An Examination of the Plagioclases of Some Hekla Lavas.

By

HENNING SØRENSEN.

Abstract.

The examination was undertaken by means of the universal stage. It is concluded that fine results may be obtained by combining the determination methods of REINHARD and KÖHLER. The last-named method seems to give the most accurate determinations of the anorthite content of the plagioclases.

The plagioclases of the lavas have chiefly high-temperature optics, but low-temperature optics are encountered too.

Devitrification has caused the formation of inverse zonal structure of the plagioclases of the older lavas.

Introduction.

In the autumn of 1948 Professor A. NOE-NYGAARD handed over to me a series of thin sections of lavas from the Icelandic volcano *Hekla*. The rock samples of which the sections were made were collected by Dr. G. KJARTANSSON of Reykjavik. Most of the known eruptions of Hekla are presumably represented in the samples, including the last eruption in April, 1947.

A considerable number of careful measurements made on the universal stage are published in this paper, since it is found to be of importance to get as much data on the optics of the plagioclases as possible. Several works on the subject have been published already, but only a few in English. Some remarks will, therefore, be made on the determination methods used in the present work.

Description of the Rock Material.

The petrography of the lavas will be described by Professor NOE-NYGAARD. Only information of importance to the following will therefore be given here.

The rocks are aphanitic or fine-grained with small phenocrysts of plagioclase. The very dense groundmass, the grain size of which is less than 0.01 mm, usually contains tiny laths of plagioclase which often have forked ends and as a rule consist of only two twin lamellae. In addition, pyroxene and iron ore are observed in the groundmass of some sections. Glass may be the dominant component. This is especially true of the lavas of the eruption of 1947. The older lavas are generally devitrified to such a degree that the glass has totally disappeared.

The structure varies. Some sections have the small plagioclase laths orientated at random, while others have a pronounced flow structure with the plagioclase grains arranged parallel to one another. The elongation of the pores of the lavas is often parallel to the flow direction.

A few rocks have a more coarse-grained groundmass with a grain size larger than 0.1 mm. This applies especially to the oldest lavas and is probably most often due to devitrification, in which case there is no regularity in the arrangement of the minerals. The coarse-grained rocks may, however, have flow structure too.

The phenocrysts mainly consist of plagioclase, but pyroxene and olivine are also encountered. The amount of the phenocrysts is very variable. A few sections have no phenocrysts at all. The most common thing is to have rather few plagioclase laths, not very much larger than the plagioclase of the groundmass, but some sections have a multitude of larger plagioclase grains, many of which attain a fairly large grain size. The range of the size of the phenocrysts is approximately from 0.5 × 0.1 mm to 2.0 × 0.5 mm.

The plagioclase phenocrysts are lath-shaped with well-developed crystal faces, the prismae, pinacoid and dome faces often being easily distinguishable. The outlines of the grains are very sharp and well defined. Certainly, corrosion phenomena are common, but apart from some of the oldest lavas it is only of a superficial nature as it has given rise to a thin outer "woollen" zone, which is often pigmented to some extent. Perfectly fresh grains are very common. Some sections have more than one generation of plagioclase; the oldest are thoroughly corroded with ragged margins and numerous inclusions. They may have undulating extinction.

Zonal structure is rather rare. When it is present there are always only a few zones. The border between the zones may be enriched in inclusions. Inverse zonal structure is found in the older lavas.

By far the largest part of the plagioclase phenocrysts are twinned. Two or a very few lamellae are the most common; in rare cases polysynthetic twinning is seen. The larger grains are as a rule not richer in lamellae than the smaller ones. The lamellae comprising the twins may be separated by inclusions of the groundmass or by corrosion surfaces. Inclusions of glass within the plagioclase are not rare.

The Twin Laws and the Forms of Intergrowth.

The dominant twin laws are, as might be expected, the albite, Carlsbad and complex albite-Carlsbad twin laws. Intergrowths, comprising three lamellae twinned according to the three abovementioned laws, are very common. The central lamella is often very thin and has a lower anorthite percentage than the two broader lamellae according to the REINHARD curves (see pag. 525). Repeated twinning is rare and is mostly found as a few thin lamellae between a couple of broader, all of them being twinned according to the albite law.

Manebach twins are very frequent, and in addition acline and Ala twins are encountered. Pericline twins are very rare, and so are albite-Ala twins. Baveno twins have never been observed.

The only planes of composition encountered are (010) and (001) as all measured Carlsbad twins have (010) as the composition face. Although observations are scarce, it seems as if either one or the other of the composition planes is present in each section. This does not mean that the presence of the one excludes the other, but there is always a very pronounced dominance of one of the planes. If this is true, it may be of some importance for determining the relationship between the lava flows, especially where (001) is the composition face. The method by which the maximum extinction angle of the albite twins is used for the determination of the anorthite content fails here, as the Manebach twins are mistaken for albite twins.

Unfortunately, it is not possible to present a table of the frequency of the twin laws because a table of this sort would conceal the actual conditions, because of the fact that in several of the sections it was only possible to make determinations on a single phenocryst. But it appears that the Manebach twin law is more frequent in the Hekla lavas than otherwise stated in the literature. The accompanying table might give some hints about this.

It is strange that a widely distributed twin law as the pericline law is only observed a few times here. It probably depends on the existence of the very simple twinning, with twins consisting of only a very few lamellae. Therefore, more complicated forms of twinning in which both composition planes are represented, are very rare. Even the largest phenocrysts are usually lath-shaped and elongated parallel to the direction determined by the composition plane.

Several forms of irregular intergrowth have been observed. Thus simultaneous growth of lamellae having seemingly flowed together while the lava was still fluid, has often been encountered. Especially the Carlsbad twins have this way of intergrowth (KÖHLER and RAAZ, 5). In most cases the intergrowth is almost complete so that the way of formation may be indicated only by a corrosion surface between the lamellae of a twin pair. In a few cases the intergrowth is not complete. For instance, in the two lamellae of an intergrowth, the indicatrix axes may have the opposite orientation of the one demanded if a twin law should be fulfilled; or the lamellae of a twin pair may have the theoretically correct orientation of the indicatrix axes, but they are rotated less than 180° around the twin axis. The most common irregularity is that the lamellae have not reached perfect parallellism.

The Methods Used in the Determinations.

A LEITZ universal stage with four axes, model UT4, mounted on a LEITZ microscope, model KM, was used together with the special objectives UM 3 and 4, which are provided with an iris.

The measurements have been carried out *ad modus* REINHARD (11) and the results are interpreted from his tables 2, 3, 4 and 5.

Unfortunately, it was almost impossible to make determinations on the tiny plagioclase laths of the groundmass of the lavas. Therefore, the main part of the measurements were carried out on the phenocrysts. This gives the results a one-sidedness as most of the determinations are made on the first-formed crystals. But where it was possible to determine the composition of the groundmass plagioclase, it was found that the difference in composition between the two generations of plagioclases is of so small an order, due to the rapid cooling of the lavas, that the method used is justified. In a few sections it was necessary to make the measurements on untwinned plagioclase grains. The orientation of the indicatrix in relation to the cleavages was determined. The migration curves of REINHARD's table 2 gave the composition. In these doubtful cases, RITTMANN's *zonenmethode* (12) was used as a control. The results usually showed a rather good agreement. In this way it was possible to get information on the plagioclases of the groundmass.

The indicatrix axes and the composition faces were used for the determinations. In addition the cleavages and the optic axes were measured where possible, but they were found to be of less value than the first mentioned as they are the measurements connected with the most serious errors. The composition face and the twin axis were determined by means of the stereograms of REINHARD's table 2 and 5. Thereby, the twin law was determined together with two values for the anorthite per cent.

It is often indicated in the literature that the adjustment of the composition face is connected with greater uncertainty than the adjustment of the indicatrix axes. This is quite true where the twin lamellae are broad and easily measurable. But where the grains are small and the twin lamellae are thin, the adjustment of the composition face is in many cases more accurate than the determination of the extinction positions. This is especially true of normal twins. For the sake of uniformity in the determinations, the composition face was always used.

The REINHARD method controls itself quite well, as we know that the sides of the spherical triangles of the stereogram will amount to 90° and that the great circles through corresponding projections of the indicatrix axes in the two triangles of a twin pair will intersect in one point only if the measurements are accurate. Therefore, the uncertainty of the measurements is of no high order, provided the equipment is properly adjusted.

The Low and High Temperature Optics.
The KÖHLER Method.

The measured poles rarely fitted the curves of REINHARD's table 2. They were arranged in a rather broad zone to the right of the migration curves. A diagrammatic representation of the scattering corresponds entirely with the figure published by H. TERTSCH (13, fig. 1), but the poles of the present investigation are situated in another region than are those depicted by TERSCH.

This constant position to the right of the curves is often mentioned in the literature on effusive rocks (HOMMA (1), PAULIAC (10), WENK (15), LARSSON (8), KÖHLER (3) a. o.).

A. KÖHLER has offered an explanation of the deviation to the right. He states that the plagioclases have a low-temperature as well as a high-temperature optic. As Reinhard's curves are constructed on data on deep-seated rocks, which have the low-temperature optics of the plagioclases, it is only natural that plagioclases of effusive rocks, which have the high-temperature optics, do not fit the curves.

It must now be regarded as a well-established fact that the high-temperature optics exist, above all after the investigations made by Köhler and his collaborators. The present work can only confirm this.

Köhler (3) has published curves for the determination of the composition of the high-temperature plagioclases twinned according to the most common twin laws (albite, Carlsbad, complex albite-Carlsbad). He uses the angles between corresponding projections of the indicatrix axes in the stereogram. Unfortunately the curves are rather incomplete, but Tertsch (14) has given supplementary determinations so that the curves now cover the important region 43–100% An. G. v. der Kaaden (2) has, in addition, given curves for the Manebach and the Baveno twin laws.

It is possible to construct curves for the remaining twin laws by means of the stereographical projection. It is not done here because the data available are still rather incomplete.

As, for instance, the albite and the acline twin laws have approximately the same twin axis and twin plane because the normal to (010) deviates only a few degrees from [010], it is seen that the existing curves may give some hints as to the optics of the plagioclases that are twinned according to some of the remaining twin laws.

Concerning the accuracy of the Köhler curves it is seen that in comparison with the Reinhard curves they have the advantage of showing the distinction between plagioclases of low- and high-temperature optics. At the same time they give at least three determinations of the anorthite content. Most of the curves are very steep. That means that a slight change in composition, which is represented as the abscissa of the diagram, corresponds to a great change of the Köhler values, which appear as the ordinate of the diagram. This kind of curve is the best for determination purposes, but on the other hand it must be remembered that the angle value may vary within rather wide limits without making any change in the composition. A closer discussion of the curves will follow on pag. 530.

The Köhler curves AA, BB and AB are not used in this work for the following reasons: It is true that the measurements must be very exact if the results obtained from these curves are identical with those obtained from the $\alpha\alpha$, $\beta\beta$ and $\gamma\gamma$ curves. But in a case like this, the last-named curves will probably give the same good agreement. If there is an incongruity between the values obtained from the two sets of curves, it does not necessarily mean that the measurements are of no value; it is because of the adjustment of the optic axes being reached in two stages. Thereby there is a chance of summing up the errors of the two

Table 1.

Specimen no.	Twin Law.	REINHARD value An%	Angle Values			Low-temp. Opt. An %	High-Temp.Opt. An %
			$\alpha\alpha$	$\beta\beta$	$\gamma\gamma$		
1 a[1]	A–C[2]	54 [3]	80	88	34	51–50–65[4]	51–51–53[4]
– b	C	50,53	90	115	54	49–51–58	49–49–48
– c	M	53,56	43	87	70	50–58–62	50–51–52
– d	A	55,56	142	60	72	63–÷–65	57–56–58
– e	Ala	55,56	57	58	7		
– f	A–A	53,48	38	76	64		
2	C	50	90	100	54	49–45–58	49–45–48
3 a	A–C	60,65	55	71	41	64–60–75	57–58–62
3 b	A	62	141	58	72	64–÷–65	57–43–58
– c	C	62,65	108	148	64	61–65–72	57–58–65
4 a	A	52,55	159	48	55	50–50–52	50–35–40
– b	C	48,56	94	112	48	50–50–51	50–48–42
5 a	A–C	58,54	55	70	40	64–61–73	57–58–61
– b	Acline	58,62	132	55	76		
– c	C	64,72	118	166	62	÷–74–69	÷–65–62
6	A	52,55	156	62	70	52–÷–64	52–÷–56
7 a	A	52,55	158	65	69	51–÷–63	51–÷–55
– b	A	60	143	60	70	62–÷–64	56–54–56
8 a	A–C	50,52	46	64	42	70–67–77	61–64–63
– b	A–C	55,60	62	76	40	60–56–73	55–55–61
9	C	52	104	136	57	57–59–62	54–54–52
10	C	55	100	122	50	54–54–53	52–51–44
11	C	52,58	100	125	54	54–55–58	52–51–48
12 a	C	40,50	64	92	50	36–43–53	39–43–44
– b	A	45,50	160	55	58	49–65–54	50–40–43
– c	A	52	160	61	67	49–÷–61	50–50–52
13 a	A	45	162	47	50	48–48–47	49–35–37
18 a	A	46,48	162	50	56	48–54–52	49–37–41
– b	A	50	164	61	63	47–÷–58	48–50–48
19	A–C	55	65	78	38	58–55–69	54–54–58
21 a	C	60,71	105	144	67	58–63–77	54–57–72
– b	C	52,58	100	136	61	54–59–67	52–54–59
22	C	50	97	123	56	52–54–61	51–51–51
23	C	54,56	94	118	56	50–52–61	50–50–51
24 a	C	60,62	110	149	60	64–65–66	59–58–58
– b	C	50,58	106	140	58	59–61–64	55–56–54

adjustments, although of course it is possible to control the adjustment by rotating the stage of the microscope. Apart from this, it is not always possible to determine the orientation of the optic axes.

The Köhler curves fail in some respects. When Reinhard's curves are used it is very often observed that the single lamellae of a twin pair have a different composition. As Köhler's curves are based on the fact that the lamellae have the same composition,

Specimen no.	Twin Law.	Reinhard value An %	Angle Values			Low-temp. Opt. An %	High-Temp. Opt. An %
			αα	ββ	γγ		
24 c	A–C	50,58	75	87	37	53–51–68	52–52–57
25	A–C	50,60	76	84	34	53–52–65	52–52–53
26 a	C	60,66	110	144	59	64–63–65	59–57–56
– b	Ala	56,60	74	75	4		
– c	P	62,63	143	59	72	60–61–59	56– –50
– d	M	53,54	47	93	69	52–58–60	52–52–51
28 a	A	56,65	152	66	57	55–÷–53	53–÷–42
– b	A–C	60,62	75	85	35	54–52–66	52–52–54
– c	M	56,58	57	78	77	58–61–67	54–55–61
29	A–C	50,60	66	78	36	58–55–67	54–54–56
30	A–C	45,50	77	85	37	52–52–68	52–52–57
31	Acline	62	133	59	80		
32 a	C	50,53	84	120	54	46–53–59	47–50–48
– b	M	49	36	107	63	48–48–58	48–45–44
– c	C	48	88	110	52	48–49–56	48–48–45
33 a	M	52,60	45	94	78	50–53–69	50–50–61
– b	Ala	56,60	56	54	8		
35	A–C	50	95	93	31	45–48–61	48–50–46
36 a	C	54,60	105	136	58	58–59–64	54–54–54
– b	M	60	63	78	72	64–61–64	59–55–57
– c	A–C	70	48	62	36	68–69–67	60–67–56
– d	Ala	70	92	91	3		
– e	C	5)	106	143	62	59–62–69	55–57–61
37 a	C	66,72	105	148	66	58–64–75	54–58–70
– b	C	60,70	106	149	64	59–65–72	55–58–65
38 a	A	58	151	64	72	56–÷–65	53–÷–58
38 b	A–C	50,52	72	83	36	55–53–67	53–53–56

1) *a* means the first investigated phenocryst in the section, *b* the second etc.

2) *A* stands for albite, *C* for Carlsbad, *A–C* for complex albite–Carlsbad, *M* for Manebach and *A–A* for complex albite–Ala, *P* for pericline.

3) The values are obtained from Reinhard's table 2.

4) The figures indicate the anorthite percentage determined by means of the curves *αα*, *ββ* and *γγ* for low- and high-temperature optics, respectively.

5) The composition face could not be determined.

it is easily understood that the curves in these cases give results less consistent than usual.

OFTEDAHL (9, pag. 14) and others have stated that there is a gradual transition from high- to low-temperature optics. The rate of cooling below the crystallization temperature is decisive for the optical orientation. This is probably responsible for the well-known scattering zone to the right of the migration curves of REINHARD's table 2. Therefore, a REINHARD stereogram, on which curves for high-temperature optics have been drawn, does not give as indisputable results as those obtained from the KÖHLER curves. The transition does not appear from the KÖHLER curves.

The Results.

As the determination curves are still incomplete and as the facts on which they are constructed are scarce so that they are more or less defective, it is of value for geologists working on the plagioclases to have as many determinations available as possible. Therefore, the results of the present investigation are published in table 1. All measurements in the table have either a point as the triangle of error or an extremely small triangle of error. Thus, the results should be as exact as it is possible to get them by this method (cf. C. OFTEDAHL, 9, pag. 12).

It appears from table 1 that the results obtained by using the KÖHLER curves show good coincidence and that either the high-or the low-temperature curve is satisfied. Only in rare cases, both sets of curves seem to be satisfied by the angle values.

It is seen that in most cases the difference between the three values of each determination is 1 or 2% An. Some determinations have a deviation of 3–4% An and a very few have a larger deviation.

A common feature is to have two almost identical values and a third value which differs more or less from the other two. There seems to be only two ways of explaining this.

In albite twins, the angle values $\alpha\alpha$ and $\gamma\gamma$ very often give identical results while $\beta\beta$ has a pronounced deviation. For instance, in nr. 3b, $\alpha\alpha$ and $\gamma\gamma$ give 57 and 58% An respectively. $\beta\beta$ has the angle value 58°, which gives 43% An according to the high-temperature curve. It does not touch the low-temperature curve at all. As the $\beta\beta$-curves from 40% An to 100% An have a very flat course, it is easily understood that a slight error in the measurements can explain this deviation. If the $\beta\beta$-angle had been 60°, it would have given the same anorthite percentage as the $\alpha\alpha$- and $\gamma\gamma$-angles.

In some measurements the $\beta\beta$-value does not fall on any of the albite curves. A $\beta\beta$-angle as high as 66° was measured. Other measurements gave 62°, 64° and 65°. Now, errors on the measurements can explain this to a certain extent, but as all the published determinations have a very small triangle of error or even a point as the triangle of error, it seems to be unlikely that errors can explain this rather large deviation. But it appears from the table that the REINHARD determination in these cases seems to indicate that the two lamellae of the twins have different compositions, which is probably the best available explanation of the irregularity; but maybe the $\beta\beta$-high-temperature curve has slightly too low a position. An elevation of the curve would in most cases give a better coincidence between the three determinations on the albite twins. KÖHLER (7, pag. 595) gives an example of the use of the new curves where the $\beta\beta$-angle is as high as 62°, which according to his statement should correspond to 54% An on the high-temperature curve. Thus it seems as if KÖHLER has corrected the first-published curve.

The other twin laws show the same features as the above-mentioned. Particularly in the Carlsbad twins, the three values vary in a very irregular way. Here too, the results in a few cases do not touch the curves. For instance, in nr. 5c the angle $\alpha\alpha = 118°$ does not touch the curves at all, but as the REINHARD values show that the two lamellae probably have a different composition, this explains the deviation. That the Carlsbad twins have a more irregular variation of the obtained An percentage is probably due to their way of formation by the flowing-together of different lamellae (pag. 525).

In the complex albite-Carlsbad twins the $\gamma\gamma$-angle gives a higher An% than the two other angles. Maybe the curve has slightly too low a position.

In a few cases it is impossible to tell from the angle curves whether the measured grain has high-or low-temperature optics, as both set of curves give coincident results. But by combining the information obtained from the angle values with the other observations on the twins, it is possible in most cases to distinguish between the two temperature forms. All the doubtful cases of table 1 could be explained by reference to the optic axial angle of the plagioclases concerned. The examples of table 1 are the following:

no. 24a: 58% high-or 65% low-temperature optics. +2V=88° gives 66% low temp.
no. 26a: 57% high-or 64% low-temperature optics. +2V=84° gives 64% low temp.
no. 36b: 58% high-or 64% low-temperature optics. +2V=84° gives 64% low temp.

Thus, the above-mentioned cases are found to have low-temperature optics.

It is seen that the REINHARD determinations and the KÖHLER determinations show coincidence within 5% An, except in rare cases. Where the twins, according to the REINHARD determinations, seem to have lamellae of different composition, the KÖHLER values as a rule lie within the limits determined by the REINHARD values.

Many determinations show an excellent coincidence between the three KÖHLER values, while the REINHARD method indicates that the two lamellae probably have a different composition. But we must remember that the REINHARD curves are constructed on data from low-temperature plagioclases. Therefore we cannot expect the curves to be too sensitive when we have plagioclases with high-temperature optics. An obliquity can for this reason very easily be formed in the stereographic projection. A slight error on the adjustment of the composition plane has the same effect. The cases where the difference between the results of the two methods is larger than 5% An might be explained in the same way.

Concerning the accuracy of the KÖHLER method, it is seen that the uncertainty on the good determinations may be estimated at ± 1% An, and that the main part of the determinations have an uncertainty of less than 2% An. The accuracy of the REINHARD method is generally estimated to be ± 5% An, thus the KÖHLER method seems to give more accurate results, provided of course that the results on which the curves are based are reliable.

The result of these conciderations is as follows: The best method of examining the plagioclases is a combination of the two methods discussed. The composition plane and the twin axis are determined by the REINHARD tables 2 and 5. Hereby the twin law is obtained together with two fairly independent values for the anorthite percentage (tables 3 and 4 may be used as a control on the preceding determinations). The anorthite percentage and the presence of low-or high-temperature optics is determined by the KÖHLER curves. This is a very accurate method and it does not take longer time than the use of only one of the methods.

Petrogenetic Considerations.

As the petrography and the petrogenesis of the lavas will be described by Professor A. NOE-NYGAARD, only the conclusions which can be drawn from the optic conditions of the plagioclases will be discussed here.

A. KÖHLER has in several papers (5, 6 & 7) drawn attention to the importance of the plagioclases for the understanding of the history of the formation of the rocks of which they are components.

In the present case, where the history of formation is well known from observations in the field, there at first seem to be no problems at all. The first-formed plagioclase of the aphanitic lavas—the phenocrysts—has high-temperature optics; well-developed crystal faces; few twin lamellae; is almost free of corrosion; and zonal structure is very rare. All this is evidence of formation at rather high temperature and of rapid cooling. As there is no pronounced zoning, the last crystallized plagioclase must have almost the same composition as the first formed, which was confirmed by the determinations.

The problems appear when we look at the coarser lavas, in which low-temperature optics have been observed.

There seem to be only two ways of explaining this. The first is that the specimen of which the thin section has been made belongs to the inner regions of the lava flows where the cooling has been a little slower so that the lava has been capable of retaining a fluid state during a longer period. The second is, as stated by Professor NOE-NYGAARD, that the original aphanitic, glass-rich groundmass of the oldest lavas has been devitrified and attained a rather large grain size[1]).

In favour of the first hypothesis is the fact that the largest laths of plagioclase in several of the rocks are parallel, which indicates a flow. On the other hand, several of the coarse-grained lavas have grains of plagioclase arranged at random. This might be expected

---

[1]) Oral information.

if the lava consolidated under quiet conditions, but it is inconsistent with the scarce zoning and the slight corrosion. Even the apparently oldest plagioclases, the phenocrysts, are as a rule very fresh, or they may have an outer narrow pigmented corrosion zone. Where normal zonal structure is present, there is only a thin outer zone with an anorthite content that is a little lower than in the core of the grain. Thus, by the appearance of the plagioclase phenocrysts, it does not look as if the grains have been present in a melt capable of reacting with the plagioclase. Also the examination of the hand specimens reveals that the specimens do not belong to the inner regions of the lava flows as they have a multitude of vesicles. On the other hand, low-temperature optics are observed in a single case in one of the lavas of the eruption of 1947 (section no. 13).

In favour of the second hypothesis is, apart from the abovementioned objections to the first, that the oldest lavas taken as a whole are the most coarse-grained rocks, and that they are generally free from glass or contain only traces of it. (A few of the old lavas are rich in glass).

Additional information is obtained from the zonal structures and the distribution of the low-and the high-temperature optics.

Normal Zonal Structure. This type of zoning occurs as a thin outer zone of the phenocrysts. The difference in composition between the core and the margin of the grain is never large. This zoning was formed while the lava was still fluid as it is observed that zoned grains have flowed together. In most cases it was only possible to determine the composition of the zones by means of the REINHARD curves, which gave the relative proportion between the anorthite content of the core and the zones. The measurements of the thin zones were very difficult to carry through and are not very exact, but they gave the trend of the variation in composition.

Inverse Zonal Structure.

This type of zoning occurs only in the older lavas. There are two varieties of inverse zoning. The first has more and very thin, regularly developed outer zones and is a combination of normal and inverse zonal structure (fig. 1). The other has a very irregular zoning, which is often confined to one end of the grain and is present in all twin lamellae. The contact with the core is very irregular, often with a more or less gradual transition in composition from the core to the outer part. Twinning is occasionally found in this outer zone (see pag. 536 and fig. 1), and the twins have low-temperature optics. Besides, where the inverse zoning is confined to one end it is possible to observe that the original grain has a high-temperature, the last formed part a low-temperature optic. As, in addition, the unzoned grains which have the same composition as the outer zones have low-temperature optics it seems to be evident that this zoning cannot have any orthomagmatic origin but must necessarily be due to a much later readjustment—a devitrification—of the originally consolidated lava. Not only the groundmass, but also the phenocrysts have taken part in this alteration. The inverse zoning often occurs as a sort of wavy extinction, probably as a result of the attempts of the grain to conform to the new physical conditions of the lava. Thus, no mechanical effects have the responsibility for this extinction: it is simply due to the fact that the grain has not yet attained the same composition throughout. The corroded grains of this type were difficult to measure, but a few rather good determinations showed that they had high-temperature optics in the core.

It is the general opinion that inverse zonal structure means total remelting and recrystallization except in cases where the grains in question are regarded as xenocrysts. In this case, the last-named possibility can be excluded because of the low-temperature optics of the outer zones. On the other hand, we know with certainty from the field evidence, as some of the lavas have been extruded in historical times, that the conditions can never have favoured remelting of the lavas as they have never been covered by younger lavas. The only explanation left is that the inverse zoning is connected with the devitrification of the lavas.

A couple of examples will elucidate this.

Specimen no. 26. Lavafront north-east of Knafahólar belonging to one of the prehistoric Hekla lavas.

The groundmass is rather dense, but it is possible, by using the high-power objective, to distinguish its individual components, mainly ore and small thin laths of plagioclase, which have well-developed faces and by no means look like crystal skeletons. Pyroxene is present, and so is glass in a very small amount.

In this groundmass, phenocrysts of plagioclase, pyroxene and olivine occur. The plagioclase occurs in large, elongated, lath-shaped twins, comprising two or a few lamellae. The crystal faces are well developed, and corrosion is as a rule confined to a narrow outer zone, but some phenocrysts are heavily corroded and are thoroughly pigmented. Inclusions are widely distributed in the plagioclases, especially as pyroxene in small rounded grains. Zonal structure is common, especially of the inverse type. A few grains of plagioclase will be described:

1. A small, heavily corroded grain twinned according to the Manebach law. The one side of it has an irregular outer zone. The core has, according to the REINHARD curves, 53 and 54 percentage anorthite, the outer zone 67%. The KÖHLER curves give for the core 52% An, high-temperature optics.

2. A Carlsbad twin with two lamellae. It is very fresh and almost without corrosion, and it shows well-defined faces. Determination after REINHARD gives: 60 and 66% An, with both poles hitting the curves. A cleavage gave 62% An, and + 2V was 84°. As stated on pag. 532 (no. 26a), the grain has probably low-temperature optics and the composition 64% An.

3. The third grain (fig. 1) looks forked because of the concentration of inclusions in one end. The main part of the grain is regularly zoned. Twinning has taken place in the outer zone, the small lamella to the left being in twin position to the largest lamella. The measurements gave the following results: REINHARD values: the core of the largest lamella, 42% An ($+2V=80°$), the zones from the core outwards: 64% An, 58% An ($+2V=78°$) and 63% An ($+2V=82°$). The small lamella gave 62% An ($+2V=82°$). The KÖHLER curves gave as the most probable result: pericline twin, 60% An and low-temperature optics.

The above-mentioned examples are recorded in table 1 as nos. 26d, a and c.

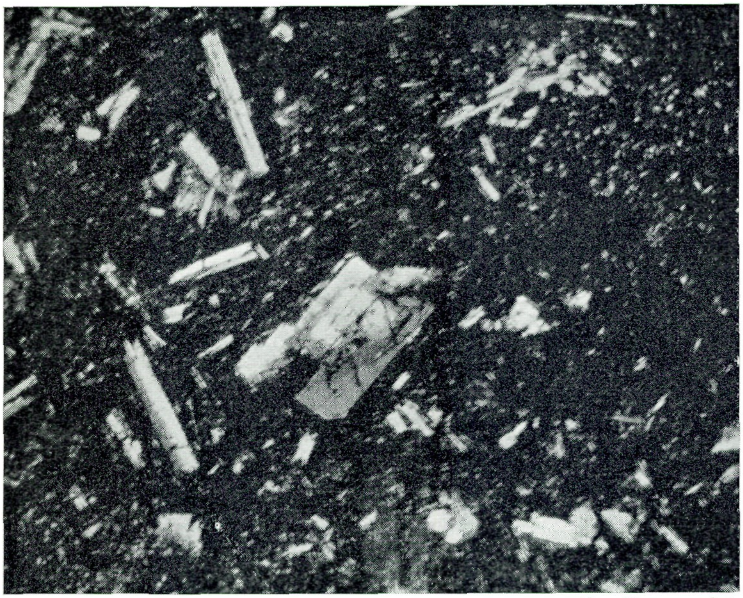
The second example is specimen no. 36, Lambafitarhraun extruded in 1913.

The groundmass of this rock is almost equigranular and cryptocrystalline and composed mainly of pyroxene and iron ore, but also of plagioclase in small laths. The facts related about the phenocrysts of the preceding section applies to this one. Only the plagioclase of no. 36 has not as well-developed faces as the plagioclase of no. 26. Here, too, a few plagioclase grains will be described.

1. A little, rather fresh grain twinned according to the Carlsbad law. REINHARD: 54 and 60% An, KÖHLER: 54% An, high-temperature optics.

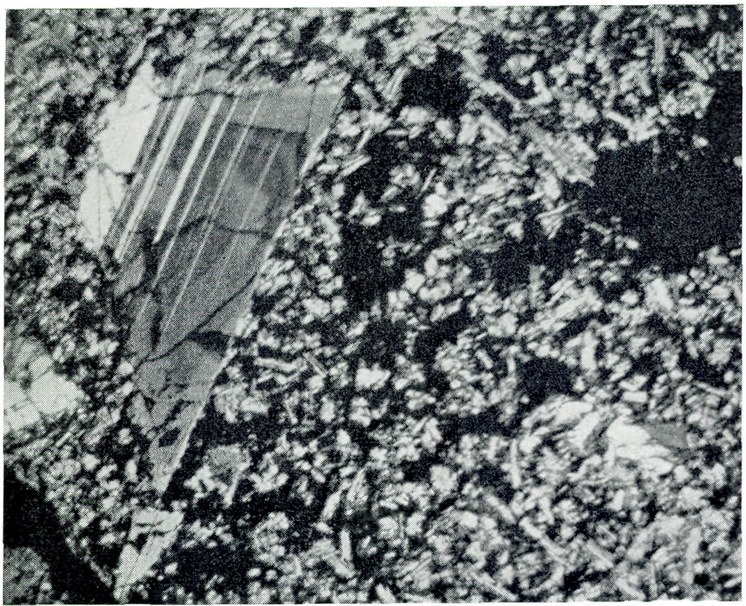
2. A small grain with an inclusion of pyroxene. The twin law is the complex albite-Carlsbad law. REINHARD: 70% An, the poles hitting the curve, KÖHLER: 68% An, low-temperature optics.

3. A large, much corroded grain. The contact plane between the two lamellae is very irregular, and the one lamella has a very irregular outer zone. The composition plane could not be determined. Therefore the twin axis was used. The twin was found to be twinned according to the Carlsbad law, and REINHARD's table 5 gave the following composition of the core: 63% An. A cleavage trace (which actually was a very thin pericline lamella) gave 58% An for the core and 63% An for the outer



CHR. HALKIER phot.

Fig. 1. Lava from Knafahólar. Explanation in the text pag. 536. + nic, 35 ×.



CHR. HALKIER phot.

Fig. 2. Lava from Blautakvist. The central part of the plagioclase phenocryst has a composition of 80% An (low-temperature optics), the outer zone has 74% An (low-temperature optics). + nic, 35 ×.

zone. According to KÖHLER, the core has probably 58% An, high-temperature optics.

The examples are recorded in table 1 as nos. 36a, c and e.

Thus we have in both examples a *high-temperature generation* which has the composition 50–58% An and a low-temperature stage of the composition 58–68% An.

The results of the present petrogenetic considerations are in summary: The presence of low-temperature optics in some of the plagioclases of the lavas of the eruption of 1947 indicates that the lavas may consolidate at so low a temperature that low-temperature plagioclases are formed. The inverse zoning of plagioclases at low temperature has no orthomagmatic origin, on the contrary it is formed in a late post-magmatic stage because of devitrification of the lavas.

The importance of the information on low-temperature optics in these considerations must be emphasized.

Appendix.

Measurements have been carried out on thin sections of rock specimens of the lavas which form the basement of the Hekla lavas.

The rocks in question are almost identical, they differ from the rock types so far dealt with in having very large plagioclase phenocrysts, the size of which very often exceeds half a centimeter. These large phenocrysts (fig. 2) are especially significant and differ from the plagioclases of the Hekla lavas not only in size, but also in twinning, in composition, and in their mode of occurrence. They have rather sharp margins but usually contain numerous inclusions in their outer parts. Zoning is common and is mainly of the inverse type, described above. The grains have several irregular fractures. Repeated normal twinning is very common and is often associated with parallel or complex twinning.

The groundmass is rather coarse grained, probably due to devitrification. Small, corroded grains which were supposed to be older than the devitrification were measured, and a composition of about 70% An (high-temperature optics) was found.

The determination of the composition of the phenocrysts did not give indisputable results. Unfortunately, the grains were found to have a composition that caused the poles to fall on the (010)-as well as on the (001)-curves of REINHARD's table 2. If (010) is the composition plane, the composition is 80–90% An, while (001) as the composition face gives a value of about 70 % An. The last-named possibility shows the best agreement with the groundmass plagioclase but involves the presence of repeated Manebach twinning and of two new twin laws with (001) as the composition face and (110) and (1$\bar{1}$0), respectively, as the twin planes.

A chemical analysis was undertaken of the phenocrysts of specimen no. 14, as material for the analysis was easily attainable because of the large grain size of the phenocrysts. (As the grains are zoned, only the cores were picked out and used for the analysis).

The analysis made by the writer gave the following results:

SiO_2	46.20 %
Al_2O_3	33.99 %
Fe_2O_3 (total Fe)	0.31 %
MgO	tr.
MnO	tr.
CaO	17.98 %
BaO	nil.
K_2O[1]	0.09 %
Na_2O	1.24 %
	99.81 %

This corresponds to the following composition: $Or_1Ab_{11}An_{88}$. Thus it appears that the composition face is (010).

For comparison the results of the optical determinations are recorded in table 2.

As a discussion of the occurrence and composition of these large phenocrysts is beyond the scope of the present work, only a few remarks will be made on the results of the combined optical and chemical determinations.

Although care was taken to prevent the zoning from disturbing the analysis, it is seen that the composition of the phenocrysts seems to vary within rather wide limits according to the optical determinations. But as the REINHARD curves have their greatest inaccuracy in their anorthite ends, and as the KÖHLER curves have an almost horizontal course in the same region, it is easily understood

---

[1] The determination of the alkalis was made according to the LAWRENCE SMITH-method. After the sintered cake had been leached with hot water and filtrated, the residue on the filter was not soluble in hydrochloric acid. Under the microscope the residue was found to consist of silica.

Thus the presence of an insoluble residue did not in this case owe its existence to incomplete decomposition, as stated in the analytical textbooks.

Table 2.

Specimen no.	Twin Law.	REINHARD value An%	Angle Values			Low-temp. Opt. An %	High-Temp. Opt. An %
			$\alpha\alpha$	$\beta\beta$	$\gamma\gamma$		
14	A	79,81	123	56	85	80–81–80	75–85–75
–	–	82	118	56	90	85–81–89	82–85–87
–	–	78,81	120	60	90	83– –89	80– –87
–	–	82,88	120	50	84	83–95–78	80– –72
–	–	82,83	117	57	89	86–77–86	84–80–84
–	–	82,83	118	56	89	85–81–86	82–85–84
–	–	82,85	119	55	86	84–84–81	81–90–77
–	C	80,82	108	176	72	90–91–88	90–86–91
–	–	85	110	176	73	85–91–92	82–86–
–	–	82,85	110	174	71	85–81–85	82–88–85
–	–	82,100	110	176	70	85–83–83	82–86–83
–	A–C	85,100	28	54	46	86–89–89	86–89–84
15	–	98,100	24	52	45	91–98–86	– –75
–	A	75,90	119	52	90	84–91–89	81– –87
–	–	80,90	116	58	88	87– –85	85–75–82
–	–	85,100	114	56	86	89–81–81	88–85–77
–	C	88	110	172	68	85–79–79	82–90–77
–	–	88,100	106	168	74	94–96–97	55–99–
–	–	88,90	106	173	76	94–93–	55–89–
–	–	85,98	108	173	71	90–93–85	90–89–85
39	–	75,78	110	176	68	85–83–79	82–86–77
–	–	95	104	172	73	97–94–92	53–90–
–	A	75,95	118	54	86	85–87–81	82–77–
40	–	70,88	120	64	86	83– –81	80– –77
–	–	82	116	62	86	87– –81	85– –77
–	–	85	117	53	85	86–89–80	84– –75
41	–	80,82	120	60	90	83– –89	80– –87
–	C	82,86	111	171	69	82–78–81	79–92–80

that the uncertainty of the curves explains at least part of the deviation. This appears, too, when the angle values are examined as they show a very limited variation which probably originates in errors on the measurements. Still, there seems to be a difference in composition, and therefore the chemical determination may be taken only as an average value of the composition of the phenocrysts.

As the low- and high-temperature curves of the KÖHLER diagrams almost coincide in their anorthite ends, it is not always possible to distinguish between the two types of optics, but it seems as if both types are present. It is seen that the highest anorthite percentages are encountered in plagioclases of low-temperature optics. Thus, we have probably the same trend of development as in the Hekla lavas.

Acknowledgments. It is difficult adequately to express my great gratitude to Professor A. NOE-NYGAARD for entrusting me with the material for the investigation, for introducing me to the determination-methods, and not least for the critical reading of the manuscript. I am indebted to Professor NOE-NYGAARD for the excellent laboratory facilities at the Mineralogical Museum, where the work was carried out.

My best thanks are also due to Mr. A. H. NIELSEN, Analyst at "KRYOLITSELSKABET ØRESUND", who introduced me to the methods of silicate analysis and also this time gave me many valuable suggestions and much kind help in the analytical work.

Mr. C. HALKIER, preparator at the Mineralogical Museum, has undertaken the photographical work.

LIST OF REFERENCES

1. HOMMA, F. Über das Ergebnis von Messungen an zonaren Plagioklasen aus Andesiten mit Hilfe des Universaldrehtisches. Schweiz. Min. u. Petr. Mitt. XII, 2, pp 345–352. 1932.
2. KAADEN, G. VAN DER, Die Zwillingsoptik der Bavenoer- und Manebacher-Zwillinge von hoch- und tieftemperierten Plagioklasen. Tsch. Min. u. Petr. Mitt. vol. 1, 3rd ser. pp. 295–299, 1949.
3. KÖHLER, A. Die Abhängigkeit der Plagioklasoptik vom vorgegangenen Wärmeverhalten. Min. u. Petr. Mitt. vol. 53, pp. 24–49, 1941.
4. — Drehtischmessungen an Plagioklaszwillingen von Tief- und Hochtemperaturoptik. ibid. vol. 53, pp. 159–179, 1941.
5. — und RAAZ, F. Gedanken über die Bildung von Feldspatzwillingen in Gesteinen. Geol. B.-A. Wien Verh. Jg. 1945, pp. 163–171. 1947.
6. — Erscheinungen an Feldspaten in ihrer Bedeutung für die Klärung der Gesteinsgenesis. Tsch. Min. u. Petr. Mitt. vol. 1, 3rd ser., pp. 51–67, 1948.
7. — Recent results of investigations on the feldspars. Journ. of Geology, vol. 57, pp. 592–599, 1949.
8. LARSSON, W., Petrology of interglacial volcanics from the Andes of northern Patagonia. Bull. Geol. Inst. Upsala, vol. 28, pp. 191–405, 1940.
9. OFTEDAHL, C., The igneous rocks of the Oslo region. IX, The feldspars. Det Norske Vid. Ak. i Oslo. I. Mat. Naturvid. Klasse, 1948 No. 3.
10. PAULIAC, G., Untersuchungen der Plagioklase einiger tertiärer Ergussgesteine Siebenbürgens. Schweiz. Min. u. Petr. Mitt. XII, 2, pp. 423–443, 1932.
11. REINHARD, M., Universaldrehtischmethoden. Basel 1931.
12. RITTMANN, A., Die Zonenmethode. Schweiz. Min. u. Petr. Mitt. IX, 1, 1929.
13. TERTSCH, H., Die optische Orientierung des Hochtemperatur-Anorthites, Min. u. Petr. Mitt. vol. 53, pp. 50–66, 1941.
14. — Zur Hochtemperaturoptik basischer Plagioklase. Ibid. vol. 54, pp. 193–217, 1942.
15. WENK, E., Statistische Drehtischuntersuchungen an Plagioklasen rumänischer Ergussgesteine. Schweiz. Min. u. Petr. Mitt. vol. 13, 1933, pp. 205–219.

Resumé.

I efteråret 1948 fik jeg af professor A. NOE-NYGAARD overdraget en serie tyndslib af Hekla lavaer. Det var meningen, at lavaernes plagioklasers sammensætning skulle bestemmes ved hjælp af den af REINHARD (11) udarbejdede metode. Det viste sig hurtigt, at de benyttede bestemmelseskurver var utilstrækkelige. De indmålte fladepoler faldt for det meste i en ret bred zone til højre for kurverne, en uregelmæssighed der ofte er omtalt i litteraturen. A. KÖHLER (3) har forklaret denne konstante afvigelse ved at antage, at plagioklaserne har såvel en lav- som en højtemperatur optik. REINHARD's kurver er konstrueret på grundlag af plagioklaser fra dybbjergarter; afvigelsen til højre er altid iagttaget, når målingerne er foretaget på plagioklaser fra vulkanske bjergarter. Kun de sidstnævnte har høj temperatur optik, da de er dannet ved forholdsvis hurtig afkøling fra høj temperatur.

KÖHLER's bestemmelseskurver blev derfor benyttet og med tilfredsstillende resultat. REINHARD's og KÖHLER's metoder diskuteres; det fremgår af resultaterne i tabel 1, at KÖHLER's metode synes at være behæftet med mindst usikkerhed.

Lavaernes dannelse diskuteres ud fra plagioklasernes optiske forhold. Det konstateres, at devitrification har resulteret i, at lavaernes plagioklas strøkorn har fået invers zonar struktur.

Til slut anføres såvel kemiske som optiske undersøgelser af lavaer fra Hekla lavaernes underlag.

Færdig fra trykkeriet den 15. januar 1951.