American Mineralogist, Volume 69, pages 660–676, 1984

Probable relations between plagioclase zoning and magma dynamics, Fuego Volcano, Guatemala

Alfred T. Anderson, Jr.

Department of the Geophysical Sciences
The University of Chicago, Chicago, Illinois 60637

Abstract

Millimeter-sized plagioclase phenocrysts were explosively erupted in high-alumina basaltic ash from Fuego volcano, Guatemala on October 14, 1974. The crystals have unzoned, patchy-zoned and oscillatory-zoned parts. Unzoned, inclusion-poor cores, up to 2 mm thick have round edges and compositions between An_{97} and An_{88}. Patchy-zoned cores and regions are rich in inclusions of glass and gas, about 50 μm thick and An_{90} to An_{83}. Oscillatory-zoned regions surround the cores and occur between patchy-zoned regions; compositions are An_{90} to An_{83} except for thin rims (An_{75} to An_{70}).

Patchy-zoned, inclusion-rich regions probably crystallized in gas-saturated environments during episodes of relatively large supersaturation because: (1) such regions are either cores (homogeneous nucleation?) or have flat inner terminations suggestive of a constructive rather than resorptive origin, (2) most such regions are relatively sodic (relatively large concentration gradients in the nearby melt?), (3) such regions terminate outward with irregular, convolute oscillatory zones suggestive of morphological instability, and (4) such regions are rich in inclusions of gas many of which are large and flat against the inner boundary suggesting onset of patchy-zoned growth together with effervescent decompression. Crystallization with effervescence is supported by decreasing Cl/K_2O with increasing K_2O for inclusions of glass. Patchy-zoned regions alternating with oscillatory-zoned regions suggest episodes of accelerated decompression.

Oscillatory zones are 0.5 to 8 μm thick; average internal compositional variation is about 1% An, with the most calcic portion being earliest. Although individual zones are thinnest on {010}, many thin zones on some forms correspond to non-oscillatory-zoned growth on {010} and other slow-growing forms, not cessation of growth. Consequently, zones are generally thinnest and most numerous on the fastest growing forms: {001}, $\{\bar{2}01\}$, $\{1\bar{1}0\}$, and {110}. Discontinuous zones suggest dominant sideways rather than radial growth for individual zones. Thickening of zones on irrational or curved surfaces and in reentrants suggest dominant surface-attachment control of growth rate. Most of the zones correlate between opposite faces of the same crystal form on individual crystals. Some zones correlate between different crystals. The number of zones from the outside of the crystals to patchy-zoned regions or other disturbances cluster around 25 and 50. The various textural and compositional features of the zones are consistent with modulation of growth by hypothetical pulses of upward motion of a gas-saturated magma which sheared the boundary layer of melt near the growing crystals, thereby renewing the level of supersaturation at the crystal face. Tidal triggering of the motion seems likely. The oscillatory zones on the fast growing faces of the Fuego plagioclases probably are twice daily "ticks" of a volcanological "clock".

Probably the Fuego magma body inherited initial unzoned crystals (cores). Subsequent growth probably accompanied ascent and was alternately patchy or oscillatory, possibly associated with various distances from the walls of the body: a crystal temporarily near a wall might ascend relatively slowly, experience only moderate decompression and supersaturation, and consequently grow only oscillatory zones; a crystal near the center of the body might ascend rapidly, experience greater decompression and supersaturation, and consequently grow some patchy-zoned regions. Explosive eruption could coextrude crystals from the various environments.

0003–004X/84/0708–0660$02.00

Introduction

It would be petrologically useful to know when and how fast crystals grow because such knowledge could lead to an increased understanding about the eruptive behavior of volcanoes and their connections, if any, with plutons.

The estimation of time and rate in igneous processes is more difficult than the estimation of temperature and pressure. Even in lava flows, dikes, and sills where heat flow theory is useful, a generally unknowable amount of crystallization took place before the magma stopped moving. Volumetric and linear rates of migration of magma are plausibly estimated from surface deformation, rates of extrusion of magma or gas, heights of lava fountains, migration of seismicity, and the dimensions of vents and dikes. Probably crystallization commonly accompanies movement because of cooling along walls and effervescence of gas rich in H_2O with decompression. Consequently, it is reasonable to associate textural records of crystal growth with magma movement as was done by Ewart (1963) for zoned phenocrysts of plagioclase in dated eruptions of ignimbrite. The present study also associates zones on phenocrysts of plagioclase with likely times of movement of magma.

The origin of zoning in plagioclase, particularly oscillatory zoning, is uncertain and controversial (see review by Smith, 1974, and recent contributions by Sibley et al., 1976; Haase et al., 1980; Allegre et al., 1981; Loomis, 1981; and Lasaga, 1981, 1982). The ideas may be divided into dynamical and static categories, according to whether the idea implicates motion of the plagioclase crystal, either absolutely or relative to the surrounding melt. Static models (Harloff, 1927; Hills, 1936; Bottinga et al., 1966; Sibley et al., 1976; Haase et al., 1980, and Allegre et al., 1981) are proposed only for continuous oscillatory zoning without major abrupt jumps and resorption. Dynamical models are proposed for most kinds of zoning including continuous oscillatory zoning. A dynamical mechanism is inferred in this work.

Table 1. Proportions of various plagioclase crystals hand-picked from ash, Fuego 1974 (VF74–53)

Portion[1]	Mass (g)	Percent by Weight	No. of Grains	Subequant Prisms	Platy Rhombs	Other[2]
a	0.032	3.6	95	32	30	33
b	0.042	4.7	142	n.d.	n.d.	
c	0.034	3.8	86			
d	0.005	0.6	16			
e	0.008	0.9	14			
f	0.762	86.3	n.d.			

[1]*a = euhedral single crystals of plagioclase coated with medium brown groundmass; b = subhedral crystals of plagioclase largely coated with medium brown groundmass; c = crystals of plagioclase partially (rarely completely) coated with dark brown to black groundmass; d = clear, inclusion-free anhedral crystals of plagioclase; e = miscellaneous fragments rich in plagioclase; and f = remainder of sample (mostly lumps rich in groundmass).*

[2]*Includes mostly grains with too much adhering groundmass to be sure of shape, some aggregates of crystals are present.*

In this paper there are two related parts: First, I describe certain textural and compositional features of zones in plagioclase phenocrysts from Fuego volcano, Guatemala. Second, I use the features to correlate zones and arrive at a working hypothesis for the origin and significance of oscillatory zones.

Selection and preparation of crystals

Euhedral plagioclase phenocrysts are abundant in air-winnowed basaltic ash (sample VF74-53 of W. I. Rose) which fell on October 14, 1974, about 7 km from Fuego's summit vent (Rose et al., 1978). Most particles in the ash have diameters between 0.3 and 3 mm. Most of the plagioclase phenocrysts are individual, euhedral to subhedral platy rhombs and sub-equant prisms. Partly glassy to devitrified groundmass coats most of the phenocrysts (Table 1). Accidental particles from the vent walls probably comprise less than about 20 wt.% of the ash because the eruptive jet was intense and incandescent in daylight (Rose, pers. comm., 1982). Some broken fragments of plagioclase with partial coatings of dense, devitrified matrix may be accidential, but the euhedral crystals coated with partly glassy to devitrified groundmass probably were free-swimming crystals immersed in magma before eruption.

Of 133 euhedral phenocrysts of plagioclase mounted and sectioned, 21 were optimally oriented for seeing zones with thicknesses down to about 0.5 μm and internal compositional amplitude as small as about 1% An (Anderson, 1983). This study is primarily based on the 21 optimally oriented crystals. They include both platy rhombs and subequant prisms, but the platy rhombs are underrepresented because of an inadvertent orientation bias.

Definition of zone

For the purposes of this report a zone is a repeat unit of microscopic crystal thickness. Like a waveform its beginning is arbitrary. The Nomarski interference contrast views of etched polished sections reveal pairs of light and dark bands corresponding to the alternating ridges and valleys produced by differential etching of the polished surface. Each zone thus consists of two parts: an etch-resistant (sodic) part and a less etch-resistant (calcic) part. The average composition of successive zones may be identical.

Zoning textures of the plagioclases

Three varieties of zoning are present: (1) no zoning (An_{96-93}); (2) patchy-zoning (An_{92-82}); (3) oscillatory zoning (An_{92-83} and about An_{75-70}). There may be some continuous compositional variation within unzoned regions. Some unzoned regions contain inclusions of olivine or glass and in one case hornblende. Patchy-zoned regions are rich in inclusions of gas and glass. Some oscillatory-zoned regions contain a few inclusions of olivine and/or glass. Although unzoned regions are restricted to cores of crystals, the patchy-zoned and oscillatory-zoned regions occur in various sequences from core to rim. The thicknesses of rims of oscillatory and patchy-zoned regions in large, centimeter-sized phenocrysts from an unsorted ash flow are similar to the dimensions of such rims and regions in the smaller, millimeter-sized crystals from the sample of winnowed ash. Two or more sub-regions with different average compositions comprise many oscillatory zoned regions. Faint, thin, and relatively sodic (An_{75-70}) oscillatory zones characterize the microphenocrysts and the outermost few tens of microns of the phenocrysts.

There is a correlation between crystal shape and internal texture (Table 2), suggesting two separate modes of crystal growth.

Features of oscillatory zones

Zone continuity

Some zones are discontinuous (Figs. 1–3). Most discontinuous zones have prominent bright bands. Some discontinuous zones end in a step perpendicular to the face. It is common for discontinuous zones with particularly bright bands to be absent on or near crystal edges (Fig. 2). Other discontinuous zones with bright bands have irregular interruptions (Fig. 3). A few discontinuous zones are succeeded outward by patchy-zoned regions.

Some zones are truncated near crystal edges. Some truncations are smooth, round edges (Fig. 2) and along smooth, round reentrants. Irregular interruptions are repetitious on rare plagioclase crystals which are enclosed by glass free of crystallites and devitrification products.

Zone discontinuity commonly occurs at the edge between adjoining faces where a zone on one face is not

Table 2. Shape and patterns of zoning of sectioned phenocrysts of plagioclase: Fuego 1974 (VF74–53)

Zoning pattern core → rim[1]	Shape: Platy rhombs	Subequant prisms	Uncertain	Total
u o	1	10	7	18
p o	21	10	10	41
u o p o	1	1	1	3
o p o p o	8	9	3	20
o p o	2	1	2	5
n.d.	14	9	11	34
m	2	3	8	13
Total	49	43	42	134

[1]*u = unzoned region; o = oscillatory zoned region; p = patchy-zoned region; n.d. = zoning regions not evident, mainly because of unfavorable orientation for etching to reveal oscillatory zones; m = miscellaneous patterns including one oscillatory zoned crystal in which many oscillations are ragged and discontinuous (resorbed?).*

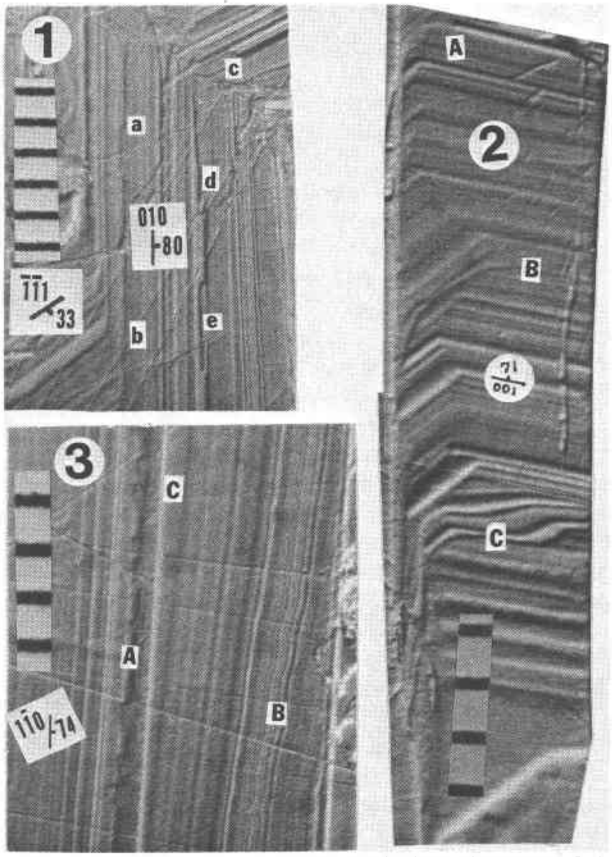

Fig. 1. Discontinuous zones on plagioclase phenocryst 2–1. The outer margin of the crystal is along the right margin of the photograph. Bright bands end at (a), (b), (c), (d), and (e). At (c) two bright bands end. Bright bands at (d) and (e) project out over underlying dull bands and probably are skeletal protrusions.

This and all following photographical illustrations are reflected light, Nomarski interference contrast views of etched, polished thin sections. See text and Anderson (1983) for details. The scale divisions are 10 μm apart in all cases. The attitudes of some zones and crystallographical axes are shown with conventional strike, dip, and plunge symbols referenced to the plane of polish as horizontal. Compositions [100 Ca/(Ca + Na) atomic] determined by microprobe analysis are indicated by numbers in white circles at the position of the analysis.

Fig. 2. Truncated, irregular and discontinuous zones on plagioclase phenocryst 4–1A. At (C) 5 inward lying zones are truncated and overlain by irregular zones which are thickest where curvy (irrational). Along the dark band (B) numerous zones are truncated on the grain edge. Near (A) several brightly banded zones are discontinuous on {001}. Zones are generally thicker toward the grain interior at the bottom of the photograph.

Fig. 3. Curvy zones and an irregular zone on crystal 2–9. The rim of the crystal is along the right margin of the photograph. The irregularly spaced reentrants into zone (A) are confined to that zone. Zone (C) and some outward lying neighboring zones thicken toward the top of the photograph. About 8 zones near (B) are curvy. The outermost zones are truncated at the outer sodic rim.

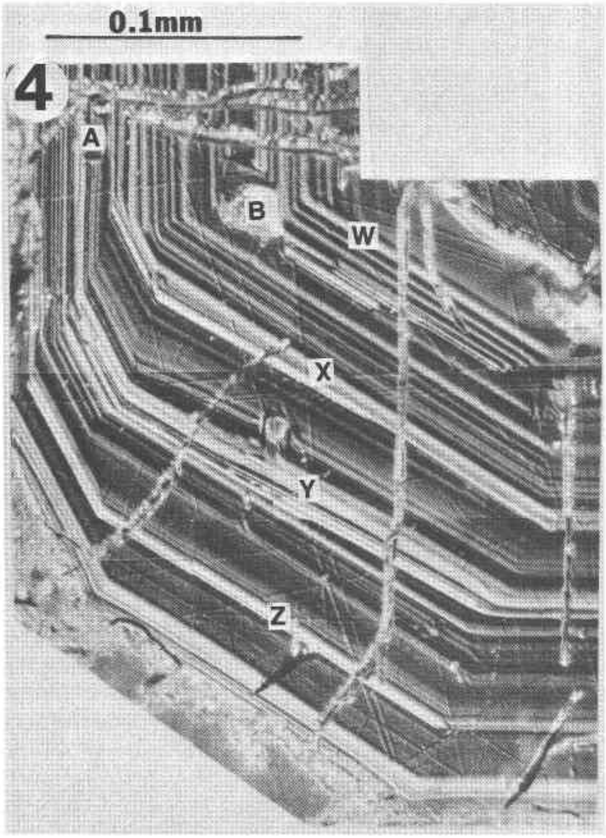

Fig. 4. Groups of bright (W, X, Y, Z) and dull zones on (110). Between (W) and (X), (X) and (Y), and (Y) and (Z), 25 to 30 individual zones may be counted. Fewer zones can be counted on other faces. Groups (X) and (Y) contain some zones which appear to thicken toward the crystal edge as can be seen by sighting subparallel to the surface of the picture.

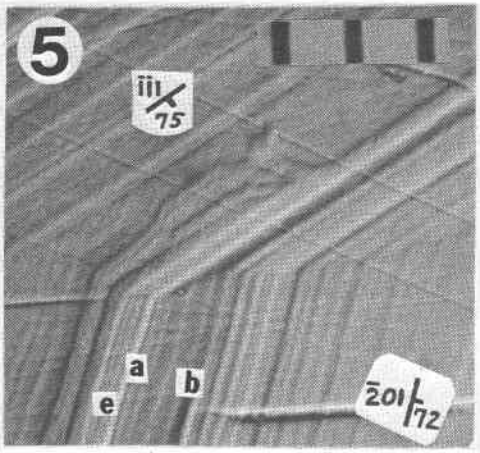

Fig. 5. Oscillatory zones (near e and between a and b) on ($\bar{2}01$) continue as single zones on ($\bar{1}\bar{1}1$). Because the edges of the zones on ($\bar{2}01$) extend beyond the trace of the zones on ($\bar{1}\bar{1}1$), it may be concluded that unzoned growth on ($\bar{1}\bar{1}1$) accompanied zoned growth on ($\bar{2}01$). See text for further discussion.

evident on the adjoining face. Consideration of this important phenomenon is taken up below under the topic of zone thickness.

Zone flatness

Most zones are flat (no curvature apparent to the eye in interference contrast views), but many are curvy, particularly on the {110} and {111} forms. Zones in patchy-zoned regions are curvy as are many zones filling reentrants. Curvy zones make up uncommon protrusions particularly on {010}. Rare curvy zones are wavy (Fig. 3).

Zone thickness

There are two ways to consider zone thickness. First, the thickness of an individual zone may vary as it is traced along one face, around an edge, and into the adjoining face. Second, the average thickness of zones may vary from one face to another and from the interior of the crystal toward its rim. There is no necessary connection between the two because not all zones correlate from face-to-face.

Individual zones vary in thickness on a single face. On a particular face, an individual zone may show edge thickening, reentrant thinning, and reentrant thickening. Edge thickening and reentrant thinning are mostly restricted to the outer sodic rims on the phenocrysts. An example of edge thickening within the interior of a phenocryst can be seen for some of the more contrasting zones in Figure 4 by holding the figure nearly parallel to the line of sight and by sighting along the zones. It is not possible to be certain, however, that the thickenings apparent in Figure 4 are thickenings of individual zones or slightly curvy zones overlying discontinuous zones present only near the edge. Thickening of zones on a single face is mostly associated with underlying irrational surfaces (Fig. 2).

Individual zones vary in thickness from one face to another (Fig. 5). Relative thicknesses of individual zones vary by less than a factor of about three from form-to-form. Zones on {010} have the same or smaller thicknesses as their continuations have on other faces including the typically curvy faces {110} and {111}.

Termination of a zone at a crystal edge may occur even though growth continues on both faces meeting at the edge. Figure 5 reveals several zones which are present on ($\bar{2}01$) but absent on ($\bar{1}\bar{1}1$). The ends of several zones between a and b on Figure 5 define a line which makes an angle (of about 15°) with the trace of the ($\bar{1}\bar{1}1$) zones. This angle reveals that growth on ($\bar{1}\bar{1}1$) accompanied growth of the zones on ($\bar{2}01$). However, the growth on ($\bar{1}\bar{1}1$) was unzoned, or imperceptably zoned. Evidently non-oscillatory-zoned growth occurs relatively slowly on some faces concomitantly with oscillatory-zoned growth on other faces.

The above observation is important because some ideas for the origin of oscillatory zoning postulate stop-

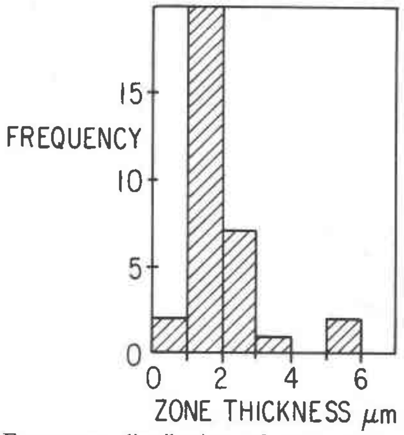

Fig. 6. Frequency distribution of zone thicknesses. The thicknesses shown are for the outer 32 consecutive zones of {0$\bar{2}$1} of crystal 50–1–1 (see Fig. 4). The zones dip at a shallow angle of 44° facilitating accurate measurement of individual thicknesses. The average thickness of the outer 13 zones is 1.4 μm and of the inner 19 zones is 2.25 μm if two thick zones are included or 1.9 μm if the two thick zones are excluded.

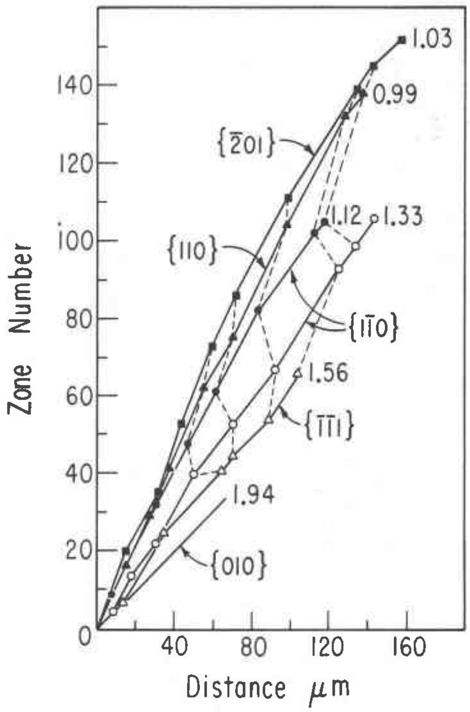

Fig. 7. The relation between zone number and perpendicular distance from the rim for various crystal forms on crystal 2–9. Dashed lines connect the positions of correlated marker bands on the various forms. The numbers at the ends of the lines indicate the distance divided by zone number for the final point on the lines, and equal the mean width of zones. The ordinate records the accumulated number of zones inward from the rim (0).

page of growth to account for missing zones (Bottinga et al., 1966; Sibley et al., 1976). The above facts reveal that there is no necessary connection between the absence of zones and stoppage of growth. Close scrutiny suggests that in regions of missing zones, growth occurs but at a slow rate.

Successive zones on individual faces vary in thickness by a factor of about 10, but the thicknesses of most zones on a particular face vary by less than a factor of 3 (Fig. 6). The average thicknesses of zones vary with crystal form (Fig. 7) in a different way than predicted from variations of equivalent zones on different forms. For example zones on {010} are thicker on the average than zones on other forms (Fig. 7). However, equivalent zones traced from {010} to other forms are thinnest on {010}. Some thin zones on other forms are not evident on {010}, where they appear to be represented by unzoned growth. Thus, the thicker, fast growing forms have more zones which grew faster than zones on thin forms such as {010}.

Zones generally decrease in thickness toward the outer margins of individual grains (Figs. 7 and 8), but the decreases roughly correspond to constant volume per zone (Fig. 8). There are some reversals to the general trend on most of the large grains. The average thicknesses of zones in the outer 60 μm of the 21 crystals are independent of grain size and range from about 2 μm to 0.7 μm with one exception at about 3 μm per zone.

Average zone thickness is independent of average composition. Thick zones tend to lie toward the inside of exceptionally bright (sodic) bands. However, I have not been able to adequately resolve the compositional variation within zones; consequently, the present data are not sufficient to demonstrate a relation between compositional structure within zones and their relative thicknesses.

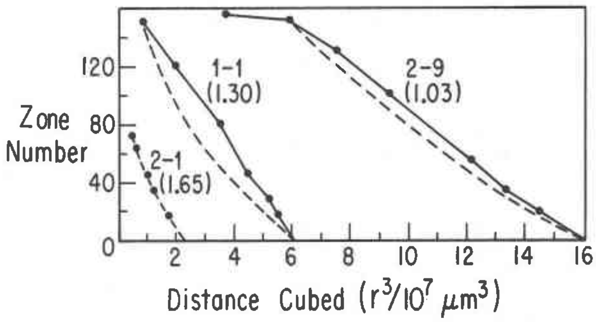

Fig. 8. Relation between zone volume and distance. Distance (r) is dip corrected from the central axis of the crystal. The value of r at the "center" of the crystal is taken as zero. The center of volume of the crystal cannot be determined for sectioned crystals. The cube of the distance is plotted. The crystal numbers are given together with the mean zone width (in parentheses). Measurements were on the {$\bar{2}$01} form. Note that the inverses of the slopes of lines on the graph have units of volume per zone. The dashed lines indicate how zone number would relate to distance if the zones had uniform thickness equal to the mean thickness. Approximate linearity of the curves indicates that zones are approximately equal volumetric increments on individual crystals. Curves for larger crystals have gentler slopes (greater volumes per zone).

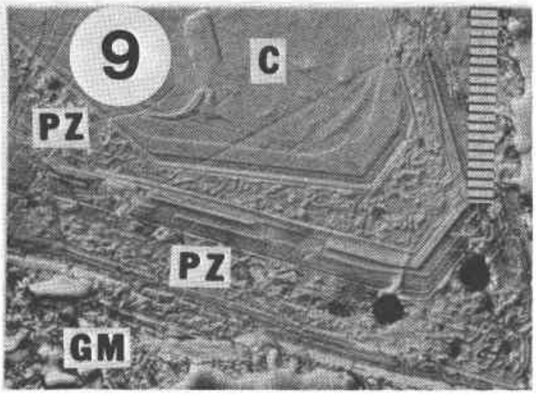

Fig. 9. Patchy-zoned regions on crystal 3–8. A slightly zoned core (C) is rimmed by successive oscillatory zoned and patchy-zoned (PZ) regions. Groundmass (GM) is attached to the rim of the crystal. Two inclusions of gas appear as black circles about 30 μm in diameter and are next to the inner boundary of the outer patchy-zoned region. The inner boundaries of both patchy-zoned regions are flat, but the outer boundaries are curvy on some forms.

Features of patchy-zoned regions

Most of the crystals of plagioclase in the ash sample have one or more patchy-zoned regions. Such regions have irregular zones and inclusions of glass and gas (Fig. 9). Most patchy-zoned regions have a flat contact next to the interior of the crystal (Fig. 9). The largest inclusions of gas are preferentially located adjacent to the inner, flat contact (Fig. 9). About one-third of the patchy-zoned regions are associated with discontinuous zones. Typically one or more discontinuous zones lie inward of or adjacent to a patchy-zoned region (Fig. 10). The outer-parts of patchy-zoned regions have protruding edges and are capped by irregular, curvy zones (Fig. 10).

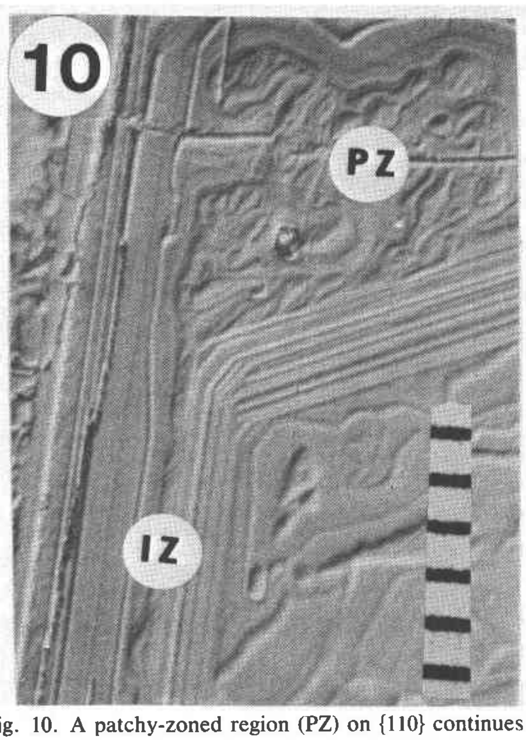

Fig. 10. A patchy-zoned region (PZ) on {110} continues into an irregular zone (IZ) on {010}. The inner limit of the patchy-zoned region is flat, whereas the outer limit is overlain by curvy oscillatory zones. Three discontinuous zones lie inward from the patchy-zoned region.

Correlations of oscillatory zones in the same crystal

Most oscillatory zones on opposite faces of the $\{1\bar{1}0\}$ and $\{\bar{2}01\}$ forms correlate, but some do not (Figs. 11 and 12). The features which correlate between opposite faces are: (1) the relative brightness (probably relative Na enrichment) of bands; (2) the relative thicknesses of zones; (3) groups of dully or brightly banded zones; (4) irregular or incomplete zones.

The $(\bar{2}01)$ and $(\bar{1}10)$ faces share a common edge as do $(20\bar{1})$ and $(1\bar{1}0)$ at the opposite end of the crystal. The ends of the crystals are up to about 0.7 mm apart and separated from each other by extensive faces (mostly {010} and {001}). Growth on {101} appears comparable to that on $\{\bar{2}01\}$ and $\{\bar{1}10\}$; consequently it is possible for a zone which might initiate on $(\bar{2}01)$ to run around the crystal via $(\bar{1}10)$ and (001) to $(\bar{1}\bar{1}1)$, $(20\bar{1})$ and $(1\bar{1}0)$. Alternatively the correlated zones on opposite ends of a crystal reflect independent growth under environmental conditions which were similar up to 0.7 mm distant. The correlations of incomplete zones suggest the second alternative because their incompleteness makes lateral propagation around edges questionable.

Correlations of patchy-zoned regions in the same crystal

Patchy-zoned regions vary in character from face-to-face and form-to-form. One face may have a thick patchy-zoned region and the opposite face of the same form may have only a thin irregular zone. However, most patchy zoned regions can be traced around at least half of the perimeter of a section through an individual crystal. Most crystals have fewer than three patchy-zoned regions; consequently, patchy-zoned regions may facilitate correlations between grains.

Correlations between crystals

Some representative correlations between crystals are shown in Figures 13 and 14. On twelve crystals patchy-zoned regions occur near zone numbers 25 and/or 50.

In terms of total numbers of zones the grains fall into two groups (Fig. 15): most crystals have fewer than about 100 zones, but some larger crystals have 140 to 200 zones. About a third of the crystals have 40 to 60 zones with patchy-zoned cores or regions. Most large crystals have unzoned calcic cores (mostly greater than about An_{92}).

Groups of dully and brightly banded oscillatory zones correlate between grains and are respectively relatively calcic and sodic. The patchy-zoned regions are relatively sodic but overlap the compositions of the brightly banded regions. Thus the average composition of various segments may be of some correlative value, but the details of the compositional structure are too fine to be resolved with the microprobe.

A smaller proportion of zones correlates between crystals than correlates between opposite or similar faces on a single crystal. For some groups of crystals about one out of five zones is sufficiently similar in thickness, brightness and morphology to justify correlation between the crystals. Such correlations are subjective, but comparable to correlations of equivalent zones on individual crystals. No individual zones on different crystals appear identical, and it is likely that lack of identity is real and not an artifact of various angular relationships, etching and so on.

Compositions of glassy inclusions

Inclusions of glass in plagioclase phenocrysts have variable and mostly low ratios of Cl/K_2O compared to inclusions in olivine (Rose et al., 1978). These facts suggest some effervescence of Cl during the crystallization of plagioclase.

A plagioclase crystallization model

Two groups of phenocrysts

My interpretation of the mechanism of growth and origin of zoning of the Fuego plagioclases adopts a dynamical body of magma in which crystals can have variable physical/chemical histories, based on the following facts and ideas.

Two groups of phenocrysts are defined on the basis of the numbers of zones on grains (Fig. 15). The division made on this basis is supported by different correlation groups (group 1 = Fig. 14, group 2 = Fig. 13). Each group includes both platy crystals with patchy-zoned cores and prismatic crystals with non-oscillatory zoned subround cores. The Fuego magma body may have received two injections of magma which contained non-oscillatory zoned plagioclase crystals. Because there are no regions on the group 1 crystals (more than 140 zones, Fig. 14) which are comparable to the prominent patchy-zoned regions and cores of the group 2 crystals at zone numbers near 25 and 50 (Fig. 13), the two groups of phenocrysts may have grown in different parts of the magma body.

Non-oscillatory zoned cores

The non-oscillatory zoned cores of many plagioclase phenocrysts are relatively calcic, and commonly subhedral, subequant and subround in shape. The lack of oscillatory zoning in the cores may reflect growth in an environment which was either physically more stable or chemically more uniform than for the zoned exteriors. The subround shapes of most of the cores probably reflect partial resolution before the oscillatory zoned rims began to grow. Partial resorption could be caused by decompression of a system undersaturated with H_2O vapor, addition of H_2O or heating (as by falling into or mixing with hot magma).

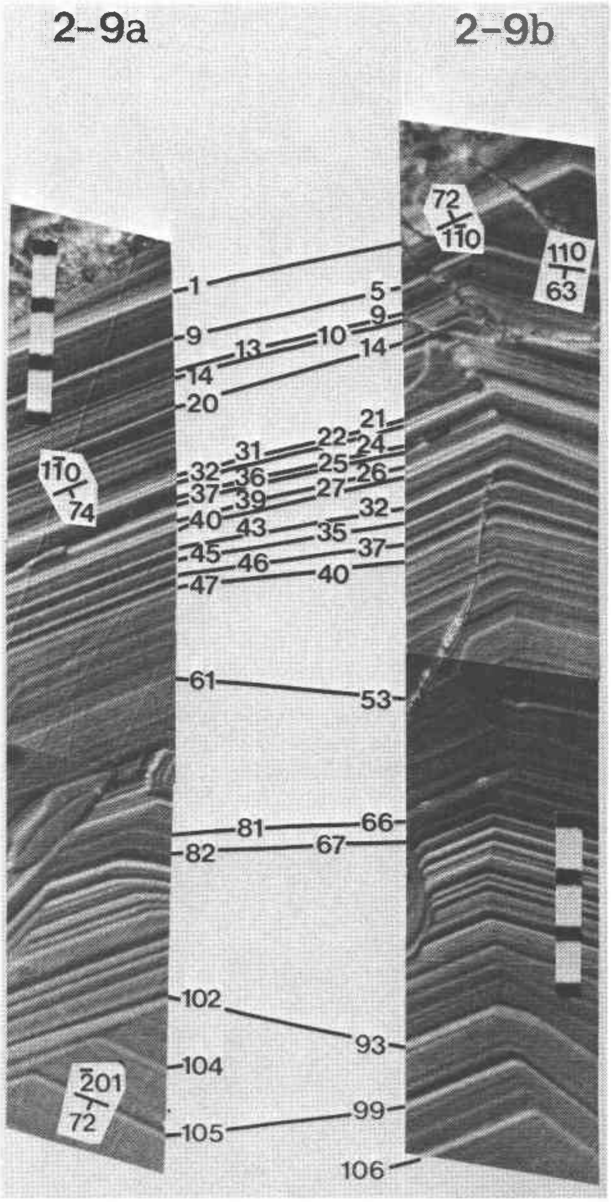

Fig. 11. Correlation of bright bands between alternate faces of the {1$\bar{1}$0} form on crystal 2–9. The rim of the crystal is near the top of both photographs (2–9a and 2–9b). The correlated bands are numbered inward from the sodic rim (about An75) of the crystal. About half of the zones can be easily correlated.

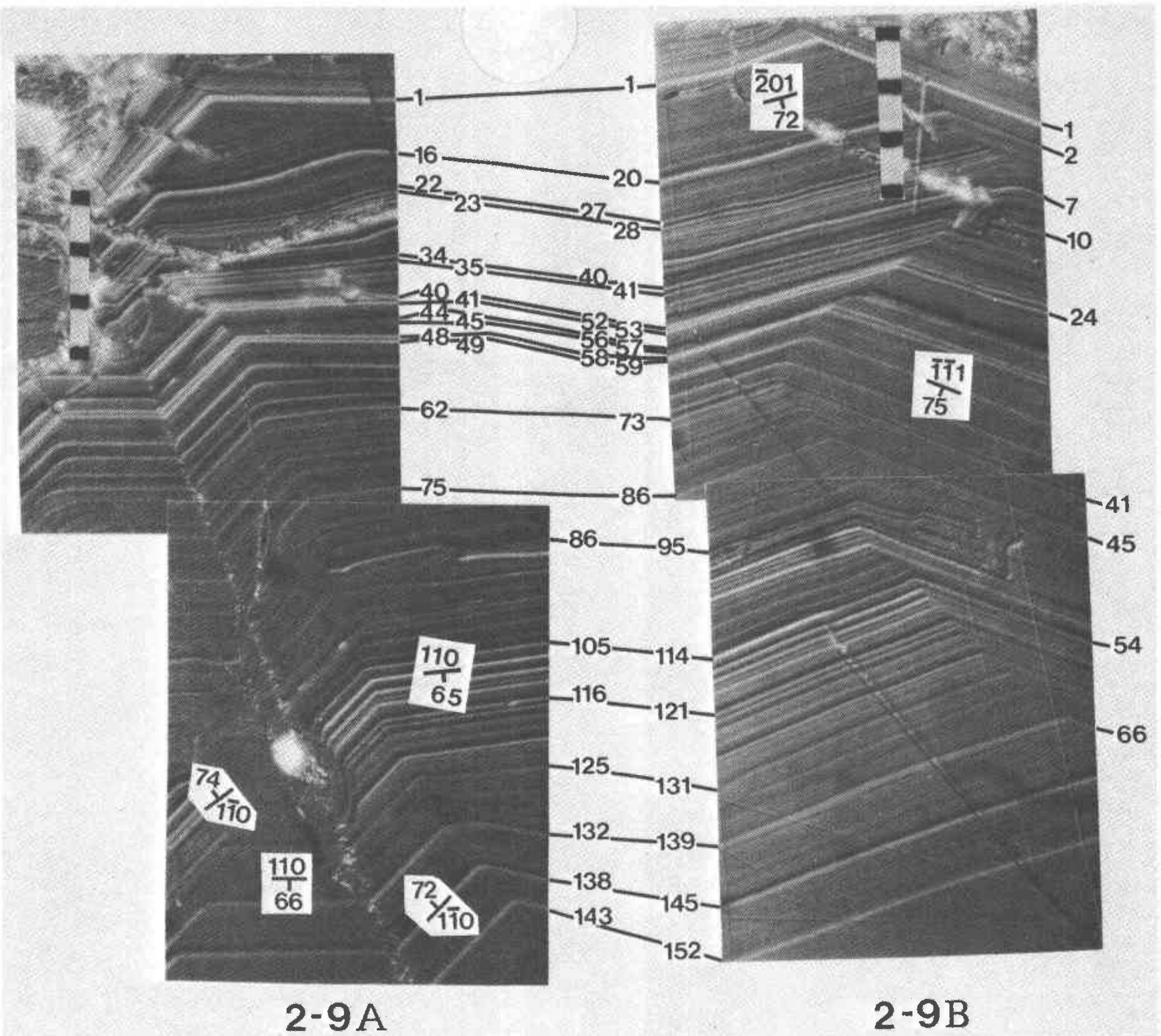

Fig. 12. Correlations of bands between {110} and {$\bar{2}$01} forms on opposite ends of crystal 2–9. The rims of the crystal are near the upper margins of the photographs. Some bands are more curvy on {110} than on {$\bar{2}$01}.

Patchy-zoned regions

The features of patchy-zoned regions suggestive of or consistent with relatively large supersaturation of plagioclase are: (1) the composition of patchy-zoned regions commonly is more sodic than the adjacent oscillatory zoned regions. (2) Most patchy-zoned regions have an irregular outer margin suggestive of cellular growth. (3) Most patchy-zoned regions are thicker at the corners between principal crystal forms than inwardlying oscillatory zones. (4) Patchy-zoned regions are rich in inclusions of gas and glass. (5) Patchy-zoned regions form subeuhedral platy cores of most phenocrysts suggesting that homogeneous nucleation is associated with the development of patchy-zoned regions. These features are interpreted more fully below.

For a given melt composition, supercooling correlates positively with sodium content of the plagioclase (Lofgren, 1974a,b). Cellular growth morphology is suggested by (2) and (4) above and is typical of rapid growth rates and larger supercooling than faceted growth (Lofgren, 1974b; Kirkpatrick, 1975). Corner growth ((3) above) is favored during rapid growth because sharp corners "see" more liquid within a small distance than do flat faces. Inclusions of glass are consistent with resorption, as well as cellular growth (Vance, 1965). Resorption is not consistent, however, with either the euhedral inner boundary of many patchy-zoned regions or the paucity of flat

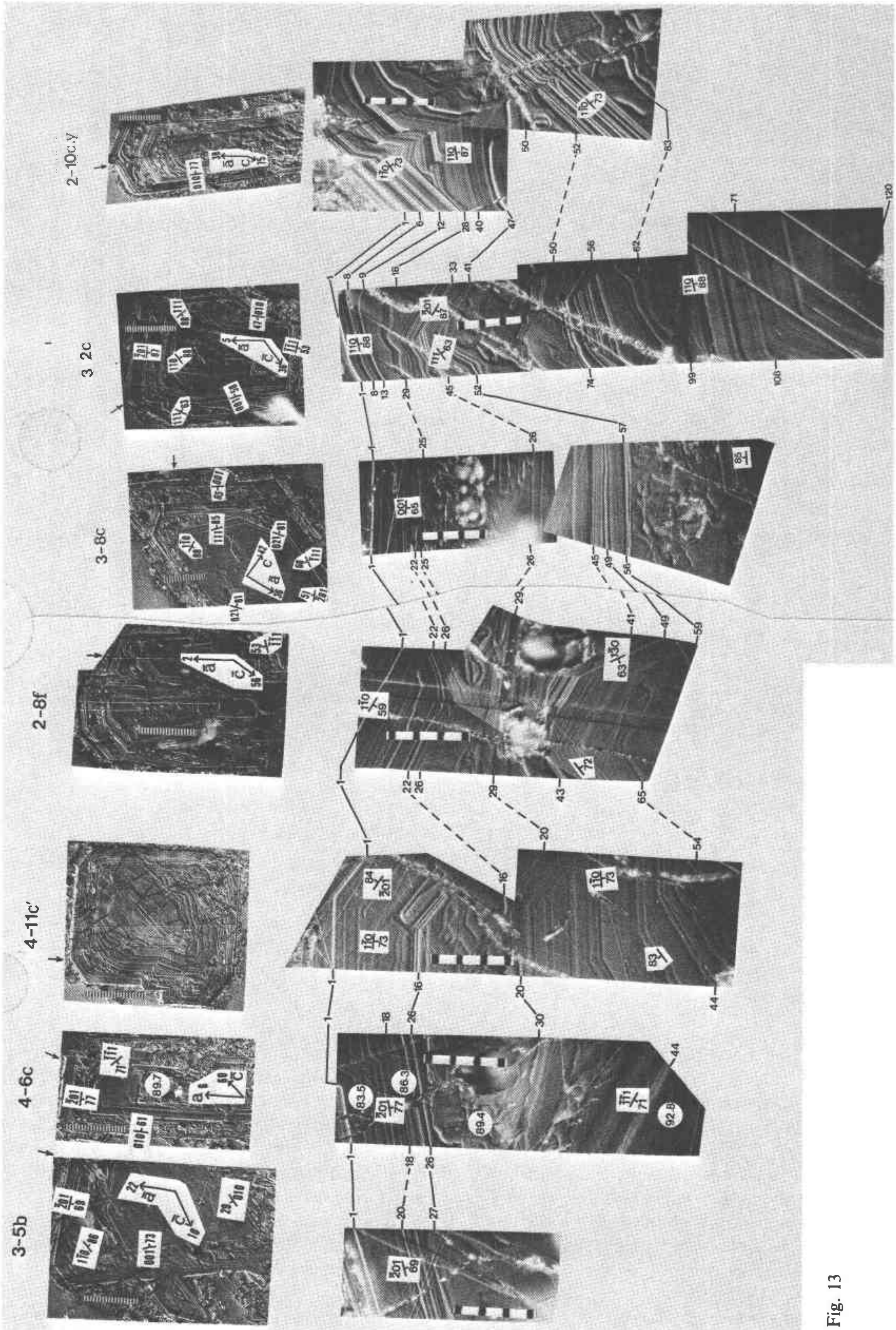

Fig. 13

Fig. 13, 14. Correlations of zoning patterns between crystals. The rims of the crystals are in the top parts of the photographs. From top to bottom each crystal is represented by a symbol (1–10 c, y, etc.), a low magnification view and a high magnification view. The black arrows pointing toward the rims of the upper views indicate the positions and orientations of the high magnification views.

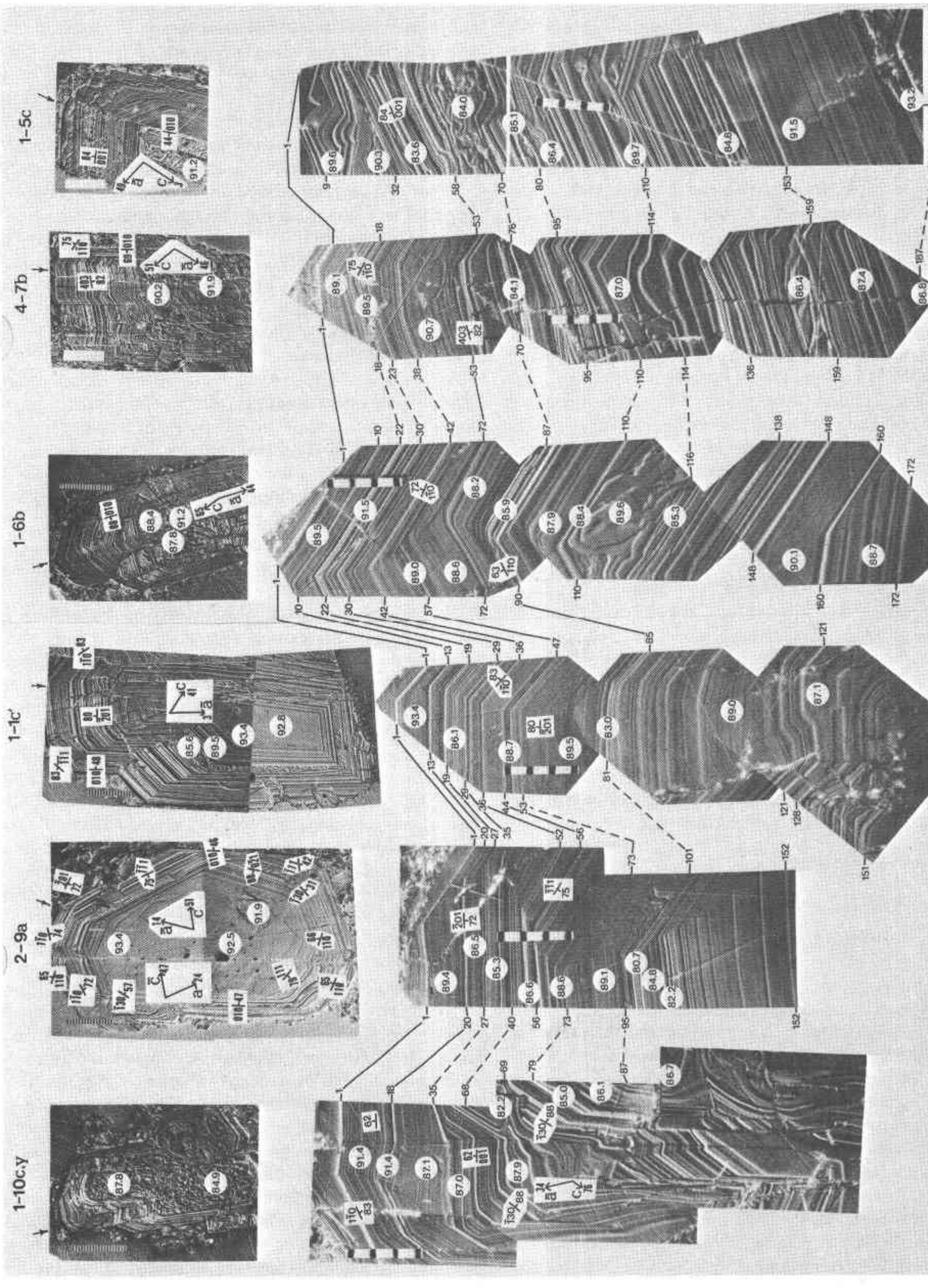

Fig. 14

oscillatory zones within the patchy-zoned region. Resorption, like etching, proceeds preferentially along lattice defects and tends to produce an irregular, vermicular border on a subround rather than euhedral core. The zones which are present within patchy-zoned regions have sinuous outlines subparallel to the walls of inclusions indicating a constructional origin related to the inclusions rather than a relic of destructive resorption. I conclude that the patchy-zoned regions grew during episodes of greater supersaturation and faster crystal growth than the oscillatory zoned portions of the phenocrysts.

The following attributes suggest or are consistent with the presence of bubbles of vapor in the melt during growth of the patchy-zoned regions: (1) inclusions of gas are present within the patchy-zoned regions. Commonly the largest inclusions of gas are located adjacent to the inner boundary of the patchy-zoned region (Fig. 9). (2) The greater modal abundance of plagioclase in the first pulse of the eruption (Rose et al., 1978) can be explained by rafting of grains by attached bubbles. (3) The variation in Cl/K_2O ratio for inclusions of glass in plagioclase is consistent with degassing (Rose et al., 1978).

Probably the preferred location of gas bubbles against the inner margin of patchy-zoned regions is best explained by initial nucleation on the surface of the rapidly growing crystal of plagioclase because of an enhanced concentration of H_2O in the melt next to plagioclase from which it is rejected. Possibly the growth of the patchy-zoned regions was accompanied by accelerated effervescence of the magma, perhaps caused by comparatively rapid decompression.

Discontinuous zones, many of which lie inward and adjacent to some patchy-zoned regions (Fig. 10, and see p. 11), possibly mark an intermediate condition of supersaturation whereby zones start growth faster than they complete growth. The bright bands typical of discontinuous zones are consistent with greater than average supersaturation if supersaturation and composition are related as found by Lofgren (1947b).

Oscillatory-zoned regions

The evidence bearing on the mechanism of oscillatory zoning can be put in three categories: (1) textural evidence for growth influenced by surface attachment kinetics; (2) textural and compositional evidence for growth during vapor-saturated decompression and therefore ascending motion of magma; and (3) textural evidence for periodic changes in supersaturation. The evidence for each of the above is presented in sequence below.

Surface attachment kinetics. Growth influenced by surface attachment kinetics is suggested by three features. Individual zones are thicker where curvy or irrational as expected according to the relations between surface roughness and the rate of interface attachment (Hartman, 1973; Kirkpatrick, 1975). Individual zones are thinnest on (010) consistent with Dowty's (1976) prediction based on surface morphological considerations. Curvy zones are uncommon and generally succeeded outwards by within five or fewer zones by flat zones consistent with a stable interface without runaway bumps projecting into a strongly supersaturated region beyond a boundary layer (Sekerka, 1973).

Vapor saturation. The textural position of oscillatory zoned regions outside of and between patchy-zoned regions and the continuous decline in Cl/K_2O with increasing K_2O in melt inclusions are consistent with the presence of gas during growth of both kinds of regions, because once vapor saturation is attained an increase in pressure is required if it is to be redissolved. Probably the rate of generation of gas was less during growth of oscillatory zones than during growth of patchy-zoned regions; however, repeated increases as well as decreases in pressure cannot be ruled out for crystals within dynamical bodies of magma.

Periodic changes in supersaturation. Regions of patchy-zoning (including correlative incomplete zones and irregular zones) occur preferentially at or near zone numbers 25 and 50 (Fig. 13). The supersaturation of many crystals apparently went through a maximum at about zone 50 and again at about zone 25. Shortly after zone 1 formed the crystals were extruded. Thus major events in the growth of the plagioclase phenocrysts occurred at subequal intervals corresponding to about 25 oscillatory zones.

The origin of periodic changes in supersaturation is speculative and rests on auxilliary geological and volcanological data. The outer sodic rim may be related in time to the onset of eruptive outgassing and quenching which probably occurred on October 10, when the first eruption of steam occurred (Rose et al., 1978). October 10, 1974 was close to the fortnightly minimun (neap tide). The eruption times of Fuego corresponded to semidiurnal minima during the 1974 eruption (Martin and Rose, 1981). The eruptive behavior of Ngaruhoe is similar to Fuego and correlates with fortnightly minima (Michael and Christoffel, 1975). The descent of the Fernandina caldera floor occurred at 6 hour tidally correlated intervals (Filson et al., 1973). Tidal oscillations of Halemaumau lava lake occurred in 1919 (Shimozuru and Nakagawa, 1969). Extrusion and seismicity correlate with tides for the Islas Quemadas dome in 1879–1880 (Golombeck and Carr, 1978). Other similar correlations have been noted in other regions by Mauk and Johnston (1973) and Mauk and Kienle (1973). In short, tidal stresses appear to play a role in the rise and fall of material in volcanic regions. It is reasonable therefore to associate the 25 zone interval between the outer rim and the first major patchy-zoned or disturbed region with the 28 tides in a fortnight. Possibly each twice daily low tide triggers increments of magma ascent leading to definition of a zone. On or near the forthnightly minimum solid-earth tide, some magma may sprint upwards resulting in relatively large supersaturation and consequent transition to patchy-zoned growth and nucleation of patchy-zoned cores of crystals.

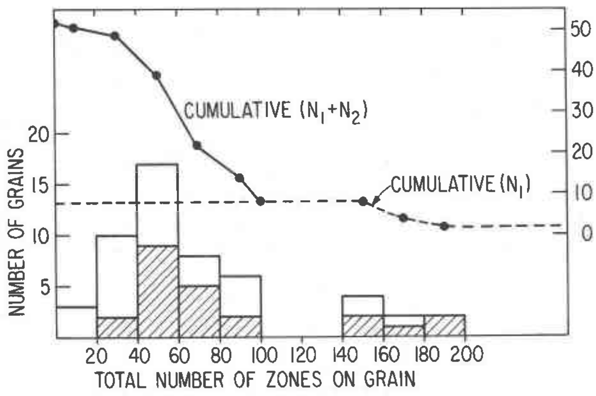

Fig. 15. Frequency of grains according to number of oscillatory zones. The 21 best etched grains are shown with pattern. Total distribution of 52 best and fairly etched grains is shown without pattern. Two groups are present: grains with 140 to 200 zones (group 1) and grains with 100 or fewer zones (group 2). The curves show the cumulative numbers of grains in the two groups with decreasing numbers of zones: N_1 = group 1, N_2 = group 2. The scale for the histogram is at left and the scale for the cumulative curves is at right.

Sodic rims

Virtually all of the phenocrysts of plagioclase have similarly thick rims (on {201} about 20 μm) with about 10 percent more albite component than the adjacent interior (An_{75} compared to An_{85}). Assuming that the effect of non-equilibrium undercooling on composition found by Lofgren (1974b) for plagioclase melts can be generalized to basaltic melts a supersaturation equivalent to an undercooling of about 40°C is implied. At such undercoolings Lofgren (1974b) found a transition to skeletal morphology consistent with the edge thickening and reentrant thinning evident for the sodic rims. Johannes (1978, 1980) has shown that the equilibrium plagioclase composition is sensitive to the SiO_2 content of the melt. Inasmuch as the residual liquid from which the sodic rims crystallized differs from the pure plagioclase plus H_2O system (the liquid has substantial normative qz, for example), it may be anticipated that the relations between plagioclase composition and undercooling of the actual melt will differ from those found by Lofgren. Although it is not possible to predict the actual relations in the natural magma, it is worthwhile to pursue the implications of Lofgren's results in order to show how such knowledge could be petrologically useful. The key idea is that an abrupt change in plagioclase composition can be taken as a measure of an impulse of supersaturation whether by sudden cooling or loss of H_2O. The latter process is pressure dependent: the same loss of H_2O at low pressure results in a larger supersaturation than if it occurred at higher pressure. Undercooling (supersaturation) caused by loss of H_2O seems more likely in the case of Fuego than a sudden and uniform thermal chilling of the whole body of magma. If the magma had negligible H_2O dissolved in it after the event of supersaturation, then a decompression of about 100 atmospheres would suffice to provide the undercooling (compare the effect of P_{H_2O} on plagioclase-out curves for andesitic liquids by Eggler, 1972 and Sekine et al., 1979). If 300 atmospheres of H_2O pressure remain after decompressive supersaturation then a decompression of about 200 atmospheres would be required. These figures are close to seismic estimates of the short term strength of rocks and plausibly relate to initial rupturing of the conduit to the surface on October 10, 1974 when the first major steam blast of the 1974 eruption occurred. A hypothetical pulse of effervescent decompression that possibly led to the abrupt decrease in An recorded by the sodic rims may have been comparable to those which possibly led to much smaller decreases in An recorded by the patchy-zoned regions.

A dynamical model for the origin of oscillatory zones

Oscillatory variations of composition evident in the phenocrysts of plagioclase from Fuego seem to rule out equilibrium causes of oscillatory growth, because the equilibrium composition is so insensitive to both pressure (0.5% An/1000 atm, Lindsley, 1968, and see discussion by Pringle et al., 1974), H_2O (1% An/1000 atm—Yoder et al. 1957; Johannes, 1978), and temperature (1%/10°C—Kudo and Weill, 1970; Drake, 1976). Consequently, unlikely changes in these parameters are implied by the more than 200 zones with an average of about 1% An or more change of composition within zones (see Anderson, 1983).

Although composition is not sensitive to supercooling either (about 2–3% An/10°C, Lofgren, 1974b; Loomis, personal communication, 1982) concentration gradients may amplify the effects. Variations in supersaturation are indicated by the variable growth modes: oscillatory and patchy zoning. Furthermore, some instances of oscillatory zoning seem related to motion of magma (Anderson, 1981; Anderson et al., 1982). The presence of roughly 25 zones between patchy-zoned regions suggests that oscillatory zones on Fuego's phenocrysts may be tidally triggered. Consequently, it seems plausible to seek an explanation of oscillatory zones connected with variable motion and supersaturation in the melt.

The idea advanced here is that pulses of motion within a body a magma result in a rearrangement of nearby crystals as a consequence of viscous shear past a stationary wall such as the wall of a dike. As a result of the shear each crystal is brought into a slightly new environment where it must compete with newly arranged crystal neighbors. During the shear pulse preexisting gradients of composition associated with the individual crystals are distorted and on the average the melt near each crystal is compositionally replenished. After the shear-pulse accelerated growth of relatively Ca-rich plagioclase occurs because the replenished melt is richer in Ca and more supersaturated.

The above model introduces an extrinsic dynamical mechanism to account for changes in either the rate of growth or the composition of new growth or both. The mechanism consists of pulses of shearing motion throughout the magma as suggested by precursory seismicity, eruptive episodicity and repetitious and partially correlative zoning textures of coextruded phenocrysts. The concept of concentration gradients in the melt next to growing crystals is adopted from earlier workers (see Bottinga et al., 1966; and Smith, 1974 for reviews; Hasse et al., 1980; Allegre et al., 1981; Lasaga, 1981, 1982 for recent treatments). The shear pulse mechanism differs both from the extrinsic dynamical mechanisms proposed by early workers (e.g., Paliuc, 1932) and from the intrinsic dynamical mechanism proposed recently by Loomis (1981). The early dynamical mechanisms which relied upon changes in pressure (or water pressure) and temperature in an equilibrium context (for example see Pringle et al., 1974) seem not feasible for micron-thick oscillatory zones in view of their large number and compositional amplitude. Loomis' (1981) mechanism of intrinsic face-specific fluid motion and the various static diffusional mechanisms are grain-specific; consequently, grain-to-grain correlations of zones would be largely accidental. In view of the imperfect grain-to-grain correlations a process with both a grain specific as well as a general or common aspect seems required. The shear-pulse mechanism is general but has a grain-specific aspect which arises because non-uniformly distributed crystals will develop geometrically distinct concentration gradients around individual crystals.

Loomis (1981) considered it possible that melt next to a growing crystal face might move in response to local composition-related gradients of density. He followed the treatment of this problem by Shaw (1974) who considered the velocity of fluid flow in a boundary layer next to a vertical wall of solidifying magma. In exploring the same approach I adopted the following values of various properties: length of crystal edge (1 mm), viscosity (710 poise), density (2.39 gm/cm^3), effect of crystallization of plagioclase on melt density

$$\left(0.06 = -\frac{1}{\rho}\frac{\Delta\rho}{\Delta \mathrm{An}}\right)$$

and diffusivity of anorthite (9×10^{-6} cm^3/sec) for the crystallizing Fuego basaltic melt with 3 wt.% H_2O at 1020°C. Two notable results are: (1) as also found by Loomis, a significant maximum velocity of melt movement is predicted to occur near a growing crystal edge. I estimated this to be 30 μm per day if a 2 μm thick layer of plagioclase is extracted from the intergranular melt at 10% crystallization, because the appropriate formulation of the non-dimensional density change term in the Rayleigh number is

$$\frac{1}{\rho}\frac{d\rho}{df}\Delta f$$

where f refers to the fraction of liquid remaining. In the calculation a 2 μm layer of new plagioclase corresponds to a Δf of 6×10^{-5}. Thus the liquid near to the crystal face is predicted to move faster than the crystal face is advancing. (2) The boundary layer in which movement is calculated to occur is predicted to be thicker than the distance between crystals, however. This is a consequence of the Rayleigh number being less than unity (about 0.06). The physical significance of this result seems to be that motion of the liquid near a growing crystal cannot occur without cooperation from neighboring crystals. In this case the viscosity is inappropriate, because suspensions have larger viscosity and probably are non-Newtonian. Thus a yield stress would need to be considered. I do not know how to handle such a complex problem but consider it likely that boundary layer melt next to growing crystals in a Fuego-like magma will move much slower than the 30 μm/day predicted rate because of the distributed drag related to the neighboring crystals.

The feasibility of extrinsically forced motions remains to be evaluated. There are two parts to the problem: (1) what will be the distance range of crystallization-related gradients of composition? (2) Will externally forced motions sufficiently reorganize the gradients? The range of composition gradients is at least a millimeter if the time between successive growth zones is of order 40,000 sec (12 hours) and if the gradient develops or relaxes approximately in accordance with the model of diffusion from a semi-infinite sheet with a boundary composition fixed by equilibrium with the crystal face (following Burton et al., 1953, and Lasaga, 1981). If there is an initially large concentration change for melt near the growing crystal, then the crystal grows fast for a short time and subsequently the concentration gradient largely relaxes before new growth begins. The distance out to which the gradient reaches depends mainly on the time between growth sprints and the diffusivity. In roughly 12 hours time the gradient reaches almost halfway to the neighboring crystal. As a consequence of the dimension of the gradient approximating the length of the crystals and the half-distance between them, a shearing motion of about

$$1 = \frac{\Delta l}{l}$$

will easily deform the region in which the gradient has half or more of its maximum value after 40,000 seconds.

The above analysis does not validate the shear pulse notion, however. This is because it is not known whether the distortion of the concentration gradients by the hypothetical shear pulse is a significant perturbation of the system. If growth is initially rapid (5 to 10 times the average rate), then the initial gradients associated with growth will be much larger than those remaining after

40,000 seconds of relaxation. Further destruction of the gradients by shearing motion would then seem to be of little consequence. If the growth rate varies only by a few percent as zones develop, then the shearing motions would be the major perturbations of the concentration gradients. The small variations in zone thickness from face-to-face, unzoned growth and the rarity of incomplete zones seem to me to be more consistent with the latter view. Accordingly, I think it is reasonable to suggest that tidally-triggered pulses of shearing motion in an ascending magma modulate oscillatory growth by periodically reorganizing weak gradients of composition associated with the growing crystals.

Finally we may ask: Is the accumulated shearing motion implied by 200 zones on some crystals consistent with the probable ascent of Fuego's magma? The thickness of Fuego's near surface feeding dike or conduit is probably less than about 20 meters (Rose et al., 1978). The total upward transport probably is at least 5 kilometers (Rose et al., 1978, and Harris, 1979). The total shear thus may be of the order of 5000/20 or 250. If there are some 200 pulses then the shear per pulse is of order unity. Because the crystals are about as far apart as they are large (Fig. 16), an average pulse with unit shear would place each crystal in the vicinity of a new neighbor, as implied by the model. If the shear were only 0.1 per pulse, it would be difficult to see how the motion would significantly perturb the boundary layer around an individual crystal.

There are several ways in which tidal stresses might trigger the ascent of magma. Tidal stresses could accelerate the propagation of cracks. Tidal stresses could trigger the fall of calderas (Filson et al., 1973) and other large blocks of crust into chambers of magma thereby displacing magma upward along conduits. Tidal stresses could trigger the accumulation or redistribution of tectonic stress in the vicinity of magma reservoirs thereby forcing magma toward the surface. Thus, the source of energy to move the magma upwards against gravity could be its own buoyancy, the potential energy of falling blocks, or stored tectonic strain.

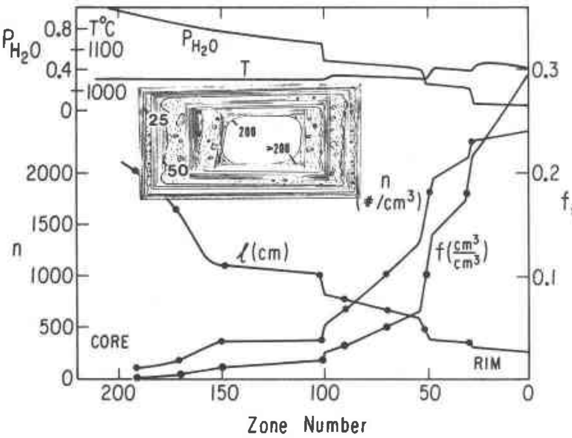

Fig. 16. Summary model of crystallization of plagioclase in the Fuego high alumina basalt of October 14, 1974. Plotted with respect to zone number are the temperature (T), water pressure (P_{H_2O}), average distance between the surfaces of neighboring crystals (l), the number of crystals per cm (n) and the volume fraction of plagioclase in the magma (f).

The curves for l, n and f are schematic but based on data given in Fig. 15. See text for details.

Summary of plagioclase crystallization

It is possible to infer a crude history of the nucleation and growth of the plagioclase phenocrysts, if it is assumed that the outermost zone (zone 1) on each crystal is contemporaneous and the other zones measure time similarly on all crystals. Thus the crystals with the largest number of zones are assumed to have been in the magma longest and the crystals with patchy-zoned cores and smaller numbers of zones are assumed to have nucleated later, closer in time to extrusion. The relative number of crystals with various total numbers of zones is taken to reveal the increase in the accumulated number (n) of crystals per cm^3 of magma as a function of time (decreasing zone number).

It is important to stress that time is measured backward with zone number. This was the only effective way to proceed, because the most justifiable assumption is that the rims of all crystals are coeval.

A simple model was adopted to compute relations between the crystal size (a), spacing (l), and number density (n) and the total crystal fraction (f). According to the model the magma contains regularly spaced cubical grains which vary in size and proportion with time (zone number) as indicated by observed proportions of crystals with various numbers of zones and sizes. Zones are taken to be equally thick on all grains. The equations are:

$$\frac{1}{f} = 1 + 3\frac{l}{a} + 3\left(\frac{l}{a}\right)^2 + \left(\frac{l}{a}\right)^3 \qquad (1)$$

$$f = n\,a^3 \qquad (2)$$

The results were obtained by combining increments of crystallization due to the large crystals with more than 140 zones and increments due to crystals with fewer than 100 zones. The results rely on the data presented in Figure 15 for 52 grains of plagioclase and on a final fraction of plagioclase in the magma at extrusion of 0.3 as measured in large lapilli, a crystal edge of 0.02 cm for both the non-oscillatory zoned cores of the large crystals and the patchy-zoned cores of the other crystals, and 0.06 cm and 0.05 cm for the final cubical edges of big crystals and the average crystal.

The modeled values of the various parameters are depicted in Figure 16. The curves are schematic in detail, because values were calculated for large intervals of zones corresponding to Figure 15. Various kinks in the curves reflect an attempt to portray bursts of nucleation and growth of patchy-zoned material. As crystallization increases from zone 200 to zone 1, the volume fraction of plagioclase (f) in the void-free magma increases from 0 to 0.3 in a crudely exponential way reflecting both the increased number (n) of crystals and their increased size. This is the expected result of the model which assumes equal thickness for successive zones. The area of crystal surface increases exponentially with crystal growth and is further augmented by additional nucleation. Thus the modeled increment of total crystallization corresponding to zone 40 (for example) is more than twice that corresponding to zone 100. Average zone thickness does decrease slightly toward the rim of many crystals (Figs. 7 and 8), but the increasing total surface area due to the increase in the number density of crystals is so large that a general increase in total crystallization per zone is probable with progressive crystallization, if the assumption of contemporaneity of zones is roughly correct.

The average size of the phenocrysts of plagioclase increases irregularly with crystallization from 0.02 cm to 0.05 cm. It should be recognized that there is no requirement that the average grain size increase with crystallization. A large proportion of small, late grown grains would result in a decrease in average grain size. Many small crystals are indeed present but these are considered to constitute a separate microphenocryst population coeval with the sodic rims on the phenocrysts. It should be recalled, however, that the ash sample is air winnowed; consequently phenocrysts smaller than about 0.05 cm may be underrepresented in the sample. It is nevertheless the case that, for the population of 52 crystals, the grain size increases with an increasing proportion of crystals with fewer than 100 zones. This relation is a consequence of the initial growth of patchy-zoned cores which constitute the bulk of the grains. It seems likely that crystals with relatively few zones have comparatively large patchy-zoned cores; however, the possible effect of winnowing on this relation also needs more study.

Accompanying crystallization of the Fuego plagioclases were probable changes in temperature and water pressure. The curves plotted on Figure 16 although constrained by various facts are schematic and are intended primarily to convey the idea of pulses of nucleation and patchy-zoned crystallization (and temporary storage of released latent heat) associated with episodes of rapid decompression (and H_2O effervescence). The curves are roughly self-consistent. For example a burst of crystallization of 5 percent corresponds to a release of latent heat of about

$$80 \text{ cal/gm} \times \frac{.05 \text{ gm}}{\text{gm}}$$

or 4 cal/gm of magma yielding a warming of less than about

$$4 \frac{\text{cal}}{\text{gm}} / 0.2 \text{ cal/gm}^\circ$$

or 20°C. (A small but uncertain fraction of the released latent heat is consumed by the effervescence process [Harris, 1980, 1981]). With crystallization, transitory increases in temperature are assumed to associate with abrupt decreases in P_{H_2O} and increases in fraction of plagioclase (f). The initial and final temperatures for the Fuego magma are based on olivine/glass compositional data evaluated in the light of data by Roeder (1974), Anderson and Sans (1975), and Yoder and Tilley (1962) and explained by Rose et al. (1978). The maximum P_{H_2O} is based on Harris' (1980) results, and the minimum is assumed to be 1 atm. I assumed that a given decrease in P_{H_2O} would yield a greater fraction of crystallization and heating at lower pressures than at higher pressures, but made no attempt to scale the relations in view of particular experimental melting curves. The essential features of Figure 16 are the general trends and the existence of at least three separate kinks corresponding to bursts of patchy-zoned growth. These may be related to the zoned crystal sketched in Figure 16. I think it is likely that the bursts of patchy-zoned plagioclase reflect tidally triggered acceleration of ascent, but this is not an essential feature of Figure 16.

For the Fuego phenocrysts the transition from non-oscillatory zoned cores with round corners to oscillatory and patchy-zoned regions is plausibly related to the initial transfer of a small portion of magma from a large body with suspended crystals of non-oscillatory zoned plagioclase upwards into a thin conduit with concomittant rounding of corners by resorption caused by decompression of a hydrous magma not saturated with a H_2O-rich gas (Fig. 16). Subsequently with pulsed ascent within the thin conduit crystals plausibly grew oscillatory zones as pulses of upward motion sheared the crystals past each other and deformed their compositional boundary layer of surrounding melt. Finally the largely degassed Fuego magma stiffened, fractured and lost a final burst of gas (probably on or about October 10, 1974) prior to eruption yielding a large supersaturation and consequent crystallization of sodic rims and microphenocrysts which have barely discernible oscillatory zones. Increase in gas pressure caused by the microphenocryst crystallization opened the vent and blew out the upper part of the magma body on October 14, 1978. In my model the oscillatory zoning of the plagioclase phenocrysts is related to the dynamical ascent of the magma in a way that is suggested by volcanological, textural, mineralogical and glass inclusion data.

Conclusions

My principal conclusion is as follows: the 1 μm thick oscillatory zones on the Fuego plagioclase probably are like the ticks of a clock. Various textural and compositional features provide circumstantial evidence supporting a triggered mechanism for the clock: pulses of motion modulate growth. Growth is rate limited by interface attachment kinetics and yields concentration gradients in the melt which result in decreasing An outward within each zone. Reading the zones as ticks of a clock faces the problem that not all forms of the crystal tick at the same rate, but several fast growing forms ($\{\bar{2}01\}$, $\{110\}$, $\{1\bar{1}0\}$) tick at about the same rate. Development of 1 μm thick zones on the Fuego plagioclase appears restricted to growth rates less than those for patchy zoning (interface instability) and greater than those for the non-oscillatory-zoned interiors of grains. The interpretation is that the Fuego plagioclase grew at linear rates of 0.2 to 25 μm per day, consistent with the notion that most 1 μm scale zones on fast growing forms reflect tidally triggered pulses of shearing motion within the magma.

Acknowledgments

I thank W. I. Rose for giving me the ash samples to study and for encouragement and stimulating discussion. My student, David Harris, provided many helpful discussions. Victor Barcilon, Frank Richter, Roscoe Braham, and Ramesh Srivastava helped sharpen my thinking about tidal mechanisms, correlations and growth of raindrops and crystals. The book by J. V. Smith (1974) was an invaluable source throughout my study. I thank J. V. Smith for the loan of his universal stage and T. Peterson for help with the SEM. Part of this research was supported by NSF grants EAR76-15016 and EAR79-26485. I thank Y. Bottinga for careful and penetrative criticisms of earlier drafts of this manuscript, and T. Grove, T. Loomis, and W. Melson for helpful suggestions on the last draft.

References

Allegre, C. J., Provost, A., and Jaupart, C. (1981) Oscillatory zoning: pathological case of crystal growth. Nature, 294, 223–228.

Anderson, A. T., Jr. (1981) Micron thick oscillatory zones on plagioclase: A volcanological clock (abstr.). Geological Society of America, Abstracts with Programs, 13, 396.

Anderson, A. T., Jr. (1983) Oscillatory zoning of plagioclase: Nomarski interference contrast microscopy of etched polished sections. American Mineralogist, 68, 125–129.

Anderson, A. T., Jr., Friedman, R., Otto, J., Vander Wood, T., and Wyszynski, J. (1982) Fractional crystallization of plagioclase in the Hat Creek basalt: observations and theory. Journal of Geology, 90, 545–558.

Anderson, A. T., Jr. and Sans, J. R. (1975) Volcanic temperature and pressure inferred from inclusions in phenocrysts. International Geothermometry and Geobarometry Symposium, Pennsylvania State Univ. (abstr.).

Bottinga, Y., Kudo, A., and Weill, D. (1966) Some observations on oscillatory zoning and crystallization of magmatic plagioclase. American Mineralogist, 51, 792–806.

Burton, J. A., Prim, R. C., and Slichter, W. P. (1953) The distribution of solute in crystals grown from the melt. Part I. Theoretical. Journal of Physical Chemistry, 21, 1987–1991.

Dowty, E. (1976) Crystal structure and crystal growth: I. The influence of internal structure on morphology. American Mineralogist, 71, 448–459.

Drake, M. J. (1976) Plagioclase-melt equilibria. Geochimica et Cosmochimica Acta, 40, 457–465.

Eggler, D. H. (1972) Water-saturated and undersaturated melting relations in a Paricutin andesite and an estimate of water content in the natural magma. Contributions to Mineralogy and Petrology, 34, 261–271.

Ewart, A. (1963) Petrology and petrogenesis of the Quarternary pumice ash in the Taupo area, New Zealand. Journal of Petrology, 4, 392–431.

Filson, J., Simkin, T., and Leu, L.-K. (1973) Seismicity of a caldera collapse: Galapagos Islands 1968. Journal of Geophysical Research, 78, 8591–8622.

Golombeck, M. P. and Carr, M. J. (1978) Tidal triggering of seismic and volcanic phenomena during the 1879–1880 eruption of Islas Quemadas volcano in El Salvador, Central America. Journal of Volcanology and Geothermal Research, 3, 299–307.

Haase, C. S., Chadam, J., Feinn, D., and Ortoleva, P. (1980) Oscillatory zoning in plagioclase feldspar. Science, 209, 272–274.

Harloff, C. (1927) Zonal structure in plagioclase. Leidsche geologische Meddelungen, 2, 99–114.

Harris, D. M. (1979) Pre-eruption variations of H_2O, S, and Cl in a subduction zone basalt (abstr.). American Geophysical Union, Transactions, 60, 968.

Harris, D. M. (1981a) Vesiculation and eruption of a subduction zone basalt (abstr.). American Geophysical Union, Transactions, 62, 1084.

Harris, D. M. (1981b) The concentrations of H_2O, CO_2, S and Cl during pre-eruption crystallization of some mantle-derive magmas: implications for magma genesis and eruption mechanisms. Ph.D. Dissertation, The University of Chicago, 223 p.

Hartman, P. (1973) Structure and morphology. In P. Hartman, Ed., Crystal growth: an introduction, p. 367–402. North Holland, Amsterdam.

Hills, E. S. (1936) Reverse and oscillatory zoning in plagioclase feldspars. Geological Magazine, 73, 49–56.

Johannes, W. (1978) Melting of plagioclase in the system Ab–An–H_2O and Qz–Ab–An–H_2O at P_{H_2O} = 5 kbars, an equilibrium problem. Contributions to Mineralogy and Petrology, 66, 295–304.

Johannes, W. (1980) Metastable melting in the granite system Qz–Or–Ab–An–H_2O. Contributions to Mineralogy and Petrology, 72, 73–80.

Kirkpatrick, R. J. (1975) Crystal growth from the melt: a review. American Mineralogist, 60, 798–814.

Kudo, A. M. and Weill, D. F. (1970) An igneous plagioclase thermometer. Contributions to Mineralogy and Petrology, 25, 52–65.

Lasaga, A. C. (1981) Implications of a concentration-dependent growth rate on the boundary layer crystal-melt model. Earth and Planetary Science Letters, 56, 429–434.

Lasaga, A. C. (1982) Toward a master equation in crystal growth. American Journal of Science, 282, 1264–1288.

Lindsley, D. H. (1968) Melting relations of plagioclase at high pressures. In Y. W. Isachsen, Ed., Origin of anorthosite and related rocks. New York State Museum and Science Service, Memoir 18, 39–46.

Lofgren, G. (1974a) Temperature induced zoning in synthetic plagioclase feldspar. In W. S. MacKenzie and J. Zussman, Eds., The Feldspars, p. 362–375. Manchester University Press.

Lofgren, G. (1974b) An experimental study of plagioclase crystal morphology: Isothermal crystallization. American Journal of Science, 274, 243–273.

Loomis, T. P. (1981) An investigation of disequilibrium growth processes of plagioclase in the system anorthite–albite–water by methods of numerican simulation. Contributions to Mineralogy and Petrology, 76, 196–205.

Loomis, T. P. (1982) Numerical simulations of crystallization processes of plagioclase in complex melts: the origin of major and oscillatory zoning of plagioclase. Contributions to Mineralogy and Petrology, 81, 219–229.

Martin, D. P. and Rose, W. I., Jr. (1981) Behavioral patterns of Fuego Volcano, Guatemala. Journal of Volcanology and Geothermal Research, 10, 67–81.

Mauk, F. J. and Johnston, M. J. S. (1973) On the triggering of volcanic eruptions by earth tides. Journal of Geophysical Research, 78, 3356–3362.

Mauk, F. J. and Kienle, J. (1973) Microearthquakes at St. Augustine volcano, Alaska, triggered by earth tides. Science, 182, 386–389.

Michael, M. O. and Christoffel, D. A. (1975) Triggering of eruptions of Mt. Ngauruhoe by fortnightly earth tide maxima, January 1972–June 1974. New Zealand Journal of Geology and Geophysics, 18, 273–277.

Paliuc, G. (1932) Untersuchungen der Plagioklase einiger tertiärer Ergussgesteine Siebenbürgens (Rumänien) mittelst der Universaldrehtischmethode. Schweizerische mineralogische und petrographische Mitteillungen, 12, 423–444.

Pringle, G. J., Tembeth, L. T., and Pajari, G. J., Jr. (1974) Crystallization history of a zoned plagioclase. Mineralogical Magazine, 39, 867–877.

Rose, W. I., Anderson, A. T., Bonis, S., and Woodruff, L.(1978) The October 1974 basaltic tephra from Fuego volcano Guatemala: description and history of the magma body. Journal of Volcanology and Geothermal Research, 4, 3–53.

Sekerka, R. F. (1973) Morphological stability. In P. Hartman, Ed., Crystal growth: an introduction, p. 403–443. North Holland, Amsterdam.

Sekine, T., Katsura, T., and Aramaki, S. (1979) Water saturated phase relations of some andesites with application to the estimation of the initial temperature and water pressure at the time of eruption. Geochimica et Cosmochimica Acta, 43, 1367–1376.

Shaw, H. R. (1974) Diffusion of H_2O in granitic liquids: Part I, experimental data; Part II, Mass Transfer in magma chambers. In A. W. Hofmann, B. J. Giletti, H. S. Yoder, Jr., and R. A. Yund, Eds., Geochimical Transport and Kinetics, p. 000–000. Carnegie Institute of Washington, Publication 634.

Shimozuru, D. and Nakagawa, I. (1969) Tidal oscillation of Halemaumau lava lake, Kilauea, Hawaii and its implication for existence of a magma reservoir. Proceeding of the Sixth International Symposium of the Earth Tide, Strasburg.

Sibley, D. F., Vogel, T. A., Walker, B. M., and Byerly, G. (1976) The origin of oscillatory zoning in plagioclase: a diffusion and growth controlled model. American Journal of Science, 276, 275–284.

Smith, J. V. (1974) Feldspar Minerals, vol. 2, Chemical and textural properties. Springer-Verlag, Berlin.

Vance, J. A. (1965) Zoning in igneous plagioclase: patchy-zoning. Journal of Geology, 73, 636–651.

Yoder, H. S., Stewart, D. B., and Smith, J. R. (1957) Ternary feldspars. Annual Report Dir. Geophysical Laboratory, Carnegie Institute of Washington Year Book 56, 206–214.

Manuscript received, May 7, 1982;
accepted for publication, March 5, 1984.