A note on the $\bar{2}01$ *spacing of some lime-rich alkali feldspars from Kangerdlugssuaq, East Greenland*

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Summary. The values of 2θ $\bar{2}01$ for some homogenized lime-rich fine microperthites from the Kangerdlugssuaq alkaline intrusion, East Greenland, are investigated and found to be consistently high when compared with the values used in the standard curves for estimating the Or content of alkali feldspars. This deviation, which is approximately proportional to anorthite content, results in anomalously low Or percentages being obtained and is ascribed to a distortion of the structure due to the unusually high calcium content of the microperthites.

THE Kangerdlugssuaq alkaline intrusion, East Greenland, comprises a series of concentric rings passing gradually from an outer quartz nordmarkite through reduction in quartz to a quartz-free transitional pulaskite, a nepheline-bearing pulaskite, and finally to a nepheline- and sodalite-rich core of foyaite. The intrusion is described by Wager (1965). Whilst investigating the mineralogy of the intrusion some 65 natural alkali feldspars have been studied by X-ray diffraction and single-crystal methods. The majority were taken from average rocks and, ignoring the remainder, which come from veins and pegmatites and show a wide compositional range from Or_{30} to Or_{80}, they fall into two groups.

The first group consists of zoned low-albite–orthoclase microperthites (fine microperthites), spanning the range $Or_{17}(Ab+An)_{83}$ to $Or_{32}(Ab+An)_{68}$. The second group, low-albite–orthoclase and –microcline microperthites (coarse microperthites), range from $Or_{33}(Ab+An)_{67}$ to $Or_{59}(Ab+An)_{41}$. Compared with the coarse microperthites, which show coarse perthitic lamellae, the fine microperthites are nearly homogeneous optically. They show a very fine perthitic structure and have patchily developed albite twinning.

The fine microperthites occur as large dark xenocrysts[1] in the nordmarkite and transitional pulaskite in variable proportions; the remainder of the feldspar is a lighter coloured coarse microperthite

[1] Wager (1965) uses the term porphyroblastic cryptoperthites for the xenocrysts.

usually rimmed by a sodic plagioclase. The whole series of fine microperthites (Or_{17} to Or_{32}) is less potassic than any of the 'groundmass' coarse microperthites (Or_{33} to Or_{59}) and thus forms a parallel series of low Or content, with no overlap. The dark fine microperthites are not found in the feldspathoidal main pulaskite and foyaite, which contain the most potassic coarse microperthites. In some cases (nos. 1 to 4 and 9, table I), the fine microperthites occur in xenoliths, which are believed to have been basalt, largely made over to a microsyenite by metasomatism; others seem to have a similar origin but are detached from the xenoliths and are found close to them in the syenite. The remainder (nos. 5 to 8, 10, and 11) are of doubtful origin; they are possibly crystals that crystallized early in the cooling sequence from the syenitic magma. In all the dark fine microperthites, the calcium content is notably high for alkali feldspars. In the case of the xenolithic fine microperthites, including those separated from the xenoliths, this is presumably a direct result of their having formed in a calcium-rich environment. A metasomatic paragenesis such as this is rare and would seem to have given rise to feldspars of an unusual ternary composition.

Experimental results. X-ray diffraction patterns using smear mounts were obtained and in the 2θ region 20·5° to 22·5° it appeared in all cases that both groups of feldspar contained sodium and potassium phases, presumably unmixed from high-temperature homogeneous alkali feldspars. The 2θ region 29° to 31° was also examined and showed that in addition to the albite phase the fine microperthites contained a single monoclinic (orthoclase) potassium phase whilst the coarse microperthites contained a monoclinic or triclinic potassium phase or both. Four out of five coarse microperthites had triclinic phases for which the obliquity was measurable. This ranged from 0·63 to 0·89, with an average of 0·79. In just over half, a weak 131 peak (monoclinic feldspar) was also present.

Single-crystal oscillation photographs of selected feldspars of both groups were taken and interpreted using the technique of Smith and MacKenzie (1955). Ni filtered Cu radiation was used and the crystals were mounted along the *b*-axis and oscillated through 15°, the X-ray beam being parallel to (001) at the centre of the oscillation. The sodium phases were found to be albite-twinned low-temperature sodic plagioclase, near to low-albite, the values of α^* and γ^* being given in table I and plotted in fig. 1. The potassium phases were monoclinic in the fine microperthites and mainly triclinic in the coarse microperthites, in agreement with the diffractometer evidence.

TABLE I. Partial chemical analyses and X-ray data for alkali feldspars from the Kangerdlugssuaq alkaline intrusion

No.	Oxides: wt. %			Components: wt. %			Total	Recalculated to 100 %			Sodium phase in unheated feldspars (albite twinning)		Or wt. % from $\bar{2}01$ X-ray method	$2\theta(\bar{2}01$, feldspar) $-2\theta(10\bar{1}0$, quartz)	Deviation
	Na_2O	K_2O	CaO	Or	Ab	An		Or	Ab	An	α*	γ*			
1.	8·42	2·97	2·03	17·56	71·19	10·09	98·84	17·8	72·0	10·2	86° 23′	89° 56′	10·0	1·04°	0·10°
2.	8·73	3·12	—	—	—	—	—	18·5	73·8	7·7	—	—	22·2	0·96	0·025
3.	8·27	3·19	—	—	—	—	—	18·9	69·9	11·2	—	—	14·5	0·995	0·07
4.	8·43	3·24	—	—	—	—	—	19·2	71·2	9·6	86 20	89 58	13·0	1·01	0·09
5.	7·84	4·19	1·91	24·78	66·26	9·48	100·52	24·7	65·9	9·4	—	—	21·8	0·912	0·05
6.	7·89	4·71	—	—	—	—	—	27·8	66·7	5·5	—	—	25·0	0·88	0·045
7.	7·35	4·58	1·38	27·09	62·12	6·85	96·06	28·2	64·7	7·1	86 24	90 16	27·0	0·86	0·034
8.	7·75	4·79	—	—	—	—	—	28·4	65·5	6·1	—	—	25·0	0·88	0·057
9.	7·61	4·96	1·07	29·34	64·32	5·31	98·97	29·6	65·0	5·4	—	—	27·0	0·86	0·05
10.	8·05	5·13	—	—	—	—	—	30·3	68·0	1·7	—	—	27·8	0·852	0·046
11.	7·66	5·32	—	—	—	—	—	31·5	64·7	3·8	—	—	28·0	0·85	0·055
12.	7·14	6·07	0·93	35·90	60·34	4·61	100·85	35·6	59·8	4·6	86 36	90 33	35·0	0·77	0·012
13.	7·19	6·22	0·69	36·79	60·77	3·43	100·99	36·4	60·2	3·4	86 30	90 24	35·0	0·77	0·027
14.	6·84	6·63	0·67	39·22	57·81	3·33	100·36	39·1	57·6	3·3	86 29	90 33	40·6	0·70	negative
15.	6·55	6·72	0·76	39·75	55·36	3·77	98·88	40·2	56·0	3·8	—	—	40·3	0·705	0·007
16.	4·96	9·38	0·54	55·48	41·92	2·66	100·06	55·4	41·9	2·7	86 45	90 21	53·3	0·55	ca. 0·02

Nos. 1 to 5 and 9 to 11. Fine microperthites in nordmarkite.
Nos. 6 to 8. Fine microperthites in transitional pulaskite.
Nos. 13 and 15. 'Groundmass' coarse microperthite of nordmarkite.
No. 12. 'Groundmass' coarse microperthite of transitional pulaskite.
No. 14. Coarse microperthite of main pulaskite.
No. 16. Coarse microperthite of foyaite.

Analyst: D. R. C. Kempe

All the feldspars were homogenized by dry heating at 1025° C for an approximate period of seven days. Their compositions were then estimated by measurement of the $\bar{2}01$ spacing using the X-ray diffraction method of Bowen and Tuttle (1950). Quartz was used throughout as an internal standard since interference from highly potassic feldspars

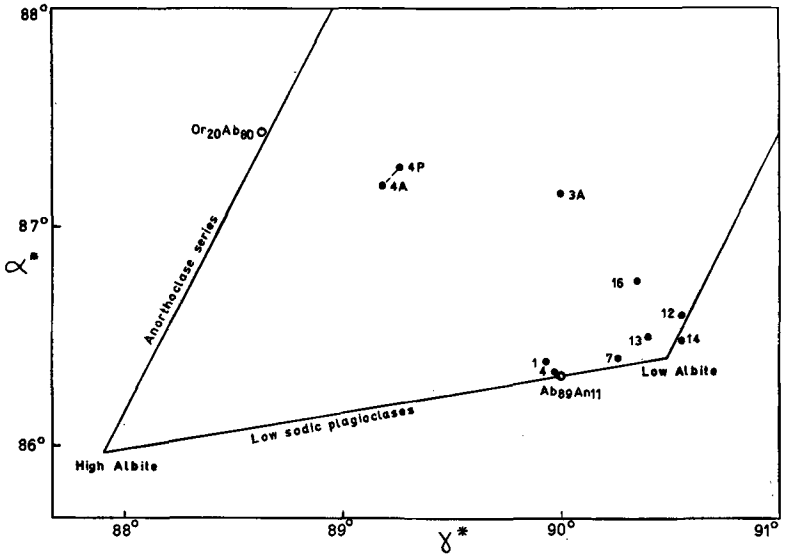

FIG. 1. Plot of α^* against γ^* of the sodium phases of the Kangerdlugssuaq fine and coarse microperthites. Letters after numbers refer to α^* and γ^* for homogenized feldspars measured by albite twinning (A) and pericline twinning (P). (After MacKenzie and Smith, 1962, with two of their reference points of known composition.)

does not occur in the range under consideration. The average value of $2\theta(\bar{2}01$, feldspar$)-2\theta(10\bar{1}0$, quartz) was taken after scanning the 2θ range 20·5° to 22·5° three times, twice in the ascending and once in the descending direction, the smear mount being moved slightly between measurements. Second samples of two of the most calcium-rich fine microperthites (nos. 1 and 4) were heated for a period of 14 days to observe any change in the position of the $\bar{2}01$ spacing. The average value of $2\theta(\bar{2}01)-2\theta(10\bar{1}0)$ of no. 1 was 0·03 less and of no. 4, 0·03 more, than in those heated for 7 days, indicating an orthoclase content of 3 % more and 3 % less, respectively. In both cases the figures given in table I and used in figs. 2 and 3 are the averages of the two sets. The

reason for this variation is thought to be the limited accuracy of the X-ray method ($\pm$3–4 %) or the fact that the composition of the feldspars varies noticeably even within a single hand specimen, especially in the case of the xenolithic fine microperthites.

Compositions of the feldspars (wt. % Or) were read off for the appropriate value of $2\theta(\bar{2}01)-2\theta(10\bar{1}0)$ using table I of Tuttle and Bowen (1958). The diffraction pattern in the 2θ region 29° to 31° was again obtained after heating to observe any detectable changes in the structural state of the feldspars. In the fine microperthites, where only a monoclinic potassium phase (orthoclase) was present before heating, the orthoclase 131 peak had merged with the albite $1\bar{3}1$ peak into a single peak (triclinic feldspar). The coarse microperthites, which variously contained monoclinic and triclinic potassium phases, also showed that merging had taken place. This suggested that both types of feldspar had homogenized during heat treatment. To confirm that the fine microperthites at least had been totally homogenized, i.e. converted to high-temperature alkali feldspars (anorthoclases), single-crystal photographs were taken of two of the most calcium-rich samples (nos. 3 and 4). It was found that in no. 4 only a single phase was present, twinned according to the albite and pericline laws. The values of α^* and γ^* were 87° 11′ and 89° 11′ (calculated from albite twinning) and 87° 16′ and 89° 16′ (calculated from pericline twinning). The agreement here is within the degree of error suggested by Smith and MacKenzie (1955), i.e. $\pm$3′ to 10′ of arc, and consistent with the presence of only one phase (see MacKenzie and Smith, 1962). The pericline twinning produced by heating in a feldspar previously showing only albite twinning of the sodium phase is consistent with pericline twinning being a feature of feldspars of a higher-temperature structural state (MacKenzie and Smith, 1962, p. 99). In no. 3 the potassium phase had disappeared but twinning of the new single-phase feldspar had not reached completion. Weak pericline twinning could be seen in some reflections whilst albite twinning appeared as streaks. An attempt to measure α^* and γ^* gave 87° 9′ and 90°, suggesting that whilst the potassium phase had been absorbed the feldspar had not progressed far towards the high-albite–orthoclase join. The homogenized feldspars are also plotted in fig. 1 and fall in the lower part of the central region within the parallelogram. The only natural feldspars yet reported that lie in this area are those of Mukherjee (1961). An attempt was also made to take a single-crystal X-ray photograph of no. 1. This sample showed only single spots but the material was too poor to give an

oriented photograph, partially due to the presence of blebs and rims of feldspar glass. It is concluded from these photographs that even if the feldspars have not all completely attained the high-temperature state (anorthoclase) the potassium phases have been absorbed, and the products of the heat treatment can be regarded as single feldspars.

The compositions of nine fine microperthites and coarse microperthites

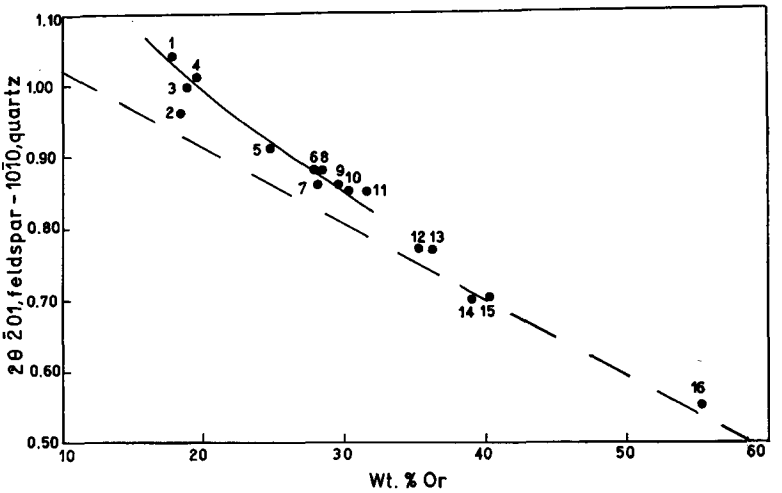

FIG. 2. $2\theta(\bar{2}01$, feldspar$) - 2\theta(10\bar{1}0$, quartz) of the Kangerdlugssuaq fine and coarse microperthites plotted against Or (wt. %) found by chemical analysis. Upper solid curve, that of the author; lower broken curve, that of Orville (in Carmichael and MacKenzie, 1964), extrapolated from Or_{40}.

were determined by partial chemical analysis (table I). The alkalis were measured by flame photometer and the lime by titration with E.D.T.A. Alkali determinations were carried out on a further seven fine microperthites and the anorthite content estimated by difference.

The 2θ values for the fine microperthites were found to give Or percentages appreciably lower than those obtained from chemical analysis when related to Bowen and Tuttle's (1950) curve. This deviation becomes progressively larger as the albite end of the curve is approached and, for those fine microperthites containing more than ca. 5 % An, it is approximately proportional to anorthite content. Since this deviation has not been noticed previously for other albite-rich feldspars, it is considered that it must be governed by anorthite content. A curve for the fine microperthites is shown in fig. 2. In the case of feldspars containing less than 5 % An, the deviation appears

to be random; however this may well be due to experimental inaccuracy and the deviation may become small and constant.

Carmichael and MacKenzie (1964) have given a method of deriving the ternary compositions of homogeneous anorthoclase feldspars more potassic than Or_{15} and their conclusion concerning the relationship between values of $2\theta(\bar{2}01) - 2\theta(10\bar{1}0)$ and anorthite content has prompted this note. They state (p. 952) that for natural feldspars the $\bar{2}01$ spacing is independent of calcium content. The new synthetic lime-free feldspar curve (P. M. Orville, in Carmichael and MacKenzie, 1964) is also shown in fig. 2; it can be seen that there is reasonable agreement between compositions determined by chemical analysis and by the $\bar{2}01$ spacing method for the coarse microperthites. The values obtained, however, generally conform with the data of Orville (1958), Koritnig (1961), and Parsons (1965), who found that the high temperature (synthetic) curve gave slightly low Or percentages for homogenized natural alkali feldspars.

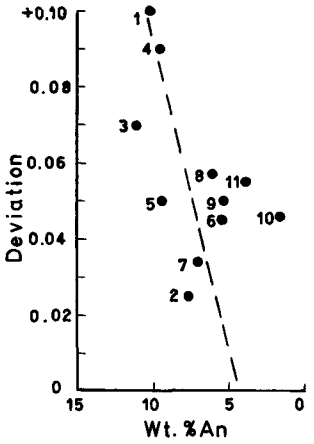

FIG. 3. Deviation of $2\theta(\bar{2}01$, feldspar$) - 2\theta(10\bar{1}0$, quartz$)$ of the Kangerdlugssuaq fine microperthites from the curve of Orville (see fig. 2) plotted against An content (wt. %).

In fig. 3 the deviation between values of $2\theta(\bar{2}01) - 2\theta(10\bar{1}0)$ from Orville's curve and those found by the writer for the fine microperthites, using compositions from chemical analysis, is plotted against anorthite content. An attempt was made to plot the deviation of the anorthoclases studied by Carmichael and MacKenzie (1964) but here the relationship seems, as these authors contend, to be random.

Before briefly considering the cause of the relationship between the $\bar{2}01$ spacing and calcium content, some sources of experimental error should be mentioned: In partially analysing the feldspars BaO and SrO have not yet been determined and therefore any effects caused by celsian and strontium feldspar in the structure have not been taken into account. The fine microperthites found in or believed to be derived from the metasomatized xenoliths contain small inclusions of biotite, amphibole, and pyroxene, which it is virtually impossible to eliminate; these never exceed 2 or 3 % by mode but they will have a small effect on CaO, Na_2O, and K_2O; to some extent, however, the effect on these

oxides will be self-cancelling. One of the totals of the feldspar components before recalculation to 100 % (table I) lies outside the maximum error of ±2 % suggested as permissible by Carmichael and MacKenzie (1964, p. 961). In seven samples the anorthite content is

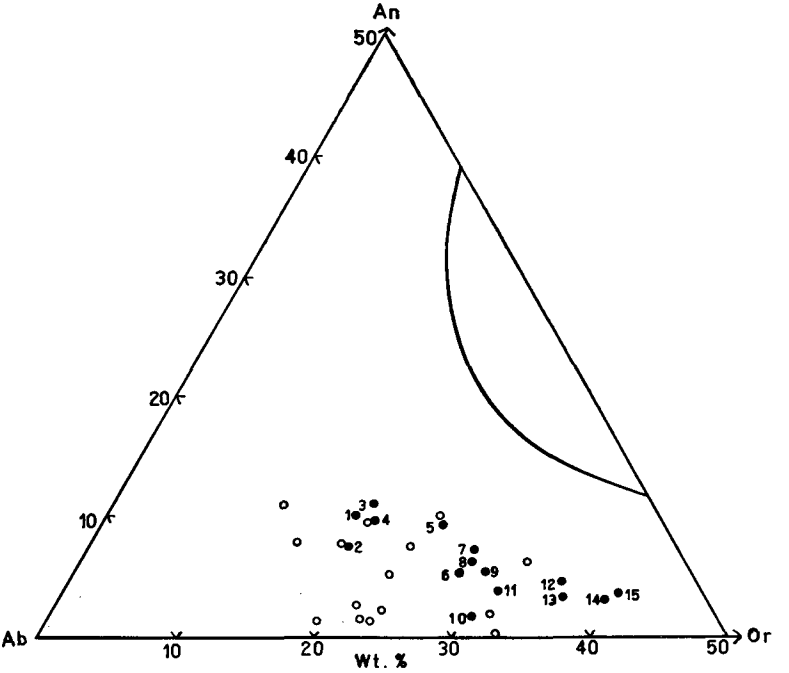

FIG. 4. Plot of soda-rich part of ternary system $NaAlSi_3O_8$–$KAlSi_3O_8$–$CaAl_2Si_2O_8$. Numbered solid circles: Kangerdlugssuaq fine and coarse microperthites. Open circles: anorthoclases from Carmichael and MacKenzie (1964).

calculated by difference. Some errors will inevitably exist here but it is thought that they cannot seriously affect the results obtained.

Discussion. Assuming virtually complete homogenization of the fine microperthites during heat treatment, it should be possible to compare their lattice parameters directly with those of the anorthoclases studied by Carmichael and MacKenzie (1964). Leaving aside their different cooling histories and parageneses—the anorthoclases occur as phenocrysts in lavas and small intrusions—the only important difference seems to be in bulk composition. The Kangerdlugssuaq feldspars are plotted in fig. 4, together with the 15 anorthoclases studied by Carmichael and

MacKenzie (1964). In plotting the latter celsian has been included with orthoclase and Sr feldspar with anorthite. It can be seen that the fine microperthites show a general tendency to higher An content relative to their Or/Ab ratio than the anorthoclases.

The approximate lattice parameters after homogenization of the three most calcium-rich fine microperthites were calculated from the

TABLE II. Approximate lattice parameters of the fine microperthites. For key to specimens, see table I

No.	Wt. % Or	a	b	c	α	β	γ
1.	17·8	8·19 Å	12·87 Å	7·11 Å	93·03°	116·08°	90·23°
3.	18·9	8·22	12·83	7·14	92·15	116·08	90·03
4.	19·2	8·20	12·86	7·13	92·93	116·06	89·13

No.	V	a^*	b^*	c^*	α^*	β^*	γ^*
1.	671·5 Å^3	0·136 Å^{-1}	0·078 Å^{-1}	0·157 Å^{-1}	86·52°	63·87°	88·25°
3.	675·5	0·136	0·078	0·156	87·58	63·90	88·92
4.	674·1	0·136	0·078	0·156	87·17	63·95	89·55

Lattice parameters of anorthoclases of comparable Or content (Carmichael and MacKenzie, 1964, table III)

No.	Wt. % Or	a	b	c	α	β	γ
3.	17·8	8·236 Å	12·921 Å	7·136 Å	92·56°	116·34°	90·15°
4.	18·7	8·239	12·930	7·133	92·40	116·29	90·27
5.	18·8	8·239	12·935	7·141	92·26	116·38	90·28

No.	V	a^*	b^*	c^*	α^*	β^*	γ^*
3.	679·6 Å^3	0·136 Å^{-1}	0·077 Å^{-1}	0·157 Å^{-1}	87·07°	63·62°	88·57°
4.	680·4	0·135	0·077	0·157	87·19	63·67	88·52
5.	681·0	0·136	0·077	0·156	87·34	63·59	88·56

diffractometer powder trace using a least-squares computer programme (written by Dr. P. J. Woodrow). It was found (table II) that most of the parameters showed appreciable differences from those of the anorthoclases of comparable Or content (nos. 3, 4, and 5 in Carmichael and MacKenzie, 1964). It can be seen that the values of a, b, β, and V (volume) are lower in the fine microperthites; b^* and β^* are higher; c, α, γ, α^*, and γ^* show inconsistent differences; and a^* and c^* are the same. The values of α^* and γ^* (see also fig. 1) suggest that total chemical homogenization (i.e. absorption of the potassium phase) has been achieved but that the feldspars have not completely attained the high-temperature state. The differences between α^* and γ^* for nos. 3 and 4 obtained by diffractometer and by single-crystal X-ray photographs are thought to be due to the fact that a single crystal, especially in

material that has been homogenized by heat treatment, cannot be truly representative of the sample. The $\bar{2}01$ spacing does not depend on α^* and γ^* but, in the direct cell, on a, c, and β. The consistently low values of a, by analogy with low- and high-albite, would suggest that retention of a low-temperature state might be the explanation of the deviation. However, c and β should then be too high and this is not the case. In the reciprocal cell $d_{\bar{2}01}$ depends on a^*, c^*, and β^*. The values of a^* and c^* are the same as those of the anorthoclases but β^* is consistently higher. It is concluded therefore that the unusually high Ca content of the fine microperthites causes a distortion of the structure which results in the $\bar{2}01$ deviations. Although the deviation is not found in synthetic ternary feldspars, in which varying the proportions of Ab and An has no effect on the $\bar{2}01$ spacing as a measure of Or content (Prof. W. S. MacKenzie and Dr. D. L. Hamilton, personal communication), it is tentatively suggested that homogenization might show it to exist in other low-temperature natural feldspars of similar ternary composition, in which the An content is unusually high relative to the Or/Ab ratio. Some examples are the Kûngnât K 105 (Upton, 1960) with 7 % An, and the Oslo larvikites nos. 1 and 8 with 10 % and 14 % An respectively (Muir and Smith, 1956). Care should therefore be exercised in estimating the compositions of such feldspars by the $\bar{2}01$ method.

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