13. TRACE ELEMENTS: FRACTIONAL CRYSTALLIZATION AND PARTIAL MELTING PROCESS, HETEROGENEITY OF UPPER MANTLE MATERIAL

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INTRODUCTION

From a study of trace elements, including first transition series elements and low parition coefficient elements or so-called hygromagmatophyle elements (Treuil and Varet, 1973; Treuil and Joron, 1976), we will try to establish the three fundamental parameters (mantle material, partial melting, and crystallization) which influence the formation of basalts recovered during Leg 46. Data are presented in connection with shipboard study; a tentative interpretation is given taking into account our present knowledge of the behavior of trace elements during magmatic processes and comparing the results of FAMOUS, Leg 37 and Leg 45. We ask the reader to look at our Leg 45 report (Bougault, et al., 1978) to gain information about analytical procedures and geochemical methods of investigation.

DESCRIPTION OF LEG 46 RESULTS

Several chemical units were defined onboard (Shipboard Scientific Party, this volume). Downhole they correspond to three aphyric units (A1, A2, and A3), then two phyric units (B1 and B2) with a final aphyric unit (C). All samples (except 396B-19-1, 4-6 cm) were chosen for being as fresh as possible. The last aphyric sample (396B-32-1, 45-47 cm) is different from Unit C. As expected, the difference between aphyric and plagioclase phyric samples is clearly shown by Al_2O_3 and CaO; only slight differences (Table 1, average and sigma values) can be observed within aphyric units or within phyric units except for TiO_2, which is the best discriminant among major or minor elements because of its low partition coefficient.

Trace element concentrations expressed in ppm, including Ni, Cr, Zr, and Sr which were measured onboard, are reported in Table 2. Ti, Mn, and Fe expressed in ppm are included to have the full first transition series (except Sc), all elements being classified as a function of increasing atomic number. All the trace elements measured (especially low partition coefficient [LPC] hydromagmatophile elements such as Zr, Eu, Tb, Hf, Ta, and Th) confirm the classification and the definition of chemical units which were made onboard. Table 3 shows concentrations and sigma values of investigated elements for each unit. Since there is no change in the definition of chemical units, we refer the reader to the Site Report (this volume) for complete descriptions of each unit.

Co, Cu, and Zn concentrations are remarkably constant. This can now be considered a well-established fact for oceanic tholeiites. A general correlation between V and LPC elements including Ti can be observed confirming that V has a partition coefficient lower than one; but V cannot be really considered as a true LPC element because this correlation has already been proved to be not very good and among this data an inversion is observed between Unit A2 (Ti =9160 ±99; V=293±5) and A3 (Ti=9822±113; V=282±5). Sr varies between 126 to 145 ppm for Units Al, A2, A3, B1, B2, and is a little higher in Unit C (i.e., 156 ppm). Highest Sr values are not observed in plagioclase phyric units (B1=133 ppm, B2=135 ppm) as was the case in Hole 395A.

It can be observed that Unit A3 is homogeneous with respect to all analyzed elements except for K_2O (which is

TABLE 1
Major Element Average Values for Each Unit in Hole 396B

Unit	A1	A2	A3	B1	B2	C
No. of Samples	6	9	7	6	5	6
SiO_2	49.69 0.25	50.03 0.17	49.94 0.23	49.67 0.20	49.63 0.29	49.10 0.20
Al_2O_3	15.59 0.31	15.29 0.13	15.19 0.19	16.91 0.13	17.66 0.24	15.86 0.19
Fe_2O_3(t)	10.15 0.32	10.53 0.22	11.00 0.24	9.45 0.29	8.73 0.22	10.44 0.26
MnO	0.18 0.01	0.18 0.01	0.17 0.00	0.17 0.01	0.16 0.00	0.19 0.01
MgO	7.93 0.15	7.72 0.28	7.75 0.27	7.78 0.36	7.84 0.53	7.76 0.34
CaO	11.83 0.32	11.63 0.14	11.12 0.11	12.34 0.22	12.66 0.10	11.51 0.23
Na_2O	2.56 0.04	2.58 0.08	2.72 0.08	2.40 0.12	2.36 0.08	2.64 0.07
K_2O	0.24 0.05	0.25 0.04	0.23 0.08	0.22 0.01	0.20 0.02	0.27 0.07
TiO_2	1.41 0.03	1.53 0.02	1.64 0.02	1.23 0.05	1.06 0.07	1.51 0.05
P_1O_5	0.14 0.01	0.15 0.01	0.16 0.01	0.12 0.01	0.10 0.01	0.16 0.01
Total	99.72	99.89	99.92	100.27	100.40	99.44
L.O.I	-1.72	-2.40	-2.41	-2.09	-2.87	-0.88

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TABLE 2
Trace Element Concentrations (ppm) in Hole 396B

Sample	Ti	V	Cr	Mn	Fe		Co		NI		Cu	Zn	Sr	Zr		Eu	Tb	HI	Ta	Th
(Interval in cm)	XRF	XRF	XRF	XRF	XRF	XRF	AA	NA	XRF	NA	AA	AA	XRF	XRF	NA	NA	NA	NA	NA	NA
4-1,103-105(#9)	8600	238	275	1394	71400	41	45	46	146	146	66	80	126	97	104	1.25	0.75	2.50	0.176	0.125
5-1,86-88(#9)	8200	266	306	1394	70070	40	45	41	124	128	57	77	118	89	110	1.21	0.74	2.44	0.169	0.140
5-2,51-53(#6A)	8400	282	313	1316	71470	42	41	43	140	141	67	80	120	95	97	1.29	0.73	2.52	0.176	0.120
6-1,55-57(#7)	8600	250	278	1316	67060	39	41	45	138	142	67	80	146	90	110	1.26	0.73	2.52	0.176	0.105
7-1,53-55(#7)	8520	272	297	1471	73290	41	41	43	133	134	66	80	122	99	92	1.25	0.72	2.49	0.175	0.136
7-1,132-134(#11)	8520	288	319	1394	72940		41	44	133	143	66	80	124	96	106	1.20	0.72	2.38	0.169	0.120
8-1,62-64(#8)	9060	291	313	1471	74270	43	41	43	124	131	62	78	131	92	95	1.34	0.76	2.56	0.185	0.155
8-2,60-62(#6)	9300	303	282	1471	72030	43	41		130		67	80	141	109						
10-8,51-53(#9A)	9420	295	(364)	1549	76300	43	41	43	120	128	68	82	128	111	104	1.34	0.81	2.67	0.194	0.136
11-1,56-58(#6)	9240	295	279	1549	74970	41	41	43	120	128	63	84	126	103	120	1.42	0.78	2.56	0.185	0.114
11-2,5-7(#1)	9240	291	277	1394	74270	44	41	44	131	128	64	88	132	103	108	1.36	0.78	2.76	0.187	0.150
12-1,127-129(#8)	9060	295	281	1394	73430	45	45	44	126	137	64	77	136	99	105	1.28	0.75	2.70	0.182	0.148
13-1,45-47(#4)	9180	285	275	1394	74550	41	41	42	131	132	65	80	124	100	98	1.35	0.76	2.68	0.182	0.115
13-2,49-51(#5)	9060	297	278	1316	71820	46	41	44	138	138	61	76	130	99	112	1.25	0.74	2.60	0.179	0.140
13-2,89-91(#10)	9060	288	278	1316	72030	43	41	46	145	144	63	84	144	94	100	1.35	0.76	2.65	0.182	0.112
13-3,4-6(#1)	10020	287	255	1316	73990	40	45	48	156	165	63	88	146	126	121	1.48	0.89	3.04	0.207	0.14
14-2,17-19(#2)	9840	283	269	1316	75670	45	45	45	155	154	65	75	143	129	141	1.43	0.86	2.88	0.19	0.123
15-1,85-87(#1)	9900	272	260	1316	77060	46	41	45	150	147	63	84	146	119	132	1.43	0.87	2.98	0.192	0.156
15-2,129-131(#2)	9780	(235)	(237)	1316	78400	38	41	42	119	132	63	80	142	124	121	1.43	0.85	2.90	0.194	0.147
15-3,16-19(#2B)	9780	287	277	1316	77280	43	41	42	119	133	63	82	140	116	100	1.43	0.84	2.80	0.189	0.155
15-4,76-79(#4)	9780	283	268	1394	78050	43	41	43	116	138	63	80	142	117	118	1.52	0.85	3.10	0.20	0.160
15-5,70-73(#9)	9660	282	263	1394	78610	45	41	44	149	152	64	86	156	111	130	1.46	0.85	3.03	0.196	0.160
16-1,83-85(#10)	7200	238	301	1239	64470	39	37	41	129	138	65	74	127	78	89	1.12	.64	2.08	0.138	0.104
16-2,40-42(#4A)	7200	296	317	1316	66150	42	41	43	155	163	69	71	133	77	86	1.03	0.59	2.01	0.135	0.090
16-4,20-22(#2)	7980	271	316	1394	69860	42	41	42	118	122	69	77	130	83	98	1.20	0.70	2;29	0.157	0.094
16-5,96-98(#11)	7260	248	301		64330	39	41	42	133	138	66	81	135	81	90	1.09	0.63	2.15	0.139	0.082
17-1,132-134(#llB)	7260	245	315	1316	66640	44	41	43	144	149	69	71	142	79	92	1.10	0.61	2.14	0.136	0.12
18-1,117-119(#7D)	7260	244	307	1316	65520	40	37	40	119	125	63	71	131	81	90	1.10	0.62	2.16	0.137	0.11
19-1,4-6(#1)	7980	282	306	1471	73220	41	49	44	102	106	73	80	143	88	93	1.21	0.68	2.39	0.153	0.12
20-1,53-55(#4B)	6240	238	311	1239	61670	39	37	40	119	128	65	71	148	74	84	1.01	0.58	1.98	0.133	0.098
20-3,33-35(#4)	6600	217	350	1239	60830	39	45	41	139	148	70	65	141	66	78	0.97	0.53	1.85	0.118	0.106
20-5,16-18(#2)	6960	226	342	1239	63420	43	45	41	139	146	73	63	144	73	76	0.97	0.57	1.87	0.122	0.084
21-2,24-26(#2)	6060	212	342	1160	60130	41	37	41	157	166	71	70	124	68	56	0.98	0.53	1.70	0.116	0.091
22-1,93-95(#11)	5940	180	342	1239	59430	44	37	41	154	162	70	64	121	63	62	0.89	0.52	1.62	0.113	0.066
23-1,87-89(#12)	9480	284	305	1394	74064	39	41	40	140	139	65	78	163	106	123	1.40	0.79	2.86	0.322	0.33
24-1,94-96(#15)	9240	257	282	1394	73150	41	41	41	133	149	65	77	161	109	113	1.88	0.75	2.55	0.315	0.28
26-1,7-10(#1)	8940	289	272	1471	72310	42	37	42	139	144	61	78	157	115	136	1.30	0.76	2.55	0.307	0.218
30-1,60 Basaltic Sand	8940	275	298	1471	76020	39	41	40	128	138	(116)	75	156	(80)	133	1.24	0.76	2.54	0.259	0.200
30-1,60 Glass of Sand	9000			1471	71890		41		137		66	82	150	103						
32-1,45-47(#7)	8700	266	301	1394	70910	41	41	41	122	130	67	72	154	108	121	1.28	0.74	2.50	0.271	0.178
32-1,69-71(#10)	7320	230	322	1084	57610	39	41	38	155	164	61	64	162	85	95	0.92	0.62	2.07	0.226	0.180

TABLE 3
Trace Element Average Values (ppm) for Each Unit in Hole 396B

Unit		Ti	V	Cr	Mn	Fe		Co		Ni		Cu	Zn	Sr	Zr		Eu	Tb	Hf	Ta	Th
		XRF	XRF	XRF	XRF	XRF	XRF	AA	NA	XRF	NA	AR	AR	XRF	XRF	NA	NA	NA	NA	NA	NA
A1	x̄	8473	266	298	1380	70920	40.6	42.3	43.7	136	139	65	79.4	126	94	103	1.24	0.73	2.47	0.174	0.124
	s	153	19	18	58	2168	1.1	2.1	1.7	7.5	6.7	4	1.2	10	4	7.3	0.03	0.01	0.05	0.004	0.01
A2	x̄	9160	293	282	1428	73741	43	41	43.5	129	133	64	81	132	101	104	1.35	0.76	2.65	0.182	0.136
	s	89	5	12	87	1537	1.6	1.3	1.3	8	5.5	2.2	3.8	6	6	7	0.04	0.02	0.006	0.005	0.016
A3	x̄	9822	282	265	1338	77010	43	42	44	118	134	63	82	145	120	123	1.45	0.86	2.96	0.195	0.149
	s	113	5	7.7	38	1661	1	0.7	0.8	1.7	3.2	0.8	4.3	5.3	6.3	13	0.03	0.017	0.10	0.006	0.013
B1	x̄	7360	257	309	1316	66161	41	39	42	133	139	67	74	133	80	91	1.10	0.63	2.14	0.14	0.100
	s	305	22	7.5	54	2025	2	2	1.2	14	15	2.5	4	5	2.2	4	0.05	0.038	0.09	0.008	0.014
B2	x̄	6360	214	337	1223	61096	41	40	41	141	150	70	67	135	69	71	0.96	0.52	1.8	0.12	0.089
	s	417	21	15	34	1541	2	4	0.4	15	15	3	3.6	12	4.6	11.7	0.04	0.03	0.14	0.008	0.015
C	x̄	9050	276	291	1432	730566	40	40	41	133	140	65	77	156	108	125	1.30	0.76	2.6	0.295	0.22
	s	272	13	14	42	1806	1.3	1.6	0.8	7	7	2.3	3.3	4.7	4.4	9	0.06	0.02	0.14	0.03	0.04

significant because it is alternation-dependent) and Ni. Ni values for Samples 396B-15-2, 179-181 cm and 396B-15-3, 16-18 cm to 396B-15-4, 76-79 cm are lower (both XRF and NA data) than other samples of Unit A3. Olivine abundance within the unit is lower than 1 per cent, and no significant variation of phenocrysts is mentioned.

Unit C is not homogeneous in respect of Th, Ta, and Hf and shows the highest values for these elements.

DISCUSSION AND INTERPRETATION OF RESULTS

From the shipboard study, we received information on Ti and Zr concentrations. These elements plot on the same straight line passing through the origin as Leg 37 and 45 samples (Figure 1). It has been mentioned (Bougault et al., 1978) that aphyric samples have higher TiO_2 and Zr than

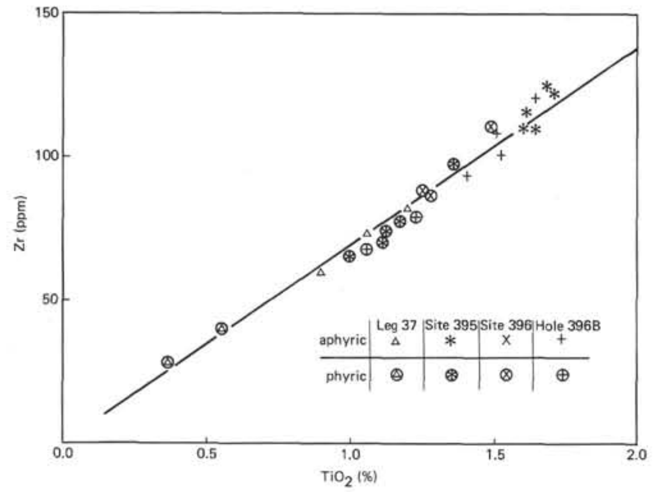

Figure 1. *Zirconium versus titanium (TiO_2), comparison of results from Legs 45 and 37. Note a shift along the line from Leg 37 to Leg 45 with samples for phyric samples on one hand and aphyric on the other.*

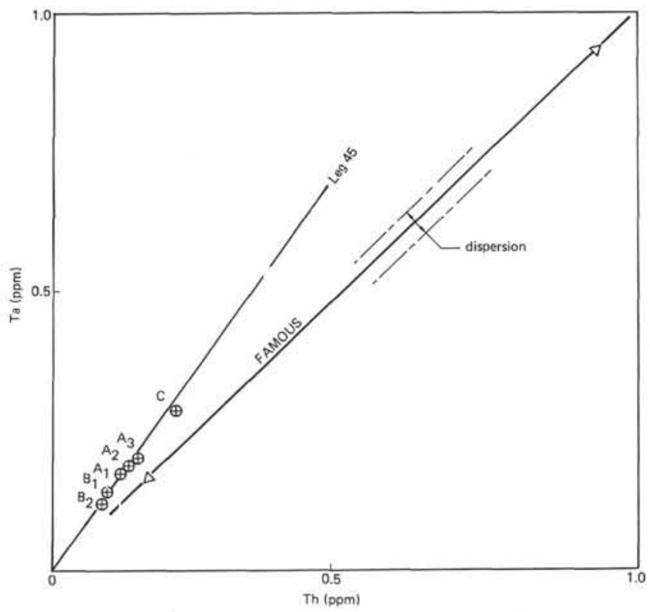

Figure 2. *Tantalum versus thorium, a low partition coefficient (LPC) hygromagmatophyle element as a function of a very low LPC hygromagmatophyle element, showing upper mantle heterogeneity (difference between Legs 45 and 46 on one hand and FAMOUS on the other). (Note that samples from Holes 396, 396A, 396, and 396B plot on the same line.)*

phyric samples. This can be attributed to a difference of partial melting range and a different initial mantle material.

Leg 46 samples plot in same ranges as Leg 45 samples both for aphyric and phyric samples. This suggests a similarity between Holes 396, 396B, and those at Site 395 (which are symmetric to Site 396 with respect to the Mid-Atlantic Ridge). This suggests that similar conclusions can be derived from Hole 396B (Leg 56) as they were from Holes 395 and 396 (Leg 45) with regards to the nature of the upper mantle material at 20°N compared with 36°N (FAMOUS).

Hygromagmatophyle elements with low partition coefficients Ta, Hf, Tb, Zr, and Ti have been plotted as a function of Th in Figures 2, 3, 4, 5 and 6. FAMOUS samples are also presented on these figures. Leg 46 samples plot on the same straight line passing through the origin as Leg 45 samples confirming the above-mentioned conclusion for Sites 395 and 396. It can be noted that Unit C does not plot on the same line; it is the only unit showing this feature among Leg 45 and 46 results. We do not know if this can be attributed to the possibility of partial melting of a different material at a same site on the ridge, or to another effect. We mention again that this unit shows the maximum of dispersion for LPC elements and that sand and gravels are present in this unit.

The following are the main conclusions of this study regarding Leg 45 LPC elements: (1) the ratio of one LPC element to another LPC element is the same for Sites 395 and 396 (symmetric with respect to the MAR), (2) these ratios differ between 20°N (Leg 45 and 46) and 36°N (FAMOUS), implying a different nature of the initial upper mantle material melted at these latitudes.

Log Cr versus log Ni is plotted in Figure 7, where Leg 37 and FAMOUS sample fields (aphyric and phyric) are mentioned, as well as Leg 45 data. Leg 46 units plot in a narrow range on the FAMOUS aphyric trend, with a similar slope, except one of the two subunits of A3.

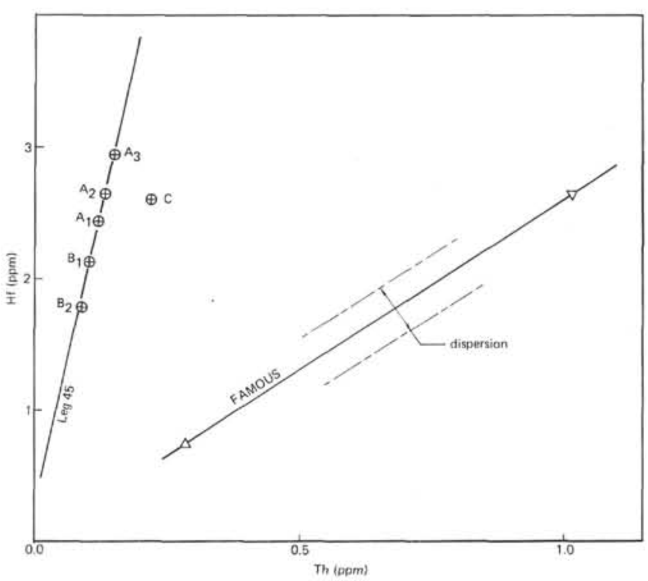

Figure 3. *Hafnium versus thorium, a LPC element as a function of a very low LPC element, showing upper mantle heterogeneity of variable partial melting. All units except Unit C plot on the same line as Leg 45 samples.*

All units can be classified in the same way: increasing LPC elements, and decreasing Ni and Cr. This suggests that these basalts were derived from melts produced by similar partial melting. It is conceivable that B1 derives from B2. It

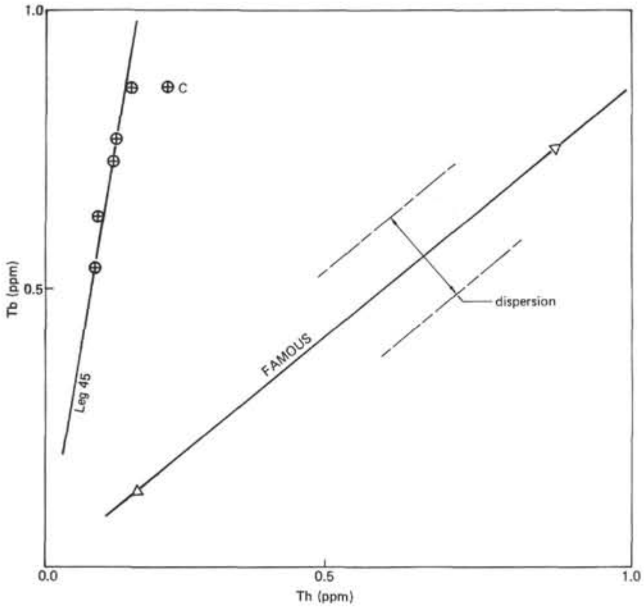

Figure 4. *Terbium versus thorium, same information as Figure 3.*

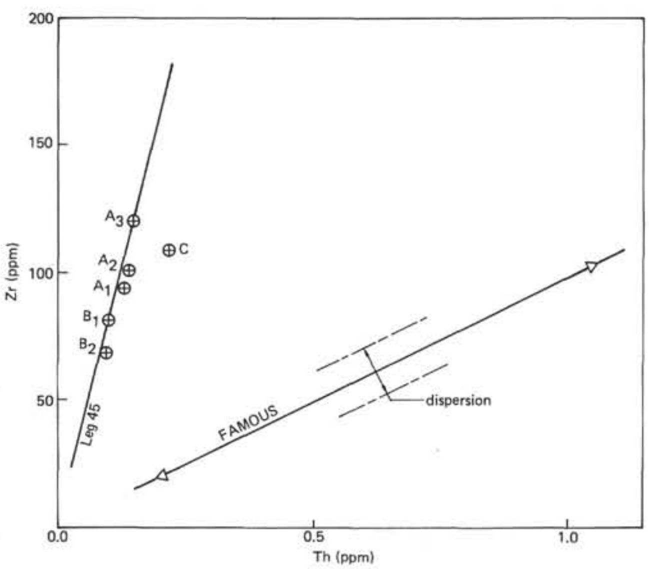

Figure 5. *Zirconium versus thorium, same information as Figure 3.*

is more difficult to make A1, A2, and A3 derive one from each other because of their stratigraphy (as the less evolved unit would be at the top).

CONCLUSION

Trace elements data allow classification of samples recovered during Leg 46, following the same units obtained from major elements by the shipboard study.

From high partition coefficient nd ttw partition coefficient elements, the following can be concluded: (1) none of the basaltic samples recovered can be considered as primary liquids, (2) all have undergone a substantial history of

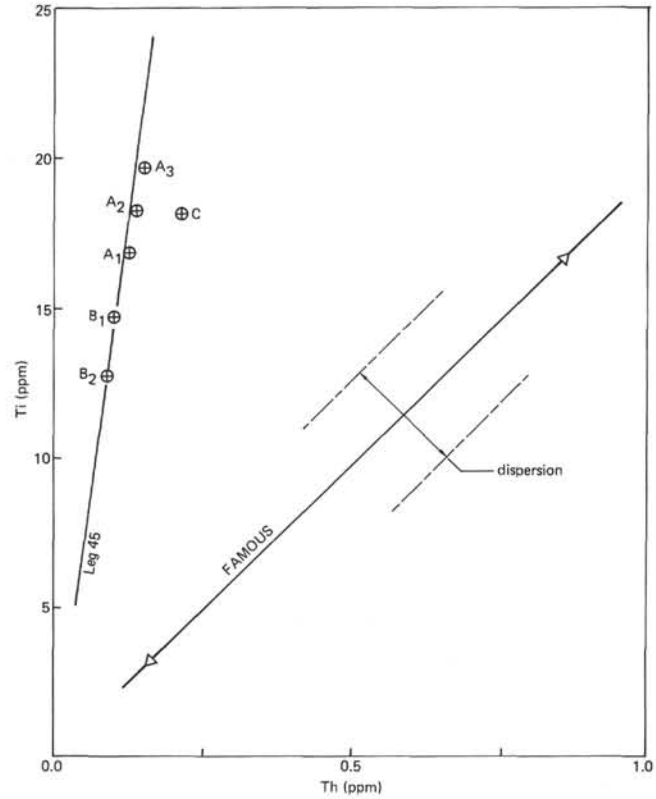

Figure 6. *Titanium versus thorium, same information as Figure 3.*

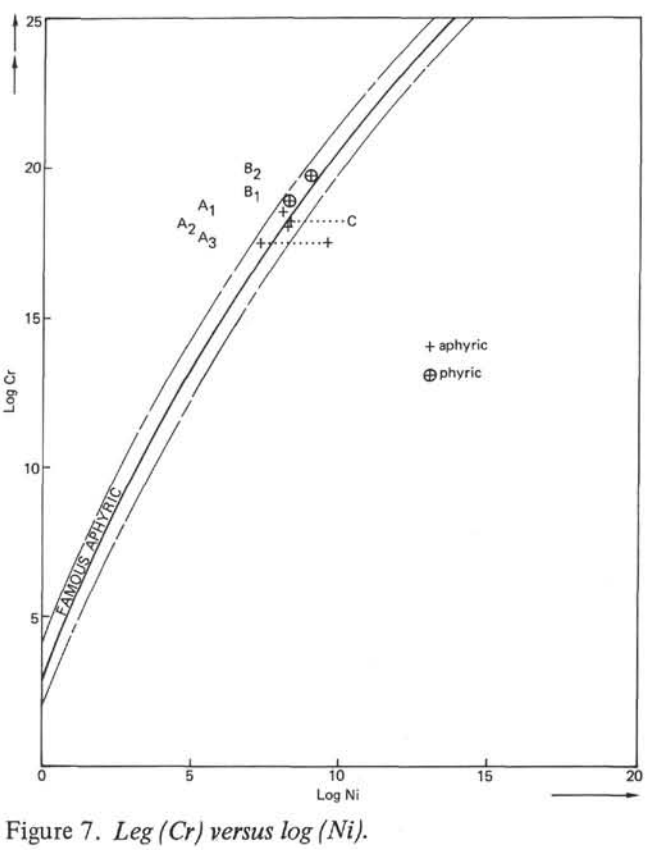

Figure 7. *Leg (Cr) versus log (Ni).*

crystallization, and (3) they can be derived from melts produced by similar partial melting.

Low partition coefficient hygromagmatophyle elements confirm Hole 396 data. Material found at Sites 395 and 396 (symmetric with respect to the MAR) are derived from similar initial mantle material. The initial mantle material at 20°N (Legs 45 and 46) is different from initial mantle material at 36°N (FAMOUS area).

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