3. COMPOSITION AND CRYSTALLIZATION TEMPERATURES OF PRIMARY MELTS FROM HOLE 896A BASALTS: EVIDENCE FROM MELT INCLUSION STUDIES¹

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ABSTRACT

Glass and mineral geochemical data are presented for basalts from Ocean Drilling Program (ODP) Hole 896A. Phenocryst assemblages are dominated by calcic plagioclase $(An_{76-94.5})$ with olivine $(Fo_{80-91.6})$, Cr-Al spinel, and clinopyroxene. The origin of the calcic plagioclase phenocrysts was investigated by heating-stage experiments on silicate melt inclusions in plagioclase and olivine mineral separates. Trapping temperatures of 1195°–1215°C are inferred for plagioclase $(An_{83-94.5})$. Inclusion compositions, interpreted to be in equilibrium with host plagioclase, are similar to the range of pillow-rim glasses from this hole. Primary melts, in equilibrium with $Fo_{91.6}$, are estimated to have ~15 wt% MgO and crystallization temperatures of ~1340°C.

INTRODUCTION

High anorthite contents (to $An_{94,5}$) are a characteristic feature of plagioclase phenocrysts from basalts drilled near the Costa Rica Rift in Ocean Drilling Program (ODP) Holes 504B and 896A. Plagioclases of similar composition have been reported from a variety of midocean ridge basalts (MORB); the Mid-Atlantic Ridge (Deep Sea Drilling Project Leg 37, Aumento, Melson, et al., 1977; Donaldson and Brown, 1977; FAMOUS, Stakes et al., 1984), the South East Indian Ridge (Price et al., 1986), the East Pacific Rise (Siqueiros Fracture Zone; Natland, 1989), and the Galapagos Platform (Sinton et al., 1993), and are commonly associated with megacrysts of Cr-rich magnesian diopside, forsteritic (Fo₈₈₋₉₁) olivine, and Cr-Al spinel.

Experimental results suggest that melts with CaO/Na₂O >10 are required to crystallize plagioclase of >An₉₀ under anhydrous conditions at pressures of <5 kbar (Fisk, 1984; Panjasawatwong, 1991), although more recent data show that high melt Al₂O₃ will stabilize high-An plagioclase at lower CaO/Na₂O (Haskall et al., 1993; Panjasawatwong et al., 1995).

A survey of primitive MORB glass compositions from the literature (T.J. Falloon, pers. comm., 1994) indicates that only one (glass 212; Melson et al., 1976) has the necessary CaO/Na₂O to crystallize plagioclase of $\sim An_{90}$, but not higher. The paucity of erupted liquids of this composition may be explained by pre-eruption processes (magma mixing, low-pressure fractionation, and magma chamber density filters; Sinton and Detrick, 1992). However, samples of such a liquid may be retained in melt inclusions trapped during growth of early formed phenocrysts, and such inclusions have been reported in the literature (e.g., Danyushevsky et al., 1988; Sobolev and Shimizu, 1993).

Two approaches have been employed in the study of melt inclusions. The first involves analysis of naturally quenched inclusions (e.g., Anderson, 1974; Clocchiatti, 1977; Falloon and Green, 1986; Natland, 1989). The compositions of such melt inclusions have been modified to varying degrees by post-trapping crystallization; however, ratios of elements incompatible with the host are thought to preserve some of the chemical signature of the parental melt. In addition, trapping temperatures are difficult to estimate because of uncertainty regarding the amounts and compositions of minerals formed by posttrapping crystallization.

The second approach, experimental studies of melt inclusions, involves reheating the inclusions to melt-back phases formed by posttrapping crystallization and thereby "homogenizing" the inclusion. Homogenization is defined as the moment of dissolution of the last phase inside an inclusion, normally a shrinkage gas bubble, producing a homogeneous melt (Roedder, 1984). In an ideal fluid-saturated system the composition of the inclusion at the moment of homogenization is equal to that of the trapped melt, and the temperature of homogenization matches the temperature of trapping. Two techniques are employed; heating in a 1-atm furnace, under controlled oxygen fugacity (Sinton et al., 1993; Johnson et al., 1995), or in a visually controlled heating stage with a pure He atmosphere (Sobolev et al., 1980).

In this contribution we document the petrography and major element geochemistry of glass and phenocryst phases from Hole 896A basalts, and use heating-stage experiments on plagioclase and olivine to determine the trapping temperature and chemistry of silicate melt inclusions. From these data we estimate melt compositions in equilibrium with plagioclase $An_{94,5}$ and model possible primary magmas.

ANALYTICAL AND EXPERIMENTAL TECHNIQUES

Glass samples were carefully picked from pillow rims, mounted in epoxy, and polished. The glasses and any phenocryst phases present were then analyzed by electron microprobe. Seven samples were selected on the basis of analyzed glass chemistry and phenocryst abundance, and mineral separates were prepared by crushing and sieving. Phenocrysts were picked from the 0.3- to 1.0-mm size fraction, mounted in epoxy and polished. Between 120 and 190 plagioclase grains in each sample and all olivine, spinel, and, where present, clinopyroxene were analyzed to establish the range of phenocryst compositions for each sample.

Electron Microprobe Analysis

All analyses were done on an automated three-spectrometer Cameca SX-50 microprobe at the University of Tasmania, Central Science Laboratory. Standards used were San Carlos Olivine (USNM 111312/444), plagioclase LPL (USNM 115900), Augite KA (USNM122142) (Jarosewich et al., 1980), spinel UV-126 (Lavrentev et al., 1974), and basaltic glass VG-2 (USNM 111249/52). Analytical conditions and counting times for each analytical label used are given

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Table 1. Electron microprobe experimental conditions.

		Count tin	nes (peak/backg	ground; s)	
Oxide	Plagioclase	Olivine	Pyroxene	Spinel	Glass
SiO2	10/5	10/5	10/5	10/5	10/5
TiO ₂			10/5	20/10	10/5
Al ₂ Õ ₃	10/5		10/5	20/10	10/5
FeO	20/10	20/10	20/10	20/10	20/10
MnO		20/10	20/10	20/10	10/5
MgO	10/5	10/5	10/5	10/5	10/5
CaO	10/5	20/10	10/5		10/5
NapO	10/5		10/5		10/5
K ₂ Ô	20/10				20/10
P2Os					10/5
Cr ₂ O ₃		20/10	20/10	10/5	10/5
NiŌ		20/10		10/5	
ZnO				10/5	
Voltage (kv)	15	15	15	15	15
Current (nA)	0	20	20	20	20
Beam (µm)	1	1	1	1	5 × 8

Note: Blank spaces indicate that element was not analyzed.

in Table 1. Relevant standards were analyzed at the start and end of each session, and at approximately 4-hr intervals during longer sessions. Each standard analysis is the average of three analyses, mineral and melt inclusion analyses are averages of two points, and glass analyses are averages of four points.

Fourier Transform Infrared Analysis

The H₂O contents of glass samples were determined by Fourier transform infrared spectroscopy (FTIR) using a Bruker IFS 66 spectrometer with attached optical microscope and Bruker Opus/IR data reduction software at the Central Science Laboratory, University of Tasmania. The same glass chips used for electron microprobe analysis were used for FTIR analysis. Sample preparation, standards, and experimental conditions used have been described elsewhere (Danyushevsky et al., 1993).

High-temperature Microthermometry

Grain mounts used for electron microprobe analysis were cut and polished to 250–350 µm thickness and grains hosting primary melt inclusions suitable for microthermometry were extracted. The heating stage used is an optically controlled system using a high-purity He atmosphere, the same as that described by Sobolev et al. (1980). This stage design allows more rapid quenching than with commercially designed equipment. Using visual control and experimental techniques developed at Vernadsky Institute of Geochemistry, Moscow, homogenization temperatures (T_h) may be estimated to within ±10°–20°C (Sobolev, 1983; Sobolev et al., 1989).

Following the technique referenced above, the sample phenocryst was placed on a 200- to 300- μ m thick plate of transparent, refractory mantle olivine and a small piece of Au was placed on the sample grain as close as possible to the inclusions of interest. The melting point of Au was used to calibrate temperature during each run. The sample was then placed on a Pt ring inside the tubular Pt₉₀Rh₁₀ foil heater; the heating stage was sealed and then flushed with He for 5–6 min before heating began.

Both plagioclase and olivine were heated rapidly to 1150°C and then at a rate of 5°C per min, as determined from a series of kinetic experiments on plagioclase, until close to T_h , as assessed by observing small (~10 µm diameter) inclusions in plagioclase and small (10– 20 µm) inclusions in olivine. Temperature was then held constant or increased slightly until the inclusions of interest were homogenized. Time at high temperature (>1190°C) was limited to <6 min for plagioclase, as it was found that if an inclusion did not homogenize within this time then it was unlikely to homogenize in a reasonable time (i.e., <1 hr). After an experiment, each grain was mounted in epoxy



Figure 1. Downhole variations in glass CaO/Na₂O. Glass groups are based both on CaO/Na₂O values and variations in elements shown on Figure 2.

and polished until the inclusions of interest were exposed and these were then analyzed.

RESULTS

Glass Chemistry

Major element analyses of 43 glasses, forming a stratigraphic section of Hole 896A, are summarized in Figures 1 and 2. Full analyses are presented in Fisk et al. (this volume). On the basis of these data, the drilled section was divided into four intervals with samples from each interval forming subsequent groups: Group 1 comprised samples from Cores 148-896A-1R to 20R, Group 2 from Cores 148-896A-25R and 26R, Group 3 from Core 148-896A-27R, and Group 4 from Core 148-896A-30R. The transition from Group 1 to 2 occurs across the massive flow of Cores 148-896A-20R to 24R, and transitions between the lower groups are in pillow lava sequences and appear over 2 m of core. These transitions do not appear to correlate with changes in either phenocryst assemblage or abundance, as defined by shipboard logging. Most samples are from Groups 1 and 4. These two groups form a single trend on element-MgO plots, consistent with olivine-plagioclase co-crystallization. Glasses from Group 2 have higher Na₂O, TiO₂, and Al₂O₃ compared with the main trend (Fig. 2) whereas those from Group 3 have higher MgO, CaO, and FeO, and lower Al₂O₃ and Na₂O than the main trend.

The H₂O contents of pillow-rim glasses are all <0.1% and there is no variation of H₂O content between the glass groups, within the precision of the technique used. These low abundances are consistent with analyses of glasses of similar Mg# (= $100 \times Mg/[Mg + Fe]$) and K₂O from the East Pacific Rise and Galapagos Ridge (Byers et al., 1986; Michael, 1988).

Seven glasses, all from the high MgO part of the suite, from Groups 1, 2, and 3 were selected for microthermometry (Table 2). The following discussion of mineralogy and melt inclusion compositions refers only to these samples.

Petrography and Phenocryst Mineral Chemistry

The petrography of Hole 896A basalts has been described in detail by the Shipboard Scientific Party (1993) and only the major characteristics of selected samples are summarized here. The samples used are all from glassy pillow rims and inner variolitic zones, and they



from Cores 148-896A-9R, 25R and 27R, suggesting that it is more widespread but in low abundances.

Plagioclase

Plagioclase occurs as anhedral to euhedral phenocrysts that range from 0.1 to 5 mm, with those >0.9 mm interpreted to be megacrysts on the basis of crystal size distribution patterns (Shipboard Scientific Party, 1993). Plagioclase occurs as single crystals, in glomerocrysts with olivine and/or clinopyroxene, and may be included in olivine and in the rims of some clinopyroxenes. Red-brown spinel and glass inclusions are common. Plagioclase phenocrysts commonly have striking optical zoning, and are both normally and reversely zoned. These zoning patterns are described in detail by Shipboard Scientific Party (1993).

Plagioclase "core" compositions range from An78 to An94.5 (Table 3; Fig. 3) and are similar to those from the extrusive section of nearby Hole 504B (Natland et al., 1983). However, most samples host plagioclase grains of up to An₉₂₋₉₃ only, and plagioclases of >An₉₃ were found only in Sample 148-896A-9R-1 (Piece 24). Despite the wide range of plagioclase compositions in each sample, histograms of An content (Fig. 3) are characterized by well-defined maxima that are statistically indistinguishable from the arithmetic means of An content for each sample. To check if these maxima reflect compositions of plagioclases in equilibrium with the host glasses, the arithmetic mean of An content is plotted vs. the CaO/Na2O of the host glass on Figure 4. Two observations can be made: (1) samples from each pillow-rim glass group, with similar CaO/Na₂O, are characterized by similar mean plagioclase compositions; and (2) an increase in melt CaO/Na2O with increasing An is consistent with low-pressure experimental data on plagioclase-melt equilibria. This indicates that most plagioclases from each sample are in equilibrium with their host glasses.

Olivine

Olivine phenocrysts were separated from all samples except Sample 148-896A-4R-1 (Piece 2), and representative analyses are given in Table 4. They generally compose <4% of the sample and range in size from 0.1 to 5 mm. The olivines are euhedral, commonly with skeletal overgrowths, and may include spinel, plagioclase, and glass. The phenocrysts are unzoned, with variations of <1 Fo unit from core to rim. As with the plagioclase phenocrysts, olivines also have a significant compositional range, from Fo₈₀ to Fo_{91.6}, and a well-defined distribution maximum. However, unlike the plagioclases all samples used have this maximum at the same Fo of 87-89 (86% of analyses). The Mg# values of all seven glasses are very similar (64-65.7). Assuming an olivine-melt Mg-Fe2+ Kd of 0.3, liquids in equilibrium with olivines ~Fo₈₈ (the most abundant Fo of studied samples) should have an Mg' (= $100 \times Mg/[Mg + Fe^{2+}]$) of 68.8. To obtain this result, the Fe³⁺/ Σ Fe of the studied glasses should be ~0.17. This value is significantly higher than expected for normal MORB (Christie et al., 1986; Michael and Chase, 1987), suggesting that the dominant olivine compositions (Fo87-89) are not in equilibrium with the host glasses and, most likely, are crystallized from more primitive melts. Assuming a more realistic Fe3+/2Fe of 0.10-0.09, the calculated olivine in equilibrium with the studied glasses is Fo886-87.

We note also that plagioclase inclusions analyzed from five olivine phenocrysts (Fo_{88-88.8}) have a wide compositional range (An_{86.3-} $_{92.3}$); significantly, this range of compositions occurs in a single olivine (see Table 3).

Spinel

Spinels are a minor component of the phenocryst assemblage in all samples examined, occurring as phenocrysts and inclusions in plagioclase and olivine. Grain size ranges from 10 to 150 µm. Representative analyses are included in Table 5. Spinels show a well-defined

Figure 2. Selected major oxides vs. MgO for Hole 896A pillow-rim glass samples. Glass groups have been defined on the basis of these variations and CaO/Na₂O as shown on Figure 1.

Table 2. Analyses of representative pillow-rim glass samples from Hole 896A.

25R-1

80_03

11

412.2

48.96

0.87

16.53

8.99

0.16

9.09

12.89

2.14

0.02

0.03

0.07

0.08

99.83

25R-2

61-64

11

413.4

49.24

0.85

9.17

0.15

9.09

12.81

2.16

0.02

0.05

0.05

0.08

100.22

27R-1

105-109

13

431.6

49.28

0.67

16,17

9.26

0.13

9.45

13.64

1.62

0.02

0.03

0.05

0.05

100.37

27R-1

124-130

15

431.8

49.03

0.64

9.12

0.12 9.43

13.66

1.62

0.02

0.03

0.07

0.05

99.86

9R-1

125-130 24

267.95

49.68

0.81

9.03

0.14

8.96

1.72

0.01

0.05

0.07

0.08

99.17

12.83

Core, section:

Interval (cm):

Glass group:

Depth (mbsf):

Piece no.:

SiO

TiO₂ Al₂O₃

FeÔ

MnO

MgO

CaO

Na₂O K₂O

P204

H20

Total

CroO:

3R-1

16-18

4

210.1

48 94

16.45

0.70

8.73

9.36

13.02

1.70

0.02

0.04

0.07

0.07

99.22

4R-1

2

219.0

49.11

0.72

16.27

8.80

0.15

9.35

13.00

1.74

0.03

0.04

0.05

0.07

99.33

10-13

Mg#	65.7	65.6	64.0	64.4	64.0	64.7	65.0
CaO/Na ₂ O	7.7	7.5	7.5	6.0	5.9	8.4	8.4
Notes: See text	for details	on glass	groups. A	All Fe as	FeO. Mg	# = 100 ×	[Mg/(Mg

range from sparsely porphyritic (1%-2% phenocrysts) to highly porphyritic (>10% phenocrysts). Throughout most of the drilled section, and in all samples used in this study, plagioclase is the dominant phenocryst phase, with lesser olivine (fresh only in glassy rims), clinopyroxene, and spinel. Shipboard descriptions indicate that clinopyroxene phenocrysts are restricted to the interval 353.1–387.5 m below seafloor (mbsf) (Cores 148-896A-18R to 22R); however, we recovered grains of phenocrystal pyroxene (high Mg# and Cr₂O₃)



Analysis no.:	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO ₂	44.58	46.38	44.67	46.16	47.40	43.92	44.02	45.19	47.31	46.26	45.72	4 6.37	44.66
Al ₂ Õ ₃	34.63	33.77	35.08	34.46	33.72	35.07	35.06	34.29	32.56	33.71	34.46	33.52	34.70
FeO	0.27	0.28	0.36	0.37	0.51	0.36	0.37	0.34	0.53	0.43	0.34	0.55	0.57
MgO	0.20	0.31	0.20	0.27	0.24	0.16	0.14	0.23	0.40	0.21	0.28	0.25	0.19
CaO	18.93	17.71	18.79	18.18	17.61	19.07	19.30	18.20	16.43	17.90	18.23	17.52	18.65
Na ₂ O	0.75	1.24	0.79	1.30	1.61	0.61	0.63	1.17	1.80	1.42	1.12	1.54	0.86
K ₂ Ō	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.04	0.01	0.01	0.00	0.00
Total	99.36	99.69	99.89	100.75	101.09	99.20	99.52	99.43	99.07	99.94	100.16	99.75	99.63
Cations calcul	ated on the	basis of 8 o	xygens										
Si	2.075	2.141	2.067	2.114	2.159	2.050	2.049	2.099	2.193	2.135	2.106	2.143	2.074
Al	1.899	1.837	1.914	1.860	1.810	1.929	1.924	1.877	1.779	1.834	1.871	1.826	1.900
Fe	0.011	0.011	0.014	0.014	0.019	0.014	0.014	0.013	0.021	0.017	0.013	0.021	0.022
Mg	0.014	0.021	0.014	0.018	0.016	0.011	0.010	0.016	0.028	0.014	0.019	0.017	0.013
Ca	0.944	0.876	0.932	0.892	0.859	0.954	0.963	0.906	0.816	0.885	0.900	0.868	0.928
Na	0.068	0.111	0.071	0.115	0.142	0.055	0.057	0.105	0.162	0.127	0.100	0.138	0.077
K	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.001	0.002	0.001	0.001	0.000	0.000
Total	5.010	4.996	5.011	5.014	5.007	5.014	5.017	5.016	5.000	5.012	5.009	5.013	5.015
An	93.3	88.8	92.9	88.5	85.8	94.5	94.4	89.5	83.3	87.4	89.9	86.3	92.3
Ab	6.7	11.2	7.1	11.5	14.2	5.5	5.6	10.4	16.5	12.5	10	13.7	7.7
Or	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.1	0.1	0.0	0.0
Mg#	56.9	66.4	49.8	56.5	45.6	44.2	40.3	54.7	57.4	46.5	59.5	44.8	37.3

Table 3. Representative plagioclase analyses, Hole 896A.

Notes: Alphanumeric codes following sample numbers are identifiers of grain mount and grain number. 1 = Sample 148-896A-9R-1 (Piece 24), A9–54 (hosts melt inclusion 1, Table 7). 2 = Sample 148-896A-9R-1 (Piece 24), A9–21 (hosts melt inclusion 2, Table 7). 3 = Sample 148-896A-27R-1 (Piece 15), A13–116 (hosts melt inclusion 3, Table 7). 4 = Sample 148-896A-9R-1 (Piece 24), 12–15 (hosts inclusion 4, Table 7). 5 = Sample 148-896A-9R-1 (Piece 24), 12–16 (hosts inclusion 5, Table 7). 6 = Sample 148-896A-9R-1 (Piece 24), A9–51. 7 = Sample 148-896A-9R-1 (Piece 15), A13–93 (hosts spinel 2, Table 5). 9 = Sample 148-896A-9R-1 (Piece 2), T-2 (hosts spinel 3, Table 5). 11 = Sample 148-896A-4R-1 (Piece 2), T-5 (hosts spinel 4, Table 5). 12 and 13 = Sample 148-896A-27R-1 (Piece 15), A13–93 (hosts spinel 1, Table 5). 13 = Sample 148-896A-27R-1 (Piece 15), A13–93 (hosts spinel 2, Table 5). 14 = Sample 148-896A-27R-1 (Piece 15), A13–93 (hosts spinel 2, Table 5). 14 = Sample 148-896A-27R-1 (Piece 15), A13–93 (hosts spinel 4, Table 5). 12 and 13 = Sample 148-896A-27R-1 (Piece 15), A13–88 (inclusion in olivine 1, Table 4).

trend of decreasing Mg' with Cr# (= $100 \times Cr/[Cr + AI]$) (Fig. 5A), similar to other MORB suites (e.g., Sigurdsson and Schilling, 1976), indicating that spinel crystallization accompanied olivine and plagioclase fractionation (Allan et al., 1988). Calculated Fe²⁺/Fe³⁺ values of all spinels have a narrow range, with an average of 2.2 (Fig. 5B). Although there is a possible trend of increasing Fe²⁺/Fe³⁺ with increasing Cr#, we think that the average Fe²⁺/Fe³⁺ is representative of this suite.

Clinopyroxene

Clinopyroxene is present as both phenocrysts and quenched crystals. Phenocrysts range from 0.5 to 7.0 mm long, are subhedral, often with a rounded or corroded form, and may partially enclose plagioclase phenocrysts (Shipboard Scientific Party, 1993). Representative analyses are given in Table 6.

Melt Inclusions

Melt inclusions that would be classified as primary, secondary, and pseudo-secondary, using the criteria of Roedder (1984), occur in all phenocryst types. Inclusions in plagioclase and olivine were used in heating experiments, and are described in detail below.

Primary inclusions occur in ~30% of plagioclase grains. They range from 2 to 350 µm across and vary in shape from round to rounded negative crystal forms. The inclusions occur in three main patterns: randomly distributed in the cores of crystals having inclusionfree rims; scattered throughout the grain (often arranged parallel to, and elongate along, 010); and more rarely, concentrated in concentric zones. Inclusions that lack fluid bubbles are rare, as are daughter crystals, although sulfide blebs occur in some larger inclusions. Rarely, inclusions are associated with arcuate fractures in the host plagioclase. There are some downhole variations in inclusion occurrence; inclusions from samples higher in the hole (Cores 148-896A-3R, 4R, and 9R) are typically larger (most large primary inclusions are 40– 350 µm), more rounded, and occur more commonly randomly distributed throughout the grains. Those from Cores 148-896A-25R and 27R are much smaller (generally <40 µm diameter), are associated with more fracturing than those from higher in the drilled section, occur concentrated in the cores of phenocrysts, and are more numerous.

Planes of 2- to 5- μ m rounded inclusions, of larger irregularly shaped inclusions, some of which are linked by healed fractures, and of large (>50 μ m) irregularly shaped inclusions typically with crystallographic control, are the three main types of secondary and pseudo-secondary inclusion seen. The last type of inclusion commonly has a complex three-dimensional form and may comprise a large component, by volume, of the host crystal. These inclusions may result from rapid crystal growth, represent glass joining two crystals, or may result from resorption followed by rapid overgrowth; whatever the case, they are not useful for heating experiments and will not be discussed further.

Primary inclusions in olivine range from 10 to 500 μ m in diameter, but are generally 20–100 μ m, and were recorded in 70%–80% of grains, although most phenocrysts host only one or two inclusions. Most inclusions lack vapor bubbles, have a round to rounded-tubular form, and are clear green to brown with only rare obvious daughter crystals. Composite inclusions (consisting of simultaneously trapped glass and plagioclase) were found in a single phenocryst from Sample 148-896A-25R-1, Piece 11. There appears to be no dominant crystallographic control on inclusion orientation.

Compositions of primary inclusions in plagioclase, olivine, and spinel, which were quenched during eruption as glass or glass with a fluid bubble (naturally quenched melt inclusions), are given in Table 7. The bulk compositions of these inclusions are variably modified by post-entrapment crystallization of overgrowths on the host mineral. As can be seen on Figure 6A, variations in Al2O3 and MgO content are much larger in naturally quenched inclusions than in pillow-rim glasses, and also define a trend perpendicular to that produced by cotectic olivine-plagioclase crystallization. Many inclusions in plagioclase have higher MgO and lower Al₂O₃ contents than the glasses, whereas inclusions in olivine show the opposite effect (i.e., increasing Al2O3, decreasing MgO). These variations are interpreted to result from post-trapping overgrowths on the walls of inclusions. The field of pillow-rim glasses overlaps a small segment of the trend defined by the inclusions. This implies that inclusions which have compositions similar to the glasses are the least modified by post-trapping



Figure 3. Histograms of plagioclase phenocryst composition from glass samples used in this study. Pc. = piece.

crystallization, and deviation of MgO (or Al₂O₃) from the glass field is a measure of the extent of post-trapping modification. A simple calculation demonstrates that the least magnesian inclusion (MgO \approx 4 wt%) and the most magnesian inclusion (MgO ~16 wt%) are produced by post-trapping crystallization of ~15 wt% olivine and ~45 wt% plagioclase, respectively.

Whereas post-trapping modification does not significantly affect Na₂O contents of inclusions we analyzed in olivine, it has a dramatic effect on the Na₂O content of inclusions in plagioclase (Fig. 6B) and thus CaO/Na₂O values (Fig. 6C). When only the least modified inclusions (i.e., those with MgO similar to the pillow-rim glasses) are considered, the range of CaO/Na₂O values in inclusions in plagioclase is approximately twice that shown by the pillow glasses (Fig. 6D). Inclusions in plagioclase from Group 1 samples have CaO/Na₂O values that cover the entire range. However, inclusions in plagioclase from

Group 2 have low CaO/Na₂O values, and inclusions from Group 3 have relatively high CaO/Na₂O values when compared with Group 1 glasses. Also, inclusions in olivine (all from Group 3) have CaO/Na₂O values that are similar to inclusions in plagioclase from the same group.

There is a remarkable difference in the range of TiO_2 contents between inclusions in olivine and plagioclase (Fig. 6E). The range in olivine is the same as that in the glasses, whereas inclusions in plagioclase show large variations in TiO_2 content that are independent both of the degree of post-trapping modification and of the sample group. Inclusions in both olivine and plagioclase show a wide range of K₂O contents, several times that of the pillow-rim glasses (Fig. 6F), that are also independent both of the degree of post-trapping modification and of the glass group. Inclusions with least modified compositions (i.e., those with MgO similar to the glasses) are shown



Figure 4. Correlation of plagioclase phenocryst An contents and CaO/Na₂O values of equilibrium melts for melt inclusions and pillow-rim glasses. 1 to 3 = Group 1 to 3 glasses, respectively (symbols are the same as on Fig. 2), 4 to 6 = experimentally reheated inclusions in plagioclase from Groups 1 to 3, respectively. For comparison the field of 1-atm experiments on MORB compositions is also shown (data from Bender et al., 1978; Duncan and Green, 1987; Gaetani et al., 1994; Grove and Bryan, 1983; Grove et al., 1982; and Walker et al., 1979).

separately on Figure 7. Variations in K_2O , TiO₂ and, Na₂O content of these inclusions are not related to each other or to the glass group. However, we note that all our analyzed high K_2O inclusions have high Na₂O contents, although low K_2O inclusions with high Na₂O content also exist. Inclusions in spinel do not show any unusual compositional features and are not shown on these plots as they overlap with the pillow-rim glasses.

In summary, the compositions of naturally quenched inclusions have a much wider range than the pillow-rim glasses, and inclusions in plagioclase show much more compositional scatter than those in olivine and spinel. We emphasize the large variation in TiO₂ contents of inclusions in plagioclase, which is not seen in inclusions from olivine and spinel and the pillow-rim glasses. In addition, some inclusions in both olivine and plagioclase are characterized by unusually high K₂O contents. Inclusions in plagioclase interpreted to have undergone significant post-trapping modification are characterized by severe Na2O depletion and subsequent increase in CaO/Na2O values. The low Na₂O and high CaO/Na₂O that are characteristic of many naturally quenched inclusions in plagioclase are not matched by compositions of inclusions in olivine and spinel or compositions of the pillow-rim glasses. A thorough analysis of these features is beyond the scope of this paper, however we note that the results presented above highlight the danger of using even incompatible element ratios from naturally quenched inclusions in plagioclase as petrogenetic indicators.

Fluid Inclusions

Fluid inclusions were found in plagioclase phenocrysts and indicate that the melt was fluid saturated during plagioclase crystallization. However, no fluid inclusions were found in olivine phenocrysts.

Plagioclase

Inclusions of 10–30 µm diameter were found to be the most useful for experiments, as most inclusions >30 µm diameter leaked during reheating (indicated by increased bubble size and T_h), whereas those of <10 µm diameter were too small to easily observe the homogenization process. All inclusions used for experiments were glassy, with no obvious daughter crystals at room temperature.

On heating to 600°-800°C, the inclusions darkened as daughter crystals formed and bubbles appeared (if none were present initially). In some grains, considerable fracturing was observed at temperatures of >400° to 600°C. With increasing temperature, generally at >1150°C, the color of the inclusions became lighter again, as the daughter crystals started melting. Closer to Th, at >1190°C, most silicate daughter crystals within the volume of the inclusion had melted, leaving a fluid bubble, and in many experiments a small, black, ~2to 3-µm diameter, Fe-Cu-Ni sulfide globule (identified using EDS on the microprobe). These sulfides often coalesced with the fluid bubble at temperatures close to T_h , making accurate determination of the exact temperature of bubble disappearance difficult. In large inclusions, the daughter crystals often recrystallized to a single olivine of $\sim 2 \,\mu m$ diameter that could not be remelted in the time available. On quenching a successful run, most small (<15 µm diameter) inclusions remained glassy, with no bubble; however larger inclusions often had a vapor bubble indicating that they were not homogenized.

As the melt has been demonstrated to be fluid-saturated during plagioclase crystallization, then T_h , which corresponded to the disappearance of the fluid bubble, should equal the trapping temperature (Sobolev and Danyushevsky, 1994). Homogenization was achieved in 40 runs; 118 inclusions were analyzed from these runs. Homogenization temperatures ranged from 1195° to 1225°C. Based on these results, no correlation exists between T_h and the host plagioclase An content. However, as the range of T_h obtained is within the error of the technique used (+15°C), the existence or otherwise of a correlation between T_h and host anorthite cannot be determined.

Compositions of homogenized inclusions are shown on Figure 8. The compositional range of major elements overlaps that of the pillow-rim glasses but shows more scatter. The compositional ranges of minor elements (TiO2, K2O, and Na2O) show significantly more variation, with a similar range to the compositions of least modified naturally quenched inclusions (Fig. 7). As can be seen on Figures 2 and 8 and as discussed in the mineralogical section, the compositional variations of this suite are consistent with cotectic olivine-plagioclase crystallization. As plagioclase phenocrysts are in general in equilibrium with pillow-rim glasses, melt trapped by these plagioclases should be co-saturated with olivine and plagioclase. However, as is obvious from Figure 8, the major element compositions of many inclusions lie off the cotectic as defined by the glasses. Assuming that no chemical exchange occurred between host and inclusion after trapping, then three major processes can affect the composition of an analyzed inclusion. Overheating during the run (homogenization obtained at higher temperature than the temperature of trapping, a function of the kinetics of melting) and/or analytical overlap with the host plagioclase, caused by the uncontrolled thickness (depth) of inclusions being analyzed, will both result in enrichment of the melt in plagioclase components. Poor quenching, particularly common in small inclusions such as those used in this study, will result in depletion of the melt in plagioclase components.

Olivine and plagioclase mineral-melt geothermometers are a useful tool that can reveal inclusion compositions affected by these processes. In this paper, we use a calibration by Danyushevsky et al. (in press), developed to estimate the olivine-plagioclase cotectic, that uses the olivine-melt geothermometer of Ford et al. (1983) and the plagioclase-melt geothermometer of Weaver and Langmuir (1990). A correction has been introduced to the latter to obtain a best fit of the olivine-plagioclase cotectic over the MORB compositional spectrum. Compositions affected by trapping of the host mineral during

Table 4. Representative olivine analyses, Hole 896A.

Analysis no.:	1	2	3	4	5	6	7	8	9	10
SiO ₂	40.23	40.02	40.52	40.45	40.04	40.28	40.40	40.71	38.77	39.63
FeO	11.15	11.46	10.63	10.96	12.12	10.59	10.13	8.25	17.97	14.04
MnO	0.12	0.15	0.20	0.10	0.15	0.21	0.16	0.15	0.30	0.23
MgO	47.55	47.58	47.80	47.68	46.84	48.60	48.58	50.16	41.94	45.64
CaO	0.33	0.35	0.30	0.32	0.55	0.32	0.34	0.32	0.23	0.30
Cr ₂ O ₃	0.06	0.07	0.04	0.06	0.36	0.03	0.04	0.06	0.03	0.04
NiÕ	0.26	0.26	0.28	0.26	0.20	0.27	0.21	0.26	0.17	0.23
Total	99.70	99.89	99.77	99.83	100.26	100.30	99.86	99.91	99.41	100.11
Cations calcu	lated on the	e basis of 4	oxygens							
Si	0.997	0.992	1.001	1.000	0.993	0.991	0.995	0.994	0.996	0.992
Fe	0.231	0.238	0.220	0.227	0.251	0.218	0.209	0.168	0.386	0.294
Mg	1.757	1.758	1.760	1.757	1.731	1.782	1.784	1.826	1.606	1.703
Ca	0.009	0.009	0.008	0.008	0.015	0.008	0.009	0.008	0.006	0.008
Mn	0.003	0.003	0.004	0.002	0.003	0.004	0.003	0.003	0.007	0.005
Cr	0.001	0.001	0.001	0.001	0.007	0.001	0.001	0.001	0.001	0.001
Ni	0.005	0.005	0.006	0.005	0.004	0.005	0.004	0.005	0.004	0.005
Total	3.002	3.007	2.999	3.000	3.004	3.009	3.005	3.006	3.004	3.008
Fo	88.3	88.1	88.9	88.6	87.3	89.1	89.5	91.6	80.6	85.3

Notes: Alphanumeric codes following sample numbers are identifiers of grain mount and grain number. 1 = Sample 148-896A-27R-1 (Piece 15), A13–88 (hosts plagioclase 12 and 13, Table 3). 2 = Sample 148-896A-27R-1 (Piece 15), A13–141 (hosts melt inclusion 7, Table 7). 3 = Sample 148-896A-3R-1 (Piece 4), A14–10 (hosts melt inclusion 6, Table 7). 4 = Sample 148-896A-27R-1 (Piece 13), A10–40 (hosts melt inclusion 8, Table 7). 5 = Sample 148-896A-25R-2 (Piece 11), A15–82 (hosts spinel 5, Table 5). 6 = Sample 148-896A-9R-1 (Piece 24), A9–6 (hosts spinel 6, Table 5). 7 = Sample 148-896A-25R-1 (Piece 11), A15–82 (hosts spinel 5, Table 5). 7 = Sample 148-896A-25R-1 (Piece 11), A15–82 (hosts spinel 6, Table 5). 7 = Sample 148-896A-25R-1 (Piece 11), A3–8. 9 = Sample 148-896A-25R-1 (Piece 11), A8–8. 9 = Sample 148-89

Analysis no.:	1	2	3	4	5	6	7	8	9
SiO ₂	0.08	0.13	0.07	0.09	0.16	0.03	0.11	0.08	0.08
TiO ₂	0.45	0.19	0.20	0.21	0.57	0.84	0.21	0.30	0.28
Al ₂ Õ ₃	25.6	37.22	34.85	35.64	24.96	14.35	39.73	37.58	23.03
Fe ₂ O ₃	6.77	5.99	5.64	5.37	6.57	14.08	5.42	5.59	5.87
FeO	14.93	10.51	11.02	9.96	12.42	18.99	10.12	10.57	12.80
MnO	0.16	0.05	0.14	0.11	0.15	0.19	0.14	0.13	0.20
MgO	13.91	18.00	17.08	17.98	15.49	9.99	18.74	18.02	15.07
Cr ₂ O ₃	38.32	28.31	30.09	30.27	38.80	40.55	27.18	28.30	43.32
NiO	0.24	0.24	0.19	0.19	0.08	0.11	0.23	0.20	0.15
ZnO	0.09	0.09	0.06	0.14	0.03	0.12	0.04	0.10	0.03
Total	100.55	100.74	99.35	99.96	99.23	99.25	101.91	100.87	100.83
Cations calcu	lated on the	e basis of 32	oxygens						
Si	0.019	0.029	0.016	0.020	0.039	0.008	0.024	0.018	0.019
Ti	0.082	0.032	0.035	0.036	0.104	0.166	0.035	0.050	0.051
AL	7.270	9.843	9.449	9.537	7.109	4.444	10.273	9.913	6.542
Fe ³⁺	1.227	1.013	0.977	0.917	1.194	2.785	0.894	0.942	1.064
Fe ²⁺	3.009	1.973	2.121	1.891	2.510	4.172	1.856	1.978	2.580
Mn	0.033	0.010	0.027	0.021	0.031	0.042	0.026	0.025	0.041
Mg	4.997	6.021	5.858	6.086	5.580	3.913	6.129	6.013	5.414
Cr	7.301	5.022	5.473	5.434	7.413	8.424	4.715	5.008	8.255
Ni	0.047	0.043	0.035	0.035	0.016	0.023	0.041	0.036	0.029
Zn	0.016	0.015	0.010	0.023	0.005	0.023	0.006	0.017	0.005
Mg	62.4	75.3	73.4	76.3	69.0	48.4	76.8	75.2	67.7
Cr#	50.1	33.8	36.7	36.3	51.0	65.5	31.5	33.6	55.8

Table 5. Representative spinel analyses, Hole 896A.

Notes: Alphanumeric codes following sample numbers are identifiers of grain mount and grain number. Fe₂O₃ calculated assuming stoichiometry. 1 = Sample 148-896A-4R-1 (Piece 2), T-2 (inclusion in plagioclase 10, Table 3). 2 = Sample 148-896A-4R-1 (Piece 2), T-5 (inclusion in plagioclase 11, Table 3). 3 = Sample 148-896A-27R-1 (Piece 15), A13–93 (inclusion in plagioclase 9, Table 3). 4 = Sample 148-896A-27R-1 (Piece 15), A13–133 (inclusion in plagioclase 8, Table 3). 5 = Sample 148-896A-25R-2 (Piece 11), A15–82 (inclusion in olivine 5, Table 4). 6 = Sample 148-896A-27R-1 (Piece 24), A9–6 (inclusion in olivine 6, Table 4). 7 = Sample 148-896A-25R-1 (Piece 11), A3–2, 9 = Sample 148-896A-27R-1 (Piece 15), A12–13, Mg' = 100 × [Mg/(Mg + Fe²⁺)].

analysis are identified by calculated plagioclase temperatures higher than the run temperature, whereas poor quenching will yield lower calculated temperatures (Fig. 9A). Comparison of olivine- and plagioclase-calculated temperatures can reveal inclusion compositions that are the result of overheating or poor quenching (Fig. 9B).

Sixty-three inclusions from 29 runs were found to satisfy the criteria discussed above. Their T_h and compositions are given in Table 8 and are compared with pillow-rim glasses on Figure 10. The remaining inclusions have a more restricted major element compositional range, consistent with olivine-plagioclase cotectic crystallization, but they still show wide variations in minor element contents. Good correlation exists between CaO/Na₂O values of inclusions and host An contents (Fig. 4), consistent with low-pressure experimental results on plagioclase-melt equilibria and with plagioclase-host glass relationships. This indicates that the compositions of homogenized inclusions are in equilibrium with host plagioclases. As with the leastmodified naturally quenched inclusions (Fig. 6D), homogenized inclusions from different groups vary consistently in CaO/Na₂O; inclusions from Group 1 span the range of observed CaO/Na₂O values. The ranges in CaO/Na₂O of homogenized inclusions appear to be slightly smaller than those of naturally quenched inclusions, but this may be related to sampling. In both cases, CaO/Na₂O values higher than those in the pillow-rim glasses were found. The trend of Al₂O₃ and CaO vs. MgO defined by inclusions is the same as those of glasses; however, it appears that inclusions have higher SiO₂ and lower FeO contents at the same MgO than the glasses. Higher SiO₂ contents



Figure 5. Compositional variation of spinels. **A.** Cr# (100 × Cr/[Cr + Al]) vs. Mg' (100 × Mg/[Mg + Fe²⁺]) for groundmass spinels and spinels included in olivine (Fo contents as indicated) and plagioclase. **B.** Calculated Fe²⁺/Fe³⁺ vs. Cr# for all spinels.

were also observed in the least-modified naturally quenched inclusions.

Olivine

Inclusions of <100 μ m diameter were selected for experiments as it was found that larger inclusions often leaked during heating. A slower heating rate was initially required than for plagioclase to nucleate a fluid bubble at 750°–900°C, and recrystallization of the inclusion occurred from 1000° to 1080°C; melting began at ~1130°C. Unlike inclusions in plagioclase, homogenization could be achieved after keeping inclusions at a constant temperature for more than 10 min, indicating slower melting kinetics in inclusions in olivine. For example, after homogenization of the smaller 20–40 μ m inclusions, up to 20 min was required to homogenize larger inclusions. After 2– 3 min at T_h , small (<1 μ m) black minerals (most likely magnetite, the result of oxidation; Sobolev and Danyushevsky, 1994) crystallized in all inclusions, although the relative amount varied from inclusion to

Table 6. Representative clinopyroxene analyses, Hole 896A.

Analysis no.:	1	2	3	4	5
SiO ₂	53.97	50.60	46.04	50.49	51.63
TiO ₂	0.17	0.56	1.42	0.60	0.30
AbŐa	1.51	4.48	8.64	4.74	3.16
FeO	3.19	6.03	8.98	6.40	4.56
MnO	0.08	0.15	0.16	0.18	0.08
MgO	17.77	15.33	12.22	15.18	16.39
CaO	22.89	22.37	21.68	21.98	22.45
Na ₂ O	0.11	0.22	0.37	0.18	0.17
Cr ₂ O ₃	0.42	0.44	0.04	0.21	0.86
Total	100.11	100.18	99.55	99.96	99.60
Cations calcu	lated on the	basis of 6 d	oxygens		
Si	1.960	1,866	1.737	1.866	1.902
Ti	0.005	0.016	0.040	0.017	0.008
Al	0.065	0.195	0.384	0.206	0.137
Fe	0.097	0.186	0.283	0.198	0.141
Mn	0.002	0.005	0.005	0.006	0.002
Mg	0.962	0.843	0.688	0.836	0.900
Ca	0.891	0.884	0.877	0.870	0.886
Na	0.008	0.016	0.027	0.013	0.012
Cr	0.012	0.013	0.001	0.006	0.025
Total	4.001	4.022	4.043	4.018	4.014
En	49.3	44.1	37.3	43.9	46.7
Fs	5.0	9.7	15.3	10.4	7.3
Wo	45.7	46.2	47.4	45.7	46.0
Mg#	90.9	81.9	70.8	80.9	86.5

Notes: Alphanumeric codes following sample numbers are identifiers of grain mount and grain number. 1 = Sample 148-896A-9R-1 (Picce 24), A9–30. 2 = Sample 148-896A-27R-1 (Picce 15), A13–83. 3 = Sample 148-896A-3R-1 (Picce 4), A14–24. 4 = Sample 148-896A-9R-1 (Picce 24), A9–26. 5 = Sample 148-896A-27R-1 (Picce 15), A13–67. All Fe as FeO. Mg# = 100 × [Mg/(Mg + Fe)].

inclusion. On quenching, most inclusions were glassy, with scattered magnetite(?) dust and vapor bubbles in some of the larger inclusions.

Homogenization was achieved in six experiments, with T_h ranging from 1190° to 1200°C for host olivines of Fo87.9-88.7. As with plagioclase, no correlation exists between olivine composition and T_b , probably because of the very narrow range of experimental temperatures and olivine compositions. Temperatures of olivine saturation calculated from inclusion compositions, using the calibration of Ford et al. (1983), agree well with experimental temperatures (Fig. 11), indicating that equilibrium was obtained during the runs and that no significant quench modification occurred. Compositions of homogenized inclusions are shown on Figure 12. Contrary to the mineralogical evidence, which suggested that olivines of ~Foss should be in equilibrium with more magnesian melts than the host glasses, the MgO contents of homogenized inclusions are significantly lower than those of the host glasses. Also Na₂O, TiO₂, Al₂O₃, and FeO contents of these inclusions differ significantly from the field of pillowrim glasses, a feature not observed in the least-modified naturally quenched inclusions. In addition, the Mg#s of these inclusions are far too low to be in equilibrium with their hosts (Table 9). These compositional features may be produced if T_{μ} is lower that the trapping temperature. This would be the case for a fluid-undersaturated melt; as no fluid inclusions were found in olivine phenocrysts, we suggest that these inclusions were trapped from such a melt. To obtain the true composition of the trapped melt, more olivine should therefore be added to these inclusion compositions. As magnetite precipitation during the run could introduce additional compositional variations, we estimated the melt composition in equilibrium with olivine phenocrysts by simulating the reverse of olivine crystallization on inclusion walls for the least-modified naturally quenched inclusions. Calculations were performed using the olivine-melt model of Ford et al. (1983) and a melt Fe^{2+}/Fe^{3+} of 7.9 ($Fe^{3+}/\Sigma Fe = 0.112$). This value was obtained from the average spinel Fe2+/Fe3+ (2.2; from Fig. 5B), using the equation of Maurel and Maurel (1982). Results are shown on Figure 12. Calculated compositions are consistent with their being more primitive melts of the same suite as the host glasses, with calculated equilibrium temperatures of 1240°-1260°C.

Table 7. Representative analyses of naturally quenched melt inclusions, Hole 896A.

			Plagioclase				Olivine		Spinel
Analysis no.:	1	2	3	4	5	6	7	8	9
SiO ₂	50.63	53.19	50.12	50.48	50.36	49.22	50.53	50.61	49.77
TiO ₂	0.59	0.16	0.75	0.77	0.99	0.67	0.66	0.66	0.93
Al ₂ Õ ₃	8.71	9.20	12.36	15.29	15.36	18.41	17.66	18.70	16.39
FeO	11.90	9.34	11.04	8.69	9.89	8.79	8.87	8.01	7.11
MnO	0.24	0.20	0.10	0.27	0.27	0.12	0.08	0.14	0.09
MgO	13.59	13.47	12.04	9.21	7.92	6.62	5.90	3.90	9.98
CaO	12.77	13.88	12.73	12.36	13.11	14.59	14.74	16.26	13.24
Na ₂ O	1.12	0.72	1.44	2.25	1.87	1.78	1.71	1.65	1.88
K ₂ Õ	0.01	0.01	0.03	0.21	0.04	0.01	0.10	0.02	0.02
PoO ₅	0.05	0.01	0.06	0.03	0.00	0.07	0.11	0.06	0.03
Cr_2O_3	0.04	0.09	0.08	0.04	0.04	0.06	0.14	0.03	0.43
Total	99.65	100.27	100.75	99.60	99.85	100.34	100.50	100.04	100.59
Mg#	67.2	72.1	66.2	65.5	58.9	57.4	54.4	46.6	71.6
CaO/Na ₂ O	11.4	19.3	8.8	5.5	7.0	8.2	8.6	9.9	7.0
Host	94.0	93.3	92.9	88.5	85.8	88.9	87.8	88.6	

Notes: Alphanumeric codes following sample numbers are identifiers of grain mount and grain number. 1 = Sample 148-896A-9R-1 (Piece 24), A9–54 (hosted by plagioclase 1, Table 3). 2 = Sample 148-896A-9R-1 (Piece 24), A9–21 (hosted by plagioclase 2, Table 3). 3 = Sample 148-896A-27R-1 (Piece 13), A13–116 (hosted by plagioclase 4, Table 3). 4 = Sample 148-896A-9R-1 (Piece 24), 12–15 (hosted by plagioclase 4, Table 3). 5 = Sample 148-896A-9R-1 (Piece 24), 12–18 (hosted by plagioclase 5, Table 3). 5 = Sample 148-896A-9R-1 (Piece 24), 12–18 (hosted by plagioclase 5, Table 3). 5 = Sample 148-896A-9R-1 (Piece 24), 12–18 (hosted by plagioclase 5, Table 3). 5 = Sample 148-896A-9R-1 (Piece 24), 12–18 (hosted by olivine 2, Table 4). 7 = Sample 148-896A-27R-1 (Piece 15), A13–141 (hosted by olivine 3, Table 4). 8 = Sample 148-896A-27R-1, Piece 13, A10–40 (hosted by olivine 4, Table 4). 9 = Sample 148-896A-25R-1 (Piece 11), A8–57 (hosted by spinel 7, Table 5). All Fe as FeO. Host mineral composition (host): anothite = Ca/(Ca + Na) and forsterite = Mg/(Mg + Fe).

As with inclusions in plagioclase, both homogenized and naturally quenched inclusions in olivine have a larger range and extend to higher CaO/Na₂O values than the pillow-rim glasses. However, unlike inclusions in plagioclase, unusually low TiO₂, FeO, and Na₂O contents have not been found in inclusions in olivine.

DISCUSSION

Compositions of both homogenized and the least-modified naturally quenched inclusions in plagioclase and olivine have a significantly wider range of CaO/Na₂O than the pillow-rim glasses, although there are some correlations with the glass group. All inclusions from Group 2 have lower CaO/Na₂O than inclusions from Group 3; however, those from Group 1 cover the entire range (Figs. 6, 10). This suggests that magma mixing may have played an important role during the evolution of this suite. Mixing is also suggested by olivine-plagioclase mineralogical relationships, where plagioclases, interpreted to be in equilibrium with host glasses (Fig. 4), are included in olivines that are too magnesian to be in equilibrium with the same glasses, suggesting mixing of primitive and more evolved melts. A detailed examination of evidence for mixing will be presented elsewhere.

Many inclusions in plagioclase and some in olivine have significantly higher K_2O (up to 0.74%; Figs. 6, 10) than pillow-rim glasses. Higher K_2O in plagioclase inclusions has also been reported from the extrusive sequence of Hole 504B (Natland, et al., 1983). The reasons for this are unclear. However, unlike the suggestion of Natland et al. (1983) that they may reflect kinetic effects during trapping, we favor a hypothesis linking high K_2O content of some inclusions with local contamination by seawater-derived hydrothermal fluids. Investigations of the H_2O content of inclusions with variable K_2O content are currently in progress.

Inclusions in plagioclase show wide variations in TiO_2 , SiO_2 , and FeO contents not seen in the pillow-rim glasses and inclusions in olivine and spinel. The SiO_2 contents of inclusions in plagioclase are higher, whereas FeO and TiO_2 contents are lower, in comparison with pillow-rim glasses. The occurrence of these variations only in plagioclase suggest that they may result from some reequilibration with plagioclase after trapping, although the mechanism of this process and why it does not occur in olivine and spinel are not known. The lack of correlation between Ti, Fe, Si, and Na and the independence between the magnitude of their variations and MgO contents indicate no systematic pattern of these variations and their independence from degree of fractionation. In contrast to some recent studies of melt inclusions in plagioclase from other MORB suites (e.g., Nielsen et al., 1994), which suggest that such variations, particularly in TiO₂, preserve primary melt increments before aggregation, we suggest that the evolved nature of these melts and the evidence for mixing presented above, make preservation of such features in these samples unlikely.

Our data suggest that plagioclase An₉₄ crystallized from melts with major element compositions similar to the most magnesian (~9.5% MgO) pillow-rim glasses but with higher CaO/Na2O values. It appears that variations in CaO/Na₂O values of Group 1 and 3 melts are independent of other element concentrations and mainly reflect variations in Na₂O content. Thus, differences in composition of high-An plagioclase reflect differences in CaO/Na2O values of equilibrium melts rather than degree of fractionation. Such melts were in equilibrium with olivine Fo86-87, suggesting (especially as olivines of up to ~Fossas were found in all glass groups) that these plagioclases crystallized from relatively evolved melts. This implies that an interval of olivine-only crystallization preceded cotectic olivine-plagioclase crystallization. As our experimental results with inclusions in olivine have been shown to be unreliable due to underheating and magnetite precipitation, these inclusions cannot be used to characterize melt compositions in the olivine-only field. However, compositions of primary melts can be estimated by calculations of the reverse of olivine crystallization from the composition that corresponds to the start of cotectic crystallization. Primary melts for each group can be defined as melts in equilibrium with the most magnesian olivine. Although Fo91.6 was found in Group 2 samples only, we think that the similarity of mineralogical features between all groups indicates that this is a sampling effect. Compositions of primary melts for Groups 1 and 3 were calculated from the compositions of the most primitive glasses from these groups.

Using the Petrolog program (Danyushevsky et al., 1990), olivine was added to the glass compositions until it was in equilibrium with olivine of $Fo_{91.6}$ (the most primitive olivine sampled). Melt Fe^{2+}/Fe^{3+} , required for this calculation, was found to be 7.9 using calculations as described above. The resultant parental melts are given in Table 10. The range of CaO/Na₂O values displayed by inclusions from these two groups, being independent of variations in other elements, should reflect variations in CaO/Na₂O values of primary melts for



Figure 6. Compositions of naturally quenched melt inclusions in plagioclase and olivine. MgO vs. **A.** Al₂O₃, **B.** Na₂O, and **C.** CaO/Na₂O. Variations in Na₂O, Al₂O₃ and CaO/Na₂O define trends that are interpreted to reflect differing amounts of post-trapping crystallization. **D.** CaO/Na₂O vs. MgO, for least modified inclusions (i.e., those with MgO similar to that of the pillowrim glasses). MgO vs. **E.** TiO₂ and **F.** K₂O. TiO₂ in plagioclase, and K₂O in both plagioclase and olivine, have a much wider range in the naturally quenched inclusions than in the pillow-rim glasses. Symbols are defined as follows: 1 = pillow-rim glasses; 2 = inclusions in olivine; 3, 4, and 5 = inclusions in plagioclase hosted by Group 1, 2, and 3 glasses, respectively. Pillowrim glasses on Figure 6D are subdivided using symbols as on Figure 2.

each group. For Group 1, this range is 6.9 to 7.9; for Group 3, the range is from 8.3 to 8.4. We have no evidence, however, to suggest that other elements varied in primary melts for these two groups. Glasses from Group 2 are more evolved, making calculations of the primary melt for this group impossible. However, as Mg-Fe covariations of these glasses are indistinguishable from those of Group 1, we think that the primary melt for this group had similar MgO to Group 1 but lower CaO/Na₂O. By comparison with the data of Falloon and Green (1988), the estimated primary melts can be produced by melting MORB mantle sources at ~15 kbar.

SUMMARY

Glass samples from pillow rims show systematic compositional variations with depth, particularly in CaO/Na₂O and TiO₂; however, they generally are characterized by high CaO and MgO and low Na₂O and TiO₂, when compared with glasses from nearby Hole 504B (Nat-



Figure 7. TiO_2 vs. variations in A. K_2O and B. Na_2O . C. Variations in K_2O vs. Na_2O for naturally quenched inclusions in plagioclase and olivine, and pillow-rim glasses. Symbols as on Figure 6D.

land et al., 1983). Water contents (<0.1%) are consistent with other MORB suites of similar Mg# and K₂O. Seven samples were selected for detailed mineralogical and melt inclusion studies on the basis of these major element variations.

The phenocryst assemblages of the selected samples are dominated by plagioclase $An_{78-94.5}$, with lesser olivine $Fo_{80-91.6}$, Cr-Al spinel, and clinopyroxene (Mg# = 85–91). A correlation between plagioclase composition and pillow-rim glass CaO/Na₂O is interpreted to indicate their equilibrium. Textural and chemical correlations between major phenocryst phases and glasses suggest that the most common olivine compositions (Fo₈₇₋₈₉) crystallized from more primitive melts than recorded in the pillow-rim glasses.

Heating-stage experiments indicate trapping temperatures of $1195^{\circ}-1215^{\circ}C$ for melt inclusions in plagioclase phenocrysts of An_{83-94.5}. The compositions of these inclusions are comparable to those of the host glasses, with the exception of anomalous TiO₂ and K₂O, and inclusion compositions more primitive than the most magnesian glass (MgO = 9.5%) were not found.

The CaO/Na₂O of melt inclusions hosted by plagioclase of \sim An₉₄ is ~9.5, which is considerably lower than the value required by current experimental data to crystallize plagioclase of >An₉₀ (i.e., CaO/Na₂O >10).

Crystallization of plagioclase An_{94} occurred from relatively evolved melts, the result of ~15% olivine-only fractionation. Primary melts for this suite had MgO \approx 15 wt%; these melts are characterized by variable CaO/Na₂O values but relatively constant contents of other elements. Such melts can be produced by melting MORB mantle sources at ~15 kbar.

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1160 | 1160 1170 + (°C) 1230 1180 T_{PL} 1200 (°C) 1220 1240 1190 T_{RUN} Figure 9. A. Calculated plagioclase temperatures (using the modified plagioclase-melt geothermometer of Weaver and Langmuir, 1990) vs. run temperature for experimentally homogenized inclusions in plagioclase. B. Calculated olivine temperature (using the geothermometer of Ford et al., 1983) vs. calculated plagioclase temperature for all homogenized inclusions in plagioclase. Solid symbols represent inclusions thought to be representative of trapped melt compositions. T_{CALC} = calculated temperature, T_{RUN} = run tem-

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perature, OL = olivine, and PL = plagioclase. See text for discussion.

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Figure 8. Compositional variations of all experimentally homogenized inclusions in plagioclase. Pillowrim glasses are plotted for comparison. Symbols as for Figure 6A.

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Table 8. Experimentally homogenized melt inclusions in plagioclase, Hole 896A.

Core, section, piece no.	Experiment	Inclusion	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Cr ₂ O ₃	Total	CaO/ Na ₂ O	Host An	Temperature (°C)
3R-1, 4	P2	А	50.91	0.35	15.53	8.86	0.14	8.13	13.19	1.91	0.01	0.01	0.08	99.12	6.91	85.8	1210
3R-1, 4	P4	A	51.86	0.36	15.85	9.20	0.14	8.41	12.86	1.74	0.28	0.02	0.05	100.77	7.39	85.1	1210
4R-1, 2	P10	A	52.25	0.54	15.50	9.23	0.10	8.79	12.84	1.92	0.02	0.00	0.05	101.24	6.69	86.8	1200
4R-1, 2 4R-1, 2	P10 P10	C	51.90	0.55	15.57	9.29	0.07	8.78	13.19	1.83	0.00	0.00	0.04	101.08	7.25	87.4	1200
4R-1, 2	P14	Ă	49.22	0.30	15.16	10.21	0.17	8.46	13.17	1.86	0.43	0.09	0.05	99.12	7.08	88.0	1200
4R-1, 2	P15	A	51.68	0.64	15.88	7.92	0.11	9.33	13.65	1.73	0.01	0.04	0.10	101.09	7.89	90.3	1205
4R-1, 2	P15	B	51.37	0.59	15.65	8.01	0.10	9.14	13.75	1.54	0.02	0.09	0.06	100.32	8.93	91.0	1205
4R-1, 2 4R-1, 2	P75	2	50.57	0.55	14.80	9.42	0.15	9.43	13.19	1.04	0.01	0.05	0.07	99.52	6.63	87.1	1205
4R-1, 2	P76	3	50.67	0.74	14.70	9.64	0.13	8.27	13.07	1.85	0.01	0.05	0.09	99.22	7.06	87.1	1195
9R-1, 24	P78	4A	49.94	0.44	16.37	9.01	0.12	9.31	13.54	1.38	0.12	0.06	0.04	100.33	9.81	93.7	1215
9R-1, 24	P81	2	50.59	0.13	15.53	9.37	0.16	9.20	12.90	1.85	0.03	0.01	0.09	99.86	6.97	92.2	1195
9R-1, 24	P82	iB	50.14	0.18	16.45	8.22	0.17	9.31	13.39	1.58	0.02	0.12	0.07	100.05	8.16	90.7	1195
9R-1, 24	P85	i	51.05	0.67	14.86	9.30	0.14	8.20	12.77	1.96	0.01	0.03	0.07	99.06	6.52	85.7	1195
9R-1, 24	P85	3	49.91	0.69	15.63	9.80	0.21	8.34	11.92	2.00	0.74	0.02	0.03	99.29	5.96	87.9	1195
9R-1, 24	P86	3	50.86	0.56	14.99	9.24	0.17	8.17	12.77	1.99	0.02	0.03	0.06	98.86	6.42	86.7	1195
9R-1, 24 9R-1, 24	P86	5	51.14	0.65	15.08	9.55	0.12	8 24	13.02	2.02	0.04	0.04	0.04	99.55	6.41	87.1	1195
25R-1, 11	P5	Ă	51.09	0.77	15.53	9.12	0.15	8.69	12.86	1.91	0.01	0.00	0.10	100.23	6.73	85.9	1200
25R-1, 11	P61	1	51.31	0.76	15.19	8.60	0.16	8.45	13.19	2.12	0.04	0.03	0.04	99.89	6.22	84.6	1205
25R-1, 11	P61	2	50.74	0.84	15.12	8.69	0.18	8.41	12.98	2.14	0.04	0.06	0.03	99.23	6.07	84.6	1205
25R-1, 11	P61	4	50.96	0.78	15.04	8.83	0.10	8.65	12.95	1.97	0.02	0.07	0.08	99.15	6.58	86.7	1205
25R-1, 11	P61	6	50.89	0.74	15.09	8.68	0.12	8.56	12.93	2.10	0.03	0.04	0.07	99.25	6.16	83.2	1205
25R-1, 11	P64	1	50.29	0.87	15.09	9.32	0.14	8.19	13.03	2.20	0.01	0.04	0.05	99.23	5.92	79.6	1205
27R-1, 13	P42	3	50.64	0.20	15.56	8.73	0.16	8.73	13.19	1.69	0.04	0.04	0.08	99.06	7.80	89.7	1215
27R-1, 13	P42 P45	í	50.45	0.28	15.75	8.57	0.10	9.10	13.36	1.69	0.02	0.00	0.04	99.45	8.00	89.9	1215
27R-1, 13	P45	2	50.34	0.20	15.68	8.63	0.16	9.28	12.83	1.71	0.01	0.01	0.05	98.90	7.50	89.4	1215
27R-1, 13	P45	4	50.36	0.24	15.57	8.41	0.17	9.34	13.03	1.67	0.03	0.01	0.09	98.92	7.80	90.7	1215
27R-1, 13	P45	5	50.28	0.22	15.98	8.39	0.11	9.31	13.12	1.60	0.01	0.00	0.06	99.08	8.20	90.4	1215
27R-1, 13	P45	7A	50.32	0.19	15.89	8.18	0.13	9.25	13.05	1.55	0.04	0.00	0.00	90.04	7.90	90.2	1215
27R-1, 13	P46	3	50.83	0.21	15.59	8.80	0.16	8.66	13.27	1.73	0.02	0.02	0.07	99.36	7.67	90.2	1210
27R-1, 13	P46	4	50.18	0.27	16.05	8.78	0.17	9.29	13.21	1.62	0.01	0.02	0.09	99.69	8.15	90.0	1210
27R-1, 13	P46	5	49.98	0.27	15.88	8.92	0.13	9.27	13.16	1.66	0.01	0.01	0.08	99.37	7.93	90.8	1210
27R-1, 13	P48	2	50.17	0.26	15.47	9.50	0.15	9.15	12.09	1.61	0.26	0.02	0.08	98.99	7.72	90.5	1210
27R-1, 13	P48	3	50.07	0.27	16.15	9.29	0.19	8.96	12.72	1.65	0.28	0.07	0.02	99.67	7.71	90.3	1210
27R-1, 13	P50	1	50.11	0.53	16.51	7.67	0.11	9.39	13.12	1.66	0.02	0.02	0.09	99.23	7.90	90.9	1215
27R-1, 13	P51	2	50.84	0.27	16.04	8.72	0.14	8.42	13.50	1.90	0.01	0.00	0.04	99.88	7.11	89.8	1210
27R-1, 15	P56	0	50.82	0.24	15.08	9.04	0.16	8.87	12.64	1.72	0.03	0.01	0.04	99.63	7.73	88.4	1195
27R-1, 15	P56	6	51.06	0.65	14.93	8.61	0.16	8.69	12.42	1.61	0.03	0.03	0.01	98.20	7.71	88.5	1195
27R-1, 15	P57	1	50.45	0.48	15.71	9.50	0.16	8.99	13.03	1.50	0.03	0.00	0.08	99.93	8.69	89.3	1205
27R-1, 15	P57	2	49.96	0.53	15.19	10.46	0.11	8.25	12.28	1.75	0.30	0.00	0.06	98.89	7.02	89.3	1205
27R-1, 15 27R-1, 15	P57	3	49.62	0.51	15.51	8.98	0.17	8.75	12.85	1.40	0.03	0.03	0.00	98.73	7.16	89.5	1205
27R-1, 15	P66	2	50.34	0.40	15.48	8.68	0.14	8.99	12.99	1.57	0.02	0.02	0.07	98.70	8.27	89.3	1200
27R-1, 15	P66	3	50.64	0.42	15.37	8.63	0.15	8.97	13.09	1.62	0.04	0.01	0.04	98.98	8.08	89.1	1200
27R-1, 15	P66	7	50.19	0.52	15.38	8.75	0.14	8.83	12.79	1.51	0.54	0.00	0.07	98.72	8.47	90.9	1200
27R-1, 15	P67	4	51.22	0.48	15.62	8.84	0.10	0.90	13.02	1.07	0.03	0.07	0.09	100.14	7.19	89.8 90.0	1205
27R-1, 15	P67	5	51.05	0.42	16.57	8.52	0.14	8.92	13.28	1.73	0.01	0.03	0.10	100.77	7.68	89.3	1205
27R-1, 15	P68	1	51.27	0.59	15.30	9.77	0.17	8.08	12.86	1.79	0.01	0.06	0.05	99.95	7.18	88.2	1200
27R-1, 15	P68	3	51.11	0.57	15.37	9.82	0.17	8.15	13.10	1.81	0.01	0.04	0.08	100.23	7.24	89.3	1200
27R-1, 15	P68 P69	14	51.52	0.49	15.12	9.63	0.12	8.52	12.88	1.81	0.04	0.01	0.04	99.98	7.12	89.1	1200
27R-1, 15	P69	15	51.31	0.57	14.99	9.84	0.17	8.77	12.90	1.75	0.01	0.02	0.09	100.42	7.37	89.0	1200
27R-1, 15	P69	4	50.64	0.53	15.46	9.40	0.15	8.62	12.76	1.63	0.02	0.01	0.05	99.27	7.83	89.1	1200
27R-1, 15	P70	2	50.34	0.65	15.98	9.25	0.15	8.84	13.27	1.65	0.02	0.03	0.07	100.25	8.04	90.2	1205

Note: All Fe as FeO.

PRIMARY MELT COMPOSITION AND CRYSTALLIZATION



Figure 10. Compositional variations in homogenized inclusions in plagioclase unaffected by overheating, poor quenching or analytical overlap with host plagioclase. See text for discussion. Symbols as for Figure 6A. Pillowrim glasses are plotted for comparison (symbols as for Fig. 2).



Figure 11. Comparison of calculated olivine temperature (using the geothermometer of Ford et al., 1983) and run temperature for all homogenized olivine inclusions. All results indicate equilibrium has been obtained. T_{CALC} = calculated temperature, T_{RUN} = run temperature.



Figure 12. Compositional variations of homogenized inclusions in olivine phenocrysts. Solid stars are inclusions from Group 3, open stars are inclusions from Group 1. Pillow-rim glasses are included for comparison (see Fig. 2 for symbols). Solid and open crosses are the compositions of naturally quenched inclusions in olivine recalculated to be in equilibrium with their host. See text for calculation procedures. The solid lines show reverse fractionation paths for the most primitive glasses of Groups 1 and 3. These were calculated by the modeling of reverse of olivine only crystallization, see text for description of the technique used. Note that compositions of recalculated naturally quenched inclusions in olivines ($\sim Fo_{88}$) match these trends for all elements.

Table 10. Calculated parental melt compositions, Hole 896A.

Analysis no.:	1	2
SiO ₂	47.84	48.18
TiO ₂	0.57	0.61
Al ₂ Õ ₃	13.85	14.38
Fe ₂ O ₃	1.16	1.12
FeO	8.24	7.94
MnO	0.10	0.10
MgO	15.13	14.69
CaO	11.59	11.38
Na ₂ O	1.40	1.49
K ₂ Õ	0.02	0.02
P205	0.03	0.03
Cr ₂ O ₃	0.07	0.06
Total	100.00	100.00
Calculated temperature (°C)	1348	1340

Notes: 1 = Sample 148-896A-27R-1 (Piece 15). 2 = Sample 148-896A-3R-1 (Piece 4).

Core, section,															CaO/		Host	Temperature
piece no.	Experiment	Inclusion	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K_2O	P_2O_5	Cr ₂ O ₃	Total	Na ₂ O	Mg#	An	(0°)
27R-1, 13	OLI	-	48.74	0.59	15.20	11.20	0.12	8.62	12.64	1.54	0.01	0.05	0.05	98.76	8.2	57.8	88.2	1195
27R-1, 13	OLI	2	49.19	0.63	15.77	10.12	0.11	8.60	13.09	1.54	0.03	0.09	0.04	99.21	8.5	60.2	88.0	1195
27R-1, 13	0L2		50.09	0.61	16.41	9.75	0.14	8.85	13.20	1.59	0.01	0.06	0.15	100.86	8.3	61.8	88.3	1200
27R-1, 13	OL2	6	49.30	0.59	16.08	10.83	0.14	8.44	13.19	1.52	0.01	0.03	0.12	100.25	8.7	58.1	88.2	1200
27R-1, 13	OL3	-	49.06	0.59	15.98	10.02	0.17	8.43	13.38	1.52	0.03	0.05	0.17	99.4	8.8	60.0	88.3	1195
27R-1, 13	OL4	-	49.58	0.60	16.45	9.80	0.11	8.58	13.51	1.55	0.01	0.08	0.05	100.32	8.7	60.9	88.3	1195
27R-1, 15	OL5		48.59	0.66	15.99	10.86	0.14	8.27	13.24	1.47	0.01	0.08	0.04	99.35	0.6	57.6	87.9	1190
9R-1.24	OL8	-	49.49	0.69	15.82	9.68	0.14	8.23	12.61	1.89	0.03	0.06	0.03	98.67	6.7	60.2	88.4	1195
9R-1, 24	OL8	0	51.15	0.68	16.45	9.59	0.13	8.77	12.58	1.92	0.01	0.07	0.01	101.36	6.6	62.0	88.7	1195

Table 9. Experimentally homogenized melt inclusions in olivine from Hole 896A.

Notes: All Fe as FeO. Mg# = 100 × [Mg/(Mg + Fe)].