PLAGIOCLASE ZONING PROFILES OF A SMALL PLUTON IN ARIZONA

by

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ABSTRACT

Compositional zoning profiles of plagioclase from the Ninemile Granodiorite Stock (Cochise, County, Arizona) were measured by microprobe. The core compositions of crystals were around 40% An and the rim values were grouped tightly around 14% An regardless of the composition of the adjacent mineral. Profiles displayed no systematic variation related to position in the stock. The lack of systematic changes in the profiles and the lack of a porphyritic texture suggests the absence of water concentration in the center of the pluton during crystallization. The constant rim values of crystals suggest a melt that had very efficient diffusion or transfer of components during crystallization.

One possible explanation for the lack of variation in the profiles is that the center of the pluton may not have yet been exposed by erosion. Another possibility is that some buffering mechanism may have been effective during crystallization. The most likely mechanism would have been a rapidly convecting magma core. The mixing could provide a thermal buffer as long as the mixing volume was large enough to be an effective heat source.

INTRODUCTION

The formation of compositionally zoned minerals in an igneous system is a disequilibrium process. The end result is dependent upon the temperature, pressure, and melt composition evolution during crystallization. If the zoned mineral is resistant to intracrystalline diffusion, the zoning profile can be treated as a record of the conditions under which the crystal grew.

Zoned plagioclase crystals make useful records of conditions of crystallization in igneous systems. Plagioclase is a very common mineral and crystallizes over a large portion of the crystallization interval of most igneous bodies. Intracrystalline diffusion is very slow in this mineral as is shown by the preservation of intricate zoning. The composition of plagioclase crystallizing from a melt is sensitive to temperature, pressure, composition of the melt and to the variation of these variables with time. With a qualitative understanding of the effects of the controlling variables of the plagioclase system, it is possible through the study of zoning profiles and their systematic variations within a pluton to develop a history of crystallization of the body of rock.

The usefulness of zoned plagioclase in the study of igneous systems has been shown by several previous workers. Greenwood and McTaggart (1957) were able to successfully correlate zoning profiles between grains in both pluton and batholyth-sized systems. Vance (1962, 1965) set forth models to explain the formation of observed profiles in igneous plagioclase. Weibe (1968), Maaloe (1978), and Loomis and Welber (ms) all conducted systematic studies of compositional zoning in plagioclase and interpreted them in terms of magmatic processes such as intrusion, magma mixing and convection, and water saturation.

The objective of this study is to measure the compositional zoning of plagioclase in the Ninemile Stock, Cochise County, Arizona, and develop a cooling history for the stock from interpretations of these profiles in terms of crystallization models for the plagioclase system.

PLUTON DESCRIPTION

Location

The Ninemile Stock is located approximately six miles south of the town of Bowie and six miles north of Apache Pass, in the southeast corner of the Dos Cabezas Mountains, Cochise County, Arizona. Most of the pluton's outcrop area is contained in sections 8, 9, 15 and 17, T14S, R28E, Salt River and Gila Baseline and Meridian.

General Geology

The stock is a simple intrusion of light colored granodiorite with a fresh and massive outcrop that is four square miles in extent. Almost all of the stock displays a uniformly coarse-grained texture. Numerous aplitic dikes crosscut the main body of the pluton. These aplitic dikes are cut by later-formed pegmatite dikes.

Potassium-Argon dating of biotite from the Ninemile Stock gives an age of 29.0$\pm$ 1.7my (Erickson, 1969). The mid-tertiary stock intrudes both the Precambrian Pinal Series and the Precambrian Sheep Canyon Quartz Monzonite Gneiss.

The contact of the intrusion shows a very thin chill zone on the order of 10 cm where observed. In one area, a two foot wide dike of the main body that intrudes the country rock shows only 10 cm of chill zone on either side. The texture at the center of the dike is similar to that of main body.

The stock appears to be composed of a series of dome-like structures (figure 1). However, the rock shows no definite flow alignment of grains from which to judge emplacement movements.

The stock also contains biotite-rich schlieren which, according to Erickson (1969), show partial melting effects. He suggests that these may represent partially molten xenoliths of the country rock.

Petrography

Three distinct rock textures are present in the pluton and in the two types of dikes (figure 2).

The main body of the pluton is an equigranular hypidiomorphic granodiorite consisting of plagioclase, orthoclase, quartz, magnetite, biotite, and minor apatite and zircon. The plagioclase grains range in size from two to five mm, while some orthoclase and quartz grains reach dimensions of up to 1.5 cm.

The bulk composition of the pluton appears from petrographic observation to be uniform throughout the area sampled. The mineralogy is constant throughout the pluton and the average anorthite content of the plagioclase grains show no systematic changes with position in the pluton.

The plagioclase is euhedral to subhedral with strong optical zoning (figure 3). The cores and some zones of the crystals show a tendency to be sericitized. Albite and Carlsbad twins are widespread in all samples. An occasional grain will show patchy zoning, which

Figure 1: Photograph of Dome-like Structure in the Ninemile Stock

Figure 2: Photograph of Aplite and Pegmatite Dikes in the Main Pluton Rock.--The pencil is resting on the main pluton rock with the tip pointing to a light colored pegmatite dike which is next to an aplite dike of roughly equal width.

Figure 3: Photomicrograph of a Plagioclase Grain Showing Strong Optical Zoning

may suggest a history of resorption (Vance, 1965), but cores that show resorbed outlines are very rare. Vermicular intergrowths of quartz and plagioclase were observed on the edges of a few plagioclase grains.

Biotite is the main phyllosilicate present in the granodiorite. It shows good birds-eye extinction and is pleochroic brown under plain light except where altering to chlorite. The chlorite exhibits anomalous blue interference colors and is pleochroic green in plain light.

Magnetite is present as both a primary mineral and as a by-product of hydrothermal alteration. Magnetite is commonly associated with chlorite and is most likely a by-product of biotite altering to chlorite. The secondary magnetite has a needle-like habit. The primary magnetite shows crystal forms ranging from euhedral cross-sections to anhedral blebs.

Orthoclase appears to have crystallized late in the granodiorite. The orthoclase is anhedral and fills the interstices between grains of other minerals. It contains inclusions of plagioclase, biotite, quartz, zircon, and magnetite. Many grains show well developed cross hatch twinning. The orthoclase is perthitic with exsolution visible in some grains.

Quartz is also a late crystallizing phase in the pluton and exhibits a tendency to be anhedral, to contain inclusions of plagioclase, and to fill the interstices between more euhedral

minerals. The quartz also shows well-developed undulatory extinction.

Minor amounts of apatite and zircon are also present in the stock. Small amounts of muscovite are present in some samples, but whether it is of primary or secondary origin can not be determined.

Also noted in the mainbody of the pluton was an unusual feature at the boundaries between plagioclase grains and grains of orthoclase showing exsolution lamellae. A rim of albite-rich composition seems to be plated onto the plagioclase (figure 4). This extra layer of plagioclase is only present at plagioclase-orthoclase boundaries; it ends where the edge of the plagioclase grain comes into contact with another phase.

The mineralogy of the aplite dikes is similar to that of the main body but the texture is quite different. The aplite dikes have a sugary texture and are more coarse-grained in the areas close to the center of the stock than in areas near the contact. The grains range in average size from 0.8 mm near the center of the stock down to 0.4 mm close to the contact. Plagioclase and magnetite grains in the more coarse-grained dike samples also are more euhedral than in samples from near the contact. The major minerals present are plagioclase, orthoclase, quartz, muscovite and magnetite. The plagioclase is zoned and shows the same twinning as in the coarse grained rocks. The orthoclase is twinned also, but unlike that in the main body, it does not contain inclusions. The quartz has

Figure 4: Photomicrograph of an Orthoclase-plagioclase Boundary.--A zoned plagioclase grain nearly at optical extinction except for a rim of Albitic composition which is present at the boundary with orthoclase.

neither inclusions nor undulatiory extinction. The main mineralogical difference between these dikes and the main body is that muscovite is the major phyllosilicate in the dikes, and it shows much less alteration than its coarse-grained equivalent in the pluton.

The pegmatite dikes are so coarse-grained that it is impractical to make thin sections from the samples. The grain sizes in these dikes range from 3 to 10 cm in size. From hand sample specimens, feldspars, quartz, muscovite and an occasional garnet could be identified.

DATA COLLECTION AND REDUCTION

Sample Collection

Samples were taken along a traverse through what was thought to be the center of the pluton. By taking samples across the pluton it was hoped that any significant zoning changes resulting from changes in the variables controlling crystallization would be sampled. The traverse started at the contact with the Pinal Series on the south, went over one of the dome-like structures and ended at the valley gravels on the north. See sample location map, figure 5.

Sample Preparation

Thin sections were cut from each sample and inspected for degree of alteration and optical zoning in the plagioclase. Samples that were fresh with abundant zoned plagioclase had polished sections made from them for microprobe analysis.

Probe Technique

Compositional zoning in the plagioclase grains from the samples was measured using an ARL Scanning Electron Microprobe Quantometer with a Tracor Northern Automation System at the University of Arizona. The microprobe was run at 15 Kv and 15 nanoamps sample current.

Stepscans were run from the apparent core of the measured grains to their rims. Due to the lack of resorbed cores in the

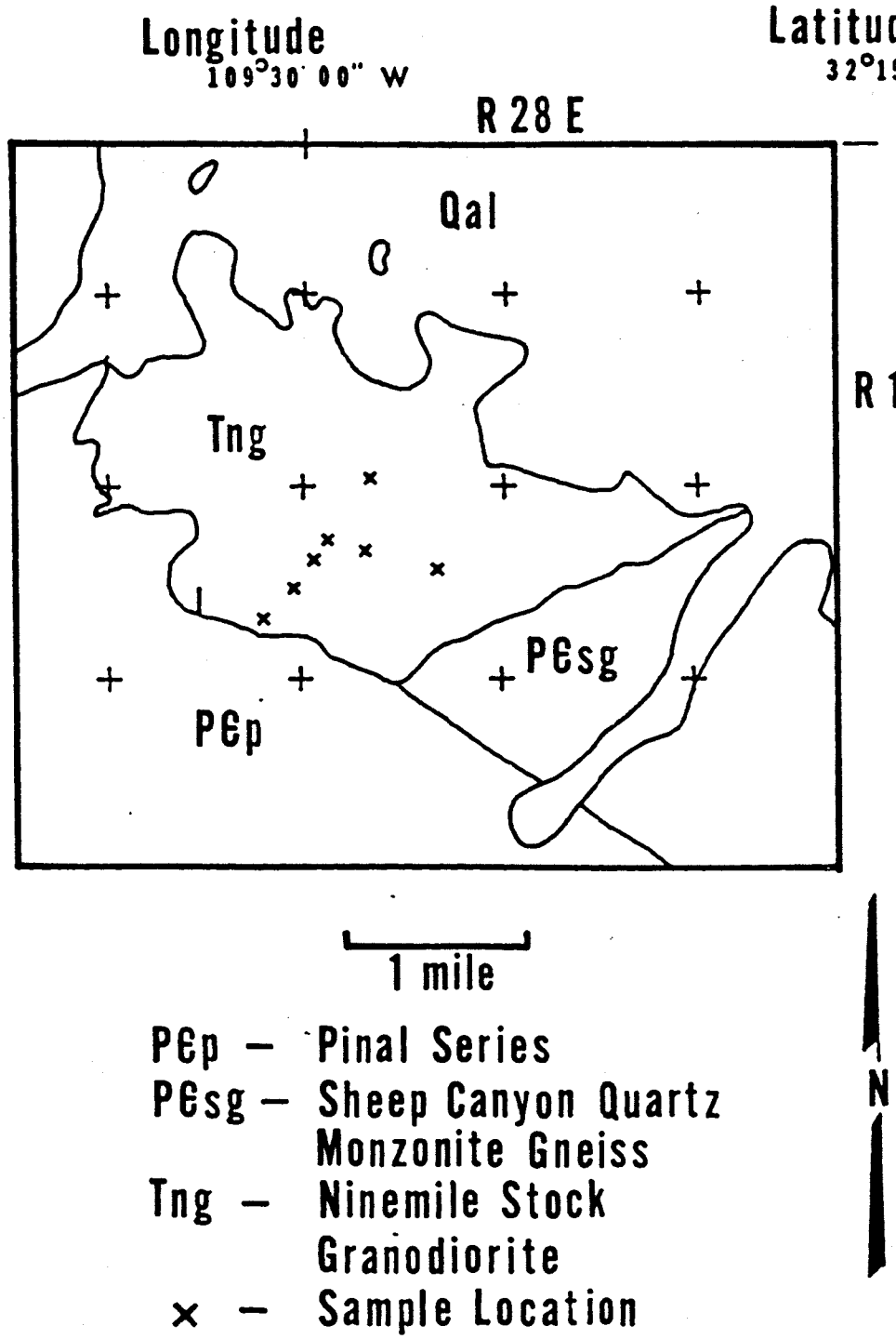

Figure 5: Sample Location Map and General Geology of the Ninemile Stock

plagioclase, it is very difficult to determine if the probe section cuts through the actual compositional core of the grain. Many grains probably have been cut at some position between the rim and the core. To assume that the cores of all the plagioclase grains will have an anorthite content greater than some value also requires the assumption that all of the plagioclase nucleated under the same conditions throughout the pluton, which is very unlikely. Some profiles, where the center of the grain was identified by resorbtion outlines, show core values that have lower An values than zones midway to the rim as shown by Weibe (1968). Identifying an arbitrary minimum limit, or assuming the highest value to be the core, makes it possible to misinterpret an outer layer as the core. Thus, grains were chosen for analysis simply if they displayed strong optical zoning without attempting to identify ones cut through the compositional core.

The program TRAV, developed by Tom Teska and Paul Welber, was used to run the stepscans. The electron beam was stepped across the sample incrementally by a motorized x-y stage. Peak counts were taken for three elements (Si, Al and Ca) for ten seconds at each step. The raw data were recorded on paper tape.

A spot analysis of the grain was taken before and after each traverse. The first spot analysis was used in the reduction of the data. The second analysis was used to test for beam drift. The estimated analytical error is ± 5 mole percent anorthite.

Data Reduction

The raw data from the microprobe stepscans were reduced using a program, STPCRT, designed and written by Paul Welber and Dr. Timothy Loomis. The program was run on a DEC 10 interactive system at The University of Arizona.

First the raw data was transferred from the paper tape to disk storage using an optical reader at The University of Arizona Computer Center. The STPCRT program then converted the total counts to counts per second and subtracted the background counts for each element. The background counts were measured by the pretraverse spot analysis. This left background corrected counts per second. Assuming a linear relationship between the cation formula number and the counts per second, as shown by Welber (1977), the cation formula number can be calculated for each spot in the following manner:

CFN(I) = CTS/SEC(I) X CFN(J)/(CTS/SEC(J))

CFN(I) = cation formula number at the point on the traverse

CTS/SEC(I) = corrected counts per second from the traverse

CFN(J) = cation formula number at the spot analysis

CTS/SEC(J) = corrected counts per second from the spot analysis.

Bad data points due to cracks, alteration, or inclusions were identified by a stoichiometric test. If the CFN for Ca is subtracted from that for Al the remainder should be one. The

points that are significantly different from one can be zeroed in the data file.

An mole percent is calculated for plotting by simply multiplying the CFN(Ca) by 100.

Profiles of An mole percent were then plotted on a tektronix graphics terminal. The profiles were plotted as anorthite mole percent vs. distance in microns. On the plots the center of the grain is at zero and the rim is to the right. Bad data points are left as blanks in the plots.

DISCUSSION OF PLUTONIC CRYSTALLIZATION

"Equilibrium" Crystallization

Bowen (1913) described a simple system for albite-anorthite crystal-melt equilibria assuming ideal mixing for albite and anorthite in the melt and in plagioclase. By assuming an activity model for the interaction of H_2O with plagioclase melts the system can be expanded to albite-anorthite-H_2O.

The major variables for the system are temperature, pressure, and composition. If the composition and pressure are fixed the temperatures of the solidus and liquidus are defined. In the dry system, pressure will have a small effect on the liquidus. Pressure becomes much more important for a water saturated melt. In a saturated melt, the increased solubility at high pressures allows the water content to increase. An increase in the water content of a plagioclase melt will cause the equilibrium melting loop to shift to lower temperatures in a subparallel manner. A change in the shape of the loop caused by the shifting will show as an opening of the loop for an ideal simple system (Loomis, 1979). The fact that water content can affect the equilibrium melting loop shows that it is a very important variable for the plagioclase system.

In nature plutons are probably not adequately represented by simple systems. To develop a thermodynamic model of a complex melt it would be necessary to know the non-ideal mixing characteristics of the components and the thermodynamic data for the melts.

Not enough is known about the above at present to calculate an accurate model, but empirical models such as the one developed by Loomis (1979) are useful.

The empirical model shows almost the same qualitative features as does the simple system, except for one trend. In the empirical model of Loomis (1979), the addition of water causes a very small closing of the loop instead of an opening, along with the lowering of the position of the loop (figure 6). As a result of this, the crystal composition is not very sensitive to the water content, and significant error would be encountered by using the simple system instead of the empirical model (Loomis, 1979). The small decrease of anorthite content and large decrease of liquidus temperature caused by an increasing mole fraction of water are shown by calculations with this empirical model (figure 7).

Rayleigh fractional crystallization (Rayleigh, 1896) is one possible process to create a zoned crystal. Rayleigh fractionation models assume that (1) diffusion and transfer of components in the melt is fast enough to maintain a homogenous melt, (2) that intracrystalline diffusion is insignificant, and (3) that the crystallizing layer of plagioclase is in equilibrium with the melt. I refer to this as an "equilibrium" process since the last layer on the crystal is in equilibrium with the melt even though the whole system is not in equilibrium. The zoning created by this mechanism in the crystal as it grows would be solely due to depletion of the

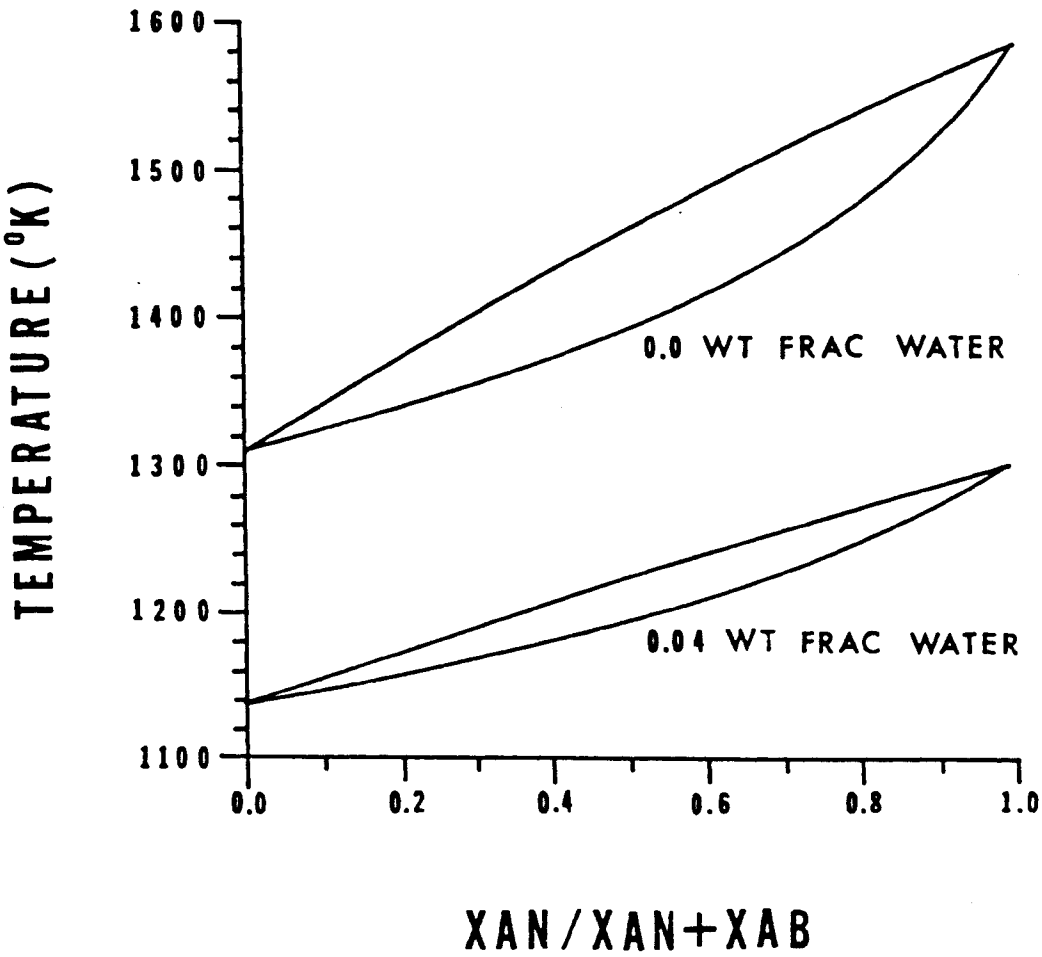

Figure 6: Illustration of the Subparallel Depression of the Liquidas Loop by an Increase of Water in the Melt.--Figure calculated from an empirical model of plagioclase equilibrium (Loomis, 1979). The total plagioclase for the calculations was 49.48% of the melt.

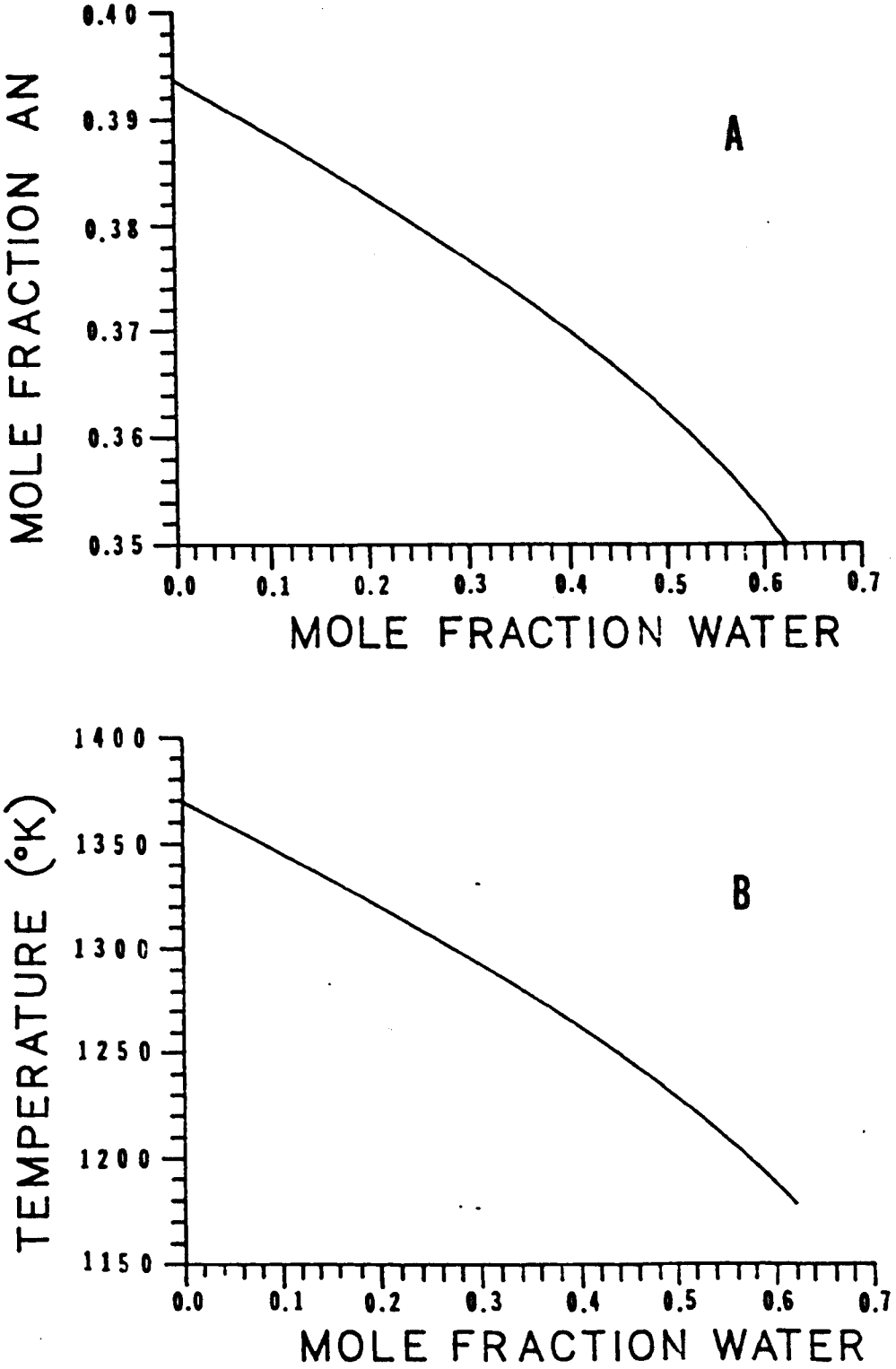

Figure 7: Diagrams Showing the Effects of Water on Temperature and Crystal Composition.--The effect of melt water content on (A) equilibrium crystal composition and (B) liquidus temperature for the Rocky Hill bulk composition, according to the empirical model of Loomis (1979).

melt. The "equilibrium" composition of the plagioclase being removed from the melt will shift the melt composition to the albite side. This shift will also make the subsequent "equilibrium" crystal composition more albitic, giving rise to the zoning.

The shape of the zoning profile generated by dry Rayleigh fractionation is distinctive. The core of the profile is a high flat plateau with an anorthite value corresponding to that of the equilibrium crystal composition for the bulk composition of the melt. Most of the zoning is in the outer half of the profile and consists only of normal zoning. The whole profile is smooth with a lack of compositional breaks, due to the "equilibrium" nature of the crystallization process. A gradual depletion process can not be called on to give a compositional discontinuity. The end composition will reach zero mole percent anorthite. Figure 8 shows a computed zoning profile for the approximate Ninemile Stock composition from the program, MASBAL, designed and written by Loomis. The discussion of the data used to calculate this curve is presented in a section below.

If the initial magma is considered to be homogeneous, then the most important controlling feature in this model is how well the magma mixes. This feature can be considered in two end member examples, one being referred to as isolated crystallization and the other as communicating crystallization. In the isolated case, a plagioclase crystal can be thought of as growing from a packet of

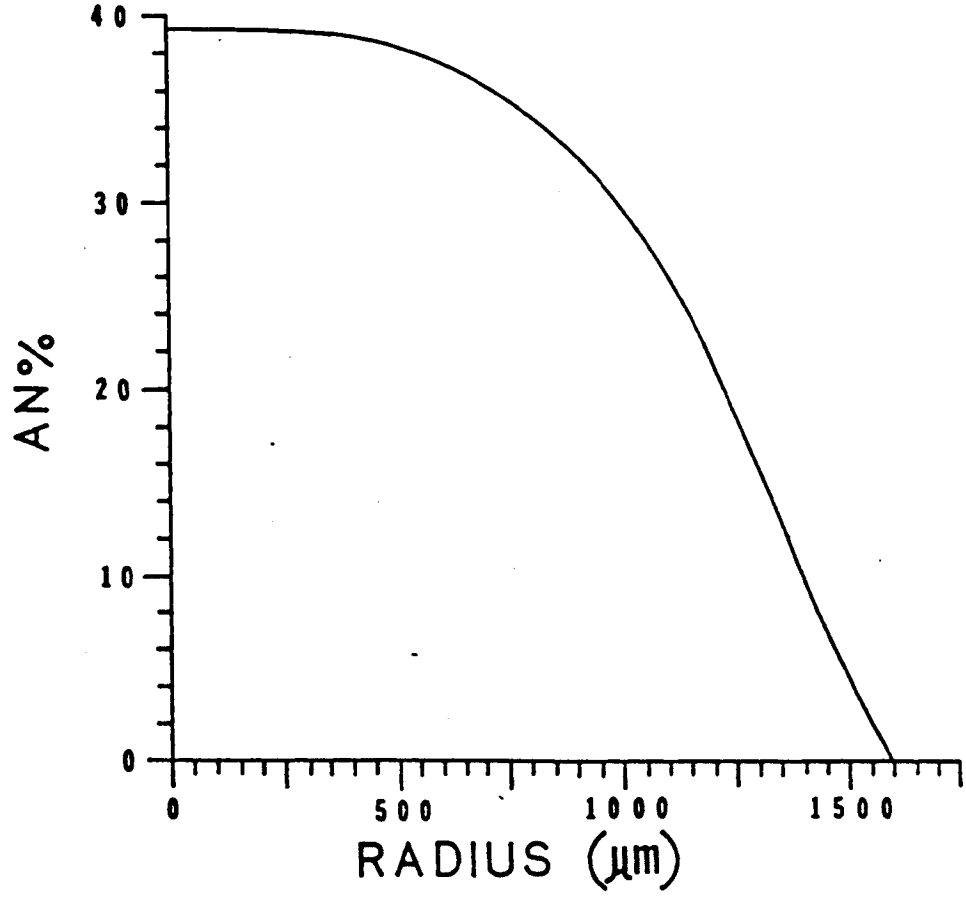

Figure 8: Rayleigh Fractionation Profile Calculated for the Bulk Composition of the Ninemile Stock.--Calculation was made assuming the melt to have been dry.

melt that does not interact with any melt affected by any other plagioclase grain. In the communicating case, the opposite will be true where the melt adjacent to the growing crystal will mix or exchange with melt that is adjacent to other plagioclase crystals. The difference between the two is merely a matter of the scale on which the melt mixes.

In the isolated case, the cores should all be of the "equilibrium" composition for the initial melt, assuming each packet of melt to be of the same initial composition. Due to the lack of interaction between the packets of melt, no depletion effect will change the composition of the melt that the core nucleates from. On the other hand, the rims may show a range of compositions. The last segment of each profile should reflect the type of mineral that was growing adjacent to the plagioclase. For example, the profile rim composition next to quartz would be different from that next to orthoclase. Each mineral affects the melt differently and it would be expected that the rim compositions would be dependent on the composition of the adjacent mineral and its competition with plagioclase for components in the melt.

Due to exchange throughout the melt in the communicating case, variable core compositions would be expected for plagioclase nucleating at different times. With the growth of early plagioclase and a bulk depletion in plagioclase components, late nucleating plagioclase will show more sodic core compositions than the

early ones. In the perfectly communicating case, the rim compositions would be expected to be constant and show no dependence on the adjacent mineral. With perfect communication any competition effects at the rim of a plagioclase grain would be spread over the whole melt.

These are limiting cases. The natural system will undoubtedly be in-between. If the isolated case is carried too far, mixing within each packet of melt will not be effective enough to allow enough exchange of components to allow crystal growth at all. There is a finite limit to the distance over which components will exchange, especially as crystallization becomes complete, so a perfect communicating case will not be possible. Still, enough characteristics of the end member cases should be measurable to be able to distinguish which of these cases is more closely approached. Even under conditions of disequilibrium crystallization, these features should be apparent and useful.

Disequilibrium Crystallization

The conditions required by the assumptions of Rayleigh fractional crystallization models are only occasionally approximated in natural systems. Diffusion in natural systems will probably not be effective enough to keep the melt homogenous and "equilibrium conditions" will not be maintained. In this case the growth of a zoned mineral in an igneous system will be a disequilibrium process.

A certain amount of supersaturation is required for both nucleation and crystal growth (for example, Kirkpatrick, 1976). This will occur when the magma becomes supercooled with respect to some phase. The amount that a melt is supercooled by is described as undercooling, ΔT. Undercooling is the difference between the liquidus temperature for the melt composition and the actual temperature of the melt (figure 9).

The dependence of the nucleation rate on undercooling is different from the dependence shown by the crystallization rate. Both will increase to a maximum with increasing undercooling and then decrease with a further increase in undercooling (Kirkpatrick, 1976). The crystallizing rate will reach a maximum at lower values of undercooling than will the nucleation rate (figure 10).

Undercooling can be thought of as providing the driving force necessary for crystallization. Some of the many processes that undercooling must overcome or provide energy for are interface attachment kinetics, excess energy of crystal lattice defects, and excess energy of inclusions (Lofgren, 1974).

The composition of the crystal growing from the melt is very dependent on undercooling. As would be expected, as the temperature drops below the liquidus the crystal composition crystallizing will deviate from the equilibrium crystal composition. In the plagioclase system, as the ΔT increases the composition of the crystallizing crystal is very hard to predict due to uncertainty in

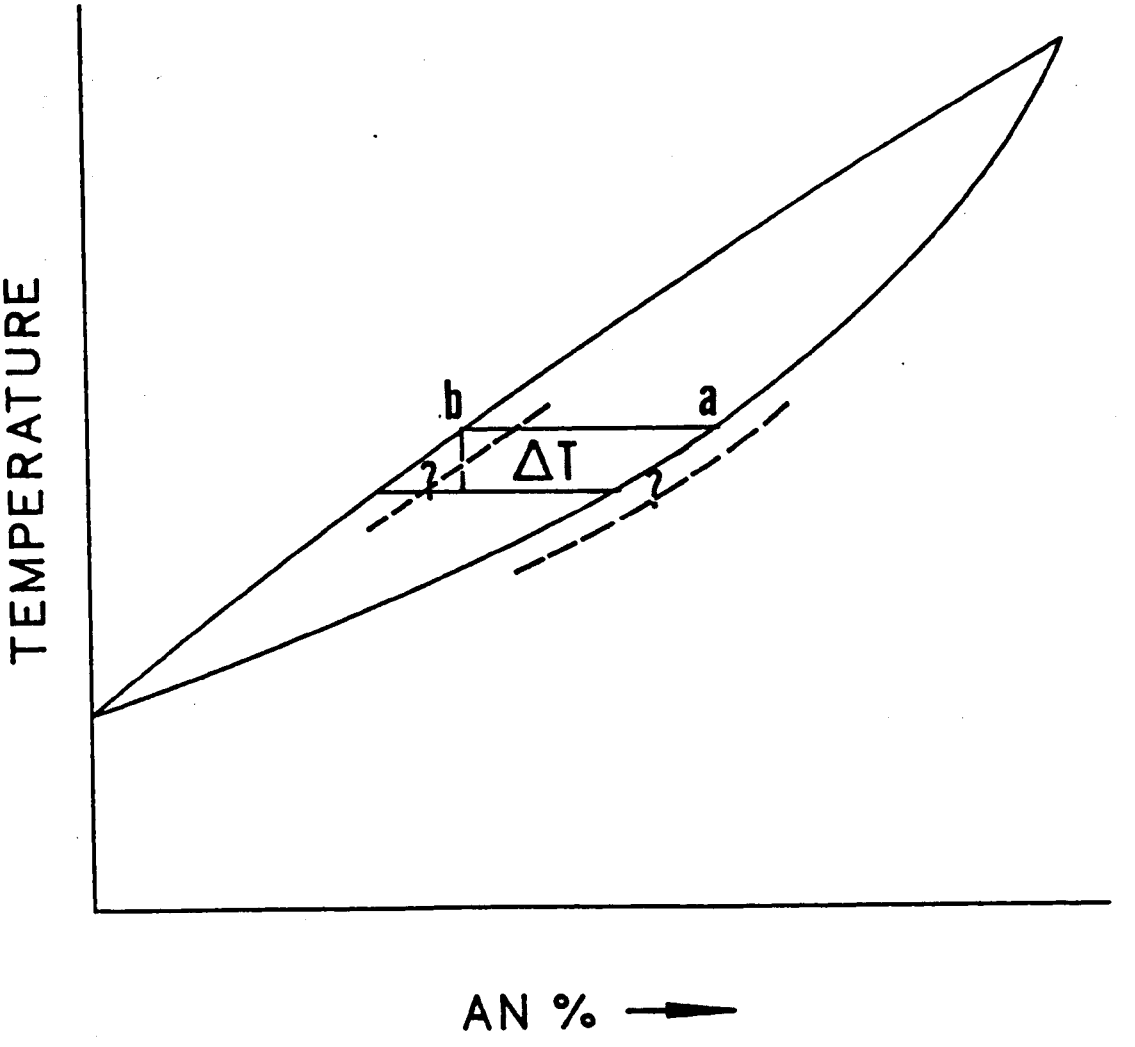

Figure 9: Illustration Showing the Effect of ΔT on Crystal Composition.--A. is the equilibrium crystal composition for the bulk composition b. The difference between the Equilibrium Crystallization Temperature and the actual temperature shown by the lower cross line is ΔT. The crystal composition is changed by ΔT, but the actual value depends on the non-equilibrium partitioning model used. The change from the equilibrium partitioning to non-equilibrium partitioning is shown by the dashed line.

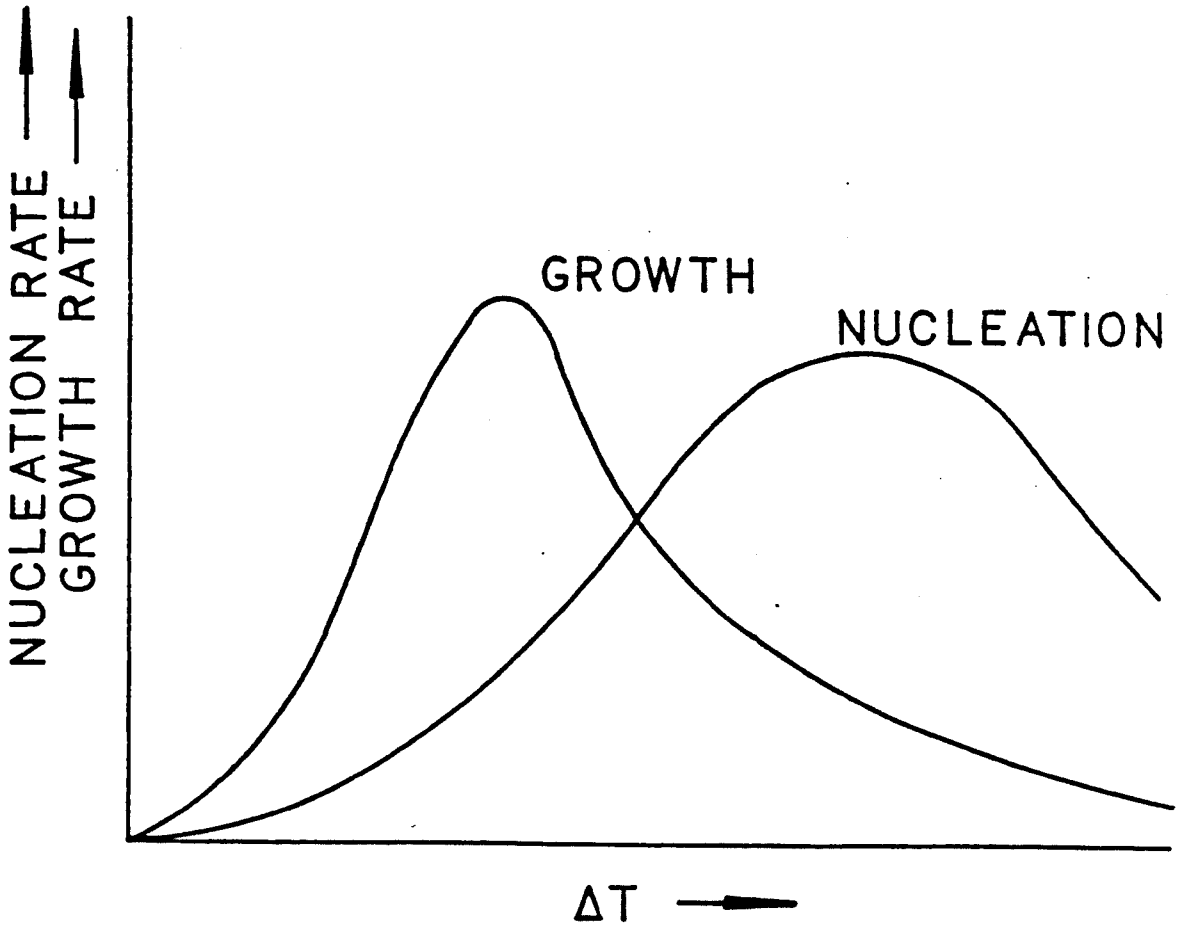

Figure 10: Schematic Diagram Illustrating the Different Relations of Nucleation and Growth Rate to Undercooling

non-equilibrium partitioning models, but the composition most likely becomes more albite-rich (Loomis, ms). The actual deviation of the crystal composition from the equilibrium composition shows almost a linear relationship with ΔT (Loomis, ms).

Increasing and decreasing the ΔT as the crystal grows can cause zoning of a complex nature even with a constantly uniform bulk composition of melt at the interface. Sudden changes in ΔT can even cause compositional breaks in zoning profiles. Some things that can cause sudden increases in ΔT are the chilling effect of the surrounding country rock on a pluton as it is emplaced, pressure release of volatiles from a pluton, or other mechanisms that cause quick increase in cooling rates.

Boundary Layer Effects

Bottinga, Kudo, and Weill (1966) reported measuring compositional gradients in the boundary layers adjacent to plagioclase in volcanic glass. They believed the gradients in the glass could be regarded to be representative of conditions present during crystallization. If the velocity of crystal growth is faster than that of diffusion in the melt, then at the interface of a crystal growing from a melt, a layer will exist in which components that are included preferentially into the crystal structure are depleted, whereas components that are not preferentially included in the crystal will be enriched in this layer. Compositional gradients

will persist in this layer if the growth rate causes the depletion and enrichment to proceed faster than diffusion can smooth them out. For plagioclase crystal growth from a plagioclase melt, water would be enriched and anorthite depleted.

The gradients will have a definite effect on crystal growth. The water built up at the interface will cause a lowering of the liquidus temperature in the boundary layer and, thus, a lowering of the ΔT that a crystal face experiences. The build up of albite and depletion of anorthite at the boundary layer will provide a shift in composition of the melt that the crystal face is in contact with. The compositional effect will also have the effect of lowering the ΔT at the interface.

Large Scale Mechanisms of Pluton Crystallization

Other mechanisms that affect crystal growth are large scale processes such as convection and pluton-wide compositional changes.

As a pluton crystallizes from its contact inward, the remaining magma may become progressively enriched in water. The crystallization of anhydrous phases will tend to increase the water content of the magma if the magma is not dry. As long as water loss through the crystallized wall of the pluton is not rapid, either diffusion or magma convection will move water from the build up at the magma chamber wall to the magma, causing the magma to be enriched in water. Magma convection is more effective than

diffusion for concentrating the water into the core. This concentration of water can have a profound effect on crystallization.

Fracturing is another process which is very important to the crystallization of a pluton, especially through its effect on volatiles. Hydrofracturing caused by a build up of water pressure will cause a very quick release of that pressure and a switch to adiabatic crystallization. The change in crystallization due to an increase in ΔT will cause a change in rock textures. Fracturing can also be the result of thermal effects (Knapp, 1978) which will cause both tension and shear fractures. These fractures would less likely cause the release of volatile pressure, but if they did the result would be the same.

The build up of water to the saturation point could cause a porphyritic texture in the center of the pluton. A porphyritic texture can form without a fracturing event, but the fracturing event will enhance the undercooling and can promote the formation of a porphyritic texture if large crystals previously formed.

A consequence of a rapidly convecting magma is that it will cool more quickly than a statically cooling pluton because a convecting pluton tends to maintain a higher thermal gradient. The mixing magma will keep a constant temperature as long as a large volume is mixing and this allows the maintenance of that high gradient. The thermal buffering caused by a large convecting core of a pluton can give a fairly uniform increase in ΔT as the magma

freezes onto the wall of the pluton. This effect will only work while the convecting magma is large enough to provide an effective heat source.

PLAGIOCLASE ZONING IN THE NINEMILE STOCK

Probably the most useful set of data for a study relating plagioclase zoning to the crystallization history of a pluton is a set of zoning profiles of plagioclase from samples that represent all of the exposed parts of the pluton. Zoning profiles will contain a large amount of information that can be interpreted by the theories discussed above.

Variation of Zoning Profiles within a Sample

Each sample showed a range of values for An content of the cores of the plagioclase grains. The high for each sample was a core of around 40% An. One sample had a core of 52% An, but it was the only grain analyzed with a visibly resorbed core. As noted before, the general lack of resorbed cores makes it hard to tell if the probe section actually cuts the core of the grain. The range of core compositions could be due to cutting effects alone, but the possibility of depletion and late nucleation could also be a cause of some of the variation.

The rim compositions have no complications associated with their measurement due to cutting effects. The average rim composition was 14.27% An (figure 12). The data set had a one sigma value of 3.22% An for the rim values, which is close to the accuracy of the microprobe measurement of rim compositions. Because the rim compositions were consistently close to this value in each sample

they had to be independent of the mineral adjacent to the spot where the profile ended.

The average An content was calculated for each profile by integration and a range of values was found in each sample. This average value will be affected by cutting problems since it is very important to hit the core of the grain with the beginning of the profile. This is shown by the positive correlation between core composition and the average An content for that grain (figure 11).

The data seem to support the communicating melt model over that of the isolated melt model for crystal growth. The observed positive correlation between the average An content and the core composition can not distinguish between the two cases due to the uncertainty of whether the probe section cuts the core of the grain or not. The plot can not distinguish between this and the possibility of depletion together with late nucleation. However, the tight grouping of the rim compositions and the lack of variation of the rim composition with adjacent mineral type is convincing support of the communicating model (figure 12).

Profile Variation within the Pluton

As with the core and rim values and the average An content of the plagioclase crystal cores, the shapes of the profiles show no systematic change with position in the pluton. Similarities exist between profiles that start out at the same apparent core values throughout the exposed parts of the pluton (figure 13).

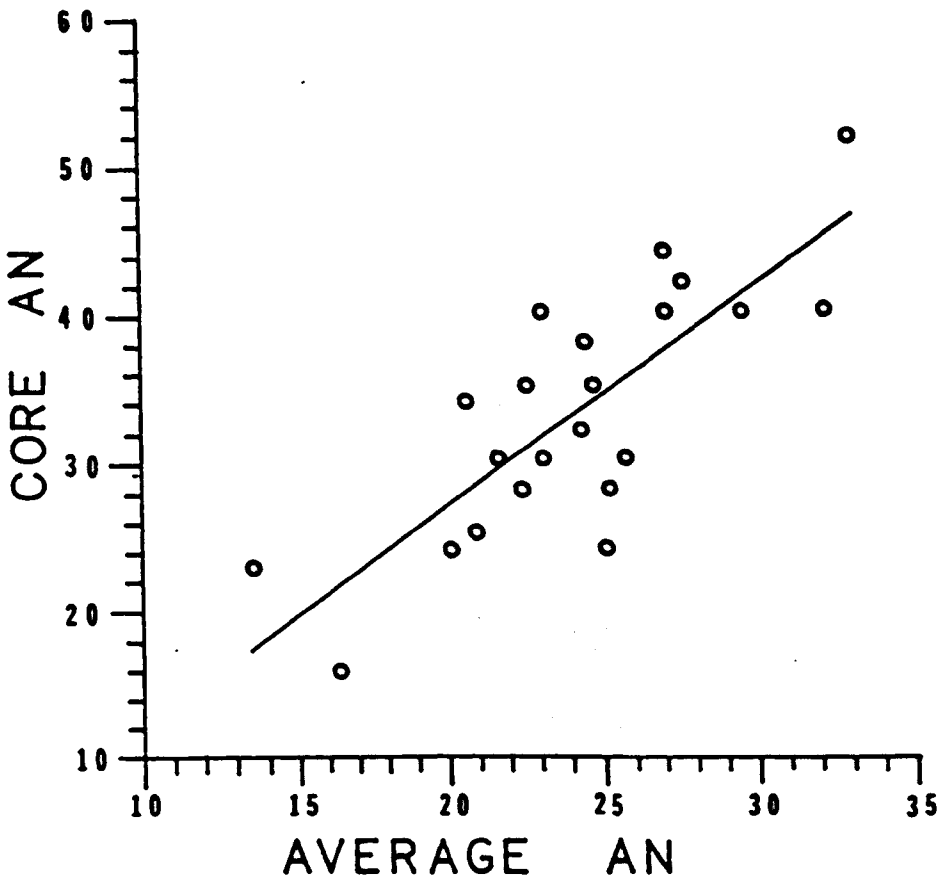

Figure 11: Diagram Showing the Positive Correlation between Average An Content and Core Composition

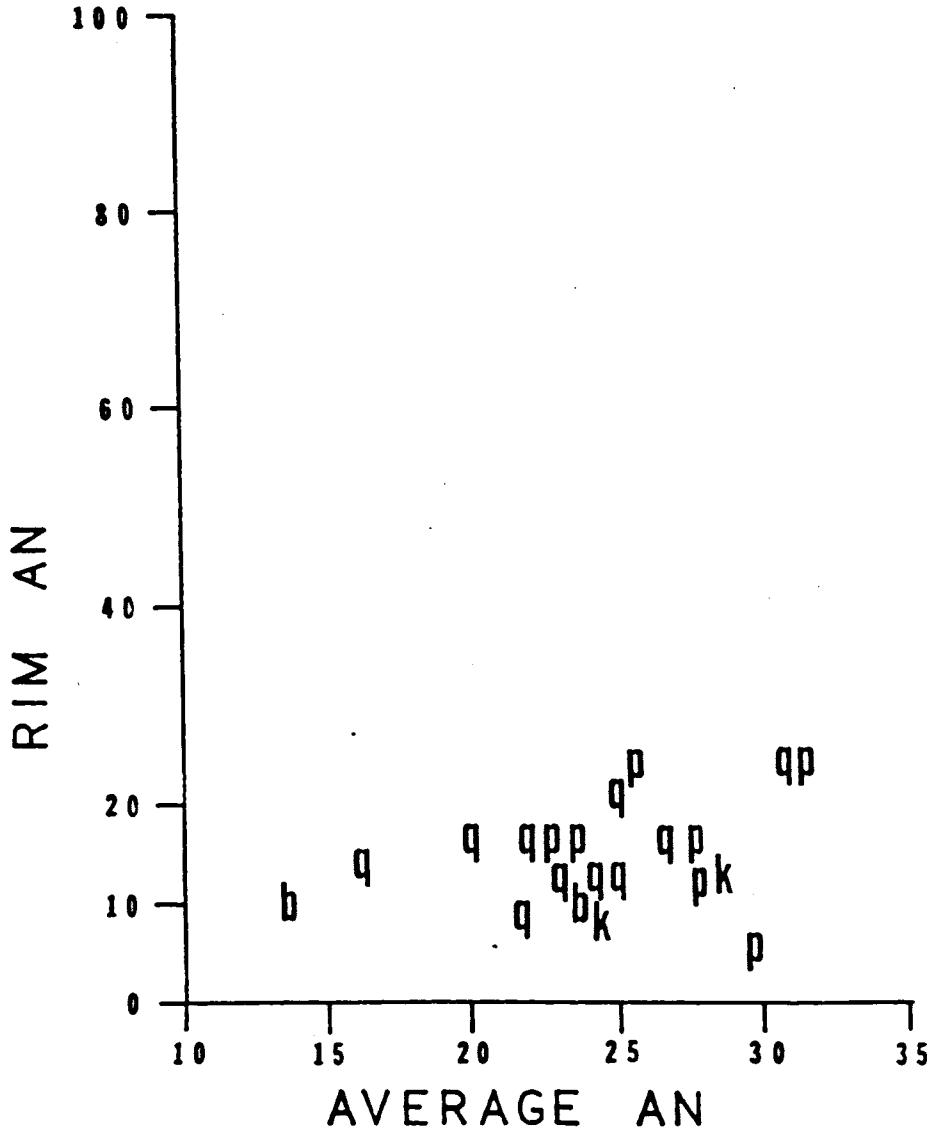

Figure 12: Diagram Showing the Tight Grouping of Rim Values and the Lack of Dependence on Adjacent Minerals.-- "q" represents quartz as the mineral the traverse ended in, p for plagioclase, b for biotite and k for orthoclase.

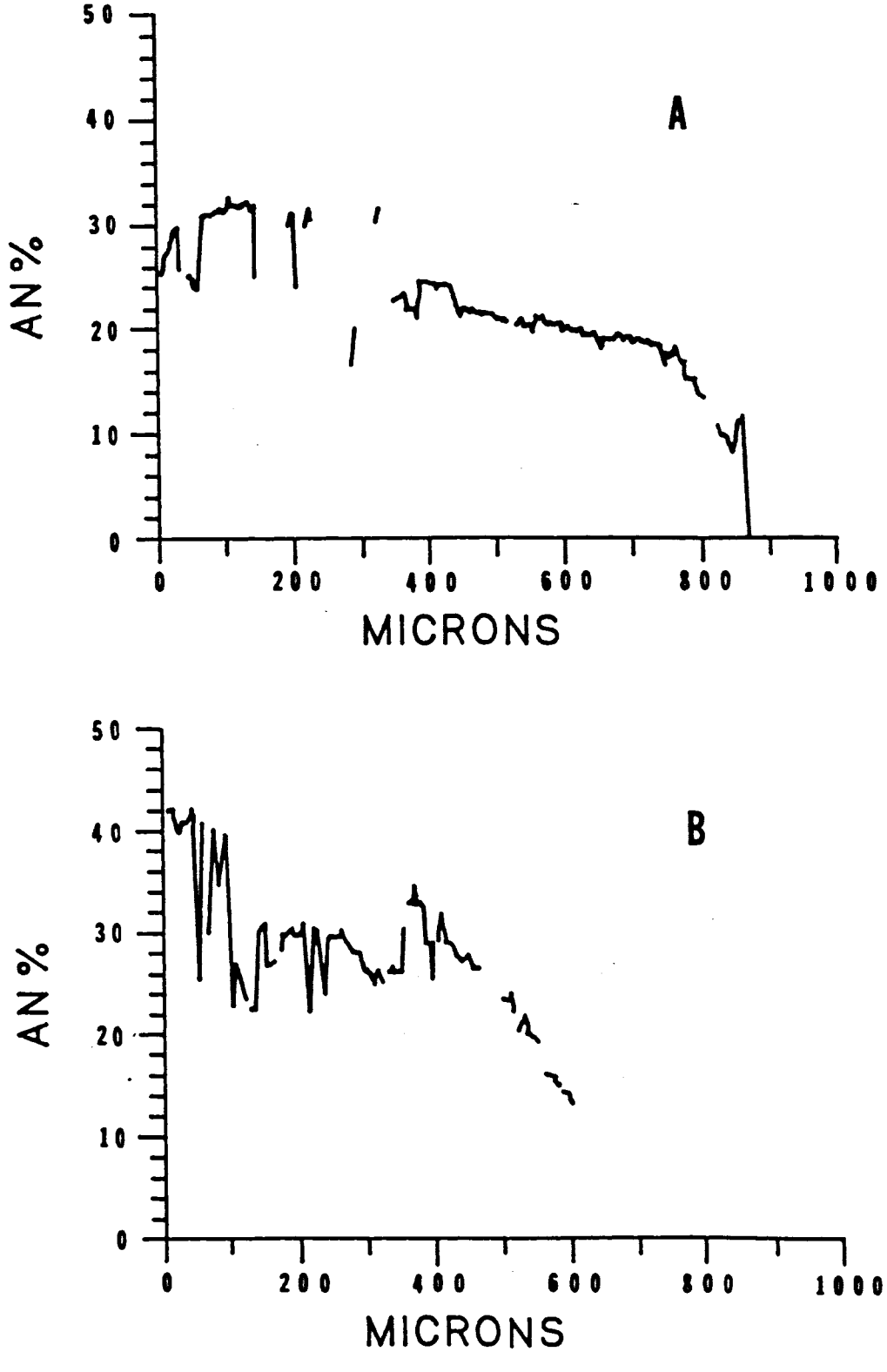

Figure 13: Diagrams Showing the Similarity of Profiles Throughout the Pluton

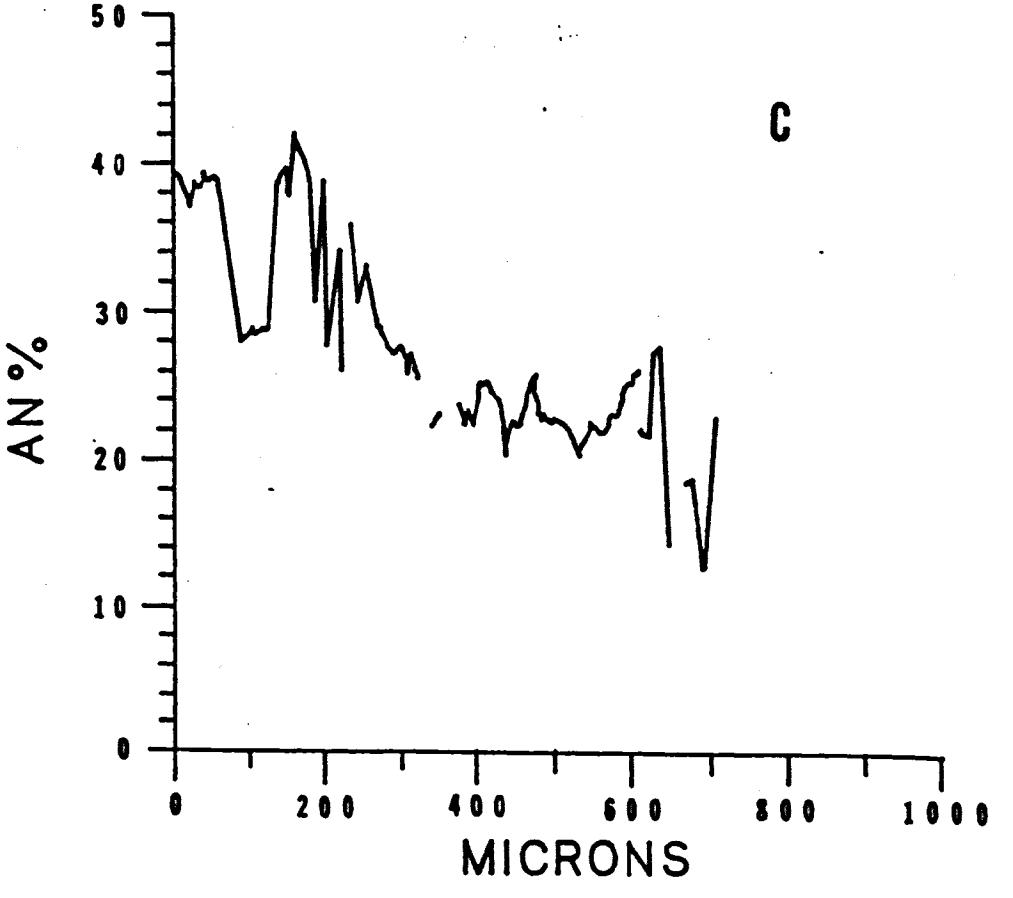

Figure 13--Continued

Relatively flat cores with occasional drops in An content are very common among the profiles that start at values above 30% An (figure 13). The plateaus are of variable length and are followed by a sharp compositional break. These breaks are approximately 10% An in magnitude. Following the compositional break the general trend is one of normal zoning, although the profiles show breaks in the normal zoning of plateaus and discrete jumps in An content. These features appear in combination or alone.

The profiles that have lower apparent core values may or may not have flat cores. Those that do not have the flat cores have morphologies that are quite similar to the outer portions of the profiles just described. The profiles that start with lower An content cores could either be the result of cutting problems or late nucleation coupled with depletion. If it is late nucleation then they resemble the outer parts of the other profiles because both grew at the same time.

Superimposed on every portion of each profile is a very fine scale oscillatory zonation. Some profiles show less of it due to a large step distance used in the stepscan. This small scale zoning ranges from two to four percent An, which is close to the limit of the microprobe accuracy.

The general lack of systematic variation of zoning profiles as a function of location in the pluton suggests a similar ΔT history for all samples. Since ΔT depends upon temperature and the

liquidus, and the liquidus depends on the water content, this observation argues against significant water build up within the part of the pluton that was sampled. The lack of a large chill zone may also indicate some sort of thermal buffering mechanism, such as rapid convection. A buffering mechanism would also help provide a uniform cooling history from sample to sample.

The mechanism of crystallization of plagioclase, in terms of "equilibrium" and disequilibrium processes, can be elucidated by comparison of the observed profiles with the theoretical Rayleigh fractionation curve (figure 4).

The calculation of the fractionation curve involved several uncertainties. These uncertainties were nucleation history, water content, and bulk composition of the anhydrous melt. The nucleation density was estimated from petrographic observations. The original water content is unknown, but changes in water content will only affect the starting anorthite content for the curve through its effect on the liquidus. The shape of the curve will be essentially the same, so the calculations were made for a dry melt. The analysis for the bulk composition was only semi-quantitative. Its lack of accuracy will have a quantitative effect on the curve, but the morphology will not be profoundly affected. The shape of the curve is most strongly determined by the An-Ab ratio in the crystal being higher than in the melt. Bulk composition and water content of the melt will have an effect on the curve, but will not reverse the preferential partitioning of anorthite into the crystal.

The Rayleigh fractionation profile calculated for the Ninemile Stock composition gives a flat core of 39% An, in probably fortuitous agreement with the core compositions of grains with high An compositional plateaus. The grains with high plateaus seem to have experienced close to "equilibrium" crystallization in the early parts of their growth. This "equilibrium" growth is ended by the formation of the large compositional breaks and other disequilibrium features that make the profiles rough. The amount that the profiles drop away from the Rayleigh fractionation curve is a good indicator of ΔT, since there is almost a linear relationship between ΔT and deviation from equilibrium (Loomis, ms). Thus, disequilibrium crystallization processes record sharp change of ΔT during growth. The apparent randomness of these details argue for an element of local control. A complex combination of competition for components, water build up, and limited effective communication range could easily give rise to the variability of the profiles even within one of these samples (for example, figure 14).

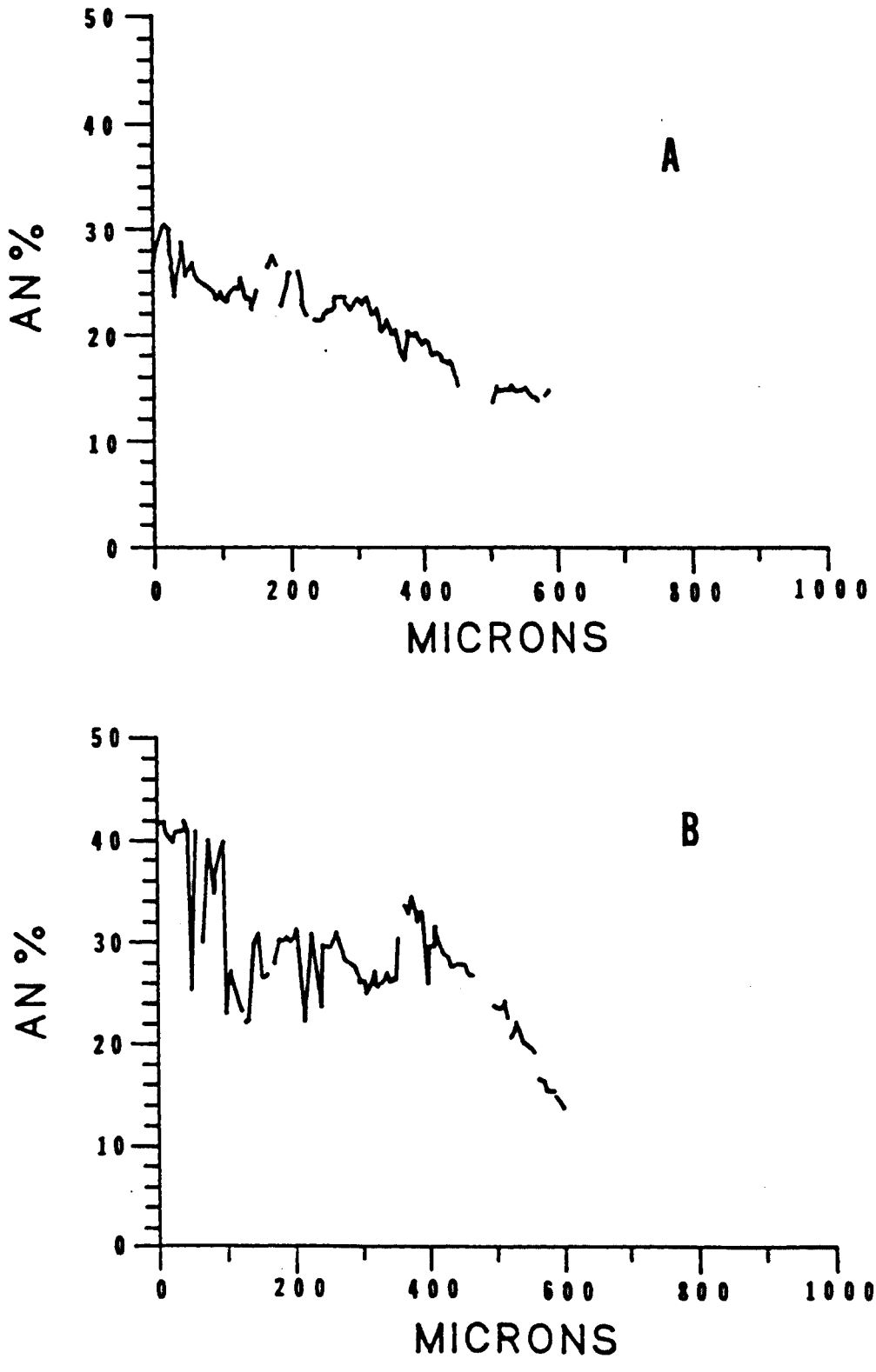

Figure 14: Diagrams Showing the Variation of Profiles Within One Sample

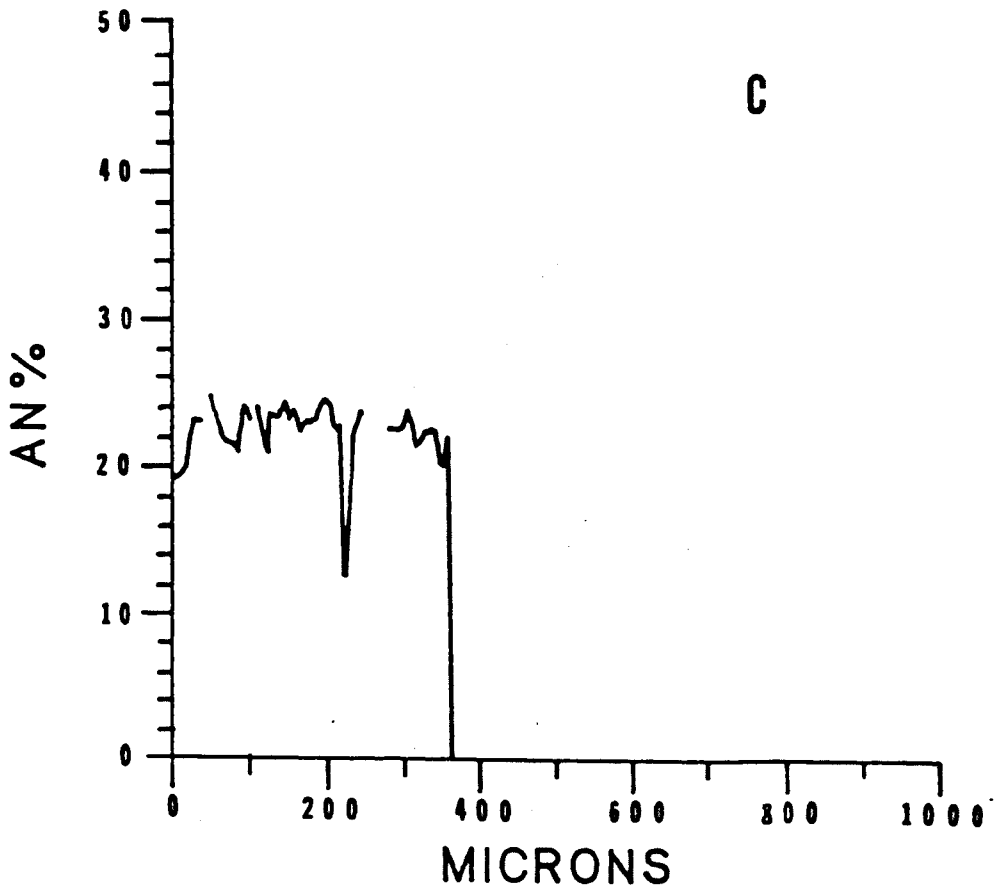

Figure 14--Continued

CONCLUSIONS

The lack of variation in the zoning across the pluton can be the result of several different factors, including thermal buffering, erosion, and a dry initial magma.

Changes in conditions of crystallization should occur rapidly as you move into the pluton from the contact, but the thin chill zone at the contact, coarse-grained texture of the pluton and the lack of change in the plagioclase profiles argues that this change was restricted to an extremely small distance at the pluton edge. This most likely is the result of some thermal buffering mechanism that kept the ΔT at low and fairly constant values in all of the samples. A mechanism that can keep the cooling rate small will provide an effective buffer against changes in ΔT. Rapid magma convection can achieve this by exchanging hot magma from the chamber interior with the chilled magma at the chamber wall. This will tend to keep a high temperature, and low ΔT, melt at the wall of the chamber for the plagioclase to crystallize from. The high, flat An core composition of some profiles could easily form under conditions caused by convection, and the compositional breaks could form when the crystal becomes attached to the wall of the pluton. As long as rapid convection can provide an effective thermal buffer, plagioclase zoning profiles might show little systematic changes with distance

from the contact. By the time that a convecting central portion of a pluton is too small to provide a thermal buffer, the cooling rate should be slow enough so that the ΔT could remain small. A convecting magma core can cause a thermal buffering that allows similar ΔT of crystallization from close to the contact to the pluton core.

Another way to get similar profiles is for all of the samples to be from approximately the same position in the pluton with respect to the contact. This could be the case if erosion has not exposed the core of the pluton. In the Ninemile Stock this could have easily happened if the sampling traverse ran over one of the dome-like structures.

A water build up does not seem to have occurred to any significant extent in the Ninemile Stock. The systematic profile changes and reverse zoning that indicate a progressive water build up were not observed in the Stock. A buried core of the pluton could possibly show the effects of water build up, but the data gathered gave no indication of one.

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