

*The alkali feldspars of the Ardara pluton, Donegal*

By A. HALL

Geology Department, King's College, London, W.C.2

[Read 4 November 1965]

*Summary.* The alkali feldspars in the Ardara pluton are microcline- and orthoclase-micropertthites. Their compositions have been determined by the  $20\bar{1}$  X-ray method, both before and after homogenization. The bulk compositions are very rich in potassium as a result of postmagmatic recrystallization of the alkali feldspar. There is no significant variation in either the bulk composition or the composition of the potassic phase in different parts of the intrusion. The structural state of the feldspars has been studied by measurement of  $2V$  and obliquity of the potassic phases, and the reciprocal lattice angles  $\alpha^*$  and  $\gamma^*$  of the potassic and sodic phases in selected crystals. Most of the specimens contain near-maximum microcline, but there is a decrease in the obliquity of the potassic phase at the eastern end of the intrusion. This can be related to the subsequent intrusion of the Main Donegal Granite.

THE Ardara pluton is a roughly circular granite intrusion of Caledonian age situated on the west coast of Donegal, Ireland. The geology of the pluton has been described by Akaad (1956), who showed that it is made up of two units: an earlier, highly contaminated, granodiorite ('tonalite'), forming an outer ring; and a later granodiorite, which is contaminated in the northern and eastern parts, forming the central mass. The pluton is surrounded by Dalradian country rocks except at the eastern end, where it is truncated by a later intrusion, the Main Donegal Granite (Pitcher *et al.*, 1959).

The rocks in the Ardara pluton contain approximately 15 to 20 % of alkali feldspar, mostly as microcline-micropertthite with well developed cross-hatched twinning, but also in some cases apparently as orthoclase-micropertthite. For the purpose of this study the alkali feldspar was separated from sixteen samples of rock, located as shown in fig. 1, by a combination of magnetic and heavy liquid methods. The object was to discover whether they showed any chemical or structural variations that could be related to the geological history of the intrusion.

*Composition.* The bulk compositions of the alkali feldspars were determined by the  $20\bar{1}$  X-ray method (Orville 1963). Each specimen was homogenized by heating at  $1000^\circ\text{C}$ . for 3 days. The X-ray powder patterns of the homogenized samples were then obtained using a

diffractometer with  $\text{Cu-K}\alpha$  radiation and  $\text{KBrO}_3$  as an internal standard. The specimens remained triclinic after the heat treatment, although the separation of 131 and  $\bar{1}\bar{3}1$  peaks was generally reduced, and the compositions were therefore estimated from the determinative data given by Orville (1960) for triclinic potassium feldspars. The powder patterns of unheated samples were also obtained using  $\text{KBrO}_3$  as an

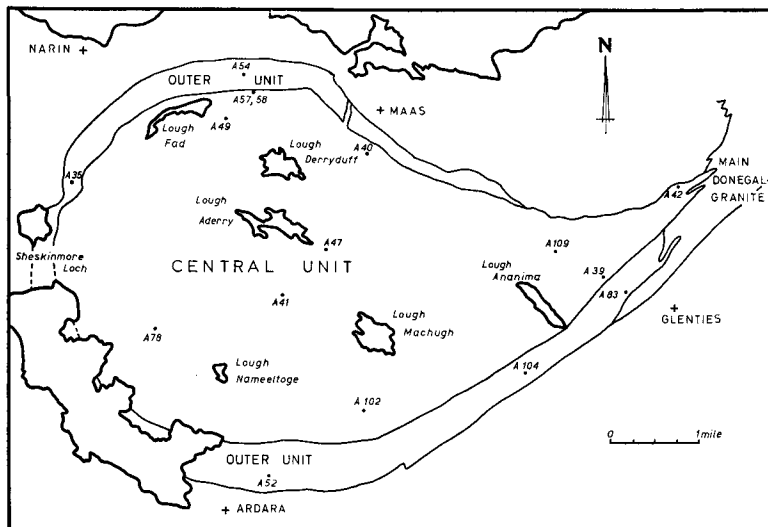


FIG. 1. Map of the Ardara pluton showing specimen localities.

internal standard, and the  $20\bar{1}$  method was used to determine the amount of sodium remaining in solid solution in the potassium phases of the perthites.

The first two columns of table I show the (albite + anorthite) contents of the alkali feldspars: in col. 1 the bulk compositions of the perthitic feldspars determined from the homogenized samples; in col. 2 the amount of sodium remaining in the potassic phases after exsolution. The differences between the two sets of figures represent the amount of the sodic phase in the perthites, and in all the samples it is found that the sodic phase makes up less than 10% of the total.

Petrographic examination shows that the sodium content of the alkali feldspars must originally have been much greater, because a substantial amount of recrystallized albite on the borders of alkali feldspar crystals is clearly derived from the alkali feldspar. Recrystallized albite

is found only on those grain boundaries where an alkali feldspar crystal is in contact with another feldspar crystal, and not on boundaries with other minerals. On plagioclase-alkali-feldspar boundaries it usually takes the form of an outgrowth from the plagioclase into the alkali feldspar. The replacive nature of these outgrowths can be seen from the presence of relict inclusions of the adjacent potassium feldspar crystal. On mutual boundaries between alkali feldspar crystals the recrystallized albite takes the form of discrete grains; these are usually coaxial with the albite lamellae in one of the adjacent alkali feldspar crystals, and they may contain inclusions of the adjacent microcline showing that they are also replacive. The present bulk compositions are therefore more potassic than the original compositions, and are governed by the amount of postmagmatic recrystallization that has taken place, rather than by the composition or conditions of crystallization of the magma.

The amount of albite remaining in solid solution in the potassic phases of the perthites varies up to a maximum of 6 wt. %. Goldsmith and Laves (1961) found that microcline usually contains less than 5 % of albite in solid solution, while orthoclase may contain 10 % or more; but although some of the Ardara feldspars are monoclinic, or of low obliquity, the potassic phases of these samples are no more sodic than those of the maximum-microcline perthites.

*Structural state.* The crystallographic and optical properties of the potassium feldspars depend on variations in sodium content, Si-Al order, and the presence or absence of submicroscopic twinning. Since the sodium contents of the potassic phases in the Ardara feldspars are small (2.5 to 6.0 wt. %), the variation in sodium content will be neglected in considering the variation in properties between them. Goldsmith and Laves (1961) have shown that the presence of sodium has a negligible effect on the reciprocal lattice angles  $\alpha^*$  and  $\gamma^*$  between  $Or_{100}$  and  $Or_{70}$ . No precise information is available on the effect of sodium content on the optic axial angle, although the work of Tuttle (1952) suggests that the presence of sodium would cause a slight increase in  $2V_\alpha$ .

Information on the structural state of the potassic phases has been obtained from measurements of  $2V$ , which depends largely on the degrees of Si-Al order,<sup>1</sup> and the obliquity, expressed either as  $\gamma^*$  or as  $\Delta (= 12.5(d_{131} - d_{1\bar{3}1}))$ , which also depends on the presence or

<sup>1</sup> Marfunin (1961) has calculated that submicroscopic twinning would decrease  $2V_\alpha$  of microcline by not more than 3 degrees.

absence of submicroscopic twinning. The results of these measurements are given in table I.

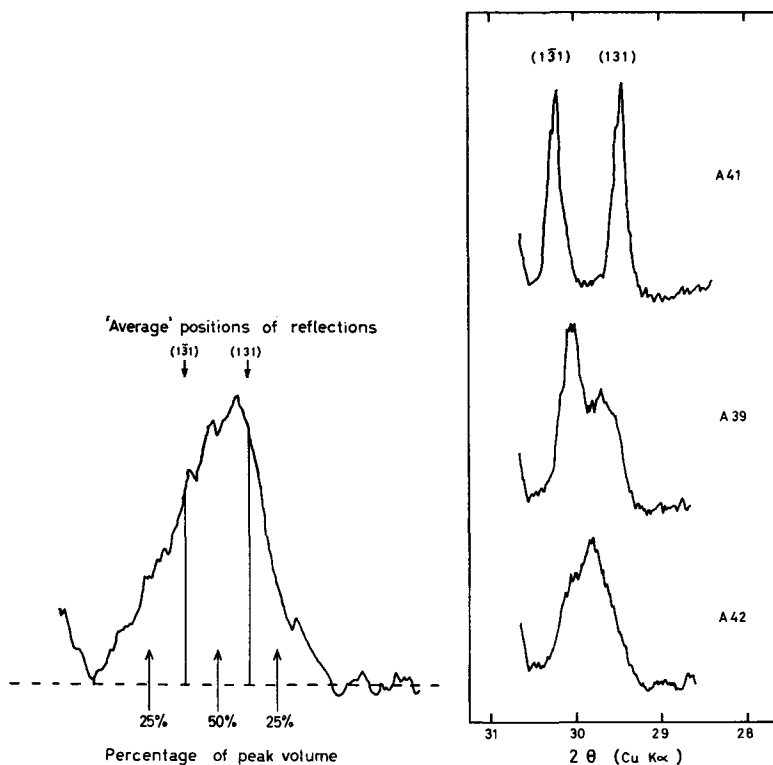
The optic axial angle was measured by direct orthoscopic examination on a 3-axis universal stage, using an average of ten crystals from each rock. The values of  $\Delta$  and  $\gamma^*$  were obtained from the X-ray powder patterns, the separation of the 130 and  $\bar{1}\bar{3}0$  peaks being used to calculate  $\gamma^*$ . The obliquity of specimens with a single broad 131– $\bar{1}\bar{3}1$  peak

TABLE I. Compositions and crystallographic data of alkali feldspars from the Ardara granites

No.	Composition (wt. % Ab + An)		$2V_\alpha$	$\Delta$	$\gamma^*$
	Total	K-phase			
A35	8.0	5.0	82°	0.90	92° 20'
A39	7.0	2.5	70°	0.58	—
A40	7.5	4.0	78°	0.85	92° 15'
A41	7.5	6.0	80°	0.94	92° 14'
A42	6.0	3.5	68°	0.45	—
A47	12.0	3.0	78°	0.92	92° 15'
A49	8.5	5.5	80°	0.94	92° 18'
A52	8.5	4.0	82°	0.89	92° 10'
A54	7.5	6.0	81°	0.96	92° 15'
A57	10.0	5.5	81°	0.99	92° 17'
A58	12.5	6.0	79°	0.97	92° 18'
A78	8.5	4.5	81°	0.97	92° 20'
A83	8.5	6.0	68°	0.50	—
A102	9.5	3.0	79°	0.83	91° 55'
A104	11.5	4.5	69°	0.34	—
A109	12.5	3.5	78°	0.82	91° 57'

was expressed in terms of average  $2\theta_{131}$  and  $2\theta_{\bar{1}\bar{3}1}$  values, derived as indicated in fig. 2. This method gives a measure of the average obliquity, and is preferred to the alternative method described by Dietrich (1962), which gives undue weight to the most triclinic parts of structurally inhomogeneous specimens.

Most of the samples examined have near-maximum obliquity values and optic axial angles, but there are four exceptions, A39, A42, A83, and A104, all of which are from the eastern end of the intrusion. These four samples not only have lower obliquity and  $2V$ , but are less homogeneous than the others in that their optic axial angles vary over a wider range and their 131 and  $\bar{1}\bar{3}1$  X-ray reflections are broadened (fig. 3). In other parts of the intrusion there is no significant variation in properties; neither  $2V$  nor  $\Delta$  can be related to the distance from the outer contact or to the degree of contamination (fig. 4). The values



FIGS. 2 and 3: FIG. 2 (left). Method used for measuring the obliquity of specimens whose X-ray powder patterns show broadened or combined 131 and  $1\bar{3}1$  peaks. The combined peak is assumed to be made up of reflections from 131 and  $1\bar{3}1$  planes in roughly equal proportions, so that approximately 50% of the peak volume can be assigned to 131 and 50% to  $1\bar{3}1$ . 25% of the total peak volume then lies at angles greater than the average  $2\theta_{131}$  and 25% at angles less than the average  $2\theta_{1\bar{3}1}$ . The triclinicity value  $\Delta$  is calculated from  $2\theta_{131}$  and  $2\theta_{1\bar{3}1}$  in the usual way. The method should not be used for very asymmetrical peaks. FIG. 3 (right). The appearance of the 131 and  $1\bar{3}1$  reflections in the X-ray powder patterns of alkali feldspars from different parts of the Ardara pluton.

obtained from the pegmatite specimens A57 and A58 are similar to those in the surrounding granites.

In order to find out whether the sodic phases of the perthites show any similar variation in structural state a number of crystals were examined by means of  $b$ -axis oscillation photographs, as described by Smith and MacKenzie (1955). Examples of crystals with a potassic phase of high obliquity were obtained from several rocks, but the

samples whose potassic phases are of lower obliquity are severely granulated, and attention was confined to A83, in which the alkali feldspar crystals were large enough to be used. There is, of course, no reason why extremely small crystals should not be used, but the amount of sodic phase present ( $\sim 5\%$ ) is such that even crystals of 0.1–0.5 mm diameter require long exposure times to give measurable sodic reflections.

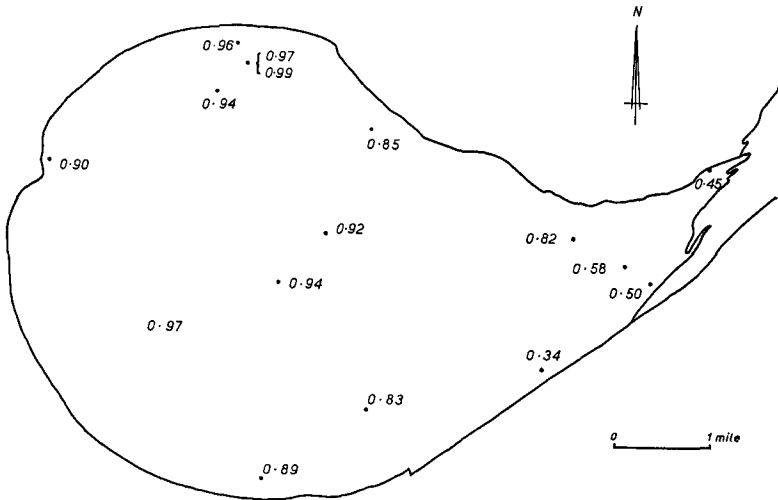


Fig. 4. The distribution of  $\Delta$  (obliquity) values of the potassium feldspars in the Ardara pluton.

The results of the measurements are given in table II. Most of the photographs, both of the potassic and of the sodic phase, show reflections that are related by albite twinning. Weak pericline twinning was found in only a few perthitic crystals, in both potassic and sodic phases, although it was often well developed in crystals whose lattice angles were not measured because they contained no sodic phase. These crystals also appeared to have much more closely spaced twin lamellae than those that showed only albite twinning. The diagonal association described by Smith and MacKenzie (1959) was not found in any of the crystals examined.

The angles  $\alpha^*$  and  $\gamma^*$  of the coexisting phases are plotted in fig. 5. The crystals from specimens A47, A54, and A58 contain a potassic phase near maximum microcline, as might be expected from the  $\gamma^*$  and

$\Delta$  measurements on the bulk samples, together with a sodic phase near low albite. The sodic phase in crystal 3 from A54 is exceptional in having  $\gamma^*$   $89^\circ 37'$  (low albite:  $\gamma^*$   $90^\circ 29'$ ), but this could be due to the presence of calcium in the sodic phase and does not necessarily indicate any departure from a low-temperature structural state.

TABLE II. Measurements of reciprocal lattice angles of the coexisting phases in alkali feldspar crystals. All the measurements given in this table were made from albite-twin reflections. Pericline-twin reflections were either absent or too weak to measure, except in the potassic phases of the crystals from A47 (crystal 1:  $\alpha^*$   $90^\circ 15'$ ,  $\gamma^*$   $92^\circ 09'$ ; crystal 2:  $\alpha^*$   $90^\circ 13'$ ,  $\gamma^*$   $92^\circ 09'$ )

Rock No.	Crystal No.	K-phase		Na-phase	
		$\alpha^*$	$\gamma^*$	$\alpha^*$	$\gamma^*$
A58	1	$90^\circ 21'$	$92^\circ 09'$	$86^\circ 28'$	$90^\circ 16'$
	2	$90^\circ 21'$	$92^\circ 07'$	$86^\circ 27'$	$90^\circ 15'$
A47	1	$90^\circ 21'$	$92^\circ 04'$	$86^\circ 28'$	$90^\circ 17'$
	2	$90^\circ 14'$	$91^\circ 52'$	$86^\circ 27'$	$90^\circ 28'$
A54	1	$90^\circ 24'$	$92^\circ 11'$	$86^\circ 32'$	$90^\circ 15'$
	2	$90^\circ 24'$	$92^\circ 13'$	$86^\circ 34'$	$90^\circ 16'$
	3	$90^\circ 22'$	$92^\circ 11'$	$86^\circ 20'$	$89^\circ 37'$
A83	1	Monoclinic		$86^\circ 13'$	$89^\circ 24'$
	2	$90^\circ 13'$	$91^\circ 26'$	$86^\circ 24'$	$89^\circ 36'$
	3	† { Monoclinic $90^\circ 11'$ $91^\circ 35'$ }		$86^\circ 10'$	$89^\circ 22'$
	4	Triclinic (untwinned)		$86^\circ 26'$	$89^\circ 45'$
	5	Triclinic (untwinned)		$86^\circ 20'$	$89^\circ 27'$
	6	Triclinic (untwinned)		$86^\circ 14'$	$89^\circ 26'$
	7	Triclinic (untwinned)		$86^\circ 15'$	$89^\circ 27'$
	8	Triclinic (untwinned)		$86^\circ 16'$	$89^\circ 16'$

† The potassic phase in crystal 3 from A83 shows strong monoclinic and triclinic reflections joined by streaks indicating the presence of material with intermediate obliquity.

The crystals from A83 show a greater variation in the lattice angles of the potassic phase. The potassic phase is monoclinic in crystal 1 and triclinic in crystal 2; crystal 3 contains both monoclinic and triclinic material; and the potassic phases of the other crystals do not show any twinning in the X-ray photographs, although examination of intensities shows that they are triclinic. The obliquity of the potassic phases in these untwinned crystals may be estimated from the extinction angles  $\alpha' \wedge (010)$  on  $(001)$ , which were found to range from  $0^\circ$  to  $15^\circ$ , compared with  $12^\circ$  for crystal 2 ( $\gamma^*$   $91^\circ 26'$ ) or approximately  $16^\circ$  for maximum microcline ( $\gamma^*$   $92^\circ 20'$ ). The lattice angles of the sodic phases in A83 are much less variable, and there is no significant difference between the sodic phases coexisting with a monoclinic potassic phase and those

coexisting with a triclinic potassic phase. There is therefore no evidence that the structural state of the sodic phase varies in the same way as that of the potassic phase. The position of the sodic phases on the diagram of  $\alpha^*$  against  $\gamma^*$  is again possibly due to the presence of calcium. There is such a small amount of sodic phase in A83 ( $\sim 2.5\%$ —

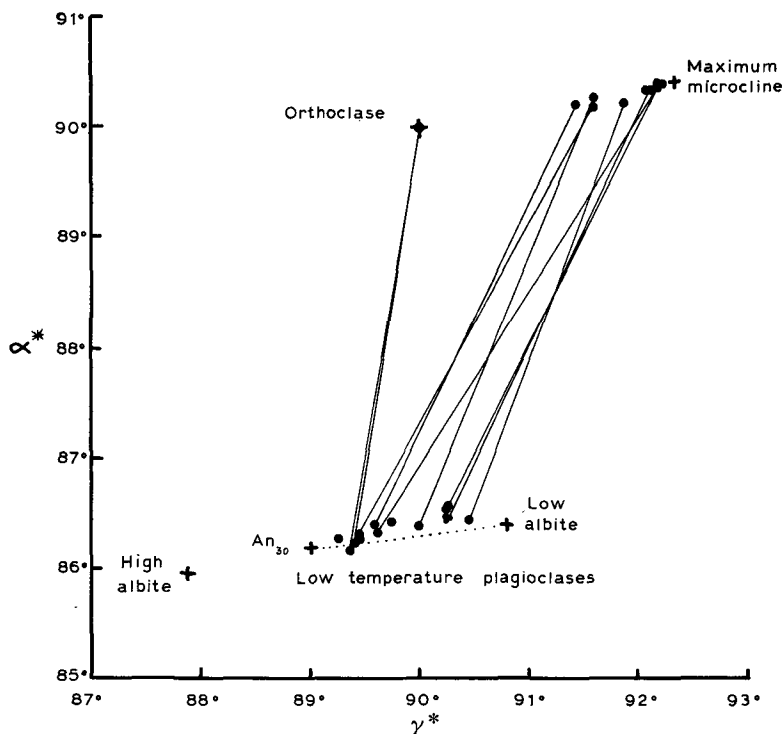


FIG. 5. Plot of  $\alpha^*$  against  $\gamma^*$  for the coexisting phases in perthitic alkali feldspars from the Ardara pluton.

see table I) that even a small amount of calcium in the original feldspar ( $\sim 0.5\%$ ) could give rise to a sodic phase with a composition of An<sub>20</sub>, assuming that all the calcium of the original feldspar was concentrated in the sodic phase.

*Discussion.* The only appreciable variation in the alkali feldspars is in the structural state of the specimens from the eastern end of the intrusion. Microscopic examination of the rocks shows that this variation is related to the proximity of the later Main Donegal Granite. As the Main Donegal Granite is approached the rocks of the Ardara



pluton show increasingly severe cataclastic deformation, which can be related in the field to a lineation dipping at about 20° to the southwest, and in addition to becoming more and more granulated the potassic feldspar gradually loses its characteristic cross-hatched twinning. The latter feature is clearly related to the decrease in triclinicity, because the extinction angles on (001), which are a measure of triclinicity, are

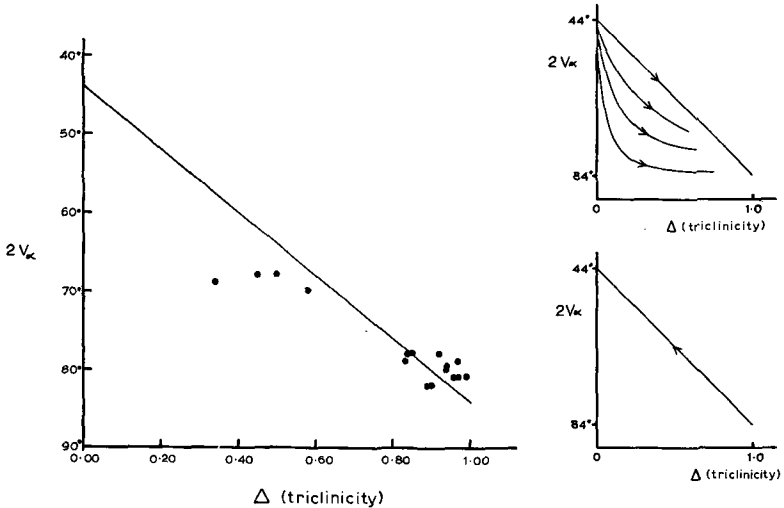


FIG. 6 (left). The relation between  $2V$  and  $\Delta$  (obliquity or triclinicity) of the potassic phases of alkali feldspars from the Ardara pluton. FIG. 7 (right). Diagram to illustrate the difference between the various ways in which a high-temperature potassium feldspar can become ordered (a, top), and the single way in which a maximum microcline can become disordered (b, bottom).

higher in crystals that retain their cross-hatched twinning than in those that are untwinned.

The thermal history of the feldspars may be illustrated by the diagram of  $2V$  against obliquity (fig. 6). During the original cooling following crystallization and unmixing the potassic phases would have become more and more ordered, resulting in increasing  $2V$  and eventually the development of triclinic symmetry. The final product would have a high  $2V_{\alpha}$  and maximum obliquity. If a growth of triclinic regions kept pace with ordering the specimens during cooling would always have had the maximum possible obliquity; if not, there would have been an intermediate state of high order (high  $2V$ ) but low obliquity,

i.e. orthoclase, and in many granitic rocks this intermediate state is preserved.

Subsequent heating of a maximum microcline would result in disordering, but without the development of submicroscopic twin-related regions such as may form during cooling. While the specimens were being heated they would therefore have had the maximum obliquity possible at each stage of disordering. In other words there is only one path from maximum microcline to less ordered varieties of potassium feldspar (fig. 7*b*), in contrast to the variety of paths that may be followed during cooling (fig. 7*a*). The data given by Marfunin (1961) indicate that the limit of obliquity corresponds roughly to the straight line shown in fig. 6, joining specimens with a  $2V_\alpha$  of  $44^\circ$ , which are always monoclinic, to specimens with  $2V_\alpha$  of  $84^\circ$  having maximum obliquity.

The high  $2V$  and obliquity of most of the Ardara specimens shows that they have the maximum degree of Si-Al order and that their structure is made up of triclinic regions large enough to give the maximum degree of triclinic character to the optical properties. Those specimens that have been reheated by the Main Donegal Granite can be seen from fig. 6 to have obliquity values less than the maximum possible in specimens of their degree of Si-Al order (as indicated by  $2V$ ). Thus not only have these specimens failed to re-attain their maximum degree of order after heating, but the growth of triclinic regions during re-ordering has also been very sluggish.

The incomplete return of the naturally reheated samples to their ordered form may be contrasted with the complete ordering of those that have not been reheated subsequently to their initial recrystallization. Donnay, Wyart, and Sabatier (1959) have suggested that water is necessary as a catalyst for the ordering process to take place, and if this is so the incomplete re-ordering of the feldspars may indicate that the granites contained more interstitial water during their initial cooling than during their later period of cooling (i.e. after reheating).

The effect of contact metamorphism on the structural state of the alkali feldspars is not accompanied by any change in their composition. It may be seen from table I that the specimens of low obliquity (A39, A42, A83, and A104) have similar bulk compositions to those with high obliquities, and the amounts of sodium in solid solution in their potassic phases are also similar. The reason for this is probably that migration of the large cations in feldspars takes place more readily than ordering or disordering, so that during their reheating the feldspars would have become homogenized, preventing any loss of exsolved albite. Exsolution

would then have taken place again on cooling, giving a distribution of sodium similar to that in the other parts of the intrusion. The structural states of the alkali feldspars are thus a more useful guide to their thermal history than are their compositions.

*Acknowledgements.* I would like to thank Dr. R. A. Howie for a critical reading of the manuscript of this paper. Collection of specimens was aided by a grant from the Central Research Fund of London University.

#### *References*

- AKAAD (M. K.), 1956. *Quart. Journ. Geol. Soc.*, vol. 112, p. 263.  
DIETRICH (R. V.), 1962. *Norsk. Geol. Tidsskr.*, vol. 42 (feldspar volume), p. 394.  
DONNAY (G.), WYART (J.), and SABATIER (G.), 1959. *Zeits. Krist.*, vol. 112, p. 161.  
GOLDSMITH (J. R.) and LAVES (F.), 1961. *Cursillos y Conferencias del Instituto 'Lucas Mallada'*, vol. 8, p. 81.  
MARFUNIN (A. S.), 1961. *Ibid.*, vol. 8, p. 97.  
ORVILLE (P. M.), 1960. *Bull. Geol. Soc. Amer.*, vol. 71, p. 1939.  
— 1963. *Amer. Journ. Sci.*, vol. 261, p. 201.  
PITCHER (W. S.), READ (H. H.), CHEESMAN (R. L.), PANDE (I. C.), and TOZER (C. F.), 1959. *Quart. Journ. Geol. Soc.*, vol. 114 (for 1958), p. 259.  
SMITH (J. V.) and MACKENZIE (W. S.), 1955. *Amer. Min.*, vol. 40, p. 733.  
— — 1959. *Ibid.*, vol. 44, p. 1169.  
TUTTLE (O. F.), 1952. *Amer. Journ. Sci.*, Bowen volume, p. 553.

[*Manuscript received 1 September 1965*]

---