Zoned plagioclases in layered gabbros of the Skaergaard intrusion, east Greenland.

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I. INTRODUCTION.

A LIMITED amount of careful optical work has been carried out on three analysed felspars of gabbros belonging to the main layered series of the Skaergaard intrusion, east Greenland (Wager and Deer, 1939). The work was begun with the intention of providing precise optical data to be used in further defining the relationship between composition and optics. The primary precipitate felspar crystals, hitherto thought to be devoid of zoning, were found, however, to possess a zoning which prevents the data being used in this way. Nevertheless, the zoning itself proved of interest. The majority of crystals possess a mild degree of normal zoning, but in one of the three specimens a small proportion of the primary precipitate felspars are oscillatory-zoned. The latter feature seems of particular significance.

II. DESCRIPTION OF THE PRIMARY PRECIPITATE ZONING.

Wager and Deer showed that the layered gabbros are composed of primary precipitate crystals in a matrix of interprecipitate material. The primary precipitate crystals formed as successive crops of crystals from the well-stirred magma, while the interprecipitate material crystallized with falling temperature from the trapped interstitial liquid. The interprecipitate felspar is estimated to form 20 % or less of the total plagioclase. In thin section a strong normal zoning[1] at once distinguishes it from the euhedral primary precipitate crystals. The latter are enclosed, either partially or completely, within interprecipitate felspar. The interprecipitate zoning, often culminating in highly sodic felspar, is a general feature of the layered gabbros and requires no further description or explanation.

The primary precipitate zoning of the three felspars which have been chemically analysed (Wager and Mitchell, 1951, table 5) has been determined by methods described in the appendix, and the results are summarized in table I, together with the calculated normative composition

[1] Throughout this account the term 'normal zoning' is used in the accepted sense of an outward trend to a more sodic composition.

TABLE I. The range of primary precipitate zoning in the investigated plagioclase felspars.*

Specimen.	Normative composition by analysis†		(001) α′	(001) γ′	(010) α′	(010) γ′	Range of An % determined by R.I. method.	Range of An % determined by Zone method§	Probable zonal range.‖	Type of zoning.
4145 Ferrohortonolite-ferrogabbro height 2200 m.	$An_{38}Ab_{60}Or_2$	Range of R.I.‡	1·5498–1·5480	1·5551–1·5538	1·5493–1·5469	1·5545–1·5515	43–39	—	$An_{43} \rightarrow An_{37}$	Normal
		No. of flakes used	24	20	25	58				
		Normative % An	43–40	42–39	43–39	44–39				
2580 Hortonolite-ferrogabbro height 1800 m.	$An_{41}Ab_{56}Or_3$	Range of R.I.	1·5520–1·5490	1·5565–1·5553	1·5510–1·5492	1·5553–1·5531	46–42	46–40	$An_{46} \rightarrow An_{40}$	Either normal or oscillatory-normal
		No. of flakes used	18	11	20	8				
		Normative % An	46–42	44–42	45–42	46–42				
4077 Hypersthene-olivine-gabbro height 500 m.	$An_{55}Ab_{43}Or_2$	Range of R.I.	1·5590–1·5573	1·5654–1·5632	1·5685–1·5568	1·5640–1·5615	59–55	60–52	$An_{59} \rightarrow An_{52}$	Normal
		No. of flakes used	16	18	11	15				
		Normative % An	58–55	59–55	58–55	60–56				

* All values for An are in weight %.
† Including interprecipitate felspar. Analyst, W. A. Deer (Wager and Mitchell, 1951, p. 146).
‡ Refractive indices ±0·001.
§ The range for specimen 2580 concerns an oscillatory-zoned crystal.
‖ For the calcic limit of each range the estimated degree of error is ±1 part An, whilst the sodic limits are ±2 parts An except in the case of 4145, for which the sodic value is only approximate.

representing the bulk felspar composition of the rock. From these data it is concluded that the zoning of the primary precipitate crystals involves a change in composition of no more than six or seven parts anorthite.

Of the three gabbros from which felspars have been taken, the lowest in the main layered series is the hypersthene-olivine-gabbro 4077. Like

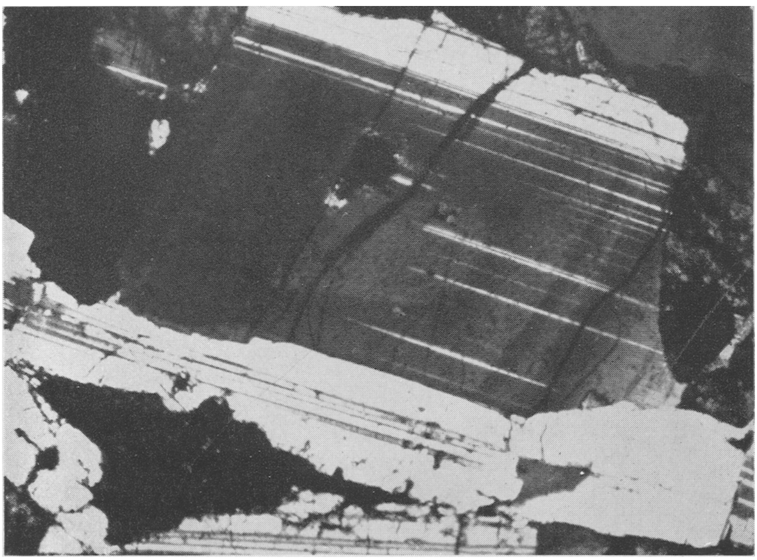

FIG. 1. A felspar crystal in hortonolite-ferrogabbro 2580. Showing primary precipitate zoning of oscillatory-normal type. The darker zones are the more calcic. Thus there are three reversals, each followed by normal zoning. The latter is strongest midway between the reversals. Size of crystal 3 mm., crossed nicols.

all the layered rocks it has the primary precipitate felspar as tabular crystals enlarged only slightly by the interprecipitate addition. The felspars, averaging 3–4 mm. in length, are fresh, and twinning, especially on the albite law, is frequent. The zoning is normal in type and results in a compositional range of about 7 parts of anorthite. The innermost parts of the crystals are An_{59} (table I and appendix). Except for an occasional patchiness, the zoning is gradual from the centre to the margin. A small proportion of the crystals fail to show zoning. Probably its absence is more apparent than real; a disadvantageous orientation to the plane of section is to be expected in some cases.

The primary precipitate zoning in the felspar of the hortonolite-ferrogabbro 2580 is of two types. About two-thirds of the crystals are zoned in a similar fashion to those of the lower hypersthene-olivine-gabbro 4077. The remaining crystals possess a very regular oscillatory-normal zoning, as defined by Phemister (1934). There occurs a succession of reversals, up to three in number and all of a calibre estimated as 3 parts of anorthite (fig. 1). Between successive reversals is normal

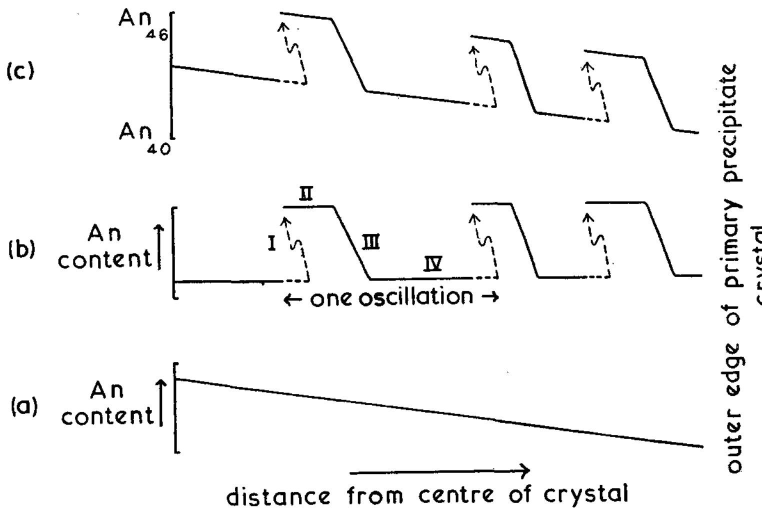

FIG. 2. Diagrams of the oscillatory zoning seen in fig. 1 and of its separate components. Broken lines and arrows denote resorption. (*a*) The simple component of normal zoning. (*b*) The oscillatory component. Roman numerals identify the successive stages of zoning. (*c*) The resultant zoning, as observed.

zoning in three well-defined stages. The first and last stages are of a zoning so gentle as to be scarcely perceptible; these are separated by an intermediate and short-lived stage of relatively strong zoning (fig. 2*c*). The composition immediately preceding each reversal is slightly more albitic than that of any material previously deposited. The boundaries of each zone are idiomorphic, though occasionally resorption prior to reversal has produced irregularities. For example, the nucleus of the crystal seen in fig. 1 is embayed by the innermost reversal, though the irregularity is poorly visible in the microphotograph.

In discussing the origin of this oscillatory-normal zoning it will be found convenient to regard it as the resultant of two components, one being oscillatory and the other simple in character. The components and the observed zoning, their resultant, are shown diagrammatically in fig. 2. The overall range in composition of an oscillatory-zoned crystal was measured as 6 parts of anorthite (table I). Since the calibre of the reversals is estimated as 3 parts of anorthite, this overall range is contributed by the components in roughly equal proportions.

The evidence for normal zoning in the primary precipitate felspar of the highest-occurring specimen, ferrohortonolite-ferrogabbro 4145, lies in the determined range of composition, from An_{43} to An_{39} (table I). The zoning is, however, masked by the fine semi-opaque dust of included matter that prevails throughout all felspars of this specimen.

A cursory examination of a representative collection of gabbros from other horizons in the main layered series only showed oscillatory-normal zoning to affect the primary precipitate felspar of the middle gabbro 1919 (900 metres below the previously-described example).

Oscillatory zoning is usual in the felspar of the gabbros belonging to the transitional layered series. There is reason to believe, however, that these rocks differed considerably from those of the main layered series in their manner of formation. The zonal pattern of their felspars is not entirely similar and has not been fully studied. The 'perpendicular felspar rock' of the border group also possesses oscillatory-zoned felspars, but again has a specialized origin (Wager and Deer, 1939, p. 144).

III. The probable origin of the primary precipitate zoning.

In order to explain many of the outstanding structural features of the Skaergaard intrusion, Wager and Deer found it necessary to assume that a system of convective circulation was active in the magma-chamber throughout the period of formation of the main layered series (Wager and Deer, 1939, pp. 267–8). They postulated that cooled and partly-crystallized magma descended at the walls, whilst hotter magma rose along the central axis of the intrusion. Growth of the primary precipitate crystals was thought to begin in cooling magma close to the roof, to continue during descent and only to cease when the crystal was deposited on the floor and buried by others. The authors believed that the magma was effectively stirred by its convective circulation, so that temperatures in the cooler, descending currents did not differ greatly from those in the uprising magma. As a measure of the existing temperature differences Wager and Deer (1939, p. 268) accepted the estimate of Jeffreys that a thermal gradient of about 0·3° C. per kilometre should be established in convecting basalt magma.

The depth of the residual Skaergaard magma-chamber at the time of formation of the middle gabbros was about 1·5 kilometres. The available information therefore indicates the maximum difference of temperature then prevailing in the magma to have been less than 1° C. In view of this apparent uniformity of temperature (and thus of magma composition) it is suggested that zoning was mainly caused by variation in hydrostatic pressure due to vertical movement of the convecting magma and crystals. It is considered that crystallization giving the simple normal zoning shown by the majority of crystals is the result of increasing pressure during descent. Theoretically, the effect of pressure changes on plagioclase composition is governed by the change in shape of the liquidus and solidus curves with pressure, regarding which no experimental evidence is available.[1] Existing data suffice only to afford an estimate of the increase in melting-point of the pure end-members with pressure;[2] the value dT/dP for albite is thereby indicated to be approximately four and a half times that for anorthite. Using this relationship, fig. 3 shows diagrammatically the manner in which the required change towards a more albitic solid phase might occur as pressure increases.

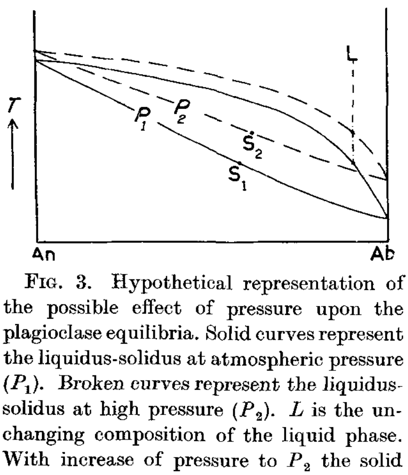

FIG. 3. Hypothetical representation of the possible effect of pressure upon the plagioclase equilibria. Solid curves represent the liquidus-solidus at atmospheric pressure (P_1). Broken curves represent the liquidus-solidus at high pressure (P_2). L is the unchanging composition of the liquid phase. With increase of pressure to P_2 the solid phase in equilibrium would change from S_1 to the more sodic composition S_2.

The simple zoning of most crystals is thus regarded as an inevitable accompaniment of the accepted process of crystallization during descent. For the oscillatory-zoned felspars, however, a more complicated growth-history must be envisaged. In the homogeneous Skaergaard magma a reversal of plagioclase zoning could only occur through a relief of pressure. It is therefore assumed that a selection of the crystals experienced

[1] The writer is indebted to H. S. Yoder, of the Geophysical Laboratory, Washington, for advice concerning this point.

[2] The Clausius-Clapeyron equation is $dT/dP = T\Delta V/\Delta H$. The values of the partial volume change ΔV (albite 0·036 c.c./gm., anorthite 0·008 c.c./gm.) were computed by H. S. Yoder from the measured densities of synthetic crystals and glass at room-temperature (Birch et al., 1942, p. 15). The enthalpies ΔH have been measured (Kracek and Neuvonen, 1952, p. 293). ΔH albite = 49·2 cal./gm., ΔH anorthite = 64·7 cal./gm. Since the values of ΔV do not strictly apply at melting temperatures, and because both ΔV and ΔH are functions of pressure, the obtained values of dT/dP are close approximations only.

a stage of ascent which led to renewed crystallization of calcic material under reduced pressure. The number of reversals present in a crystal is believed to be the same as the number of times that the crystal was carried round in the magma before finally coming to rest. That each ascent took the crystal to a similar height in the chamber is shown by the uniform calibre of all reversals (fig. 2*c*). Nevertheless, there is a constant trend of comparable and later zones towards a more albitic composition, so that the later reversals fail to achieve the earlier calcic composition. Pressure variation seems incapable of explaining this part of the zoning, which is therefore attributed to a change in the composition of the magma as overall cooling and differentiation of the intrusion proceeded. In fig. 2*a* and *b* respectively the observed zoning is resolved into this component of normal zoning and into an oscillatory component that is wholly due to pressure variation. The distinction allows the pressure effect to be studied more readily. Thus, in fig. 2*b*, a full oscillation of zoning was achieved during a complete circulation of the crystal around the magma-chamber, and its four stages correspond to successive stages in the movement of the crystal. During the first stage of a renewed circulation, namely ascent, the crystal experienced a relief of hydrostatic pressure that caused instability and resorption of its outermost sodic layers (stage I). Reversal occurred when pressure had ceased to fall and the crystal was travelling outward beneath the roof. In this high-level current the felspar suffered little or no vertical movement, so that stage II is free of zoning due to pressure change. The relatively strong zoning that follows (stage III) is comparable in origin to that affecting the simply-zoned felspars, and marks the descent stage. To complete the circulation low-level currents carried the crystal inwards to the centre of the intrusion. This final stage, being primarily one of horizontal movement, resulted in a uniformly sodic zone (stage IV). In the event of a further circulation of the crystal taking place, the zone would be partially destroyed by ensuing resorption.

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Appendix.

Notes on the measurement of the zoning.

Values for the ranges of primary precipitate zoning are afforded by: (*a*) refractive index measurements performed on cleavage-flakes (Tsuboi, 1923); and (*b*) measurement of maximum extinction angles in the zone [010] (the zone method of Rittmann, described by Emmons, 1943). The two methods, of which the second was carried out on two of the specimens only, yield results which differ slightly at the sodic limit (table I). Whereas the zone method permits a ready distinction between primary precipitate and interprecipitate material, these two phases, when observed in the crushed state, are separable only by arbitrary means. At the time the refractive index determinations were made the prevalence of zoning in the primary precipitate felspar was not properly appreciated, and separation of the two phases was essayed by rejecting from measurement all flakes which showed zoning. The wider values obtained by the zone method seem to show that this rejection procedure was too drastic, and that it resulted in an incomplete assessment of the zoning at the sodic end. For this reason the values due to the zone method are accepted as the probable range of primary precipitate zoning.

The calcic limit of plagioclase 4077 is confirmed by a measurement of the composition of the central part of a selected crystal, using the Fedorov method.[1] The transposed poles of cleavage-planes and twin-axes gave four values of An_{59} and one each of An_{58} and An_{60}. These values agree closely with those obtained by the other methods.

No estimates of the volume and average composition of the interprecipitate felspar can be of sufficient accuracy for the determined ranges of primary precipitate zoning to be confirmed from the bulk analysed compositions.

The technique adopted for each method is described below.

(*a*) Measurement of refractive indices on cleavage-flakes.—An improvised but effective temperature-variation method was used. The specially-prepared immersion liquids possessed indices successively differing by 0·001, on average. An Abbe refractometer was used in constructing dispersion-curves for all liquids. During the felspar measurements full precautions were taken to preserve accuracy. The swing-in thermometer was calibrated with that of the refractometer, and monochromatic light was used. The pure felspar was crushed and sieved to a flake-size of 0·007 mm. Because of the primary precipitate zoning the suitable flakes in a sample possessed rather variable indices. The temperature of the stage was noted when the liquid matched an index of one or more flakes. Having risen farther it was then allowed to fall and a further observation made, not necessarily on the same flakes. In

[1] Migration-curves due to Spaenhauer and reproduced by C. T. Barber (1936) were employed.

table I 'number of flakes used' means the number of such matchings. The experimental error, discounting that due to zoning, is estimated as ±2 parts of anorthite.

(*b*) Measurement of maximum extinction angles (zone method).—A Leitz universal stage was used. Normal multiple twinning was identified as advised by Emmons (1943, p. 129). Albite-Carlsbad twins were preferred, since a maximum value was thus assured. The zone [010] was made vertical by obtaining equal illumination of the albite twin-units under the sensitive plate and with the (010) trace at 45° to the nicols. Each recorded value was verified as at a maximum and represents the mean of at least four readings. The nucleus and the margin of the primary precipitate crystal were each measured. Compositions were interpreted from the curves given by Winchell (1951, p. 262). This method of measuring plagioclase composition has been found by the writer, during an extensive investigation of a suite of felspars from Skye, to be as accurate as any other method employed on zoned felspar. The limit of error in the present case is ±2 parts of anorthite.

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