27. ABYSSAL GLASSES, PETROLOGIC MAPPING OF THE OCEANIC FLOOR AND "GEOCHEMICAL LEG" 82¹

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ABSTRACT

The compositions of abyssal glasses obtained on Leg 82 of the *Glomar Challenger* and the MAPCO cruise of *Jean Charcot* have been investigated. Two main compositional groups of Atlantic glasses (A_1 and A_2) that are separated in space and time were identified. The distribution of these groups in the studied area allowed mapping of the transition zone from A_1 to A_2 between 30–35°N MAR. We infer that the compositional groups of abyssal glasses of the Atlantic and other occeans reflect the depth of separation of primary melts from the oceanic mantle. Specifically, the primary melt of Group A_1 separates from the mantle at a depth of 30–60 km (spinel-peridotite facies) and those for Group A_2 from a depth of 15–30 km (plagioclase-peridotite facies). Modifications of dynamic models of the ocean lithosphere are discussed.

INTRODUCTION

Layer 2—the volcanic layer—of the ocean crust was originally thought to be homogeneous. This view led to fairly simplified geologic and geophysical models of the ocean lithosphere and gave little reason for deep-sea basement drilling on the flanks of mid-ocean ridges or in abyssal planes. With more data, it became clear that ocean basalts are fairly diverse in composition and form (e.g., pillow flows, sheet flows, etc.). The data on their regional variations appeared to be most interesting, as first noted by Shido and Mijashiro (1973), who showed that the area of the Mid-Atlantic Ridge at 36°N reflected a rather sharp change in tholeiite compositions to the north and to the south.

The existence of this boundary required explanation. Therefore, a number of expeditions were undertaken between 1974 and 1979, including the work on FAMOUS project, Leg 37 of *Glomar Challenger* (Aumento, Melson, et al., 1977), the MAPCO cruise of *Jean Charcot* (Bougault and Treuil, 1980), and DSDP Leg 82. This study focuses on Leg 82 samples provided by the Deep Sea Drilling Project and on MAPCO samples provided by Henri Bougault.

PETROCHEMICAL CRITERION OF CLASSIFICATION

The compositional variation of basalts obtained at one site (i.e., from one drill hole) most probably reflects the origin of the magma as well as its pre-eruption cooling history, which may include crystal fractionation. In some cases, it is difficult to discriminate between these two processes when only bulk rock analyses are available. The composition of glass in pillow rinds yields liquid compositions directly, unmodified by the often irregular abundances of phenocrysts. Interpretations of the analyses of numerous such glasses (Melson et al., 1977) and our data have been published in a number of papers (Dmitriev et al., 1978; 1979a, b; 1980). The highlights of these interpretations follow below.

There are at least two main groups of abyssal glasses. They are simply identified with the help of an eightcomponent discriminant function (D):

 $D = 16.53 \text{ Na}_2\text{O} + 16.19 \text{ TiO}_2 + 3.114 \text{ SiO}_2 + 2.93 \text{ MgO} + 1.45 \text{ CaO} + 0.92 \text{ Al}_2\text{O}_3 - 32.94 \text{ K}_2\text{O} - 1.46 \text{ FeO}$ $D_0 \text{ value} = 258.09 \text{ (Sushevskaya et al., 1983).}$

The standard error of D calculated from the data on the accuracy of microprobe analyses is ± 3.0 . A histogram of D is in Figure 1 where the area of uncertainty related to the analytical error is also plotted.

The variations within each group may result from the differences in the composition of primary melts, the degree of their differentiation, and magma mixing. All these processes influence the D value. Without going deeper



Figure 1. Histogram of the discriminant function D (an eight-component discriminant; see text) for the Atlantic. Uncertainty limit is between the dotted lines (see text). N is the number of analyses.

 ¹ Bougault, H., Cande, S. C., et al., *Init. Repts. DSDP*, 82: Washington (U.S. Govt. Printing Office).
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into the problem of D dependence on these processes, we shall only note that its values are used in the present work as a general classification feature.

Figure 2 is a schematic map of the Atlantic Ocean showing the distribution of the two groups of glass compositions. The map uses data from the catalog by Melson et al. (1977) and our data published before 1980. Data from Leg 7 of *Prof. Shtokman* (20-30°S MAR, 1982) (Dmitriev, Charin, et al.; in press) were also used. The region of Leg 82 and the MAPCO cruise is outlined. One of the groups (solid circles, Fig. 2) is located along the ridge axis, terminates at 36°N, and continues southward to 35°S. The other group has a wider regional distribution, occurring not only on the northern section of the Mid-Atlantic Ridge but on the ridge flanks and



Figure 2. Schematic map of the Atlantic. Open circles = A_1 , abyssal glass composition; closed circles = A_2 , abyssal glass composition. Described area lies within center box.

abyssal plains as well. These compositions are referred to as Group I (A₁) or as "peripheral" types. The other compositions, located along the ridge axis, are referred to as Group 2 (A₂), or as "central" types.

Figure 3 shows D values plotted against latitude, quantitatively distinguishes the boundary between compositions of A_1 and A_2 in the north, and outlines this boundary in the south.

Basalts containing the glasses of the two groups also differ in petrographic and mineralogic features as well as in the concentration of some trace elements. A_1 basalts are frequently strongly differentiated, have phenocrysts with more basic compositions (Fig. 4), and are relatively enriched by the siderophile trace elements. A_2 basalts are often less differentiated, aphyric or sparsely phyric rocks; they have a less basic phenocryst composition; and they are relatively enriched in some cases by the lithophile trace elements.

MID-ATLANTIC RIDGE (25-40°N)

A great deal of detailed data are available for the region. In this paper, we confine our interpretations to the shipboard data from Leg 82 and the data from the MAPCO cruise (Bougault and Treuil, 1980). These data are summarized in Table 1.

These data, as well as previously available data, show that basalts at 25-40°N have features of typical ocean tholeiites. The examined samples are glassy fragments of pillow lava rinds. They include rocks with the phenocryst assemblage plagioclase + olivine. Some of them contain large plagioclase phenocrysts of up to 1 cm across. There are also conglomeroporphyritic rocks as well as sparsely phyric, plagioclase-phyric, and aphyric basalts.

Clinopyroxene phenocrysts are rare, although Bougault et al. (1980) describe basalt rich in clinopyroxene phenocrysts. This paper deals only with the chemical analyses of the glassy rinds. The compositions of glasses were determined with the HMA5 and JXA-5A electron microprobes (Japan) using an acceleration voltage of 15 kV, beam current I = $40-60 \ 10^{-9}$ amps, and a beam diameter of 5-10 microns. Analytical procedure includes intensity accumulation at 4-5 spots with 10 s counting time for each grain. To prevent Na and K leaks under the beam, the samples were moved slowly during analysis. Reference samples were natural basalt glass USNM 111240/52 (VG-2) for Si, Al, Ti, Fe, Mg, Ca, and Na (kindly supplied by E. Jarosewish), described in Jarosewish et al. (1979), and pure synthetic orthoclase for K. All data were corrected for matrix effects by the Bence and Albee method (1968) and the results are shown in Table 2.

Figure 5 is a schematic map of Leg 82 and of the MAPCO cruise in which the dots shown by different signs show the compositions identified by D value. The figure also shows data from previous investigations (Leg 37 *Glomar Challenger* [Aumento, Melson, et al., 1977] the FAMOUS project, and data from other expeditions, see Melson et al., 1977). It can be seen that compositions definitely belonging in Group A_1 occur in Holes 563, 564, 558, and 559 of Leg 82, in Site 97 of the MAPCO cruise, and at other sites mentioned by Bou-



Figure 3. D-variation as the function of MAR latitude. Limits are uncertain between the dashed lines. D is an eight-component discriminant (see text).

gault and Treuil (1980). Compositions belonging in Group A2 occur at Sites 98-11 and 98-15 of the MAPCO cruise and at all rift valley sites south of 30°N discussed by Melson et al. (1977). At the other sites, the distribution of compositions is less clear-cut. At these sites, the D value is close to Do (258.09). These compositions are intermediate between A_1 and A_2 and are transitional (t) from A_1 to A_2 and from A_2 to A_1 , respectively. They are arbitrarily referred to as A_1^t and A_2^t . In Hole 556, the lower horizon is represented by A1 and the upper horizon by A_1^t ; in Hole 562, the lower is A_1 , and the upper is A_2^t ; and in Hole 561, the lower is A_2^t , and the upper is A_2 . In all these sites the transition from A_1 to A_2 with decreasing age is evident. The transitional compositions A₁ are found at MAPCO Sites 98-08 and 98-14 and the A₂ compositions at MAPCO Sites 98-07, 98-09, and 98-12. The possible transition zone between both compositional groups is shaded in Figure 5. Its location at the eastern ridge flank is arbitrarily based on the idea of symmetric structure.

DISCUSSION

The data reviewed here lead to the conclusion that there are at east two main types of composition of tholeiites that appear to be regularly distributed. How is this explained?

One of the possible explanations is based mainly on trace element data. These reveal lateral heterogeneity of the mantle source of melts and different degrees of its partial melting. Bougault (Bougault et al., 1978; Bougault and Treuil, 1980) develops this approach in his papers using the data on concentration of the lithophile elements. Papers by Flower (1980; 1981) describes relationships between the spreading rate of mid-ocean ridges and basalt compositions.

Natland (1980) and Natland and Melson (1980) have argued perceptively that evidence from the chemistries of natural glasses, trace element studies, experimental petrology, and geodynamic reconstructions of magmatism at the East Pacific Rise, the Siqueiros Fracture Zone, and the Galapagos spreading center support the lateral diversity of melts formed within the upper mantle.

Papers by O'Hara (1968), Jaques and Green (1980), and Stolper (1980) suggest that differentiation of primary picrite melts could produce the entire spectrum of major and minor element compositions of ocean tholeiites. Presnall et al. (1979) and Fujii and Bougault (1983) have shown experimentally that primary high magnesian tholeiite melts can form in the transitional zone between plagioclase and spinel lherzolite. These experimental studies would be consistent with a single primary melt, but do not explain the two stable separate compositional groups observed here.

In our models, we take into account the possible influence of mantle heterogeneity on trace element concentrations and on possible connections with spreading rate. However, we assume that the mantle is fairly homogeneous for the major elements.



Figure 4. The compositions of major minerals from mid-ocean ridge basalts. A. Mg-values of clinopyroxene. B. Fo contents of olivine. C. Cr/(Cr + Al) values of spinel. D. An contents of plagioclase. N is the number of samples. Data from Ayuso et al. (1976); Baragar et al. (1977); Bonatti et al. (1977); Bryan et al. (1977); Bollinger and Semet (1980); Dick and Bryan (1978); Dickey et al. (1977); Donaldson and Brown (1977); Dungan et al. (1978); Fisk and Bence (1970); Flower et al. (1977a, b; 1978); Fujii and Fujioka (1979); Genkin et al. (1980); Graham et al. (1979); Hekinian et al. (1976); Hodges and Papike (1977); Sato et al. (1978); Sigurdsson and Schilling (1976); Sinton and Byerly (1980); Templeman (1979); and Wood et al. (1979).

Glass compositions of both groups give parallel trends in plagioclase-olivine-clinopyroxene projections (Fig. 6A). We suggest that the reason for this is the existence of two primitive initial melts with different compositions. These initial higher temperature liquids in Group A_1 contain olivine (Fo_{91.5}) and chromian spinel, and in Group A_2 , contain olivine (Fo₉₀), plagioclase (An₈₉), and chromian spinel. Experimental homogenization of the melt inclusions established that the temperature of crystallization of phenocrysts in Group A_1 is noticeably higher than for phenocrysts in Group A_2 , 1290°C and 1240°C, respectively.

The Fe^{3+}/Fe^{2+} ratio in some glass samples from both groups was determined by Mössbauer spectroscopy (Dmitriev et al., in press). We found that crystallization redox conditions of the two groups differed. Group A₁ melts crystallized under conditions close to quartz-fayalite-magnetite buffer, and those of Group A₂, close to the Ni-NiO buffer (Dmitriev, Melson, et al., in press).

The origins of the possible primary melts for the two groups was modeled by back calculation of their fractional crystallization. The calculation was performed by a computer program using steplike "dissolution" of equilibrium crystalline phases in a melt of varied composition (one step 0.1% mol.). The composition of such crystals were calculated using the equilibrium crystal-melt equations from Roeder and Emslie (1970) and Drake (1976) and the concept of highest equilibrium temperature (Nathan and Wankirk, 1978; Ariskin and Frenkel, 1982). At the end of eachs step the equilibrium parameters (the current compositions of melt, equilibrium crystal, temperature and Fe⁺³/Fe⁺² ratio) were recalculated. This procedure was repeated until the melt is in equilibrium with the highest temperature mineral assemblage known from petrography; Fo_{91.5}, for type A₁, and Fo_{90.0} + An_{89.0}, for type A₂.

The specification of a back fractionation cotectic model consists of subsequent "dissolution" of both plagioclase and olivine depending on their equilibrium temperature (the phase with the lower equilibrium temperature was "dissolved"). The chromian spinel, a well-known member of the most primitive liquids of both types, was not taken into account because of its negligible influence on the melt composition, given its extremely low concentra-

Our sample number	Hole-Core-Section	Loca	ation					
	(interval in cm) (piece number)	Latitude (all north)	Longitude (all west)	Age (Ma)	Brief petrograhy of basalt related to glasses			
1	556-4-6, 41-44 (IE)	38°56.38'	34°41.12'	34	Sparsely Pl (Ol)-phyric			
2	556-8-3, 56-58 (3C)	38°56.38'	34°41.12'	34	Pl-Ol-(Cpx) phyric. phenocrysts, 10-15%			
3	558-33-1, 33-34 (5)				Aphyric			
4	558-35-2, 84-85 (5A)	27046 21	27920 (1/	24.27	Aphyric			
5	558-37-1, 75-76 (7A)	37-40.2	37-20.01	34-37	Sparsely Ol-phyric. Mt in glass			
6	558-39-1, 25-26 (3)				Aphyric			
7	559-5-2, 11-13 (2)	35°07.45'	40°55.00'	15-17	Sparsely Pl-Ol-phyric; phenocrysts, 0.5%			
8	559-8-2, 102-103 (6)	35°07.45'	40°55.00'	15-17	Aphyric			
9	561-2-1, 92-93 (5B)	34°47.10'	39°01.70'	14-17	Sparsely Pl-Ol-phyric; phenocrysts, 2-5%			
10	561-3-1, 40-41 (5B)	34°47.10'	39°01.70'	14-17	Aphyric			
11	562-1-2, 140-142 (8)	33°08.49'	41°40.76'	15-17	Aphyric			
12	562-6-4, 45-46 (2B)	33°08.49'	41°40.76'	15-17	Sparsely Pl-phyric			
13	563-24-1, 108-109 (7B)	33°38.53'	43°46.04'	34-37	Aphyric			
14	563-25-2, 132-134 (4A)	33°38.53'	43°46.04'	34-37	Pl-phyric			
15	564-3-2, 50-51 (4)				Sparsely Pl-Ol-phyric; phenocrysts, 1%			
16	564-1-2, 99-100 (6C)	22044 261	42946 021	24 27	Aphyric			
17	564-8-1, 2-3 (5-1)	33-44.30	43-40.03	34-37	Aphyric			
18	564-9-3, 26-27 (2B)				Aphyric			
19	Ch-97-02-101	39°06'	29°45'		Aphyric			
20	Ch-98-07-G3	32°17′	40°11'		Aphyric			
21	Ch-98-08	31°54'	40°58'		Sparsely Pl (Cpx) phyric			
22	Ch-98-09-G3	31°28'	40°57'		Aphyric			
23	Ch-98-11-G4	30°41′	41°49' >	"zero age	Sparsely Ol-phyric			
24	Ch-98-12-G3	30°10'	41°55′		Aphyric			
25	Ch-98-14-L02	29°17'	43°05'		Pl-phyric			
26	Ch-98-15	27°46'	44°05′		Aphyric			
27	Ch-98-15-101	27°46'	44°05′)		Aphyric			

Table 1. General description of samples.

Note: Pl = plagioclase; Ol = olivine; Cpx = clinopyroxene; Mt = magnetite. Ch numbers are sample numbers from MAPCO cruise of *Jean Charcot* (Bougault and Treuil, 1980).

tion. Compositions of the most magnesian glasses of the two groups were selected as initial compositions for the calculations.

Group A_1 melt is a high-magnesian olivine tholeiite, almost picrite, whereas Group A_2 melt is a high-alumina tholeiite. These compositions correspond to the homogenized melt inclusions in the highest-temperature phase (Table 3). Both primary melts are highly magnesian and are in equilibrium with olivine Fo_{90-91.5}, which is similar to the olivine in ocean harzburgite (Prinz et al., 1976). Thus, both compositions correspond to the model of ocean tholeiite formation: primary lherzolite = tholeiite melt + residual harzburgite (Dmitriev, 1969).

The trends (Fig. 6B) correspond to the experimental crystallization differentiation of tholeiites of different compositions under dry conditions at a pressure of 1 atmosphere (Bender et al., 1978; Zapunny et al., 1983). This model is consistent with fractionation in intermediate magma chambers at a comparatively shallow depth beneath the ocean floor prior to eruption.

What processes have generated the two postulated primary melts? Five different models can be suggested: (1) derivation of one melt from the other by crystal fractionation; (2) different abundances of volatiles during partial melting of an otherwise uniform mantle; (3) different degrees of partial melting of a uniform mantle at a constant depth; (4) different compositions of mantle material; and (5) different depths of melt separation from a uniform mantle.

1. Simple calculations show that fractionation of olivine, orthopyroxene, clinopyroxene, garnet, spinel, and plagioclase separately or in any combination from the more magnesian melt A_1 cannot produce A_2 melts. The main limitation is the similar Mg-number of both compositions.

2. The extremely low water contents of both the glass groups (Delaney et al., 1978) and the melt inclusions of phenocrysts prohibit Model 2. The high temperature of melt inclusion homogenization also points to extremely low water contents.

3. and 4. Figure 7, based on the data of experimental melting of dry lherzolite (pyrolite) (Jaques and Green, 1980) and using data from the model of two primary melts (Table 3) developed by Sobolev et al. (in press), shows that neither different degrees of mantle melting (Model 3) nor differences in mantle composition can account for the differences in composition of melts A_1 and A_2 .

5. It is clearly shown (Fig. 7) that composition A_1 is in equilibrium with lherzolitic mantle at a pressure of around 10 kbar (spinel-peridotite depth facies) and that composition A₂ is in equilibrium with the same mantle at a pressure of 6-9 kbar (plagioclase depth facies). Figure 7 also indicates that A1 composition can form at 15-20% of mantle partial melting and A2 composition at 15%. These values are close to what we find from the partial melting reaction: ocean lherzolite (Dmitriev et al., 1972) = ocean harzburgite (Dmitriev et al., 1972) + melt A_1 (or A_2). This model gives 15% for the degree of partial melting for melt A1 and 13% for melt A2. Thus, Model 5 seems most plausible. In other words, the difference in the composition of the postulated primary melts A1 and A2 is affected by the melting depth of a homogeneous mantle with regard to major elements

Table 2. Electron microprobe analyses for abyssal glasses.

Our sample number Hole	1 5	2 56	3	4 558	5	6	7	8 559	9 5	10 51	11 5	62	13 563
Core-Section (interval in cm) (piece number) Number of analyses	4-6, 41-44 (1E) 3	8-3, 56-58 (3C) 3	33-1, 33-34 (5) 3	35, 84-85 (3-5A) 2	37-1, 75-6 (3-7) 1	39-1, 25-26 (3) 1	5-2, 11-135 (2) 1	8-2, 102-103 (5-6) 2	2-1, 92-93 (5-5B) 4	3-1, 40-41 (5-5B) 5	1-2, 140–142 (5–8) 6	6-4, 45-46 (5-2B) 4	24-1, 108-109 (7B) 2
SiO ₂	51.30 (0.5)	50.71 (0.2)	50.94 (0.34)	51.82 (0.28)	50.60	50.71	51.15	50.29 (0.21)	51.38 (0.18)	51.27 (0.38)	50.77 (0.39)	51.09 (0.65)	50.96 (0.11)
TiO ₂	1.72 (0.11)	0.98 (0.02)	1.39 (0.07)	1.28 (0.01)	1.63	1.63	1.52	1.49 (0.01)	1.64 (0.14)	1.5 (0.1)	1.64 (0.06)	1.29 (0.03)	1.14 (0.02)
Al2O3	14.47 (0.13)	15.41 (0.12)	15.55 (0.09)	15.09 (0.23)	15.38	15.19	14.90	15.17 (0.24)	15.12 (0.09)	14.76 (0.23)	14.73 (0.66)	15.34 (0.26)	15.15 (0.09)
FeO	10.75 (0.13)	8.68 (0.01)	8.61 (0.22)	9.27 (0.06)	10.23	10.49	11.64	10.09 (0.33)	11.22 (0.28)	11.27 (0.39)	10.85 (0.31)	10.15 (0.2)	10.63 (0.04)
MgO	6.58 (0.03)	7.73 (0.05)	8.06 (0.22)	8.79 (0.02)	7.76	7.35	6.91	7,49 (0,12)	7.3 (0.28)	7.18 (0.38)	7.28 (0.17)	7.72 (0.36)	7.18 (0.06)
CaO	11.35 (0.14)	13.04 (0.05)	11.95 (0.19)	11.78 (0.02)	11.41	10.99	11.62	11.27 (0.06)	11.52 (0.12)	11.65 (0.24)	11.65 (0.18)	12.15 (0.29)	12.47 (0.03)
Na ₂ O	2.55 (0.12)	2.64 (0.07)	2.45 (0.07)	2.14 (0.07)	2.57	2.56	2.36	2.53 (0.03)	2.54 (0.03)	2.60 (0.06)	2.6 (0.08)	2.31 (0.12)	2.23 (0.00)
K2Õ	0.18 (0.02)	0.17 (0.0)	0.32 (0.0)	0.31 (0.06)	0.32	0.31	0.08	0.36 (0.01)	0.09 (0.01)	0.09 (0.02)	0.09 (0.02)	0.12 (0.03)	0.07 (0.01)
Total	98.90 (0.67)	99.36 (0.31)	99.27 (0.37)	100.48 (0.44)	99.90	99.23	100.18	98.69 (0.61)	100.81 (0.54)	100.32 (0.5)	99.61 (1.01)	100.17 (0.27)	99.83 (0.01)
D	257.1 (1.7)	254.5 (1.3)	253.8 (2.5)	250.3 (3.7)	254.4	252.5	254.1	248.2 (0.8)	261.1 (2.0)	259.0 (1.8)	260.2 (2.1)	253.8 (2.5)	249.4 (0.8)

Note: Results for DSDP holes are given in averages, with standard deviations; D refers to an 8-component discriminant (see text for discussion). Ch numbers are from MAPCO cruise of Jean Charcot (Bougault and Treuil, 1980)



Figure 5. Schematic map of MAR between $25-40^{\circ}$ N showing locations of glass compositional groups. The dashed area corresponds to the transitional zone between A₁ and A₂.

under dry conditions and at a similar degree of partial melting.

This model offers an explanation for the heterogeneity of basalts with regard to trace elements. Vertical trace element compositional heterogeneity of the mantle resulting from diapirism is suggested. Diapirism—the rise of plastic, partially melted mantle—should be accompanied by solid phase transitions of garnet-peridotite, then spinel-peridotite, and finally, plagioclase-peridotite assemblages. During these transformations, the redistribution of trace elements between phases will take place and their concentration may change at different depth levels, especially in the presence of ascending melt and fluid flow. The trace element enrichments of a primary tholeiite melt derived from the mantle at different depths and from different phase assemblages subjected to partial melting will also differ. Such an explanation has a number of advantages; above all, it does not require primary lateral heterogeneity of the mantle. Should primary lateral heterogeneity exist, it would still require special explanation. In the suggested model, the degree of mantle melting in both groups is low (about 15%), which is in good agreement with the calculations of optimal physical conditions for the separation of melt from the solid mantle (Arndt, 1976). Our model also seems to account more realistically for the occurrence of both melt groups in the same boundary area provided that their eruption is separated in time (i.e., in one drill hole). In such cases, repeated changes in the depth of melt separation from mantle and the mixing of both melt groups in an intermediate chamber may occur.

In summary, magmato-tectonic conditions along the MAR have been changing. For the last 15-17 Ma, for example, the process of melt separation southward of 36°N has risen from the depth of spinel-peridotite facies (30-60 km) to the level of plagioclase-peridotite facies (15-30 km). Between 35 and 30°N, the ascent appears to have been gradual, possibly with repeated changes in the depth of melt separation. To the south of 30°N during the same period of time, the depth of melt separation remained the same and corresponds to the plagioclase-peridotite mantle facies.

The regional difference in the composition and the dynamics of the lithosphere on each side of the Azores-Gibraltar Triple Junction is also probably connected to the change in the depth of melt separation beneath the spreading center. Lukashevich et al. (1982) found a change in the values of the free air gravity anomaly from 50 to 20 mGal between 35 and 30°N. The change of ridge morphology within the same latitude range Sclater et al., 1975; Lukashevich et al., 1982) as well as the data outlined here on the proposed difference in the depth of melt generation in the Atlantic lithosphere also favor this possible connection (Marillier and Mueller, 1982).

It is probable that a similar change in the geotectonic regime postulated for the Atlantic lithosphere also took

Table 2. (Continued).

15	16 564	17	18	19	20	21	22	23	24	25	26	27
3-2, 50-51	7-2, 99–100	8-1, 2-3	9-3, 26-27	Ch97-02-101	Ch98-07	Ch98-08	Ch98-09	Ch98-11	Ch98-12	Ch98-14	Ch98-15	Ch98-15-101
2	2	(3-1)	(26)	1	1	1	1	- 1	1	1	1	1
51.09 (0.75)	51.52 (0.43)	51.0 (0.19)	51.3	50.99	50.86	50.58	50.39	50.81	51.22	50.09	50.65	50.21
1.48 (0.03)	1.53 (0.0)	1.52 (0.0)	1.59	1.16	1.38	1.66	1.45	1.45	1.44	1.60	1.39	1.29
14.87 (0.21)	14.83 (0.11)	15.03 (0.06)	15.20	15.32	15.23	14.35	15.20	14.92	14.88	15.45	15.43	16.10
11.06 (0.07)	11.52 (0.03)	11.62 (0.03)	11.65	9.01	10.27	11.41	10.40	9.82	10.21	10.30	9.39	9.18
6.99 (0.04)	6.95 (0.07)	6.92 (0.007)	7.04	7.59	7.77	7.25	7.49	9.44	8.54	7.37	8.15	8.27
11.53 (0.09)	11.46 (0.007)	11.33 (0.07)	11.37	12.02	11.41	11.04	11.52	11.00	11.31	11.26	11.53	11.78
2.45 (0.07)	2.30 (0.01)	2.38 (0.03)	2.33	2.02	2.55	2.60	2.60	2.33	2.45	2.49	2.59	2.64
0.15 (0.03)	0.14 (0.007)	0.15 (0.07)	0.15	0.12	0.08	0.12	0.08	0.07	0.08	0.08	0.09	0.09
99.62 (1.02)	100.25 (0.36)	99.95 (0.19)	100.63	98.23	99.55	99.01	99.13	99.84	100.13	98.64	99.22	99.56
253.4 (2.9)	252.6 (1.2)	251.4 (1.6)	253.2	247.61	258.56	257.20	258.18	260.91	260.88	257.9	261.16	260.63
	15 3-2, 50-51 (4) 2 51.09 (0.75) 1-48 (0.03) 14.87 (0.21) 11.06 (0.07) 14.53 (0.09) 2.45 (0.07) 0.15 (0.03) 99.62 (1.02) 253.4 (2.9)	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$				

Table 3. The compositions of primary melts for Atlantic tholeiites.

Group		A1		A ₂				
Analysis number	1	2	3	4	5	6		
SiO ₂	49.5	48.8	49.0	50.6	49.7	50.7		
TiO ₂	0.6	0.5	0.6	1.2	0.9	0.8		
Al2O3	16.7	15.1	15.0	16.3	18.0	17.2		
Fe ₂ O ₃ ^a	1.0	0.8		1.7	1.3			
FeO	7.4	7.7	7.6	7.3	6.3	7.9		
MgO	10.2	13.9	13.0	8.5	9.5	9.0		
CaO	12.8	11.6	12.3	12.0	11.9	12.3		
Na ₂ O	1.7	1.5	1.6	2.4	2.3	2.4		
K ₂ Õ	0.05	0.05	0.06	0.05	0.04	0.05		
Total	99.95	99.95	99.16	100.05	99.94	100.35		
$Mg/Mg + Fe^{2+}$	0.711	0.763	0.753	0.675	0.729	0.670		
T _{calc} °C ^b	1242	1308		1202	1218			
Phase calcb	Ol (89.1)	OI (91.5)		OI (87.4)	OI (90.0)			
				P1 (75.4)	PI (78.5)			
Thom [°] exp ^c Phase host ^c			1290 Ol (91.0)			1240 Pl (88.6)		
x	0	OI 10.5		0	OI 7.5			
					Pl 17.1			

Note: Analyses 1 and 4 are averages for the most magnesian glasses of Groups A_1 and A_2 from Dmitriev et al. (1979); Analyses 2 and 5 are calculated primary melts for Groups A_1 and A_2 ; Analysis 3 is composition of experimentally homogenized highest temperature for Group A_1 melt inclusion in olivine from Sample 332B-35-1, 130 cm, DSDP Leg 37; Analysis 6 is the average for six experimentally homogenized highest temperature for Group A_2 inclusions in plagioclase from Sample 21-2B, Vema Fracture Zone, Atlantic Ocean.

^a Separation of Fe was calculated using the data of Sack et al. (1980) and oxygen fugacities corresponding to buffers QFM (for Group A₁) and Ni-NiO (for Group A₂).
^b Composition of equilibrium liquidus phases Fo-content for olivines (OI) and An-content for

Composition of equilibrium liquidus phases Fo-content for olivines (OI) and An-content for plagioclases (PI) and temperatures calculated using the data of Drake (1976) and Roeder and Emslie (1970).

^c Temperature of homogenization of primary melt inclusions and compositions of their host minerals. For an elaboration on this method, see Roedder (1979).

X = Calculated mole-fraction of crystals to be added to initial compositions 1 or 4 to construct primary melt compositions 2 or 5.

place in the South Atlantic at 35° S at the junction of the Rio Grande and Walvis ridges, with this junction serving as a magmatic-tectonic barrier. Analogous data on other oceans are useful for comparisons with our Atlantic model. We found magma (A₁ and A₂) groups, simply discriminated by D (Suschevskaya et al., 1983), are also recognizable in the Indian and Pacific oceans. Their distribution in space and time appears to follow the same patterns. It was also pointed out by Sushevskaya et al. (1984) that the basalts of the Red Sea and the Aden Gulf belong to the differentiation products of Group A₁ melts, whereas A₂ basalts occur only along the axis of the Carlsberg Ridge. Also, during formation of the Philippine Sea, the transition from the earlier to the later stages of tholeiite magmatism (i.e., from the West Philippine Basin to the Mariana Trough and to the Shikoku Basin; Zakariadze et al., 1980; Nesterenko and Sushevskaya, 1981) was accompanied by the gradual change of compositions from A_1 to A_2 .

Hence, it looks as if earlier stages of ocean opening are characterized by melt separation from mantle at the depth of the spinel-peridotite facies. The ascent of mantle melting to the level of plagioclase-peridotite facies takes place during a later stage of crustal evolution. These are consistent with depth of melting as the main controlling factor in the composition of ocean tholeiites for



Figure 6. A. Two fields of the Atlantic abyssal glass compositions in Ol-Cpx-Pl (olivine-clinopyroxene-plagioclase) triangle. Data from Dmitriev et al. (1978). B. Cotectic lines with compositions A₁ from experimental data (open circles, Bender et al., 1978) and A₂ (filled circles, Zapunny et al., 1983) at 1 atm pressure. Arrow inside field A₁ shows temperature decrease from 1263 to 1190°C. Arrow in field A₂ shows a decrease from 1244 to 1185°C.

major, and possible trace, elements from a fairly homogeneous mantle composition in all oceans at the same depth level.

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Figure 7. The relationship between melt composition (screened areas), degree of melting (%), pressure (kb), and phase equilibrium boundaries for dry lherzolite (pyrolite) after Jaques and Green (1980). Primary melt compositions: A_1 , A_2 (see Table 3). Pl = plagioclase; Ol = olivine; Opx = orthopyroxene; Q = quartz, L = melt, Hy = hyperstene, cpx = clinopyroxene.

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L. V. DMITRIEV, A. V. SOBOLEV, N. M. SUSCHEVSKAYA, S. A. ZAPUNNY

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