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Master's degree in Geology

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CONSTITUTIONAL SUPERCOOLING, A MECHANISM FOR OSCILLATORY ZONING IN PLAGIOCLASE

By

Vivian Kay Bust

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Geology

1980

ABSTRACT

CONSTITUTIONAL SUPERCOOLING, A MECHANISM FOR OSCILLATORY ZONING IN PLAGIOCLASE

By

Vivian Kay Bust

This study provides evidence which is interpreted to support constitutional supercooling as a viable mechanism for oscillatory zoning in plagioclase.

Constitutional supercooling requires concentration gradients in the liquid immediately adjacent to a growing crystal, therefore, the presence or absence of these gradients provides the test of the model. Concentration gradients occur in the glass matrix adjacent to only those crystals which exhibit oscillatory zoning at the crystal perimeter. No concentration gradients occur in the glass matrix adjacent to normally zoned crystallographic faces.

Constitutional supercooling is controlled only by the environment immediately adjacent to the growing crystal face; therefore, if this mechanism is valid different zone patterns may occur on different crystal faces of the same crystal. Furthermore, correlation of oscillatory zoning between crystals should be limited. Two crystals observed in this study contain oscillatory zoning isolated to just one crystal face, while the remaining faces are normally zoned. Also, there appeared to be only limited zone pattern correlation between crystals sampled from the same rock type.

Dedicated to my parents

ACKNOWLEDGMENTS

I would like to express my sincere appreciation to Tom Vogel for his patience throughout this study.

A special thanks to my friends who encouraged the completion of this project.

My most heartfelt thanks to my family for their continued support and understanding.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Theory

Sibley et al. (1976) proposed that the periodic oscillatory zoning present in plagioclase is due to supersaturation of the liquid which causes concentration gradients at the melt-crystal interface. This is defined as constitutional supercooling by Rutter and Chalmers, 1953; Chalmers, 1964. The purpose of this study is to test this constitutional supercooling model as a mechanism for oscillatory zoning in plagioclase.

Constitutional supercooling is a result of solute enrichment in the liquid in contact with an advancing solid-liquid interface having a composition different from that of the bulk liquid. The liquid in contact with this interface has a lower liquidus temperature than the bulk liquid further from the interface.

In constitutional supercooling, there is a mutual variation of solute concentration and liquidus temperature with distance from the interface. At the interface the solute concentration is maximum with respect to the bulk liquid and the liquidus temperature is minimum with respect to the bulk liquid (Chalmers, 1964).

According to Chalmers (1964), under assumed initial steady-state condition, if the interface remains planar it should be possible to supercool the liquid by an amount equal to the interval between the liquidus and solidus. This situation would imply that the liquid ahead of the interface could be constitutionally supercooled. This degree of supercooling is never fully realized because only a small amount of supercooling is sufficient to set up an instability* which leads to a departure from the steady-state condition.

Klein and Uhlmann (1974) studied the crystallization behavior of anorthite from its melt over a range of undercoolings. It was found that the morphology of the crystal-liquid interface was faceted, growth took place preferentially in the crystallographic C direction and that the fraction of preferred growth sites on the crystal-liquid surface increases with increasing undercooling.

Klein and Ulhmann (1974) suggested that anorthite grew by the formation and lateral propagation of two-dimensional nuclei on a planar interface. This situation implies that a certain amount of undercooling is necessary to nucleate steps on the interface.

To account for the periodic oscillatory zoning in plagioclase, Sibley et al. (1976) proposed a model based on constitutional supercooling. In this model, the driving force for oscillatory zoning is the variable growth rate which is produced by varying degrees of supercooling and the planar nature of the plagioclase crystal-liquid interface. Oscillatory zoning in this model is independent of external variables in the magma chamber, i.e., confining pressure, hydrostatic pressure and temperature.

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*Instability is due to interface attachment kinetics.

The mechanism, proposed by Sibley et al. (1976), by which constitutional supercooling produces oscillatory zoning in plagioclase is as follows, with reference to Figure 1. In order to allow crystallization of a stable nuclei a liquid, of some composition X, is initially supercooled to temperature T_1 by some mechanism other than constitutional supercooling. The solid will crystallize such that, at equilibrium, the composition of the solid will be S_1 and the composition of the liquid in contact with the solid will be L_1. During initial growth, if diffusion of the albite molecule away from the interface or the anorthite molecule to the interface is less than the growth rate of the crystal, a concentration gradient will develop in the melt away from the crystal. This situation causes the formation of a boundary layer adjacent to the growing crystal which has a composition different from that of the bulk liquid. It is this boundary layer and not the bulk liquid that will be of composition L_1 when the crystal composition is S_1.

Assuming the amount of supercooling at the interface is maintained then after a period of initial cyrstallization, the bulk liquid composition will be of some intermediate composition (L_3) between the initial liquid composition X and the boundary composition L_1. At this point the flux of solute is maximum because of the large compositional difference between L_1 and L_3. As diffusion of the solute from the bulk liquid to the boundary proceeds the composition of the boundary layer (L_1) becomes more calcic and migrates off the liquidus curve to some composition L_2.

Because plagioclase grows with a faceted, planar interface, nucleation is impeded and diffusion of the solute through the melt may cause the liquid to migrate a considerable distance off the liquidus before the crystal starts to grow again. If plagioclase grew with a diffuse interface, growth rates would respond immediately to the changing composition (L_2).

The new boundary layer composition L_2 represents the supercooling necessary to nucleate new steps on the crystal-liquid interface to begin a new growth cycle. The exact composition of the new zone cannot be predicted but would be located to the left of S_1. The solid and liquid compositions would then migrate back toward S_1 and L_1. The growth rate will exceed the diffusion rate until the solid and boundary layer composition are at S_1 and L_1. At S_1 and L_1, the diffusion rates again exceed growth rates and the cycle will begin to repeat itself.

For each cycle, the maximum anorthite content of a zone is determined by the position of L_2 which is a measure of constitutional supercooling necessary to initiate growth on a planar interface. The maximum albite composition is determined by the position of S_1 and L_1 on the binary phase diagram (Figure 1).

Previous Work

Bottinga et al. (1966) divided theories which produce zoning in plagioclase into two categories: those in which oscillatory zoning is caused by repeated changes in the plagioclase-liquid equilibrium variables and the theory of Harloff (1927)

Figure 1. An-Ab Binary Phase Diagram.

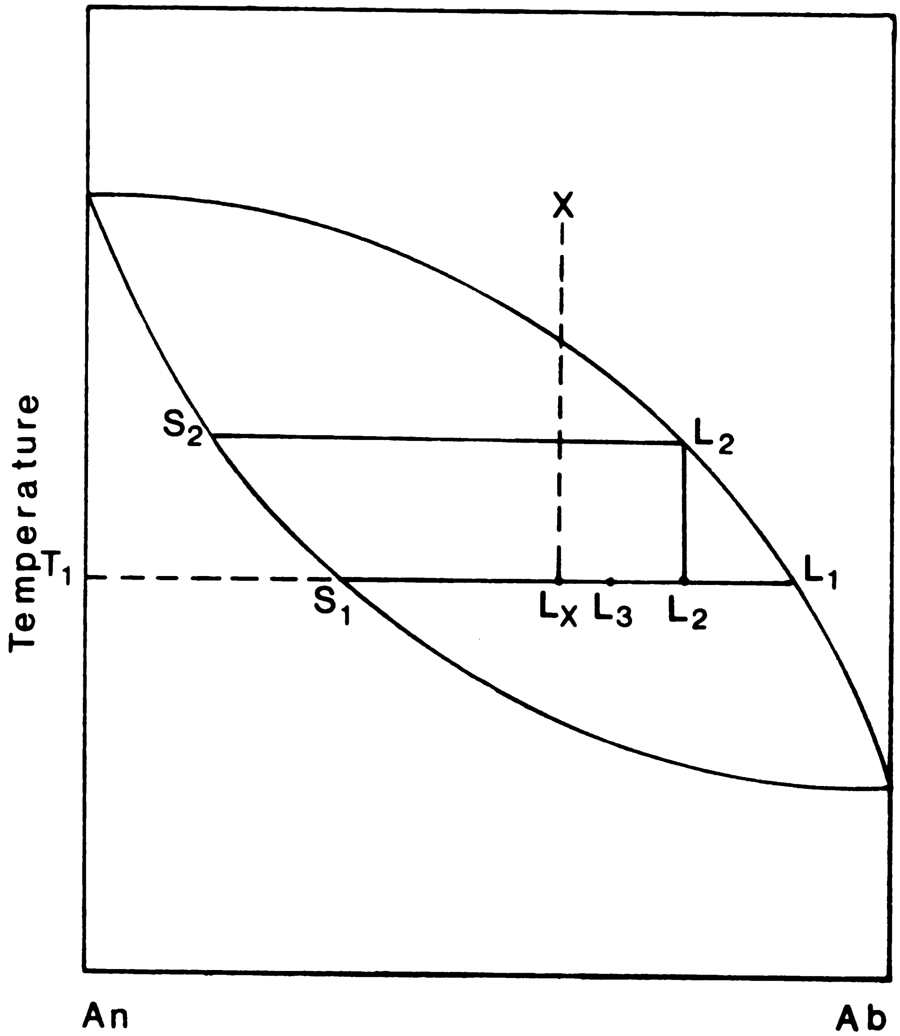


FIGURE 1

which is a diffusion-supersaturation model. Vance (1962) and Smith (1974) also reviewed and summarized theories which may produce oscillatory zoning in plagioclase. A modified version of the theory of Harloff (1927) was presented by Bottinga et al. (1966) to explain periodic oscillatory zoning in plagioclase.

Bottinga et al. (1966) further developed Harloff's model and suggested that once the driving force (supersaturation) has exceeded the minimum required for two dimensional nucleation of steps on the crystal surface, growth of a zone begins and proceeds by lateral propagation of steps across the smooth (planar) interface. Relying on work done by Cahn (1960) Bottinga et al. (1966) reasoned that because two dimensional nucleation of an incomplete surface (diffuse) is not much more difficult than on a smooth surface the interface becomes diffuse.

The change from a <u>planar</u> to a <u>diffuse</u> interface is attractive because it increases the number of favorable nucleation sites on the growth surface and a lower driving force is needed to maintain a diffuse interface. According to Cahn (1960) at this stage the interface is propagated normal to itself rather than repeated by lateral steps across the surface.

The interface remains diffuse as the driving force decreases and further growth is limited to only the most favorable sites on the interface. Finally, the interface becomes planar and a steady-state is reached when growth and diffusion rates are equalized. The growth cycle will begin once more when supersaturation of the melt adjacent to the planar interface exceeds the minimum required for two dimensional nucleation of steps across the crystal surface.

Bottinga's data, which he cited as support of this diffusion-supersaturation model, was obtained from an electron-microprobe analysis of the glass-bytownite interface. A "representative" chemical profile of these analyses, recorded at selected points along a 40 micron traverse to the interface, is shown in Figure 3 of Bottinga et al., 1966. This profile shows the presence of Si, Al, Mg and Fe concentration gradients and the absence of Ca and Na concentration gradients in the glass adjacent to a bytownite crystal, which displays faint oscillatory zoning.

Klein and Uhlmann (1974) studied the crystallization behavior of anorthite over a wide range of undercoolings. Their data supports growth of plagioclase by two dimensional nucleation and lateral propagation of steps across a planar interface at all undercoolings rather than a diffuse interface. In light of Klein and Uhlmann's work Bottinga's model is suspect because it depends on a diffuse interface.

Lofgren (1974a) proposed a model for reverse zoning in plagioclase which is similar to the constitutional supercooling model proposed by Sibley et al. (1976). However, Lofgren's model is dependent on both a diffuse interface and the development of steady-state conditions.

TEST OF MODEL

If constitutional supercooling is a valid process, concentration gradients should occur in the liquid surrounding a growing crystal which contains oscillatory zoning and the oscillatory zone patterns in adjacent crystals should be somewhat independent. The presence of Si, Ca and Na concentration gradients in the glass matrix adjacent to the oscillatory zoned plagioclase crystals would be a major test of the model.

Second, if oscillatory zone patterns of each plagioclase crystal within the same rock sample are independent of each other then one would expect that a comparison of zone patterns between plagioclase crystals to yield an insignificant correlation. Insignificant correlation of oscillatory zone patterns would provide subsequent support of the model. Wiebe (1968) has shown that only abrupt zoning discontinuities in plagioclase can be correlated and that the fine oscillatory zoning cannot be correlated.

Because Klein and Uhlmann (1974) have shown that anorthite grows with a planar interface and an anisotropic manner, one may expect different oscillatory zone patterns on various crystal faces. Constitutional supercooling would be supported if different oscillatory zoning patterns occur on different crystal faces from the same grain. This would indicate that both the interface attachment kinetics and the boundary layer melt are the controlling parameters for oscillatory zoning in plagioclase.

To test the constitutional supercooling model as a mechanism for oscillatory zoning in plagioclase, the rock must satisfy two requirements: (1) the plagioclase phenocrysts must have crystallized from the same magma, i.e., they cannot be xenocrysts; and (2) these phenocrysts must also be set in a glass matrix. The glass matrix may be assumed to represent the last liquid surrounding the crystal at the time the magma was quenched.

The rock types selected to meet the above requirements are recent volcanics containing normal and oscillatory zoned plagioclase crystals surrounded by a glass matrix. A basalt and rhyodacite sampled from the Galapagos are on loan from the Smithsonian Institution. A quartz latite sampled from the Superstition-Superior volcanic area in central Arizona are on loan from J. S. Stuckless (U.S. Geological Survey, Menlo Park, California).

ANALYTICAL METHODS

Grain Selection

Three principle factors were used to select oscillatory zoned plagioclase crystals for analysis. These factors include clarity of oscillatory zones at the 2 micron scale, clean and relatively unaltered grain boundaries and a clear glass matrix adjacent to the plagioclase crystals.

The orientation of the zoned plagioclase crystals within each rock sample was assumed to be random. Therefore, these samples were cut at three mutually perpendicular directions to maximize the probability of cutting plagioclase crystals perpendicular to compositional zones. Optimal crystal orientation for chemical analysis of zone patterns was when the concentric zones within the crystal are perpendicular to the plane of the microscope stage. To determine if the plane of concentric zoning lies perpendicular to the plane of the stage, each crystal was checked using the Universal Stage. Deviations of from 5°-10° were tolerated and these crystals were also used for chemical analyses.

Procedure

Quantitative compositional data for this study of oscillatory zoned plagioclase was generated using a three spectrometer ARL EXM microprobe set at an accelerating potential of 15 KV and

100 nanoamperes beam current. The beam spot size was approximately .5 microns in diameter. The LiF, RAP and ADP detector crystals were used to measure the K_α peaks of Ca, Na and Si respectively. Samples of 100% albite, 95% anorthite and quartz were used as standards; both peak and background counts were recorded for each standard.

The three spectrometer microprobe allowed simultaneous analysis of Ca, Na and Si at each point along the line traverse. A line traverse is generated by moving the crystal in a series of equally spaced steps, two microns apart, under a static electron beam while recording x-ray signals. Several line traverses were generated such that they began in the adjacent glass and extend across the crystal-glass boundary into the crystal. Other line traverses include portions of the glass matrix on either side of the crystal and extend across the entire crystal. These line traverses were at right angles to the concentric zoning patterns in the crystal, i.e., in the direction of concentration gradients.

ANALYSIS OF DATA

Compositional Gradients

The first part of the analysis was to establish the presence or absence of concentration gradients in the glass matrix immediately adjacent to the oscillatory zoned crystals.

A plot of the line traverse was generated such that the independent variable, distance, was plotted against counts per second of the three dependent variables Ca, Na and Si. Inspection of the glass matrix portion of the plot was then carried out to determine if the chemical variation of Ca, Na and Si constituted concentration gradients.

The variation of intensity of counts per second of Ca, Na and Si at the crystal-glass boundary depend on the bulk chemical difference between the crystal and glass, the presence of concentration gradients in the glass, width of crystal edge and the type of crystal-glass boundary. Electron scatter at the crystal-glass boundary is minimal due to the highly polished thin-section surface.

In Figure 2 the chemical difference at the crystal-glass boundary is skematically represented for three types of crystal-glass boundaries. The effective width of the crystal edge depends somewhat on the slope of the crystal-glass boundary. In the traverses examined, the slope was steep enough to have negligible effect at a distance X from the apparent edge.

The effective width of the crystal edge is defined as the difference between the apparent and the effective crystal edge. The apparent edge is the surface intersection of the plagioclase crystal with the glass matrix. The effective edge is at a distance X away from the apparent edge. The distance X is dependent on the type of crystal-glass boundary, the area activated that produces x-rays under the electron beam and the depth of x-ray penetration. The effective width of the crystal edge can be measured with a micrometer under high magnification. The area that produces x-rays under the electron beam and the depth of x-ray penetration can be calculated.

The area activated on either side of the spot beam is approximately 1 micron. The depth of x-ray penetration is dependent on density and the accelerating potential. Assuming a density of 2.65 gm/cm^3 and using an accelerating potential of 15 KV the depth of x-ray penetration is approximately 2.5 microns.

The effective crystal edge width of Type 1 boundary is the apparent edge (minimum edge width, Table 1) plus 1 micron. Although no Type 2 boundaries were observed on the crystals tested, the effective edge width is the apparent edge width plus 1 micron. The effective crystal edge width of a Type 3 boundary is the apparent edge plus 2 microns. Since the slope of the crystal edge, extending under the glass matrix, is steep this width would compensate for any summing of chemical variations of both crystal and glass at the boundary.

A comparison of the maximum edge width limit (maximum limit of crystal edge extending under glass matrix) and the effective crystal edge width in Table 1 shows a 1-4 micron difference. Since the minimum edge width (apparent edge) plus a distance X is sufficient to compensate for any summing of chemical variations of both crystal and glass, the effective edge width is utilized to define the boundary between chemical variations due to the crystal and those due to the glass. Chemical variations within the area between the apparent edge and the effective edge are due to the summing of both crystal and glass chemical variations and are referred to as the "edge effect."

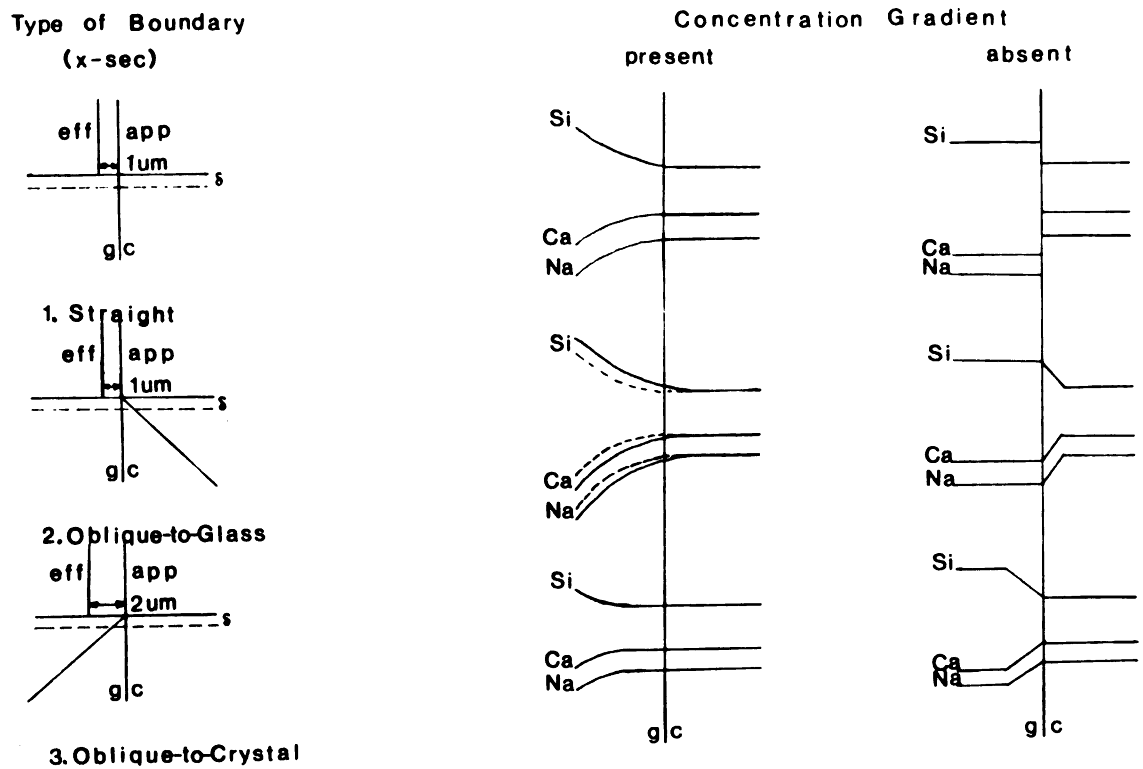
If the chemical variations present at the crystal-glass boundary are due to concentration gradients in either Ca, Na or Si then one would expect to find these, similar to those skematically represented in Figure 2(b), to extend away from the effective edge into the glass matrix.

For each crystal-glass line traverse the length of the line traverse in the adjacent glass matrix, type of periphery zoning and the presence or absence of Ca, Na or Si concentration gradients are summarized in Table 2. Inspection of the 23 line traverses, shown in Figures 3-15, reveal that concentration gradients are present only in the glass matrix adjacent to crystals which exhibit oscillatory zoning at their periphery.

Eight of the line traverses are adjacent to the periphery of oscillatory zoned crystals and six of these show the presence of

Figure 2. Skematic Profile of Crystal-Glass Boundary Types and Chemical Variation at Boundaries.

FIGURE 2



g=glass
c=crystal
app=apparent edge
eff = effective edge
$ = x-ray penetration depth (2.5 um)
(not to scale)

an Si concentration gradient in the adjacent glass matrix. One of these six also shows a definite concentration gradient in both Ca and Na.

Fifteen of the line traverses are adjacent to the periphery of normally zoned crystals and none of these show concentration gradients in either Si, Ca or Na in the adjacent glass matrix.

Quartz Latite

To summarize, three of the five line traverses adjacent to the periphery of oscillatory zoned crystals show the presence of concentration gradients and six other line traverses adjacent to the periphery of normally zoned crystals show the absence of Si, Ca and Na concentration gradients in the adjacent glass matrix.

Examination of crystal 1 (Plate 1) reveals six, evenly spaced, fine oscillatory zones within the perimeter zone of one crystal face. The perimeter zone of the remaining crystal faces do not contain these fine oscillatory zones. The preferred location of oscillatory zoning for one face over other faces may be due to the chemical environment immediately adjacent to the growing crystal and the growth kinetics of individual crystal faces.

Two line traverses were generated across the oscillatory zoned perimeter of crystal 1 (Figure 3). One line traverse, 1-bb', shows a Si concentration gradient present in the adjacent glass matrix. The other line traverse, 1-aa', shows anomalous behavior of Si at the crystal-glass boundary and in the glass matrix. Both 1-aa' and 1-bb' show no concentration gradients in either Ca or Na in the glass adjacent to the crystal-glass interface. A third line traverse, 1-cc', across the normally zoned perimeter of crystal 1 shows the absence of Ca, Na and Si concentration gradients in the adjacent glass matrix (Figure 3).

Crystal 2 (plate 1) is normally zoned at its periphery. Two line traverses 2-dd' and 2-ee' across a crystal-glass boundary show the absence of Ca, Na and Si concentration gradients in the glass matrix (Figure 4).

The normally zoned perimeter of crystal 3 (Plate 2) contains 14 oscillatory zones of variable width. These oscillatory zones are located between the crystal edge and the first abrupt zoning discontinuity. Of the 14 zones 5-6 are concentrated at the crystal perimeter. Line traverse 3-ff' (Figure 5) shows the absence of Ca, Na and Si concentration gradients in the glass matrix adjacent to crystal 3.

In crystal 4 (Plate 2) there are 11 oscillatory zones of variable width located between the crystal perimeter and the first major zoning discontinuity. Both line traverses 4-gg' and 4-hh' across the crystal-glass boundary of the same crystal face exhibit Si concentration gradients in the glass matrix. Line traverse 4-hh' also exhibits definite Ca and Na concentration gradients in the adjacent glass matrix (Figure 6).

In crystal 5 (Plate 2) the normally zoned outer boundary contains no oscillatory zoning. Line traverse 5-ii' and 5-kk' across the same crystal face did not show Ca, Na, Si or Al concentration gradients in the glass matrix adjacent to the crystal-glass

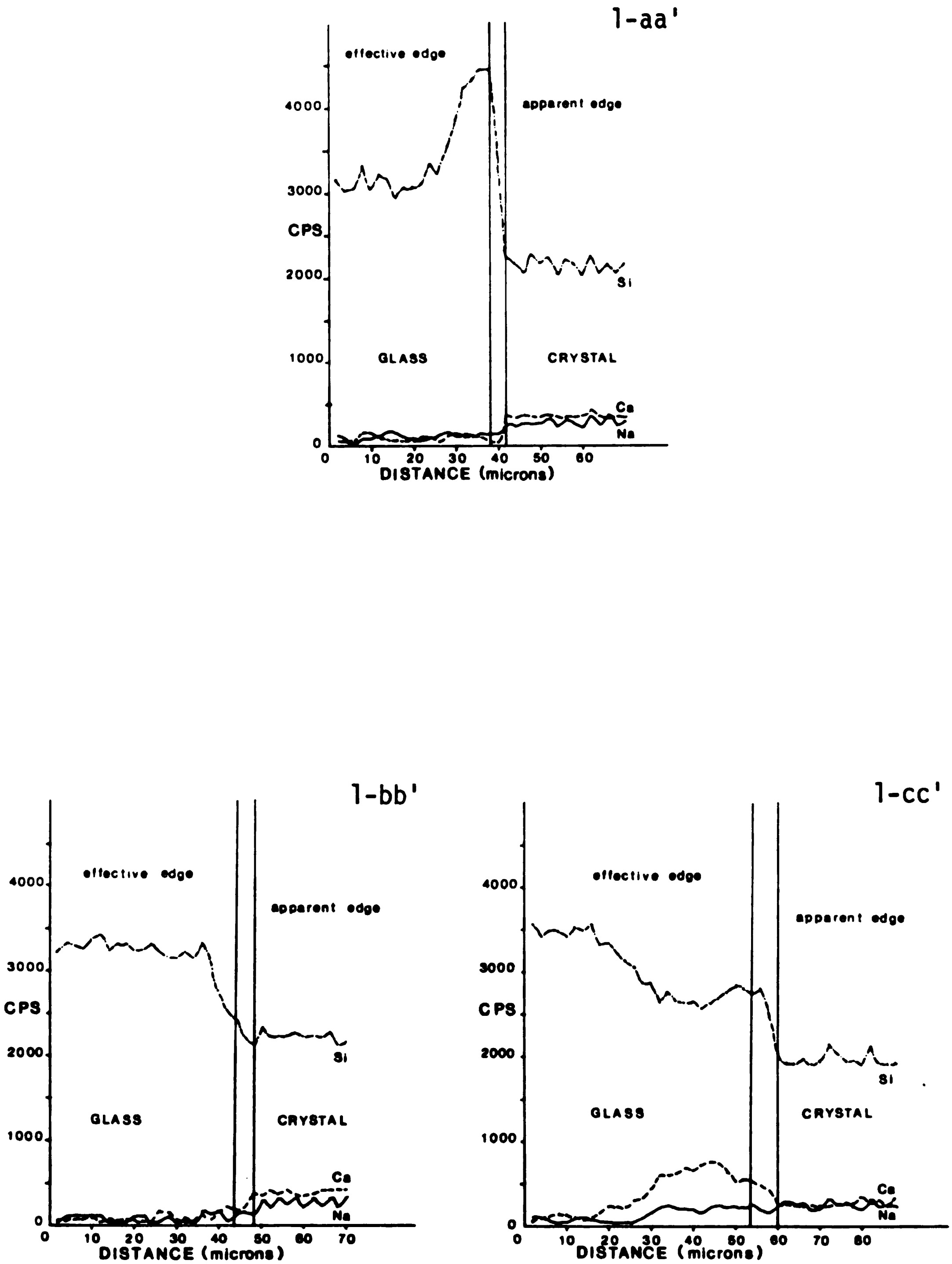


Figure 3. Quartz Latite Crystal 1.

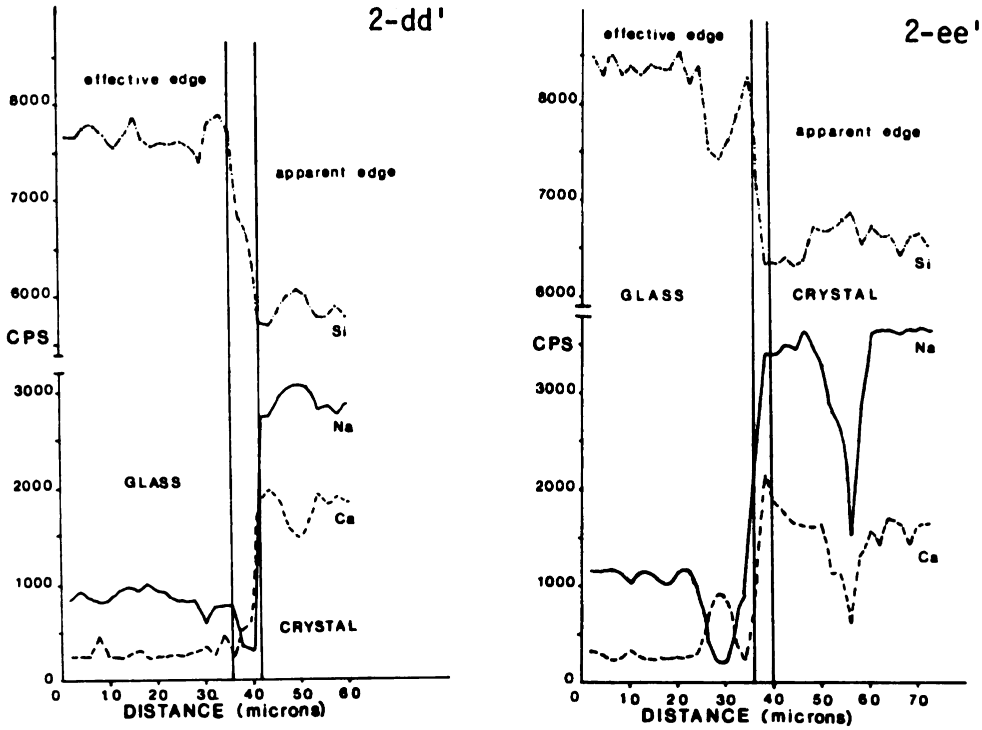


Figure 4. Quartz Latite Crystal 2.

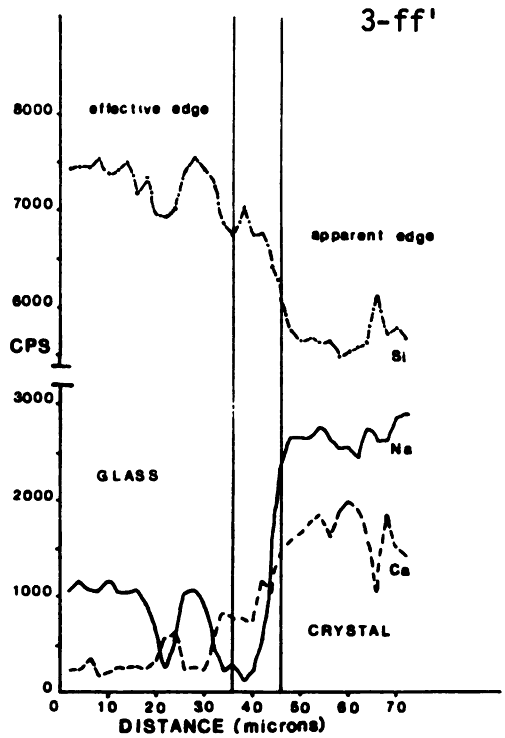
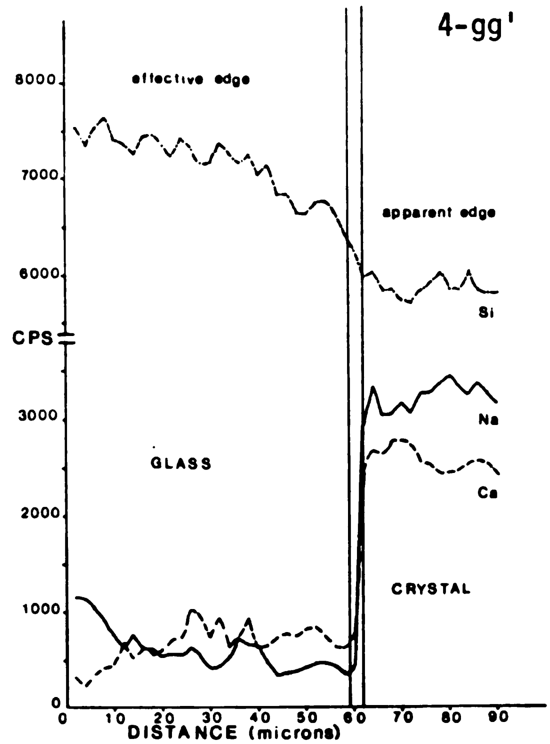


Figure 5. Quartz Latite Crystal 3.



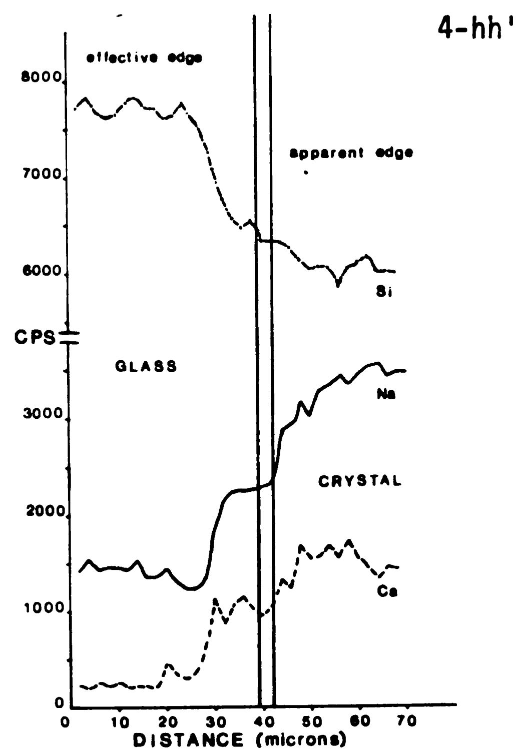


Figure 6. Quartz Latite Crystal 4.

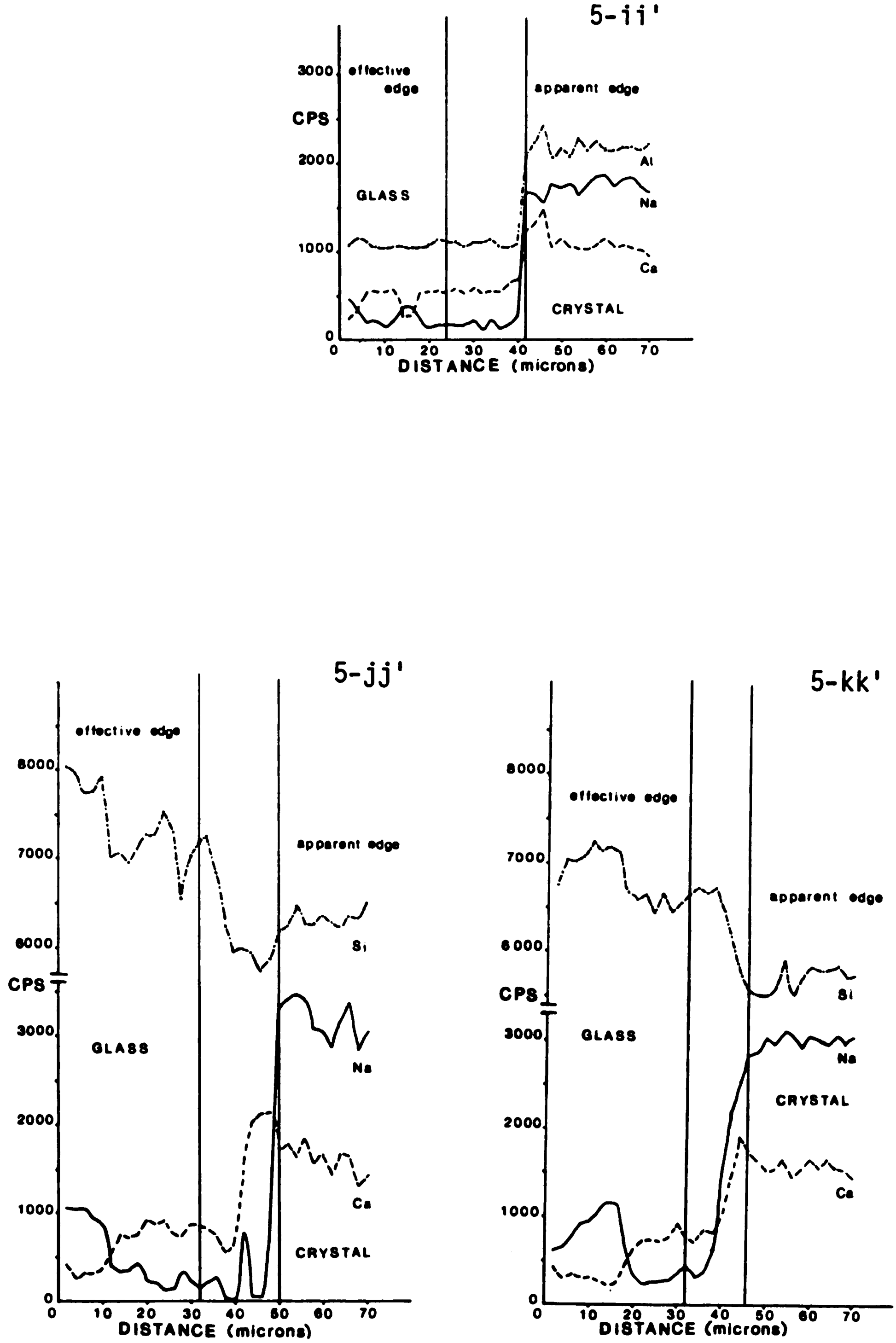


Figure 7. Quartz Latite Crystal 5.

interface. A third line traverse, 5-jj', across the crystal-glass boundary of another face of crystal 5 did not show the presence of Ca, Na and Si concentration gradients in the adjacent glass matrix (Figure 7).

Rhyodacite

To summarize, the line traverse adjacent to the periphery of oscillatory zoned crystals show only the presence of Si concentration gradients in the adjacent glass matrix. The remaining line traverses, across normally zoned peripheral boundaries, do not exhibit Ca, Na or Si concentration gradients in the adjacent glass matrix.

Line traverses across the normally zoned periphery of crystals 1, 2 and 3 (Plate 3) show the absence of Ca, Na and Si concentration gradients in the glass matrix adjacent to the crystal-glass interface (Figures 8-10).

In crystal 4 (Plate 3) there are 9-10 oscillatory zones of variable width located between the crystal perimeter and the first major zoning discontinuity on one crystal face. Line traverse 4-ff' across the crystal-glass interface of this crystal face exhibit an Si concentration gradient but no Ca or Na concentration gradients in the adjacent glass matrix (Figure 11).

In crystal 5 (Plate 4) there are 4 faint oscillatory zones located between the crystal edge and the first major zoning discontinuity and extending around the circumference of the crystal. Line traverse 5-gg' across a crystal-glass boundary exhibits an Si concentration gradient in the adjacent glass matrix (Figure 12), but no Ca or Na concentration gradients were observed in the glass matrix.

Crystal 6 (Plate 4) is normally zoned at its periphery. Line traverses 6-hh' and 6-ii' across the crystal-glass interface, of two different crystal faces, did not show Ca, Na or Si concentration gradients in the adjacent glass matrix (Figure 13).

In crystal 7 (Plate 4) there are 12 oscillatory zones of variable width, located between the crystal edge and the first abrupt zoning discontinuity, which extend around the entire circumference of the crystal. Line traverse 7-jj' across a crystal-glass boundary reveals the presence of an Si concentration gradient and the absence of both Ca and Na concentration gradients in the adjacent glass matrix (Figure 14).

Two line traverses, 8-kk' and 8-ll', across a crystal-glass interface of the normally zoned perimeter of crystal 8 (Plate 4) showed the absence of Ca, Na and Si concentration gradients in the adjacent glass matrix (Figure 15).

Basalt

The glass matrix of the basalt sample was devitrified and it was not possible to determine if concentration gradients were present in the glass matrix adjacent to the zoned plagioclase crystals.

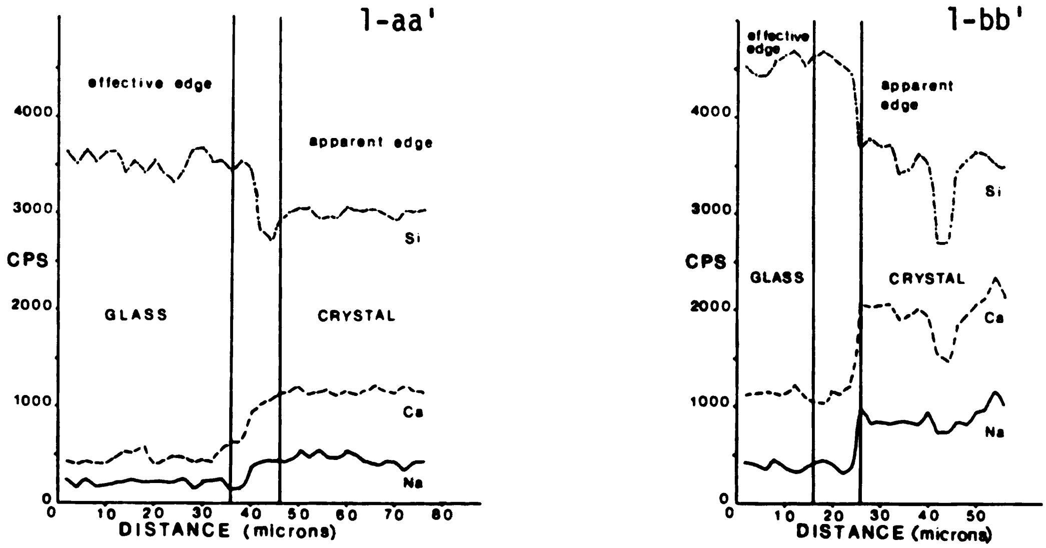


Figure 8. Rhyodacite Crystal 1.

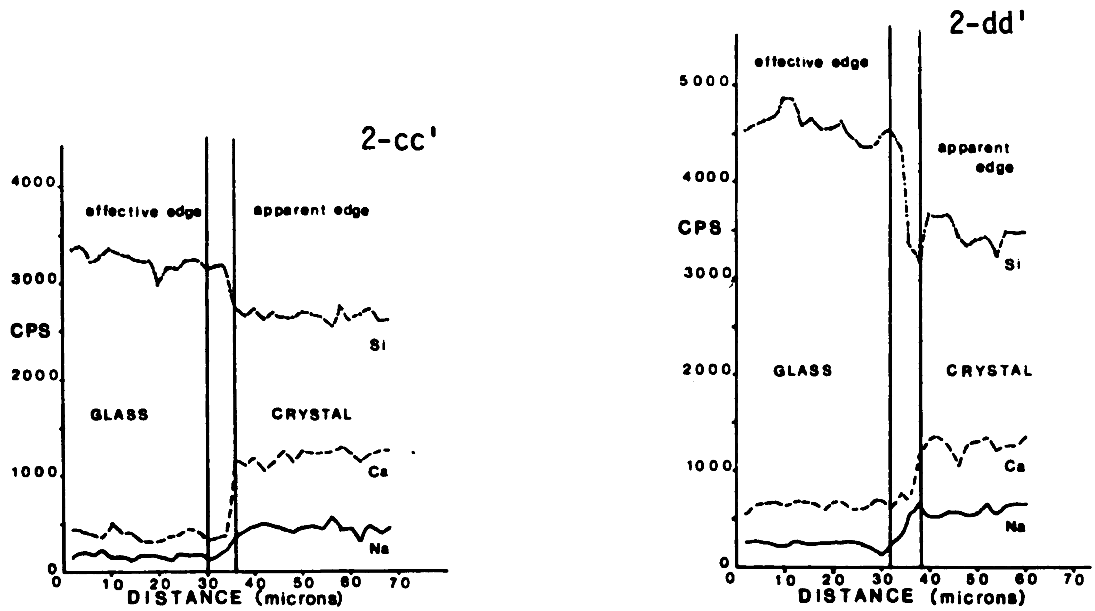


Figure 9. Rhyodacite Crystal 2.

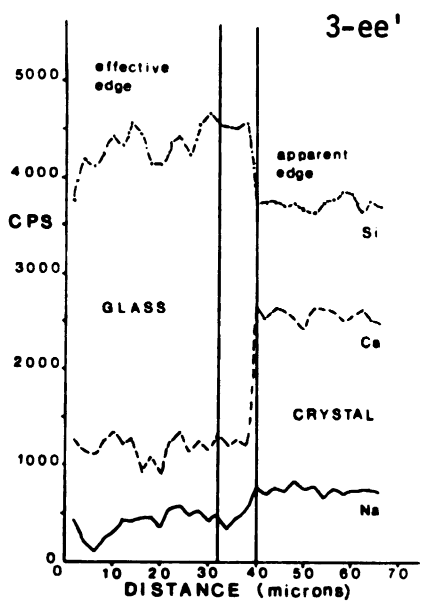


Figure 10. Rhyodacite Crystal 3.

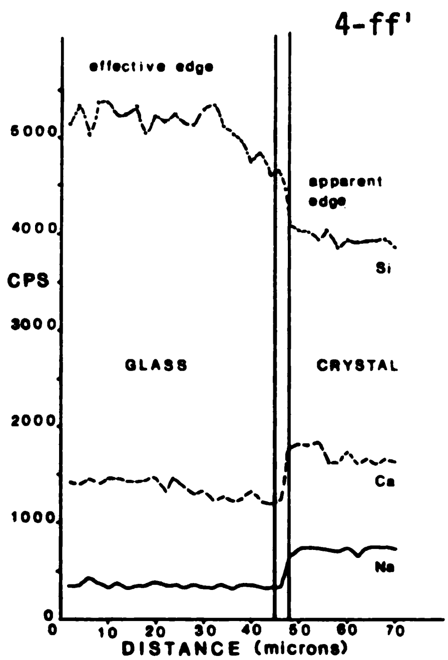


Figure 11. Rhyodacite Crystal 4.

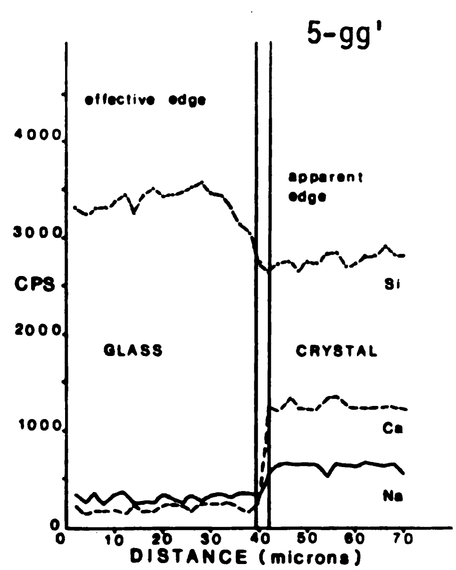
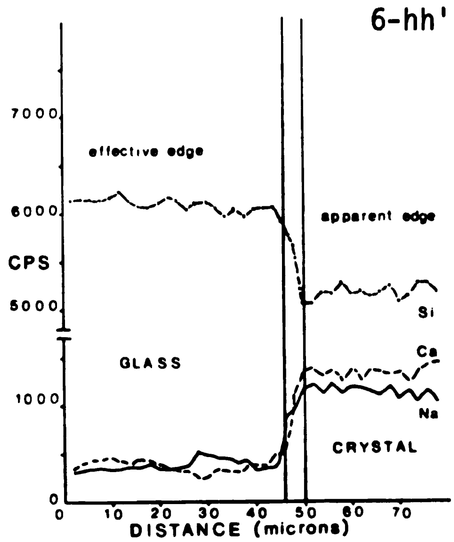


Figure 12. Rhyodacite Crystal 5.



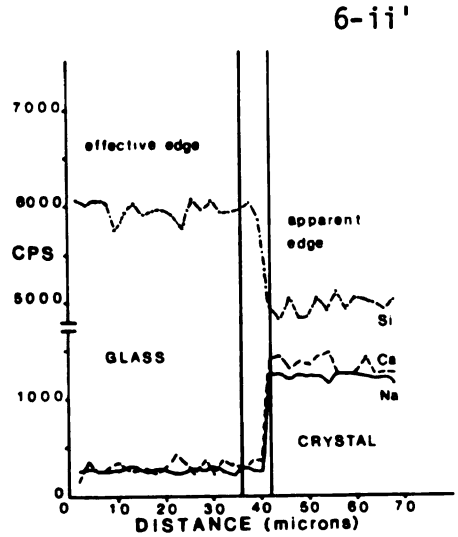


Figure 13. Rhyodacite Crystal 6.

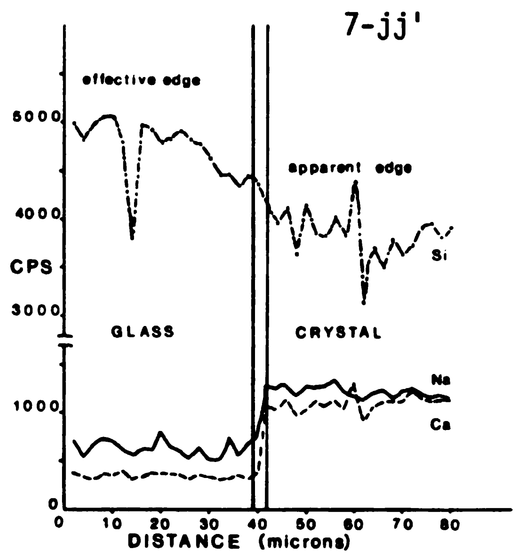
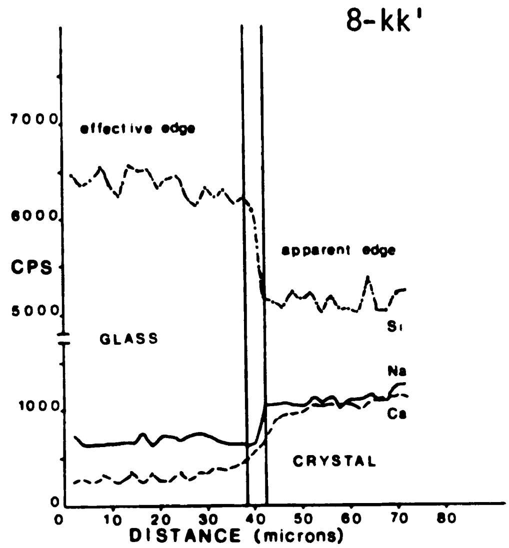


Figure 14. Rhyodacite Crystal 7.



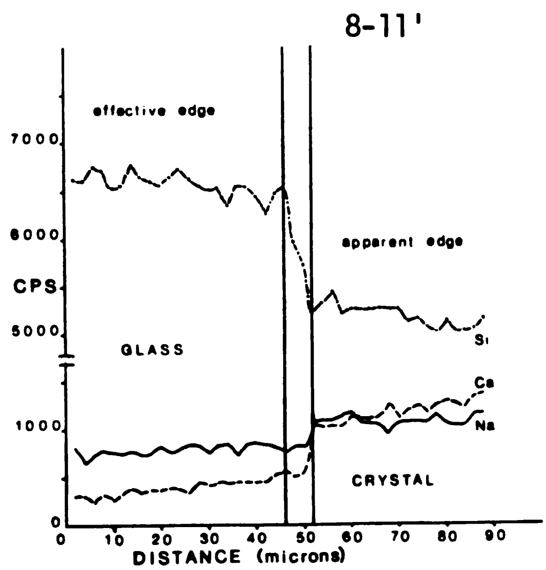


Figure 15. Rhyodacite Crystal 8.

Table 1. Effective Crystal Width and Glass-Crystal Boundary Types.

LINE TRAVERSE	CRYSTAL EDGE WIDTH LIMITS (min	max)	EFFECTIVE CRYSTAL EDGE WIDTH	BOUNDARY TYPE
QUARTZ LATITE				
1 - aa′	2	4 um	4 um	3
1 - bb′	2	4	4	3
1 - cc′	4	6	6	3
2 - dd′	4	6	6	3
2 - ee′	8	10	10	3
3 - ff′	2	4	3	1
4 - gg′	2	4	3	1
4 - hh′	2	4	3	1
5 - ii′	16	20	18	3
5 - jj′	16	20	18	3
5 - kk′	12	18	14	3
RHYODACITE				
1 - aa′	8	10	10	3
1 - bb′	8	10	10	3
2 - cc′	4	6	6	3
2 - dd′	4	6	6	3
3 - ee′	6	8	8	3
4 - ff′	2	4	3	1
5 - gg′	2	4	3	1
6 - hh′	4	6	6	3
6 - ii′	2	4	4	3
7 - jj′	2	4	3	1
8 - kk′	2	4	4	3
8 - ll′	4	6	6	3

Table 2. Periphery Zoning Type and Glass Matrix Concentration Gradients.

LINE TRAVERSE	LENGTH OF LINE TRAVERSE	PERIPHERY ZONING	CONCENTRATION GRADIENT (Y/N)		
QUARTZ LATITE	(in glass only)	TYPE	Si	Ca	Na
1-aa′	42 um	osc	N	N	N
1-bb′	48	osc	Y	N	N
1-cc′	60	norm	N	N	N
2-dd′	42	norm	N	N	N
2-ee′	46	norm	N	N	N
3-ff′	38	osc	N	N	N
4-gg′	62	osc	Y	N	N
4-hh′	42	osc	Y	Y	Y
5-ii′	42	norm	N**	N	N
5-jj′	50	norm	N	N	N
5-kk′	46	norm	N	N	N
RHYODACITE					
1-aa′	46 um	norm	N	N	N
1-bb′	26	norm	N	N	N
2-cc′	36	norm	N	N	N
2-dd′	38	norm	N	N	N
3-ee′	40	norm	N	N	N
4-ff′	48	osc	Y	N	N
5-gg′	42	osc	Y	N	N
6-hh′	42	norm	N	N	N
6-ii′	50	norm	N	N	N
7-jj′	42	osc	Y	N	N
8-kk′	42	norm	N	N	N
8-ll′	42	norm	N	N	N

** aluminum was counted

Pattern of Oscillatory Zones

In the second part of the analysis the oscillatory zone patterns of each plagioclase crystal were examined to determine if the patterns between crystals could be correlated.

First each line traverse extending across a zoned crystal was subjected to the FILTER program (Appendix). The FILTER program prepared the data for further analyses by performing three functions.

First, it deleted the segments of the line traverse extending beyond the crystal-glass boundary into the adjacent glass matrix, leaving intact the portion of the line traverse representing the plagioclase compositional stratigraphy.

Second, it searched for data points throughout the remaining portion of the line traverse which did not exhibit mutual variation in all three major elements. These points were assumed to represent crystal imperfections or impurities on the crystal surface. Because Cross-Correlation and possibly Fourier analysis were contemplated as analytical tools (both require data points at equally spaced intervals) these points were not deleted from the line traverse but were instead displaced to a new position. The new position was produced by averaging the two data points on either side of the displaced point. The percent of these points per line traverse varied from 0-3% which is considered insignificant.

Third, the FILTER program transformed the line traverse from counts per second to weight percent anorthite using methods and correction factors of Bence and Albee (1969). This data was then presented in the form of an orthogonal plot of weight percent anorthite verse distance (in microns) across the crystal (Figures 16-29).

This data (in the form of a plot) was evaluated to determine if the zone patterns between crystals could be correlated. Correlation of the compositional stratigraphy between crystals is based on a match of both the number of zones and the zone width. However, before correlation between crystals could proceed a good correlation must exist between optically observed zone patterns and those exhibited by the line traverse. This is necessary because recording x-ray signals at two micron increments may not adequately define zones which are from 1-4 microns in width.

Quartz Latite

In the quartz latite 2 of the 4 line traverses show limited agreement between optically observed and line traverse zone patterns. In both plagioclase crystals, line traverses 4-ab and 5-1m, there is a distinct increase in weight percent anorthite in the portion of the line traverse representing the core of the crystal. Within the core of each crystal there were 3-4 large zones varying in width from 50-75 microns. The cores and the 3-4 large zones within the cores were the only zone patterns which could be correlated between line traverses 4-ab and 5-1m (Figures 17 and 18). No further correlation of zone patterns between these two line traverses were found.

The zone patterns represented by the remaining two line traverses 2-ab and 6-ab (Figures 16 and 19) could not be correlated with respect to the number of zones and zone width observed optically.

Although there was a lack of agreement between the optically observed and line traverse zone patterns, optical examination of the zone patterns in these four crystals (Plates 1 and 2) and examination of the line traverses reveal a large variability of both zone width and the number of zones per crystal. Therefore, except for the crystal cores of line traverses 4-ab and 5-lm, there appears to be poor correlation of zone patterns between these crystals.

Rhyodacite and Basalt

In the rhyodacite and basalt all the crystals examined show a lack of agreement between their optically observed zone patterns and their respective line traverse zone patterns (Figures 20-29).

The lack of agreement may be due partially to the small chemical variation within these microphenocrysts. In most cases the chemical variation across the crystal is less than 10 percent anorthite. Although a small change in weight percent anorthite between zones may be observed optically, this change may not be recognized as the termination of one zone and the initiation of another zone in the line traverse.

As stated earlier, recording x-ray signals at two micron increments may not adequately define zones which are from 1-4 microns in width and this may contribute to the lack of agreement between optically observed and line traverse zone patterns.

As displayed in Plates 3-5 there is a wide variability in the number of zones per crystal and the zone width of the crystals sampled from the rhyodacite and the basalt. Again by inspection of the optical zone patterns it was concluded that there was poor zone pattern correlation between crystals of each rock type.

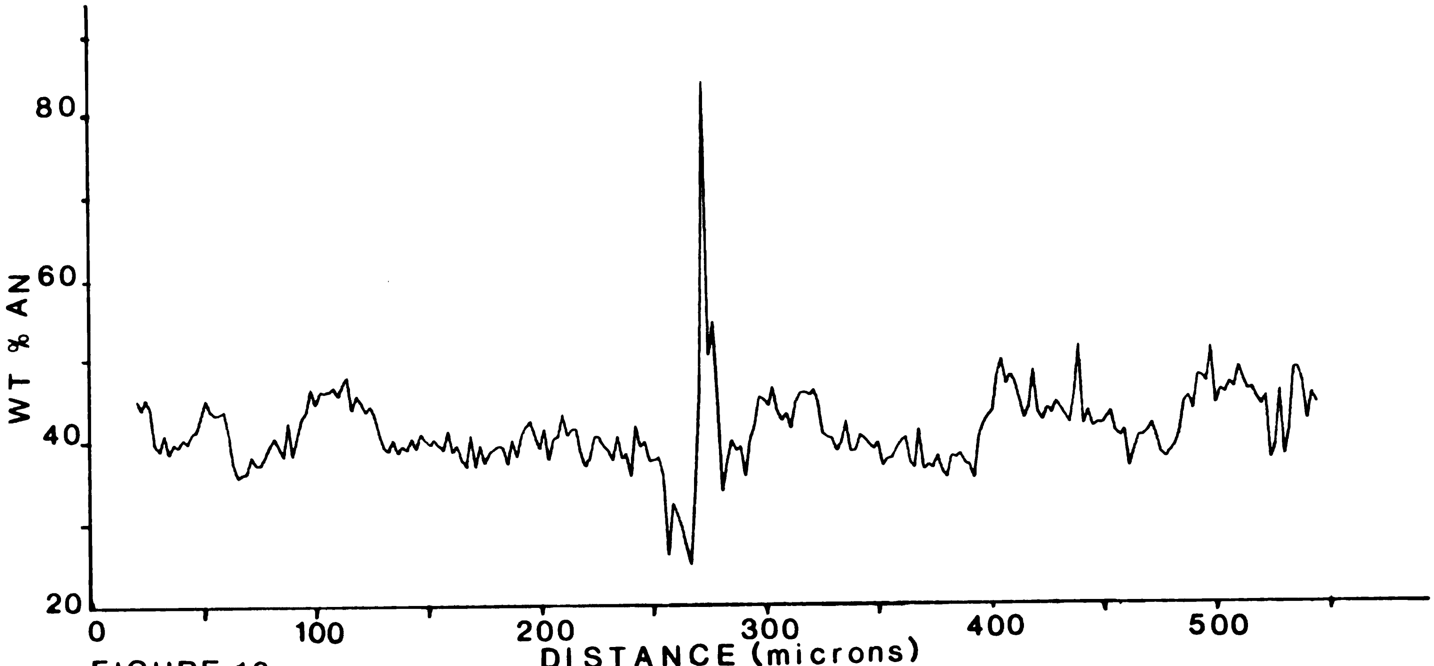


FIGURE 16
Quartz Latite 2-ab

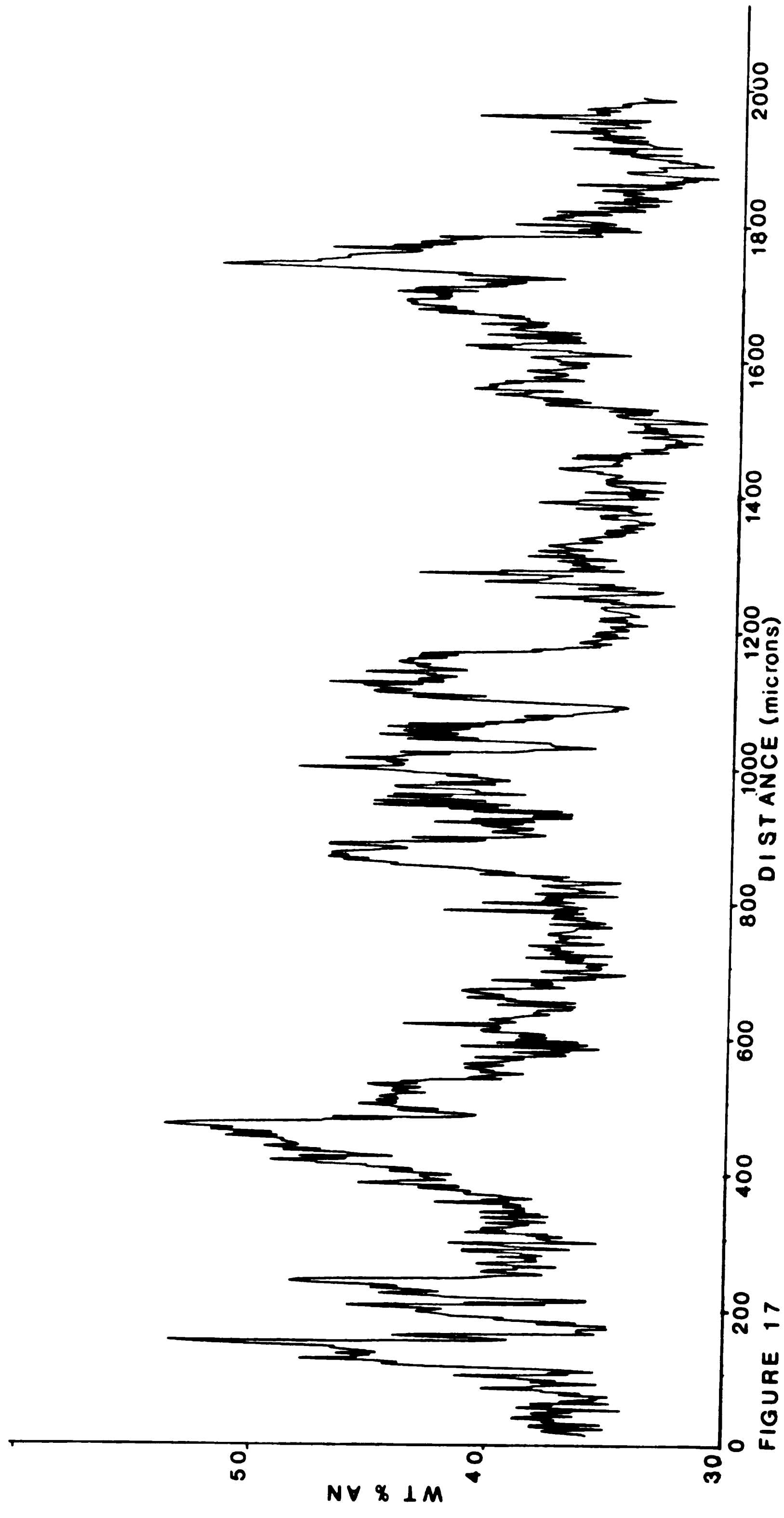


FIGURE 17
Quartz Latite 4-ab

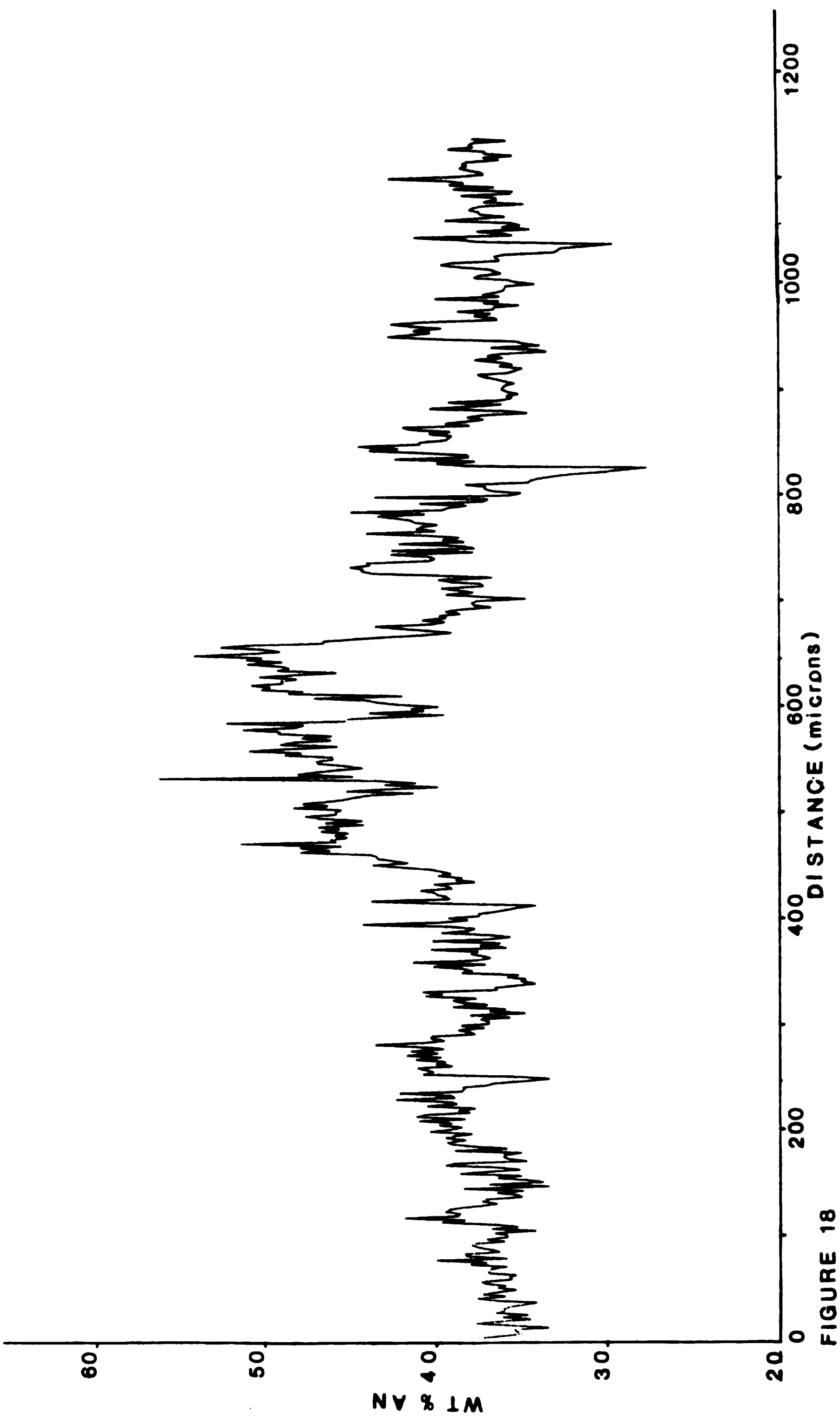


FIGURE 18
Quartz Latite 5-Im

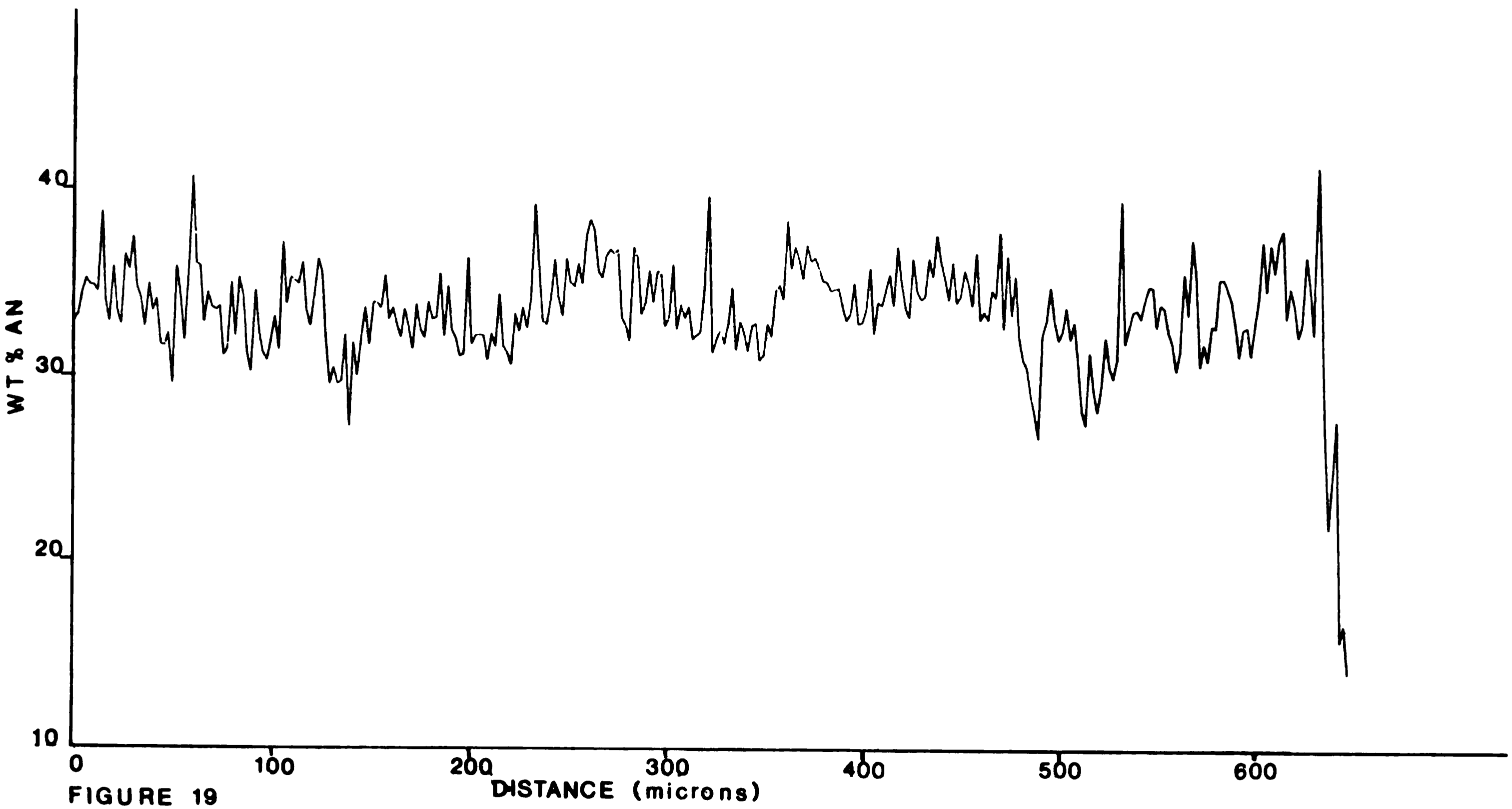


FIGURE 19
Quartz Latite 6-ab

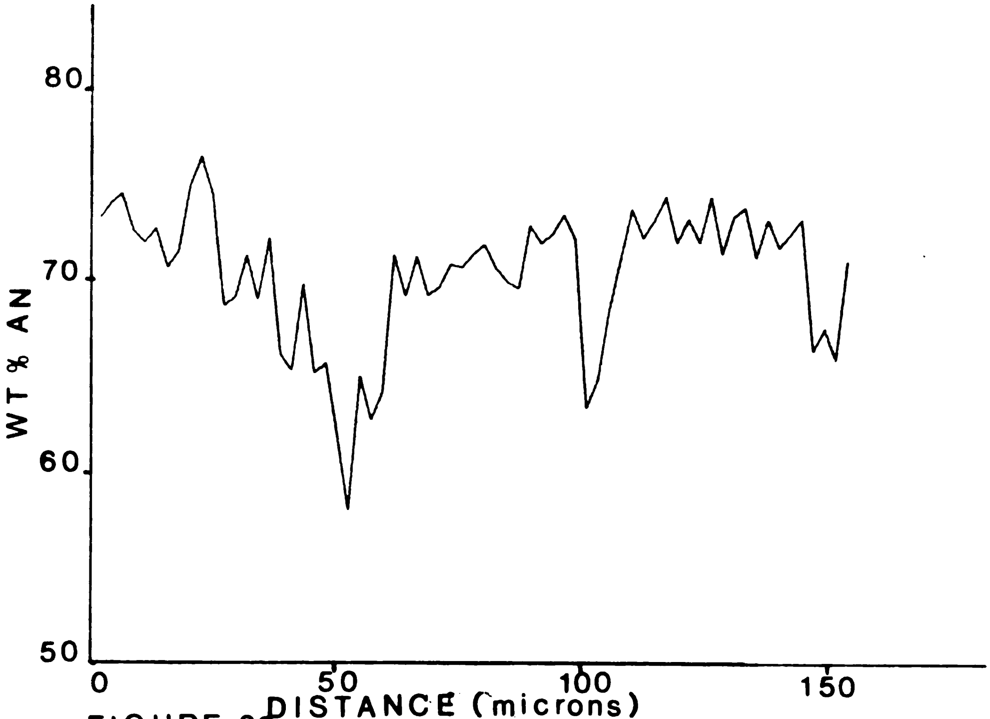


FIGURE 20
Rhyodacite 2-pq

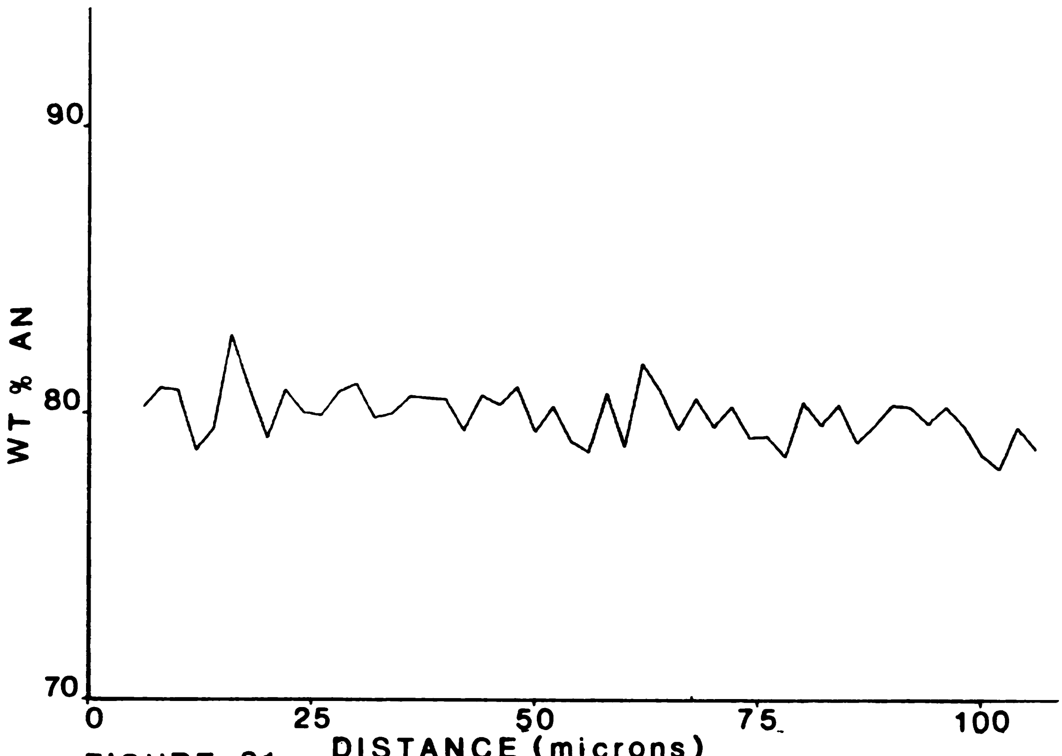


FIGURE 21
Rhyodacite 3-ab

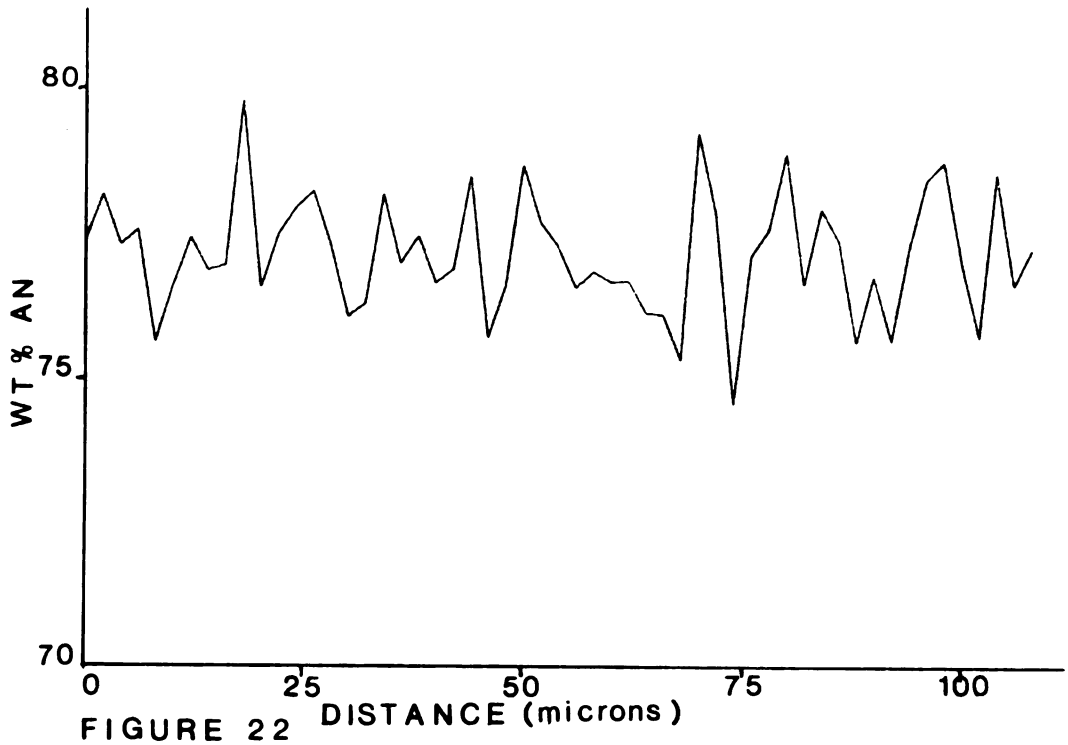


FIGURE 22
Rhyodacite 4-tu

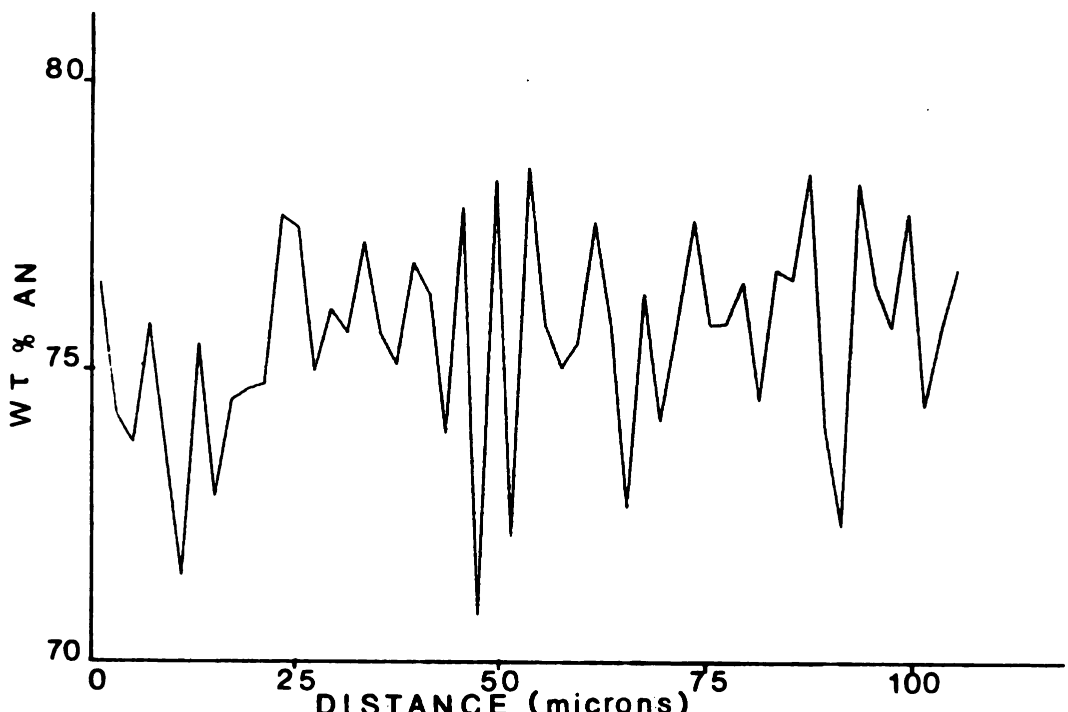


FIGURE 23
Rhyodacite 4-ut

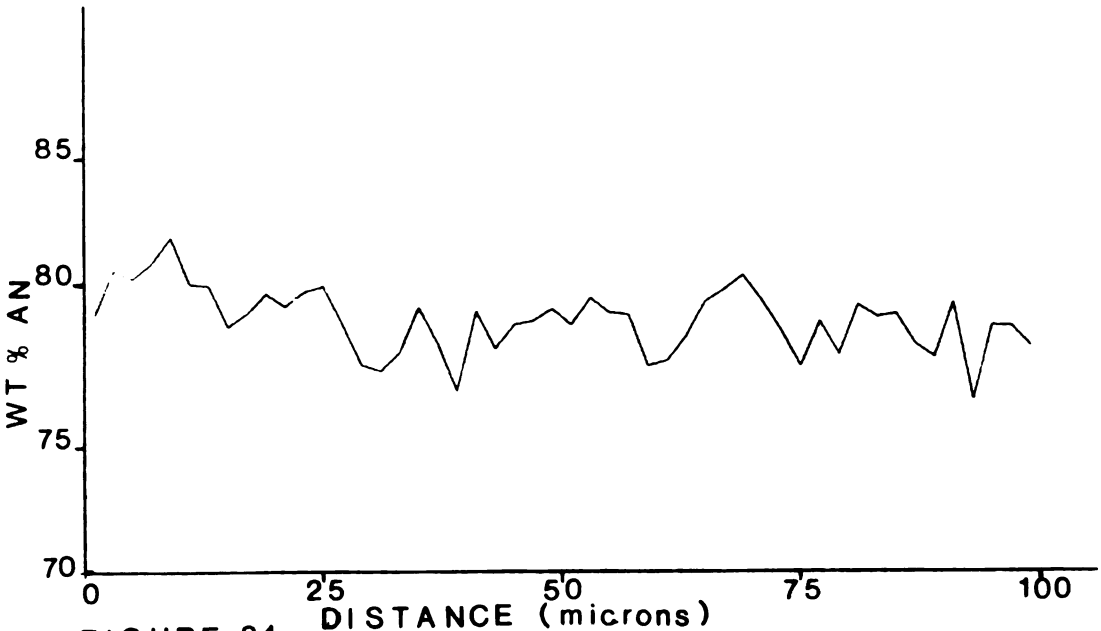


FIGURE 24
Rhyodacite 4-sr

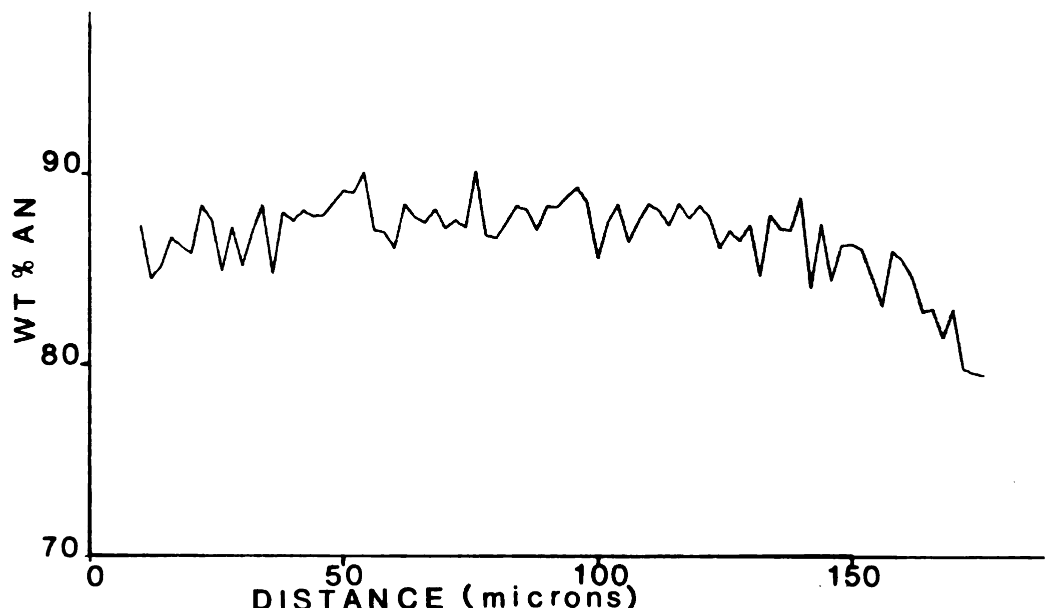


FIGURE 25
Rhyodacite 8-cg

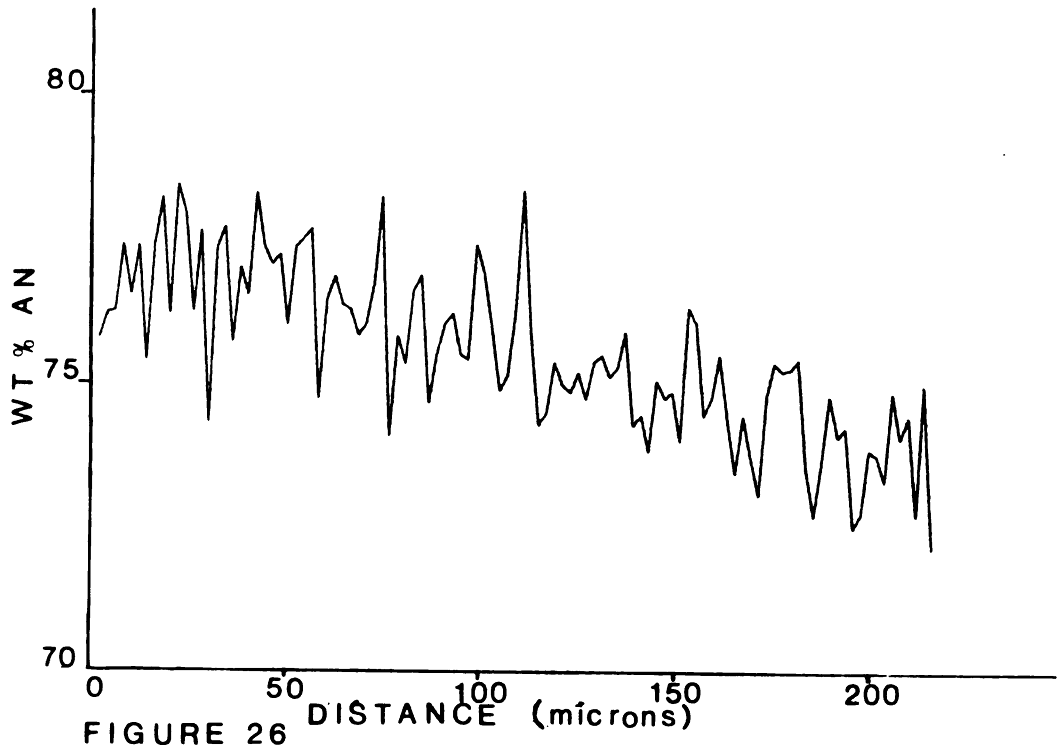


FIGURE 26
Basalt 1-xo

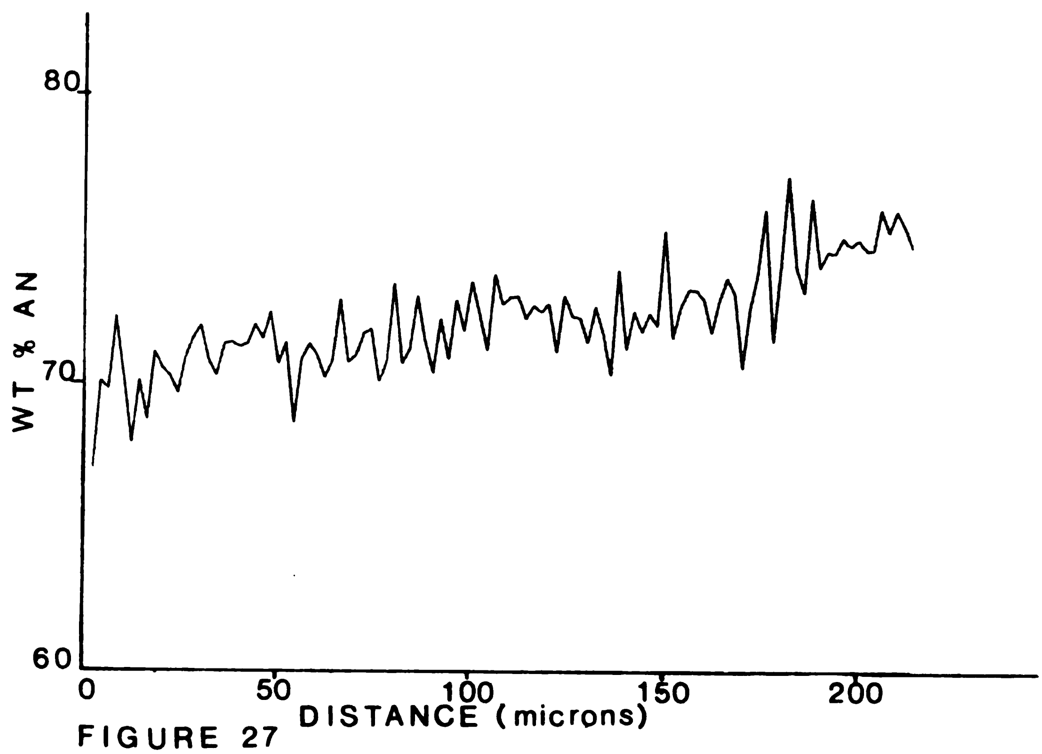


FIGURE 27
Basalt 1-pz

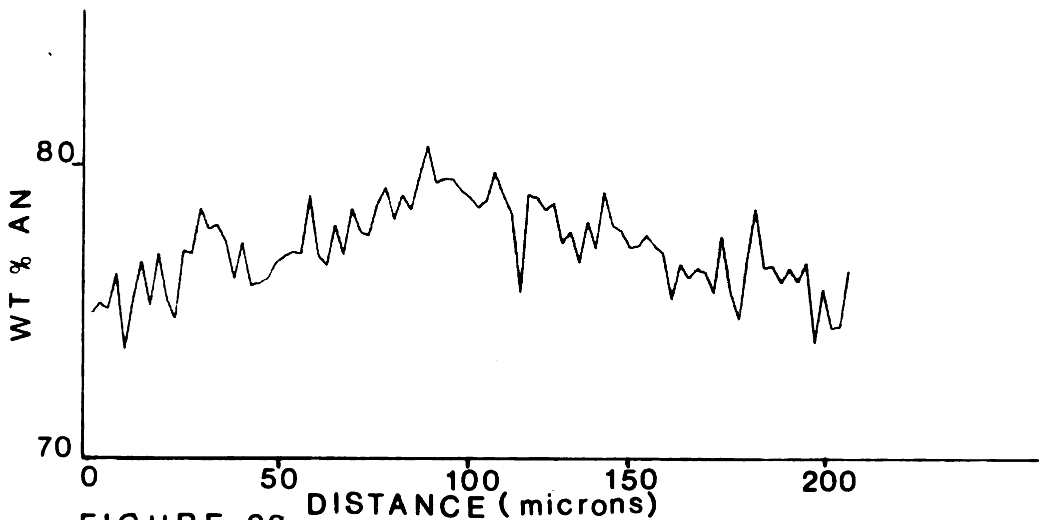


FIGURE 28
Basalt 2-kj

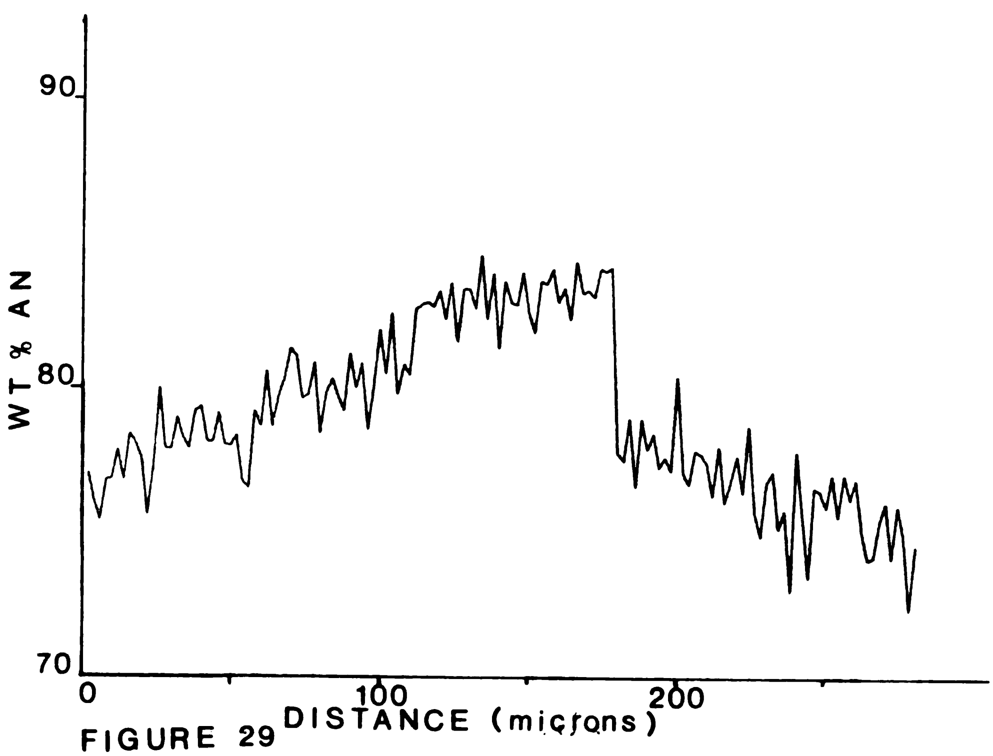


FIGURE 29
Basalt 3-gb

DISCUSSION

The presence of concentration gradients in the glass matrix adjacent to oscillatory zoned crystal faces is predicted if oscillatory zoning in plagioclase results from constitutional supercooling. This data provides support for the constitutional supercooling model as a mechanism by which oscillatory zoning is produced.

Evaluation of the data presented in the Compositional Gradient section reveals that concentration gradients are present in the glass matrix adjacent to crystals which exhibit oscillatory zoning at their peripheral boundary. The peripheral boundary is defined as that area between the crystal edge and the first abrupt zoning discontinuity. In all line traverses exhibiting Si concentration gradients only one, quartz latite 4-hh', also exhibits a definite Ca and Na concentration gradient in the glass matrix. The absence of Ca and Na concentration gradients at crystal-glass boundaries, where Si concentration gradients are present in the glass matrix, may be due to the higher ionic mobility of Ca and Na compared to Si and Al.

In both the quartz latite and rhyodacite the distribution and number of oscillatory zones within the crystal's peripheral boundary varies significantly from crystal to crystal. The number of oscillatory zones contained in the peripheral boundary varies from 6-14 for plagioclase sampled from quartz latite and from 4-2 for plagioclase sampled from the rhyodacite.

In all three rock types oscillatory zoned plagioclase crystals occur along with plagioclase crystals which are not oscillatory zoned. If the oscillatory zoning were produced by general environmental variables, all of the plagioclases would contain oscillatory zones (unless they were xenocrysts).

A third supportive point is that there are no concentration gradients observed in the glass matrix adjacent to normally zoned crystal perimeters, even when these crystals were in the neighborhood of other crystals exhibiting oscillatory zoned perimeters. This suggests that a favorable chemical environment necessary to produce oscillatory zoning in the former did not exist in the melt adjacent to those growing crystals.

A fourth point of prime importance is that at the boundary of two crystals, quartz latite 1 (Plate 1) and rhyodacite 4 (Plate 3), oscillatory zoning is isolated to just one crystal face while the remaining perimeter of each crystal is normally zoned. This suggests that the growth kinetics of individual crystal faces and the boundary layer melt are the controlling parameters which determine if oscillatory zoning is produced in a crystal.

The oscillatory zoned crystal faces may represent repetitive advance and completion of the planar growth interface, here the growth rate of the crystal exceeds the diffusion rate of the solute in the melt. The planar nature of the interface may inhibit nucleation on those crystal faces exhibiting normal zoning and solute diffusion rates in the melt exceed crystal growth rates, which is indicated by the absence of a concentration gradient in the adjacent glass matrix.

Finally, in all crystals except two, quartz latite 4-ab and quartz latite 5-1m, there is no zone pattern correlation between crystals sampled from the same rock type and in many cases there is a variation in zone pattern in different crystallographic planes. It is also interesting to note that the average composition of these neighboring zones is relatively constant. This may indicate that crystallization occurred under nearly isothermal conditions.

Although there was not a good correlation between optically observed zone patterns and those exhibited by the line traverse, the lack of agreement is not thought by the author to be due to analytical error for two reasons. First, line traverses across the larger phenocrysts, sampled from the quartz latite, do show agreement between the optically observed and line traverse zone patterns. This agreement is found at the abrupt change in weight percent anorthite at the core and not at other points of more subtle change in composition. Second, parallel rhyodacite line traverses 4-tu and 4-ut (Figures 22 and 23) across a single crystal and located along an identical path exhibit good agreement with respect to the recorded chemical variation when the plots are superimposed on each other. This demonstrates the repeatability of the method.

The author's interpretation of this data presented above is that in the quartz latite there is limited zone patterns correlation between two crystals (4-ab and 5-1m) and no zone pattern correlation between crystals sampled from either the rhyodacite or basalt.

This data is interpreted to mean that the parameters which control oscillatory zoning are localized about the crystal-melt interface and are not a function of changes in general environmental variables in the magma chamber.

The presence of concentration gradients in the glass matrix adjacent only to the periphery of oscillatory zoned crystals provides the strongest support for constitutional supercooling as a mechanism for oscillatory zoning in plagioclase.

CONCLUSION

In conclusion, this study provides four major lines of evidence which support the constitutional supercooling model as a mechanism by which oscillatory zoning in plagioclase can be produced.

The first is the presence of concentration gradients in the glass matrix adjacent to only those crystals which exhibit oscillatory zoning at their perimeter. Second, no concentration gradients are present adjacent to normally zoned crystal faces. Third, at the boundary of two crystals, quartz latite 1 and rhyodacite 4, oscillatory zoning is isolated to just one crystal face and the remaining perimeter is normally zoned. Fourth, there appeared to be only limited zone pattern correlation between crystals sampled from the same rock type.

Therefore, this study provides evidence which is interpreted to support constitutional supercooling as a viable mechanism for oscillatory zoning in plagioclase.

APPENDIX

```
      PROGRAM FILTER(INPUT,OUTPUT=65,TAPE2,TAPE7,TAPE10,TAPE11)
      REAL MICRON,NA
      INTEGER MICINC
      REAL MAX,MIN
      REAL MICTOP,MICBOT
      REAL LOCMIC
      INTEGER TOKEN,NPROC,TOP,BOT
      INTEGER PFN
        COMMON/EXECMSG/MNF
      COMMON/EMULAT/IBAUD,XSISE,YSIZE,YMIN,XMIN
      COMMON DUM,MICRON(1002),SI(1002),CA(1002),NA(1002)
      COMMON/PLOTB/PLOTBF(1049)
      COMMON/FDB/FDB(30),PFN(4)
      IBAUD=1200
      XSISE=25.0
      YSIZE=25.0
      XMIN=0.0
      YMIN=3.0
      REWIND 2
      CALL RETURNF(5LTAPE7)
      REWIND 7
      PRINT 900
900   FORMAT(* ENTER SAMPLE-*)
      READ 899,PFN(2)
899   FORMAT(A10)
      PRINT 901
901   FORMAT(* ENTER GRAIN-*)
      READ 899,PFN(3)
      PRINT 902
902   FORMAT(* ENTER TRACE-*)
      READ 899,PFN(4)
      PFN(1)=10HVIV-DATA
      CALL PFFDB(5LTAPE7,PFN,FDB,20)
      CALL PFFAP(FDB,"RP",300)
      MAX=0.0
      MIN=10000000.0
      PRINT 1237
1237  FORMAT(*0READING THE DATA....*)
      NIN=0
1     CONTINUE
      NIN=NIN+1
      READ(2,1000)MICRON(NIN),SI(NIN),CA(NIN),NA(NIN)
      IF(NIN.EQ.1)GOTO 1
      IF(EOF(2).NE.0.0)GOTO 11
      IF(SI(NIN).GT.MAX)MAX=SI(NIN)
      IF(CA(NIN).GT.MAX)MAX=CA(NIN)
      IF(NA(NIN).GT.MAX)MAX=NA(NIN)
      IF(SI(NIN).LT.MIN)MIN=SI(NIN)
      IF(CA(NIN).LT.MIN)MIN=CA(NIN)
      IF(NA(NIN).LT.MIN)MIN=NA(NIN)
      IF(NA(NIN).LE.0.0)PRINT *,NA(NIN),NIN
      IF(NIN.LT.1000)GOTO 1
      PRINT 2000
2000  FORMAT(* TOO MUCH DATA....*)
11    CONTINUE
      NIN=NIN-1
      NIN=(NIN/2)*2
      PRINT 2001,NIN
2001  FORMAT(*       *,I5,* CASES READ IN*)
      IF(NIN.LT.5)STOP "TOO LITTLE DATA"
1000  FORMAT(F4.0,3F8.0)
      CONSTY=10.0/(MAX-MIN)
      CONSTX=(FLOAT(NIN)/25.0)
```

```
      IF(CONSTX.GE.40.0)CONSTX=40.0
      CONSTX=CONSTX/MICRON(NIN)
C
C         END OF THE DATA INPUTTING PORTION...
C
      PRINT 3901
3901  FORMAT(*ODO YOU WANT TO SEE THE UNFILTERED PLOT?*)
      CALL VETO(TOKEN,NPROC,XNUM)
      IF(TOKEN.EQ.1HN)GOTO 300
      CALL PLOTCP(NIN,MAX,MIN,3,NIN-2,CONSTX,CONSTY)
300   CONTINUE
C
C NOW WE COMPUTE THE GLASS EDGES....
C
      PRINT 3000
3000  FORMAT(*COMPUTING THE GLASS EDGES...*)
      BOT=1$TOP=NIN
      MICINC=INT(MICRON(5)-MICRON(4))
      IF(MICINC.EQ.0)MICINC=1
      MICINC=9/MICINC
      IF(MICINC.LE.0)MICINC=1
      NN=NIN-5
      DO 2 NUP=6,NN
      UPUP=NA(NUP+MICINC)+NA(NUP+MICINC+1)
      UPDN=NA(NUP-MICINC)+NA(NUP-MICINC-1)
      IF((BOT.EQ.1).AND.((UPDN*5.0).LT.UPUP))BOT=NUP
      IF((UPUP*5.0).LT.(UPDN))TOP=NUP
2     CONTINUE
C
      PRINT 3001,MICRON(BOT),MICRON(TOP)
3001  FORMAT( *  BOTTOM OF GLASS SEEMS TO BE * ,F6.1, * MICRONS * /
     +         *  TOP OF GLASS SEEMS TO BE * ,F6.1, * MICRONS * )
C
      PRINT 3002
3002  FORMAT(* DO YOU WISH TO CHANGE THE GLASS LOCATIONS-Y/N*)
      CALL VETO(TOKEN,NPROC,XNUM)
      IF(TOKEN.EQ.1HN)GOTO 20
36    CONTINUE
      PRINT 3003
3003  FORMAT(* ENTER BOTTOM OF GLASS-*)
      READ *,MICBOT
      PRINT 3004
3004  FORMAT(* ENTER TOP OF GLASS-*)
      READ *,MICTOP
      IF(MICBOT.GE.MICTOP)GOTO 36
      BOT=TOP=1
      DO 21 N=1,NIN
      IF(MICRON(N).LT.MICTOP)TOP=N
      IF(MICRON(N).LT.MICBOT)BOT=N
21    CONTINUE
20    CONTINUE
      TOP=TOP-4
C
      BOT=BOT+4
C  THE LOCATION HAS BEEN SET FOR THE TOP AND BOT OF THE GLASS
C
      LOCMIC=10000000.0
      MFIRST=0
254   CONTINUE
      PRINT 2367
2367  FORMAT(*OBEGINNING THE FILTERING PORTION...*)
```

```
      N=BOT+6
      AVSI=SI(N)
      AVCA=CA(N)
      AVNA=NA(N)
      TOKEN=1HN
      NLIST=0
      IF (MFIRST.NE.0)GOTO  2924
3     CONTINUE
      N=N+1
      AVSI=(AVSI*5.0+SI(N-1)-SI(N-6))/5.0
      AVCA=(AVCA*5.0+CA(N-1)-CA(N-6))/5.0
      AVNA=(AVNA*5.0+NA(N-1)-NA(N-6))/5.0
      DIFFSI=ABS(SI(N)-AVSI)*4.0
      DIFFCA=(AVCA-CA(N))*1.4
        DIFFNA=(AVNA-NA(N))*1.4
      IF(DIFFSI.GT.AVSI)GOTO 31
      IF(DIFFCA.GT.AVCA)GOTO 31
      IF(DIFFNA.GT.AVNA)GOTO 31
      IF(LOCMIC.LE.MICRON(N))GOTO 31
      GOTO 30
31    CONTINUE
      IF(TOKEN.EQ.1HC)GOTO 32
      PRINT 4000,MICRON(N),SI(N),CA(N),NA(N)
4000  FORMAT(* *,F6.0,* MIC..SI=*,F8.3,,* CA=*,F8.3,* NA=*,F8.3,* DO YOU
       + WISH TO DELETE*)
      IF(TOKEN.EQ.1HL.AND.NLIST.LE.NPROC)GOTO 32
      CALL VETO(TOKEN,NPROC,XNUM)
        NLIST=0
   2924  CONTINUE
        IF(MFIRST.EQ.0)GOTO 3214
        PRINT *,"MICRON-"
        READ *,LOCMIC
  3214  CONTINUE
      IF(TOKEN.EQ.1HS)N=TOP
      IF(TOKEN.EQ.1HS)GOTO 30
      IF(TOKEN.EQ.1HN)GOTO 30
32    CONTINUE
      NLIST=NLIST+1
C HERE WE PLOT THE LINE THAT MARKS THE BAD POINTS
C
      SI(N)=AVSI
      CA(N)=AVCA
      NA(N)=AVNA
30    CONTINUE
      IF(N.LT.(TOP))GOTO 3
      IF(MFIRST.EQ.1)GOTO 3904
      MFIRST=1
      PRINT *,"DO YOU WANT TO DELETE MORE POINTS?"
      CALL VETO(TOKEN,NPROC,XNUM)
      IF(TOKEN.EQ.1HY)GOTO 254
3904  CONTINUE
C
C NOW WE PLOT THE FILTERED DATA IF REQUESTED
      PRINT 3902
      DO 9876 K=BOT,TOP
        IF(NA(K).LE.0.0)PRINT *,K,NA(K), " NA LE 0.0"
9876  WRITE(11,8765)K,MICRON(K),SI(K),CA(K),NA(K)
8765  FORMAT(1X,I5,5F10.3)
3902  FORMAT(* DO YOU WANT TO SEE THE FILTERED PLOT?*)
      CALL VETO(TOKEN,NPROC,XNUM)
      IF(TOKEN.EQ.1HN)GOTO 3999
```

```
C
      CALL PLOTCF(NIN,MAX,MIN,BOT,TOP,CONSTX,CONSTY)
C
3999  CONTINUE
C
C  NOW WE DO THE PLAGIOCLASE ANALYSIS
C
      PRINT 5000
5000  FORMAT(* DO YOU WANT A PLAGIOCLASE ANALYSIS DONE*)
      CALL VETO(TOKEN,NFROC,XNUM)
      IF(TOKEN.EQ.1HN)GOTO 7000
      CALL PLAG(TOP,BOT,CONSTX)
C
C  NOW WE STORE THE DATA......
C
      PRINT 6000
6000  FORMAT(* DO YOU WANT THE DATA STORED?*)
      CALL VETO(TOKEN,NFROC,XNUM)
      IF(TOKEN.EQ.1HY)CALL STORE
7000  CONTINUE
      END
       SUBROUTINE VETO(TOKEN,NFROC,XNUM)
       INTEGER TOKEN,NFROC
       PRINT 1000
 1000  FORMAT(* ?*)
 1     CONTINUE
       CALL NOBLANK
       READ 2000,TOKEN,XNUM,NFROC
 2000  FORMAT(2A1,I10)
       IF(TOKEN.EQ.1HY.OR.TOKEN.EQ.1HN.OR.TOKEN.EQ.1HC)RETURN
       IF(TOKEN.EQ.1HL.OR.TOKEN.EQ.1HS)RETURN
       PRINT 1001
 1001  FORMAT(* Y OR N?*)
       GOTO 1
       RETURN
       END
       SUBROUTINE PLOTCF(NIN,MAX,MIN,BOT,TOP,CONSTX,CONSTY)
       INTEGER PFN
       REAL MICRON,NA
       REAL MAX,MIN
       INTEGER BOT,TOP
       COMMON N,MICRON(1002),SI(1002),CA(1002),NA(1002)
       COMMON/FDP/FDP(30),PFN(4)
       COMMON/PLOTB/PLOTBF(1049)
         CALL PLOTS(PLOTBF,1027,0)
       CONSTY=CONSTY*.565
       CALL PLIMIT(45.0)
 C
 C FIRST WE DRAW THE LEGEND
 C
       CALL NEWPEN(3)
       CALL SYMBOL(0.0,0.0,.14,10H       ..NA,0.0,10)
       CALL NEWPEN(2)
       CALL SYMBOL(0.0,.25,.14,10H       ..CA,0.0,10)
       CALL NEWPEN(1)
       CALL SYMBOL(0.0,.5,.14,10HLEGEND..SI,0.0,10)
       CALL SYMBOL(0.0,1.0,.28,PFN(4),0.0,10)
       CALL SYMBOL(0.0,1.4,.28,PFN(3),0.0,10)
       CALL SYMBOL(0.0,1.8,.28,PFN(2),0.0,10)
       CALL PLOT(2.0,1.0,-3)
 C
```

```
C    NOW WE PLOT THE AXISES
C
C    X-AXIS...
C
      CALL PLOT(-.3,0.0,3)
      X=0.0
10    CONTINUE
      X=X+200.0
      XCOORD=CONSTX*(X)
      CALL PLOT(XCOORD,0.0,2)
      CALL PLOT(XCOORD,-0.2,1)
      CALL NUMBER(XCOORD-.2,-.4,.14,X,0.0,0)
      CALL PLOT(XCOORD,0.0,3)
      IF(X.LT.MICRON(NIN))GOTO 10
C
C THE Y-AXIS...
C
      CALL PLOT(0.0,-.3,3)
      Y=0.0
20    CONTINUE
      Y=Y+200.0
      YCOORD=CONSTY*(Y)
      CALL PLOT(0.0,YCOORD,2)
      CALL PLOT(-.2,YCOORD,2)
      CALL NUMBER(-.4,YCOORD-.2,.14,Y*10.0,90.0,1)
      CALL PLOT(0.0,YCOORD,3)
      IF(Y.LT.(MAX-99.0))GOTO 20
C
C PUT THE TITLES IN
C
      CALL SYMBOL(-1.0,3.0,.28,3HCPS,90.0,3)
      CALL SYMBOL(2.0,-1.0,.28,10HSI/CA/NA   ,0.0,10)
C
C  NOW WE PLOT THE LINES...
C
      I=3
      DO 40 K=BOT,TOP
      XCOORD=CONSTX*MICRON(K)
      YCOORD=CONSTY*(SI(K))
      CALL PLOT(XCOORD,YCOORD,I)
      I=2
40    CONTINUE
      I=3
      CALL NEWPEN(2)
      DO 50 K=BOT,TOP
      XCOORD=CONSTX*MICRON(K)
      YCOORD=CONSTY*(CA(K))
      CALL PLOT(XCOORD,YCOORD,I)
      I=2
50    CONTINUE
      CALL NEWPEN(3)
      I=3
      DO 60 K=BOT,TOP
      XCOORD=CONSTY*MICRON(K)
      YCOORD=CONSTY*(NA(K))
      CALL PLOT(XCOORD,YCOORD,I)
      I=2
60    CONTINUE
      CALL PLOT(0.0,0.0,999)
      RETURN
      END
```

```
      SUBROUTINE PLAG(TOP,BOT,CONSTX)
      INTEGER TOP,BOT
      INTEGER EL
      DIMENSION IRED(2)
      LOGICAL ITEST
      COMMON/PLOTBF/PLOTBUF(1049)
      COMMON//N,DYN1(1002),DYN2(1002),DYN3(1002),DYN4(1002)
      DIMENSION ID(2)
      DIMENSION BETA(5),CPS(3),ISTD(3),EL(3),CPSSTD(3,3),W(3),C(3)
      INTEGER LFORMF
      DATA ISTD/"AN","AB","OR"/
      DATA BETA/1.118,1.289,1.162,0.0,0.0/
      DATA ICHECK/"Y"/
      DATA EL/"CA","NA","K "/
      DATA IRED/10HRMARGIN,13,1L6/
      IF(BOT.LT.1)GOTO 996
      IF(TOP.GE.1000)GOTO 996
      IF(TOP.LE.BOT)GOTO 996
      GOTO 997
996   CONTINUE
      PRINT 998,TOP,BOT
998   FORMAT(* TOP=*,I8,* BOT=*,I8)
      STOP "PLAGOCLASE ERROR 1..BAD TOP/BOT"
997   CONTINUE
      NCUT=BOT
      LIMIT = 0
      CPSSTD(1,1) = CPSSTD(2,2) = CPSSTD(3,3) = 0.0
      PRINT *," WILL BACKGROUND CORRECTIONS BE REQUIRED? Y OR N"
      READ 87,IB
87    FORMAT(A1)
      ITEST = IB .EQ. ICHECK
      DO 50 I=1,3,1
          PRINT 2,ISTD(I)
2         FORMAT(/10X," ENTER CPS FOR ",A2," STANDARD.")
          DO 40 K=1,3,1
              IF(I .NE. K) GOTO 40
              IF( ITEST) GOTO 901
                  PRINT 3,EL(K)
3                 FORMAT(1X,A2,"=")
      READ *,CPSSTD(I,K)
      GOTO 902
901   CONTINUE
                  PRINT 30,EL(K)
30                FORMAT(1X,A2," BACKGROUND VALUES ARE ")
                  BKG = AVG("BACKGRD")
                  PRINT 31,EL(K)
31                FORMAT(1X,A2," PEAK VALUES ARE")
                  PEAK = AVG("PEAKVAL")
                  CPSSTD(I,K) = PEAK - BKG
                  PRINT 32,CPSSTD(I,K)
32                FORMAT(10X,"CORRECTED INTENSITY = ",F10.2/)
902   CONTINUE
40        CONTINUE
50    CONTINUE
      DMIN2 = DMIN3 = DMIN4 = 1.0E300
      DMAX2 = DMAX3 = DMAX4 = -1.0E300
      WRITE(10,111) ID,DATE(I),TIME(I),CPSSTD(1,1),CPSSTD(2,2)
111   FORMAT("   SAMPLE :",2A10,10X,A10,10X,A10/"0","  AN STANDARD = ",F
     +8
     +.2,"  AB STANDARD = ",F8.2//)
      X=CONSTX*(DYN1(TOP))
```

```
1000  CONTINUE
      XMCI=DYN1(NOUT)
      CPS(1)=DYN3(NOUT)
      CPS(2)=DYN4(NOUT)
      CPS(3)=0.0
      NOUT=NOUT+1
      SUM = 0.0
      DO 70 I=1,3,1
       IF(CPSSTD(I,I).NE.0.0)C(I) = CPS(I) /( CPSSTD(I,I) * BETA(I))
          IF(CPSSTD(I,I) .EQ. 0.0) C(I)=0
          SUM = SUM + C(I)
70    CONTINUE
      SUM = SUM * 0.01
      DO 80 I=1,3,1
          W(I) = C(I) / SUM
80    CONTINUE
      LIMIT = LIMIT + 1
      IF(LIMIT .GT. 1000) CALL SYSTEM(52,"      TOO MUCH DATA")
      DYN1(LIMIT) = XMCI
      DYN2(LIMIT) = W(1)
      DYN3(LIMIT) = W(2)
      DYN4(LIMIT) = W(3)
      WRITE(10,85)(ISTD(K),W(K),K=1,3),XMCI
      DMIN2 = AMIN1(DYN2(LIMIT),DMIN2) $ DMIN3 = AMIN1(DYN3(LIMIT),DMIN3
     +)
      DMIN4 = AMIN1(DYN4(LIMIT),DMIN4) $ DMAX2 = AMAX1(DYN2(LIMIT),DMAX2
     +)
      DMAX3 = AMAX1(DYN3(LIMIT),DMAX3) $ DMAX4 = AMAX1(DYN4(LIMIT),DMAX4
     +)
85    FORMAT(1X,"NORMALIZED PLAGIOCLASE IS ",3(A2,1X,F6.2,1X)," MICRONS
     +ARE ",F7.2)
      IF(NOUT.LE.TOP)GOTO 1000
      Y=12.0
      N=LIMIT
      PRINT 4231
4231  FORMAT(* DO YOU WANT TO SEE THE PLAGIOCLASE PLOT*)
      CALL VETO(TOKEN,TOKEN2,XNUM)
      IF(TOKEN.EQ.1HN)RETURN
      PRINT *,"ENTER PLOT WANTED..1=AN,2=AB,3=OR"
      READ *,ITYPE
      CALL PLOTS(PLOTBUF,1027,0)
        CALL FACTOR(.5)
      CALL FLIMIT(45.0)
      DYN1(LIMIT+1) = 0.0
      DYN1(LIMIT+2) = DYN1(LIMIT) / X
      CALL PLOT(1.0,1.0,-3)
      CALL AXIS(0.0,0.0,"MICRONS",-7,X,0.0,DYN1(LIMIT+1),DYN1(LIMIT+2))
      GOTO (197,198,199), ITYPE
197   DYN2(LIMIT+1) = DMIN2
      DYN2(LIMIT+2) = (DMAX2 - DMIN2) / Y
      CALL AXIS(0.0,0.0,"PERCENT AN",10,Y,90.,DYN2(LIMIT+1),DYN2(LIMIT+2
     +))
      CALL LINE(DYN1,DYN2,LIMIT,1,0,0)
      CALL NEWPEN(3)
      GOTO 33333
198   DYN3(LIMIT+1) = DMIN3
      DYN3(LIMIT+2) = (DMAX3 - DMIN3) / Y
      CALL AXIS(0.0,0.0,"PERCENT AB",10,Y,90.,DYN3(LIMIT+1),DYN3(LIMIT+2
     +))
      CALL LINE(DYN1,DYN3,LIMIT,1,0,0)
      CALL NEWPEN(3)
```

```
      GOTO 33333
199   DYN4(LIMIT+1) =DMIN4
      DYN4(LIMIT+2) = (DMAX4 - DMIN4) / Y
      CALL AXIS(0.0,0.0,"PERCENT OR",10,Y,90.,DYN4(LIMIT+1),DYN4(LIMIT+2
     +))
      CALL LINE(DYN1,DYN4,LIMIT,1,0,0)
      CALL NEWPEN(3)
33333 CALL PLOT(0.,0.0,999)
      CALL REMARK("     FINISHED !")
      END
      FUNCTION AVG(NOTE)
      LOGICAL FINISH,IDCA,IDDYN2
      SUM = 0.0
      KOUNT = -1
      FINISH = .FALSE.
904   CONTINUE
      IF(FINISH)GOTO 905
          PRINT 10,NOTE
10        FORMAT(" NEED VALUE FOR ",A7/)
          READ *,TEMP
          FINISH = TEMP .EQ. 0.0
          SUM = SUM + TEMP
          KOUNT = KOUNT + 1
      GOTO 904
905   CONTINUE
      AVG=SUM/FLOAT(KOUNT)
      IF(KOUNT .EQ. 0) AVG=0.0
      RETURN
      END
      SUBROUTINE STORE
      COMMON//N,DYN1(1002),DYN2(1002),DYN3(1002),DYN4(1002)
      COMMON/FDE/FDB(30),FFN(4)
      CALL RETURNF(5LTAPE7)
      N=(N/2)*2
      IF(N.GE.5)GOTO 30
      PRINT 2000,N
2000  FORMAT(* N=*,I6)
      STOP "STORE ERROR 3..TOO FEW POINTS"
30    CONTINUE
      PRINT 1000
      READ 1100,FFN(1)
1000  FORMAT(* FILTER OR FOURIER?*)
1100  FORMAT(A10)
      PRINT 900
900   FORMAT(* ENTER SAMPLE-*)
      READ 899,FFN(2)
899   FORMAT(A10)
      PRINT 901
901   FORMAT(* ENTER GRAIN-*)
      READ 899,FFN(3)
      PRINT 902
902   FORMAT(* ENTER TRACE-*)
      READ 899,PFN(4)
      CALL PFFDB(5LTAPE7,FFN,FDB,20)
      CALL PFPAR(FDB,"RP",300)
      PRINT 3000
3000  FORMAT(* STORING THE DATA.....*)
      BUFFER OUT(7,1)(N,DYN4(1002))
      X=PFCAT(FDB)
      IF(X.EQ.0.0)GOTO 40
      CALL CKPFERR(X,0)
      STOP "STORE ERROR 4..BAD CATALOG"
40    CONTINUE
      PRINT 4000,N
4000    FORMAT(* *,I5,* POINTS STORED*)
      RETURN
      END
```

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PLATES

Plate 1

All photo widths equal 770 microns except where otherwise noted.

Figure	
1	Quartz Latite Crystal 1: Line Traverses 1-aa', 1-bb', 1-cc'.
2	Quartz Latite Crystal 1: Line Traverses 1-aa', 1-bb' (130 um).
3	Quartz Latite Crystal 1: Line Traverse 1-cc' (130 um).
4	Quartz Latite Crystal 2: Line Traverses 2-ee', 2-dd', 2-ab.
5	Quartz Latite Crystal 2: Line Traverse 2-ee' (330 um).
6	Quartz Latite Crystal 2: Line Traverse 2-dd' (210 um).

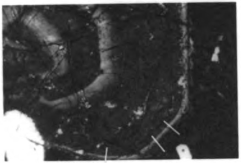
PLATE 1

Fig. 1

1-bb′

1-aa′

1-cc′

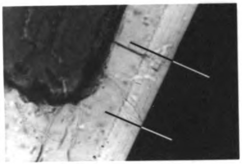


2-ab

2-ee′

Fig. 4

2-dd′



1-bb′

Fig. 2

1-aa′

Fig. 3

1-cc′

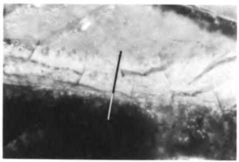


Fig 5 2-ee′

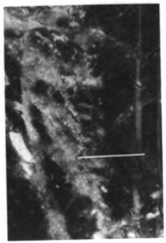


Fig. 6 2-dd′

Plate 2

All photo widths equal 770 microns except where otherwise noted.

Figure	
1	Quartz Latite Crystal 3: Line Traverse 3-ff'.
2	Quartz Latite Crystal 4: Line Traverses 4-gg', 4-hh'.
3	Quartz Latite Crystal 6: Line Traverse 6-ab (1320 um).
4	Quartz Latite Crystal 5: Line Traverse 5-ii', 5-jj', 5-kk', 5-lm (3166).
5	Quartz Latite Crystal 5: Line Traverse 5-ii', 5-kk'.
6	Quartz Latite Crystal 6: Line Traverse 5-jj'.

PLATE 2

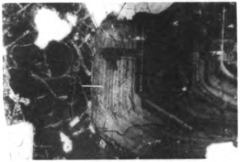


Fig. 1

3-ff′

Fig. 2

4-gg′
4-hh′

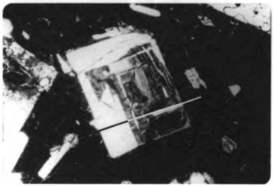


Fig. 3

6-ab

Fig. 4

5-ii′, 5-kk′ 5-lm 5-jj′

Fig. 5 5-ii′, 5-kk′

Fig. 6 5-jj′

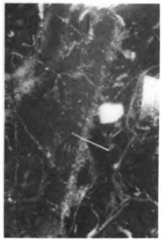


Plate 3

All photo widths equal 770 microns except where otherwise noted.

Figure	
1	Rhyodacite Crystal 1: Line Traverse 1-aa', 1-bb' (330 um).
2	Rhyodacite Crystal 2: Line Traverse 2-cc', 2-dd', 2-pq.
3	Rhyodacite Crystal 3: Line Traverse 3-ee', 3-ab.
4	Rhyodacite Crystal 4: Line Traverses 4-ff', 4-sr, 4-tu, 4-ut (330 um).
5	Line Traverse 4-ff' (130 um).

PLATE 3

Fig. 1

1-aa′ 1-bb′

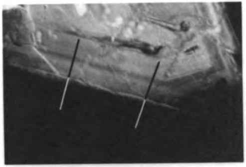


Fig. 2

2-pq
2-dd′ 2-cc′

Fig. 3

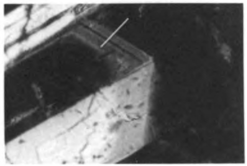
3-ab

3-ee′

Fig. 4

4-tu 4-sr 4-ff′
4-ut

Fig. 5



4-ff′

Plate 4

All photo widths equal 770 microns except where otherwise noted.

Figure	
1	Rhyodacite Crystal 5: Line Traverse 5-gg'
2	Rhyodacite Crystal 6: Line Traverse 6-hh', 6-ii'.
3	Rhyodacite Crystal 7: Line Traverse 7-jj' (330 um).
4	Rhyodacite Crystal 8: Line Traverses 8-kk', 8-ll', 8-cg (330 um).

PLATE 4

Fig. 1

5-gg′

Fig. 3

7-jj′

Fig. 2

6-ii′ 6-hh′

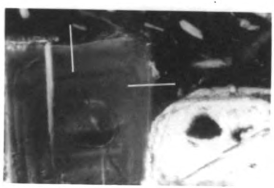


Fig. 4

8-kk′ 8-cg 8-ll′

Plate 5

All photo widths equal 770 microns except where otherwise noted.

Figure	
1	Basalt Crystal 1: Line Traverses 1-xo, 1-pz (330 um).
2	Basalt Crystal 3: Line Traverse 3-gb.
3	Basalt Crystal 2: Line Traverse 2-kj.

PLATE 5

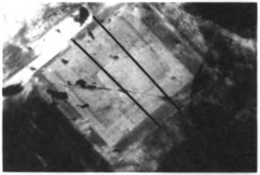


Fig. 1
1-pz
1-xo

Fig. 2
3-gb

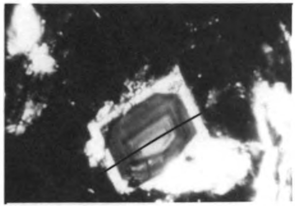


Fig. 3
2-kj

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