

21. THE DEGREE OF HETEROGENEITY IN BASALTS NEAR THE HAYES FRACTURE ZONE, MID-ATLANTIC RIDGE: HOLES 561, 562, AND 564¹

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ABSTRACT

Analyses of samples from Chemical Group II, Hole 561; Chemical Group I, Hole 562; and two pillows and a flow from Hole 564 show that the chemical groups and the individual structures are compositionally homogeneous for the data presented here except for the alkalis, Na₂O and Cs, and transition metals, FeO* and Co, and sometimes Sc and Cr. The scatter in the alkalis is attributed to alteration and the scatter in the transition metals is attributed to a short-range segregation model. Although the pillows and flow from Hole 564 are each compositionally homogeneous, their compositions are distinct from one another. These results cannot support the preliminary interpretation by shipboard scientists that the basalts from Hole 564 comprise a single chemical group.

INTRODUCTION

Geologists often assume that a single sample is petrographically and chemically representative of an entire rock body, especially if there are no visible textural heterogeneities. It is also commonly assumed that such a sample is homogeneous to within the limits of analytical uncertainty. These assumptions have been accepted by generations of geologists who could easily obtain large samples from the field. With the advent of lunar science and drill core studies where sample availability, sample size, and the knowledge of field relations are restricted, it is prudent to shed these assumptions.

Quantitative petrogenetic modeling is used in an effort to describe compositional differences among related basalts and their mantle sources. One factor that affects accuracy of model predictions is the degree of heterogeneity of a basalt flow. This study was undertaken to determine the degree of compositional heterogeneity in three proposed chemical groups of Leg 82 basalts.

METHODS

Samples were obtained as either one-fourth core segments of the working half of the core or as 1-inch paleomagnetic cores that were bored from the original core, investigated, and then returned to the working half of the core. Calcite veins and fractures were avoided during sampling. The external surfaces that were in contact with the drilling equipment were ground off with silicon carbide grinding paper. The samples were placed in an ultrasonic cleaner in distilled water to remove any loose particles and then dried at 90°C. Each sample was crushed in a Plattner steel mortar to pea-sized particles and then powdered and homogenized in an alumina canister with a Shatterbox (SPEX Industries, Inc., Metuchen, N J). The total masses of the samples range from 2.9–11.8 g for Hole 561, 6.2–25.0 g for Hole 562, and 11.0–26.1 g for Hole 564.

Instrumental neutron activation analysis (INAA) was used to analyze 100-mg splits of the powder that had been weighed and sealed into clean ultrapure silica tubing (T21 Suprasil, Heraeus-Amersil, Sayreville, New Jersey, outside diameter = 5 mm). Samples from Holes

562 and 564 were analyzed in the first experiment and samples from Hole 561 plus another split of the powdered sample from Hole 564 (564-6-4, 38–40 cm [Piece 2D]) were analyzed in a second experiment. In both experiments, samples and standards were irradiated for 20 hrs. with a thermal neutron flux of $4.0 \times 10^{13} \text{ cm}^{-2} \text{ s}^{-1}$ in the University of Missouri (Columbia) research reactor. Samples were each radioassayed twice, once between 6–12 days and again between 27–32 days after the irradiation. Gamma-ray spectral data were reduced with the TEABAGS programs of Lindstrom and Korotev (1982).

The following comparator standards were used. The concentration value used is listed in parentheses (same units as Table 1). USGS basalt BCR-1: FeO* (total Fe as FeO, 12.1), Na₂O (3.27), Sc (31.6), Co (36.0), Cs (0.94), La (24.6), Ce (53.7), Sm (6.80), Eu (1.92), Tb (1.10), Yb (3.37), Lu (0.526), Hf (5.2), and Th (6.0). Knippa basalt (in-house standard): Cr (485), Ni (360), and Ta (6.3). For Br, no standard was used. Concentration values were estimated from the 554.4 keV photopeak of ⁸²Br using the pertinent nuclear and detector efficiency parameters. Because of the uncertainties in these parameters, particularly the flux and neutron capture cross section, all Br concentrations may be systematically high or low, but the values are known relative to one another within each experiment.

A separate split of powdered sample from 564-6-4, 38–40 cm (Piece 2D) was analyzed in each of the two experiments. These results (Columns 1 and 2) and the difference between them (Column Δ) along with the estimate of analytical precision (Column σ) are listed in Table 1. The estimate of precision is one standard deviation (1σ) based on the counting statistics and other factors associated with a single analysis (Lindstrom and Korotev, 1982). Tests in this laboratory involving multiple analyses of the same sample have shown this to be a good approximation to the true sample standard deviations. The ratio s/σ , where s is the sample standard deviation, averages unity over all elements and ranges from 0.3–3.0 (R. Korotev, pers. comm., 1983). Column Δ in Table 1 reflects both typical analytical precision and sample heterogeneity for the samples analyzed here. For only FeO*, Cr, and Hf, does Δ exceed σ by more than a factor of 2. The estimate of relative analytical precision at these concentration levels for the elements listed in Table 1 ($100[\sigma/\bar{x}]$) is listed in the last column and is applicable to the data listed in all other tables.

The discrepancies found in FeO*, Cr, and Hf concentrations between two splits of the same powder could be explained as (1) an underestimate of analytical precision for those elements at those concentration levels or (2) by heterogeneity within the powdered portion of the sample. Sample 1 listed in Table 1 was radioassayed twice in the same experiment. The differences between the concentrations for each element including FeO*, Cr, and Hf are less than or equal to σ , except for Co, Yb, and Hf, which are less than 2σ . This suggests that the discrepancies found in FeO*, Cr, and Hf concentrations can be attributed to small-scale heterogeneity in splits from the same sample powder ($100[\Delta/\bar{x}]$ = relative heterogeneity; 2.3% for FeO*, 5.5% for Cr, and 7.1% for Hf).

¹ Bougault, H., Cande, S. C., et al., *Init. Repts. DSDP*, 82: Washington (U.S. Govt. Printing Office).

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Table 1. Precision of replicate analyses of Sample 564-6-4, 38-40 cm (Piece 2D).

	1	2	\bar{x}	Δ	σ	A.U. (%)
FeO*	11.02	10.77	10.90	0.25	0.11	1.0
Na ₂ O	2.31	2.31	2.31	0	0.03	1.3
Sc	41.9	41.8	41.85	0.1	0.4	1.0
Cr	228	241	234.5	13	3	1.3
Co	44.8	44.4	44.6	0.4	0.4	0.9
Ni	97	134	106	18	26	25
Cs	0.34	0.31	0.325	0.03	0.05	15
La	3.85	3.91	3.88	0.06	0.06	1.5
Ce	11.3	10.8	11.05	0.5	0.3	2.7
Sm	3.47	3.42	3.445	0.05	0.06	1.7
Eu	1.21	1.21	1.21	0	0.03	2.5
Tb	0.94	0.98	0.96	0.04	0.04	4.2
Yb	3.72	3.69	3.705	0.03	0.08	2.2
Lu	0.579	0.58	0.58	0.001	0.015	2.6
Hf	2.78	2.59	2.685	0.19	0.09	3.4
Ta	0.37	0.41	0.39	0.04	0.04	10
Th	0.30	0.22	0.26	0.08	0.05	19

Note: 1, 2 = two separate splits of 564-6-4, 38-40 cm (Piece 2D); \bar{x} = mean; Δ = the difference in concentrations of 1 and 2; σ = one standard deviation uncertainty estimate of a single analysis based principally on counting statistics; A.U. (%) = % analytical uncertainty = (σ/\bar{x}) 100; and FeO* = total Fe as FeO. FeO* and Na₂O concentrations are weight percent (wt. %), all others are parts per million (ppm).

CHEMICAL GROUPS I AND II, HOLE 561

Only 6 m of basalts and basalt breccias from a 15-m cored section of the basement at Site 561 were recovered. Three lithologic units from the basement-sediment interface to the bottom of the core were identified (aphyric basalt, basalt breccia, and aphyric pillow basalt). On the basis of shipboard XRF (X-ray fluorescence) analyses, two compositionally distinct chemical groups were identified; Chemical Group I is LREE (light rare earth element) enriched and Chemical Group II is LREE depleted relative to chondrites. Chemical Group I correlates with Lithologic Unit 1 and Chemical Group II correlates with Lithologic Units 2 and 3. Subsequent analyses of samples from this site confirm the shipboard results. Analyses for 1 sample from Chemical Group I (a split of powder from a shipboard sample) and 15 samples from Chemical Group II are listed in Table 2.

The LREE-enriched nature of basalts from Chemical Group I relative to a chondritic REE (rare earth element) distribution and the LREE-depleted nature of basalts from Chemical Group II are illustrated in Figure 1 (chondrite values from Haskin et al., 1968). Mixed occurrence of both LREE-enriched and LREE-depleted basalts at DSDP sites is uncommon. Site 561 is the second hole drilled during Leg 82 where both types of basalts were recovered. This mixed occurrence was found before at Holes 413 (Leg 49) and 504B (Legs 69-70). The significance of finding both enriched and depleted basalts at the same site is discussed by Bougault et al., Drake et al., Weaver et al., Hertogen et al., Jenner et al., Rideout and Schilling, Dupré et al., all this volume.

The basalts identified on the basis of similar composition to Chemical Group II are fine-grained vesicular aphyric pillow basalts or basalt breccias. The vesicles (2 mm in size), some of which are clay filled, are dispersed

throughout the basalts and are impractical if not impossible to avoid in a sample. Both Lithologic Units 2 and 3 contain fractures and calcite veins. Minor alteration, which manifests itself as brown coloration as opposed to the gray color of the fresh portions of the rocks, occurs along these fractures. This type of alteration appears to be related to the ease of access of seawater along cracks, joints, and generally more permeable areas. Lithologic Unit 2 has undergone brecciation of the basalt, sedimentation, and consolidation of that sediment. Only fresh portions of the basalt were collected as samples.

In addition to the analyses of samples from Hole 561, Table 2 lists the mean (\bar{x}) and sample standard deviation (σ) for Chemical Group II, and one sigma (σ) uncertainty estimate of a single analysis. Specimens from Samples 561-2-3, 52-54 cm (Piece 4A) and 561-3-2, 56-60 cm (Piece 3E) are not included in the mean or standard deviation because they contain higher Br concentration (by a factor of 3) than the average sample from Hole 561. Presumably increased Br concentration corresponds to increased seawater-rock interactions. For only FeO*, Co, and Cs, does σ exceed σ by more than a factor of 2.

Hart (1976) lists the average MORB (mid-ocean ridge basalts) Cs concentration as 0.013 ppm. This low abundance element provides a sensitive indicator for alteration in the abyssal tholeiites. Very often Cs concentrations are high in samples that show no other chemical effects of alteration processes (Hart, 1969). Clays, which fill the vesicles of this basalt, display marked cation exchange properties. Usually Ca²⁺ and Na⁺ are the exchangeable cations, but K⁺, Cs⁺, Sr²⁺, and Mg²⁺ are exchangeable to varying degrees (Deer et al., 1966; Hart, 1969). The range in Cs concentrations in Chemical Group II of Hole 561 (0.06-0.33 ppm) yields a higher sample standard deviation than analytical uncertainty and can be attributed to addition of Cs during alteration.

Br and Cs concentrations are not well correlated in these samples. Cs concentrations probably vary directly with the amount of clay present in the sample, and Br concentrations are probably higher in samples that are closer to cracks and joints that seawater can permeate more easily. A plausible explanation for the lack of correlation between Br and Cs is that clay-filled vesicles are found throughout the basalts at this site, rather than just near cracks and fractures.

Two samples each were cut from two different pieces of basalt from Sections 561-2-1 and 561-2-2 (Samples 561-2-1, 71-73 cm [Piece 4D]; 561-2-1, 78-80 cm [Piece 4D]; 561-2-2, 18-21 cm [Piece 1D]; and 561-2-2, 25-28 cm [Piece 1D]). The specimens from 561-2-2 (Piece 1D) have essentially identical concentrations for all elements listed in Table 2 to within 1 σ analytical uncertainty. Such is not the case for the specimens from 561-2-1 (Piece 4D). Co, Th, and FeO* concentrations are outside 2 σ analytical uncertainty of each other, but all other element concentrations are identical within 1 σ analytical uncertainty. These differences found in samples 5 cm apart on a single hand-specimen are approximately the same order of magnitude as small-scale sample heterogeneity analo-

Table 2. Elemental abundances of basalts from Chemical Groups I and II, Hole 561.

Core-Section Interval (in cm) Piece	1-1 28-31 1C	1-1 119-122 9A	1-2 3-6 1A	1-2 36-38 3	2-1 6-8 1B	2-1 71-73 4D	2-1 78-80 4D	2-1 86-88 4E	2-2 18-21 1D	2-2 25-28 1D	2-2 61-63 2A	2-2 80-82 3	2-3 28-30 2	2-3 ^a 52-54 4A	3-1 140-142 9J	3-2 ^a 56-60 3E	σ	\bar{x}	s
FeO*	9.02	10.15	9.90	11.21	10.38	11.06	10.00	10.72	10.57	10.45	10.12	10.65	10.60	8.91	10.40	9.01	0.11	10.48	0.39
Na ₂ O	2.37	2.40	2.34	2.45	2.46	2.39	2.42	2.39	2.48	2.48	2.43	2.34	2.52	2.55	2.43	2.34	0.03	2.42	0.05
Sc	35.6	42.0	41.8	41.7	42.1	40.7	40.9	41.3	42.4	42.0	41.7	41.2	42.7	46.0	41.8	43.4	0.4	41.7	0.6
Cr	399	231	226	228	235	222	228	228	226	223	230	226	229	240	224	232	3	227	3
Co	44.9	51.0	52.0	54.2	49.1	44.8	48.0	42.8	49.2	48.7	48.6	51.4	46.5	56.1	49.4	48.3	0.5	48.9	3
Ni	165	180	160	130	180	130	140	110	110	130	160	150	120	130	120	160	25	140	24
Br ^b	0.21	0.26	0.33	0.37	0.27		0.09			0.15	0.16	0.19	0.36	0.69	0.15	0.65	0.12	0.23	0.10
Cs	0.08	0.09	0.15	0.20	0.10	0.18	0.12	0.35	0.08	0.10	0.24	0.33	0.17	0.06	0.10	0.17	0.04	0.17	0.09
La	12.5	2.61	2.65	2.65	2.65	2.49	2.59	2.54	2.64	2.62	2.60	2.60	2.71	3.13	2.58	2.69	0.05	2.61	0.06
Ce	26.9	8.2	8.3	8.1	8.5	7.8	8.4	8.1	8.3	8.3	8.5	8.4	8.7	10.0	8.1	8.6	0.3	8.3	0.2
Sm	3.71	3.18	3.24	3.16	3.20	3.04	3.08	3.05	3.22	3.20	3.14	3.10	3.25	3.73	3.15	3.22	0.06	3.15	0.07
Eu	1.21	1.10	1.10	1.13	1.12	1.09	1.06	1.10	1.14	1.16	1.15	1.11	1.14	1.33	1.14	1.16	0.03	1.12	0.03
Tb	0.78	0.91	0.91	0.89	0.93	0.87	0.84	0.86	0.88	0.91	0.85	0.86	0.91	1.00	0.83	0.89	0.03	0.88	0.03
Yb	2.54	3.52	3.65	3.52	3.50	3.38	3.46	3.45	3.79	3.73	3.70	3.64	3.73	4.41	3.72	3.78	0.07	3.60	0.13
Lu	0.425	0.589	0.576	0.561	0.572	0.548	0.566	0.557	0.572	0.570	0.573	0.561	0.595	0.696	0.576	0.575	0.014	0.570	0.013
Hf	2.47	2.30	2.24	2.30	2.23	2.25	2.18	2.22	2.45	2.41	2.36	2.38	2.43	2.58	2.36	2.42	0.08	2.32	0.09
Ta	1.43	0.20	0.21	0.24	0.18	0.16	0.18	0.09	0.22	0.20	0.21	0.17	0.20	0.20	0.10	0.17	0.03	0.18	0.04
Th	1.58	0.08	0.15	0.25	0.17	0.21	0.11	0.19	0.11	0.16	0.16	0.13	0.14	0.12	0.17	0.15	0.04	0.16	0.04
Chemical group	I	II	II	II	II	II	II	II	II	II	II	II	II	II	II	II	II	II	II

Note: Instrumental neutron activation analysis (INAA) was the method of analysis. σ = one standard deviation uncertainty estimate of a single analysis based principally on counting statistics, \bar{x} = mean, and s = sample standard deviation. FeO* = total Fe as FeO. FeO* and Na₂O concentrations expressed in wt.%, all others expressed in ppm.

^a These samples contain >0.6 ppm Br, which indicates interaction with seawater. They were not used to calculate the mean.

^b This is an estimated value, no standard was used.

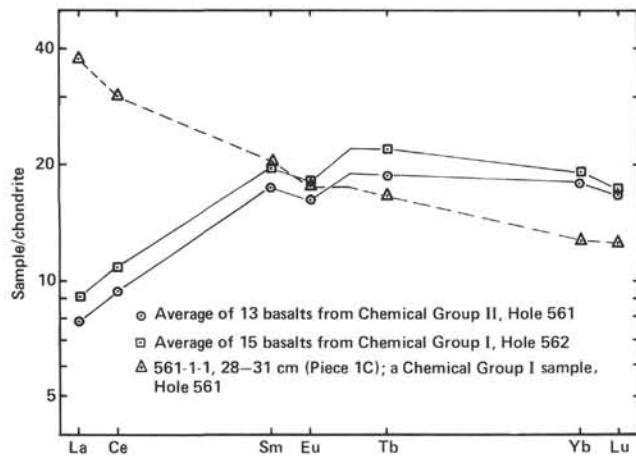


Figure 1. Rare earth element abundance patterns normalized to chondrites for basalts from Holes 561 and 562.

gous to those found in an Icelandic tholeiitic basalt by Lindstrom and Haskin (1981). Similarly, the discrepancies between analytical uncertainty and sample standard deviation for FeO^* and Co in the 15 basalts from Chemical Group II are on the same order of magnitude as small-scale heterogeneity between separate hand-specimens of this mass range (2.9–11.8 g) ($100 [s/\bar{x}] =$ relative heterogeneity; 3.8% for FeO^* and 6.1% for Co).

The composition of basalts from Chemical Group II is homogeneous for all elements listed in Table 2 to within 2σ analytical uncertainty except for FeO^* , Co, and Cs. Any quantitative petrogenetic model used to describe the relationship of basalts from Chemical Group II to other basalts or its mantle source is limited by the analytical uncertainty for those elements found to be homogeneous and by the relative heterogeneity of FeO^* , Co, and Cs.

CHEMICAL GROUP I, HOLE 562

Basalts from Hole 562 are sparsely to moderately plagioclase phyric. Most were extruded as pillows up to 1.5 m thick, but two thicker flows (3.7 and 5.1 m) occur. These are minimum thicknesses because recovery was only 62 and 77% for Cores 562-4 and 562-5, where these occur. The basalts are fresh to moderately altered with the alteration occurring primarily adjacent to fractures, veins, or glassy margins. Although no lithologic changes are apparent, two distinct chemical groups were proposed on the basis of shipboard XRF analyses. Chemical Group I is higher in TiO_2 , Fe_2O_3 (total iron as Fe_2O_3), P_2O_5 , V, Y, and Zr are lower in Al_2O_3 and CaO, relative to Chemical Group II.

Analyses of 16 basalts from Chemical Group I are tabulated in Table 3. The LREE-depleted nature relative to chondrites of these basalts is illustrated in Figure 1. Samples collected from Sections 562-4-1 through 562-4-3 are part of the 3.7-m thick flow and those from Sections 562-5-2 through 562-5-5 are part of the 5.1-m thick flow. Sample 562-4-3, 86–88 cm (Piece 2H) (collected 5 cm above the basal chilled glass rim) was not included in the mean or standard deviation because its Cs concen-

tration (0.85 ppm) is higher—by at least a factor of 3—than any other analyzed sample from this group, which indicates a greater uptake of Cs from seawater (Bougault et al., 1979). The mean and standard deviation for each thick flow were calculated, but they are not tabulated here because they are essentially identical (to within analytical uncertainty) to the mean and standard deviation of all 15 samples. For only FeO^* , Na_2O , Sc, and Co, does s exceed σ by more than a factor of 2. The scatter in the Na_2O data could be attributed to the increase of alkali metals with increased alteration (Bougault et al., 1979). The scatter in FeO^* , Sc, and Co is on the same order of magnitude as small-scale heterogeneity from one hand-specimen to the next for this mass range (6.2–25.0 g) ($100 [s/\bar{x}] =$ relative heterogeneity; 2.8% for FeO^* , 3.0% for Sc, and 2.1% for Co).

The composition of basalts from Chemical Group I is homogeneous for all elements listed in Table 3 to within 2σ analytical uncertainty except for FeO^* , Na_2O , Sc, and Co. Comparing those elements (FeO^* and Co) that are heterogeneous beyond analytical uncertainty in both Chemical Group II (Hole 561) and Chemical Group I (Hole 562), the basalts from Hole 561 are slightly more heterogeneous in those elements than the basalts from Hole 562 (3.8% relative heterogeneity as opposed to 2.8% for FeO^* and 6.1% relative heterogeneity as opposed to 2.1% for Co).

HOLE 564

At Site 564, 35 m of basalts were recovered from an 81-m cored section of the basement. Five lithologic units from the basement-sediment interface to the bottom of the core were proposed aboard ship (Unit 3, aphyric pillow basalts; Unit 4, a 4-m thick (minimum thickness) aphyric basalt flow; Unit 5, aphyric pillow basalts; Unit 6, a 2.5-m thick olivine microphyric basalt; and Unit 7, aphyric pillow basalts).

Even though a chemical gradient was apparent in the XRF shipboard analyses as a function of depth (Fig. 2), the basalts from Hole 564 were defined as a single chemical group and much of the chemical variation was attributed to analytical precision. It was noted, however, that this apparent chemical gradient with depth should be investigated onshore.

Analyses for 19 basalts from Hole 564 are listed in Table 4. Samples from 564-2-1 through 564-5-2 correspond to Lithologic Unit 3. Four samples were collected from a single pillow (A) within this lithologic unit (samples from 564-2-1 through 564-2-2). Six samples from 564-6-3 through 564-6-5 were collected from Lithologic Unit 4 (Flow B), a 4-m thick flow. Samples from Sections 564-8-1 through 564-8-2 correspond to Lithologic Unit 5. Four samples from 564-8-1 were collected from a single pillow (C) in this pillow sequence. Sample 564-9-2, 142–144 cm (Piece 9C) is the only sample from Lithologic Unit 7. An increase in the concentrations of REE, Ta, and Th and a decrease in Cr are readily apparent as Table 4 is read from left to right (top to bottom of the core). This same type of trend of increasing incompatible trace element concentrations and decreasing Cr con-

Table 3. Elemental abundances of basalts from Chemical Group I, Hole 562.

Core-Section Interval (in cm) Piece	3-1 46-48 1D	4-1 14-16 1B	4-1 58-60 3A	4-1 78-80 3B	4-2 22-25 1A	4-3 27-29 2B	4-3 64-67 2F	4-3 ^a 86-88 2H	4-4 117-119 8B	4-5 26-28 2A	5-2 89-91 4B	5-3 9-11 1A	5-3 58-60 1E	5-4 106-108 2A	5-5 69-71 3C	5-5 95-97 4A	σ	\bar{x}	s
FeO*	10.10	10.89	10.54	10.19	10.22	10.25	10.69	10.88	9.70	10.02	10.60	10.34	10.22	10.05	10.28	10.33	0.11	10.29	0.29
Na ₂ O	2.51	2.71	2.52	2.62	2.51	2.48	2.54	2.69	2.34	2.50	2.47	2.56	2.47	2.64	2.50	2.52	0.03	2.53	0.08
Sc	40.8	42.0	41.6	42.3	39.8	39.1	40.2	42.1	37.7	40.1	40.3	40.5	39.2	40.1	40.2	39.2	0.4	40.2	1.2
Cr	235	240	239	245	234	231	237	239	226	241	243	240	234	238	238	237	3	237	4.8
Co	42.1	42.8	42.1	43.5	41.5	41.6	41.6	38.8	39.7	42.2	42.4	42.7	41.0	41.8	42.1	41.3	0.4	41.9	0.9
Ni	120	30	100	110	120	150	110	100	110	100	100	110	100	70	70	90	27	100	27
Br ^b			0.08										0.14						
Cs	0.05	0.27	0.03	0.04	0.03	0.02	0.30	0.85	0.01	0.06	0.04	0.05	0.04	0.07	0.01	0.20	0.05	0.08	0.10
La	2.70	3.03	3.07	2.94	2.90	2.85	2.91	3.08	2.94	3.06	3.14	3.17	2.99	3.12	3.10	3.01	0.06	3.00	0.12
Ce	9.0	9.8	9.4	9.6	9.0	9.0	9.4	9.6	9.2	9.8	9.9	10.0	9.4	9.8	9.6	9.0	0.3	9.5	0.4
Sm	3.49	3.69	3.68	3.59	3.51	3.46	3.45	3.73	3.43	3.68	3.64	3.71	3.56	3.65	3.66	3.57	0.06	3.58	0.10
Eu	1.22	1.29	1.29	1.27	1.22	1.20	1.26	1.30	1.19	1.24	1.27	1.25	1.22	1.23	1.22	1.19	0.03	1.24	0.03
Tb	1.02	1.06	1.07	1.06	1.03	1.02	1.05	1.12	1.00	1.04	1.06	1.05	1.01	1.03	1.04	1.04	0.06	1.04	0.02
Yb	3.72	3.86	3.88	3.88	3.64	3.62	3.69	3.91	3.61	3.88	3.80	3.93	3.74	3.91	3.97	3.79	0.11	3.79	0.12
Lu	0.570	0.59	0.598	0.58	0.566	0.542	0.55	0.60	0.56	0.59	0.59	0.60	0.59	0.59	0.61	0.58	0.02	0.582	0.019
Hf	2.73	2.74	2.75	2.73	2.54	2.57	2.63	2.81	2.56	2.68	2.74	2.69	2.60	2.66	2.66	2.57	0.12	2.65	0.08
Ta	0.16	0.18	0.20	0.19	0.19	0.21	0.19	0.18	0.19	0.19	0.23	0.21	0.22	0.22	0.19	0.22	0.03	0.20	0.02
Th	0.12	0.29	0.05	0.10	0.20	0.03	0.09	0.08	0.14	0.10	0.21	0.21	0.10	0.17	0.07	0.10	0.04	0.13	0.07

Note: Instrumental neutron activation analysis (INAA) was the method of analysis. σ = one standard deviation uncertainty estimate of a single analysis based principally on counting statistics, \bar{x} = mean, and s = sample standard deviation. FeO* = total Fe as FeO. FeO* and Na₂O concentrations expressed in wt.%, all others expressed in ppm.

^a This sample contains at least three times as much Cs than all the other samples, which indicates alteration. It was not used to calculate the mean.

^b This is an estimated value, no standard was used.

Table 4. Elemental abundances of basalts from Hole 564.

Core-Section Interval (in cm) Piece	Pillow A				Flow B								Pillow C				σ			
	2-1 145-150 10C	2-2 1-4 1	2-2 15-22 2A	2-2 65-67 4B	3-2 127-129 7A	4-2 49-51 3D	5-2 26-28 2D	6-3 141-143 10	6-4 15-17 2A	6-4 38-40 2D	6-4 139-142 2K	6-5 22-24 1E	6-5 58-61 2C	8-1 10-14 2A	8-1 25-27 2C	8-1 44-47 2E		8-1 76-79 3	8-2 22-25 2	9-2 142-144 9C
FeO*	10.73	10.73	10.67	10.82	10.46	10.66	10.26	10.98	10.33	10.41	10.75	10.44	10.77	11.30	10.88	11.46	11.74	11.14	10.84	0.11
Na ₂ O	2.33	2.38	2.36	2.42	2.30	2.30	2.31	2.34	2.36	2.32	2.41	2.31	2.34	2.51	2.40	2.48	2.54	2.42	2.38	0.03
Sc	42.4	42.8	42.1	42.2	42.0	41.6	42.0	42.6	41.6	41.8	42.6	42.2	41.5	43.0	42.7	43.2	44.6	42.6	42.5	0.4
Cr	259	267	262	245	255	248	247	244	240	235	242	239	235	220	239	240	243	239	238	3
Co	43.1	41.0	43.7	34.8	46.6	43.4	48.0	43.5	43.8	44.5	44.8	45.1	44.3	45.2	44.5	43.5	31.5	40.1	52.2	0.4
Ni	70	110	120	110	130	120	160	70	130	115	130	120	120	140	110	130	70	100	90	28
Br ^a	0.16		0.12	0.6										0.6						
Cs	0.14	0.36	0.30	0.12	0.46	0.35	0.37	0.27	0.31	0.31	0.05	0.08	0.44	0.16	0.43	0.37	0.08	0.37	0.33	0.06
La	3.38	3.45	3.34	3.51	3.49	3.48	3.75	3.89	3.93	3.89	3.84	3.95	4.00	4.42	4.11	4.26	4.49	4.19	4.24	0.06
Ce	10.1	10.0	10.1	10.5	10.6	10.5	10.8	11.2	11.1	11.1	11.1	11.0	11.2	11.5	11.9	12.1	12.5	11.7	11.7	0.3
Sm	3.35	3.39	3.31	3.33	3.33	3.30	3.41	3.47	3.46	3.45	3.44	3.49	3.45	3.58	3.54	3.65	3.82	3.59	3.47	0.05
Eu	1.15	1.20	1.18	1.19	1.19	1.19	1.20	1.22	1.20	1.21	1.21	1.21	1.20	1.27	1.25	1.29	1.32	1.23	1.22	0.03
Tb	0.93	0.90	0.94	0.93	0.90	0.97	0.97	0.99	0.95	0.96	0.98	0.99	0.99	1.06	1.03	1.03	1.05	0.99	1.00	0.06
Yb	3.58	3.63	3.59	3.58	3.64	3.60	3.72	3.72	3.64	3.67	3.63	3.60	3.57	3.79	3.75	3.76	3.93	3.71	3.62	0.09
Lu	0.57	0.58	0.57	0.57	0.56	0.56	0.58	0.58	0.58	0.58	0.575	0.579	0.575	0.593	0.578	0.603	0.640	0.581	0.567	0.018
Hf	2.45	2.69	2.48	2.46	2.58	2.56	2.73	2.66	2.67	2.65	2.84	2.78	2.73	2.83	2.81	2.87	2.91	2.80	2.67	0.11
Ta	0.22	0.28	0.28	0.37	0.33	0.32	0.34	0.37	0.37	0.38	0.36	0.32	0.33	0.37	0.39	0.36	0.38	0.35	0.35	0.03
Th	0.20	0.22	0.19	0.20	0.20	0.22	0.25	0.23	0.25	0.26	0.26	0.30	0.26	0.34	0.33	0.31	0.32	0.31	0.32	0.05
Zone	I	I	I	V	I	I	I	I	I	I	I	I	I	V	I	I	I	I	V	

Note: Instrumental neutron activation analysis (INAA) was the method of analysis. I = interior portion of pillow, V = variolitic portion of pillow or flow. σ = one standard deviation uncertainty estimate of a single analysis based principally on counting statistics. FeO* = total Fe as FeO. FeO* and Na₂O concentrations in wt.%, all others in ppm.

^a This is an estimated value, no standard was used.

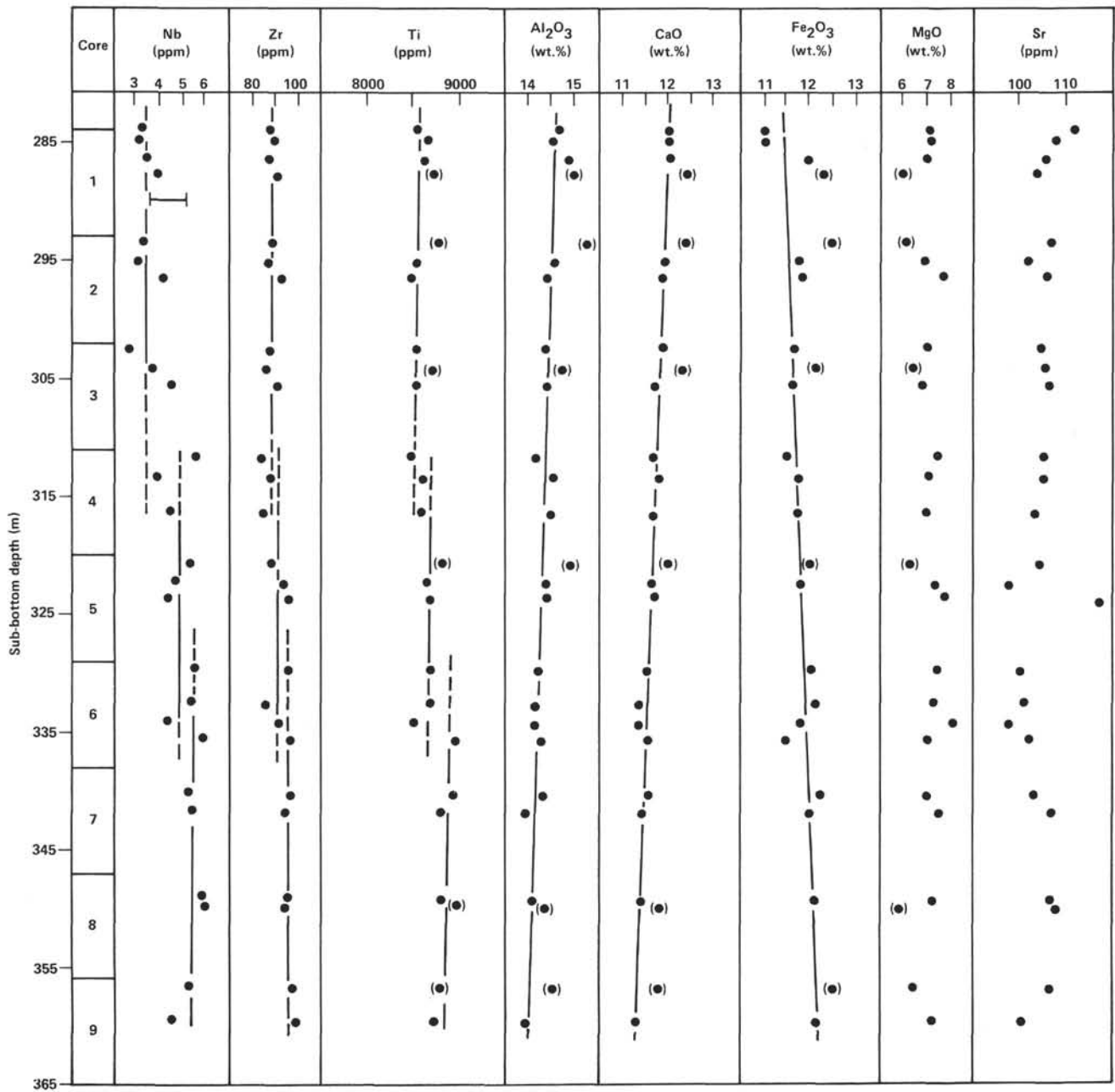


Figure 2. Downhole variations in chemical abundance of basalts from Hole 564, oxide concentrations are weight percent (wt. %), element concentrations are parts per million (ppm).

concentrations with depth in the hole was observed in a sequence of sheet flows and submarine pahoehoe units at Site 462 of Leg 61 by Batiza (1981).

The mean and sample standard deviation for three recognizable structures from Hole 564 (Pillow A, Flow B, and Pillow C) are listed in Table 5. Samples from variolitic zones from Pillows A and C that appear altered (brown coloration rather than the gray color of the unaltered basalt) are not included in the mean or standard deviation calculation. They will be discussed later in detail. Only the sample standard deviation for Co exceeds its analytical uncertainty by a factor of 2 in Pillow A. The standard deviations of FeO* and Cs exceed their an-

alytical uncertainties by a factor of 2 in Flow B. The standard deviations of FeO*, Na₂O, Sc, Co, Cs, La, and Sm exceed their analytical uncertainties by a factor of 2 in Pillow C.

Analyses of multiple samples from separate structures in this core gives us an idea of the intrastructure chemical variations. Pillow A is homogeneous to within 2 σ analytical uncertainty for all elements listed in Table 5 except Co. This can be attributed to small-scale heterogeneity within the pillow with a relative heterogeneity of 3.3%. Flow B is homogeneous to within 2 σ analytical uncertainty except for FeO* and Cs. Variations in Cs concentrations are again more easily explained by uptake of

Table 5. Average elemental abundances and standard deviation for Pillows A and C and Flow B for the basalts from Hole 564.

n	Pillow A		Flow B		Pillow C		σ
	\bar{x}	s	\bar{x}	s	\bar{x}	s	
FeO*	10.71	0.03	10.70	0.26	11.36	0.44	0.11
Na ₂ O	2.36	0.02	2.35	0.04	2.47	0.07	0.03
Sc	42.4	0.3	42.1	0.5	43.5	1.0	0.4
Cr	263	4	239	4	241	2	3
Co	42.6	1.4	44.3	0.6	40	7	0.4
Ni	100	26	114	22	103	31	28
Cs	0.27	0.11	0.24	0.15	0.29	0.19	0.06
La	3.39	0.06	3.92	0.06	4.29	0.19	0.06
Ce	10.07	0.06	11.12	0.08	12.2	0.3	0.3
Sm	3.35	0.04	3.46	0.018	3.67	0.14	0.05
Eu	1.18	0.03	1.208	0.008	1.27	0.02	0.03
Tb	0.92	0.02	0.977	0.018	1.037	0.012	0.06
Yb	3.60	0.03	3.64	0.05	3.81	0.10	0.09
Lu	0.573	0.006	0.578	0.002	0.591	0.013	0.018
Hf	2.54	0.13	2.72	0.08	2.86	0.05	0.11
Ta	0.26	0.03	0.36	0.02	0.377	0.015	0.03
Th	0.20	0.015	0.26	0.02	0.320	0.010	0.05

Note: n = number of samples analyzed. σ = one standard deviation uncertainty estimate of a single analysis based principally on counting statistics, \bar{x} = mean, and s = sample standard deviation. FeO* = total Fe as FeO. FeO* and Na₂O concentrations expressed in wt.%, all others expressed in ppm.

Cs from seawater, and small-scale intrastructure sample heterogeneity can account for the variability of FeO* (2.4% relative heterogeneity).

Pillow C is homogeneous to within 2σ analytical uncertainty except for FeO*, Na₂O, Sc, Co, Cs, La, and Sm. The section (564-8-1) that contains this pillow is described as moderately to highly altered in the core description of the site chapter for Site 564 (this volume). Even though only the freshest portions of the pillow were sampled, the general degree of alteration is greater than that found in Pillow A and Flow B. This increased alteration may account for much of the scatter in the data for all these elements, certainly it does for Na₂O and Cs. The scatter found in the data of FeO*, Sc, Co, La, and Sm may be analogous to the short-range segregation model in which the proportions of phenocrysts, ground-mass minerals, and residual liquid vary randomly among different samples of an Icelandic tholeiitic flow (Lindstrom and Haskin, 1981). There is some petrographic evidence for this process. These basalts are characterized by varying proportions of domains with contrasting grain size and texture. Coarse-grained domains range from 10–15% to 60–70% of the rock. For a more detailed description, see the site chapter, Site 564, this volume. The relative heterogeneities for these elements are FeO* = 3.9%, Sc = 2.3%, Co = 17.5%, La = 4.4%, and Sm = 3.8%.

The intrastructure chemical variations have been established for the two pillows and the 4-m thick flow. Pillow A and Flow B are quite homogeneous and Pillow C is less so.

Are these three structures, which are each in a different lithologic unit, chemically alike or different? A t-test can be used to answer this question (Till, 1974). The ratios of the means of the elements for each structure to the other two structures and the composite sample standard deviations illustrate the results of the t-test graphi-

cally (Fig. 3). The means of Pillow A and Flow B are statistically different for Cr, La, Ce, Sm, Tb, Ta, and Th. The means of Pillow A and Pillow C are statistically different for Cr, La, Ce, Eu, Tb, Hf, Ta, and Th. The variance (s^2) for FeO*, Sm, and Yb is statistically different for Pillows A and C, thus the t-test cannot be used. The positions of their ratio on Figure 3 are comparable to those ratios of means that are found to be statistically different. Although this observation is not a statistical test, by analogy FeO*, Sm, and Yb appear to be different in Pillows A and C. The means of Flow B and Pillow C are statistically different for FeO*, Na₂O, Sc, Eu, Tb, Yb, Hf, and Th. The t-test cannot be used to determine the differences of the means for elements La, Ce, or Sm for these two structures. Again the means of these elements appear to be different in Flow B and Pillow C. These results do not support the idea that all the basalts from Hole 564 comprise a single chemical group.

There are also other observations that do not support the single chemical group idea. The ratios of the means of Pillows A and C and their respective variolitic zones

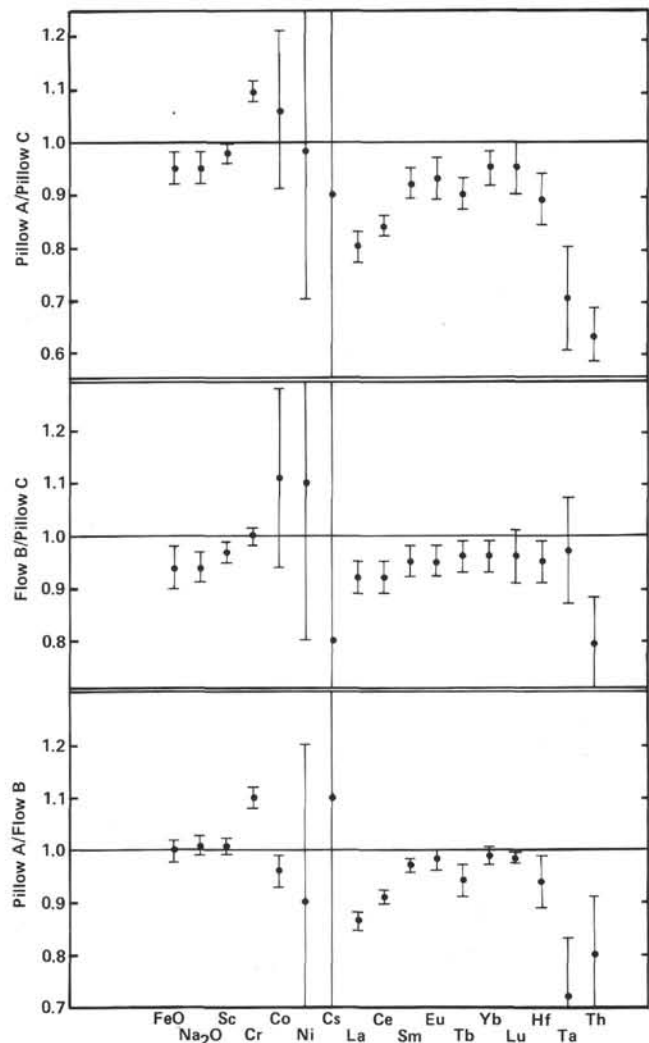


Figure 3. The ratios of average element abundances in three separate structures from Hole 564.

are shown in Figure 4. The variolitic zone of Pillow A appears to be depleted in Co and enriched in Ta compared to the mean. All other elements in these two portions of the pillow are identical to each other with the composite error of Pillow A sample standard deviation (s) and σ for the variolitic zone ($[s^2 + \sigma^2]^{1/2}$). The variolitic zone of Pillow C appears to be depleted only in Cr compared to the mean. Similar observations have been made. Frey et al. (1974) found that (compared to fresh basalt) altered glass samples are depleted in Cr, Ni, and V, but Co, Y, Zr, Hf, and Sc show little change. Staudigel et al. (1980) found that (relative to fresh glass), pagonite samples are depleted in Cr, Hf, and Sc. These variolitic zones that appear to be altered are compositionally closer to their respective pillow interiors than Pillow A, Flow B, and Pillow C are to each other. Also, the relative differences in compositions of basalts defined as distinct chemical groups at a single site (e.g., Site 562, Fig. 5) are less than the differences between these three structures at Site 564 (Fig. 6).

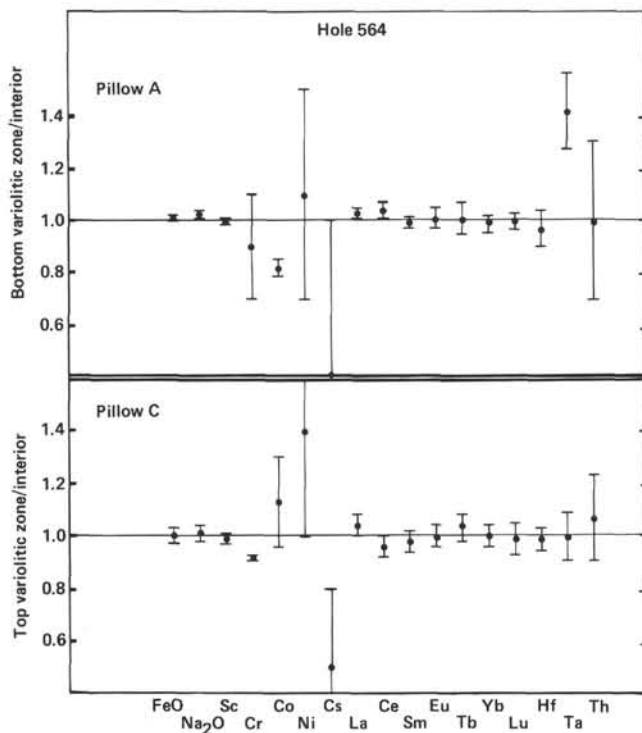


Figure 4. The ratios of element abundances in variolitic zones to the average interior abundances of two pillows.

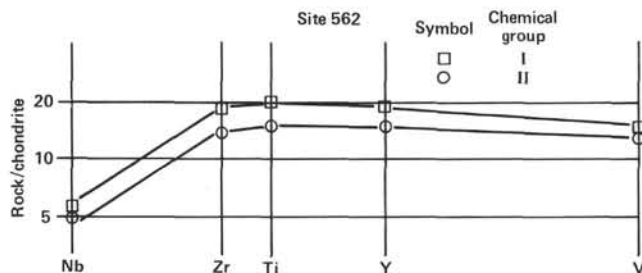


Figure 5. Extended Coryell-Masuda diagram for averages of basalts from Chemical Groups I and II.

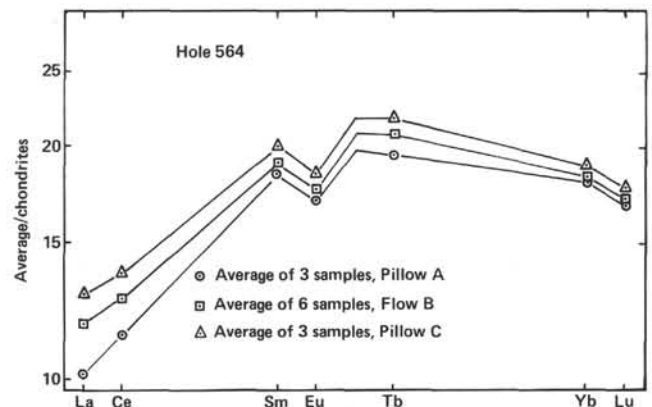


Figure 6. Rare earth element abundances normalized to chondrites for Hole 564 basalts.

SUMMARY

The composition of basalts from Chemical Group II (Hole 561) are homogeneous to within 2σ analytical uncertainty from those elements listed in this paper except for FeO^* , Co, and Cs. The basalts of Chemical Group I (Hole 562) are homogeneous except for FeO^* , Na_2O , Sc, and Co. Individual pillows and a 4-m thick flow from Hole 564 are homogeneous except for Co in Pillow A, FeO^* , and Cs in Flow B, and FeO^* , Na_2O , Sc, Co, Cs, La, and Sm in Pillow C.

The scatter in the alkalis is attributed to the addition of these elements during alteration. Often, no other chemical indication of alteration is detectable in otherwise fresh samples. Much of the scatter found in Pillow C may be attributed to alteration, because it is noted to be moderately to highly altered in the core description.

Transition elements Fe, Sc, and Co repeatedly have sample standard deviations that exceed 2σ analytical uncertainty. This scatter is on the same order of magnitude as the short-range segregation model of Lindstrom and Haskin (1981).

The basalts from Hole 564 were previously defined as a single chemical group even though downhole chemical gradients were found (Site 564 chapter, this vol.). Three individual homogeneous structures that are in separate lithologic units were found to be compositionally distinct to the same degree as the separate chemical groups found in Hole 562. These results do not support the idea that all the basalts from Hole 564 comprise a single chemical group. Obviously, a single sample in this core is only representative of its own structural unit (pillow or flow).

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