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Petrofabrics of laminated gabbros from the Centre 3 igneous complex, Ardnamurchan Scotland

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SUMMARY. Petrofabric analysis of five specimens of laminated gabbro from the Centre 3 igneous complex, Ardnamurchan, was carried out by measuring orientations of grains of plagioclase, olivine, and augite with a Universal-stage. Linear alignments of primary precipitate mineral grains within the laminar fabrics were revealed by plots of data for coexisting plagioclase and olivine or augite. The plagioclase grains involved have tabular forms elongated parallel to their *a*-axes (rather than their *c*-axes). The olivine grains have flattened ovoid forms and the augite grains have sub-ophitic forms developed about prismatic primocrysts. In all specimens plagioclase displayed alignment of long grain-axes directed approximately down the dip of the lamination, save for one case in which a weak oblique alignment was observed. These lineations were reproduced by accompanying olivine and augite. The alignments are tentatively ascribed to flowage of a viscous boundary zone to the magma body in which crystal growth was taking place.

THE gabbroic rocks of the Centre 3 igneous complex, whose ring-structure was originally described by Richey and Thomas (1930), may be summarized briefly as consisting of an ovoid area of rather unvarying olivine gabbro (eucrite) in which occur concentric crescentic outcrops of laminated (fluxioned) olivine gabbro and magnetitic orthogabbro which also generally possesses a degree of lamination (Fortey, 1978). Though contact exposures between these units are uncommon it does appear that the boundaries of the units of laminated rock and their internal laminar structures are concordant. In all cases these laminar structures strike more or less circumferentially with respect to the over-all ring pattern, and with very few exceptions are inclined radially inwards. The gabbroic rocks resemble many other layered gabbro bodies in these features, and their laminar textures are regarded as having formed during, or very soon after, the initial formation of the rocks.

Linear alignment of crystals within the laminar fabrics is visible at outcrop only rarely. Where seen, a down-dip configuration is apparent. That such lineation may be more widespread in the complex was suggested during routine thin-section examination by the frequency with which, in certain sections cut perpendicular to the lamination, distinct crystal sections such as the basal pyroxene section were met with.

To understand better the textures of the laminated rocks a programme of Universal-stage measurements was carried out. The techniques used in specimen-orientation and grain-measurement are set out in the Miniprint Appendix. Five specimens were selected from three units of laminated gabbro (fig. 1). Two, AD 480 and AD 483, were taken from a body of laminated olivine-gabbro. AD 480 represents the average rock of this unit, and AD 483 represents a thin anorthosite

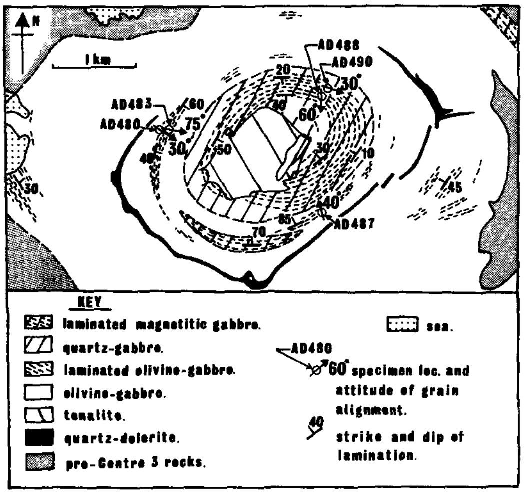

FIG. 1. Outline geological map of the Centre 3 igneous complex showing specimen locations for the rocks described and the orientations of linear alignments obtained.

band in a 1-m-thick band of thinly interbanded (on a centimetre scale) anorthosite and melagabbro. The third, AD 487, represents a second unit of laminated olivine gabbro. The remaining two, AD 488 and AD 490, represent a unit of laminated magnetitic orthogabbro. Before the measurements had been made the only indication of linear alignments of grains in these specimens was what appeared to be a high frequency of basal augite sections in thin sections of AD 488 and AD 490.

Grain orientations were made on standard thin sections using a 5-axis Leitz Universal-stage (Emmons, 1943) equipped with a sliding reference-orientation bar.

Petrography. The five specimens represent two types of laminated gabbro found in Centre 3 (Fortey, 1978). The laminated olivine gabbro resembles mineralogically the majority olivine gabbro (eucrite) of the complex. It contains labradorite-plagioclase grains with bytownite cores. Olivine is ubiquitous. Augite may occur as interstitial skeletal crystals or as prismatic grains in the laminated rock, but is almost always skeletal in the surrounding host gabbro. Other constituents are of very minor volumentric importance. The laminated texture suggests closely spaced primocrysts with interstices filled by adcumulus plagioclase and intercumulus to adcumulus augite.

In the magnetitic orthogabbro interstitial quartz, apatite, and alkali-feldspar are minor but persistent constituents; the plagioclase is labradorite to calcic andesine; olivine is absent or represented only by isolated serpentinitic pseudomorphs; biotite is a minor subsolidus constituent, and magnetite-ilmenite grains often form 10% or more of the rock. Plagioclase and augite appear to be primocrysts.

Specimen AD 480 is typical of the laminated olivine gabbro. Augite is interstitial, and was not investigated. The thin section of AD 483 spans a boundary between a band of augite melagabbro and one consisting largely of labradoritic plagioclase. The melagabbro here has a laminated granular texture, but in other specimens examined this component becomes a very coarse, non-laminated augitite. The anorthosite band in AD 483 consists of a very well packed, strongly laminated, fabric of plagioclase crystals conformable with the banding of the rock, with a sparse content of remarkable skeletal interstitial augite. A few small, rounded olivine grains are also present. Specimen AD 487 resembles AD 480 (see above) in being a laminated olivine gabbro with interstitial augite.

The magnetitic orthogabbro specimens AD 488 and AD 490 are both coarse-grained rocks which conform to their type and are representative of the laminated unit they come from. They are less well laminated than the olivine gabbro specimens.

Certain observations apply to the plagioclase grains in all five specimens to varying degrees. They show considerable variation within thin sections in size, up to a maximum thickness of 2 mm and as observed in thin sections have aspect ratios from 1 to 9. They tend to be subhedral, tabular to lath-like crystals modified only marginally by growth interference. They frequently display growth features including partially resorbed cores with % An values greater than 80, normal zoning, fine oscillatory zoning, and a high incidence of Carlsbad, Carlsbad-Albite, and Baveno twins, and thus appear to be primary precipitation minerals (cf. Suwa, 1979).

Over 50% of the plagioclase grains observed in the thin sections showed aspect ratios of 2 or less and almost all the grains in which two cleavage sets were visible were of this type. Plagioclase grains have often been regarded as being elongated parallel to their *c*-crystallographic axes (e.g. Brothers, 1964). If this were so in the rocks discussed here then crystal sections showing both the (010) and (001) cleavages should have the largest aspect ratios, not the smallest. It may be concluded that these crystals have trapezoidal forms, with dimension ratios on their *a*, *c*, and *b* axes respectively near 4:1.5:1, marginally modified by late growth, and that they are thus elongated parallel to their (010)/(001) cleavage intersections (their *a*-crystallographic axes) rather than their *c*-crystallographic axes. Alignments of (010)/(001) therefore reflect the physical orientations of the plagioclase grains.

The olivine grains generally have rounded forms suggestive of some resorption of primary crystals. Augite grains, where participating in laminated fabrics, have euhedral prismatic forms modified by subpoikilitic overgrowths and development of sinuous mutual grain boundaries.

Results. In each case the laminar fabric is created largely by the alignment of the broad faces of the plagioclase crystals and is thus reflected in clusterings of the poles to the plagioclase (010) cleavage. What is sought here is a second cluster of data within the laminar fabric, hence perpendicular to the poles to (010).

Fig. 2 shows results for plagioclase and olivine in AD 480. Plagioclase poles to (010) show a strong clustering (fig. 2*a*). In the corresponding (010) girdle a remarkable alignment of (010)/(001) intersections (fig. 2*b*) indicates the presence of a down-dip linear alignment of the long *a*-axes of the crystals. Olivine X-vibrations (parallel to *b*-crystallographic axes) are clustered parallel to the poles to plagioclase

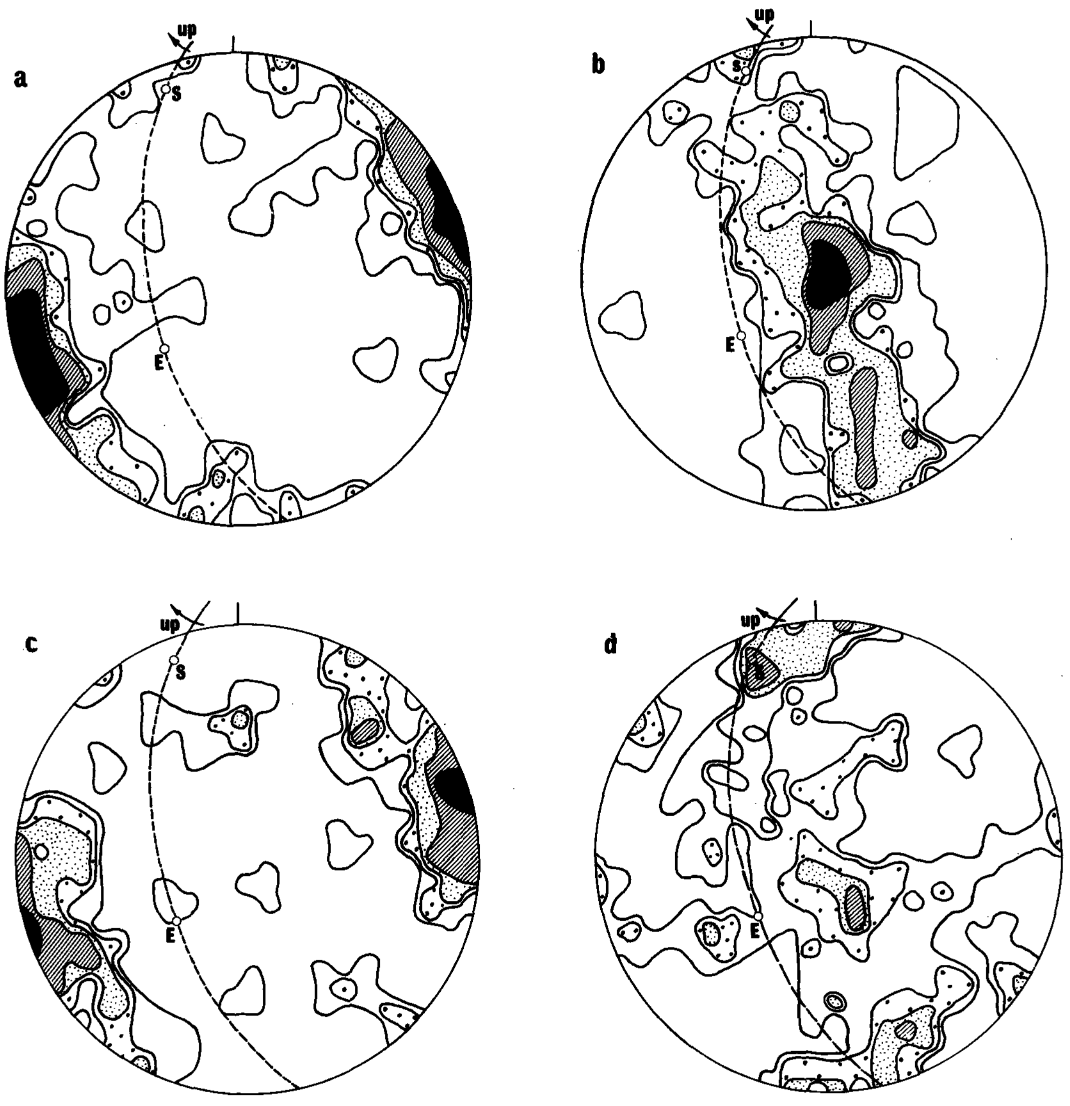

FIG. 2. Contoured equal-area stereograms showing petrofabric results for specimen AD 480: (*a*) plagioclase, poles to (010); (*b*) plagioclase, XY/cleavage intersections; (*c*) olivine, X-vibrations; (*d*) olivine, Z-vibrations. Also shown are the horizontal plane at outcrop (dashed), cardinal directions which impinge with the lower hemisphere stereonet, and the sense of way-up at outcrop.

(010) cleavages (fig. 2*c*), while the Z-directions (parallel to *c*-crystallographic axes) show groupings both parallel to, and at right-angles to, the cluster of plagioclase (010)/(001) intersections (fig. 2*d*). Thus, the olivine grains are aligned parallel to the plagioclase down-dip alignment, with either their *c*-axes or the *a*-axes aligned down-dip.

Fig. 3 shows results for plagioclase in the anorthosite band in specimen AD 483. Again, a strong clustering of poles to the (010) cleavage-planes is seen (fig. 3*a*). The corresponding girdle, however, shows a broad clustering of (010)/(001) intersections indicating only a weak alignment of the crystals approximately down the dip of the banding.

Results for plagioclase in AD 487 (not shown) resemble those for AD 480, but the down-dip alignment is much less pronounced in this case.

Fig. 4 shows results for AD 490. Here, the weaker lamination is reflected in the broad clustering of poles to (010) shown in fig. 4*a*. The (010)/(001) intersections reveal a wide girdle within which a broad clustering of data suggests a weak, oblique, linear alignment (fig. 4*b*). Augite *b*-crystallographic axes (Y-vibration directions) show a complex distribution (fig. 4*c*) in which both a girdle parallel to the plagioclase girdle (i.e. the plane of lamination) and a cluster perpendicular to the girdle appear to be present. Augite *c*-crystallographic axes show a similar pattern, but here a distinct clustering within the girdle and parallel to that shown by the plagioclase (010)/(001) intersections is present (fig. 4*d*). Hence, a weak oblique linear alignment appears to be present in both the plagioclase and the augite grain populations.

Specimen AD 488 gave a pattern (not shown) similar to that of AD 490, and in this case the presence of a linear alignment oriented down-dip within the rather weak lamination was established.

Discussion. The results confirm the presence of down-dip linear alignment of primocrysts in the laminated gabbros of the Centre 3 complex, and suggest that the feature is best developed in well-laminated rocks. However, the position is clearly complex since specimens AD 483 and AD 487 proved not to contain strong lineations despite being well laminated, while in the case of specimen AD 490 the weak alignment is markedly oblique.

Interpretation of these fabrics in the light of present ideas presents some difficulties. The textures involve the forms of the primocrysts as well as their optical configurations, and look distinctly sedimentary. They resemble those described from many layered igneous bodies by Wager and Brown (1968) and many others. Brothers (1964) regarded lineation in laminated allivalite from the Rhum Complex as indicative of current activity in the parent magma body. However, if this applies to Centre 3 then it may be difficult to account for the lack of a strong lineation in AD 483, a very-well-laminated specimen. Moreover, some of the laminated rocks in the complex have steeply inclined structures at first sight incompatible with a sedimentary origin. Down-dragging of initially shallowly inclined structures by subsequent ring faulting as described by Skelhorn and Elwell (1971) is unlikely in Centre 3 since evidence for such faults is absent (Fortey, 1978).

McBirney and Noyes (1979) have proposed an alternative generative model for igneous layering in which banding and lamination develop with *in situ* nucleation in a highly viscous, tranquil boundary zone of a magma body, in which thermal and chemical gradients create the dominant mechanisms. These authors point out that basic plagioclase should be buoyant in basaltic magma (also see Campbell *et al.*, 1978) and thus unable to be a major constituent of bottom accumulations. Yet if these ideas apply to the laminated gabbros in Centre 3 it is difficult to see why linear alignments should develop in a stationary boundary zone.

Richey and Thomas (1930) regarded the laminated textures as having arisen by flow banding in mobile crystal-mushes. They specifically envisaged such phenomena occurring in intrusions of such materials. Confirmatory evidence for the

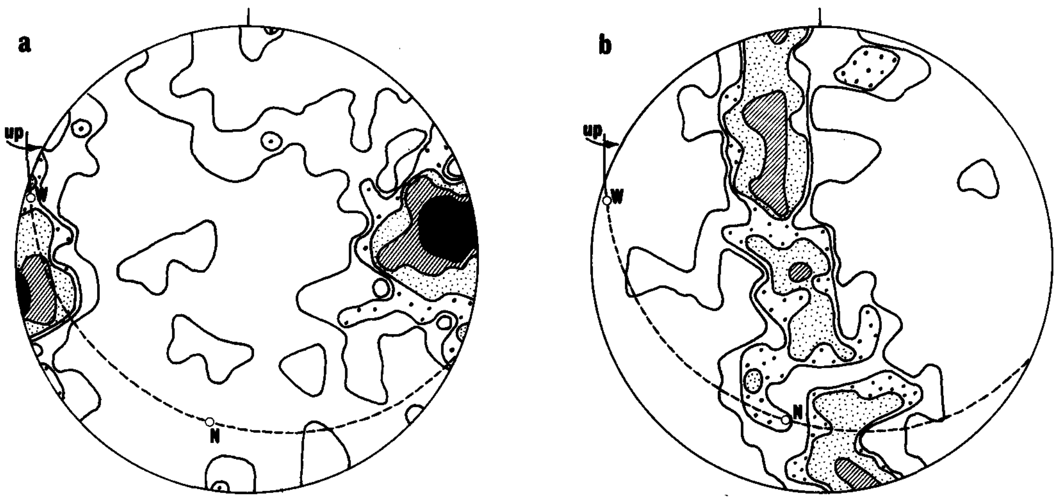

FIG. 3. Contoured equal-area stereograms showing petrofabric results for specimen AD 483: (*a*) plagioclase, poles to (010): (*b*) plagioclase, XY/cleavage intersections. Other details as for fig. 2.

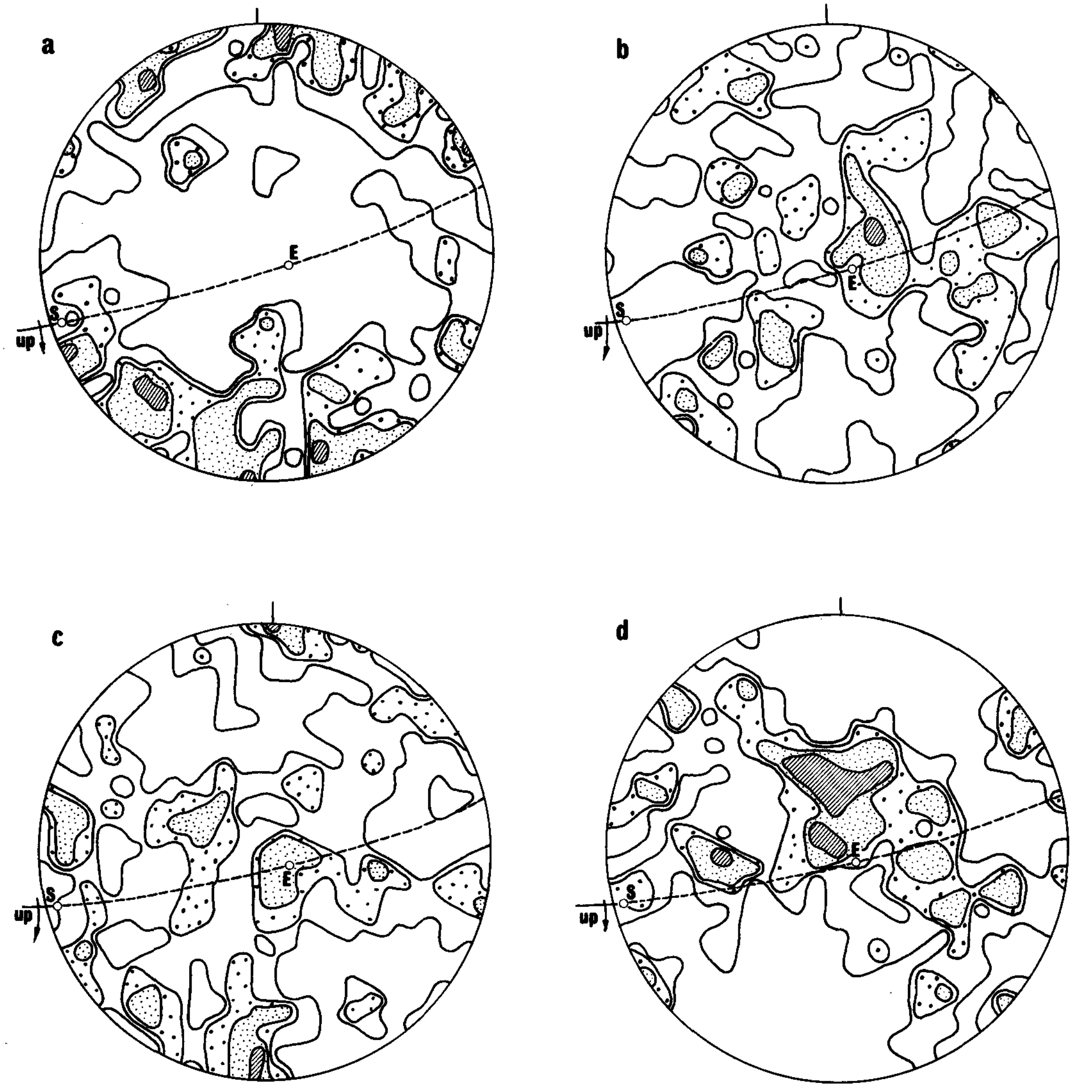

FIG. 4. Contoured equal-area stereograms showing petrofabric results for specimen AD 490: (*a*) plagioclase, poles to (010); (*b*) plagioclase, XY/cleavage intersections. (*c*) augite, *b*-crystallographic axes; (*d*) augite, *c*-crystallographic axes. Other details as for fig. 2.

existence of these intrusions has not been obtained (Fortey, 1978), yet the concept of flow-banding suggests an explanation of the lineations. Stresses due to flowage of a viscous boundary zone in which nucleation was taking place could bring about alignment of growing primocrysts. Causes of such flowage could include frictional drag due to interaction of the boundary zone with convection taking place in the inner, less viscous parts of the magma body, and gravitational slumping due to increases in the density of the boundary zone with the formation of ferro-magnesian minerals and oxides.

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PROCEDURE IN PETROFABRIC STUDY OF GABBRO : APPENDIX TO PETROFABRICS OF LAMINATED GABBROS FROM THE CENTRE 3 IGNEOUS COMPLEX, ARDNAMURCHAN, SCOTLAND

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SAMPLING

Rock specimens were oriented at outcrop by measuring, using conventional compass-clinometer techniques, the attitudes of specimen faces. Horizontal lines were scratched onto the measured faces, with additional marks to indicate the sense of slope.

PREPARATION

In view of the coarseness of the gabbros it was necessary to prepare three thin-sections for each specimen, except for the near monomineralic anorthositic band studied in specimen AD 483. This ensured adequate populations of mineral grains, avoided the danger of inadvertently measuring individual grains more than once, and allowed measurements to be spread over about 18 cm^2 of a surface approximately normal to the obvious lamination.

Rock-slices cut from the specimens normal to the laminations were marked to indicate where they should be cut to yield the rectangular thin-sections and which way up the pieces should be mounted on the glass slides. By copying on to tracing paper, records of these marks and the outlines of the rock-slices were kept.

Using a protractor and a sheet of card, and resting the specimens on their cut surfaces, the angles between the cut-surfaces and the specimen-faces, and between the horizontal (at outcrop) lines scribed on the faces and the intersections of the faces with the cut surfaces, were measured. These two measurements, together with the tracing-paper records of the thin-section orientations with respect to the cut-surfaces, allowed the thin-section orientations with respect to the outcrop to be constructed. Referring all angles measured to the fixed reference axes provided by the Universal-stage itself made it possible to plot the horizontal plane and cardinal directions at outcrop on to the stereograms as in Figures 2 to 4. In doing this it was important to indicate way-up at outcrop (the arrows labelled "up" in the stereograms) as this would not otherwise be implicit.

MEASUREMENT

The measurement of plagioclase grain-orientations presents some difficulty as a result of its triclinic symmetry and the variation with composition of the orientation of its optical indicatrix with respect to cleavage-directions. The (010) cleavage is usually present, and measurement of the pole to this provides a direction normal to the broad side-pinacoid face of a lath-like or tabular plagioclase grain. To complete the orientation measurement of a second direction perpendicular to the pole to (010) was required.

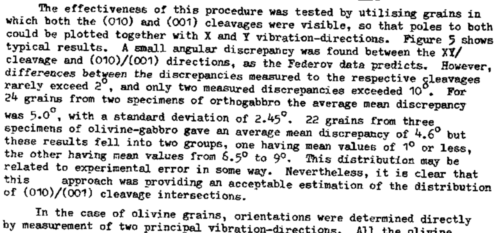
Brothers (1964) achieved this by constructing the intersection of the (010) cleavage with the plane containing the respective X-vibrations of complementary Albite-law twin lamellae. The crystals concerned were considered to be elongated parallel to their c-crystallographic axes. These XX'/(010) intersections lie in the (010) plane but at an appreciable angle to both the c-crystallographic axis and the (010)/(001) cleavage-intersection. An alignment of c-axes would generate two clusters of XX'/(010) directions displaced to either side of the true alignment. Using this approach linear alignments of plagioclase grains in laminated gabbroic rocks from the Rhum Complex and the Skaergaard intrusion were demonstrated.

In the case of plagioclase grains in Ardnamurchan Centre 3 gabbros, measurement of XX'/(010) intersections was impractical for two reasons. In many grains the twinning observed was not in the Albite-law, while in others showing Albite-law twinning one set of twin-lamellae proved too fine to permit satisfactory measurement of optical directions. It was therefore necessary to adopt a different approach.

It was found that the XY-plane of the optical indicatrix of the plagioclase grains investigated came close to containing the direction of the intersection of their (010) and (001) cleavage planes (the a-crystallographic axis). This relationship was obtained for Albite-law, Carlsbad-law, Carlsbad-Albite-law and Acline-law twins. It was confirmed by constructing cleavage-intersections from orientation data used in Federov's method of plagioclase study (see Emmons, 1943, Plate 12). It provided a rapid, simple technique dependent only on the presence of either cleavage.

The measurement procedure adopted starts with the selection in a grain of an area showing optical uniformity and containing suitable cleavage planes. Two principal vibration directions and the direction normal to the cleavage are measured and plotted on an equal-angle stereonet. If either X or Y is not measured directly it is constructed from the other two vibration-directions. The XY plane of the indicatrix and the cleavage plane are then constructed, their intersection measured and recorded. The tabulated XY/cleavage intersections are replotted on an equal-area stereonet to obtain the profabric analysis. Only one grain in twenty five, approximately, showed no cleavage, and in all cases such grains were small, often corners of larger grains. It seems unlikely that the results would be altered significantly if all the grains encountered could have been measured.

Figure 5 Stereograms (equal-angle) showing poles to (010) and (001) cleavages, X, Y and Z vibration-directions for two plagioclase grains. (a) shows results for a Carlsbad-law twin, and (b) shows results for an Albite-law twin.



The effectiveness of this procedure was tested by utilising grains in which both the (010) and (001) cleavages were visible, so that poles to both could be plotted together with X and Y vibration-directions. Figure 5 shows typical results. A small angular discrepancy was found between the XY/cleavage and (010)/(001) directions, as the Federov data predicts. However, differences between the discrepancies measured to the respective cleavages rarely exceed 2°, and only two measured discrepancies exceeded 10°. For 24 grains from two specimens of orthogabbro the average mean discrepancy was 5.0°, with a standard deviation of 2.45°. 22 grains from three specimens of olivine-gabbro gave an average mean discrepancy of 4.6° but these results fell into two groups, one having mean values of 1° or less, the other having mean values from 6.5° to 9°. This distribution may be related to experimental error in some way. Nevertheless, it is clear that this approach was providing an acceptable estimation of the distribution of (010)/(001) cleavage intersections.

In the case of olivine grains, orientations were determined directly by measurement of two principal vibration-directions. All the olivine grains encountered could be measured, the mineral being fresh and not twinned. Augite grain-orientations were determined by measurement of Y-vibration directions (parallel to the b-crystallographic axis), and by plotting the intersection of the plane perpendicular to this with either the (110) cleavage or the (100) parting, to derive a direction parallel to the prism axis (the c-crystallographic axis). Grains in which neither (110) nor (100) could be observed were approximately one in thirty.

The orientation data were plotted onto lower-hemisphere, equal-area stereonets, then contoured at 1%, 2%, 4%, 8% and 16% as required. Results for three specimens are shown in Figures 2, 3 and 4. Each stereogram contains results for over 100 grains together with the orientation of the horizontal plane at outcrop, the cardinal directions and the way-up with respect to this plane.

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