

TEXTURES AND GENESIS OF PHENOCRYSTS AND MEGACRYSTS IN BASALTIC LAVAS FROM THE PINACATE VOLCANIC FIELD

JAMES T. GUTMANN

Department of Earth and Environmental Sciences,
Wesleyan University, Middletown, Connecticut 06457

ABSTRACT. The Pinacate volcanic field, Sonora, Mexico, contains alkali basalts and hawaiites of Pleistocene age. These rocks are characterized by the presence of phenocrysts and megacrysts of labradorite, olivine, and, in much lesser abundance, calcic augite and magnetite. In contrast to many other suites of megacrysts described from mafic, alkaline lavas elsewhere, subhedral to euhedral crystals of plagioclase dominate both phenocryst and megacryst assemblages volumetrically, and the plagioclase megacrysts are among the most *calcic* feldspars, or nearly so, in their host units. The labradorite megacrysts, which are as much as 10 cm long in some units, grade continuously downward in size into phenocrysts and microphenocrysts. Many of these smaller crystals are as calcic as the associated megacrysts, although others exhibit re-sorbed cores ranging downward in anorthite content to calcic andesine.

The compositions of the lavas cannot be derived from one another by addition and subtraction of olivine and plagioclase. The groundmasses of rocks rich in coarse labradorite crystals are correspondingly depleted in plagioclase. The gem-quality labradorite megacrysts, which are in fact megaphenocrysts, contain primary tubular fluid inclusions of large size and probably grew within the upper crust concomitant with evolution of fluid from adjacent silicate melt. Many of the phenocrysts *and megacrysts* exhibit skeletal crystal forms typical of rapid growth from melts moderately to strongly supersaturated with crystalline phases.

A petrogenetic model for near-surface crystallization in rising magmas is proposed. This model involves evolution of water from the melts, perhaps initially by partitioning into a separate, CO₂-rich, fluid phase. Supersaturation promoted by this exsolution of water may be nil or only slight at first but evidently induced formation of numerous skeletal crystals, some more than 1 cm long, at depths within or not far below the Pinacate volcanic pile. Caution is indicated in interpreting the textures and paragenesis of coarse crystals in volcanic rocks.

INTRODUCTION

The Pinacate volcanic field is located in northwestern Sonora, Mexico, east of the northern end of the Gulf of California. The field contains more than 650 flows of alkali basalt and hawaiite within its 2000 km² area. Many of these volcanic rocks are of late Pleistocene age. Pyroclastic activity was especially abundant in the field as evidenced by the presence of more than 300 cinder cones. The flows are moderately to highly vesicular and are characterized by the presence of coarse crystals of labradorite, olivine, augite, and magnetite. The labradorite crystals attain as much as 10 cm in maximum dimension, and the other phases attain comparable, albeit lesser, dimensions. The term "megacrysts" shall herein denote those crystals greater than 0.5 cm in maximum dimension, whereas the other crystals larger than groundmass grain size are referred to as "phenocrysts." The term "coarse crystals" is used here to refer to phenocrysts and megacrysts combined.

Considerable attention is devoted in recent literature to the origin and implications of large crystals (megacrysts) in basaltic volcanic rocks (for example, Binns, Duggan, and Wilkinson, 1970; Irving, 1974; Knutson and Green, 1975). The purpose of this paper is to describe the occur-

rence of the phenocrysts and megacrysts in Pinacate lavas and their relationships to one another and to crystals of the groundmass. It will be shown that the preponderance of the Pinacate megacrysts evidently grew from the liquids whose other crystalline products now enclose them. Thus, they are truly megaphenocrysts. Furthermore, the coarse crystals in these rocks exhibit a remarkable array of textural peculiarities which, together with compositional and other data, suggest that some were derived from considerable depth, whereas others were not and may have grown at very shallow depth indeed.

The data given here represent rocks from various parts of the Pinacate volcanic field, although much of the chemical data comes from rocks in the eastern portion of the field, mainly at and near Crater Elegante, a large, maar-like depression which formed chiefly by caldera collapse.

Published reports on the Pinacate volcanic field include a general description of the collapse depressions (Jahns, 1959) and a description of tubular fluid inclusions in the coarse crystals of labradorite (Gutmann, 1974). The volcanic field was described and mapped at a scale of 1:62,500 by Donnelly (ms). Gutmann (1976) described the eruptive history of Crater Elegante and the field relationships among the volcanic units there; many of these units are referred to in the present paper.

GENERAL PETROGRAPHY OF THE LAVAS

The average thickness of the Pinacate flows is about 5 m, although some are less than 0.5 m thick locally. Their tops commonly are aa surfaces. Most of the flows can be traced sourceward to a vent complex marked by a cinder cone. The groundmasses of the flows typically are holocrystalline with intergranular or, less commonly, subophitic texture. The average volumetric abundance of the major groundmass constituents of seven relatively aphyric flows at Crater Elegante is: labradorite-andesine, 57 percent; augite, 19 percent; olivine (typically Fe_{70-80}), 14 percent; magnetite plus ilmenite, 9 percent. Apatite and traces of alkali feldspar complete the bulk of the primary mineral assemblage.

TABLE 1
Abundance of coarse crystals in eight chemically
analyzed lavas from Crater Elegante

Sample number Volcanic unit*	J-5 w	J-6 d	J-7 lb ₃	J-8 lb ₂	PE-31a ubc	PE-32 lbc	PE-172 gc	PE-173 lb ₁
groundmass	69	66	96	99	66	70	93	92
plag > 0.25 cm	12	17	1	0	12	4	2	3
plag < 0.25 cm	14	11	2	0.5	16	19	3	4
olivine	5	5	1	0.7	5	2	2	1
augite	0.6	0.7	0.1	0	1	2	0.2	tr
magnetite	tr	0.2	0.1	0	0.3	3	0.1	0.1

* Symbols for volcanic rock units correspond with those used to identify map units by Gutmann (1976). In particular, w denotes The Wedge intrusion; d is a composite dike; ubc and lbc are upper and lower members of the brown cinders; gc, gray cinders; and lb_{1,2,3} are flows exposed in the crater walls.

The abundance of crystals larger than groundmass size in eight analyzed Elegante lavas is presented in table 1. For plagioclase crystals, the data are divided between crystals greater than and less than 0.25 cm in maximum dimension. The modal data were gathered by point counting 3 to 6 thin sections and several sawed slabs of each rock unit. The data pertaining to a composite dike (described by Gutmann, 1976) were obtained from numerous thin sections and slabs representing different parts of this texturally heterogeneous intrusion; the results were weighted and combined to reflect the bulk composition of the dike as represented by the bulk chemical analysis given in table 2.

Plagioclase is by far the dominant constituent in all these assemblages of coarse crystals with the exception of the most nearly aphyric unit (flow lb₂; analysis J-8 in table 2), wherein olivine predominates. Among the numerous Pinacate flows of which the phenocryst contents

TABLE 2
Compositions* and CIPW norms** of eight lavas from Crater Elegante

Volcanic unit*** Sample Number	w	d	lb ₃	lb ₂	ubc	lbc	gc	lb ₁
	J-5	J-6	J-7	J-8	PE-31a	PE-32	PE-172	PE-173
SiO ₂	49.82	48.83	47.24	47.31	49.0	49.0	47.0	46.8
TiO ₂	2.27	2.04	3.39	2.82	2.37	2.60	2.83	2.90
Al ₂ O ₃	15.75	18.72	15.58	16.27	18.1	17.6	16.8	17.2
Fe ₂ O ₃	1.73	1.27	9.14	5.62	4.9	12.1	7.1	5.4
FeO	9.66	7.68	5.09	7.04	6.06	0.78	5.34	7.39
MgO	6.43	5.64	4.25	5.38	5.02	3.96	5.15	5.37
MnO	0.23	0.13	0.21	0.18	0.18	0.20	0.19	0.18
CaO	9.34	10.93	7.70	8.80	8.55	7.72	8.57	9.13
SrO	—	—	—	—	0.053	0.055	0.053	0.053
BaO	—	—	—	—	0.037	0.052	0.035	0.025
Na ₂ O	3.45	3.56	3.94	3.62	4.02	4.24	4.05	3.95
K ₂ O	0.98	0.90	1.62	1.25	1.53	1.71	1.52	1.21
P ₂ O ₅	0.38	0.34	0.59	0.49	0.48	0.73	0.54	0.50
H ₂ O ⁺	0.05	0.14	0.63	0.72	—	—	—	—
H ₂ O ⁻	0.01	0.03	0.32	0.37	—	—	—	—
Total	100.10	100.21	99.70	99.87	100.3	100.7	99.2	100.1
q	—	—	0.04	—	—	—	—	—
or	5.79	5.32	9.57	7.39	9.04	10.11	9.06	7.15
ab	29.19	25.47	33.34	30.63	32.97	35.88	31.45	28.37
an	24.60	32.44	20.04	24.45	26.82	23.94	23.38	25.63
ne	—	2.52	—	—	0.56	—	1.69	2.74
di	15.82	16.00	11.13	12.79	10.12	3.57	12.59	13.32
hy	5.20	—	5.42	2.87	—	6.30	—	—
ol	11.74	11.79	—	6.01	8.03	1.34	4.98	8.38
mt	2.51	1.84	7.27	8.15	7.05	—	9.71	7.82
he	—	—	4.13	—	—	12.13	0.43	—
il	4.31	3.87	6.44	5.36	4.50	2.08	5.42	5.51
sph	—	—	—	—	—	3.70	—	—
ap	0.90	0.81	1.40	1.16	1.14	1.73	1.29	1.18

* Analysts: J-5 through J-8: Don Maynes (chiefly gravimetric); PE-31a through PE-173: Norman H. Suhr (chiefly spectrometric).

** CIPW norms calculated from analyses as reported.

*** For explanation of symbols, see table 1.

were estimated both in the field and in thin section by Donnelly, none lack olivine phenocrysts whereas three carry phenocrysts only of olivine (Donnelly, ms, app A, B). Evidently olivine was the primary low-pressure liquidus phase in at least some Pinacate lavas. However, plagioclase is the most abundant phenocryst in the vast majority of Pinacate basalts. Plagioclase also is by far the dominant phase, volumetrically, within the *megacryst* fraction of all or nearly all the coarse-crystal assemblages observed by the writer.

The augite and magnetite phenocrysts and megacrysts occur in much lesser amounts than do plagioclase and olivine. Augite is the most abundant phenocrystic phase in only one among hundreds of flows, is rare in most, and is absent from many (Donnelly, ms). Coarse crystals of magnetite are even more scarce.

Chemical analyses and CIPW norms of eight lavas from Crater Elegante are presented in table 2. The color indices of the rocks range from 39 to 47 with an average value of 43. These indices together with the basic character of the rocks ($\text{SiO}_2 = 47\text{-}50$ percent) suggest classification as basalts. Total content of alkalis (4.4-6.0 percent) relative to silica places the bulk compositions well within the "alkalic" field of Macdonald and Katsura (1964). However, the normative plagioclase most commonly is andesine (average value An_{45}), and the ratio $\text{Na}_2\text{O}:\text{K}_2\text{O}$ invariably is significantly greater than 2. Thus, most of the lavas fit the criteria for hawaiites given by Macdonald (1960) and should be classified as such, although they are somewhat poorer in alkalis and richer in MgO than are most hawaiites (compare Thompson, 1973, 1974). The rock analyses of Donnelly (ms) suggest classification as hawaiites of many more lavas in the Pinacate field; only a small fraction of these rocks contain normative labradorite and are alkali basalts.

SIZE DISTRIBUTION OF THE CRYSTALS

The Pinacate lavas are most spectacularly porphyritic with respect to their contained plagioclase crystals. The labradorite crystals in some units attain at least 10 cm in maximum dimension. The olivine crystals can be as much as 3 cm long, although most are less than 1 cm in length. Crystals of augite observed in Elegante lavas rarely exceed 2 cm in maximum dimension, but individuals at least 7 cm across occur in other parts of the volcanic field. The magnetite crystals evidently do not exceed 1.5 cm in length.

The labradorite megacrysts always occur in association with numerous smaller crystals of plagioclase. Those units with especially large and abundant labradorite megacrysts tend to contain an unusually high proportion of phenocrysts as well, although exceptional units do occur. The lavas are seriate, rather than hiatal, feldspar porphyries. Their plagioclase crystals appear to grade smoothly and continuously downward in size from the largest crystals present to crystals of *groundmass* size in each rock. The distinction between the smallest phenocrysts and the largest

groundmass crystals in any sample is essentially arbitrary, even in pyroclastic ejecta.

In order to test the smoothness of this seriate variation, the size distribution of plagioclase crystals apparent in outcrops of each of several volcanic units was determined quantitatively with the aid of mapping on photographic enlargements at scales approaching 1:1. The results, which will be discussed in detail elsewhere, indicate that no hiatus in maximum dimension separates the largest feldspar crystals present from crystals of the groundmass; furthermore, they suggest that the volumetric abundance of plagioclase crystals in a given size range increases logarithmically as mean size decreases.

Crystals of olivine also appear to exhibit a seriate size distribution, and the size distinction between small phenocrysts and groundmass grains is similarly arbitrary. This situation is especially perplexing in one nearly aphyric flow (lb₂ of Gutmann, 1976), wherein scattered olivine crystals about 1 mm across are not much larger than many olivine grains in the relatively coarse-grained groundmass and may represent products of intratelluric crystallization in part or not at all. Some of these 1 mm olivine crystals include one or more minute laths of plagioclase near their cores. Even some of the larger olivine crystals in this unit, which are as much as 2 mm across, are aggregates of several smaller grains, differing very slightly from one another in orientation, but together comprising a patchwork crystal with essentially euhedral external form.

In contrast to the problem posed by crystals of plagioclase and olivine, the distinction between phenocryst and groundmass grains generally is obvious for crystals of augite and magnetite. These phases occur only in very minor amounts in most units and are absent from many; typically, their crystal outlines are subhedral or anhedral, and many show embayments. An outstanding exception to these generalizations is provided by the rocks of one pyroclastic unit (brown cinders of Gutmann, 1976) and a related lava flow (ub₁). Both lower and upper members of the brown cinders are exceptionally rich in coarse crystals (30 and 34 percent, respectively) and contain more phenocrystic augite and magnetite than nearly any other unit. Many of the magnetite crystals are euhedral to skeletal, and numerous augite crystals, including megacrysts up to 2 cm long, are perfectly euhedral and exhibit sharp, unresorbed edges and corners. Furthermore, these rocks apparently are seriate porphyries with respect to augite and perhaps to magnetite, although most of the lavas are not.

COMPOSITIONS OF THE CRYSTALS

The compositions of plagioclase crystals were estimated by the four-axis universal stage method of Turner, as revised by Slemmons (1962), and by refractive indices. Precision and accuracy of the results for twelve megacrysts was judged by comparison with their true compositions as determined by complete chemical analyses (Gutmann and Martin, 1976). Anorthite contents estimated by the Turner method agree very well with

the chemical data. Surprisingly, anorthite contents obtained via x' refractive indices of cleavage flakes are systematically 2 to 5 percent An in excess of true values; the discrepancies vary directly with the total amounts of ferrous and ferric iron plus magnesium plus titanium in these crystals, totals that are as much as 0.73 wt percent. Accordingly, comparison of the plagioclase compositions is based solely on data obtained with a universal stage. This method has the added advantage of permitting compositional determinations of very numerous crystals both of large and of microscopic size. The variation of crystal core composition with maximum dimension of the plagioclase crystals is shown for two volcanic units in figure 1.

The labradorite megacrysts show little compositional variation among themselves in each volcanic unit. In marked contrast to the sodic plagioclases typically observed in high-pressure megacryst assemblages (for ex-

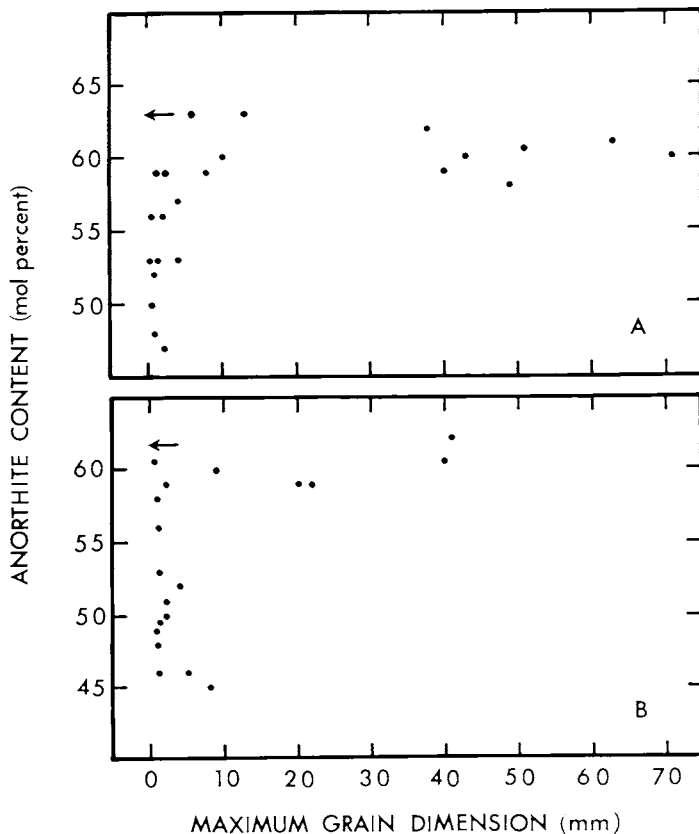
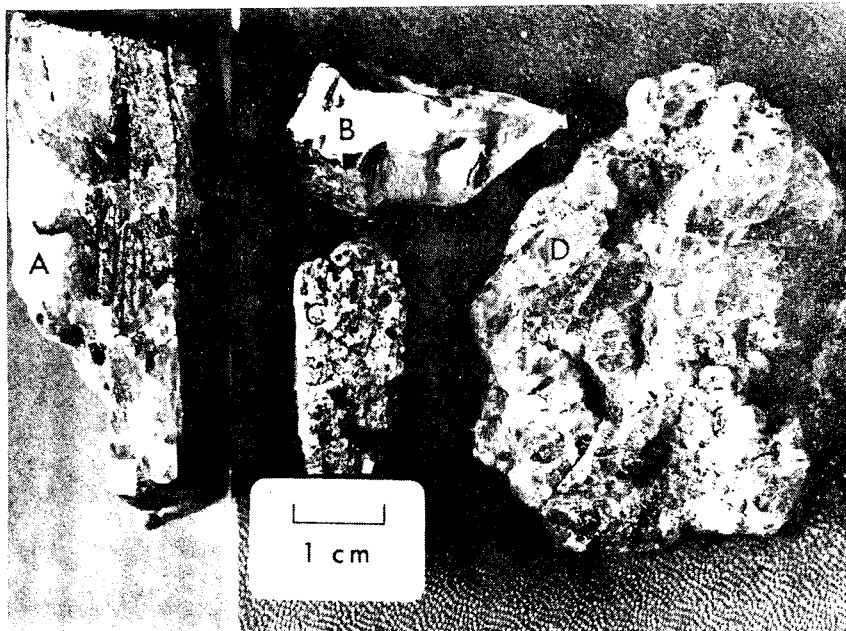


Fig. 1. Variation with crystal size of the compositions of cores of coarse plagioclase crystals in two lavas from Crater Elegante, Pinacate volcanic field. (A) Crystals from upper brown cinders of Gutmann (1976). (B) Crystals from gray cinders. Most calcic feldspar in groundmass of each rock is denoted by an arrow.

PLATE 1



Labradorite megacrysts from cinder cones of the Pinacate volcanic field. (A) Crystal with set of platy inclusions of basaltic glass oriented parallel to (010). (B) Fragment of crystal of gem quality. (C) Crystal riddled with inclusions of basaltic glass. (D) Crystal with blocky surface texture.

ample, Laughlin, Manzer, and Carden, 1974), the Pinacate megacrysts are very nearly the most *calcic* feldspars in their host units.

Many of the labradorite megacrysts are colorless to pale citrine and of gem quality (pl. 1-B). Their cores commonly are quite homogeneous in composition. Oscillatory zoning on a very fine scale is discernible just before extinction in some of these crystals, however, and broad zones are present in others. A few apparently are unzoned. The compositional variation within megacryst cores is less than 1 or 2 percent anorthite in many specimens. Paper-thin rims, if present, are more calcic by 1 to 3 percent An or more sodic by at least as much as 8 percent An than cores. Some of the plagioclase megacrysts are riddled with inclusions of vesicular basaltic glass or groundmass material (pl. 1-C); such crystals are strongly zoned with zones trending parallel to the margins of adjacent inclusions of melt.

The compositions of cores of the plagioclase *phenocrysts* (crystals less than 0.5 cm across) span a broad range (13-17 percent An) in each of six volcanic units studied in detail. Much of the compositional range in a volcanic unit can be inferred from crystals in any one thin section of that unit. The cores of many phenocrysts are enclosed within rims that can be either more sodic or more calcic than the cores. However,

calcic rims predominate. Compositions of rims were estimated relative to those of cores via the extinction angle x' to (010) in the a direction. The compositions of rims obtained in this manner indicate that most of the plagioclase occurring as sodic or calcic rims lies within the compositional range defined by the cores alone. Thus, the sodic cores of phenocrysts commonly are jacketed with calcic rims of composition similar to that of cores of other phenocrysts.

Plagioclase of the groundmass in these lavas can be as calcic as An_{60} , although the cores of most groundmass feldspar laths are in the range An_{50} to An_{60} . The laths are normally zoned, with rims at least as sodic as An_{30} . The composition of the most calcic feldspar in the groundmass is shown in figure 1 for both the lavas represented there. No obvious compositional hiatus separates the megacrysts from the most calcic feldspar in the groundmass of these or any of the other Pinacate lavas examined.

The compositions of olivine crystals were estimated by universal stage measurement of optic axial angles. Cores of the coarse olivine crystals typically lie in the range Fo_{70} to Fo_{80} . Olivine grains in the groundmass are of similar composition and commonly are normally zoned.

The augite megacrysts are black with vitreous luster and conchoidal fracture; their color in thin section is golden tan or pale tan except for the small, euhedral crystals in the brown cinders of Crater Elegante, some of which are faintly greenish tan. The augite megacrysts are optically homogeneous save for margins on certain crystals which are slightly paler in color than the cores. Optic axial angles of augite crystals in the groundmasses are mainly in the range 50° to 53° (+); those of the coarse crystals of augite almost all are in the range 54° to 61° (+), with the megacrysts typically exhibiting values of $60^\circ \pm 1^\circ$.

Chemical analyses of two augite megacrysts are presented in table 3. These crystals were collected from Salvatierra Cone, a large cinder cone

TABLE 3
Compositions of two clinopyroxene megacrysts
from the Pinacate volcanic field*

Sample number	PS-Px-1	PS-Px-4		PS-Px-1	PS-Px-4
SiO ₂	48.30	49.40	Al ^{IV}	0.203	0.178
Al ₂ O ₃	6.43	6.27	Al ^{VI}	0.079	0.095
TiO ₂	1.93	1.34	NaCrSi ₂ O ₆	0.0	0.6
Fe ₂ O ₃	2.66	2.11	NaFeSi ₂ O ₆	5.5	3.4
FeO	7.32	5.79	NaAlSi ₂ O ₆	0.0	0.0
MgO	12.97	14.52	CaTiAl ₂ O ₆	5.4	3.7
CaO	19.61	19.61	CaFeAlSiO ₆	2.0	2.5
MnO	0.204	0.151	CaAl ₂ SiO ₆	7.7	8.8
Na ₂ O	0.75	0.56	Ca ₂ Si ₂ O ₆	31.6	31.5
K ₂ O	0.02	0.01	Mg ₂ Si ₂ O ₆	36.0	40.2
Cr ₂ O ₃	<0.005	0.208	Fe ₂ Si ₂ O ₆	11.7	9.3
Total	100.19	99.97			

* Analyzed by Norman H. Suhr as described in text; analyses recast based on 6 oxygens, and hypothetical end-members calculated as described in text.

located in the central part of the volcanic field. Sample PS-Px-1 was a subhedral crystal, 2.5 cm in maximum dimension, with smooth surfaces apparently rounded and embayed by resorption. Sample PS-Px-4 was an irregular crystal fragment about 2 cm across. The analyses were performed by Norman H. Suhr as follows. Silica was determined gravimetrically, ferrous iron by titration, the alkalis by flame photometry, and all other constituents by atomic absorption. Hypothetical pyroxene endmembers were calculated by the method of Kushiro (1962) after allocating Cr to $\text{NaCrSi}_2\text{O}_6$ (following Binns, Duggan, and Wilkinson, 1970). The crystals are calcic augite and contain no jadeite component according to this method of calculation but do contain 7.7 and 8.8 mol percent Ca-Tschermak's molecule, $\text{CaAl}_2\text{SiO}_6$.

Factors favoring the entry of Ca-Tschermak's molecule into clinopyroxenes include increased pressure (Binns, Duggan, and Wilkinson, 1970). The two analyzed megacrysts lie within the field defined by igneous clinopyroxenes of high-pressure origin in the Al^{VI} versus Al^{IV} plot of Aoki and Kushiro (1968). However, despite the fact that Pinacate lavas themselves are relatively rich in alumina (avg 17 wt percent Al_2O_3), the amounts of $\text{CaAl}_2\text{SiO}_6$ in the Pinacate megacrysts are substantially less than the amounts reported by Binns, Duggan, and Wilkinson (1970) in most of their samples and by Aoki and Kushiro (1968) in many of theirs. The results of Hollister and Gancarz (1971) indicate the need for caution in interpreting the presence of $\text{CaAl}_2\text{SiO}_6$ in clinopyroxenes, especially where rapid growth may be involved. These workers observed clinopyroxene phenocrysts sector-zoned with respect to $\text{CaAl}_2\text{SiO}_6$ and suggested that its presence may depend also on growth-rate phenomena. Thus, the implication of the $\text{CaAl}_2\text{SiO}_6$ in the analyzed Pinacate megacrysts is not clear. The resorbed appearance and apparently hial size distribution of the coarse crystals of augite in most of the Pinacate volcanic units suggest that these crystals became unstable in the silicate melts, presumably owing chiefly to decrease in pressure since their formation. The unfailling occurrence with augite megacrysts of megacrystic An_{60-64} , commonly in much greater abundance than the augite, suggests that, whatever the pressure of formation, crystallization of this calcic plagioclase must have accompanied and may have preceded that of the giant augite crystals.

CHEMICAL RELATIONSHIPS BETWEEN LAVAS, COARSE CRYSTALS, AND GROUNDMASSSES

Considering the large size and abundance of the megacrysts in many units, and the probable low viscosity of their host liquids, the lavas of the Pinacate field are likely candidates to display some evidence of crystal settling and accumulation. The large olivine crystals should sink rapidly, perhaps several meters per day. On the other hand, the density of plagioclase (An_{60}) at 1200°C is 2.64 g/cc (Bottinga and Weill, 1970), while the density of Pinacate liquids at the same temperature would be approximately 2.68 g/cc based on lava grain densities (2.95 g/cc) and data from

Clark (1966, table 6-9). Although the presence of dissolved water would have decreased the original liquid densities somewhat (Bottinga and Weill, 1970), it would appear that the plagioclase megacrysts could not have been much more dense and might have been less dense than their host liquids. Ferromagnesian crystals would thus tend to accumulate apart from plagioclase crystals. However, nearly all the lavas rich in coarse crystals of plagioclase contain relatively abundant coarse olivine crystals as well. Volcanic units rich in coarse crystals mainly of olivine (and/or augite and magnetite) are absent.

The variation of silica percentage among the eight analyses presented here is nearly equalled or even surpassed by variations in the percentages of other oxides. Silica variation diagrams for these lavas appear as a set of oval scatterings of points and are of little help in aiding the perception of chemical relationships between the rocks. Bulk compositions of the lavas cannot, in general, be satisfactorily derived from one another by addition and subtraction of olivine and/or plagioclase of appropriate composition. Yet these are the only phenocrystic phases present in many Pinacate lavas.

To a first approximation, at least, the differences in content of coarse crystals between these lavas appear to be due simply to differences in the amount of intratelluric crystallization of host liquids. Lavas rich in coarse crystals of plagioclase tend to be comparably rich, relative to other lavas, in those of olivine; in the crystal-rich brown cinders of Crater Elegante, augite and magnetite also occur as abundant, euhedral phenocrysts. Additional, and conclusive, evidence is provided by the amounts of plagioclase contained in the *groundmass* of holocrystalline units especially rich in coarse labradorite crystals. A composite dike exposed in the eastern wall of Crater Elegante contains very numerous crystals of labradorite, many of which are more than 1 cm long. In the lower parts of this heterogeneous intrusive mass, megacrysts up to as much as 10 cm long are particularly abundant together with phenocrysts. The average abundance of all these coarse feldspars from chilled margin to chilled margin across the vertical dike here is 23.5 percent by volume. The abundance of plagioclase in the enclosing groundmass is 46.5 percent, based on tabulation of more than 2000 points from several thin sections. The indicated total amount of modal plagioclase in the dike is 59 percent. This amount is comparable to those in the weakly porphyritic rocks: flow lb₁ (designation of Gutmann, 1976) contains 61 percent total feldspar, and flows lb₂ and lb₃ contain 58 percent. Evidently the numerous labradorite megacrysts in the dike grew from the liquid whose other solid products now enclose them. They are *megaphenocrysts*.

Another example is provided by rocks of The Wedge intrusion at Crater Elegante: rocks in the marginal part of this unit contain about 53 percent total plagioclase, of which 26 percent forms phenocrysts and megacrysts. Flow differentiation may have removed some coarse crystals to the inaccessible interior parts of this mass, accounting for the slightly low total content of plagioclase. However, there can be no doubt that

the liquid was drastically depleted in potential plagioclase, for it contained only about 39 percent at the time of intrusion. Labradorite megacrysts in The Wedge also are megaphenocrysts, as probably are most all of the large, individual crystals in Pinacate lavas.

TEXTURES OF THE COARSE CRYSTALS

The megaphenocrysts and phenocrysts in Pinacate lavas are characterized by their textural heterogeneity. The coarse crystals within a given thin section typically exhibit a remarkable array of morphologies and inclusion textures. Some of these textures clearly reflect periods of resorption. Many coarse crystals provide no clue to the origin of their curious shapes and textures. Others, including numerous examples of skeletal and amoeboid crystals, probably represent products of rapid and imperfect growth.

Evidence of resorption of some of the crystals is provided most unequivocally by samples of plagioclase. Scattered crystals in many volcanic units exhibit anhedral, inclusion-free cores with compositional zones that are abruptly truncated at core margins. Rims surrounding these resorbed cores are several to about 15 percent An more calcic than the cores; these rims can be inclusion-free or, commonly, include tiny crystals and numerous blebs and elongate reentrants of groundmass material (pl. 2-A). Many of the rims are normally zoned. The resorbed parts of such crystals, which may have been carried up from considerable depth, are conspicuously sodic (An_{45} - An_{55}) relative to most of the phenocrysts and megaphenocrysts; they account for much, but by no means all, of the broad spectrum of phenocryst core compositions appearing in diagrams such as figure 1. Some of the smaller phenocrysts, with cores typically near An_{55} , are euhedral and normally zoned throughout.

Many of the plagioclase phenocrysts display zones riddled with inclusions of basaltic glass or groundmass material. These zones may form the margins of the crystals, jackets separating clear margins from cores, or the cores themselves. The origins of these sieve textures are not apparent. Many of the phenocrysts comprise broad cores rich in vermicular blebs of basaltic groundmass and surrounded by clear rims of composition the same as or slightly more calcic than the cores (pl. 2-B). These might most obviously be ascribed to resorption, and indeed many such cores are deeply embayed and relatively sodic compared to the composition of most of the phenocrysts and essentially all the megaphenocrysts; however, others are not so sodic or obviously embayed. The boundary of the core of the phenocryst in plate 2-B is euhedral. This and many similar crystals are aggregates of lath- or wedge-shaped domains which differ very slightly from one another in orientation. Some of these crystals enclose clear, anhedral masses of more sodic plagioclase that doubtless represent relicts of corroded crystals. Whether the inclusion-rich zones surrounding the relicts or forming the entire crystals are the products of corrosion and embayment or the products of rapid growth about sodic nuclei is not evident. Similar textures in many other volcanic rocks from

PLATE 2

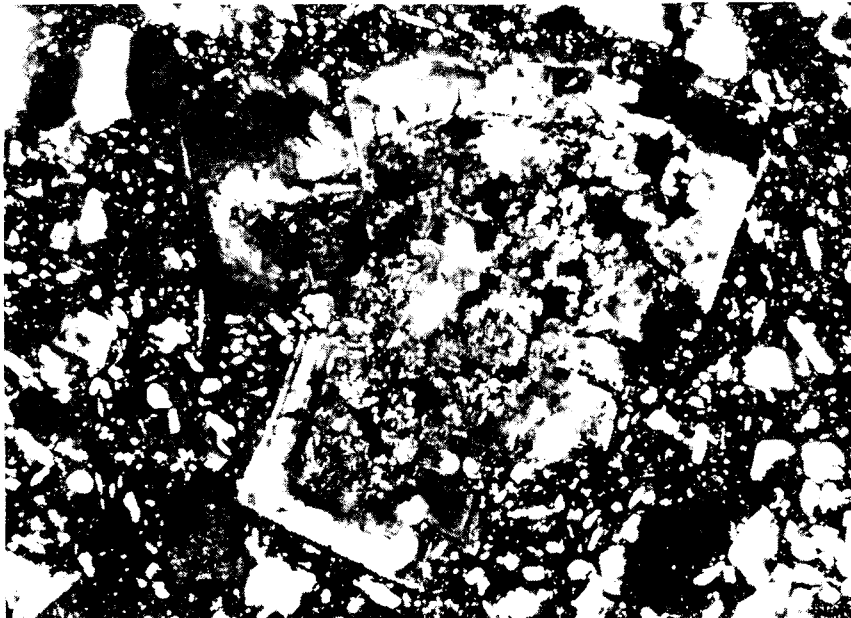


A. Photomicrograph of plagioclase phenocryst with anhedral, resorbed core and calcic, normally zoned rim. Note truncation of compositional zones at margin of core. Crossed nicols. Width of field is 1.6 mm.



B. Euhedral plagioclase phenocryst with sieve-textured core and clear rim. The large, dark patch within the crystal is vesicular basaltic glass. Note wedge-shaped domains that differ slightly from one another in orientation. Crossed nicols. Width of field is 2.6 mm.

PLATE 3



A. Photomicrograph of plagioclase phenocryst with coarsely sieve-textured core. The blebs of feldspar in the core are compositionally zoned and crudely repeat zoning in the phenocryst rim. Crossed nicols. Width of field is 2.3 mm.



B. Skeletal plagioclase phenocryst. Crossed nicols. Width of field is 2.6 mm.

various parts of the world have been assumed *a priori* to represent resorption. A somewhat similar and common texture is illustrated in plate 3-A. This crystal, like many others, is enclosed by a jacket of relatively clear plagioclase. The compositional zonation in this jacket is crudely repeated by the set of zones appearing in each little bleb of feldspar in the core. If the core represents the remains of a resorbed crystal, most or all of this crystal must have been resorbed. Possibly this sieve texture reflects instead rapid growth of a skeletal feldspar crystal which included much basaltic liquid as it grew. A phenocryst wherein some such process is more evident appears in plate 3-B. This crystal appears to merge with the enclosing and included groundmass and represents a skeletal product of rapid growth.

The majority of the coarse plagioclase crystals, however, are relatively inclusion-free tablets. A study of crystal growth in a natural olivine tholeiite reported by Lofgren (1974) indicates that undercooling in excess of 30°C was required to produce skeletal morphologies in plagioclase grown from this basaltic melt; thus, the predominance of relatively clear crystals is to be expected. Some of the megaphenocrysts in the size range 2 to 8 cm contain comparably large inclusions of basalt glass whose primary origin is indicated by the parallelism of oscillatory zones in the crystal to inclusion margins. Other unusually large megaphenocrysts contain platy reentrants and inclusions of glass oriented parallel to major growth directions (pl. 1-A). Most, however, are of clear, gem-quality labradorite. Many of these giant labradorites are euhedral crystals with sharp interfacial angles, although others are subhedral, and rounded, apparently resorbed crystals with anhedral form also occur. Some of the feldspar megaphenocrysts exhibit a curious, blocky surface texture (pl. 1-D). The shapes of the giant feldspars typically are blocky or tabular; some are markedly elongate parallel to a , and length-to-width ratios of the megaphenocrysts can be as much as 10:1.

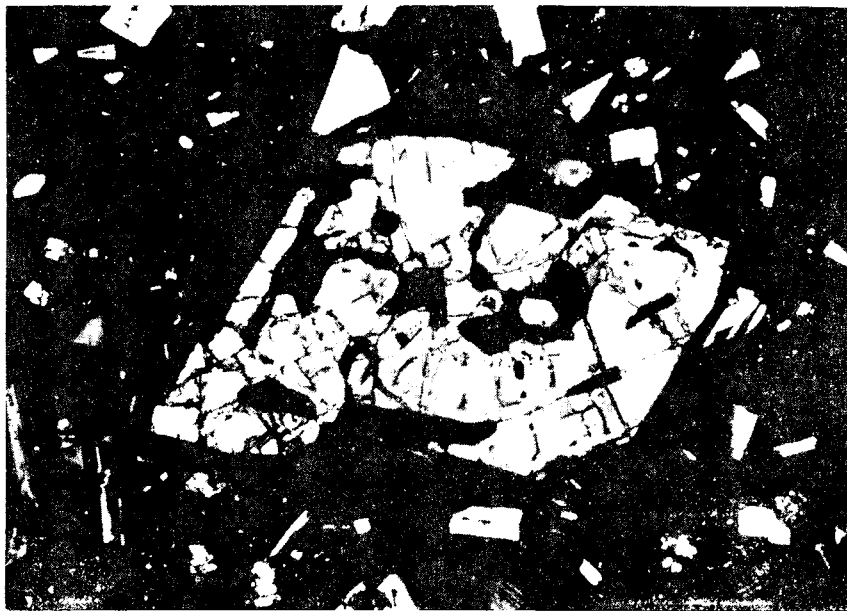
Some of the giant labradorites contain tubular voids as much as 2 mm in diameter and 1 cm in length. These voids typically occur in families of a few to several tens of mutually parallel, straight tubes within a single crystal. The tubes are oriented perpendicular to crystal faces and, thus, parallel to crystal growth directions. They pinch and swell along their lengths, and some are entirely sealed within their host, while others open upon the margin of the crystal. These and other textural features of the tubes (Gutmann, 1974) indicate that they represent primary inclusions of fluid derived from the melt as the giant crystals grew. The origin and implications of these textural features will be discussed below.

We consider next the textures of the coarse crystals of olivine. Many of these exhibit outlines that strongly resemble the skeletal growth forms described and attributed to rapid growth by Drever and Johnston (1957). Forms similar to that of the phenocryst in plate 4-A occur in olivine megaphenocrysts more than 1 cm long. Such crystals are elongate parallel

PLATE 4

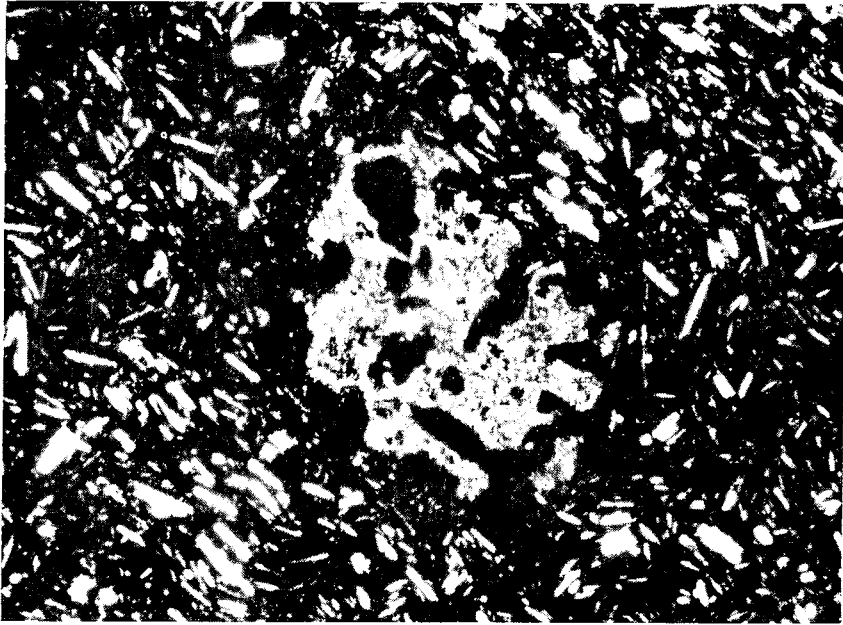


A. Photomicrograph of elongate, skeletal olivine phenocryst. Crossed nicols. Width of field is 2.3 mm.

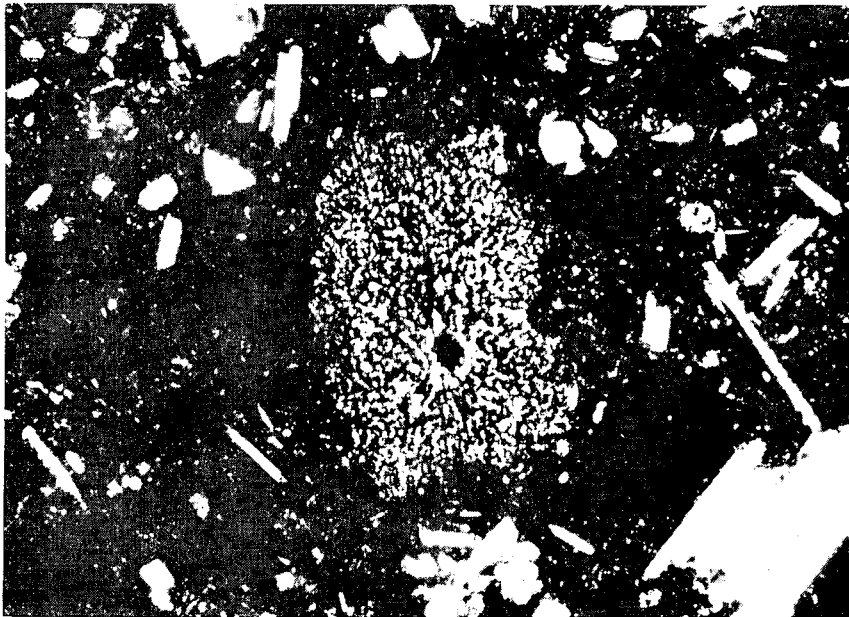


B. Equant, skeletal olivine phenocryst. Crossed nicols. Width of field is 2.6 mm. Crystal shapes comparable to A and B occur among crystals as much as 1 cm long.

PLATE 5



A. Photomicrograph of skeletal to amoeboid olivine phenocryst charged with minute to large inclusions of basaltic glass. Crossed nicols. Width of field is 2.3 mm.



B. Sieve-textured olivine phenocryst with numerous tiny inclusions of basaltic glass. Note radiating pattern. Dark patch at center of crystal is a magnetite granule. Crossed nicols. Width of field is 2.3 mm.

to *c.* Equant skeletal crystals (pl. 4-B) are more common; these also can attain lengths of at least 1 cm.

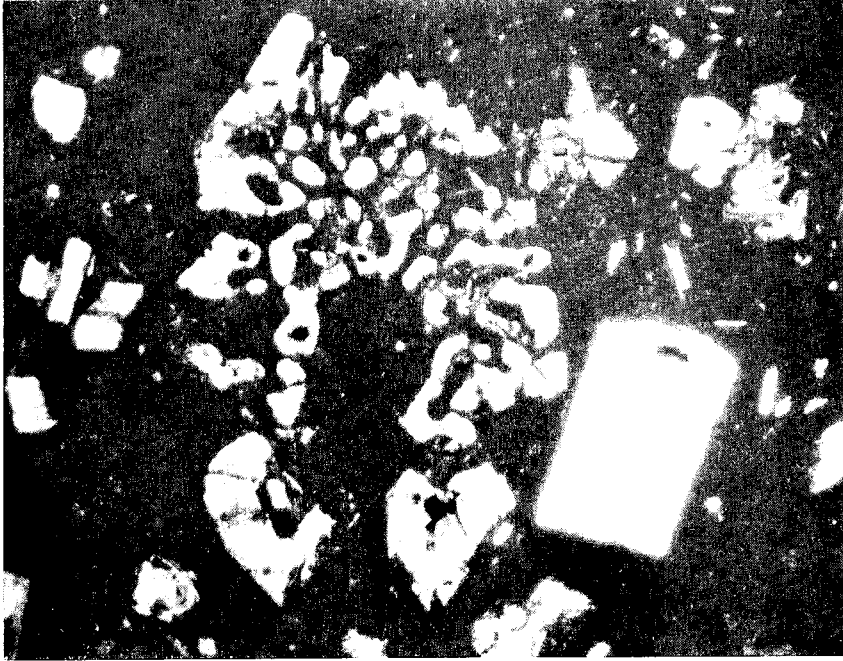
Martin and MacLean (1973) described microphenocrysts from the hawaiitic lava of Heimaey among which complete gradation occurs from skeletal crystals of olivine and titanomagnetite through incomplete skeletons bounded by curvilinear boundaries and one or two planar faces, into lobate grains devoid of crystal faces. These authors attribute all these forms, including the lobate, anhedral grains, to rapid growth. Similar gradation occurs among the olivine phenocrysts from Pinacate lavas. Plate 5-A illustrates a lobate or "amoeboid" crystal without well-developed planar faces and densely populated with tiny as well as large inclusions of basaltic glass. The olivine crystal in plate 5-B likewise contains numerous minute inclusions of glass, although it is not skeletal or lobate. The olivine in this small crystal forms a radiating pattern centered about a magnetite granule; this sieve texture probably reflects extreme undercooling. Also represented among the small olivine phenocrysts are arborescent patterns of olivine with numerous glass inclusions. Such textures apparently do not occur in the olivine megaphenocrysts and seem restricted to crystals less than 1 or 2 mm across.

Much larger inclusions of melt than those appearing in plate 5-B are illustrated in the skeletal olivine crystal in plate 6-A. The array of inclusions in this crystal is rather similar to that in the crystal shown in plate 6-B which, with its clear rim, may be analogous to the sieve-textured labradorite crystals with clear rims (compare pl. 3-A). In this connection it is worthy of note that those lavas that contain numerous skeletal olivine crystals tend to contain numerous sieve-textured feldspars as well. The reverse does not always hold. Some of the sieve-textured feldspars may reflect resorption instead.

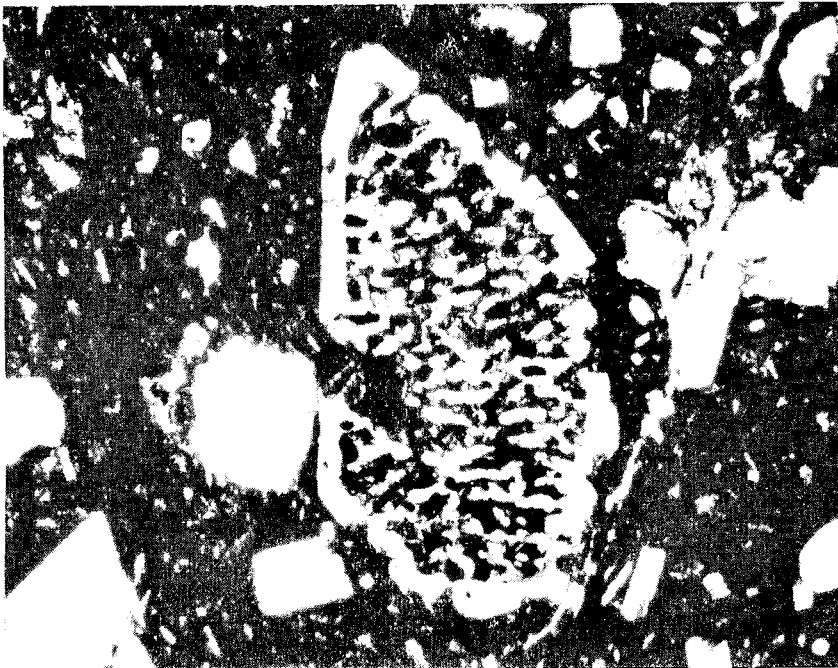
The literature contains numerous references (for example, Liou, 1974; Bryan, 1972) to very small, skeletal olivines that formed in rapidly-cooled basaltic melts. However, with the exception of the spinifex olivines in ultramafic flows (for example, Pyke, Naldrett, and Eckstrand, 1973), some of which attain more than 1 m in length, there seem to be few if any published descriptions of skeletal olivine crystals occurring in extrusive or pyroclastic rocks which are comparable in size to the skeletal olivine megaphenocrysts in some of the Pinacate lavas.

The phenocrysts of augite typically are anhedral or subhedral, and many probably are resorbed. The augite megaphenocrysts can be grossly euhedral, but the corners and edges of these crystals are rounded in most instances. Augite phenocrysts and megaphenocrysts in the crystal-rich brown cinders of Crater Elegante can be sharply euhedral and exhibit apparently seriate size distribution; some contain scattered small inclusions of basaltic glass. Very rare augite phenocrysts in a few of the lavas are sector-zoned crystals; their hourglass pattern of zonation probably reflects rapid growth (Nakamura, 1973; Leung, 1974). The sector-zoning has not been observed in augite crystals more than 1.3 mm across.

PLATE 6



A. Photomicrograph of coarsely sieve-textured, skeletal olivine phenocryst. Crossed nicols. Width of field is 1.3 mm.



B. Coarsely sieve-textured olivine phenocryst with inclusion-free rim (compare pl. 3-A). Crossed nicols. Width of field is 1.6 mm.

The coarse crystals of magnetite also are anhedral in most instances. However, sharply-faceted skeletal magnetite crystals as much as 1 cm across occur in several volcanic units (pl. 7-A). As observed in microphenocrysts of titanomagnetite by Martin and MacLean (1973), the skeletal megaphenocrysts grade texturally through incomplete skeletons into lobate or amoeboid forms wherein the intricate crystal boundaries are curvilinear (pl. 7-B).

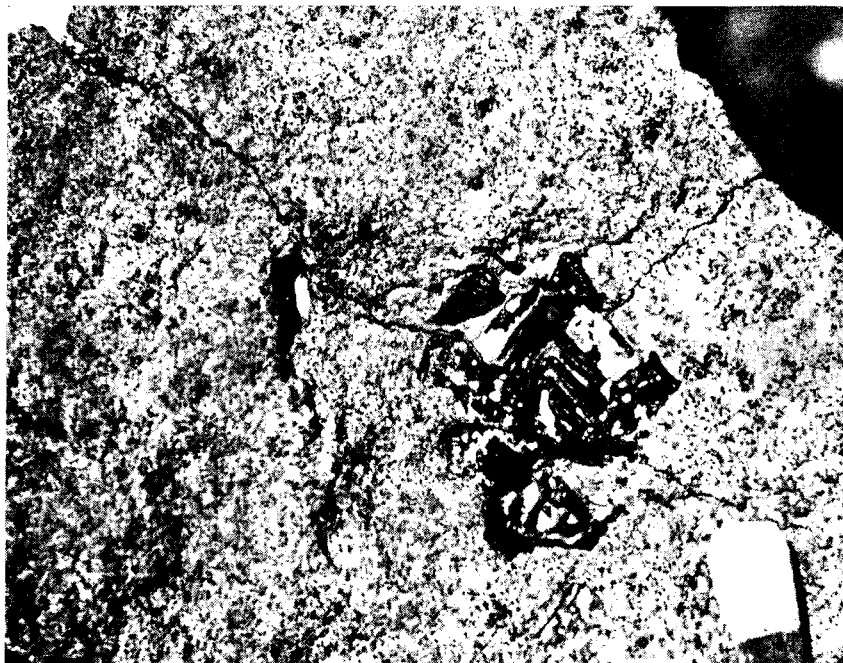
DISCUSSION

Assemblages of coarse crystals in volcanic rocks from many parts of the world have been described variously as groups of "phenocrysts" (Wright, 1968), "xenocrysts" (Wilshire and Binns, 1961), or "megacrysts" (Binns, Duggan, and Wilkinson, 1970; Irving, 1974; Aoki, 1970; Laughlin, Manzer, and Carden, 1974). In many instances, these crystals are believed to have originated at moderate to high pressures; they occur in mafic and/or alkaline lavas, where they are commonly associated with various sorts of ultramafic nodules and xenoliths. The megacryst assemblages typically include one or many of the following group of phases: orthopyroxene, spinel, garnet, kaersutite, phlogopite, chromian diopside, anorthoclase, and sodic plagioclase (commonly oligoclase or andesine). Olivine and aluminian augite are present in most occurrences, and magnetite and ilmenite appear in some examples.

Donnelly (ms) reports the occurrence of rare, small (less than 2 mm) crystals of orthopyroxene, fringed with clinopyroxene, in only 5 of the hundreds of Pinacate volcanic units he examined; he also noted the presence of coarse kaersutite crystals in one flow. Apart from these examples and a few additional occurrences of orthopyroxene found by the writer, the only phases from the first-named group (above) identified in Pinacate lavas are the resorbed andesine crystals. Gabbroid nodules occur in many of the lavas, but ultramafic nodules, although present at a few localities, seem notably rare; these rocks will be described in a forthcoming contribution. Xenocrysts derived from gabbroic or ultramafic xenoliths doubtless are present in the Pinacate volcanics but probably constitute only a very small fraction of the megacrysts or smaller crystals in these rocks.

The abundant labradorite megaphenocrysts evidently are not high-pressure phases. They are the most calcic feldspars, or nearly so, in their host units and are similar in composition to calcic cores of the ground-mass feldspar laths. The results of Cohen, Ito, and Kennedy (1967), T. H. Green (1968), and Thompson (1972) indicate that the early-formed plagioclase in equilibrium with a given basaltic liquid becomes more sodic with increased confining pressure. The calculations of Bacon and Carmichael (1973) indicate that a basanitoid lava in equilibrium with aluminous augite and An_{72} at 1.4 kb could have been in equilibrium, at about 10.4 kb, with crystals of highly aluminous augite and An_{37} . This marked effect of pressure presumably accounts for the fact that the plagioclase crystals in megacryst assemblages normally are andesine or

PLATE 7



A. Microphotograph of skeletal crystal of magnetite. Maximum dimension of crystal in this view is 1.0 cm. Head of paper match in lower right corner.



B. Microphotograph of amoeboid crystal of magnetite. Maximum dimension of crystal in this view is 0.8 cm.

oligoclase (Binns, Duggan, and Wilkinson, 1970; Laughlin, Manzer, and Carden, 1974; Aoki, 1970).

The compositional homogeneity of the Pinacate labradorite megaphenocrysts, and especially the absence of any systematic compositional variation from their centers outward, indicates that these crystals did not form synchronously with release of large amounts of pressure. However, the tubular primary inclusions of fluid in these crystals apparently require that fluid was exsolving from host liquids as the crystals grew (Gutmann, 1974). It is possible that the crystals grew at exceedingly shallow depth within the volcanic pile (less than, say, 1 km), where the release of only small amounts of pressure would result in evolution of substantial quantities of water from a liquid saturated with respect to an aqueous fluid phase. Alternatively, if the crystals grew at a sufficiently rapid rate, evolution of fluid could occur at the crystal-liquid interface even in magmas that, in bulk, were *undersaturated* with an aqueous phase, as demonstrated experimentally by Fenn and Luth (1973). This would reflect a slow rate of diffusion of water dissolved in the melt relative to the rate of increase of water concentration in liquid adjacent to the growing crystals. The latter process apparently could operate at any depth and requires only that the crystals grow at a sufficiently rapid rate from liquids containing dissolved fluid.

The common occurrence of the Pinacate megaphenocrysts as single, euhedral crystals and the relative scarcity of megacrystic samples comprising intergrowths of more than one crystal indicate that these coarse crystals grew freely within their liquid hosts. Although pegmatitic crystal aggregates do occur in some of the volcanic units, the megaphenocrysts were not derived chiefly from such aggregates (compare Irving, 1974), wherein the abundance of fluid dissolved in interstitial melt might have been substantially greater than in normal basaltic liquid. These aggregates are relatively rare, and their feldspar crystals are smaller than many of the labradorite megaphenocrysts. The megaphenocrysts evidently formed from melts that commonly contained as little as 1 to 3 percent of coarse crystals upon eruption.

The maximum volumetric abundance of the tubular voids within the giant Pinacate labradorite crystals affords an estimate of the *greatest* pressure at which these primary fluid inclusions could have formed. Let us assume that the megaphenocrysts did not grow at extremely shallow depth and that the evolution of fluid concomitant with crystal growth resulted instead from the increased fluid concentration in boundary-layer liquid. The tubular voids occupy approximately 10 percent by volume of their host crystals in some specimens, as judged from the volume and mass of regularly shaped samples and the specific gravity of An₆₁. Thus, as much as 0.01 cc of fluid must have been generated in boundary-layer liquid for each 0.09 cc of labradorite removed from the melt. For simplicity, let us consider 1 cc of melt, although the amount chosen is of no consequence to the argument. Extraction of 0.09 cc of labradorite from this melt implies crystallization of approximately 9 percent by

volume of the melt, since the density of crystalline labradorite at 1200°C could not have been greatly different from that of the host liquid (see above). Assuming that there is no large effect on fluid solubility of small changes in melt composition, *no more than* 9 percent of the fluid dissolved in the 1 cc of melt could be evolved as a separate phase. Although the melts may well have been saturated with a fluid phase rich in CO₂ (Mysen, 1975), they probably were not in equilibrium with an H₂O-rich fluid phase at pressures greater than 0.25 to 0.5 kb. Thus, the increase in *water* concentration in melt adjacent to growing crystals need not have resulted in immediate separation of an aqueous phase; furthermore, water in the boundary-layer liquid would have diffused away from, instead of toward, the crystal-liquid interface. Therefore, only *substantially less* than 9 percent of the water held in 1 cc of melt could finally have made its way to a fluid bubble growing on the surface of the crystal. Yet the fluid entrapped as a result must occupy 0.01 cc, whatever its composition.

Let us assume that the fluid was chiefly CO₂. At 1200°C and 1.4 kb, the density of CO₂ is nearly 0.4 g/cc (extrapolated from data gathered at 1.4 kb by Kennedy, 1954). Therefore, in order to account for the abundance of fluid in the crystals, 0.004 g of CO₂ must have been liberated from 0.09 cc of melt owing to crystallization of that melt. This implies solubility of CO₂ in the basaltic liquid (density approx 2.68 g/cc) of more than 1.6 percent by weight at 1.4 kb. That such high solubility of CO₂ is improbable at this pressure is evident from the results of Mysen, Arculus, and Eggler (1975). These workers report that the solubility of pure CO₂ in tholeiitic liquid attains 1.66 wt percent at 30 kb, 1450°C, and that the solubility decreases with decrease in pressure or temperature. The likelihood of forming the tubular voids by evolution chiefly of CO₂ is not increased at pressure greater than 1.4 kb owing to increasing density of the fluid. At 0.3 kb, the amount of CO₂ that must be held in solution in the melt (0.4 wt percent) still is prohibitively high (Khitarov and Kadik, 1973). At lesser pressures, the evolution of *water* from the melt becomes likely. Evidently CO₂ cannot have been the principal constituent of the fluid filling the tubular voids. Whatever the pressure, water probably was the dominant constituent of this fluid phase.

Let us assume that the fluid included appreciable H₂O. The potassium contents of Pinacate basaltic rocks are appropriate for initial water contents of about 0.9 wt percent, as judged from the data of Moore (1970). On the other hand, Knutson and Green (1975) estimate water contents of a hawaiite magma to have been about 2 wt percent; the hawaiite studied by these workers is considerably richer in K₂O and Na₂O and poorer in CaO and MgO than the Pinacate basaltic hawaiites. Let us assume an initial water content in Pinacate liquids as great as 1.75 wt percent, although they may well have contained less.

What about the volume contribution of CO₂ evolved from boundary-layer liquid? The data of Khitarov and Kadik (1973) show that the solubility of CO₂ in basalt in equilibrium with a CO₂-H₂O fluid phase will not be greater than about 0.5 wt percent at 3 kb; that the labradorite

megacrysts could not have formed at very much greater pressure will be shown below. At 1000°C, 1.4 kb, the density of CO₂ is 0.43 g/cc (Kennedy, 1954), or about twice that of water (0.24 g/cc) under the same conditions (Burnham, Holloway, and Davis, 1969). The same density relationship holds at 0.3 kb. Hence, 0.5 wt percent of CO₂, if evolved as a fluid in the upper crust, will occupy about the same volume as 0.25 wt percent H₂O. Assuming ideal mixing with respect to volume, it seems unlikely, therefore, that Pinacate liquids could have evolved a greater volume of fluid in the upper crust than that which would result from exsolution of 1.75 wt percent H₂O plus 0.25 wt percent H₂O (in place of CO₂), or 2.00 wt percent of water.

Finally, we return to the implications of the primary tubular fluid inclusions. Given no more than 2 wt percent of water held in the melt, crystallization of 0.09 cc of labradorite from 1 cc of melt could release no more water than 0.18 wt percent of that cc of melt, or 0.0048 g H₂O (assuming melt density of 2.68 g/cc). At what pressure and temperature will 0.0048 g H₂O occupy 0.01 cc? The implied specific volume is 2.08 cc/g. The specific volume of water at 1000°C, 3.3 kb, is 2.09 cc/g (Burnham, Holloway, and Davis, 1969). The temperature of appearance of plagioclase in one Pinacate basalt (analysis PE-31a, table 2) is 1165° ± 10°C at atmospheric pressure and f_{O₂} very near that defined by the assemblage Ni-NiO (Gutmann, unpub. data). The presence in solution of 1 wt percent H₂O would depress this temperature by approximately 50°C (estimated from fig. 30 of Yoder and Tilley, 1962) to about 1115°C. Graphical extrapolation of the data of Burnham, Holloway, and Davis (1969) from 1000° to 1115°C, with the risks inherent in this extrapolation, indicates that the specific volume 2.08 cc/g would be attained at about 3.8 kb. Since the specific volume decreases with pressure, this pressure represents the estimated *maximum* pressure at which the tubular voids could have formed. The real pressure of formation must have been *less* to the extent that (1) H₂O was present in amounts less than 1.75 wt percent, (2) water was held in solution despite the increase in water concentration in the boundary-layer liquid, and (3) water diffused away from the crystal-liquid interface or, for whatever reason, failed to nourish a growing bubble partially trapped within the crystal. Clearly, the above estimate of confining pressure may be greatly in excess of the true value. In fact, the volume relationships suggest the hypothesis that the megaphenocrysts grew at very low pressures indeed.

CONCLUSIONS AND PETROLOGIC MODEL

The origin of the relatively small phenocrysts with cores of calcic andesine and sodic labradorite is not known. Many of these cores are resorbed and jacketed by a more calcic rim, and it is tempting to speculate that they may have formed at considerable depth, perhaps together with an unknown amount of phenocrysts of the other principal phases.

In contrast, the giant labradorite crystals are among the most calcic feldspars, or nearly so, in their host units; they grade downward in size

into compositionally similar phenocrysts and thence into microphenocrysts and crystals of the groundmass. Their calcic compositions and voluminous (in many crystals) primary fluid inclusions suggest that the megaphenocrysts formed at high levels in the crust and at pressures not greater than about 3.8 kb. However, it does not seem likely that most of these giant crystals grew at extremely shallow depth (less than, say, 1 km), since many of the big feldspars appear slightly rounded by resorption, as do most of the augite megaphenocrysts associated with them. Once water had begun to exsolve from the melt in substantial quantity near the surface, resorption of the feldspar crystals should be inhibited in favor of rapid crystallization. The importance of even very small increments of dissolved water in depressing the temperature of appearance in basaltic melts of *plagioclase in particular* is evident from the experimental results of Yoder and Tilley (1962) and Hamilton, Burnham, and Osborn (1964). The effect of evolution of water in promoting the formation of plagioclase from rising basaltic magmas would be comparably great. The observed resorption is most reasonably attributed to decrease in pressure prior to exsolution of substantial quantities of water from the rising melts.

The effect of dissolved water on phase equilibria can account for the observation that resorbed augite megaphenocrysts coexist with those of labradorite in lavas poor in coarse crystals, whereas sharply euhedral augite phenocrysts seem restricted to volcanic units in which a high proportion of small crystals had formed prior to eruption. Evidently the temperature of appearance of augite in Pinacate liquids is considerably below that of plagioclase at very low pressure, a suggestion that has been confirmed by 1-atm quenching experiments on sample PE-31a at f_{O_2} near Ni-NiO (Gutmann, unpub. data). However, the results of Yoder and Tilley (1962, fig. 30) demonstrate that this thermal interval would be greatly narrowed if the melt held 1 wt percent H_2O in solution during crystallization at depth.

Many of the phenocrysts and even some megaphenocrysts as much as 1 cm long are skeletal crystals, those of olivine being most obviously so. These crystals probably grew rapidly at very shallow depth in response to evolution of water and consequent undercooling. If the melts were nearly saturated with plagioclase as they approached the surface, exsolution of 1 wt percent of H_2O during the last km of travel would induce considerable undercooling unless upward migration was very slow. *Apart from* adiabatic effects and changes in heat content owing to crystallization, vaporization, and conductive heat loss, evolution of all of this 1 percent H_2O might raise the temperature of appearance of plagioclase roughly 50°C above the temperature of the melt by the time the latter reached the surface (compare Hamilton, Burnham, and Osborn, 1964; Yoder and Tilley, 1962, fig. 30). The relationship of the liquid to phases other than plagioclase might be less drastically altered, as noted above. Lowering the rate of rise of the melts would increase conductive

heat loss but could nonetheless inhibit supersaturation as phenocrysts formed from the melts. Lofgren (1974) documented the wide array of crystal textures that could result from such a process, during which the amount of supersaturation of the melts would be expected to vary considerably. As emphasized by Lofgren (1974), Dowty, Keil, and Prinz (1974), and Lofgren and others (1974), the occurrence in an igneous rock of crystals with widely varying morphologies and sizes need not reflect a multi-stage cooling history.

However, relatively swift final ascent of magma directly to the surface presumably could yield such severe undercooling as to stabilize numerous tiny nuclei for groundmass crystallization. The results of Lofgren (1974) suggest that any small phenocrysts that formed at this time might be skeletal or spherulitic, depending on the phase in question. Lofgren also reports that synthetic crystals grown during isothermal crystallization in the system albite-anorthite-water approach the bulk composition of the melt with increased undercooling; this phenomenon evidently may be expressed in Pinacate lavas by the appearance of small, euhedral, normally-zoned, plagioclase phenocrysts with cores somewhat more sodic than the megacrysts.

Formation of phenocrysts and megacrysts very near the surface would appear to require extremely rapid rates of crystal growth. That such rates can be attained even in silicate liquids far more viscous than Pinacate lavas is demonstrated by the experimental results of Fenn (1972). Fenn observed that linear growth rates of up to 2.5×10^{-4} cm/sec are not uncommon in undercooled melts in the vapor-absent region of the system $\text{NaAlSi}_3\text{O}_8$ - KAlSi_3O_8 - H_2O . Such a growth rate, if maintained, would produce a feldspar crystal 1 cm long in about 33 min.

Furthermore, the "pressure quench" invoked here may have begun at pressure considerably in excess of that at which the melts would be saturated with 1 wt percent, say, of H_2O in the absence of CO_2 . A CO_2 -rich fluid phase probably was present in the rising magmas (Mysen, 1975), at least within the upper part of the crust. The partitioning of water between melt and a separate, CO_2 -rich phase is pressure-dependent such that a decrease in total pressure induces water to pass out of the melt and into the fluid phase (C. Wayne Burnham, written commun., 1970; Khitarov and Kadik, 1973; Rosenhauer and Eggler, 1975). The results of Kadik and Eggler (1975) indicate that this exsolution of water from the melt will occur with decreasing pressure mainly at pressures less than about 5 kb. The data of Khitarov and Kadik (1973) show that a basalt melt containing 1 wt percent dissolved water will be in equilibrium at 1 kb, 1200°C, with a separate fluid phase of composition approximately 70 mol percent CO_2 . Thus, the actual amounts of water exsolved may remain quite small, until the melts are within 1 to 3 km from the surface. Resorption of many of the giant Pinacate phenocrysts would appear to require that the direct effect of decreasing pressure on the crystal-liquid phase relationships outstrip, for a time, the opposed effect of ex-

solution of water from the melts, even at pressures perhaps substantially less than 3.8 kb. However, the latter effect must eventually become more important than the former, and crystal-bearing (non-superheated) magmas will begin to crystallize as a result (compare Holloway, 1976, fig. 6-C).

Some comparisons between Pinacate lavas and volcanic rocks elsewhere seem desirable. The near-surface "pressure quench" model is perfectly general. Indeed it seems probable that variously sized and textured phenocrysts in many volcanic rocks represent near-surface, and perhaps rapid, crystallization far more commonly than has been generally recognized by geologists. A comparably thorny problem is posed by the extraordinary size attained by some of the Pinacate phenocrysts. Anderson and Wright (1972) suggest that loss of dissolved water during ascent caused rapid crystallization of *microphenocrysts* in the basaltic lavas of Kilauea volcano; they estimate that one effect of the evolution of 0.8 wt percent H₂O from these magmas is to induce formation of about 20 percent of crystals. Anderson (1973) relates the abundance of *microphenocrysts* in high-alumina basaltic lavas to estimated before-eruption water contents of the magmas; he suggests that these tiny crystals (generally less than 0.2 mm) formed as a result of evolution of water as pressure decreased. Skeletal crystals in Pinacate lavas attain sizes more than an order of magnitude greater.

The larger Pinacate megaphenocrysts attain sizes 2 to 2.7 orders of magnitude greater than *microphenocrysts*, but these giant crystals probably did *not* form at or very near the surface. Their gross compositional homogeneity bespeaks sensibly constant magmatic conditions during growth. This growth may have occurred in conduits at depth well below the volcanic pile, where the most reasonable thermal sink is provided by cool wall rocks. Their modal abundance is relatively small in most units, and they occur only in trace amounts in many. This would suggest that they could have formed under conditions of rather slight undercooling, wherein growth rate can far outstrip nucleation rate. A striking example of the latter phenomenon was documented recently by Swanson (1974) in connection with his investigations of the kinetics of crystallization in a synthetic granodiorite. The tubular fluid inclusions in the labradorite megaphenocrysts are unusual features and probably require relatively rapid crystal growth if formed from melts undersaturated with respect to an aqueous phase. Implicit in the boundary-layer enrichment model invoked to account for them is that aqueous fluid was exsolving at the crystal-liquid interface during crystal growth. Exsolved water molecules might collect to form a thin fluid film on the surfaces of the crystals, as envisioned by Neumann (1948). Such a fluid would permit rapid transport of constituents from the melt near and along the surfaces of the crystal and perhaps a high degree of selectivity by the growing crystal as well. Hence, the gem quality of the megaphenocrysts does not deny that they, too, could have formed rapidly.

ACKNOWLEDGMENTS

I am grateful to Richard H. Jahns and William C. Luth for helpful discussions, encouragement, and assistance. Michael F. Donnelly kindly granted permission to use the data cited from his doctoral dissertation. Four rock analyses were provided by R. H. Jahns. Analyses of the clinopyroxenes were defrayed by a Wesleyan University faculty grant. The manuscript benefitted from comments by Gary Lofgren, W. C. Luth, R. J. Kirkpatrick, D. S. Barker, and C. R. Bacon.

REFERENCES

- Anderson, A. T., 1973, The before-eruption water content of some high-alumina basalt magmas: *Bull. volcanol.*, v. 37, p. 530-552.
- Anderson, A. T., and Wright, T. L., 1972, Phenocrysts and glass inclusions and their bearing on oxidation and mixing of basaltic magmas, Kilauea volcano, Hawaii: *Am. Mineralogist*, v. 57, p. 188-216.
- Aoki, K., 1970, Andesine megacrysts in alkali basalts from Japan: *Contr. Mineralogy Petrology*, v. 25, p. 284-288.
- Aoki, K., and Kushiro, I., 1968, Some clinopyroxenes from ultramafic inclusions in Dreiser Weiher, Eifel: *Contr. Mineralogy Petrology*, v. 18, p. 326-337.
- Bacon, C. R., and Carmichael, I. S. E., 1973, Stages in the P-T path of ascending basalt magma: an example from San Quintin, Baja California: *Contr. Mineralogy Petrology*, v. 41, p. 1-22.
- Binns, R. A., Duggan, M. B., and Wilkinson, J. F. G., 1970, High pressure megacrysts in alkaline lavas from northeastern New South Wales: *Am. Jour. Sci.*, v. 269, p. 132-168.
- Bottlinga, Yan, and Weill, D. F., 1970, Densities of liquid silicate systems calculated from partial molar volumes of oxide components: *Am. Jour. Sci.*, v. 269, p. 169-182.
- Bryan, W. B., 1972, Morphology of some quench crystals in submarine basalts: *Jour. Geophys. Research*, v. 77, p. 5812-5819.
- Burnham, C. W., Holloway, J. R., and Davis, N. F., 1969, Thermodynamic properties of water to 1000°C and 10,000 bars: *Geol. Soc. America Spec. Paper* 132, 96 p.
- Clark, S. P., ed., 1966, *Handbook of physical constants*: *Geol. Soc. America Mem.* 97, 587 p.
- Cohen, L. H., Ito, K., and Kennedy, G. C., 1967, Melting and phase relations in an anhydrous basalt to 40 kilobars: *Am. Jour. Sci.*, v. 265, p. 475-518.
- Donnelly, M. F., ms, 1974, *Geology of the Sierra del Pinacate volcanic field, northern Sonora, Mexico, and southern Arizona, U.S.A.*: Ph.D. thesis, Stanford Univ., 722 p.
- Dowty, E., Keil, K., and Prinz, M., 1974, Lunar pyroxene-phyric basalts: crystallization under supercooled conditions: *Jour. Petrology*, v. 15, p. 419-453.
- Drever, H. I., and Johnston, R., 1957, Crystal growth of forsteritic olivine in magmas and melts: *Royal Soc. Edinburgh Trans.*, v. 63, p. 289-315.
- Fenn, P. M., 1972, Nucleation and growth of alkali feldspars from synthetic melts [abs.]: *Am. Geophys. Union Trans.*, v. 53, p. 1127.
- Fenn, P. M., and Luth, W. C., 1973, Hazards in the interpretation of primary fluid inclusions in magmatic minerals [abs.]: *Geol. Soc. America Abs. with Programs*, v. 5, p. 617.
- Green, T. H., 1968, Experimental fractional crystallization of quartz diorite and its application to the problem of anorthosite origin: *New York State Mus. and Sci. Service Mem.* 18, p. 23-29.
- Gutmann, J. T., 1974, Tubular voids within labradorite phenocrysts from Sonora, Mexico: *Am. Mineralogist*, v. 59, p. 666-672.
- , 1976, *Geology of Crater Elegante, Sonora, Mexico*: *Geol. Soc. America Bull.*, v. 87, p. 1718-1729.
- Gutmann, J. T., and Martin, R. F., 1976, Crystal chemistry, unit cell dimensions, and structural state of labradorite megacrysts from Sonora, Mexico: *Schweizer. min. pet. Mitt.*, v. 56, p. 55-64.

- Hamilton, D. L., Burnham, C. W., and Osborn, E. F., 1964, The solubility of water and effects of oxygen fugacity and water content on crystallization in mafic magmas: *Jour. Petrology*, v. 5, p. 21-39.
- Hollister, L. S., and Gancarz, A. J., 1971, Compositional sector-zoning in clinopyroxenes from the Narce area, Italy: *Am. Mineralogist*, v. 56, p. 959-979.
- Holloway, J. R., 1976, Fluids in the evolution of granitic magmas: Consequences of finite CO₂ solubility: *Geol. Soc. America Bull.*, v. 87, p. 1513-1518.
- Irving, A. J., 1974, Megacrysts from the Newer Basalts and other basaltic rocks of southeastern Australia: *Geol. Soc. America Bull.*, v. 85, p. 1503-1514.
- Jahns, R. H., 1959, Collapse depressions of the Pinacate volcanic field, Sonora, Mexico: *Arizona Geol. Soc., Southern Arizona Guidebook 2*, p. 165-184.
- Kadik, A. A., and Eggler, D. H., 1975, Melt-vapor relations on the join NaAlSi₃O₈-H₂O-CO₂: *Carnegie Inst. Washington Year Book 74*, p. 479-484.
- Kennedy, G. C., 1954, Pressure-volume-temperature relations in CO₂ at elevated temperatures and pressures: *Am. Jour. Sci.*, v. 252, p. 225-241.
- Khitarov, N. I., and Kadik, A. A., 1973, Water and carbon dioxide in magmatic melts and peculiarities of the melting process: *Contr. Mineralogy Petrology*, v. 41, p. 205-215.
- Knutson, J., and Green, T. H., 1975, Experimental duplication of a high-pressure megacryst/cumulate assemblage in a near-saturated hawaiiite: *Contr. Mineralogy Petrology*, v. 52, p. 121-132.
- Kushiro, I., 1962, Clinopyroxene solid solutions. Part I. The CaAl₂SiO₆ component: *Japan Jour. Geology and Geography*, v. 33, p. 213-220.
- Laughlin, A. W., Manzer, G. K., Jr., and Carden, J. R., 1974, Feldspar megacrysts in alkali basalts: *Geol. Soc. America Bull.*, v. 85, p. 413-416.
- Leung, I. S., 1974, Sector-zoned titanaugites: Morphology, crystal chemistry, and growth: *Am. Mineralogist*, v. 59, p. 127-138.
- Liou, J. G., 1974, Mineralogy and chemistry of glassy basalts, Coastal Range ophiolites, Taiwan: *Geol. Soc. America Bull.*, v. 85, p. 1-10.
- Lofgren, G., 1974, An experimental study of plagioclase crystal morphology: isothermal crystallization: *Am. Jour. Sci.*, v. 274, p. 243-273.
- Lofgren, G., Donaldson, C. H., Williams, R. J., Mullins, O., Jr., and Usselman, T. M., 1974, Experimentally reproduced textures and mineral chemistry of Apollo 15 quartz normative basalts, *in Proc. Fifth Lunar Sci. Conf.: Geochim. et Cosmochim. Acta, Suppl. 5*, v. 1, p. 549-567.
- Macdonald, G. A., 1960, Dissimilarity of continental and oceanic rock types: *Jour. Petrology*, v. 1, p. 172-177.
- Macdonald, G. A., and Katsura, T., 1964, Chemical composition of Hawaiian lavas: *Jour. Petrology*, v. 5, p. 82-133.
- Martin, R. F., and MacLean, W. H., 1973, Crystal growth forms in hawaiitic lavas of Heimaey, Iceland [abs.]: *Geol. Soc. America Abs. with Programs*, v. 5, p. 726-727.
- Moore, J. G., 1970, Water content of basalt erupted on the ocean floor: *Contr. Mineralogy Petrology*, v. 28, p. 272-279.
- Mysen, B. O., 1975, Solubility of volatiles in silicate melts at high pressure and temperature: the role of carbon dioxide and water in feldspar, pyroxene, and feldspathoid melts: *Carnegie Inst. Washington Year Book 74*, p. 454-468.
- Mysen, B. O., Arculus, R. J., and Eggler, D. H., 1975, Solubility of carbon dioxide in melts of andesite, tholeiite, and olivine nephelinite composition to 30 kb pressure: *Contr. Mineralogy Petrology*, v. 53, p. 227-239.
- Nakamura, Y., 1973, Origin of sector zoning of igneous clinopyroxenes: *Am. Mineralogist*, v. 58, p. 986-990.
- Neumann, H., 1948, On hydrothermal differentiation: *Econ. Geology*, v. 43, p. 77-83.
- Pyke, D. R., Naldrett, A. J., and Eckstrand, O. R., 1973, Archaean ultramafic flows in Munro Township, Ontario: *Geol. Soc. America Bull.*, v. 84, p. 955-978.
- Rosenhauer, M., and Eggler, D. H., 1975, Solution of H₂O and CO₂ in diopside melt: *Carnegie Inst. Washington Year Book 74*, p. 474-479.
- Slemmons, D. B., 1962, Determination of volcanic and plutonic plagioclases using a three- or four-axis universal stage: *Geol. Soc. America Spec. Paper 69*, 64 p.
- Swanson, S. E., 1974, The effect of crystal growth rate and nucleation density on the texture of granodiorites [abs.]: *Geol. Soc. America Abs. with Programs*, v. 6, p. 979.

- Thompson, R. N., 1972, Melting behavior of two Snake River lavas at pressures up to 35 kb: Carnegie Inst. Washington Year Book 71, p. 406-410.
- 1973, One-atmosphere melting behaviour and nomenclature of terrestrial lavas: *Contr. Mineralogy Petrology*, v. 41, p. 197-204.
- 1974, Primary basalts and magma genesis. I. Skye, northwest Scotland: *Contr. Mineralogy Petrology*, v. 45, p. 317-341.
- Wilshire, H. G., and Binns, R. A., 1961, Basic and ultrabasic xenoliths from volcanic rocks of New South Wales: *Jour. Petrology*, v. 2, p. 185-208.
- Wright, J. B., 1968, Oligoclase-andesine phenocrysts and related inclusions in basalts from part of the Nigerian Cenozoic province: *Mineralog. Mag.*, v. 36, p. 1024-1031.
- Yoder, H. S., Jr., and Tilley, C. E., 1962, Origin of basalt magmas: an experimental study of natural and synthetic rock systems: *Jour. Petrology*, v. 3, p. 342-532.