23. GEOCHEMISTRY AND MINERALOGY OF FRESH AND ALTERED BASALTS FROM THE GALAPAGOS RIFT¹

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ABSTRACT

Basalts from the Galapagos Spreading Center were examined through chemical and petrographic means. They were found to be generally sparsely plagioclase, clinopyroxene phyric. Samples of basalts from essentially age 0 to 2.7 m.y. were studied. Fractionation trends comparable to other tholeiitic suites are applicable in relating the basalts of this study group. The higher Fe and Ti contents of Galapagos basalts can be explained by complex plagioclase, olivine, and clinopyroxene fractionation.

Alteration of the basalts occurred post-cooling and was generated by reaction with: (1) a reducing hydrothermal fluid and (2) oxygenated, descending seawater. Alteration is restricted to rinds paralleling cracks and fractures, which allowed egress of mineralizing fluids. The paragenesis of the secondary mineral suite is as follows: pyrite—K-poor smectite—K-rich smectite—Fe-oxides (hydrated) \pm calcite/zeolites.

INTRODUCTION

Samples of basalts from Deep Sea Drilling Project (DSDP) Leg 70 were obtained from Sites 506, 507, 508, and 510. Sites 506, 507, and 508 were on young crust (0.5-0.9 m.y.), with Site 510 basalts being intermediate (2.7 m.y.). These ages are calculated according to the half-spreading rate of 3.4 cm/y., as described by Sclater and Klitgord (1973). Other basalts discussed in this chapter are from DSDP Site 424 (approximately the same age as Leg 70 young crust basalts), Site 425 (intermediate in age between young crust basalts and those from Site 510), and samples obtained by a diving expedition of the submersible Alvin along the rift axis of the Galapagos Spreading Center (0-0.2 m.y.). See Rosendahl, Hekinian, et al. (1980) for more information on the basalts from Sites 424 and 425 that were retrieved on DSDP Leg 54, the first visit of the Glomar Challenger to the Galapagos mounds area.

The present chapter presents preliminary data and related interpretation concerning primarily the bulk geochemistry of fresh and altered basalts from these sampling localities. Silicate and opaque petrology are discussed in light of the chemical parameters influencing the basalt during the post-cooling phase.

SILICATE PETROLOGY

The detailed petrography of Leg 70 basalts is included in this chapter. In general, the young crust basalts exhibit the same chemical, textural, and mineralogic trends within and among samples and sample sites. Thus, they may be considered as representing one major basalt type. Site 510 basalts are, however, substantially different in modal mineralogy and chemistry from the younger basalts.

The young crust basalts exhibit textures that are variations on hyalo-ophitic. The main differences between samples are in grain size and percentage of glass. Grain size appears to be governed by the depositional environment of the basalt (e.g., the degree of supercooling), with coarser fractions toward the interior of lithostratigraphic units and glass increasing toward the margin. The sequence of grain-size increase in basalt samples seen in Figure 1, represents one mineral suite sampled at sites of decreased cooling rates (from Figs. 1A-1C).

The development of variolitic or axiolitic textures often occurs in these basalts near quenched rims existing as pillow or flow exteriors. Figure 2 represents quenching textures, with decreased rates of supercooling seen in Figures 2A-2C. During quenching, plagioclase microphenocrysts or other groundmass crystals may serve as nucleation sites for the growing microlites.

Site 510 basalts contain olivine phenocrysts, which were not recognized in the young crust basalts. These phenocrysts are often adjacent to polysynthetically twinned plagioclase phenocrysts (Fig. 3). Site 510 basalts are mostly hyalopilitic, with quench zones at cooling unit boundaries (Fig. 4).

Detailed Petrography

Site 506. Basalt was retrieved from five holes at Site 506; essentially the same type was present in all holes. The basalts are generally vesicular with varying proportions of glass, and grade from sparsely plagioclase phyric to aphyric. In phyric samples plagioclase phenocrysts often serve as nucleation sites for varioles. These variolitic samples are often also axiolitic. Varioles are mainly composed of plagioclase and clinopyroxene. The aphyric basalts have hyalopilitic textures, with approx-

¹ Honnorez, J., Von Herzen, R. P., et al., *Init. Repts. DSDP*, 70: Washington (U.S. Govt, Printing Office).



Figure 1. Textural and grain-size variations in hyalo-ophitic basalt, ×2.5. Degree of supercooling decreases in Figures 1A-1C. A. The basalt in Figure 1 is vesicular, near the cooling unit boundary, and fine-grained; Sample 506G-2-1, 90-93 cm. B. Medium-grained glomerophyric to hyalo-ophitic basalt; Sample 507B-1-1, 43-46 cm. C. Coarse-grained sparsely plagioclase phyric basalt; Sample 507B-1-1, 29-31 cm; flow interior.





А



Figure 2. Photos display variations in the development of variolitic and axiolitic textures. The degree of supercooling decreases in Figures 2A-2C. A. Axiolites with nuclei of plagioclase microlites and varioles dominate this very fine-grained, quenched basalt, ×10; Sample 507C-3-1, 31-35. B. Coarser-grained variolitic basalt with plagioclase, skeletal lath serving as nucleus for plagioclase microlites, ×10; Sample 506G-2-1, 90-93 cm. C. Coarse-grained variolitic to plumose, aphyric basalt, ×2.5; Sample 506G-2-1, 11-14 cm.



Figure 3. Altered olivine phenocryst adjacent to plagioclase phenocryst, ×10; Sample 510-8-2, 100-102 cm.

imately equal amounts of plagioclase and clinopyroxene as groundmass.

Site 507. Basalt was sampled from five holes at Site 507. The mafic rocks are moderately coarse-grained, aphyric to sparsely plagioclase, clinopyroxene phyric basalts. Vesiculation occurs in the form of abundant pinpoint vesicles. Texturally, the basalts grade from hyalo-ophitic to intergranular, with about 55% plagioclase and up to 35% clinopyroxene. The overall phenocryst content (1%-3%) is about the same as at Site 506; however, the grain size of Site 507 basalts is much coarser than that at Site 506, representing a lower degree of supercooling.

Site 508. Basalt was retrieved from two holes at Site 508. These basement rocks are aphyric to sparsely plagioclase, clinopyroxene glomerophyric basalts, ranging from hyalo-ophitic to hyalopilitic in texture. The samples are apparently from a rubble layer at the top of the basaltic pile and thus are not necessarily representative of one flow or pillow unit.

Site 510. At Site 510 one lithostratigraphic unit of medium-grained, moderately plagioclase, very sparsely olivine and clinopyroxene phyric basalt was sampled throughout 21 meters prior to loss of the hole. Based on megascopic textural variations, at least 10 cooling units were described (see site chapter, Site 510). The multilayered unit may represent either a sequential, multiple flow emplacement or a relatively dense accumulation of pillows. Basalts from this site were the only samples from



Figure 4. Contact between glassy quenched rind and variolitic interior of plagioclase, clinopyroxene glomerophyric basalt, ×2.5; Sample 510-11-1, 40-43 cm.

the Galapagos region to contain appreciable amounts of olivine phenocrysts. These basalts are generally hyalopilitic; glassy portions of the sample are often partially crystallized to plumose arrays.

Microchemistry

Microprobe analyses of representative silicate phases are presented in Table 1. In general, the plagioclase crystals shows typical chemical zoning indicative of a fractionating magma—with Na₂O enriched in rims as compared to cores. Also, groundmass plagioclase crystals are usually Na₂O enriched as compared to accompanying phenocrysts. This relationship also indicates some changes in magma chemistry between phenocryst growth and final cooling. Plagioclase from Site 510 is generally Na₂O depleted relative to the young crust basalts, and Site 510 olivines approximate Fo₇₈. Selected analyses of clinopyroxenes from all holes are presented in Table 1.

OPAQUE PETROLOGY

Introduction

Table 2 outlines the occurrence and general abundance of opaque minerals in Leg 70 basalts. Opaque phases in Site 510 are relatively coarser grained than in the young crust basalts, and Ti-magnetite is less abundant in the Site 510 samples. Opaque phases that we recognized include pyrite, pyrrhotite, chalcopyrite, Ti-mag-

							Plagioch	ase					
	50	6G			507B					507C		508	508B
Oxides	2-1, Groundm	90–93 ass Crystal	1-1, 10-13 Microphenoc	ryst	1-1, 53 Phenos	3-55 cryst	1-1, : Phene	53-55 ocryst	3. Groun	-1, 32–34 dmass Crys	3-1, tal Phe	14-16 nocryst	3-1, 14-16 Groundmass Crystal
(wt. %)				C	Core	Rim	Core	Rim			Core	Rim	
N20	3	.08	3.94		4.21	3.99	3.88	4.97		4.08	2.33	3.25	3.72
Al ₂ O ₃	34	.01	28.14	2	8.68	28.58	29.55	26.67		28.64	31.38	29.95	29.87
SiO ₂	47	.00	52.74	5	3.00	53.30	52.43	55.15		53.95	50.09	50.85	50.91
K20	0	.04	0.02		0.14	0.12	0.11	0.14		0.03	0.04	0.07	0.10
CaO	15	.60	13.26	1	2.59	12.98	13.55	11.41		12.53	15.13	14.37	13.90
	(510							
	8-2, 100	0-102	8-2, 100-102	9-	1, 80-8	32	9-1,	80-82		11-1,	98-100		
	Groundmas	ss Crystal	Phenocryst	Ground	dmass	Crystal	Pher	ocryst	Phene	ocryst Gi	oundmass	Crystal	
							Core	Rim					
N20	2.9	5	1.59		2.23		1.16	1.09	2.	.24	2.56		
Al ₂ O ₃	29.7	8	33.44		34.39		37.90	37.55	34.	.58	32.73		
SiO ₂	50.3	0	46.31		46.29		42.73	43.71	45.	.49	47.48		
K ₂ O	0.0	02	0.06		0.10		0.18	0.04	0.	.03	0.18		
CaO	15.3	4	18.05		16.42		18.98	18.20	16.	.21	15.04		
			Cli	nopyrox	ene					Olivin	e		
	506G		507B	50	07C		508B		510	510			
	2-1, 90-93	3-1, 14-16	5 1-1, 53-55	3-1,	41-45	3	-1, 14-10	9-2	, 80-82	11-1, 98-	100		
N20	0.07	0.06	0.31	_	_	0.	18 0.	21	0.24	0.26			
MgO	18.97	16.68	20.31	10.78	11.1	4 26.	13 18.	07	19.76	47.2			
Al ₂ O ₃	1.68	2.05	0.68	12.66	11.2	2 1.	00 2.	37	2.40	0.12			
SiO ₂	51.72	49.19	53.84	51.95	51.2	6 54.	68 51.	63	53.12	39.38			
K ₂ O	_			_		-			-	-			
CaO	14.86	19.40	10.60	12.14	12.6	1 4.	16 16.	35	18.25	0.36			
ΓiO ₂	1.61	1.02	1.27	1.80	1.9	8 0.	64 1.	90	1.16				
Cr2O3	0.01	0.12	0.11	_	-	0.	15 0.	32					
MnO ₂	0.14	0.12	_	_					-				
FeO	11.13	11.06	13.81	11.09	11.1	1 14.	02 9.	60	5.89	13.56			

Table 1. Microprobe analyses of representative silicate phases, Leg 70.

netite, Ti-maghemite, hematite, and goethite. No ilmenite was observed.

Detailed Mineralogy

Sites 506, 507, and 508. Opaque assemblages from these sites are sufficiently similar to lend themselves to unified description. Opaques are present in amounts ranging from 2% to 10% in the studied samples. In all samples, Ti-magnetite comprises over 90% of the total opaques and is usually less than 20 μ m along the longest dimension. These magnetites are skeletal single crystals or skeletal stacks of octahedral, "spinel" twins. Some "hopper cubes" of Ti-magnetite occur in the coarsergrained basalts, but they are not common (Fig. 5).

Oxidation of Ti-magnetite to Ti-maghemite was observed in a few samples from Holes 506D, 506G, and 507B. The Ti-magnetite crystals generally segregated into glassy pockets between plagioclase laths (Fig. 6) and occur along plagioclase crystal boundaries. These oxides obviously crystallized prior to accompanying primary sulfide spheres, since such spheres are often flattened against magnetite crystals.

Primary sulfide spheres (Fig. 7) and secondary pyrite crystals (Fig. 8) and veins (Fig. 9) are common in the

samples but rarely constitute more than 5% of the opaques. The primary sulfide spheres are dominantly of polyphase pyrrhotite and chalcopyrite mineralogy, as described by Czamanske and Moore (1977). The compositions of these spheres are presented in Table 3. Exsolved chalcopyrite in the primary spheres is most commonly observed in samples from Site 508. Secondary pyrite crystals often accompany smectite in replacing primary silicate minerals, generally clinopyroxene, and sideromelane (Fig. 10). Pyrite veins and disseminated crystals are most common adjacent to and filling cracks and fractures in the outer edges of basalt samples bounded by cooling cracks and other fissures.

Site 510. Ti-magnetic octahedra range from 3% to 8% of the total volume in samples from Site 510. These oxides are, thus, less abundant than in young crust basalts studied for this research. Sizes of the Ti-magnetite crystals range from 5 to 20 μ m in diameter along the largest dimension. Primary sulfide spheres of pyrrhotite, pyrite, and chalcopyrite are less than 5 μ m in diameter and constitute <1% of the total sample.

Secondary sulfides may occupy as much as 3% of the sample. These sulfides, mainly pyrite, occur as disseminated grains in glassy areas and as vein fillings accom-

Table 2. Ge	eneral distribu	tion of opa	que phases.
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Sample	Titanon	agnetite		Titano-	Руг	ite	Pyrrh	otite		
(interval in cm)	< 20µm	>20µm	Hematite	maghemite	Sphere	Other	Spheres	Other	Chalcopyrite	Geothite
Hole 506D										
9,CC, (17-20)	С	-		—	С	С	R	-		-
9-1. 48-31	C			R	C	C	C	-	-	
9-1, 53-56	C	-	R	-	С	С	С	-	-	-
Hole 506G										
2-1, 31-33	с	-	-	-	-		С	-	-	-
2-1, 11-14	R	C	-	_	C		C	-		
2-1, 90-93	<u> </u>	С	-	R	С	С	R	-	—	R
Hole 507B										
1-1, 53-55	R	С	-	R	С	-	С	-	R	-
1-1, 10-13	R	С	_	_	R	C	C		-	
1-1, 43-46		C	-	-	С	-	С		R	
1-1, 18-22	R	C	$\sim - 1$	\sim	С	С	R	-	R	-
Hole 507C										
2-1, 12-14	С	-	-	-	R	R	R		-	R
3-1, 31-36	C		$\sim - 1$		R	C	R			C
3-1, 12-14	C	—	—	-	С	R	С		—	-
Hole 508B										
3-1, 10-12	С	R	~ -1		С	R	С	-	R	-
4-1, 7-10	С	-	-		С	С	С		3 <u>00</u> 0	
Hole 510										
8-2, 100-102	С	R	-	-	С	С	С	_		С
8-2, 104-106	C			-	C	C	С			
9-1. 76-79	C	R	_		R		R		-	
9-1, 122-125	С	R		-	C		С		-	
9-2, 52-55	C	_	-	_	R	R	R	-	-	
9-2, 80-83	C			_	C	C	C		_	
9-2, 120-123	C	_			R	R	R			
9-3, 39-42	C			-	C		C	-	-	
9-3, 53-59	C	-		_	C	-	C	-		-
10-1. 4-6	C	R			R	C	R	-	-	
10-1, 14-18	C	_		-	C	R	C	-	_	
10-1, 73-75	č		-	-	C	R	C	-	-	_
11-1, 36-39	č	-	_	-	č		C	_	_	
11-1, 40-43	č	_		_	R	R	R	_	_	
11-1, 98-100	č		-	-	c	C	C	_		-

Note: R = rare; C = common.

panied by green smectite. In Sample 510-6-1, 50-52 cm, secondary chalcopyrite occurs, with pyrite replacing basalt glass.

The size of opaque grains is proportional to the degree of undercooling of the basalts, indicating a rather late growth of these crystals and also rather late agglomeration of the sulfide liquids relative to emplacement of the cooling lava. General paragenesis of these related phases appear to be silicates \rightarrow Ti-magnetite \rightarrow sulfides.

Microchemistry

Table 3 also presents selected representative analyses of opaque phases from the basalts. Oxide totals for the Ti-magnetite are less than 100 wt.% since the FeO value has not been partitioned between Fe^{2+} and Fe^{3+} .

It can readily be seen that the TiO_2 content of young crust magnetites is higher than that of Site 510 magnetites. However, no discernible variation exists between sulfides of young crust basalts and Site 510 basalts.

IGNEOUS GEOCHEMISTRY

Samples from six DSDP sites (424, 425, 506, 507, 508, and 510) and from the *Alvin* expedition were analyzed. Many samples had an alteration rim which was recognizable in hand specimens. In such cases, the rim was removed from the unaltered core with a trim saw and re-

tained for analysis and comparison to the core. A total of 41 DSDP and 14 *Alvin* samples, thought to be relatively unaltered, plus 23 altered rim samples, were analyzed. The following discussion relates only to unaltered samples.

Chemical analyses for all major and trace elements were made by atomic absorption spectrophotometry on triplicate preparations following fusion with LiBO₂ (major elements) or dissolution in HF-HNO₃ (trace elements). FeO* was determined colorimetrically (Shapiro, 1960). Loss on ignition (LOI) was used to determine the H₂O and volatile contents by heating to constant weight at 1000°C. USGS standards BCR-1 and BHVO-1 were used for reference, and all analyses (except LOI) were calibrated against these standards. The precision is well within $\pm 2\%$ for all major elements ($\pm 0.8\%$ for SiO₂) and $\pm 5\%$ for trace elements. Data appear in Table 4.

The samples from the various sites represent low- K_2O tholeiites, with a range in MgO values from 8.2 to 6.3%. There are no alkalic basalts, and the total alkali contents are quite low for all samples (Fig. 11); the highest Na₂O content is only 2.6% (Table 4). There is a distinct grouping of samples, based on site location, seen in the alkali/SiO₂ graph (Fig. 11), with samples from Site 510 containing significantly lower amounts of alkalies than samples from other sites.



Figure 5. Hopper cube of Ti-magnetite; reflected light, ×10; Sample 507B-1-1, 18-22 cm.

When the FeO*/MgO ratio is used as a relative indicator of fractionation, there is strong evidence that the DSDP samples are chemically related and represent variable degrees of fractionation (Fig. 12). This observation is true for major and trace elements. The fractionation relationship among the DSDP samples is best exemplified by Cr, which decreases by almost five times (from approximately 500 to 1000 ppm). Elements which are known to be especially mobile and affected by alteration (i.e., K₂O, Li) show only an ill-defined relationship to the FeO*/MgO ratio. It is important to point out that the Na₂O content apparently has not been significantly affected by alteration. The overall trends of major and trace elements, shown in Figure 12, are similar to those for shallow tholeiitic fractionation reported elsewhere (Carmichael, 1964; Batiza et al., 1977; Frey et al., 1974; Miyashiro and Shido, 1975).

Alvin basalts are relatively highly fractionated. One sample is much more fractionated than either other Alvin or DSDP samples with an FeO*/MgO ratio of 3.59 and a MgO percentage of only 4.45. While the chemistries of the DSDP and Alvin samples are quite similar in many ways, there are some rather consistent and significant differences between the two suites; the greatest differences seem to be for C, Sr, and Ni. There is no indication that these differences result from alteration, for some elements which are especially mobile during alteration (CaO, Na₂O, K₂O) are of similar abundances in both rock suites. Other constituents which are



Figure 6. Cross-section of skeletal octahedron of Ti-magnetite floating in a pocket of glass interstitial to plagioclase laths; reflected light, ×10; Sample 507C-2-1, 12-14 cm.

rather immobile (Cr, Ni) have different abundances. Thus, the data suggest that the magma chemistries of the *Alvin* and *DSDP* samples were different and not simply related in a cogenetic fashion through fractional crystallization. The difference is, however, not apparent based on the major element chemistry.

The tholeiitic fractionation trend is well displayed on a diagram of $Na_2O + K_2O/FeO^*/MgO$ (Fig. 13). Data indicate a very limited alkali distribution (representative of lack of alteration) and distinct iron enrichment. Note that *Alvin* samples closely correspond to the more fractionated DSDP sample.

The iron enrichment seen in our samples is considerably less that that reported by Byerly et al. (1976) for Galapagos tholeiites at Site D-1, which is close to our sites (up to 18.5% FeO* and 3.7% TiO₂), although one *Alvin* sample does contain 16.0% FeO* and 2.80% TiO₂—the highest contents in any of our samples (Table 4). Based on FeO* and TiO₂ contents, our samples are quite similar to those from Site D-17, described by Anderson et al. (1975) for the Galapagos Spreading Center.

These data conclusively demonstrate that the most primitive of our sample suites is that from Site 510, while others (424, 506, 507, 508, and *Alvin*) are fairly highly fractionated, and Site 425 is rather intermediate. There is a well-defined relationship between sample location, or distance from the Galapagos Spreading Ridge, and level of fractionation (Fig. 14). The *Alvin* samples



Figure 7. Sulfide sphere floating in glass pocket; reflected light, ×10; Sample 507C-2-1, 12-14 cm.

are included for reference, although there is some indication, discussed previously, that they are not strictly cogenetic with DSDP samples. Figure 12 indicates a systematic decrease in fractionation level (FeO*/MgO) away from the spreading ridge. Preliminary interpretation suggests that the parent magma which has given rise to our samples has undergone a continuous and, at least on a gross scale, rather uninterrupted history of fractionation.

In spite of the fact that basalts from Site 510 are the most primitive of those found at our DSDP sites, they do not appear to represent true parental magmas. Highest values for MgO, Ni, and MgO/FeO + MgO are, respectively, 8.20%, 105 ppm, and 0.46—these are considerably lower than those values considered representative of parental mantle melts (Green and Ringwood, 1967; Kay et al., 1970). Thus, even our most primitive suites are somewhat fractionated.

Anderson et al. (1975) and Kay et al. (1970) have previously shown that oceanic basalt fractionation can be described by a trend representative of 35% plagioclase and 8% olivine on an MgO-FeO* variation diagram. Data from our study conform well to this trend (Fig. 15), again indicating that Site 510 is relatively more primitive. The contribution of clinopyroxene as a fractionating phase can be depicted on a CaO-Al₂O₃ diagram (Fig. 16), and Anderson et al. (1975) have shown that, indeed, pyroxene does represent a significant influence on the fractionation process. Figure 16 emphasizes that the fractionation of our DSDP (and *Alvin*) samples is



Figure 8. Pyrite crystals filling primary, vugular pores, reflected light, ×8; Sample 507B-1-1, 29-31 cm.

not simply modeled by plagioclase and olivine and that pyroxene is a significant phase. It is interesting that our samples display a fractionation trend of somewhat lower Al_2O_3 content than that described by Anderson et al. (1975). Quantification of this fractionation must await modeling studies which incorporate the chemistries of phenocrystic and groundmass phases in the DSDP samples.

BASALT ALTERATION

Chemistry

In an initial effort to examine the chemistry of alteration of the DSDP samples, the composition of visibly altered rims has been compared to that of the corresponding unaltered core for 23 samples from Sites 506, 507, 508, and 510. Data appear in Table 5.

Qualitative comparisons of core and rim chemistries indicate that obvious differences exist, which can be related to alteration (Table 5). Some alteration effects are consistent in samples from all four sites; others are quite inconsistent. The most highly altered suite of samples is from Site 510, the oldest of the sites, and the least altered is from Site 506, youngest of the sites. K_2O and Rb contents (and the K/Rb ratio) increase significantly in the altered rims of samples from all sites, and the FeO* content shows a marked enrichment in the rims of most samples. The FeO*/Fe₂O₃ ratio exhibits a consistent decrease owing to oxidative alteration effects in the rims.



Figure 9. Pyrite vein filling crack and also replacing isolated sections of silicate glass; sulfide also fills two large vesicles, reflected light, ×8; Sample 510-10-1, 4-6 cm.

Perhaps one of the more interesting changes, apparently related to alteration, involves Ag, which shows a general increase in the rims of most samples except those from Site 510. It may be important that Ag enrichment (or depletion) is somewhat related to the age, or relative distance from the ridge, of the sites. Greatest rim enrichment is seen in samples from Site 506, with a general decrease in enrichment and eventually an absolute decrease in the rims in samples from Sites 507, 508, and 510. This trend may have significant bearing on the release of Ag to marine systems as a function of time and indeed may be important relative to Ag enrichment in altered rocks. A somewhat similar relationship to distance from the ridge is noted for K₂O, which consistently increases in relative concentration with distance from the ridge to eventually be quite strongly enriched in rims of 510 samples.

Uranium analyses of basalt pairs comprising altered rim and fresh cores were accomplished by neutron activation techniques. Analytical error was never greater than 5% of reported values, and all samples contained uranium in excess of the lower detection limits. Table 6 presents these data. It can readily be seen that uranium is randomly enriched or depleted in the altered rim when compared with the fresher core. There is no apparent temporal relationship with uranium enrichment or depletion as seen for silver. There does, however, appear to be a mineralogic control on uranium distribution.



Figure 10. Pyrite grains replacing outer portion of otherwise unaltered clinopyroxene phenocrysts, reflected light, ×2.5; Sample 506D-9-1, 53-56 cm.

Table 3. Electron microprobe analyses of selected opaque phases (wt.%).

Sulfide Ve (Av. of 5)	einlets, Site 51	0.	
Fe	53.10		
S	45.81		
Cu	0.21		
Zn	0.38		
Primary S (Av. of 12	Sulfide Sphere: 2)	s, Sites 506, 507	, 508, and 510.
Č.	Cu-rich	Fe-rich	
Fe	42.10	58.20	
Cu	20.90	0.80	
Ni	0.80	1.70	
Co	0.23	·0.80	

35.80

Titanomagnetites

S

		Sample (interval in c	m)	
Oxide (wt.%)	506G- 2-1, 90-93	507B- 1-1, 53-55	510- 10-1, 73-75	510- 9-1, 76-79
MgO	0.37	0.39	0.69	0.57
Al ₂ O ₃	1.51	1.46	1.71	1.82
MnO	0.49	0.53	0.42	0.51
FeO	72.12	72.38	79.43	76.48
TiO ₂	21.21	21.85	12.96	15.43

37.20



Figure 11. Alkali-SiO₂ diagram for DSDP and Alvin samples; A = alkalic and TH = tholeiitic basalt fields.

Rims depleted in uranium relative to the core are dominated by oxide phases in the altered zone. Samples with elevated uranium contents in the altered rims have green smectites as the dominant secondary mineral in the rind.

As will be discussed in the following section, smectites precede oxides in paragenesis of secondary phases. Thus, uranium seems to be concentrated in altered basalts during the initial, smectite-dominated, alteration process. The uranium probably exists as a sorbed cation on the mixed layered smectites or as a substitute (U^{4+} for Fe²⁺) in the silicate lattice. During subsequent oxidation of the reduced Fe-rich clays, uranium is oxidized to U⁶⁺ and released to solution and complexing by Clbearing seawater. Although this release of uranium during oxidation might be considered time dependent, it is also greatly controlled by such constraints as porosity, oxygen availability, diffusion rates, and fluid migration (see Gabelman, 1977).

Block (1980) states that low temperature alteration of oceanic crust is a major sink for uranium supplied to the oceans. Our data support this thesis, if the dominant alteration process involves smectite formation. However, upon oxidation, uranium may be liberated into the aqueous system and once again made available to ambient seawater. Since the oxidation of clay-rich alteration rims is seen to be common in the Galapagos area, we feel that the altered basalt is not nearly so efficient a uranium sump in this region as is suggested in general by Block (1980).

Mineral Phase Variations in Basalt Alteration

Alteration as seen in basalt from the Galapagos area represents early diagenetic, very shallow burial, and low pressure, moderate to low temperature hydrothermal processes (see Schrader et al., 1980; Humphris and Thompson, 1978). Similar patterns of alteration in basalts from other regions of the world ocean are reported by Humphris and Thompson (1978).

The term "alteration" as used here may be defined as any process that changes the bulk chemistry or mineralogy of the original igneous rock. In recent geologic literature, alteration is often equated with replacement of one phase by another more stable phase. Alteration in this latter connotation is quite rare in the studied samples. However, it is obvious that a variety of secondary minerals have formed within vugs, cracks, vesicles, and other voids of primary origin and that these secondary phases significantly alter the bulk rock chemistry of the basalts in which they occur. In a few cases, silicate glass and Fe-bearing silicate mineral phases have been replaced by secondary mineral assemblages (Fig. 17). In summary, the dominant mode of basalt alteration in the studied samples is one of secondary mineral formation without widespread concomitant replacement of primary phases.

As diagramed in Figure 18, basalt alteration occurs in rims adjacent to and paralleling cracks and fractures. The obvious explanation for this phenomenon is accessibility of reactive, migrating fluids to the lithic surfaces bounding the channels through which they travel. Within this "alteration rim," a generalized zonal arrangement of secondary minerals is observed. Four basic zones within the rim are discernible. The outermost zone is occupied by Fe-oxides filling primary pores (see Figs. 18 and 19). The second zone inward is represented by K-rich smectite coatings and fillings on vesicle walls and other void space boundaries. In the third zone inward, pores are filled with K-poor smectite often accompanied by pyrite, (Fig. 20). The fourth zone inward is not uniformly present but often occurs as a narrow (0.2 to 1-mm wide) band of secondary dispersed pyrite grains replacing silicate glass in pores (Fig. 17). No smectites occur in this sulfide zone, which serves as the boundary between the altered rim and the fresher interior. Calcite and zeolites often occur post-smectite and overprint all preceding mineral zones, being controlled by fracture porosity.

Although recognition of the variation of K content in these smectites was accomplished with the aid of electron microprobe analyses, visual identification of the zones may be appropriate. The K-poor clays are generally green to blue-green, while the K-rich smectites are more often orange-tinted and somewhat bleached. The presence of pyrite in the K-poor smectite zone and its absence in the K-rich zone may be construed as representing the dissolution of sulfide during the formation of K-rich silicates. Thus, the oxidation of pyrite may lend the Fe^{3+} ion as the chromatophore in the K-rich smectites. It must be noted that all four zones are not always discernible in any single sample and that the zones grade one into the other.

This zonal arrangement of secondary phases may be seen as sequential establishment of equilibrium under evolving chemical conditions. Figure 21 (after Garrels and Christ, 1965) allows approximation of the evolving constraints on the system. The original fluid is favorable for Fe^{2+} solution and migration and enters a field where the Fe^{2+} is precipitated as pyrite, FeS_2 . Sulfur probably is derived from the breakdown of seawater sulfates. Continued evolution of the system, perhaps during reaction of the original fluid with locally small amounts of basaltic glass, allows formation of Fe-silicates (approximating the K-poor smectites). Reversal in the slope of the evolving system is indicated by the dominance of oxides in the final assemblage. The trend toward K-enrichment in earlier formed smectites and formation of oxidized species is probably a result of descending oxygenated seawater becoming dominant over ascending reduced hydrothermal fluids. The original hydrothermal solutions need not be juvenile water but may be derived from a cyclic convection system comprising sea and connate waters (Lonsdale, 1977; Edmond et al., 1979).

Thus, it is apparent that the mineral zones in altered rims are the result of overlapping areas of various equilibrium assemblages responsive to an evolving aqueous system. The innermost zone of pyrite is but a remnant of more pervasive alteration which at one time had spanned the entire breadth of the altered rim. Sequentially deposited minerals may have reacted with pyrite to produce other more stable species in subsequent environments, or they may have been deposited after much of the pyrite has been removed by a more oxidizing fluid.

Textural evidence for secondary mineral paragenesis has been summarized in the paragenetic sequence depicted in Figure 22. An initial reducing environment allowed precipitation of pyrite, giving way to K-poor green smectite. Later encroachment of a more oxidizing environment allowed formation of the K-rich orangetinted smectites by reaction with the previously deposited smectites. The K-enrichment is thought to represent reaction of original hydrothermal smectites with descending K-bearing seawater. Finally, Fe-oxides (hydrated) and calcite/zeolites formed in the seawater-dominated environment.

Microprobe analyses of the secondary smectites in the basalts corroborate these conclusions. In Figure 23, it can be seen that secondary smectites have compositions which trend through the field of "green clay" described by analyses of nontronites found in the mounds hydrothermal field (see Schrader et al., 1980; Rosendahl, Hekinian, et al., 1980). As noted, we feel that the progressive K-enrichment reflects reaction of seawater with the original hydrothermal phase. It is interesting that several samples of smectite from the basalts are depleted in K as compared to the "mounds" nontronites, indicating the influence of ambient pore water and seawater on the chemistry of clays deposited above the basalt/sediment interface. In the few samples of smectite seen to replace glass, a loss of MgO relative to FeO* is indicated by the presence of the hydrothermal smectite. In these cases, the MgO content of secondary clays is higher than that of clays filling void spaces. Then MgO content is apparently inherited from the original glass. The K-enrichment of these smectites appears to parallel the trend indicated by the void-filling phases.

Table 7 summarizes the chemical fluxes indicated by the aforementioned petrologic and microchemical study. Overall, a net gain of K, Fe, O, and S is favored and accompanied by a loss of Ca, Mg, and Al. These fluxes correlated with processes described by Humphris and Thompson (1978) from bulk rock chemical studies of altered seafloor basalts.

SUMMARY AND CONCLUSIONS

A summary of the major points presented in this chapter includes the following:

1) The high FeO and TiO_2 basalts sampled on DSDP Leg 70 are represented by sparsely plagioclase, clinopyroxene phyric basalts probably emplaced as thin flows or pillow units.

2) Chemically and mineralogically, Site 510 basalts are distinctly different from young crust basalts sampled.

3) Lower TiO_2 content of Site 510 basalts relative to young crust basalts is reflected in lower contents of Timagnetite in Site 510 samples.

4) Secondary sulfides in veins and pores are probably the result of hydrothermal processes.

5) Young crust basalts studied here are highly fractionated as compared to basalts from Site 510 and 425 and can be related to parental magmas similar to Site 510 basalts by normal basaltic fractionation trends.

6) Basaltic alteration in young, rise-crest related basalts is dominated by filling of void spaces by hydrothermal and diagenetically precipitated minerals.

7) The paragenesis of secondary phases in the basalts studied, as well as microprobe analyses of the secondary smectites, indicate that the first alteration minerals formed are precipitated from a reducing hydrothermal fluid. Subsequent phases precipitated are derived from more oxygenated solutions and reflect the dominance of seawater.

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										Samp (interval i	le n cm)								
	506C-2	-1, 3-5	506D-9-	1, 50-55	506G-2-	1, 42-45	506G-2-	1, 56-62	506G-2-1	, 107-110	506H-C	C (18-20)	506I-1-	1, 8-11	506I-1-1,	507B-1-1,	507B-1-	1, 71-73	507B-1-1,
Component	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	22-26	20-23	Core	Rim	59-62
Oxides of ma	ajor eleme	ents (wt. %)																
SiO ₂ Al ₂ O ₃ TiO ₂ Fe ₂ O ₃ FeO MgO CaO Na ₂ O K ₂ O MnO H ₂ O	50.8 13.67 1.89 3.28 10.65 6.76 10.76 2.41 0.15 0.235 -	50.54 13.21 1.92 4.00 10.00 6.69 10.23 2.41 0.21 0.228 0.34	51.28 13.93 1.72 2.28 10.51 7.13 11.05 2.42 0.12 0.219	50.02 13.84 1.73 3.28 9.56 7.02 11.03 2.37 0.14 0.217 0.59	50.46 13.55 1.59 2.31 10.28 7.11 11.13 2.37 0.14 0.226	50.77 13.64 1.65 2.61 10.07 7.10 10.74 2.36 0.15 0.226 —	51.20 13.41 1.93 1.39 12.19 6.76 10.20 2.43 0.09 0.239 -	51.13 13.57 1.92 2.97 10.56 6.70 10.09 2.50 0.11 0.229 0.11	50.22 13.97 1.60 2.96 10.06 7.07 11.40 2.38 0.12 0.219 0.35	50.51 14.04 1.59 3.22 9.79 7.21 11.36 2.41 0.12 0.218 -	50.30 13.95 1.58 2.63 10.12 7.13 11.39 2.38 0.12 0.219	50.55 13.87 1.60 3.52 9.29 7.16 11.35 2.41 0.17 0.216 0.21	50.86 13.78 1.50 2.25 10.59 7.14 10.60 2.36 0.12 0.222	50.56 13.87 1.53 2.80 10.00 7.19 10.57 2.36 0.09 0.220 0.09	50.64 13.85 1.56 3.42 9.19 7.24 10.85 2.35 0.14 0.220 0.51	51.28 13.19 1.91 3.17 10.65 6.61 10.23 2.49 0.12 0.232	50.74 13.51 1.67 3.91 9.41 6.84 10.72 2.42 0.27 0.220 0.22	50.15 13.11 1.67 5.31 9.06 6.80 10.43 2.39 0.31 0.216 0.53	50.40 13.24 1.85 3.61 10.73 6.59 10.61 2.52 0.09 0.236 -
Total	100.64	99.78	100.66	99.80	99.17	99.32	99.80	99.89	100.35	100.44	99.82	100.14	99.42	99.28	100.99	101.06	99.93	99.98	99.88
Trace elemen	its (ppm)																		
Ag Cu Co Cr Li Ni Rb Sr V Zn	0.068 69 41.3 135 12 76 25.5 78 403 115	0.074 65 43.3 132 10.9 79 27.9 83 394 116	0.053 83 40.6 189 11.1 81 24.9 83 355 96	0.105 87 41.6 212 9.5 83 25.4 80 344 99	0.051 83 40.2 177 8.5 78 23.9 78 355 96	0.087 83 40.6 177 7.5 82 22.4 82 364 98	0.074 66 40.6 120 9.3 76 21.7 80 412 113	0.117 66 42.8 160 9.3 77 21.7 83 411 112	0.086 84 41.5 247 7.9 75 20.4 84 360 98	0.071 80 40.9 235 8.3 81 19.4 81 359 96	0.071 81 41.4 178 5.7 77 28.3 82 375 97	0.115 81 41.5 210 5.6 80 29.7 83 373 100	0.075 81 40.4 225 6.1 80 29.0 81 363 94	0.122 84 41.0 220 6.1 76 28.5 81 369 94	0.115 83 40.5 184 4.7 74 28.3 85 374 96	0.073 69 167 7.8 82 29.3 85 422 110	0.088 77 40.9 189 4.9 84 30.9 83 379 106	0.099 63 40.4 173 5.4 80 35.7 83 370 100	0.068 67 40.7 121 7.7 79 29.3 85 425 110

Table 4. (Continued).

									(ii	Sample nterval in c	m)								
	507B-2	-1, 0-2	507C-3-	1, 28-32	508B-3-	1, 12-14	508B-3-1	, 19-21	508B-3-	1, 42-46	508C-1,O	C (10-15)	510-9-	2, 8-12	510-9-2	, 56-59	510-9-2,	510-9-2,	136-140
Component	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	115-119	Core	Rim
									(wt.	%)									
SiO ₂	50.85	49.34	50.74	49.78	49.93	49.45	49.36	49.00	50.24	49.23	49.37	49.41	49.93	49.56	49.85	49.55	49.39	49.03	49.59
Al ₂ O ₃	13.39	13.41	13.41	13.02	13.29	13.33	13.16	12.81	13.68	13.22	13.11	13.41	15.67	15.70	15.98	14.93	15.06	15.18	15.12
TiO ₂	1.84	1.87	1.96	1.90	1.97	1.93	2.02	1.96	1.74	1.73	2.00	2.02	0.76	0.70	0.73	0.72	0.79	0.76	0.83
Fe ₂ O ₃	3.60	4.74	2.84	4.19	3.24	4.28	5.45	6.68	3.40	5.67	6.26	6.45	1.94	2.47	2.16	3.56	2.99	2.60	2.89
FeO	10.56	9.70	10.87	10.34	10.63	10.15	8.91	8.62	9.44	8.78	8.46	8.22	7.88	7.41	7.18	6.64	6.26	6.97	7.12
MgO	6.49	6.47	6.62	6.43	6.35	6.54	6.56	6.69	6.79	6.77	6.57	6.43	8.20	8.11	7.73	8.06	7.83	7.75	7.94
CaO	10.63	10.59	10.68	10.48	10.48	10.39	10.04	9.97	10.65	10.63	9.87	9.39	13.11	13.59	14.08	13.82	14.08	13.77	13.63
Na ₂ O	2.52	2.44	2.52	2.45	2.49	2.46	2.43	2.36	2.45	2.32	2.40	2.43	1.91	1.93	1.97	1.93	1.97	1.91	1.91
K ₂ O	0.14	0.28	0.14	0.26	0.16	0.19	0.27	0.35	0.19	0.41	0.37	0.40	0.04	0.04	0.04	0.22	0.04	0.03	0.14
MnO	0.236	0.227	0.236	0.237	0.222	0.226	0.233	0.227	0.232	0.224	0.217	0.211	0.184	0.184	0.177	0.184	0.174	0.174	0.174
H ₂ O	-	0.15	-	0.21	0.96	0.45	0.71	1.02	0.23	0.77	1.22	1.39	0.14		0.35	0.30	0.46	1.25	0.33
Total	100.26	99.22	100.02	99.30	99.72	99.40	99.14	99.69	99.04	99.75	99.85	99.76	99.76	99.69	100.25	99.91	99.74	99.42	99.67
									(ppi	n)									
Ag	0.075	0.127	0.086	0.075	0.056	0.094	0.052	0.069	0.090	0.092	0.059	0.055	0.071	0.083	0.071	0.061	0.054	0.058	0.058
Cu	67	72	70	66	77	71	68	66	72	67	65	64	97	98	101	101	102	101	97
Co	42.2	43.9	39.1	40.0	40.8	40.3	42.4	41.3	40.0	42.9	43.3	42.9	38.8	39.7	39.8	38.0	38.0	37.8	37.9
Cr	140	101	170	103	170	171	159	169	153	103	181	160	488	485	454	438	474	447	463
Li	7.6	9.3	8.3	8.8	9.8	9.9	8.8	7.8	7.1	7.6	8.1	9.0	6.1	5.8	5.1	5.3	6.7	6.0	5.0
Ni	78	101	79	73	81	76	87	82	80	83	83	82	98	97	99	91	102	92	91
Rb	29.2	33.9	28.1	32.6	29.3	30.6	3.05	33.4	24.6	31.9	29.0	26.9	16.7	18.3	23.6	29.5	24.2	23.3	26.8
Sr	85	84	87	81	79	80	87	79	84	83	83	84	62	64	64	61	63	60	61
v	412	434	430	425	429	420	153	427	412	391	440	439	257	258	251	258	265	264	257
Zn	112	116	111	109	117	112	123	112	110	104	121	115	79	69	67	63	71	73	66

										Sa (interv	mple al in cm)									
	510-9-3	3, 22-25	510-9-3	3, 69-74	510-8-C	C, 10-15	510-8-2	510-9	-1. 4-7	\$10-9-1	510-9-1	98-100	510-10-1	510-10-1	510-11	-1, 0-3	510-11-1	424-5-4	424-5-3	424-6-1
Component	Core	Rim	Core	Rim	Core	Rim	89-93	Core	Rím	49-51	Core	Rim	10-13	53-56	Core	Rim	52-57	25-27	70-72	20-22
Oxides of m	ajor eleme	ents (wt. %)																	
SiO ₂	49.98	49.38	50.36	49.98	49.31	49.21	49.26	49.83	49.58	50.70	50.16	49.72	50.35	49.89	49.59	49.15	50.70	10.10	49.61	49.97
Al ₂ O ₃	15.72	15.78	15.35	15.22	15.57	15.15	15.31	15.52	15.49	14.37	15.66	15.56	14.39	15.56	14.94	14.94	15.22	12.78	12.83	12.91
TiO ₂	0.75	0.71	0.76	0.78	0.76	0.74	0.73	0.78	0.76	0.96	0.91	0.82	0.98	0.87	0.89	0.82	0.91	1.94	1.90	2.03
Fe ₂ O ₃	1.98	3.20	2.24	3.96	2.91	3.77	2.78	1.57	3.18	3.01	2.64	3.71	2.28	2.73	2.79	4.00	2.34	3.30	3.91	4.05
FeO	6.91	6.56	7.09	6.16	6.83	6.41	7.07	7.79	6.85	8.12	6.49	6.03	8.67	6.50	6.73	6.06	7.10	10.97	10.50	10.56
MgO	7.45	7.25	7.88	7.62	7.37	7.37	7.76	7.85	7.47	7.49	7.49	7.26	7.52	7.82	7.91	7.83	7.75	6.58	6.63	6.61
CaO	13.82	12.99	13.87	13.49	13.30	13.49	13.23	13.31	13.63	11.95	13.70	13.39	13.10	13.49	13.42	13.38	13.65	10.55	10.49	10.44
Na ₂ O	1.99	1.98	1.98	1.94	1.92	1.92	1.94	1.96	1.94	2.15	1.96	1.93	2.07	1.90	1.95	1.90	1.98	2.55	2.55	2.51
K ₂ O	0.04	0.28	0.05	0.31	0.18	0.25	0.09	0.03	0.20	0.04	0.04	0.24	0.03	0.04	0.03	0.20	0.05	0.09	0.06	0.06
MnO	0.171	0.162	0.171	0.166	0.167	0.174	0.173	0.177	0.171	0.215	0.168	0.162	0.210	0.164	0.175	0.170	0.179	0.217	0.216	0.219
H20	0.39	0.72	0.21	0.34	0.65	0.74	0.19	0.28	0.20	0.08	0.50	0.73	—	0.54	0.60	0.77	0.15	0.21	1.27	0.09
Total	99.20	99.01	99.96	99.96	98.97	99.22	99.31	99.05	99.47	99.99	99.72	99.55	100.56	100.22	99.03	99.19	100.82	99.29	99.97	99.45
Trace element	nts (ppm)																			
Ag	0.093	0.053	0.059	0.063	0.054	0.068	0.054	0.064	0.056	0.054	0.090	0.072	0.052	0.052	0.074	0.062	0.052	0.054	0.045	0.041
Cu	104	86	102	87	102	104	102	101	115	94	102	95	94	102	102	92	105	78	70	69
Co	38.9	37.7	40.7	37.1	38.5	37.9	39.6	38.4	38.7	42.7	41.6	38.4	41.0	39.5	39.2	36.8	39.8	44.3	40.1	40.4
Cr	445	432	464	437	440	438	481	458	459	170	452	425	181	420	440	448	454	157	128	151
Li	5.5	5.5	6.4	6.8	7.2	6.8	7.4	7.4	7.5	7.8	7.5	8.0	7.3	8.4	7.3	8.0	6.5	11.3	9.1	10.1
Ni	98	85	105	84	91	89	88	87	90	80	103	82	76	90	88	81	89	55	57	63
Rb	22.5	27.5	23.4	30.4	27.3	28.4	24.6	22.4	26.3	23.8	20.9	26.3	20.9	18.4	17.6	20.6	15.9	29.9	29.2	30.5
Sr	71	66	60	62	65	63	66	60	63	67	67	66	64	80	59	60	62	89	81	86
V 7-	204	249	273	251	243	257	254	273	260	328	265	254	319	265	264	258	264	473	435	431
Za	/0	05	10	60	08	00	09	10	15	90	/0	04	90	/0	/1	00	12	128	111	115

Table 4. (Continued).

									Samp (interval	ole in cm)			Abula	Abria	Abrim	Abria	Abula	Abuin	Alvin
424-6-3, 21-23	425-7-1, 138-139	425-7-2, 71-72	425-8-1, 23-26	425-8-1, 135-136	425-9-3, 72-73	Alvin 715-1	Alvin 716-3	Alvin 717-4	Alvin 723-2	Alvin 726-6	Alvin 730-3	Alvin 735-1	Leg 2 Drill 5	STA 31 Drill 4	GID 8 Drill 1	STA 22 Drill 3	GID 1 Drill 1	Gid 9 Drill 1	Leg 3 Drill 6
50.26	50.00	50.30	51.39	50.22	50.36	51.30	49.67	50.74	50.46	52.03	50.34	49.97	49.79	50.39	50.17	50.01	50.08	51.04	50.94
12.80	13.52	13.93	14.16	15.52	14.31	13.52	13.58	13.48	13.61	12.55	13.39	13.75	13.68	13.65	13.83	13.76	13.80	13.56	13.76
1.94	1.42	1.25	1.29	0.98	1.14	1.76	1.71	1.77	1.79	2.80	1.68	1.70	1.68	1.70	1.58	1.77	1.67	1.66	1.75
4.55	2.65	2.79	2.83	3.34	3.08	3.24	3.04	2.41	3.19	3.48	2.84	2.54	3.06	1.71	2.76	2.10	2.44	2.83	2.84
10.16	9.56	8.57	8.26	6.70	8.04	10.89	11.01	11.37	10.70	12.86	10.63	10.82	10.56	11.66	10.70	11.61	10.92	10.46	10.63
0.00	11.59	12.11	1.35	13.07	12.10	10.90	0.88	11 22	11.00	4.45	0.80	0.34	10.57	10.91	0.89	0./1	10.92	7.03	0.91
2.56	2 30	2 23	2 20	1.97	2 14	2 43	2 43	2 30	2 47	2 97	2 38	2 41	2 42	2 30	2.42	2 51	2 39	2 42	2.45
0.08	0.04	0.02	0.05	0.11	0.03	0.13	0.12	0.12	0.13	0.30	0.13	0.13	0.14	0.13	0.12	0.124	0.10	0.09	0.12
0.220	0.200	0.179	0.189	0.170	0.183	0.236	0.228	0.225	0.232	0.266	0.224	0.233	0.225	0.226	0.229	0.231	0.224	0.221	0.227
0.25	0.33	0.31	0.06	0.30	0.04														
100.10	99.01	99.16	100.22	99.89	99.10	100.87	99.71	100.99	100.07	100.54	99.27	99.40	98.72	99.62	99.35	99.29	99.71	100.19	100.35
0.044	0.057	0.055	0.060	0.051	0.052	0.049	0.050	0.050	0.050	0.055	0.068	0.068	0.052	0.054	0.049	0.055	0.049	0.043	0.046
85	94	94	87	83	91	78	92	76	99	52	473	73	71	71	72	69	71	74	71
40.7	42.2	38.8	40.2	39.4	40.1	38	38	38	38	37	37	40	38	39	38	38	38	40	39
126	234	289	330	412	320	201	243	231	237	168	310	286	253	242	150	177	234	149	204
9.6	8.8	7.3	7.0	6.4	6.1	10	10	10	10	17	11	10	10	10	9	11	10	9	9
67	74	83	85	92	88	65	69	71	65	42	73	67	71	76	68	71	65	67	63
30.3	27.3	25.2	24.9	25.0	45.2	21	28	50	30	33	29	29	29	30	29	50	29	29	29
416	363	330	343	271	330	302	200	402	204	155	371	376	203	300	377	300	376	386	387
124	112	92	91	91	87	117	124	114	117	155	134	115	122	115	119	120	112	128	112
	424-6-3, 21-23 50.26 12.80 1.94 4.55 10.16 6.66 10.62 2.56 0.028 0.220 0.25 100.10 0.044 85 40.7 126 67 30.3 86 416	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	Superind 21-23 Superind 138-139 Superind 71-72 Superind 23-26 Superind 135-136 Superind 72-73 Alvin 715-1 Alvin 716-3 Alvin 717-4 Alvin 723-2 Alvin 726-6 Alvin 730-3 50.26 50.00 50.30 51.39 50.22 50.36 51.30 49.67 50.74 50.46 52.03 50.34 12.80 13.52 13.93 14.16 15.52 14.31 13.52 13.88 13.48 13.61 12.25 13.39 1.94 1.42 1.25 1.29 0.98 1.14 1.76 1.71 1.77 1.79 2.80 1.68 4.55 2.65 2.79 2.83 3.34 3.08 3.24 3.04 2.41 3.19 3.48 2.84 10.16 9.56 8.57 8.26 6.70 8.04 10.89 11.01 11.37 10.70 12.86 10.63 10.62 11.58 12.11 12.35 13.07 12.10 10.89 1.04 11.23	424-6-3, 21-23 425-7-1, 138-139 425-7-2, 71-72 425-8-1, 23-26 425-9-3, 135-136 Alvin 72-73 Alvin 715-1 Alvin 716-3 Alvin 717-4 Alvin 723-2 Alvin 726-6 Alvin 730-3 Alvin 735-1 50.26 50.00 50.30 51.39 50.22 50.36 51.30 49.67 50.74 50.46 52.03 50.34 49.97 12.80 13.52 13.393 14.16 15.52 14.31 13.52 13.58 13.48 13.61 12.55 13.39 13.75 1.94 1.42 1.25 1.29 0.98 1.14 1.76 1.71 1.77 1.79 2.80 1.68 1.70 4.55 2.66 2.79 2.83 3.34 3.04 3.24 3.04 2.41 3.19 3.48 2.84 2.54 10.16 9.56 8.57 8.26 6.70 8.04 10.89 11.00 18.83 11.00 18.83 11.00 18.83 11.00 11.33 10.00 <t< td=""><td>$\begin{array}{c ccccccccccccccccccccccccccccccccccc$</td><td>424-6-3, 21-23 425-7-1, 138-139 425-7-2, 71-72 425-8-1, 23-26 425-9-3, 135-136 Alvin 72-73 Alvin 715-1 Alvin 716-3 Alvin 717-4 Alvin Alvin 717-4 Alvin Alvin 712-2 Alvin 722-6 Alvin 735-1 Alvin Leg 2 STA 31 STA 31 50.26 50.00 50.30 51.39 50.22 50.36 51.30 49.67 50.74 50.46 52.03 50.34 49.97 49.79 50.39 12.80 13.52 13.93 14.16 15.52 14.31 13.52 13.38 13.48 13.61 12.55 13.39 13.75 13.68 13.65 1.44 1.25 1.29 0.98 1.14 1.76 1.71 1.79 2.80 1.68 1.70 1.68 1.70 1.55 1.279 2.83 3.34 3.08 10.89 11.01 1.77 1.79 2.80 1.68 1.70 1.68 1.70 1.66 6.57 8.57 8.26 6.70 8.04 10.89 11.01</td><td>Sample (interval in cm) Alvin 21-23 Alzs-7-1, 138-139 425-7-1, 71-72 425-8-1, 22-26 425-9-3, 135-136 Alvin 71-72 Alvin 71-73 Alvin 71-72 Alvin 22-23 Alvin 716-3 Alvin 717-4 Alvin 72-73 Alvin 71-74 Alvin 72-74 Alvin 72-73 Alvin 71-74 Alvin 72-76 Alvin 730-3 Alvin 71-75 Alvin 71-75 <</td><td>Sample (interval in cm) Alvin Leg 2 STA 31 GID 8 STA 23 21-23 138-139 71-72 23-26 135-136 72-73 715-1 716-3 717-4 723-2 726-6 730-3 735-1 Dill 4 Drill 4 Drill 4 Drill 4 Drill 4 Drill 7 0.01 13.52 13.58 13.48 13.61 12.55 13.39 13.75 13.68 13.43 13.61 12.55 13.39 13.75 13.68 13.76 1.71 1.77 1.79 2.80 1.68 1.70 1.68 1.70</td><td>Sample (interval in cm) Sample (interval in cm) Alvin Alvin</td><td>Sample (interval in cm) Alvin Alvi Alvin Alvi Alvin Alvin Alvin Alvin Alvin Alvin Alvin Alvin Alvi</td></t<>	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	424-6-3, 21-23 425-7-1, 138-139 425-7-2, 71-72 425-8-1, 23-26 425-9-3, 135-136 Alvin 72-73 Alvin 715-1 Alvin 716-3 Alvin 717-4 Alvin Alvin 717-4 Alvin Alvin 712-2 Alvin 722-6 Alvin 735-1 Alvin Leg 2 STA 31 STA 31 50.26 50.00 50.30 51.39 50.22 50.36 51.30 49.67 50.74 50.46 52.03 50.34 49.97 49.79 50.39 12.80 13.52 13.93 14.16 15.52 14.31 13.52 13.38 13.48 13.61 12.55 13.39 13.75 13.68 13.65 1.44 1.25 1.29 0.98 1.14 1.76 1.71 1.79 2.80 1.68 1.70 1.68 1.70 1.55 1.279 2.83 3.34 3.08 10.89 11.01 1.77 1.79 2.80 1.68 1.70 1.68 1.70 1.66 6.57 8.57 8.26 6.70 8.04 10.89 11.01	Sample (interval in cm) Alvin 21-23 Alzs-7-1, 138-139 425-7-1, 71-72 425-8-1, 22-26 425-9-3, 135-136 Alvin 71-72 Alvin 71-73 Alvin 71-72 Alvin 22-23 Alvin 716-3 Alvin 717-4 Alvin 72-73 Alvin 71-74 Alvin 72-74 Alvin 72-73 Alvin 71-74 Alvin 72-76 Alvin 730-3 Alvin 71-75 Alvin 71-75 <	Sample (interval in cm) Alvin Leg 2 STA 31 GID 8 STA 23 21-23 138-139 71-72 23-26 135-136 72-73 715-1 716-3 717-4 723-2 726-6 730-3 735-1 Dill 4 Drill 4 Drill 4 Drill 4 Drill 4 Drill 7 0.01 13.52 13.58 13.48 13.61 12.55 13.39 13.75 13.68 13.43 13.61 12.55 13.39 13.75 13.68 13.76 1.71 1.77 1.79 2.80 1.68 1.70 1.68 1.70	Sample (interval in cm) Sample (interval in cm) Alvin Alvin	Sample (interval in cm) Alvin Alvi Alvin Alvi Alvin Alvin Alvin Alvin Alvin Alvin Alvin Alvin Alvi							

GEOCHEMISTRY AND MINERALOGY OF BASALTS

403



Figure 12. Elemental distribution of DSDP and Alvin samples on FeO*/MgO variation diagram. A. Data for major elements are in weight percent. B. Data for trace elements are in ppm. (See legend Fig. 15 for explanation of symbols.)



Figure 13. A-F-M diagram for DSDP and Alvin samples.



Figure 14. Relationship between level of fractionation (FeO*/MgO) for samples from DSDP and *Alvin* sites and distance (in statute miles) from the Galapagos Ridge. (Each point represents the average of samples from Table 1. See legend Fig. 15 for explanation of symbols.)

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Figure 15. MgO-FeO* relationship for DSDP and Alvin samples. (Line represents fractionation change resulting from removal of 35% An₇₀ and 8% Fo₉₀. See legend Fig. 15 for explanation of symbols.)



Figure 16. Al_2O_3 -CaO relationship for DSDP and *Alvin* samples. (Lines represent fractionation trends for An_{61} , An_{76} , clinopyroxene, and olivine [from Anderson et al., 1975]. See legend Fig. 15 for explanation of symbols.)

Table 5	5. Re	lative	chan	ges	ine	eler	nental	co	ncen-
trat	ions	from	core	to	rim	in	sample	es	from
Site	s 50	6, 507	, 508	, a	nd s	510			

		S	ite	
Substance	506	507	508	510
SiO ₂		D	D	D
Al2O3	_	(D)	(D)	
TiO ₂			-	_
FeO*		I	I	Ι
MgO		-	(I)	D
CaO		(D)	_	-
Na ₂ O		(D)	-	_
K ₂ Ō	Ι	I	I	Ι
MnO		-	(D)	_
FeO/Fe ₂ O ₃	D	D	D	D
Ag	Ι	Ι	I	D
Cu		_	(D)	(D)
Co	_	_	_	(D)
Cr	(I)	D		_
Li	(D)		-	—
Ni	-		(D)	(D)
Rb	(I)	I	I	I
Sr	_		—	_
v			(D)	
Zn	_		—	-
K/Rb	I	1	I	I
Number of pairs	7	3	4	9

Note: D = decrease; I = increase; () = moderate change; underscoring = large change; and — = no change.

Table 6. Uranium concentrations in fresh and altered basalts.

Sample (interval in cm)	Altered Rim (ppm)	Fresh Core (ppm)
506G-2-1, 3-5	0.268	0.192
506G-2-1, 42-45	0.103	0.213
506G-2-1, 107-110	0.271	0.488
506H-1,CC (18-20)	0.204	0.159
506I-1-1, 8-11	0.103	0.077
507B-1-1, 20-23	0.273	0.319
507B-2-1, 0-2	1.201	1.059
507C-3-1, 28-32	0.138	0.882
508B-3-1, 12-14	0.174	0.071
508B-3-1, 19-21	0.138	0.163
508C-1,CC (10-15)	0.104	0.142
510-8,CC (10-15)	0.577	0.284
510-9-1, 4-7	0.342	0.121
510-9-1, 98-100	0.044	0.058
510-9-2, 8-12	0.179	0.039
510-9-2, 56-59	0.089	0.064
510-9-2, 136-140	0.084	0.128
510-9-3, 22-25	0.071	0.293
510-9-3, 69-74	0.125	0.081
510-11-1, 0-3	0.111	0.220



Figure 17. Disseminated pyrite grains along innermost zone of altered rind, reflected light, ×2.5; Sample 506D-9-1, 53-56 cm.



Figure 18. Generalized diagram of alteration rind in Galapagos basalts. (Zones of vesicle filling are depicted, and the abundance of secondary pyrite is graphed below expanded section of core.)



Figure 19. Vesicle filling of hydrated Fe-oxide in outermost zone of alteration rind, ×2.5; Sample 506G-2-1, 90-93 cm.



Figure 20. Vesicle filling of K-poor smectite accompanied by blocky pyrite crystals, ×2.5; Sample 506-9,CC (17-20).



Figure 21. Eh-pH diagram after Garrels and Christ (1965), depicting path of evolving fluid which altered the samples to produce the observed secondary mineral suite.



Figure 22. Paragenetic sequence of secondary minerals in altered rinds.



Figure 23. FeO*/MgO-K₂O ternary plot of smectite compositions derived by electron microprobe analyses. (Arrows suggest trends in K enrichment. "Green clay" symbols represent composition of "mounds nontronites.")

Table 7. Chemical	fluxes	in	alteration	of	ferro-
basalts.					

	Elemental Changes			
Phase	Gain	Loss		
Pyrite	Fe, S			
Smectite	200003720204			
K-poor				
void filling	Fe, Si, O	_		
after glass	—	Ca, Mg, Al		
K-rich				
after K-poor	K, Mg			
after glass	K	Ca, Al		
Fe-oxides				
after smectite	Fe	Si, K, Mg, Al		