7. PETROLOGY OF BASALTS: HOLE 396B DSDP LEG 46

R. James Kirkpatrick,¹ Scripps Institution of Oceanography, La Jolla, California

INTRODUCTION

Hole 396B penetrated 205.5 meters into basaltic basement about 160 km east of the Mid-Atlantic Ridge (22°59.14'N,43°30.90'W). The Leg 46 Scientific Party (this volume) has given general descriptions of the core recovered. They have divided the basement section into eight lithologic units. The samples discussed in this paper come primarily from lithologic Units 1 and 2 (the sparsely phyric pullow sequence), Unit 3 (the sparsely phyric cooling unit), and Unit 4 (the porphyritic pillow unit), although the shipboard chemical analyses to be used cover the entire hole.

The objective of this paper is to use the shipboard bulk chemical analyses in conjunction with petrographic and microprobe analyses of the phenocryst and groundmass mineral phases to put some restrictions the processes which acted on the magma on the conditions under which the parental magma existed before eruption.

The conclusions reached are that (1) the range of composition observed in any one of the chemical groups cannot unequivocally be explained by low-pressure differentiation of the observed plagioclase and olivine phenocrysts; (2) the variation from one chemical group to another, especially from the porphyritic to sparsely phyric groups, cannot be explained by this process; (3) many of the olivine phenocrysts in the porphyritic pillow unit are too magnesian to have grown from a liquid with the present bulk composition; (4) the plagioclase phenocrysts in the porphyritic pillow sequence cannot all have grown in the same thermal and chemical environment; and (5) the processes which resulted in the present rocks must be much more complex than simple crystal-liquid differentiation.

BULK CHEMICAL ANALYSES

The Leg 46 Shipboard Party (this volume) has presented bulk chemical analyses (XRF and AA) of the basalts. These compositions are well within the range of mid-ocean ridge basalts (Kay et al., 1970; Frey et al., 1974). In general, the porphyritic pillow basalt is richer in CaO and Al₂O₃ (higher plagioclase) than the sparsely phyric basalts.

Figure 1 is a plot of TiO_2 versus MgO for these data. The Shipboard Party has divided the hole into six chemical units, most of which can be distinguished on this plot. Units A_2 and C are stratigraphically separated, and can be distinguished by their Al₂O₃, Cr, and Sr contents. An understanding of the chemical variations will require an explanation of both the flat TiO₂-MgO trends within the groups and the increase in TiO₂ at essentially constant MgO between groups, as well as the similar variations in the other elements described by the Shipboard Party (this volume).

MINERALOGY

Like the chemistry, the mineralogy of the Leg 46 rocks is typical of mid-ocean ridge basalts (Blanchard et al., 1976). Ubiquitous groundmass phases are plagioclase, augitic clinopyroxene, olivine, titanomagnetite, sulfide blebs, and glass. Groundmass ilmenite occurs in the Core 15 cooling unit and is in the norms of all analyses. Alteration products include smectite, carbonate, and zeolites (Honnorez et al., this volume). Phenocrysts of olivine and plagioclase occur in all units. No clinopyroxene phenocrysts were found in any of the samples examined.

In the sparsely phyric pillow units, the groundmass ranges from holohyaline to microlitic interstitial. The plagioclase phenocrysts are, for the most part, ragged in outline, and may or may not be internally skeletal. A few are beautifully rounded. Others are skeletal laths which occur in clusters with skeletal olivine. Figure 2 illustrates the types of plagioclase phenocrysts observed in these units. Skeletal microphenocrysts of plagioclase are also common.

There are two kinds of olivine phenocrysts. Some are skeletal to euhedral, others are large, rounded, and sometimes twinned. Figure 3 illustrates the variation observed. Skeletal microphenocrysts of olivine are very common. Table 1 lists microprobe analyses of the olivine (Fo₈₆) and plagioclase (An₇₃) phenocrysts from these units.

The groundmass in the Core 15 cooling unit is interstitial, and most of the groundmass plagioclase and augite is skeletal. The groundmass olivine is mostly anhedral. Tables 2, 3, and 4, present microprobe analyses of groundmass plagioclase, clinopyroxene, and olivine, respectively. The plagioclase ranges from An69 to An51; with most of the analyses giving values greater than An60. Figure 4 is a plot of FeO* and MgO in the plagioclase versus An content. For the most part, FeO* increases with decreasing An, while MgO remains fairly constant. The clinopyroxene is augitic (average composition about En39W044Fs17) with little systematic variation. Figure 5 presents the data in the pyroxene quadrilateral. The implications of the titanium and chromium contents of the pyroxenes have been discussed by Kirkpatrick (this volume). The olivine ranges from about Fos4 to Foso.

The olivine and plagioclase phenocrysts in the cooling unit are similar to those in the sparsely phyric pillow units. Most are rounded.

As in the sparsely phyric pillow sequence, the groundmass in the porphyritic pillow sequence ranges from holohyaline at the pillow margins to microlitic interstitial in the pillow centers. Table 5 presents microprobe analyses of the groundmass plagioclase. Compositions range from

¹Present address: Department of Geology, University of Illinois, Urbana, Illinois.



Figure 1. TiO₂ versus MgO (shipboard analyses), illustrating the chemical units defined.

about An_{71} to An_{62} . Figure 6 is a plot of FeO* and MgO in the plagioclase versus An content (phenocryst analyses are included). For the groundmass plagioclase, both FeO* and MgO increase with decreasing An.

The textural and compositional variation is very complex in the olivine and plagioclase phenocrysts in the porphyritic pillow sequence.

The plagioclase phenocrysts vary from euhedral to extremely skeletal, and from almost groundmass size to about 1 cm. Many, but not all, occur as clusters (glomerocrysts). Figures 7 and 8 illustrate the variation in size and morphology. The plagioclase compositions (Table 6) range from An₈₅ to An₆₉. The compositions of the phenocryst cores (Table 7) cover the same range. FeO* and MgO (Figure 6) both increase with decreasing An.

The variation in zoning patterns in the plagioclase phenocrysts is also complex. Table 8 lists the patterns observed for each morphologic type. Many grains are normally zoned with a core (often rounded) of about An_{82} or so and a rim, externally faceted, of about An_{72} to An_{69} . Usually this rim is not skeletal. Other zoning patterns are also common. These include reverse zoning, covering a variety of compositions, broad-scale oscillatory zoning, and almost no zoning at all. Not all grains have the more albitic rim, and the kind of zoning does not appear to be related to whether or not the grain is skeletal.

Neither does composition appear to be related to size or morphology. Each size and morphology, except for the small skeletal crystals which are probably intertelluric, exhibits the same range of core compositions.

The olivine phenocrysts occur as large (up to 0.5 cm) rounded anhedral or euhedral grains and as smaller skeletal grains. Figure 9 illustrates some of the morphologies observed. Table 9 lists representative analyses. Figure 10 is a plot of molecular FeO/MgO in the olivine to FeOMgO in the bulk composition (analyses from the sparsely phyric pillow and cooling units are included). Many of the olivine phenocrysts from the porphyritic pillow unit are much too

magnesian to have grown from the bulk composition, assuming a distribution coefficient of 0.33 (Longhi et al., 1975). The ones that are too magnesian are the large, non-skeletal grains; the smaller, skeletal grains appear to be in chemical equilibrium. Neither do they show evidence of resorption.

A few red to red-brown spinel phenocrysts also occur in the unit. Table 10 gives representative analyses.

ORIGIN OF COMPOSITIONAL VARIATION

As noted above, two compositional variations in these rocks must be explained: variation within chemical groups and variation between chemical groups.

The simplest possibility is that these variations are ascribable to crystal-liquid fractionation of the phenocryst phases present, olivine and plagioclase. This possibility has been tested by using the linear programming-least squares procedure of Wright and Doherty, (1970). Table 11 presents the solutions for the within-group variations, along with the assumed initial and final bulk compositions and the compositions of the mineral phases used. Table 12 presents the same information for the variation between chemical groups A1 and A3, B2 and B1, B2 and A3. The bulk compositions used for the within group variations are the least and most MgO-rich analysis in each group. If there are two analyses at either end of the spectrum, they were averaged and this value used. For the between-group variation, all the analyses in each group were averaged and this value used. For the within-group variation in the sparsely phyric units, the mineral compositions used are the analyses presented in Table 1. For the within-group variations in the porphyritic units and the between-group variations, the mineral compositions were allowed to vary from the most to least magnesian olivine and the most to least anorthitic plagioclase observed. The compositions given in Tables 11 and 12 are the averages selected by the program.

Of the within-group solutions, only that for group B2, a porphyritic pillow basalt unit, demonstrates conclusively that the variation could have been caused by fractionation of olivine and plagioclase. For that group, the differences between observed and calculated least magnesian analyses are very small for all elements. For all the other groups, the difference between the calculated and observed value for at least one element is significant.

If differentiation of olivine and plagioclase is to explain the observed variation in these units, some special pleading is necessary. For group B1, differences in SiO₂, FeO*, and CaO are significantly different. The SiO₂ and FeO* are different because of one analysis, which may not be correct, but for CaO there are two analyses with high values. For group A1, SiO₂, Al₂O₃, FeO*, CaO, and TiO₂ all give poor agreement, and no simple rationalization seems possible. For group A2, the agreement is better, but SiO₂ and FeO* still give poor agreement. The SiO₂ can be reasonably interpreted as analytical error in the XRF technique used, but the FeO* is more difficult to explain. For group A3 there is acceptable agreement, although the difference of 0.1 in FeO* is a little large. For group C the difference in SiO₂, FeO*, and CaO are significant.









с

Figure 2. Plagioclase phenocrysts from the sparsely phyric pillow basalts (lithologic Units 1 and 2). (A) Skeletal, resorbed phenocryst (Sample 4-1, 135-140 cm), length of field 0.6 mm. (B) Skeletal, resorbed phenocrysts set in glass with spherulitic plagioclase growing around the margin (Sample 6-1, 81 cm), length of field 1.8 mm. (C) Rounded, non-skeletal phenocryst (Sample 7-2, 42-47 cm), length of field 1.8 mm. (D) Group of skeletal olivines and lath-shaped plagioclases with non-resorbed outlines (Sample 4-1, 142-145 cm), length of field 1.8 mm.



Figure 3. Olivine phenocrysts from sparsely phyric pillow basalts (lithologic Units 1 and 2). (A) Cluster of skeletal olivine and lath-shaped plagioclase (Sample 4-1, 142-145 cm), length of field 0.6 mm. (B) Cluster of slightly rounded olivine (Sample 5-1, 163-167 cm), length of field 7.4 mm. (C) Skeletal but faceted phenocryst set in glass with dendritic olivine and spherulitic plagioclase (Sample 4-1, 142-145 cm), length of field 0.6 mm. (D) Skeletal but faceted olivine set in glass (Sample 5-1, 164-167 cm), length of field 0.6 mm.

	TABLE 1
Elect	ron Microprobe Analyses of Phenocrysts
F	from the Sparsely Phyric Pillow Unit

	Plagioclase Sample 7-2, 42-47 cm		Olivine Sample 7-2 42-47 cm
SiO ₂	49.11		39.09
Al_2O_3	30.20		-
Cr_2O_3	-		0.09
MgO	0.22		46.14
FeO	0.43		13.57
CaO	14.98		0.30
Na ₂ O	3.02		5 <u>-</u>
K20	0.03		(-)
TiO ₂	0.10		-
MnO	-		0.13
NiO	-		0.18
TOTAL	98.06		99.50
Ab	26.7	Fo	85.7
Ab	73.3	Fa	14.3

TABLE 2 Representative Analyses of Groundmass Plagioclase From Core 15 Cooling Units

	Sample											
	15-1, 81-90 cm	15-1, 132-140 cm	15-2, 90-94 cm	15-3, 50-55 cm	15-3, 145-148 cm	15-4, 30-45 cm	15-5, 43-48 cm					
SiO ₂	52.59	53.01	52.37	53.21	51.18	50.92	51.49					
Al203	29.90	28.23	29.52	30.18	29.77	29.52	31.24					
MgO	0.28	1.38	0.28	0.27	0.27	0.25	0.23					
FeO*	0.63	1.55	0.89	0.69	0.44	0.45	0.44					
CaO	14.07	12.17	13.31	13.32	13.79	14.31	14.00					
Na ₂ O	3.57	3.90	3.87	4.04	3.73	3.60	3.67					
K20	0.03	0.16	0.02	0.03	0.03	0.03	0.04					
TOTAL	101.07	1004.0	100.26	101.74	99.21	98.98	100.80					
An	68	63	66	65	67	69	68					
Ab	32	37	34	36	33	31	32					

The main difficulty with the solutions for the sparsely phyric units lies in explaining the observed decrease in FeO* with decreasing MgO. All the solutions give higher FeO* than the observed values. This could be explained by loss of a less magnesian olivine, but none has been observed. Another possible explanation is that alteration is causing small compositional changes which cannot be explained by changes in olivine or plagioclase. This possibility could be tested by analyzing several samples from one pillow.

If these solutions are correct, they imply that in groups A1 and A3 significant plagioclase is being added to the bulk compositions. This is in agreement with the rounded phenocrysts observed in these units.

The solutions for the group to group variation do not work well at all. B2 to B1 is close, but the differences in Al₂O₃, CaO, TiO₂, and especially FeO* are large. B2 to A1 and A1 to A3 are totally unacceptable.

Addition of an augitic clinopyroxene to the crystalline assemblage (Table 13) improves the solutions some. B2 to B1 is still good and A1 to A3 becomes acceptable. B2 to A3 is still poor. The meaning of these solutions is not clear, however, since clinopyroxene is not found as a phenocryst phase. The results of these calculations, then, are equivocal. It would certainly be convenient to believe that simple crystal-liquid differentiation is the cause of the within-group variation, but it apparently cannot completely do the job. For the between-group variation, simple fractionation does not appear likely at all, unless some sort of post-cumulus growth of clinopyroxene (Hodges et al., 1976) is effective in changing the liquid composition. This is difficult to prove, however, from the present data. From the complexity of the phenocryst assemblages it seems likely that other processes were acting.

ORIGIN OF PHENOCRYSTS

The variation in morphology, composition, and compositional zoning of the plagioclase phenocrysts in these basalts (especially the porphyritic units) appears to be a key to at least putting some limits on their pre-eruption history. Three features must be explained: grain-to-grain variation in the composition of the core of each crystal, grain-to-grain variation in the zoning pattern, and grain-to-grain variation in crystal morphology (skeletal versus non-skeletal).

The morphological variation is probably a result of variation in the cooling rate under which each individual crystal grew; the more finely skeletal the crystal the higher the cooling rate (Lofgren et al., 1974; Walker et al., 1976). From the morphological variation in the plagioclase phenocrysts (Figures 7 and 8) it is clear that they must have grown under a wide range of cooling regimes. The cooling rates were not, however, as high as in extrusive conditions, because the spacings are much larger. Such a variety of cooling rates could be a consequence of cooling at different distances from the margin of one body, or could have resulted from crystallization in a number of bodies of different size or perhaps in different bodies at different depths and therefore different external temperatures. The change from skeletal to non-skeletal and non-skeletal to skeletal within one crystal implies that some crystals are able to move from one environment to another.

The observed variation in core composition (Table 7) can be explained either by initiation of growth in liquids of different composition or in the same liquid at different pressures (Kudo and Weill, 1970; Green, 1968). The pressure effect may, in fact, be important in this case. Green (1968) found that in an andesite composition the liquidus plagioclase composition changed from An_{58} at zero pressure to An_{39} at 13.5 kb. Whatever the cause, in the Leg 46 basalts the complete spectrum of core compositions, from An_{55} to An_{70} or so, is observed in both skeletal and non-skeletal crystals. Nucleation must therefore have occurred in both high cooling rate and low cooling rate environments.

The zoning patterns in the plagioclase grains (Table 8) place further constraints on the magma's history. Some grains are normally zoned, some reversely zoned, others have broad-scale oscillations, still others are almost totally unzoned. As with the core compositions, either liquid composition or pressure may be the cause. It seems unlikely, however, that low-An crystals would grow at high pressure, rise some kilometers, and grow with a higher An content, then fall back those many kilometers, grow a less

	Sample										
	15-1, 81-90 cm	15-1, 132-140 cm	15-2, 90-94 cm	15-3, 50-55 cm	15-3, 95-100 cm	15-3, 145-148 cm	15-4, 30-45 cm	15-5, 43-48 cm			
SiO ₂	46.33	47.95	48.78	49.54	48.92	49.95	48.67	47.00			
Al203	6.33	4.52	5.07	5.03	4.07	4.05	4.63	6.02			
MgO	11.69	12.39	13.12	14.73	13.69	14.56	13.69	11.77			
FeO	9.67	11.01	9.54	8.53	10.39	7.58	8.81	10.80			
CaO	21.94	20.53	21.55	19.91	20.08	21.17	20.63	21.15			
Na ₂ O	0.64	0.43	0.37	0.32	0.38	0.36	0.43	0.52			
TiO ₂	4.10	2.29	2.01	1.55	1.83	1.56	2.09	2.92			
MnO	0.19	0.24	0.25	0.20	0.21	0.17	0.19	0.26			
TOTAL	100.89	99.36	100.69	99.81	99.57	99.40	99.14	100.61			
En	35	37	39	43	40	43	41	35			
Wo	48	44	45	42	42	44	44	46			
Fs	17	19	16	15	18	13	15	19			

 TABLE 3

 Representative Clinopyroxene Analyses From Core 15 Cooling Unit

TABLE 4 Representative Olivine From Core 15 Basaltic Cooling Unit

	Sample											
	15-1, 81-90 cm	15-1, 132-140 cm	15-2, 90-94 cm	15-3, 50-55 cm	15-3, 95-100 cm	15-4, 30-45 cm	15-5, 43-48 cm					
SiO ₂	39.37	39.49	39.20	40.13	38.60	39.11	39.03					
MgO	44.94	44.60	42.93	44.55	42.30	45.10	45.34					
FeO	16.23	15.49	18.66	17.42	17.64	14.91	15.97					
CaO	0.32	0.32	0.37	0.33	0.33	0.28	0.30					
MnO	0.25	0.23	0.31	0.28	0.31	0.21	0.18					
NiO	0.20	0.29	0.17	0.16	0.18	0.28	0.15					
TOTAL	101.31	100.42	101.64	102.87	99.36	99.89	100.97					
Fo	83	83	80	82	81	84	83					
Fa	17	17	20	18	19	16	17					

An-rich outer rim, and then erupt so rapidly that no overgrowth would occur — which would be required to produce the oscillatory zoned grains. A similar argument would hold for the reversely zoned grains, which would nucleate at low pressure, descend many kilometers, grow an An-poor rim, and then erupt rapidly. Pressure changes could be the cause of the reverse zoning, however. The An-poor core would have grown at high pressure and the An-rich rim at lower pressure just before eruption. An interesting point is that none of the skeletal grains analyzed is reversely zoned, as would be consistent with initiation of growth in a deeper, more slowly cooling, environment.

Because the zoning in the olivine grains does not appear to be as complex, not as much information can be gained from them. It is clear, however, that the relatively magnesian grains (about F_{080}) must have grown from a liquid significantly more magnesian than the present bulk composition. Whether the presently observed compositions are derived from this liquid by crystal-liquid fractionation is not clear.

Dungan et al. (this volume) have postulated that the group-to-group variation in bulk composition may be a result of mixing of a primordial magnesian-calcic liquid with a differentiated residual magma left in a near-surface chamber after previous eruptions. Most of the features observed here can be so explained. The only difficulty



Figure 4. FeO* and MgO in groundmass plagioclase from the Core 15 cooling unit (lithologic Unit 3) versus plagioclase composition.

seems to be the oscillatory zoned plagioclase phenocrysts. If pressure effects on the plagioclase composition can be ruled out, then it would be necessary to pass these grains back and forth from one liquid to the other. It is difficult to see how this is possible without homogenization of the liquid. The



Figure 5. Composition of clinopyroxene from the Core 15 cooling unit (lithologic Unit 3).

hypothesis does, however, explain the presence of the very small An_{85} grains. These are extremely difficult to explain in any simple fractionation model, since they almost certainly would have a less anorthitic overgrowth if they had been in the present liquid very long.

If Dungan et al., are correct, the last mixing event must have occurred just before eruption. This is the only way to explain the too magnesian and anorthitic phenocrysts which have no overgrowth and are not rounded. The rounded or overgrown grains are presumably the result of a previous mixing event.

The phenocryst data presented here, along with the poor solutions to the crystal-liquid fraction models for the bulk composition, lend support to the mixing model proposed by Dungan et al. (this volume), and indicate a need for more detailed study of the phenocryst assemblages in mid-ocean ridge basalts, for experimental work on the crystallization and dissolution kinetics in basaltic systems and on the high and low pressure phase equilibria of magnesian compositions, and for theoretical work on the processes which might occur during mixing of magmas beneath a spreading center.

ACKNOWLEDGMENTS

I would like to thank Dr. J.H. Natland for his review of the manuscript.

REFERENCES

Blanchard, M.W., Rhodes, J.M., Dungan, M.A., Rodgers, K.V., Donaldson, C.H., Brannon, J.C., Jacobs, J.W., and Gibson, E.K., 1976. The chemistry and petrology of basalts from Leg 37 of the Deep Sea Drilling Project, J. Geophys. Res., v. 81, p. 4231-4246.

- Frey, F.A., Bryan, W.B., and Thompson, G., 1974. Atlantic Ocean Floor: Geochemistry and petrology of basalts from Legs 2 and 3 of the Deep Sea Drilling Project, J. Geophys. Res., v. 79, p. 5507-5528.
- Green, T.H., 1968. Experimental fractional crystallization of quartz diorite and its application to the problem of anorthisite origin. In Isachsen, Y.W. (Ed.). Origin of anorthisite and related rocks: Memoir 18, New York State Geological Survey — New York State Museum and Science Survey, Albany.
- Hodges, F.N. and Papike, J.J., 1976. DSDP Site 334: Magmatic cumulates from oceanic layer 3, J. Geophys. Res., v. 81, p. 4135-4151.
- Kay, R., Hubbard, N.J., and Gast, P.W., 1970. Chemical characteristics and origin of oceanic ridge volcanic rocks, J. Geophys. Res., v. 75, p. 1585-1614.
- Kudo, A.M. and Weill, D.F., 1970. An igneous plagioclase geothermometer, Contrib. Mineral. Petrol., v. 25, p. 52-65.
- Lofgren, G., Donaldson, C.H., Williams, R.J., Mullins, O., and Usselman, T.M., 1975. Experimentally reproduced textures and mineral chemistry of Apollo 15 quartz normative basalts. *Proc. Lunar Sci. Conf.*, 6th, p. 540-567.
- Longhi, S., Walker, D., and Hays, J.F., 1975. Fe-Mg distribution between olivine and lunar basaltic liquids (abstract), *Trans. Am. Geophys. Union*, v. 56, p. 471.
- Walker, D., Kirkpatrick, J., Longhi, J., and Hays, J.D., 1976. Crystallization history of lunar picritic basalt sample 12002: Phase equilibria and cooling rate studies, *Geol. Soc. Am. Bull.*, v. 87, p. 646-656.
- Wright, T.L. and Doherty, P.C., 1970. A linear programming and least squares computer method for solving petrologic mixing problems, *Geol. Soc. Am. Bull.*, v. 81, p. 1995-2008.

	37	cm	45 0	45 cm		56 cm		61 cm		cm	71	cm
	a	b	а	b	a	b	а	b	a	b	а	b
SiO ₂	50.47	51.83	50.87	51.69	49.99	52.30	51.82	52.87	51.09	52.58	50.90	52.46
Al203	30.87	29.31	30.78	28.45	30.73	28.93	29.69	29.89	30.74	30.00	29.28	29.00
MgO	0.27	0.46	0.32	0.62	0.25	0.40	0.34	0.37	0.29	0132	0.51	0.44
FeO	0.60	0.84	0.80	1.17	0.58	0.84	0.67	0.72	0.57	0.92	0.82	1.00
CaO	14.30	13.51	14.11	13.28	14.67	13.55	14.04	13.58	14.46	13.70	13.88	12.93
Na ₂ O	3.63	4.07	3.74	3.99	3.28	3.98	3.77	4.12	3.61	4.09	3.33	4.40
K20	0.03	0.03	0.02	0.10	0.02	0.05	0.04	0.04	0.02	0.04	0.21	0.04
Total	100.17	100.05	100.64	99.30	99.52	100.00	100.37	101.59	100.78	101.65	98.93	100.27
Ab	31	35	32	35	29	35	33	35	31	35	30	38
An	69	65	68	65	71	65	67	65	69	65	70	62

 TABLE 5

 Groundmass Plagioclase From Porphyritic Pillow, Core 20, Section 1, 36-80 cm











Figure 7. Plagioclase phenocrysts from the porphyritic pillow basalt (lithologic Unit 4). All specimens from Sample 20-1, 36-80 cm, all field lengths are 2.4 mm. (A) Skeletal plagioclase with non-skeletal core. Note rounded olivine at top center. (B) Cluster of non-skeletal plagioclases. (C) Part of large skeletal plagioclase with non-skeletal center.

 TABLE 6

 Electron-Microprobe Analyses of Plagioclase Phenocrysts From the Porphyritic Pillow Unit (Sample 20-1, 36-80 cm)

	1a	1b	1c	1 d	2a	2b	3a	3b	3c	4a	4b	4c	5a	5b	5c		
SiO ₂	50.08	49.79	49.69	49.16	47.03	50.87	51.80	48.77	51.13	50.29	49.87	48.74	50.48	51.80	52.50		
Al203	31.77	32.25	32.38	33.18	33.80	31.48	31.08	33.47	30.48	30.65	31.00	31.68	30.94	31.18	30.72		
MgO	0.20	0.21	0.18	0.18	0.14	0.24	0.22	0.20	0.26	0.18	0.23	0.19	0.24	0.23	0.20		
FeO	0.34	0.42	0.37	0.45	0.33	0.45	0.45	0.43	0.04	0.44	0.44	0.41	0.34	0.35	0.38		
CaO	15.66	15.95	16.16	16.12	17.57	15.09	15.21	16.80	13.61	14.35	14.84	15.45	14.73	14.51	14.63		
Na ₂ O	2.93	2.79	2.75	2.27	1.72	3.19	3.37	2.27	3.95	3.52	3.29	2.91	3.46	3.64	3.49		
K20	0.01	0.02	0.01	0.01	0.01	0.02	0.02	0.01	0.02	0.03	0.02	0.01	0.02	0.02	0.02		
Total	100.99	101.43	101.54	101.37	100.60	101.34	102.12	101.95	100.09	100.46	99.69	99.39	100.21	101.73	101.44		
Ab	25	24	24	20	15	28	29	20	34	31	29	25	30	31	30		
An	75	76	76	80	85	72	71	80	66	69	71	75	70	69	70		

Note: 1a-1d core to rim in euhedral phenocryst; 2a and 2b core and rim of euhedral phenocryst; 3a-3c core to rim of euhedral phenocryst; 4a-4c core to rim of euhedral phenocryst; 5a-5c core to rim of skeletal phenocryst; 6a-6b core and rim of skeletal phenocryst; 7a-7c core to rim of skeletal phenocryst; 8a-8d center to outside of glomerocryst of euhedral crystals; 9 small euhedral phenocryst; 10 center of medium skeletal phenocryst; 11 small euhedral plagioclase attached to skeletal olivine phenocryst; 12 small skeletal phenocryst transitional to groundmass; 13 small euhedral phenocryst; 14 small euhedral phenocryst.





Figure 8. Plagioclase phenocrysts from the porphyritic pillow basalt (lithologic Unit 4). All specimens from Sample 20-1, 36-80 cm. (A) Small skeletal and non-skeletal plagioclase. Note rounded olivine in center of upper right ¼. Length of field is 2.4 mm.
(B) Skeletal plagioclase with non-skeletal rim. Length of field is 1.8 mm. (C) Skeletal plagioclase. Note rounded olivine in lower center. Length of field is 2.4 mm.

 TABLE 6 - Continued

6a	6b	7a	7ъ	7c	8a	8b	8c	8d	9	10	11	12	13	14
48.63	51.09	47.26	47.78	47.24	47.54	45.79	46.59	49.70	47.98	49.63	49.57	49.29	49.30	46.92
32,49	30.86	33.41	32.95	34.27	32.01	33.65	33.24	31.13	32.72	31.46	30.71	31.28	32.28	33.69
0.18	0.24	0.10	0.22	0.19	0.22	0122	0.22	0.24	0.25	0.27	0.27	0.27	0.17	0.20
0.37	0.40	0130	0.32	0.34	0.23	0.31	0.32	0.47	0.32	0.33	0.46	0.54	0.50	0.36
17.25	14.99	17.13	17.16	17.54	15.81	17.49	16.96	15.31	16.80	14.91	14.97	14.85	15.59	17.66
2.04	3.30	2.04	1.97	1.83	2.17	1.77	2.09	3.04	2.25	3.20	3.25	3.22	2.65	1.73
0.01	0.01	0.02	0.00	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.02	0.00
100.97	100.89	100.31	100.40	101.42	97.99	99.24	99.42	99.90	100.30	99.81	99.24	99.46	100.51	100.56
18	28	18	17	16	20	15	18	26	20	28	28	28	24	15
82	72	82	83	84	80	85	82	74	80	72	72	72	76	85

TABLE 7 Composition (Mole % An) of Cores of Plagioclase Phenocrysts From Porphyritic Pillow Unit (Sample 20-1, 36-80 cm)

Small (<0.4 mm)	Medium	(0.4 to 1.6 mm)	Large (>1.6 mm)			
Non-Skeletal	Skeletal	Non-Skeletal	Skeletal	Non-Skeletal		
76-74	82-72 83-83-69	83-74 80-80-81-74 71-80-66	83-82-83-84 70-69-70	75-76-76-80 85-72 69-78-68 69-71-74 ^a 69-72-77 ^a		

^a The same grain in different directions.

TABLE 8 Zoning Patterns (Mole % An) Observed in Plagioclase Phenocrysts From the Porphyritic Pillow Unit (Sample 396B-20-1, 36-80 cm) (sequence given is from the core of the grain to the rim)

Small (<0.4 mm)	Medium	(0.4 to 1.6 mm)	Large (>1.6 mm)			
Non-Skeletal	Skeletal	Non-Skeletal	Skeletal	Non-Skeletal		
76-74	82-72 83-83-69	83-74 80-80-81-74 71-80-66	83-82-83-84 70-69-70	75-76-76-80 85-72 69-78-68 69-71-74 ^a 69-72-77 ^a		

^a The same grain in different directions.



Figure 9. Olivine phenocrysts from the porphyritic pillow basalt (Lithologic Unit 4). (A) and (B) Optically continuous skeletal olivine (Sample 23-1, 92-98 cm). Length of field is 2.4 mm. (C) Optically continuous skeletal olivine with plagioclase laths (Sample 20-1, 36-80 cm). Length of field is 1.8 mm. (D) Large faceted olivine (Sample 20-1, 36-80 cm. Length of field is 1.8 mm.

TABLE 9
Electron-Microprobe Analyses of
Olivine Phenocrysts From
Porphyritic Pillow Unit
(Sample 20-1, 36-80 cm)

	1 ^a	2 ^b	3 ^c
SiO ₂	39.65	39.69	39.20
MgÕ	46.44	49.02	46.36
FeO	13.32	10.72	13.56
CaO	0.32	0.33	0.37
Cr203	0.05	0.10	0.05
MnO	0.22	0.14	0.21
NiO	0.09	0.25	0.21
Total	99.77	100.25	99.96
Fo	86	89	86
Fa	14	11	14

a Skeletal phenocryst. b Euhedral phenocryst.

^c Skeletal phenocryst.



Figure 10. Molecular FeO/MgO in olivine versus molecular FeO/MgO in bulk composition, for grains analyzed in the sparsely phyric pillow unit, the Core 15 cooling unit, and the porphyritic pillow unit (assuming $Fe_2O_3/FeO+$ $Fe_2O_3 = 0.1$ for the bulk composition). The grain from the sparsely phyric pillow unit and those from the Core 15 cooling unit have compositions which indicate they could have grown from the present bulk composition. Many of those from the porphyritic pillow unit are too magnesian.

TABLE 10 Electron-Microprobe Analyses of Spinel Phenocrysts From the Porphyritic Pillow Unit (Sample 20-1, 36-80 cm)				
	1	2		
SiO ₂	0.10	0.03		
Al203	26.93	26.67		
Cr203	37.66	37.85		
MgO	14.58	14.34		
FeO	20.38	19.97		
MnO	0.26	0.15		
TiO ₂	0.57	0.59		
TOTAL	100.48	99.60		

TABLE 11	
Computer Solutions For Within-Group Compositional	Variations

	Plag.	Oliv.	Initial Bulk	Final Bulk	Calc. Final Bulk	Differ.
Group A-1	(Sparsely	Phyric)				
SiOn	50.12	39.59	50.69	50.52	50.77	-0.24
Ala	30.82	0.00	16.00	16.30	16.56	-0.25
FeO*	0.44	13.75	9.43	8.71	9.14	-0.42
CaO	15.29	0.29	11.83	12.36	12.03	0.34
MgO	0.23	46.39	8.23	7 74	7.66	0.09
NaoO	3.09	0.00	2.61	2.69	2.65	0.05
KaQ	0.04	0.00	0.19	0.26	0.19	0.08
TiOn	0.00	0.00	1.07	1 46	1.05	0.41
Solution	2.76	-0.91	98.16	1.40	1.05	0.41
Group A-2	(Sparsely	Phyric)				
SiOa	50.12	39.59	50.41	51.03	50.72	0.32
AlaOa	30.82	0.00	15.45	15.58	15.72	-0.13
FeO*	0.44	13.75	9.70	9.43	9.68	-0.24
MgO	0.23	46.39	8.25	7.30	7.29	0.02
CaO	15.29	0.29	11.73	12.02	12.01	0.01
NaoO	3.09	0.00	2.67	2.81	2.74	0.08
KaO	0.04	0.00	0.26	0.28	0.27	0.02
TiOa	0.00	0.00	1.55	1.58	1.61	-0.02
Solution	-1.02	-2.74	103.79	1,50	1.01	-0.02
Group A-3	(Sparsely	Phyric)				
SiOn	50.12	39.59	50.40	50.74	50.54	0.20
AlaQa	30.82	0.00	15.22	15.55	15.62	-0.06
FeO*	0.44	13.75	10.19	9.85	10.02	-0.16
MgO	0.23	46.39	8.15	7.57	7.55	0.02
CaO	15.29	0.29	11.20	11.41	11.40	0.02
NaoO	3.09	0.00	3.00	2.95	3.04	-0.08
K ₂ O	0.04	0.00	0.24	0.29	0.24	0.06
TiOa	0.00	0.00	1.64	1.69	1.64	0.05
Solution	1.30	-1.29	100.01	1.05	1101	0100
Group C (Sparsely P	hyric)				
SiO ₂	50.12	39.59	50.22	49.94	50.49	-0.53
Al203	30.82	0.00	16.12	16.30	16.28	0.02
Group C (Sparsely P	'hyric)				
FeO*	0.44	13 75	945	9 69	9 4 9	0.20
MgO	0.23	46 39	8 30	7.50	7 48	0.03
CaO	15 29	0.29	11.45	11.95	11.66	0.05
NacO	3.09	0.00	2 77	2.68	2.83	-0.14
KaQ	0.04	0.00	0.22	0.36	0.23	0.14
TiO	0.04	0.00	1.52	1.61	1.58	0.04
Solution	-1.61	-2.49	104.12	1.01	1.50	0.04
Group B-1	(Porphyr	itic)				
SiOa	50.04 ^a	39.79 ^b	50.09	49.79	50.47	-0.67
AlaOa	311 11	0.00	16.86	17.03	16.97	0.07
FeO*	0.45	10.76	8 60	9.04	8.91	0.07
MaO	0.43	49 14	8 4 2	7.25	7 21	0.04
CaO	14 90	0.34	12 21	12.80	12 55	0.04
Na O	2 21	0.34	2.44	2.50	2.55	0.23
TiO	0.00	0.00	1.77	1 24	1 30	0.07
K ₂ O	0.00	0.00	0.21	0.24	0.22	0.04
Solution	3 50	3.60	107.20	0.24	0.22	0.02
Solution	-5.58 An 71	-5.08 Fo 89	107.29			

TABLE 11 - Continued

	Plag.	Oliv.	Initial Bulk	Final Bulk	Calc. Final Bulk	Differ.
Group B-2	(Porphyr	itic)				
SiO ₂	48.28	39.79	49.75	50.12	50.20	-0.07
Al203	32.56	0.00	17.93	17.73	17.71	0.03
FeO*	0.38	10.76	7.72	8.00	8.05	0.06
MgO	0.22	49.14	8.46	7.46	7.47	0.00
CaO	16.45	0.34	12.63	12.81	12.85	-0.03
Na ₂ O	2.14	0.00	2.36	2.50	2.45	0.05
K20	0.00	0.00	0.19	0.22	0.20	0.02
TiO ₂	0.00	0.00	1.01	1.11	1.11	0.01
Solution	-5.99	-3.64	109.66			
	An 79	Fo 89				

 $^{a}_{b}$ Selected from the range An 71 to An 85 by the solution. $^{b}_{b}$ Selected from the range Fo 84 to Fo 89 by the solution.

TABLE 12 Computer Solutions for Group-to-Group Variations

			A-1	A-3	A-3	
	Plag.	Oliv.	Avg.	Avg.	Calc.	Differ.
A-1 to A-3						
SiO ₂	50.12	39.59	50.49	50.61	50.67	-0.05
Al203	30.82	0.00	15.84	15.40	15.12	0.28
FeO	0.44	13.75	9.29	10.04	9.79	0.28
MgO	0.23	46.39	8.06	7.86	8.00	-0.13
CaO	15.29	0.29	12.02	11.40	11.99	-0.57
Na ₂ O	3.09	0.00	2.65	2.83	2.66	0.18
K20	0.04	0.00	0.25	0.24	0.27	-0.02
TiO ₂	0.00	0.00	1.44	1.67	1.55	0.12
Solution	-6.40	-1.47	107.90			
B-2 to A-3			B-2 Avg.	A-3 Avg.	A-3 Calc.	
SiO ₂	46.92	39.79	49.91	50.61	50.99	-0.38
Al203	33.69	0.00	17.76	15.40	14.87	0.53
FeO	0.32	10.76	7.91	10.04	9.51	0.53
MgO	0.20	49.14	7.89	7.86	7.99	-0.12
CaO	17.66	0.34	12.74	11.40	12.11	-0.70
Na ₂ O	1.23	0.00	2.55	2.83	2.95	-0.11
K20	0.00	0.00	0.21	0.24	0.26	-0.01
TiO ₂	0.00	0.00	1.07	1.67	1.35	0.32
Solution	-22.60	-3.96	126.58			
An ^a Fo ^b	85	89				

TABLE 13	
Computer Solutions for Group-to-Group V	ariation
Including Clinopyroxene	

	Plag.	Oliv.	CPX	A-1 Avg.	A-3 Avg.	A-3 Calc.	Differ.
A-1 to A-3							
SiO ₂	50.12	39.59	48.55	50.49	50.61	50.76	-0.15
Al 203	30.82	0.00	5.76	15.84	15.40	15.37	0.03
FeO*	0.44	13.75	7.78	9.29	10.04	10.03	0.01
MgO	0.23	46.39	14.39	8.06	7.86	7.86	0.01
CaO	15.29	0.29	21.51	12.02	11.40	11.40	0.01
Na ₂ O	3.09	0.00	0.36	2.65	2.83	2.77	-0.03
K20	0.04	0.00	0.00	0.25	0.24	0.28	0.11
TiO ₂	0.00	0.00	1.68	1.44	1.67	1.56	
Solution	-8.14	-1.31	-5.35	114.83			
				B-2 Avg.	B-1 Avg.	B-1 Calc.	
B-2 to B-1							
SiO ₂	50.04	39.41	48.55	49.91	50.09	50.12	-0.02
Al ₂ O ₃	31.11	0.00	5.76	17.76	17.05	17.04	0.02
FeO*	0.45	13.63	7.7.78	7.91	8.59	8.59	0.00
MgO	0.24	46.60	14.39	7.89	7.85	7.84	0.01
CaO	14.89	0.38	21.51	12.74	12.45	12.45	0.00
Na ₂ O	3.31	0.00	0.36	2.55	2.55	2.58	-0.02
K20	0.00	0100	0.00	0.21	0.23	0.24	0.00
TiO ₂	0.00	0.00	1.68	1.07	1.25	1.18	0.07
Solution	-10.38	-1.65	-3.04	115.10			
				B-2 Avg.	A-3 Avg.	A-3 Calc.	
B-2 to B-3							
SiO ₂	50.04	39.41	48.55	49.91	50.61	50.56	0.05
Al203	31.11	0.00	5.76	17.76	15.40	15.45	-0.05
FeO*	0.45	13.63	7.78	7.91	10.04	10.28	-0.23
MgO	0124	46.60	14.39	7.89	7.86	7.85	0.01
CaO	14.89	0.38	21.51	12.74	11.40	11.47	-0.06
Na ₂ O	3.31	0.00	0.36	2.55	2.83	2.69	0.15
K20	0.00	0.00	0.00	0.21	0.24	0.31	-0.06
TiO ₂	0.00	0.00	1.68	1.07	1.67	1.42	0.25
Solution	-35.29	-4.94	-12.66	152.93			

 a_b Selected from the range An 71 to An 85 by the solution. b_b Selected from the range Fo 89 to Fo 84 by the solution.