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ANTIPERTHITE AND MANTLED FELDSPAR TEXTURES IN CHARNOCKITE (ENDERBITE) FROM S.W. NIGERIA

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ABSTRACT

The strongly antiperthitic plagioclases of a hypersthene-quartz-dioritic (enderbite) member of a charnockite series occurring in S.W. Nigeria were found to be commonly mantled by alkali feldspar (orthoclase microperthite). The potassium-rich phase of the orthoclase microperthite is in optical continuity with the potassium-rich phase of the antiperthites. The petrography and mineralogy of these feldspars are described, including qualitative data obtained by microprobe analysis, and the probability of a common origin for the antiperthite and mantle alkali feldspar by exsolution processes discussed. Modal analyses of the proportions of alkali feldspar to plagioclase for twelve individual crystals from the same rock specimen gave sufficiently constant values to help substantiate the proposal of exsolution origin.

INTRODUCTION

Antiperthitic plagioclase is a very common feature of the charnockitic rocks, to such an extent that it is often quoted as a characteristic of such rocks (*e.g.*, Heinrich, 1956). Because of the practical difficulties of experimental and synthetic studies inherent in the sluggish transformation kinetics of the plagioclases, antiperthite texture has not received as great attention as the perthite textures from research workers. Development of antiperthite both by exsolution and replacement processes is accepted (Deer *et al.*, 1963). An exsolution origin for the antiperthites in granulite facies rocks has been considered by Sen (1959). This worker investigated the potassium content of a series of natural plagioclase feldspars from amphibolite facies, granulite facies and volcanic rocks by means of partial chemical analyses. He found a definite increase in potassium content with increase in temperature of formation and sought to explain this trend by lattice structural considerations, *e.g.* the increasing "openness" of the plagioclase structure with increasing temperature, the resultant strengthening of the Si-O bonds by the acceptance of K and the increasing facility of coordination of K by oxygen with increasing Al/Si disorder in the plagioclase. Sen interpreted the antiperthitic plagioclase occurring in relatively high temperature rocks as products of exsolution (*i.e.*, in granulite facies, volcanic and contact metamorphic rocks) but recognized also antiperthites formed by replacement. The results of the present study point to an exsolution origin for the antiperthite.

The antiperthites of the Nigerian enderbite are mantled by a zone of alkali feldspar. Such mantling of plagioclase by alkali feldspar is not uncommon and is generally explained by reaction processes in a crystallizing magma (Tuttle and Bowen, 1958; Stewart and Roseboom, 1962; Czamanske, 1965). In the case of the enderbite antiperthites, however, the alkali feldspar mantling may have developed by exsolution processes, in a similar manner to the alkali feldspar contained within the plagioclase hosts.

The Wasimi Enderbite

The Wasimi enderbite is a member of a sequence of massive charnockitic rocks, ranging from norites to granites, which outcrop sporadically within the basement complex of S.W. Nigeria. Scattered outcrops of the quartz-diorite are found around the village of Wasimi, east of Ibadan on the Ibadan-Ife Road. Although partially metasomatized during the so-called Older Granite orogenic cycle, much of the diorite escaped and retains its petrological identity and charnockitic characters unchanged (Hubbard, 1965). It is the antiperthites of the unaltered rock which are considered in this article. The unmetasomatized rocks are readily identifiable in the field by their dark color and, mineralogically, by the retention of hypersthene, both of these features being lost on metasomatism.

Three co-existing feldspar phases characterize the rock. The rectangular andesine grains, which may be up to 1 cm in greatest length, contain and are mantled by microperthitic orthoclase. Diffuse zones of more albitic plagioclase have formed at the junctions of the alkali feldspar and the host andesine. Twinning is variably developed and oscillatory zoning, though common is very diffuse and much disturbed in the regions of antiperthite aggregations. Alkali feldspar occurs only in connection with the antiperthitic plagioclases, either within or as irregular mantles to the latter.

Hypersthene and diopside are the major mafic constituents. The pyroxenes are occasionally marginally altered to amphibole and/or biotite and are typically strongly schillerized. Biotite also occurs sparingly as a primary component; then showing a characteristic reddish-brown pleochroism. The minor quartz is interstitial or in myrmekitic intergrowth with plagioclase. The common accessories are iron ore and apatite.

The Feldspars

Petrography. The following features were noted as petrographically characteristic of the antiperthitic feldspars:

1) Alkali feldspar occurs as irregular patches within and as continuous or discontinuous mantles around the plagioclase laths.

2) The antiperthitic patches show no clear alignment with any particular direction in the plagioclase host crystals, being quite irregular in form.

3) Where the plagioclase exhibits only multiple twinning (albite and/or pericline) all the antiperthitic patches and corresponding mantle have identical lattice orientation in

each individual plagioclase grain, quasi-parallel to the plagioclase lattice. Where the plagioclase is further twinned on the carlsbad law, there is a marked tendency for the antiperthitic portions to extinguish quasi-parallel to the opposite carlsbad twin member to that in which they are contained. The latter feature is not ubiquitous (Fig. 1).

4) The alkali feldspar patches and mantles are bordered at their contacts with the andesines by a rather irregular zone of plagioclase of lower An content than the main body of the plagioclase. The contact of this zone with the alkali feldspar is sharp and distinct whilst that with the main plagioclase is indistinct and diffuse (Fig. 1).

5) Where the alkali feldspar mantles are discontinuous the corresponding albitic plagioclase zone is parallelly discontinuous.

6) In some strained specimens there is a tendency for the antiperthitic alkali feldspar to aggregate marginal to the crystal, *i.e.*, less enclosed alkali feldspar and more extensive mantles.

7) The antiperthitic and mantle alkali feldspar is always untwinned. The mantles are highly microperthitic, the included alkali feldspar less markedly so (Fig. 2).

8) Myrmekite is sparsely developed when mantles to adjoining plagioclases are in contact and plagioclase inclusions in the mantles are typically highly myrmekitized (Fig. 2).

9) The contact of the alkali feldspar with the plagioclase, although sharp, is typically ragged and embayed. This feature is best seen at the mantle contacts. Perthitic lamellae may in places be seen passing into the plagioclase.

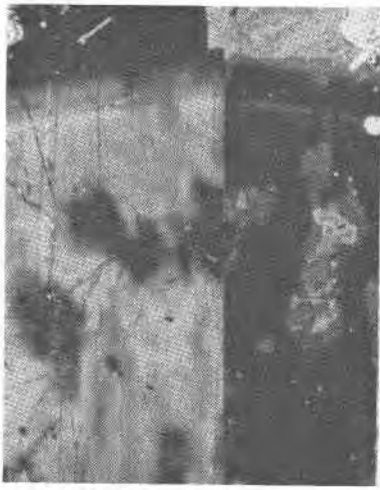

FIG. 1. Photomicrograph of carlsbad twinned antiperthitic plagioclase. The irregular form of the enclosed alkali feldspar, the acidified zones of plagioclase surrounding them, the alternate lattice orientation of the alkali feldspar with respect to the carlsbad twin units and, at the extreme left, the extension of these features to the peripheral alkali feldspar are clearly shown (See "Petrography" in text). ×100. Polars crossed. Alkali feldspar stained.

FIG. 2. Photomicrograph illustrating the microperthitic nature of the alkali feldspar phase of the antiperthites. Note formation of myrmekite where the mantling alkali feldspar is in contact with plagioclase other than its host. ×27. Polars crossed. Alkali feldspar stained.

Modal Analysis. The occurrence of a constant proportion of alkali feldspar to plagioclase in the antiperthites of any one rock would furnish excellent evidence for formation by exsolution rather than replacement since regularity of effectiveness is atypical of replacement processes. Separation of *complete*, single, antiperthite crystals suitable for analysis was precluded by the ubiquitous presence of external mantles of the potassic phase. A search was therefore made for a suitable rock for which modal analysis methods might be used to determine the relative proportions of the two feldspars of the antiperthites. The criteria for suitability were taken to be:

(a) Presence of many antiperthites in the form of sub-euhedral phenocrysts.

(b) Both peripheral and internal development of alkali feldspar must be strongly and distinctly developed.

(c) All the alkali feldspar present in the rock must be directly related to antiperthitic plagioclase (determinable by feature 3, under "Petrography.")

(d) There must be no indications of migration of the alkali feldspar from the plagioclase (see feature 6) for fear of possible coalescence of alkali feldspar from more than one antiperthite.

These conditions were satisfied, *in toto*, only by the Wasimi quartz-diorite member designated FH 1005.

The antiperthite crystals to be individually measured were selected such that only phenocrysts exhibiting good crystal forms, with the consequent greater probability that a complete crystal cross-section existed, were used. Where antiperthitic plagioclases came close together such that their alkali feldspar mantles might be confused, only that alkali feldspar, which extinguished exactly with the contained alkali feldspar of the antiperthite under analysis and which did not form myrmekite at its contact with this plagioclase, was included in the calculation (cf. features 3 and 8). Finally, antiperthites with many small patches of alkali feldspar were selected in preference to those with fewer but larger aggregates, thus ensuring the greatest possible number of phase changes in the analysis (Chayes, 1956).

A Leitz micrometer integrating ocular was used for the measurements, which were made at 120× magnification. Phase changes were measured micrometrically along continuous traverses spaced at 0.05-mm intervals. The results, in volume per cent (*i.e.*, approximately weight per cent, since the density of the two phases are very nearly equal, *ca.* 2.6), are listed for the twelve crystals measured in the table below (Table 1).

The close constancy of the proportions of the two feldspar phases is shown by the table. Since such correspondence for twelve separate crystals is unlikely to be fortuitous, even allowing for the limits of accuracy

TABLE 1. VOLUME PERCENTAGES OF THE ALKALI FELDSPAR AND PLAGIOCLASE COMPONENTS IN THE ANTIPERTHITIC CRYSTALS OF A WASIMI ENDERBITE

	Alkali feldspar	Plagioclase feldspar
	22.1	77.9
	20.4	79.6
	22.5	77.5
	21.2	78.8
	21.2	78.8
	26.7	73.3
	24.0	76.0
	21.4	78.6
	22.4	77.6
	19.8	80.2
	21.7	78.3
	23.2	76.8
Average	22.2	77.8

inherent in the method, it seems reasonable to presume a constant proportionality of the feldspar phases in the antiperthites.

Mineralogy. The composition of the main plagioclase phase of the Wasimi quartz-diorites and the mean composition of the more acid plagioclase adjacent to the alkali feldspar aggregates were determined by universal stage methods. The bulk composition of the antiperthite for the rock FH 1005 was also determined by partial chemical analysis. The results are listed in Table 2.

The antiperthites were examined by means of the microprobe *x*-ray

TABLE 2. COMPOSITIONAL DATA FOR THE PLAGIOCLASE FELDSPAR OF THE WASIMI ENDERBITE

Optical determinations[1]	Flame photometric partial analyses[2]	
Main-phase plagioclase	Antiperthite (plag.+alk. feldspar)	
An_{34-48}(Mean An_{40})	CaO% by weight[3]	8.2
Acid-zone	Na_2O% by weight	5.4
An_{19-27}	K_2O% by weight	2.3
	i.e., $Or_{13.6}Ab_{45.7}An_{40.7}$	

[1] Universal stage procedure of Slemmons (1962) checked, where practicable, by R.I. determinations (immersion).

[2] On aggregated material drilled from several crystals of the same hand specimen used for optical determinations.

[3] Interference due to Al and Si in solutions nullified by addition of $LaCl_3$ (Method of Lindqvist, in preparation for publication). Analyst: I. Lindqvist, Uppsala.

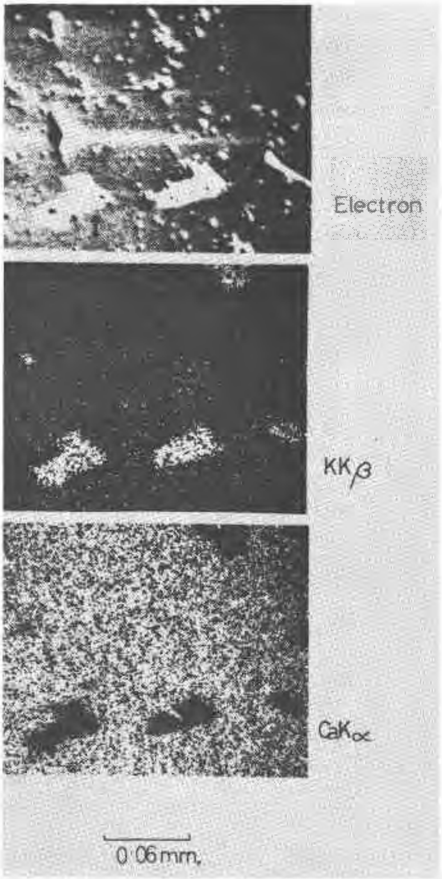

FIG. 3. The back-scattered electron and the KK_β and CaK_α x-ray fluorescence photographs of the same small portion of an antiperthite crystal. The white areas marked 1 and 2 on the back-scattered electron photograph are the alkali feldspar aggregates studied in detail.

fluorescence analyser (Cambridge Micro-scan system) to study the nature of the alkali phase and, most particularly, the acid plagioclase zone adjacent to the alkali feldspar, as regards its contacts with the main phase plagioclase and the alkali feldspar. The actual areas examined are illustrated in Fig. 3, which compares the back-scattered electron photograph with the KK_β and CaK_α x-ray fluorescence photographs for the same small portion of antiperthite. This shows the essentially pure orthoclase nature[1] of the alkali feldspar (with small amounts of exsolved plagi-

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[1] Absolute determination of K content of the potassic phase showed $K=13.5\%$ as compared with $K=14.05\%$ from pure $KAlSi_3O_8$.

oclase) and the essential absence of potassium from the plagioclase. These photographs also illustrate the abrupt, sharp nature of the alkali feldspar to plagioclase contact, but give no indications as to the nature of the relationship between the two plagioclases phases. To investigate this latter problem, the two antiperthitic regions, marked 1 and 2 on Fig. 3, were slowly traversed (scanning rate 10 mm/min at a magnification of 570×, *i.e.*, 0.0175 mm/min of the sample) and the change in CaK_α *x*-ray fluorescence, from constant high to constant high, *i.e.*, from main phase plagioclase to main phase plagioclase across the alkali feldspar, recorded (in pulses per second) on the automatic recorder. This gives a continuous measure of the change in relative calcium content along the traverse. Area 1 was similarly traversed for KK_β *x*-ray fluorescence, for comparison. The results are illustrated in Figs. 4a and 4b, with sketches showing the location of the traverses.[1]

The calcium peak within the alkali feldspar of area 2 marks a microperthitic lamella (seen as a white spot in the CaK_α photograph of Fig. 3).

The curves show clearly the abrupt nature of the change from orthoclase to plagioclase and the gradual increase in calcium content in the plagioclase on passing away from this contact to the constant maximum of the main phase plagioclase. The slight transgression of the steep limbs of the Ca and K curves across the phase interface at the "b-side" of area 1, (Fig. 4), shows overlap of the two phases within the thickness of the samples section, *i.e.*, the interface plane was not perpendicular to the surface plane of the specimen at that point.

Thus, as was suspected from the petrography, the more acid zone of plagioclase varies in anorthite content indirectly with proximity to the discrete alkali feldspar contact, increasing to that of the main phase plagioclase without discontinuity.

The alkali feldspar phase was shown to be structurally disordered by use of powder *x*-ray diffraction techniques ($\Delta = 0.12$, Goldsmith and Laves, 1954).

CONCLUSIONS AND DISCUSSION

The petrographic relationships of the three feldspar phases of the Wasimi enderbite show their close interdependence. A direct genetic connection between the mantle and enclosed alkali feldspar is suggested by their common orientation and, most strikingly, by the constancy of proportion of alkali feldspar to plagioclase found for individual crystals when mantle and included feldspar are considered together. Such a rela-

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[1] It was not possible to obtain absolute values for Ca content since the standard available, ($\mathrm{CaF_2}$), gives values which cannot be directly extrapolated to more complex Ca-bearing lattices, such as plagioclase.

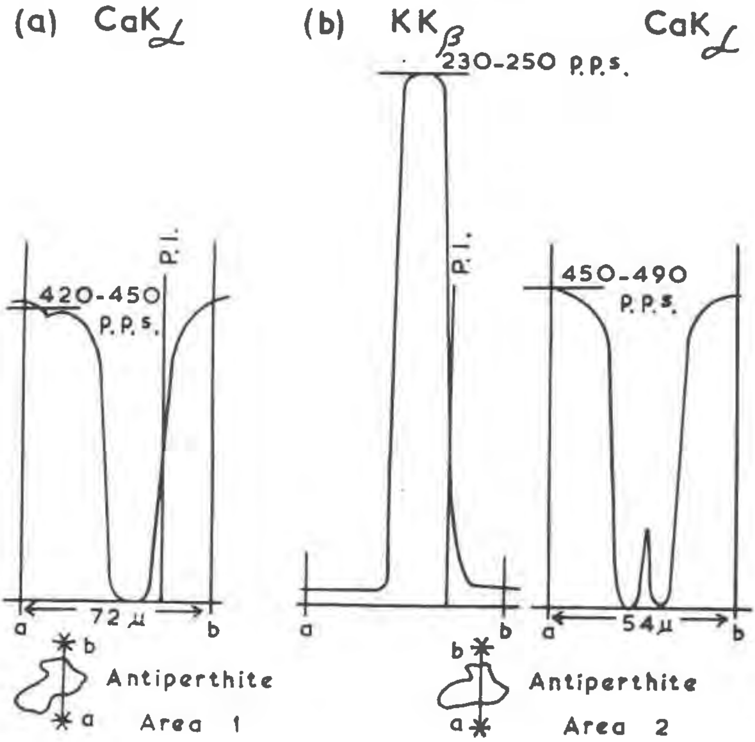

Fig. 4. X-ray fluorescence curves for antiperthite areas 1 and 2, of Fig. 3. (CaK_α at 1000 p.p.s., KK_β at 300 p.p.s.). P.I. = Phase interface.

tionship may best be explained on the basis of a common exsolution origin for the alkali feldspar. Neither crystal-melt reaction nor metasomatism would be expected to give rise to such a close proportionality.[1] The striking concordance of occurrence of the more albitic zones of plagioclase with the alkali feldspar suggests a direct inter-relationship.

The bulk feldspar partial chemical analysis gave results commensurate with a potash-and-esine (*ca.* $Or_{13}Ab_{46}An_{41}$) falling within the ternary solid solution field for the feldspars as shown by Tuttle and Bowen (1958, fig. 64, p. 132). Thus the disparate feldspar phases of the Wasimi enderbite are such as could have been produced by crystal unmixing from a feasible ternary feldspar.

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[1] Further, presumption of a magma phase, *sensu stricto*, in the formation of the charnockitic rocks, in the absence of direct evidence, is invalid. Many workers now consider dry ultrametamorphic processes to be responsible for the final development of the charnockitic rocks with no involvement of magma (Ramberg, 1952; Barth, 1962). Thus the principles of magmatic crystallization must be used with caution in interpreting such rocks.

The two locations of the alkalic feldspar in relation to the plagioclases at the crystal periphery and as aggregations in the main body of the crystals, can be interpreted, in terms of an exsolution origin, as reflecting the attraction of lattice disarray sites for precipitating material during solid-state exsolution. Such loci of relatively high free energy present preferential nucleation sites because of the ready availability of the necessary nucleation energy to create the new lattice from the old. The mantles would result as a consequence of the powerful attraction of the lattice disarray of the crystal surfaces whilst the internal alkali aggregations would represent, at least in part, growth accretions on nuclei formed at old internal lattice dislocation defects (also sites of lattice disarray). The orientation adopted by the orthoclase lattices growing on these nuclei at the expense of the plagioclase host lattice, quasi-parallel to that of the plagioclase lattice, ensures minimum interfacial energy by minimizing the lattice disarray between the two contiguous phases.

Oversaturation of K in the cooling potash-andesines would initiate the exsolution with the development of discreet orthoclase lattice frameworks around nuclei within and at the periphery of the plagioclase host lattice. The early stages of the exsolution must have been at temperatures within the stability range of potassium dominated ternary feldspars since a proportion of albite and anorthite was dissolved in the forming orthoclase. As cooling continued this plagioclase was subsequently precipitated as microperthite.

The charnockitic environment presents ideal conditions for such a developmental process as suggested above. The initial high temperature favors the acceptance of significant proportions of potassium into the crystallizing plagioclase lattices and the subsequent characteristic slow cooling enhances the possibility of retention of close thermodynamic equilibrium between the mineral components and their changing environment. It is in just such slow cooling that the small energy increments of the crystal interfaces and lattice imperfections become significant.

The occasional feature of microperthitic lamellae passing from the alkali feldspar into the adjacent more albitic zones of plagioclase and the common overall depletion in film perthite adjacent to these zones (the smaller included alkali feldspar aggregates are often completely free of perthitic plagioclase) suggest that these aureoles are related to the exsolution of plagioclase from the alkalic feldspar. The abrupt, though sometimes ragged, contact with the alkali feldspar and the diffuse gradational passage to the main-phase plagioclase shown by these zones are such as might result from a diffusive transfer of the plagioclase from the alkali feldspar into the adjacent andesine. Such a process would be energetically desirable in the slow cooling system. Expulsion of the microperthite plagioclase from the orthoclase and its incorporation in the pre-existing plagioclase lattice would result in a decrease in the number of distinct solid phases in contiguity and thus would reduce the component interfacial and strain energies of the system, *i.e.*, ΔG would be negative for the process. The gradational composition variation resulting in the plagioclase obviates the establishment of any new abrupt interface. Nucleation and growth accretion is precluded at the alkali feldspar to plagioclase contact since their quasi-parallel orientation allows minimum energy availability at the interface. Goldsmith (1952) demonstrated the virtual impossibility of homogenization of zoned plagioclase by heating because of the extreme sluggishness of interdiffusion of the plagioclasic components as a consequence of the tetrahedral rearrangements involved. In the Wasimi antiperthites the original diffuse zoning in the andesine is disturbed and nullified in the proximity of the orthoclase aggregates by the formation of the albitic zones. This suggest the degree of energetic demand for the expulsion of plagioclase from the orthoclase with its incorporation in the main-phase plagioclase.

Czamanske (1965) recently published a detailed study of the feldspars of the Finnmarka Igneous Complex in which he describes feldspar associations of striking similarity to those found in the Wasimi rocks. He summarizes on the akerite member of the Finnmarka complex: "In review, the assemblage consists of essential andesine, overgrown by distinctly more albitic plagioclase, with alkali feldspar mantling the plagioclase and forming interstitial fillings" (1965, p. 306). Unlike the diffuse gradation found in the Wasimi feldspars, Czamanske describes the contacts between the more albitic zones and the main plagioclase as being frequently sharp. He notes the intimate and unique association of the alkali feldspar with plagioclase stating, with particular reference to the granodiorite member, that alkali feldspar never occurs as individual grains (p. 303). The only reference to antiperthite texture, as such, concerns clearly marked zones in some grains in the granodiorite separating the perthitic coating from the plagioclase. Czamanske considers this antiperthite to possibly have formed by exsolution. "Poikilitic inclusions" of orthoclase are, however, considered a [illegible] racteristic, sometimes surrounded by thin rims of more albitic pla [illegible] se. The petrographic similarity of the feldspar associations of the [illegible] wegian and Nigerian rocks is manifest from this brief summary of [illegible] anske's findings. The compositional identity and the close similari [illegible] proportion of alkali feldspar to plagioclase for the Finnmarka ake [illegible] d the Wasimi enderbite is even more striking (Table 3).

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Czamanske has interpreted the Finnmarka feldspar associations on the basis of the high-level, magmatic origin accepted for these rocks. He considers the akerite feldspar associations and textures to result from a cooling magma, already containing crystals of andesine, moving to a higher crustal level during emplacement with retention of essentially constant temperature. The consequent drop in pressure would lead to partial resorption of the andesines with subsequent crystallization of more albitic plagioclase. Mantling by alkali feldspar could result by fractional crystallization if the plagioclase, by some mechanism, were essentially removed from the reactive system. Although the plagioclase (oligoclase) of the Finnmarka complex granodiorite lacks the intermediate zone of albitic plagioclase, Czamanske suggests that the poikilitic inclusions of orthoclase (and quartz) typical of these plagioclases indicate that resorption was also active in the formation of this rock.

Czamanske's interpretation presupposes a) a crystallizing magma and b) final consolidation at a high crustal level. Neither condition is characteristic of the charnockitic rocks, rather the reverse. The alternative genetic hypothesis invoking exsolution of original ternary feldspar crystallizations proposed in the present paper, on the other hand, is in full sympathy with a charnockitic emplacement environment.

ACKNOWLEDGMENTS

The study of the antiperthites, reported in this paper, forms a part of the more general study of the feldspars of the charnockites of S. W. Nigeria submitted by the writer as a thesis for the degree of *Filosofi Licentiat* of the University of Uppsala, Sweden. The writer wishes to express his thanks to Professor H. Ramberg for his guidance and encouragement and to the staff of the Mineralogical and Geological Institute of the University of Uppsala for their practical assistance. Avesta Järnverket, Sweden, kindly made available their Cambridge Microscan equipment which was operated by Fru M. Dahl.

TABLE 3. COMPOSITIONAL COMPARISONS OF THE COMPOSITE FELDSPARS OF THE FINNMARKA AKERITE (CZAMANSKE, 1956) AND THE WASIMI ENDERBITE

	Main plagioclase (mean)	Acid zone plag. (mean)	Alk. feldspar: plagioclase[1]
Finnmarka akerite	An_{40}	An_{23}	24.5: 75.5
Wasimi enderbite	An_{40}	An_{24}	22.2: 77.8

[1] The phase proportions quoted for the akerite are averages for the whole rock whilst those for the enderbite are the average for individual composite grains measured (Table 1).

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