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PLAGIOCLASE STRATIGRAPHY: A RECORD OF MAGMATIC CONDITIONS AND EVENTS IN A GRANITE STOCK

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ABSTRACT. Details of plagioclase zoning were correlated throughout a 3 square mile quartz monzonite stock located on Mount Pilchuck, 40 miles northeast of Seattle, Washington. A typical sequence of zones occurs in all phenocrysts: andesine cores with delicate oscillatory zoning, core-rim boundaries marked by sharp drops of eight to fifteen percent An, and rims normally zoned from An_{28} to about An_{15}. Embayments and patches of rim composition occur in most cores. The discontinuities between cores and rims probably represent a period of core resorption and non-crystallization caused by decrease in pressure during intrusion.

Coarse oscillations within cores, measuring three to seven percent An, probably record convection and turbulence in an inhomogeneous magma during the early stages of crystallization. The nearly constant composition of the outermost core zones indicates homogenization of the magma prior to and during intrusion. Zones immediately within the outermost core show low compositional correlation and indicate a high degree of crystal mixing.

Plagioclase zoning appears to be a useful record of conditions and events occurring within granitic magmas.

INTRODUCTION

Plagioclase zoning is a stratigraphic record of magmatic events occurring during crystallization. Assuming a primary origin for the zoning, the laws of cross-cutting and superposition are applicable for any single grain. Though difficult to interpret, the zoning is a potentially useful tool for understanding magmatic processes and for recognizing sequences of magmatic events. Interpretation of zoning must be based not only on the study of individual crystals but also on the study of the compositional and sequential variation of zoning throughout the pluton. Any process or event that affected all or a considerable portion of a pluton at a single time during its crystallization should have been recorded on growing plagioclase crystals within the affected region. Recognition of an ubiquitous zone or sequence of zones throughout the pluton may lead to recognition of some widely occurring event. Some events, such as change in pressure, would be essentially instantaneous, and the deposition or resorption recording such an event would be approximately time-correlative throughout the affected region. Those zones or sequences of zones which appear to lack correlation between grains probably result from varying local conditions and events.

This study was undertaken to test the value of plagioclase zoning as an indicator of magmatic history. In order to avoid a great number of possible complications of zoning, I chose a pluton with an apparently simple history for a test study. The Mount Pilchuck quartz monzonite pluton (fig. 1) was appropriate because of its small size, abundant fresh exposures, and apparent compositional homogeneity. There is no field indication of multiple intrusion within the mapped pluton. The quartz monzonite is fine-grained with both feldspars weakly porphyritic. Zoning in many plagioclase phenocrysts can be observed and measured in most thin-sections.

I am indebted to J. A. Vance for initially stimulating an interest in plagioclase zoning. D. U. Wise and H. R. Shaw kindly read and criticized the manuscript.

GENERAL GEOLOGIC SETTING

Mt. Pilchuck is located about 40 miles northeast of Seattle, Washington (fig. 1). The quartz monzonite stock is about 3 square miles in area and is one of several Tertiary granitic plutons that apparently were emplaced at high levels in the crust along a west-northwest-trending fault. The country rock consists of feldspathic graywacke and slaty argillite with minor amounts of chert, limestone, andesitic volcanic rocks, and conglomerate. Limestone lenses located south of the fault contain foraminifera of probable Middle Permian age (Danner, personal commun.) and tentatively all pre-Tertiary rocks south of the fault are considered Paleozoic in age. Danner (ms) included rocks north of the fault in his Mesozoic Olo Mountain unit.

Tertiary rhyolite tuffs and vitrophyres overlie the graywackes and argillites south of the fault with angular uncomformity. These rhyolites are garnet-bearing as are some fine-grained, sheared granitic rocks occurring within parts of the fault zone. Garnet is very scarce within the main pluton, but cordierite is a common accessory mineral. The distribution of garnet-bearing rhyolites near the fault zone suggests that the fault may have controlled the emplacement of both the rhyolites and the granitic rocks. The plutonic and volcanic rocks may be comagmatic. The volcanic rocks are overlain by leaf-bearing Tertiary sandstones, siltstones, and conglomerates which are at least in part continental.

Contact metamorphism reached pyroxene hornfels facies conditions within a few hundred feet of the plutonic contact north of the fault. The contact aureole is absent south of the fault, indicating post-intrusion displacement on the fault.

Granitic dikes account for over a third of the dike zone outlined in figure 1. The widths of the dike zone and contact aureole suggest that the pluton contact dips gently to the southeast and rather more steeply to the north. Dikes are clearly dilative and commonly range in thickness from 1 to 50 feet. Steeply dipping and nearly horizontal dikes are both abundant. Compositions range from granodiorite with calcic plagioclase (An_{60-30}) and only a few percent alkali feldspar to quartz monzonite with more sodic plagioclase (An_{30-15}). Cross- cutting relations consistently appear to indicate that the more calcic dikes are earlier.

METHOD OF STUDY

Field mapping and initial petrography were done in 1962 and 1963 as part of a master's thesis at the University of Washington. Plagioclase zoning was studied during the fall of 1966. I studied several phenocrysts in each of about 70 thin-sections from different specimens throughout the pluton. Most compositions were determined using the Rittmann

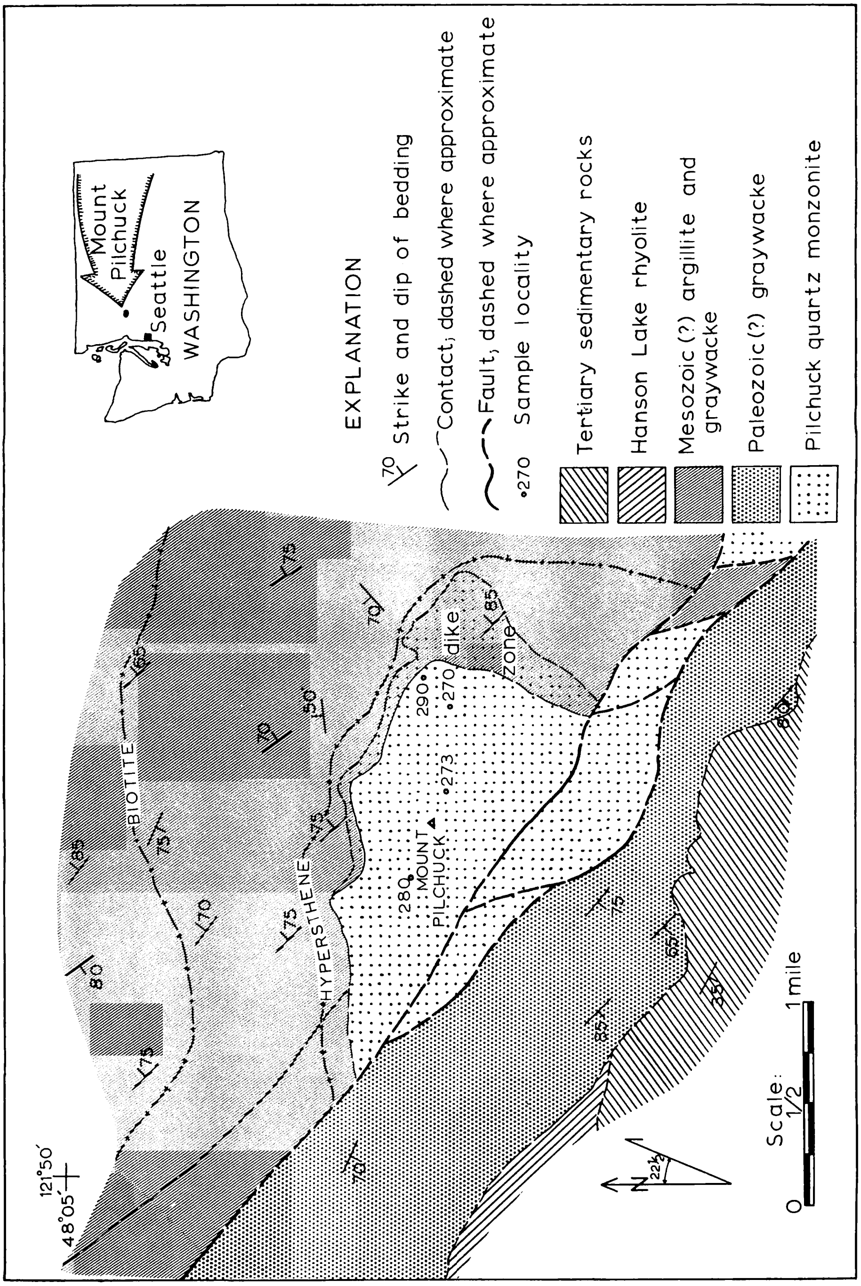

Fig. 1. Geologic and index map of the Mount Pilchuck area, Washington.

Zone Method (Emmons, 1943, p. 115), and many were checked using the techniques described by Slemmons (1962). Determinations of a single zone by both methods rarely differed by more than two percent An. 2V determinations of plagioclase ranging in composition from An_{20} to An_{40} indicate that the plagioclase is low temperature.

Because the boundary between andesine core and oligoclase rim was sharp and apparent in all phenocrysts, the compositions of the outermost core and innermost rim were consistently measured. From 4 to 15 determinations were made in each of 38 thin-sections. Locations of these thin-sections are plotted in figures 4 and 6 beside the average compositional value for each thin section.

Zoning curves, plotting An-content versus distance from center of phenocryst, were made for all measurable grains (4 to 10) in several thin-sections. The locations of these thin-sections are plotted in figure 1. Locality numbers of figure 1 correspond to those of figure 3. Greenwood and McTaggart (1957) discussed the subjective nature of correlating such curves. The value of plotting such curves lies in their aid in comparing simultaneously the range in composition and style of zoning of nearby phenocrysts and emphasizing those aspects of zoning that are relatively constant.

PETROGRAPHY

The quartz monzonite is fine-grained and hypidiomorphic with plagioclase and alkali feldspar phenocrysts up to 2 mm in length. The average of ten modes is: quartz 34.8 percent, alkali feldspar 36.0 percent, plagioclase 23.6 percent, and biotite 5.2 percent. Standard deviations for each respectively are 1.8, 3.2, 3.5, and 1.3. Accessory minerals include: cordierite, zircon, apatite, garnet, and tourmaline in total amounts less than 1 percent.

Perthitic alkali feldspar occurs as subhedral phenocrysts and as anhedral grains interstitial to plagioclase and quartz. Its $2V_X$ ranges from about 35° to 70°, and cross-hatch twinning is almost entirely absent. Quartz occurs interstitially and as small equant euhedral crystals included in alkali-feldspar. Tabular biotite is less than 1 mm in long dimension and commonly has euhedral terminations. Plagioclase phenocrysts have oscillatory-zoned cores of andesine and rims of oligoclase normally zoned from An_{28} to about An_{15}. Different phenocrysts have average core compositions ranging between An_{45} and An_{30}. For the entire pluton the average plagioclase composition is very near $An_{28\text{-}30}$. Throughout most of the pluton the ratio of core to rim is generally near 1:1. Extreme values for the core-rim ratio occur in some dikes. Core composition averages about An_{38}, and rim composition averages about An_{20}. Plagioclase of rim composition occurs interstitially and as normally zoned subhedral inclusions in alkali-feldspar.

Plagioclase appears to be the earliest major crystalline phase. The time of initial biotite crystallization is uncertain, though it was definitely crystallizing during deposition of plagioclase rims. A greatly increased nucleation rate for plagioclase and quartz appears to coincide with the time of initial rim crystallization. The lack of plagioclase inclusions with core composition in alkali-feldspar may indicate that alkali-feldspar did not begin crystallizing abundantly until the crystallization of plagioclase rims began.

TYPICAL ZONAL SEQUENCES

Although details of zoning vary in different phenocrysts, the major aspects of the zonal sequences illustrated in figure 2 occur in nearly all phenocrysts. The most prominent feature of the zonal sequence, apparent in all phenocrysts, is the abrupt decrease in An-content marking the boundary between core and rim. The discontinuity of the core-rim boundary is further marked, in most phenocrysts, by irregular embayments and patches of the more sodic rims within the cores (fig. 2A). The core-rim discontinuity is most likely a record of non-crystallization and partial resorption of the cores. This texture has all of the characteristics of patchy zoning described and interpreted by Vance (1965). Many of the criteria Vance listed as evidence for partial resorption are consistently present in these phenocrysts: (1) rim and patches have the same composition and zoning, (2) the patches and embayments are normally

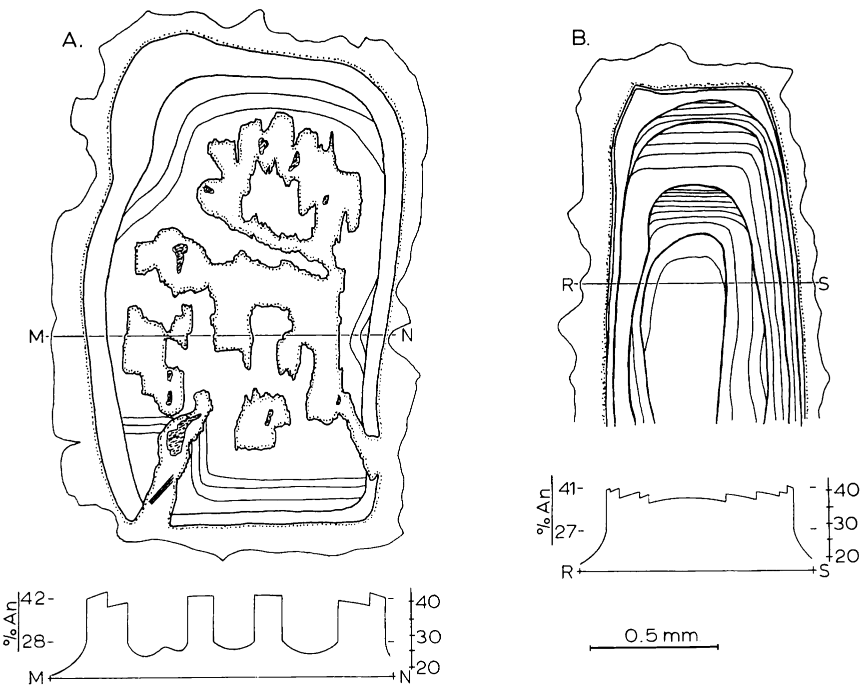

Fig. 2. Sketches of two typically zoned plagioclase phenocrysts with zoning curves representing the compositional variation along lines, MN and RS. Scale applies to both phenocrysts. (A) Phenocryst with prominent patchy zoning and inclusions of quartz (shaded) in patches. (B) Phenocryst with several coarse oscillations truncating delicate oscillatory zoning.

zoned away from their contacts with the core, (3) contacts are sharp between patches and core, (4) patches sharply truncate oscillatory zoning, and (5) inclusions of alkali feldspar and quartz in plagioclase occur only in the patches, apparently having crystallized from trapped liquid.

Appropriately sectioned and oriented phenocryst cores display as many as fifty delicate oscillatory zones of less than 2 percent An superimposed on a weak normal zoning. The normal zoning can most simply be considered the result of incomplete reaction between growing crystals and fractionating liquid in a cooling magma. The delicate oscillatory zoning is almost certainly the result of diffusion-controlled crystallization, originally postulated by Harloff (1927) and recently elaborated by Bottinga, Kudo, and Weill (1966). Vance (1962) considered other proposed origins for this type of oscillatory zoning (that is, repeated changes in pressure, temperature, partial pressure of water, or magma composition). He favored Harloff's theory because it is an internally consistent process, not appealing to repetition of special or unusual external factors.

Phenocryst cores also commonly display one of five coarser oscillations or sharp reversals which interrupt the oscillatory normal trend and generally truncate the earlier formed zones (fig. 2B). The abrupt increase in An-content is generally on the order of An_{3-7}. Truncation of earlier formed zones suggests that, prior to deposition of the more calcic zone, the phenocrysts were rounded by partial resorption. Subsequent growth of the rounded cores gradually returned the crystals to euhedral form. These oscillations clearly differ in magnitude from the delicate oscillations described above and most probably originate in some way other than diffusion controlled crystallization. One similar coarse oscillation is generally present as the outermost core zone (fig. 2). In the following discussion this oscillation is termed a "spike" in order to distinguish it from those coarse oscillations occurring at any position within plagioclase cores. The composition of the spike is relatively constant throughout the pluton, and it represents a greater increase of An the more sodic the inner core (fig. 3).

CORRELATION OF CORE ZONING AND COMPOSITION

The composition of inner cores is commonly almost as variable in an individual thin-section as in the entire pluton. Zoning curves of phenocrysts from the same thin-sections are shown together in figure 3 and indicate the magnitude of the variation. Phenocrysts that are now adjacent to one another must have grown under widely varying and different conditions during the early stages of their crystallization. There must have been considerable movement of crystals relative to one another in order to bring together plagioclase cores of such different compositions.

Compositions of outer cores, in contrast to inner cores, show fair to good correlation throughout the pluton (fig. 4) as well as in any thin-section (fig. 3). The sharply improved correlation of the outer core

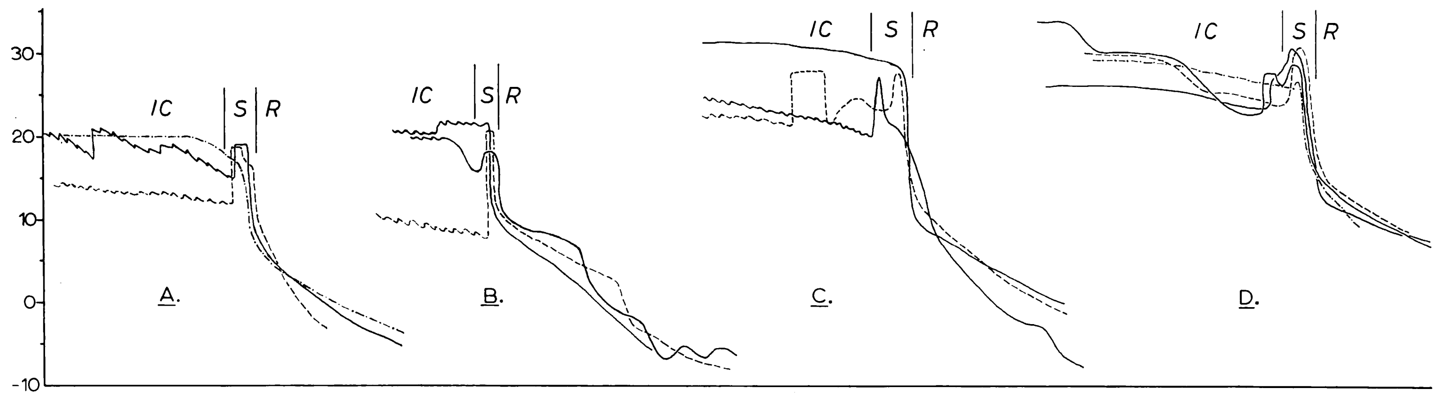

Fig. 3. Zoning curves of plagioclase phenocrysts. Vertical scale is extinction angle in *a-normal* section. Curves plotted together are from the same thin-section. Sample localities are plotted on the geologic map of figure 1. (A) #280, (B) #273, (C) #270, (D) #290. IC = inner core, S = spike and outer core, R = rim.

compositions indicates an episode of homogenization within the magma. Stirring of the magma, probably related to intrusive movement, brought together phenocrysts with different compositions and crystallization histories and homogenized the remaining liquid enough to account for the improved correlation of the outer cores and the general homogeneity of the stock.

The spike, which shows up because the average core composition of most grains is more sodic than the outermost core zone, clearly records mixing within the magma chamber. Moreover, truncation of earlier formed zones by the spike records a period of partial resorption when the more sodic phenocrysts initially came into contact with hotter, more calcic magma. Mixing is further suggested by the occasional presence in some thin-sections of more calcic phenocrysts lacking spikes (fig. 3B) which probably grew within the hotter increments of magma.

Plagioclase tends to be more abundant and more calcic (figs. 4 and 6) within a quarter mile of the eastern contact. It is similar in composition and zoning to plagioclase in some of the early intruded dikes. In some of these dikes and in some specimens from the eastern border of the pluton the plagioclase shows moderate correlation even for zones of the inner cores (fig. 3D). This correlation may result from location of these specimens near the intrusive contacts of the pluton where the effect of any stirring or convective overturn related to intrusion might

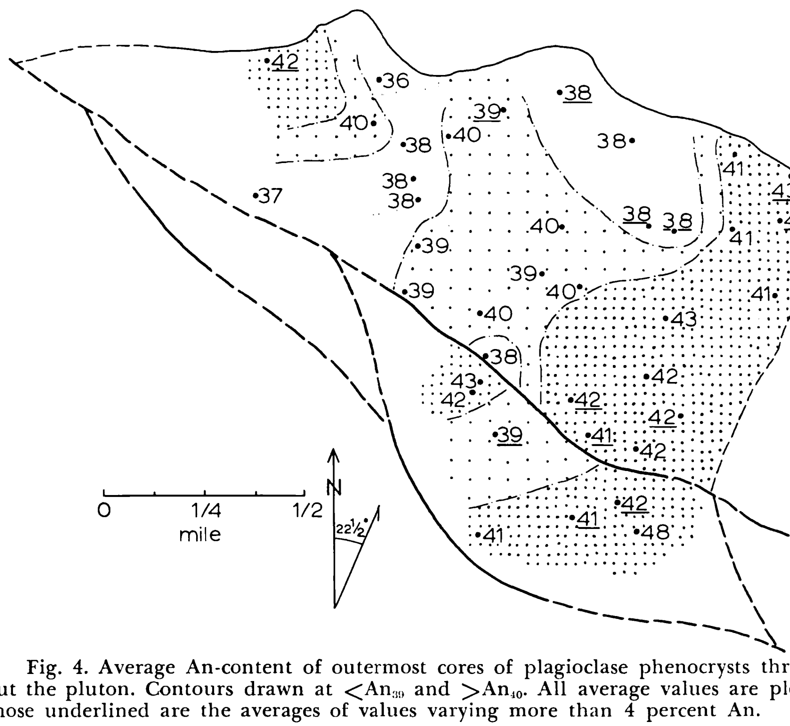

Fig. 4. Average An-content of outermost cores of plagioclase phenocrysts throughout the pluton. Contours drawn at $<An_{39}$ and $>An_{40}$. All average values are plotted: those underlined are the averages of values varying more than 4 percent An.

be at a minimum. The fact that plagioclase is somewhat more abundant and more calcic in these specimens than in most of the pluton may indicate that the eastern border of the pluton was emplaced early in the intrusive history and was largely solid when the main emplacement of the stock occurred.

Change in physical conditions might aid formation of the spike even if mixing were not important locally. In some early dikes and within the eastern portion of the pluton the spikes may be more calcic than the outer core of any phenocryst lacking a spike (fig. 3D). If mixing preceded the emplacement of these rocks, then the hotter increments of magma apparently did not carry any crystals that would indicate the mixing. Plagioclase crystals in a few calcic dikes show good correlation and prominent spikes. It seems unreasonable to suggest that mixing, effective enough to produce the spike, preceded the emplacement of each of these dikes.

The spike zone on plagioclase crystals in some dikes and in some specimens from the eastern border of the pluton may have originated or been enhanced through the effect of decreasing pressure on a slightly supercooled magma. Such a process could have operated throughout the entire pluton but might have been hidden where stirring was effective. Decreasing pressure is suggested as a major factor because of the likelihood of upward movement of the entire magma accompanying stirring.

In figure 5, L is the liquid (supercooled) from which plagioclase, X_1, is crystallizing at the higher pressure (dry) represented by the upper set of liquidus-solidus curves. Decrease in pressure would move the liquidus-solidus curves downward and the composition of the crystallizing plagioclase to X_2, thereby causing a reversal. Perhaps the following sequence of events has contributed to formation of the spike in these rocks:

1. Decrease in pressure (dry) resulting in deposition of a more calcic plagioclase,
2. Because of decreasing pressure, the amount of supercooling is reduced, and the rate of crystallization is reduced,

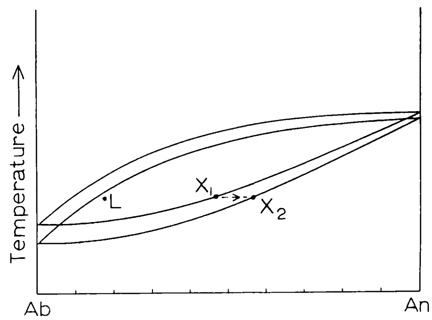

Fig. 5. Phase diagram of the system albite-anorthite showing the relations of the liquidus and solidus at lower pressure (the lower pair of curves) and higher pressure (upper pair of curves). See explanation in text.

3. The liquid cools to about the original amount of supercooling.
4. At the lower temperatures the rate of crystallization is increased and the plagioclase becomes more sodic than that formed initially upon decrease in pressure.

Intrustion might then, by itself, cause deposition of a spike.

A major assumption in the above sequence of events is that the magma acted as an anhydrous system. At the time of formation of the spike perhaps as much as 40 percent of the plagioclase was crystallized. It is not possible to say accurately how much quartz or alkali feldspar was crystallized at that time, but most textural evidence suggests that these phases did not become abundant until deposition of the plagioclase rims. Biotite probably (but not certainly) had begun crystallizing before formation of the spike. The amount is uncertain since biotite was still crystallizing during deposition of the plagioclase rims. The presence of biotite might indicate a substantial vapor pressure. If half of the biotite, 40 percent of the plagioclase, and perhaps 10 percent of the quartz and alkali feldspar had crystallized when the spike was deposited, then the magma was about 20 percent crystal and 80 percent liquid at that time. The volatile content of the magma was not greatly concentrated by crystallization at this time. However, without knowledge of the absolute pressure and volatile content of the magma it is not possible to prove that the magma acted as an anhydrous system when the spike formed.

DISCONTINUITY BETWEEN CORE AND RIM

If, as suggested above, stirring of the magma resulted in the improved compositional correlation of the outer cores, then the spike and outer core zones in general may be considered approximately time correlative throughout most of the pluton. The time correlative value is probably best within the interior of the pluton where outer cores are more nearly constant in composition, and stirring was probably more effective. Early intruded dikes and the more calcic eastern border of the pluton were probably not affected by stirring, and their outer core zones would not be time correlative with those of the pluton interior. Deposition of the spike was followed by non-crystallization and partial resorption of the phenocrysts. If the outer cores are approximately time correlative, phenocrysts at a given level of the magma chamber were probably resorbed at about the same time throughout the interior of the pluton.

Decrease in pressure due to upward intrusion is compatible with the approximate time correlative value of the resorption. Upward intrusion would also be likely to cause major stirring of the magma suggested above by the improved correlation of the outer cores and formation of the spike. Further release of pressure could well lead to resorption of the phenocrysts if the magma were not saturated in volatiles.

It is possible that, during this proposed major episode of intrusion, all important crystalline phases were being partially resorbed. The presence of numerous, fine-grained, plagioclase crystals of rim composition suggests an increased rate of nucleation contemporaneous with deposition of rims on the phenocrysts. Crystallization began at many new sites rather than just as overgrowths on previously formed crystals. The common association of small equant quartz crystals and tabular euhedral rim composition plagioclase as inclusions in alkali-feldspar suggests renewed nucleation of quartz simultaneous with that of plagioclase. The textural relationships appear to require some mechanism capable of renewing crystallization of all major phases nearly simultaneously, at least throughout the exposed level of the pluton.

Change in pressure, because of its essentially instantaneous effect, probably led to this renewed crystallization. Upward intrusion of the magma, while initially causing resorption of the crystals, might if carried far enough lead to saturation of the magma in volatiles, which in turn would initiate crystallization of the rims. Vance (1962) suggested that formation of delicate oscillatory zones might be prohibited in a saturated magma from which volatiles were actively separating. Since fine oscillatory zoning is absent in rims throughout the pluton, crystallization of this pluton may have been reinitiated when the magma became saturated in volatiles as a result of decreasing pressure.

The composition of the first plagioclase to crystallize after resorption is nearly constant throughout most of the pluton (fig. 6). The good correlation probably reflects, in part, increased homogenization of the

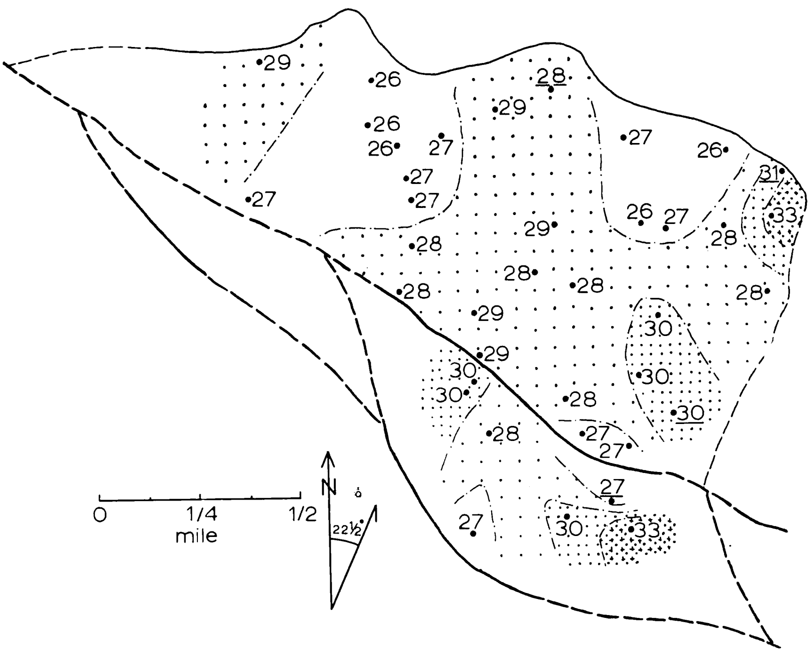

Fig. 6. Average An-content of innermost rims of plagioclase phenocrysts throughout the pluton. Contours drawn at $<An_{28}$ and $>An_{29}$. All average values are plotted: those underlined are the averages of values varying more than 4 percent An.

magma due to intrusive stirring and turbulence occurring between the times of core and rim deposition. The good correlation also suggests approximate simultaneity of renewed crystallization.

The composition of the initial plagioclase to crystallize after resorption should be a function of the shapes of the plagioclase solidus at different pressures. There is not sufficient experimental data to predict, at different P and P_{H_2O}, the effect of decreasing pressure on the detailed shape of the solidus. By adjusting the solidus curve within reasonable limits, Vance (1965) has shown the possibility of crystallizing more sodic plagioclase at a lower pressure.

In review, the discontinuity between core and rim represents a period of non-deposition and resorption which corresponds with upward intrusion of the magma. At the time of emplacement the magma was probably no more than 25 percent crystallized. Plagioclase cores are essentially intratelluric, crystallizing at some unknown depth. Due to upward movement, the magma became saturated in volatiles, and crystallization of the rims began near the level of final emplacement.

ORIGIN OF COARSE OSCILLATORY ZONES WITHIN PLAGIOCLASE CORES

Coarse oscillatory zones of inner cores are texturally similar to the spike zone but differ significantly from it in that they are variable in composition and number and cannot be correlated between phenocrysts. The variable composition indicates that they do not record an homogenization such as that recorded by the outer core zones. The coarse oscillations may record moderate stirring of an inhomogeneous magma related to convection in the chamber of depth. Shaw (1965) has shown that convection is plausible in granitic magmas. The stirring or convective overturn of the magma was probably driven by buoyant movement of hotter magma from depth, concurrent with either enlargement of the magma chamber upward or displacement of cooler magma downward. Such a setting is generally appropriate for the production of coarse oscillations and the great variation in the zonal sequence of inner cores. The complex interaction of the factors listed below preclude a unique and detailed interpretation of any given sequence of core zones:

1. introduction of new hotter magma from depth,
2. recurrent intrusive movements,
3. convection and turbulence,
4. crystal settling, and
5. variability of and degree of supercooling in the magma.

ORIGIN OF CORRODED BYTOWNITE — LABRADORITE CORES

Some plagioclase phenocrysts contain corroded inner cores of bytownite or labradorite. These inner cores are generally tabular and essentially euhdral where they are not corroded. The boundaries between them and surrounding zones are sharp and truncate faint oscillatory zoning in some of the inner cores. The inner cores have clearly been corroded prior to deposition of the surrounding zones. Interpretation of the origin and history of these calcic cores is complicated by the sequence of zones surrounding them: almost all these calcic corroded cores are surrounded directly by normally zoned rims identical to rims on typical phenocrysts. The sequence of oscillatory-normal zoned andesine cores was not generally observed between the very calcic cores and sodic rims. The common absence of typical core zones of intermediate composition suggests that most of the very calcic cores were not in contact with the magma during much of its crystallization history. The calcic inner cores cannot reasonably be considered xenocrysts, since none of the country rock appears capable of serving as a source for such calcic plagioclase. Moreover, the partly euhedral form, faint oscillatory zoning, and Carlsbad twinning, present in many cores, suggest that they are magmatic in origin. If these calcic cores represent relics of the earliest plagioclase to crystallize from the magma, then one must explain their temporary absence during crystallization of intermediate composition plagioclase.

Evidence for the rather complex history of these calcic cores is found in examination of inclusions in the quartz monzonite. While many inclusions are clearly hornfelses of country rock which have undergone varying degrees of assimilation, some inclusions consist of large euhedral calcic phenocrysts in a very fine-grained matrix of quartz, feldspar, cummingtonite (?), and biotite. The texture appears to be that of a metamorphosed volcanic or a rapidly chilled plutonic rock. Phenocrysts of these inclusions range in composition from An_{80} to An_{60}, and individual grains are either unzoned or show weak normal or oscillatory zoning. Carlsbad twins are common.

Nearly all thin sections that contain some phenocrysts with very calcic and corroded inner cores also contain the small fine-grained porphyritic inclusions. Plagioclase crystals of the inclusions are partially corroded and have overgrowths of rim composition plagioclase where they contact quartz monzonite. The calcic cores which are completely surrounded by rim plagioclase appear to have become entirely separated from the inclusions. The textural and spatial relations suggest that these inclusions served as the source for the calcic inner cores.

The inclusions probably are partially assimilated pieces of the earliest intrusions to shallow levels. The texture of the inclusions suggests very rapid cooling such as would be expected of the first small intrusive bodies to reach high level. Their inclusion by the main intrusive mass must have occurred during or after the main intrusive movement of the magma, since only sodic rims have grown on the very calcic cores. The very scarce occurrence of typical core zones superimposed on more calcic inner cores indicates that some very calcic cores were present in the magma at depth.

CONCLUSIONS

The major purpose of this study has been to emphasize the value of plagioclase zoning as an aid to understanding:

1. the behavior of and conditions within granitic magma at times between its origin and consolidation, and

2. the specific sequence of events and conditions obtaining during the development of a particular pluton.

The possibility of correctly interpreting a particular aspect of the zoning sequence is greatly enhanced by knowledge of its occurrence throughout the pluton under study. It is necessary to describe and study sequences of zones and sequences of zoning styles in individual crystals and to determine the degree and distance to which different aspects of the zoning sequence can be correlated. Only then can the maximum use be made of plagioclase zoning to interpret magmatic conditions and events within the framework of known plagioclase phase relations and physical properties of granitic magma.

The study of plagioclase zoning in the Mount Pilchuck pluton has suggested the occurrence of several events and processes:

1. convection in an inhomogeneous magma during the early stages of crystallization, perhaps related to recurrent intrusion of magma from beneath an existing chamber,
2. turbulence, very likely associated with intrusive movement, which caused the moderate compositional homogeneity of the pluton and the improved compositional correlation of the outer plagioclase zones,
3. the possibility of supercooling within the magma, and
4. the resorption of plagioclase and probably other coexisting crystalline phases during a period of decreasing pressure due to intrusion.

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