The relatively rapid cooling of the artificially heated allivalite did not allow complete reversal of the structural change in its plagioclase, whereas it seems reasonable to believe that the very slow natural cooling of this same felspar did permit a complete return to its original structural state; it is thus the totally different order of the cooling rates that is responsible for the structural (and therefore optical) differences. Had it proved possible to repeat Nature's extremely slow cooling, the allivalite plagioclase would presumably have emerged from the heat treatment unaltered.

The plagioclase from Juvinas, after identical heat treatment, behaved differently, at least in part. In the first place some grains showed no optical change after heating. Secondly the changes that did occur varied from grain to grain both in magnitude and in direction. Those Juvinas plagioclases that showed no change after heating must be assumed to have been subjected to previous natural quenching; repetition of the earlier, natural cycle would then be expected to leave the final structure unaltered. Other crystals presumably underwent slower cooling; in a few, which showed changes comparable with those in the allivalite plagioclase, the cooling may have been slow and uninterrupted.

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[1] Phil. Trans. Roy. Soc., 1956, ser. B, vol. 240, p. 48.
[2] Min. Mag., vol. 30, 1954, table 1, p. 433.