Zoned plagioclase from the charnockites of Kondapalli, Krishna district, Andhra Pradesh, India

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Summary. Zoning in plagioclase is reported from the charnockitic rocks of Kondapalli, Krishna district, Andhra Pradesh, India, for the first time. Electron-probe studies indicate that the zoned plagioclases consist of homogeneous sodic cores mantled by thin calcic shells, which show continuous zoning of the inverse type. Partial chemical analyses of twelve density fractions of the zoned plagioclase from a basic charnockite exhibit a wide variation in An content from 54·80 to 72·39 %; X-ray studies suggest that they possess 'fixed' transitional structural state.

ZONING of the plagioclase feldspar in metamorphic rocks is definitely less common than in certain igneous rocks, but is not as rare as was once considered (Misch, 1954; Cannon, 1966). Though the charnockitic rocks of many areas in Peninsular India and other countries are recognized as metamorphic in their origin (Howie, 1964), no zoned plagioclase has been reported from them apart from some casual references by Ghosh (1941), Parras (1958), and Hubbard (1965); variation in composition of the plagioclase of a charnockite, even within the limits of a single microscope slide, was observed by Ghosh (1941), Chatterjee (1954), and Naidu (1955). The plagioclases of the type charnockite area near Madras do not show zoning and are 'invariably unzoned' (Howie, 1955; Subramaniam, 1959), while those from the charnockites of Lapland are 'homogeneous and show no zoning' (Eskola, 1952). It appears that the general consensus of opinion among mineralogists and petrologists is that the charnockite plagioclases are typically unzoned.

During the course of a detailed mineralogical investigation of the charnockites from Kondapalli (16° 37′ N., 80° 32½′ E.; Krishna district, Andhra Pradesh, India), some 200 miles north of Madras, the present writer has observed zoning in some of the plagioclases from a restricted

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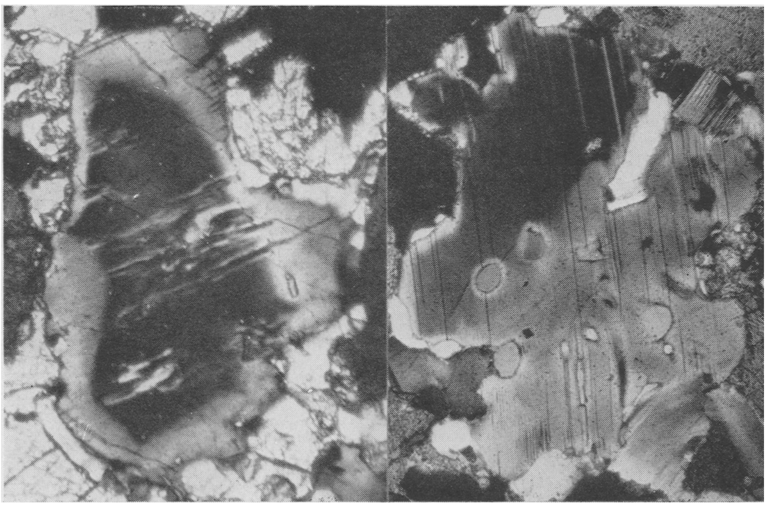
number of the rock types. Though zoned plagioclase is detected in these charnockites belonging to all the divisions of Holland (1900), it is only the plagioclase from the rocks of basic division—especially those that were subjected to greater stress and contain abundant hornblende or biotite—that exhibits zoning relatively frequently and distinctly. The zoning is generally of the reversed type and the zoned plagioclase normally contains a thin (calcic) rim of more anorthitic nature. Though the measurement of the extinction angles generally indicates a progressive gradual enrichment of the anorthite molecule from the centre outwards, this is not as conclusive and unambiguous as one may wish since the zoning in many cases is very heavily masked by the undulatory extinction of the grains. A poorly defined zoning is inferred in many strained plagioclase crystals showing slightly different extinction positions in the central and marginal portions, but this is often so indistinct that it escapes attention. When there is considerable change in composition between the core and margin, zoning is distinct and readily observed.

The plagioclase from the basic charnockite (42, a plagioclase–orthopyroxene–ore granulite with accessory biotite) dyke shows distinct zoning with an unusually thick rim (fig. 1). The rim of the zoned plagioclase is not of uniform thickness, and the crystal is untwinned or very mildly twinned and is comparable to 'zoned plagioclase of type III' described by Cannon (1966). It is pertinent to comment that there is fine-grained crushed material in one portion of this thin section and the zoning in plagioclase is relatively more frequent and intense nearer to the crushed zone.

The plagioclase in the basic charnockite A 18 was studied in detail, as many of the grains show extremely strong zoning. This charnockite specimen was collected from north-western portion of the hillock west of Toll, a few yards north of Kondapalli railway station, and occurs in close proximity to pink granitic and pegmatitic material. A local shear plane was responsible for the uneven distribution of the constituent minerals (plagioclase, orthopyroxene, hornblende, biotite, clinopyroxene; released quartz, garnet, ore, apatite, and secondary scapolite) in this charnockite, which consists of two portions with varied mineralogical assemblages—one portion being richer in hornblende and biotite than the other. Here again, as in the basic charnockite 42 described above, zoned plagioclase occurs rather more frequently near the shear plane. The coexisting pyroxenes from this specimen were analysed, and it has been demonstrated by the writer (Leelanandam, 1967) that the distribution of Fe^{2+}, Mg, and Mn in them is singularly anomalous when compared to that in seven other pyroxene pairs from Kondapalli charnockites. Evidently, the basic charnockite A 18 is an atypical member of the charnockite series.



FIGS. 1 and 2: FIG. 1 (left). Zoned plagioclase from basic charnockite (42); crossed nicols, ×80. Note irregular shape of core and thick calcic rim. A more favourable orientation may show up twinning not otherwise apparent. FIG. 2 (right). Zoned plagioclase from basic charnockite (A 18); crossed nicols, ×50. Twin lamellae traverse, without interruption, across the irregular calcic rim near margin and also across the calcic zones over quartz inclusions. Note a small unzoned crystal (top right) with multiple twin lamellae.

The zonal structure of the plagioclase A 18 is commonly two-layered; though the boundary is sharp, a Becke line is not usually observed. The zoned plagioclase consists of a relatively homogeneous sodic core of large volume, with a thin calcic rim of variable thickness (fig. 2). The twin lamellae extend uninterruptedly through the core and rim, but many zoned grains are sparsely twinned while a few are untwinned. Plagioclases with poor zoning and twinning, and unzoned plagioclases with multiple twin lamellae—corresponding to those of types IV and VII respectively of Cannon (1966)—are observed. Plagioclases with poor zoning but with rather well-defined twin lamellae (fig. 3), conforming to type V of Cannon, are not rare. Quartz, in the form of narrow wedge-shaped grains, commonly occurs bordering the zoned plagioclase grains. A few zoned plagioclase crystals contain rounded or oval quartz inclusions, which exhibit normal or wavy extinction and which are bordered by a more calcic plagioclase than the main body (figs. 2 and 3); the contact of this calcic zone with the quartz inclusions is sharp and distinct whilst that with the main plagioclase is indistinct and diffuse; such calcic zones are also noticed over the rare inclusions of clinopyroxene and biotite. The main calcic rim around the core plagioclase and calcic zones over quartz inclusions are optically continuous and appear to be of nearly the same anorthite content as judged from their extinction positions (figs. 2 and 3). Normal or oscillatory zoning in the plagioclase is suspected in rare cases but this is not proven. Whether or not there is any systematic relation between twinning and zoning in plagioclase is not evident from the present investigation.

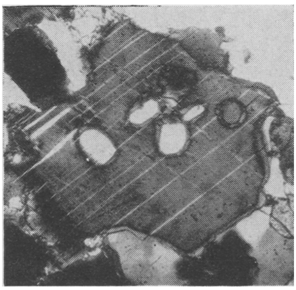
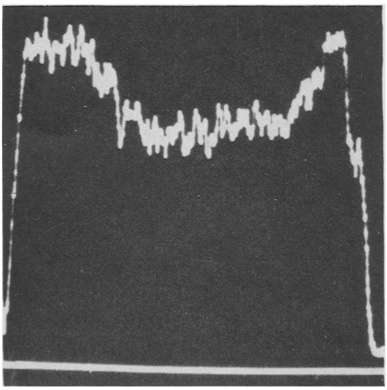
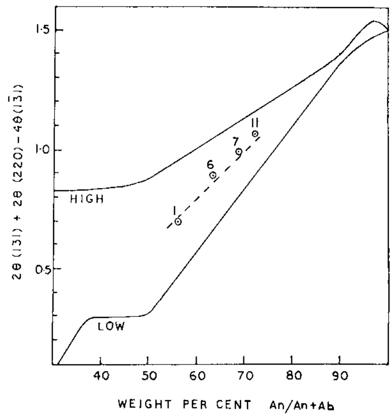


FIG. 3. Another crystal of zoned plagioclase from basic charnockite (A 18); crossed nicols, × 150. Note the regular and well spaced twin lamellae, which are not arrested at the inner boundary.

A few of the zoned plagioclase grains from A 18 were studied with the electron-microprobe X-ray analyser for estimating the approximate values of CaO from uncorrected readings obtained along the traverses made at 10 μ intervals across the grains from rim to rim and 2 μ intervals across the rims alone (fig. 4). These microprobe studies suggest: that the core of the zoned plagioclase is fairly uniform in composition; that the boundary between the core and rim is rather sharp; that the rim (though normally continuous around the core) is not of uniform thickness; that the composition of the rim, for a given grain, is unaffected by its thickness; that the rim shows within itself a progressive enrichment of the anorthite molecule outwards; and that the difference between the maximum % CaO value of the rim and minimum % CaO value of the core is not the same in the different grains, but generally ranges from 3 to 4 %. Thus the zoned plagioclases can be pictured as comprising of homogeneous sodic cores mantled by thin calcic shells, which show continuous zoning of inverse type.

Preliminary optical studies on some grains of the Kondapalli zoned plagioclase A 18 have shown that the core is sodic labradorite (50–55 % An) and the rim is sodic bytownite (70–80 % An). The plagioclase was separated and purified by using a combination of magnetic and heavy liquid techniques; as many as twelve different density fractions were obtained representing different compositions. The partial chemical analyses of these twelve fractions of the plagioclase A 18 are presented in table I. It is found that the range in composition is extremely wide (54·80–72·39 % An) and that the Or content gradually decreases and Fe_2O_3 shows a tendency to increase with an increase in the An content of the plagioclase.





FIGS. 4 and 5: FIG. 4 (left). X-ray microanalyser oscillograph trace of a zoned plagioclase A 18 (not the one represented in fig. 2 nor in fig. 3), showing variation of Ca-$K\alpha$ intensity along a traverse made from rim to rim, a distance of 150 μ; base line is zero intensity. The Ca content is lower in the central portion and higher in the marginal portions. FIG. 5 (right). Plot of $2\theta\,(131)+2\theta\,(220)-4\theta\,(1\bar{3}1)$ against composition for four density fractions of the zoned plagioclase A 18 (refer to table I), showing their 'fixed' transitional structural state.

X-ray powder diffractometer patterns were obtained for four out of the twelve fractions of the plagioclase A 18 and the functions B and Γ were calculated following Smith and Gay (1958) and plotted in fig. 5 to determine their structural state. The four points representing the four fractions (1, 6, 7, and 11 of table I) of the plagioclase A 18 can be joined by a (dashed) line as shown in fig. 5 and this line may correspond to a particular 'intermediacy index', considered by Slemmons (1962) to be a measure of order–disorder; it appears that the plagioclases have a systematic and uniform transitional structural state. This 'fixed' transitional structural state of the zoned plagioclase fractions seems to be unique; nothing like it has been reported, as far as the writer is aware, from any metamorphic terrain.

The writer has examined some of the thin sections of the Madras charnockites in the Harker Collection, Department of Mineralogy and

TABLE I. Partial chemical analyses of twelve different density fractions of the zoned plagioclase A 18. Analyst: C. Leelanandam. Alkalies determined by flame photometer, lime by EDTA titration, and iron by spectrophotometer. The term 'equivalent feldspar' is the wt. % feldspar content of the sample calculated from the analytical figures for alkalies and lime

	1	2	3	4	5	6	7	8	9	10	11	12
CaO	10·87	11·19	11·45	11·75	12·26	12·42	13·39	13·58	13·67	13·70	13·91	14·21
Na_2O	5·01	4·81	4·75	4·49	4·25	4·22	3·60	3·55	3·44	3·54	3·19	3·02
K_2O	0·35	0·33	0·31	0·27	0·31	0·25	0·24	0·20	0·21	0·20	0·17	0·23
Fe_2O_3*	0·23	0·23	0·25	0·25	0·34	0·27	0·40	0·33	0·38	0·31	0·32	0·52
Equivalent feldspar	98·37	98·14	98·83	97·86	98·60	98·81	98·30	98·62	98·17	99·07	97·00	97·38
Or	2·10	1·99	1·85	1·65	1·84	1·52	1·44	1·20	1·26	1·20	1·04	1·39
Ab	43·09	41·47	40·66	38·78	36·47	36·12	30·99	30·49	29·65	30·20	27·80	26·23
An	54·80	56·54	57·48	59·56	61·69	62·36	67·57	68·31	69·08	68·60	71·15	72·39
B	0·848	—	—	—	—	0·829	0·806	—	—	—	0·814	—
Γ	0·698	—	—	—	—	0·892	0·994	—	—	—	1·065	—
An/(An+Ab)	55·98	—	—	—	—	63·32	68·56	—	—	—	71·90	—

* Total iron expressed as Fe_2O_3

$$\left.\begin{aligned} B &= 2\theta\,(1\bar{1}1) - 2\theta\,(20\bar{1}) \\ \Gamma &= 2\theta\,(131) + 2\theta\,(220) - 4\theta\,(1\bar{3}1) \end{aligned}\right\}(\text{Cu-}K\alpha)$$

Petrology, Cambridge, studied earlier by Howie (1955) and Subramaniam (1959). Zoning of the plagioclase (similar in style but probably not in intensity to that exhibited by some of the Kondapalli plagioclases) was detected in them and distinct zoning was observed in the basic rocks 4642A and 2941 of Howie and in the rocks Ch. 199, Ch. 258, and Ch. 208 of Subramaniam. Recently the writer has also noticed zoned plagioclase in some of the charnockitic rocks of Guntur district, lying in between the charnockitic areas of Kondapalli and Madras. No quantitative data is yet obtained on these zoned plagioclases from the charnockites of Madras and of Guntur district.

The existing literature shows that the reasons for the zoning in plagioclase remain obscure in many cases (Misch, 1954) and that metamorphic zoning is frequently reverse zoning. The calcic rims of the plagioclases are attributed to progressive metamorphism (Miyashiro, 1958; Shido, 1958; Cannon, 1966), to grade-dependent breakdown of coexisting hornblendes (Binns, 1965), to addition by short range diffusion of 'anorthite-building' substances (Misch, 1964), to diaphthoresis accompanying sudden release of pressure (Hills, 1936) and consequent chemical readjustment of the mineral phases present (Subramaniam, 1956), or to structural differences as a result of strain and compositional differences during crystal growth (Hsu, 1955).[1] The relative preponderance of zoned plagioclase in basic charnockites and its scarcity in less basic charnockites may be attributed to their disparate petrogenesis,[2] as advocated first by Subramaniam (1959) and later affirmed by Howie (1965) for the type area near Madras, or to the greater availability of anorthite-building substances (clinopyroxene and hornblende) in basic members and their rarity or absence in less basic members. Though nothing definite can yet be said about the exact cause of plagioclase zoning in the Kondapalli charnockites, the occurrence of zoned plagioclase in the basic charnockite (42), devoid of clinopyroxene and hornblende, suggests that the presence of these minerals is not essential for the formation of zoning in plagioclase. One point merits repetition: both the basic charnockites (42 and A 18) described here were affected

[1] Describing some basic granulites of the Kaabong area in north-eastern Uganda, de Waard (1967) recently noticed that the plagioclase in them is zoned from An_{45} in the core to An_{85} in the rim. The presence of hypersthene and plagioclase symplektites around relicts of garnet and clinopyroxene in these rocks, according to him, demonstrates the reaction: clinopyroxene+garnet+quartz $\rightarrow$ orthopyroxene+anorthite, due to which the original plagioclase of the rocks is intensely affected, and the released anorthite component caused the reversed zoning.

[2] R. A. Howie, *priv. comm.*

by the local shear planes. The Kondapalli area is a polymetamorphic one (Grasty and Leelanandam, 1965; Leelanandam, 1965) and it is likely that the most significant processes responsible for zoning in plagioclase may be 'forces external to the rock as a whole', a suggestion put forward by Vance (1961) to account for the stresses producing glide twinning. Such forces mainly contemporaneous with or later than the metamorphic episodes might have affected the rocks under consideration. Thus it can be surmised that the local change in physical conditions has aided the process of reversed zoning, but no generalization need be made at this stage as it is by no means certain that all zoned plagioclases in the Kondapalli rocks necessarily originated in one way.

The primary purpose of this publication is to record, for the first time, the occurrence of zoned plagioclase in the charnockitic rocks of Kondapalli and of the type area near Madras. As zoning in plagioclase has been observed in these charnockites, future studies of the plagioclases from similar rock types at other localities should be specifically aimed at testing the presence or absence of this phenomenon, because a careful study of zoning 'with its implication of disequilibrium conditions, is of great help in unravelling metamorphic/metasomatic episodes' (Cannon, 1966).

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