19. CHEMICAL STRATIGRAPHY AND PETROLOGY OF THE VØRING PLATEAU THOLEIITIC LAVAS AND INTERLAYERED VOLCANICLASTIC SEDIMENTS AT ODP HOLE 642E¹

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ABSTRACT

During Ocean Drilling Program Leg 104 a 900-m-thick sequence of volcanic rocks was drilled at Hole 642E on the Vøring Plateau, Norwegian Sea. This sequence erupted in two series (upper and lower series) upon continental basement. The upper series corresponds to the seaward-dipping seismic reflectors and comprises a succession of about 122 flows of transitional oceanic tholeiite composition. They have been subdivided into several formations consisting of flows related to each other by crystal fractionation processes, magma mixing, or both. Major- and trace-element chemistry indicates affinities to Tertiary plateau lavas of northeast Greenland and to Holocene lavas from shallow transitional segments of the Mid-Atlantic Ridge, such as Reykjanes Ridge. The tholeiitic magmas have been derived from a slightly LREE-depleted mantle source. Two tholeiitic dikes that intruded the lower series derive from an extremely depleted mantle source. Interlayered volcaniclastic sediments are dominantly ferrobasaltic and more differentiated. They appear to come from a LREE-enriched mantle source, and may have been erupted in close vicinity of the Vøring Plateau during hydroclastic eruptions. The two tholeiitic dikes that intruded the lower series as well as some flows at the base of the upper series show evidence of assimilation of continental upper crustal material.

INTRODUCTION

The Vøring Plateau is located between 400 and 600 km offshore from Norway at 66° to 68°N in the Norwegian Sea (Fig. 1). It is an area of about 35,000 km² at shallow water depths ranging from 1000 to 1500 m. The Vøring Plateau Escarpment terminates a marginal high characterized by a series of seawarddipping seismic reflectors below a thin Cenozoic sedimentary cover. To the southwest, the Vøring Plateau is bounded by the Jan Mayen Fracture Zone.

DSDP Leg 38 previously drilled on top of the marginal high in the northern part of the Vøring Plateau (Sites 338 and 342) and at the base of the slope toward the Lofoten Basin (Site 343). Tholeiitic basalts of Eocene age (Kharin et al., 1976) were recovered. The geochemical character of the tholeiites varied from low-Ti (1.29-1.69 wt.% TiO₂) MORB-type at Site 338 to high-Ti (2.37-3.28 wt.% TiO2), LREE-enriched at Sites 342 and 343 (Kharin, 1976; Schilling, 1976).

During ODP Leg 104 a deep penetration hole was drilled on the outer high of the Vøring Plateau to unravel the nature and origin of the seaward-dipping seismic reflectors and to clarify the character of the rocks below. The 900-m thick volcanic section of Paleogene age drilled at Hole 642E could be subdivided into an upper and lower series (Eldholm, Thiede, Taylor, et al., 1987). Subaerially erupted plateau basalts of oceanic tholeiitic composition (about 770 m thick, 42.6% average core recovery) constitute the upper series. This succession of lava flows and

volcaniclastic sediment layers corresponds to the seaward-dipping seismic reflectors. The lower series (about 140 m thick, 32.4 % average core recovery) is made up of dacitic and basaltandesitic flows derived from the partial fusion of continental crust and from mixing of these melts with mantle-derived tholeiitic magmas (Parson et al., this volume).

In this paper we describe the chemical stratigraphy of the upper series tholeiitic flows. Their major and trace element chemistry is used to identify eruptive episodes, to model magma chamber systems and interactions with continental crust, and to infer the nature of their mantle source. We briefly comment on the analogies with Paleogene plateau basalt provinces on either side of the northeastern Atlantic and we discuss the origin of ferrobasaltic volcaniclastic sediments that are interlayered with the tholeiitic lava flows of the upper series.

The petrology of the lower series magmas is discussed in the companion paper by Parson et al. (this volume) while the radiogenic isotope geochemistry of rocks from both series is given by Taylor and Morton (this volume).

ANALYTICAL TECHNIQUES

Two electron microprobes were used for the determition of mineral compositions in polished thin sections. The "Camebax" microprobe at the Ruhr-University Bochum used a wavelength-dispersive spectrometer. The "Geoscan" probe at the British Geological Survey at Keyworth was equipped with a "Link System" energy-dispersive spectrometer.

Chemical analysis of whole-rock samples of the upper series were carried out at the Ruhr-University Bochum, the University of Leuven, the Midland Earth Science Associates, the Imperial College of Science and Technology Reactor Centre, the University of Newcastle, and at the University of Waterloo. No interlaboratory standards have been run but the Bochum and UK data sets show systematic differences of up to 10 relative % only for the minor and trace elements Na, V, Ni, Rb, Sr, and Y (see Figs. 4 and 6). Analytical methods used by the British and Canadian laboratories are discussed in Parson et al. (this volume). Procedures used at Bochum and Leuven are outlined below.

Ten major and minor elements, and eleven trace elements of about 120 whole rock samples were analyzed at Bochum by wavelength-dispersive X-ray fluorescence on glass fusion beads. Samples were coarsely crushed between tungsten-carbide plates in a hydraulic press, and were then ground in an agate mortar to minimize contamination. Fusion beads were prepared from ca. 1.5 g (dried at 110°C overnight) and ca. 6 g Li-meta/tetraborate flux (Merck A12). The beads were analyzed on

¹ Eldholm, O., Thiede, J., Taylor, E., et al., 1989. Proc. ODP, Sci. Results, 104: College Station, TX (Ocean Drilling Program).

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Figure 1. Main geological features of the Norwegian Sea and location of Leg 104 drill sites.

a fully automated Philips PW 1400 spectrometer using a Rh-tube. Counting time was 80 s or 100 s, except for Mg (10 s), Fe (20 s), Ti, Ca, K (40 s) and Rb (200 s). Analytical precision is better than 2 % relative for most elements, 5-8% for Mn, Ni, Zn, and 10-15% for Y and P₂O₅. Analytical errors for Rb and Nb are below 20% for concentrations above 5 ppm, but rapidly deteriorate as concentrations approach the determination limit of about 1 ppm. Fe²⁺, CO₂; and H₂O were determined by standard wet chemical methods.

From the least altered samples studied at Bochum, we selected 48 representative samples for a determination of the abundances of trace elements Sc, Cr, Co, rare-earth elements (REE), Hf, Ta, Th, and U by instrumental neutron activation analysis (INAA). Analyses were conducted on 800 mg aliquots of the powders prepared at Bochum. Samples were irradiated for 7 hr in a thermal neutron flux of about 2×10^2 neutrons cm⁻²·s⁻¹ in the Thetis reactor at the University of Gent, Belgium. The gamma-ray intensities were measured at the University of Leuven, with a large volume Ge(Li)-detector and a hyperpure-Ge "low energy photon detector" at intervals of 7 and 20–30 days after irradiation. For details of the techniques, see Hertogen and Gijbels (1971). Analytical precision is generally better than 2% for Sc, Cr, Co, Sm, and Eu; 6% for La, Tb, and Yb, and about 10% for Ce, Nd, Lu, Ta, Th,

and U. The samples were analyzed relative to a secondary in-house alkali basalt standard rock that has been repeatedly calibrated against international reference rocks.

LITHOLOGY

The lithology of the Vøring Plateau upper series is described in detail in Eldholm, Thiede, Taylor, et al. (1987). All flow numbers and stratigraphic depths used in this paper refer to Figure 14 and Table 6 of the Site 642 site report in that volume. Here we only present a short summary as a basis for the discussion of the stratigraphy and petrology.

The upper series is about 770 m thick (324–1090 mbsf) and comprises 122 tholeiitic lava flows (F0 through F105) and 3 dikes (D1 through D3) as well as 55 volcaniclastic sediment layers (S4 through S43) of ferrobasaltic to tholeiitic composition (see figure 2). These separate entities are designated as lithological units. Additional flow or sediment units subsequently recognized during shore-based interpretation of geophysical logging profiles (by L.M.P. and L. V.) and reinterpretation of thin sec-



Figure 2. Stratigraphic profile of ODP Leg 104, Hole 642E. Column 5: Wide shading = successions of medium-grained flows, unshaded = successions of fine-grained flows, densely shaded = mixed flows. Columns 6 and 7: Occurrence of volcaniclastic sediment layers; the sequence numbers of some layers are indicated in column 7. Column 8: Open circles indicate recovered thicknesses; filled circles represent sediment thicknesses deduced from geophysical logs. Columns 9 and 10: Horizontal bars indicate presence of pumice and quartz and mica grains in the sedimentary units. Column 11: the chemical grouping of the lavas based on the range of TiO₂ contents. Column 12 repeats column 6.

tions have been labeled with a capital letter added to the number

cussion because they contain important information on the mantle source history and magma genesis beneath the Vøring Plateau.

PETROGRAPHY

Irrespective of differences in structure and grain size, fineand medium-grained tholeiites from the upper series can neither be distinguished by their qualitative nor quantitative mineralogical composition. The groundmass consists of 55-60 volume % plagioclase, 30-35 volume % clinopyroxene, 3-4 volume % saponite pseudomorphs after-mostly oxidized-olivine, 2-3 volume % Fe-Ti-oxides, and traces of chromite as inclusions. The amounts of smectitic, formerly glassy mesostasis is less than 5 volume % in fine-grained flows, more than 5 volume % in medium-grained flows. Pigeonite is completely absent from the tholeiitic rocks of the upper series. Flows and dikes in Group I (D1 through F45) have a higher average olivine content (5-6 volume %) than in Group II (2 volume %, F46 through F64) and Group III (3 volume %, F65 through F105). However, olivine contents may occasionally reach up to 10 volume % in all groups with exceptional flows having as much as 15-20 volume % (e.g., F24 or F95).

Type and abundance of phenocrysts in the generally aphyric (<1 volume % of phenocrysts) to sparsely phyric lavas largely correlate with the degree of differentiation (as indicated by the

of the preceding lithologic unit (e.g., F3A, S19B). The lava pile is predominantly (up to 75 volume %) made up

of fine-grained, aa-type flows with intense laminar fabric and commonly reddened flow-top breccias. It has been subdivided into three lithologic groups (Group I: 324-607 mbsf; Group II: 607-799 mbsf; Group III: 799-1089 mbsf) based on the presence in Groups I and III of sets of 4 to 8 medium-grained pahoehoe-type flows, thought to be compound lava flows. There are no compositional differences between aa- and pahoehoetype flows. The lava pile also contains some mixed flows, mostly in Group III, which consist of intimately mixed fine- and medium-grained bands.

On the basis of early shore-based analyses of the high field strength (HFS) elements P, Ti, and Zr, the upper series lava flows have been subdivided into seven chemical formations (Fig. 2): from USC at the base (1089 mbsf) to USI at the top (320 mbsf). The boundaries are marked by pronounced chemical changes between geochemically rather uniform successions of flow units. The data presented in this paper allow further subdivisions and prompted a shift of the transition between chemical formations USG and USI from the F27/F25 boundary to F16/F15 boundary

Two tholeiitic dikes that intrude the lower series lavas (D5 and D6) are also included in the following description and discontents of high partition coefficient elements like Ni and Cr). Olivine-tholeiites (18 flow units) are most abundant at the base and the upper 120 m of the upper series. They are aphyric and characterized by Ni-contents greater than 110 ppm. Plagioclase is the dominant phenocryst phase (over olivine) in the more differentiated rocks. These are also mostly aphyric again, but phenocryst abundance may reach up to 25 volume % in cumulustextured lavas like flow F26, F21, or F20A. Clinopyroxene is present as additional phenocryst phase in almost 50% of the more differentiated flows (those with Ni and Cr contents below 100 ppm and 240 ppm, respectively). Only in three instances-F11, F13, and F37A-traces of clinopyroxene phenocrysts are present in more mafic tholeiitic lavas with Cr content ranging between 306 and 380 ppm. The phenocryst assemblage is thus an approximate measure of evolved character (Bryan, 1983). The presence of clinopyroxene phenocrysts is of special interest, as it is recognized to be characteristic of tholeiites from anomalously shallow mid-ocean ridge segments, as exemplified by the Azores region, Afar, Galapagos, or Iceland (Schilling et al., 1983; Grove and Bryan, 1983).

The most common alteration product in upper series rocks is Fe-saponite. Calcite, beidellite, nontron, celadonite, analcite, and heulandite are less common and occur as vesicle and vein fillings. Native copper occurs in vesicles and fractures in association with celadonite in flows with pinkish gray staining, whose formation is addressed by LeHuray (this volume). Olivine is always completely replaced by saponite, but clinopyroxene and plagioclase are generally fresh. Surface weathering prior to seawater alteration not only resulted in reddening of flow-top breccias but also in quantitative replacement of primary minerals in the upper 40 m of the lava pile (cf. chemistry). Strong albitization of plagioclase affected individual flows or intervals at 483 mbsf (F25), 523-530 mbsf (F30 through F35), 615-650 mbsf (F47 through F52), 910 mbsf (F85), and 980 mbsf (F95).

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MINERAL CHEMISTRY

Representative analyses of plagioclase, pyroxene, and oxideminerals from 13 selected lithological units are given in Tables 1 and 2.

Plagioclase phenocrysts are generally normally zoned. The compositional range of An_{85-71} is common for tholeiitic magmas (Carmichael et al., 1974; Bryan et al., 1981). Rare examples with weak reverse zoning occur in flows F18, F84, and F90. Microphenocrysts are less calcic with An_{73-63} while groundmass microlaths range between An_{69} and An_{44} . Plagioclase in tholeiitic dikes D5 and D6 in the lower series covers the less calcic range of compositions with An_{69-60} in phenocrysts and An_{58-42} in groundmass crystals (Table 1).

Pyroxenes in tholeiitic units are of iron-poor augitic composition (Wo44-25En49-45Fs08-20) with phenocrysts clustering around Wo42 En47 Fs11 (Table 2, Fig. 3). Some are marginally zoned following a typical tholeiitic iron enrichment trend of 3-10 wt.% FeO toward groundmass compositions of Wo39En42Fs19. The contents of Cr, Al, and Ti also characterize these pyroxenes as typical for tholeiitic magma compositions (Schweitzer et al., 1979). The average TiO₂ content of phenocrysts in a single flow positively correlates with that of the host rock and thus reflects the degree of Fe-Ti enrichment of the host. On the other hand, the average chromium content in pyroxenes reflects the degree of differentiation of the magma. The pyroxene phenocrysts analyzed are less magnesian than those of plateau basalts from NE-Greenland (Upton et al., 1984), but resemble those of oceanic tholeiites (Bryan et al., 1981) as well as of the least fractionated tholeiitic parts of the Skaergaard intrusion (Brown, 1957). Unlike all other plateau basalt provinces in the northeastern Atlantic, pyroxenes of pigeonific composition are absent.

Pyroxenes in dikes D5 and D6 are generally less calcic (Table 2, Fig. 3). They range from typical upper series tholeiitic augite

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Interval (cm) 117-	119		143-	145		42-	44	1	12-	14		8	4-86
Lith. unit	F5	8A		F4	3		F4	5	_	F8	2			D5
	Ph	Gm		Ph	Gm		Ph	Gm	1	Ph	Gm	1	Ph	Gm
SiO ₂	47.61	52.67		48.26	57.24		50.61	55.61	-[50.73	55.89	1	54.41	58.46
Al ₂ O ₃	32.17	28.69	- 1	31.18	25.77	1	30.03	26.19	1	29.97	25.64	1	28.06	25.32
Fe ₂ O ₃	0.53	1.33	1	0.59	0.84	1	0.44	0.94		0.80	1.07	1	0.90	1.09
MgO	0.20	0.19	1	0.21	0.12	1	0.18	0.05	1	0.16	0.07	:	0.14	0.03
CaO	16.68	12.82		16.29	9.46	1	14.80	10.58	1	14.59	9.49	1	11.73	8.75
Na ₂ O	1.92	4.18		2.35	6.15		2.97	5.22	;	3.30	5.86	1	4.84	6.51
K2 O	0.03	0.19	ł	0.00	0.27	ł	0.05	0.17	1	0.06	0.25	1	0.13	0.23
Sum	99.14	98.44	ł	98.88	99.85	ł	99.08	99.06	:	99.61	98.27	1	100.21	100.39
			N	lumber o	f ions c	on t	he basis	s of 8 o	xyg	ens				
Si	2.203	2.396	F	2.238	2.577	ł	2.328	2.529	1	2.325	2.558	1	2.457	2.612
Al	1.754	1.548	1	1.705	1.367	1	1.628	1.420	1	1.619	1.383	:	1.494	1.333
Fe	0.018	0.039	1	0.021	0.029	ł	0.015	0.032	1	0.028	0.037	1	0.031	0.037
Sum	3.976	3.982	1	3.964	3.973	ł	3.972	3.981	:	3.972	3.978	:	3.982	3.981
			:			1			1			1		
			1			1			1			1		
			1			1			1			-		
Mg	0.014	0.012	1	0.015	0.008	1	0.012	0.003	1	0.011	0.005	1	0.009	0.002
Ca	0.827	0.639	1	0.810	0.457	1	0.729	0.515	1	0.716	0.466	1	0.568	0.419
Na	0.172	0.338	1	0.211	0.537	1	0.265	0.460	1	0.293	0.520	1	0.424	0.564
K	0.002	0.014	1	0.000	0.015	ł	0.003	0.010	1	0.003	0.015	ł	0.008	0.013
Sum	1.015	1.003	;	1.035	1.017	;	1.009	0.988	;	1.024	1.005	;	1.009	0.997

Table 1. Selected electron microprobe analyses of plagioclase crystals from tholeiitic lava flows of the Hole 642E upper series and of tholeiitic dike D5 from the lower series. Ph = phenocryst; Gm = groundmass.

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Core-Section



Figure 3. Mineral chemistry of pyroxenes. Filled symbols: Phenocrysts; open symbols: In matrix. Circles: Upper series tholeiites. Diamonds: tholeiitic dikes (D5 and D6) in lower series. Stars: dacites of lower series for comparison.

compositions (Wo₃₈₋₄₀En₅₀₋₄₇Fs₁₂₋₁₃) to subcalcic compositions of Wo₂₄₋₂₅En₄₆₋₄₀Fs₃₀₋₃₅ (Fe/Fe + Mg = 0.40–0.47) reflecting the effects of strong crustal assimilation (see below).

Ti-oxide minerals include Ti-magnetite and ilmenite, but they rarely occur together in the same sample. Ti-magnetite characteristically shows TiO₂ contents between 17 and 29 wt.% with a mean of 22 wt.%. Al₂O₃ contents vary around 1.6 wt.%. MnO contents of Ti-magnetite are generally below 0.4 wt.%; with eceptional values 2 wt.% in dike D5 and 4.7 wt.% in flow F45. Ilmenite exhibits low alumina and manganese contents (below 0.2 and 0.6 wt.%, respectively), but commonly has MgO as a minor constituent (about 2.0 wt.%).

Chromite was analyzed only in dike D5 as an inclusion in replaced olivine. Its peculiar composition reflects the hybrid character of this rock (Table 5). The high Cr/(Cr + Al) ratio of 0.52 is typical for ocean floor tholeiites (Sigurdsson and Schilling, 1976). However, the high substitution of 1.5 formula units of (Cr + Al) by (Fe³⁺ + Ti) in the B-site is more typical for transitional, Fe-rich basalts, while the MgO content of about 9.45 wt.% is lower than any reported for ocean floor basalts or plateau basalts around the northeastern Atlantic.

MAJOR-ELEMENT VARIATION

From the ca. 200 analyses of the 122 upper series flows and three dikes given in Table 5 about 70 are believed to be of samples that have suffered only limited alteration (Fig. 4). These indicate that more than 90% are of typical ocean-floor tholeiitic composition. Plagioclase-tholeiites dominate over more primitive olivine-tholeiites, which are most abundant near the base and top of the flow sequence. Although none of the flows is nepheline-normative, the four flows of formations USE and USH show strong enrichment of Fe and high field strength (LFS) elements and are somewhat depleted in silica (Tables 3 and 5).

All flows and dikes have been affected by at least minor seawater alteration. The highest FeO/(FeOTotal) ratios do not exceed 0.67 and are generally below 0.6. In fresh aphyric ocean floor tholeiites this ratio varies from 0.85 to 0.73 for TiO2 contents increasing from 0.9 to 2.1 wt.% (Bryan et al., 1981). The term "fresh" as used in this study indicates that whole rock analyses have K₂O/P₂O₅ ratios lower than unity, FeO/Fe₂O₃ ratios higher than unity, and CO₂ less than 0.25 wt.% (Fig. 5). Seventy-seven samples analyzed have those characteristics and generally have less than 1.5 wt.% H₂O (Bochum data set) or less than 0.9 wt.% loss-on-ignition (LOI; UK data). In altered samples CaO may be as low as 6 wt.% (versus 10.4-12.6 wt.% in fresh samples) and is below 1 wt.% in rocks from the top of the lava pile, where primary minerals are completely replaced. Due to alteration Na₂O and MgO values may be enriched by 0.5 and 2 wt.%, respectively, while K₂O may reach 0.5-2.4 wt.%. Alteration is usually accompanied by enrichment of total iron content.

Vøring Plateau tholeiites generally have Mg-numbers of 50 to 67 [Mg—numbers are here defined as the molar ratio: Mg/(Mg + 0.85 × total Fe)]. They cover a range of MgO contents from 6.5 to 8.8 wt.% (rarely, 9-12 wt.%) typical of ocean floor tholeiites (Fig. 4). With decreasing MgO concentrations, low partition coefficient oxides TiO₂, K₂O, P₂O₅, Na₂O, and, to a lesser extent, MnO and SiO₂ increase, while FeO^T remains constant and CaO decreases. Al₂O₃ may decrease, but most often it increases and reaches values of 18.7-19.0 wt.% in plagioclasephyric flow units such as F2OA and F21 (Table 5).

Table 2. Selected electron microprobe analyses of clinopyroxene crystals from tholeiitic lava flows of the Hole 642E upper series and of tholeiitic dik
D5 from the lower series. In the last column are data for a chromite inclusion in dike D5. Ph = phenocryst; Gm = groundmass.

Core-Section Interval (cm)	36R 143-	2-1 145		37F 42-	2-2 44	ł	54F 117-	-1 119	!	105 84	R-2 -86		105R-2 84-86	
Lith. unit	F4 Ph	3 Gm.		F4 Ph	5 Gm	1	F58 Ph	A Gm	1	Ph	D5 Gm		D5	
Concernation of the second sec	energia energia	10000000 1020			and the second second	-	·	anon lane				-	and the second	
SiO ₂	52.51	51.23	;	51.60	51.42	1	52.72	51.46	1	53.09	50.78	1	0.10	
TiO ₂	0.65	0.95	;	0.88	1.03		0.42	0.70	1	0.43	0.64	1	0.28	
Al ₂ O ₃	2.46	2.49	1	3.00	2.58	1	2.31	2.68	1	2.07	1.62	1	22.99	
Fe2 O3			1	-				=	1	1.7	-	1	7.27	
FeO	6.96	10.51	1	8.38	10.53	- 1	5.57	12.37	1	8.09	21.10	1	20.83	
MnO	0.09	0.13	1	0.24	0.25	1	0.11	0.35	1	0.21	0.54	1	0.26	
MgO	16.35	15.01	1	15.88	16.14	-	16.67	14.02	1	17.09	13.45	1	9.50	
CaO	20.23	18.98	1	19.22	17.58	1	21.24	17.95	1	18.57	11.77	1	0.03	
Na ₂ O	0.29	0.24	1	0.27	0.24	1	0.15	0.43	1	0.17	0.17	1	-	
Cr2 O3	0.42	0.11	1	0.54	0.13	1	0.46	0.02	1	0.23	0.00	:	39.31	
Sum	99.09	99.65	1	100.01	99.90	ł	99.65	99.98	1	99.95	100.07	1	100.57	
				Number	of ions	on	the basi	ls of 6	oxy	gens			32	
Si	1.942	1.918	1	1.907	1.913	I.	1.938	1.930	1	1.951	1.949	1	0.025	Si
Al	0.058	0.082	1	0.093	0.087	1	0.062	0.070	1	0.049	0.051	1	6.779	Al
	in and a	the Sectors	-		- Cardmitt		New Proventions	and Group	- 12		1000 - 1000 - 100	-:	7.776	Cr
Sum	2.000	2.000	1	2.000	2.000	1	2.000	2.000	1	2.000	2.000	1	1.368	Fe ³⁺
			1			1			- 1			:	0.052	Ti
			1			1			- 1			1	-	
			1			1			1			1	16.000	Sum
Al	0.047	0.028	1	0.038	0.026	1	0.038	0.049	1	0.041	0.023	1		
Ti	0.019	0.027	1	0.024	0.029	1	0.012	0.020	1	0.012	0.018	1		
Fe	0.204	0.329	1	0.259	0.328	1	0.171	0.388	- 1	0.249	0.677	1	3.542	Mg
Mn	0.007	0.004	1	0.007	0.008	1	0.003	0.011	1	0.006	0.017	1	4.358	Fe ² +
Mg	0.895	0.837	1	0.875	0.895	1	0.913	0.784	1	0.936	0.770	1	0.054	Mn
Ca	0.794	0.761	1	0.761	0.701	1	0.836	0.721	1	0.731	0.484	1	0.007	Ca
Na	0.019	0.017	1	0.020	0.017	1	0.011	0.031	1	0.012	0.013	1		
Cr	0.007	0.003	1	0.016	0.004	1	0.013	0.001	1	0.007	0.000	1	7.962	Sum
Sum	1.993	2.007	;	2.000	2.007	1	1.998	2.005	ł	1.994	2.002			

Compared to normal depleted ocean floor basalts, the leastaltered Vøring Plateau tholeiites are deficient in Na₂O (ca. 0.2– 0.4 wt.%) and SiO₂ (ca. 1.0 wt.%), an apparent characteristic of tholeiites erupted at shallow segments of the mid-oceanic rift system (Klein and Langmuir, 1987). They are enriched in FeO^T and TiO₂ by a factor of 1.05 to 1.10 at identically low K₂O and P₂O₅ contents of 0.06–0.24 wt.% and 0.10–0.27 wt.%, respectively (Fig. 4, Tables 3, 4, and 5; Melson and O'Hearn, 1979; Bryan et al., 1981; Sigurdsson, 1981).

Upper series tholeiites thus exhibit slightly higher FeO^T/MgO ratios that range from 1.35 to 1.47 [FeO^T/(FeO^T + MgO) = 0.58-0.60] for the average composition of each formation. These FeO^T contents distinguish them from tholeiites of the deep ocean floor and place them in the field of anomalous subaerial ridge segments like Iceland or Afar (Langmuir and Hanson, 1980; Klein and Langmuir, 1987). Only the initially erupted, lowermost lavas of formation USC have low N-MORB-type FeO^T/ MgO ratios of 1.05 (Table 3) (Bryan et al., 1981). The higher FeO^T/MgO ratios (1.55–1.64) of the Ti-enriched lavas of formations USE (flows F62, F63, F64) and USH (flow F26) only in part reflect slightly higher degrees of differentiation. K_2O/P_2O_5 ratios are characteristically below 1.0 in less altered rocks. TiO₂/ P_2O_5 ratios are virtually constant at 10 to 11; only samples of formation USG range between 11 and 12.

Dikes D5 and D6 are tholeiitic basalts of low-Ti (1.0-1.4 wt.%), low-K (0.11-0.16 wt.%) and low-P (0.10-0.14 wt.%) character. Dike D5 has undergone little differentiation as well as alteration (MgO = 8.4 wt.%; FeO > Fe₂O₃, K₂O/P₂O₅ = 1.1; Na₂O = 2.1 wt.%). Dike D6 is of more differentiated composi-

tion and has been affected more strongly by alteration (MgO = 5.0 wt.%; FeO/(FeO + Fe₂O₃) = 0.25; Na₂O = 2.9 wt.%) (Fig. 5).

TRACE-ELEMENT COMPOSITION

The variation of trace elements in Vøring Plateau basalts is typical of oceanic tholeiites and corroborates mineral and major-element compositions (Fig. 6). None of the tholeiites can be regarded as a primary melt (Cr > 400 ppm; Ni > 300 ppm; Clague and Frey, 1982). The high partition coefficient elements Ni and Cr range from 180 to 50 ppm and 370 to 40 ppm, respectively; Ni values higher than 150 ppm and Cr values above 300 or below 100 ppm are rare (Tables 4 and 5; Fig. 6). With average contents of 7.9 wt.% MgO, 250 ppm Cr, and 95 ppm Ni they are moderately differentiated liquids.

The low concentrations of low (LFS) and high (HFS) field strength elements (Saunders et al., 1980) and of the light rareearth elements (LREE) in fresh samples (Fig. 7) are consistent with the low-K tholeiitic character of the magmas. Altered samples show up to 10- to 30-fold enrichment of Rb (Fig. 5). All other trace elements except copper and—interestingly—yttrium seem to be almost unaffected by alteration processes. Sr varies irregularly and is markedly low only in extremely altered samples.

The upper series lava flows are characterized by chondrite normalized REE patterns that are slightly LREE-enriched [(La/Yb)_N = 1.05-1.8] and convex-upward in the light rare earths [(La/Sm)_N = 0.8-1.1] (Figs. 7 and 8). La_N and Yb_N range from 8 to 28 and 7.4 to 16, respectively, while HFS elements vary by a factor of 3 (e.g., Zr 50 to 163 ppm). Many samples, in particu-



Figure 4. Variation of major-element oxide composition of the least-altered samples. University of Bochum data. Filled squares: formation USI. Filled diamonds: USG. Filled triangles: USF. Filled stars: USE. Filled circles: USD. Open squares: USC. Open stars: dikes D5 and D6. Outlined field in Na₂O-TiO₂ figure represents the data set of samples analyzed in UK labs; some interlaboratory bias is apparent for some elements.

lar those from formation USG, have a slight positive Eu-anomaly that is most likely due to accumulation of plagioclase phenocrysts.

This convex-upward transitional-MORB pattern is not uncommon in Tertiary plateau basalts on the northwestern European continental margin (Fig. 8; e.g., Faeroes middle/upper series; Schilling and Noe-Nygaard, 1974; Thompson et al., 1980). It has also been reported for recent lavas of the northeast Atlantic and is especially typical for rocks dredged from the Reykjanes Ridge (Fig. 8; Schilling, 1973; Tarney et al., 1979; Schilling et al., 1983). The few appropriate trace-element data available from the Tertiary tholeiites of East Greenland indicate that possibly only the lower plateau lava series at Hold with Hope (northeastern Greenland) may have a similar transitional pattern (Upton et al., 1984), while all other tholeiites are more enriched (Larsen and Watt, 1985).

The transitional character of the Vøring Plateau lavas also becomes apparent within the ternary Hf/3-Ta-Th diagram (Wood, 1980) wherein the field of transitional basalts covers Hf/Ta ratios of 9 to 6 (Fig. 9). Vøring Plateau tholeiites have Hf/Ta ratios of 7.6 to 5.8; the corresponding La/Ta ratios vary from 13.8 to 14.5. In general, flows below Unit F78 (870 mbsf) are slightly less enriched with Hf/Ta > 6.7 and La/Ta < 15. Flows F103A through F105 in the lowermost formation USC are even closer to N-MORB type $[(La/Yb)_N = 1.05; (La/Sm)_N = 0.8; Hf/Ta = 7.7-8.8)$. These basal flows show high Th/Ta ratios (2.4 to 1.9) which are typical of tholeiites from continental margins (Joron et al., 1984). Upward in the section, Th/Ta ratios decrease toward values close to unity (1.3-1.1), the constant value reported for basalts from recent mid-ocean ridges in the North Atlantic (Schilling et al., 1983).

The ocean floor tholeiitic character of the major and traceelement composition of the rocks of the upper series is consistent with the low ${}^{87}\text{Sr}/{}^{86}\text{Sr}$ ratios, which range between 0.7031 and 0.7033 when corrected for an age of ca. 60 Ma (Taylor and Morton, this volume). Several flows, especially near the base of the series, are marked by minor enrichment of radiogenic Sr (${}^{87}\text{Sr}/{}^{86}\text{Sr} = 0.7035-0.7039$). This together with enrichment of Th points to assimilation of crustal material.

The low-K tholeiitic character of dikes D5 and D6 in the lower series is also expressed by their magmaphile trace-element contents (Table 5). They are only little or moderately differentiated (D5: 268 ppm Cr, 163 ppm Ni; D6: 184 ppm Cr, 100 ppm Ni) and do not compare with any magma of the upper series. They exhibit a pronounced negative Eu-anomaly and have very low contents of Nb, Rb (both less than 2 ppm), and Sr (about 120 ppm). A LREE-depleted ocean floor tholeiitic character of N-MORB-type is indicated by (Sm/Yb)_N-ratios of about 0.7

FORMATION LITH. UNITS No of flows No of analyses	USC F103A-105 5 4	USD F65-103 43 28	USE F62-64 4	USF F30-61 40 18	USG F16-29 14 12	USH F26 1 2	USI F0-15 18 7
8i0.	49.4	49.4	49.2	49.5	49.2	49.0	49.1
TiO2	1.14	1.86	2.66	1.88	1.41	2.68	1.66
Al2 O3	14.9	14.7	14.1	15.1	16.0	14.7	15.2
FeOT	10.3	11.3	13.3	11.1	10.3	12.4	11.1
MnO	0.19	0.23	0.27	0.20	0.18	0.27	0.19
MgO	9.85	7.67	8.13	7.88	7.61	8.00	8.11
CaO	11.62	11.10	8.55	11.0	12.0	7.50	11.05
Na ₂ O	1.87	2.46	2.77	2.42	2.28	3.06	2.42
K2 O	0.10	0.12	0.25	0.14	0.10	0.25	0.13
$P_2 O_5$	0.09	0.17	0.25	0.17	0.13	0.29	0.15
FeO ^T /MgO	1.05	1.47	1.64	1.41	1.35	1.55	1.37

Table 3. Average major-element composition of each chemical formation identified in the Hole 642E upper series calculated from fresh samples (see text).

(Fig. 7B). However, these magmas have been markedly enriched in Th, La, and Ce (Table 5; Fig. 7B). These patterns indicate assimilation of continental crustal material (about 10%) similar to the dacitic glassy lavas of the lower series (Parson et al., this volume; Viereck et al., 1988). This interpretation is consistent with the 87 Sr/ 86 Sr ratios of 0.7052 and 0.7065 (Taylor and Morton, this volume).

The two dikes shown in the Hf/3-Ta-Th ternary diagram (Fig. 9) do not lie on a mixing line between upper series transitional ocean floor tholeiites and crustal rocks (represented by the dacite lavas of the lower series, and Moine shists, Torridonian metasediments and Lewisian gneiss in amphibolite facies from Thompson et al., 1986). Instead, they appear to lie on a mixing line between crustal rocks and extremely depleted N-MORB magmas. Such depleted magmas with Ta and Th contents below chondritic values were drilled on Leg 81 at DSDP Site 553 as the dipping reflector sequence on the western margin of the Rockall Plateau (Joron et al., 1984), and clearly derive from a strongly depleted mantle source.

PETROLOGIC MODELING

Binary variation diagrams of high *versus* low partition coefficient elements (e.g., Ni *versus* TiO₂; Fig. 10) clearly indicate that most of the compositional variation within each chemical formation is due to fractional crystallization processes. The Ni-Ti diagram was used to qualitatively and quantitavely estimate the type of mineral phase and the amount of crystal fractionation necessary to explain the observed trends.

For the least differentiated rocks (180–140 ppm Ni) fractionation of about 5% of olivine and minor magnesiochromite is required assuming Ni > 300 ppm and Cr > 400 ppm for primary magmas (Clague and Frey, 1982). Additional fractionation of a Ni-free phenocryst phase is required to explain the enrichment of Ti with decreasing Ni below about 140 ppm Ni. Major pyroxene fractionation is ruled out by the lack of correlation between Sc and Cr in rocks with more than 80 ppm Cr. Plagioclase, the dominating phenocryst phase, must hence be the dominantly fractionated Ni-free phase. More than 70% of the lavas (i.e., those with 140–70 ppm Ni) must also have experienced between 10 and 20 volume % of plagioclase fractionation in addition to about 6–10 volume % of olivine. Minor amounts of clinopyroxene must have fractionated only in the more advanced stage of differentiation to generate those magmas with less than 80 ppm Ni and Cr and in which Sc fell from greater than 40 ppm to less than 35 ppm. These samples experienced up to 40–50 volume % of crystal fractionation.

Crystal fractionation, however, cannot explain the chemical differences between the chemical formations. These differences, therefore, must be ascribed to petrogenetic processes occurring prior to storage of magmas in shallow reservoirs. To create a basis for further calculations, we have to remove from the most primitive magmas of each formation any fractional crystallization effects. The "primary magmas" (Ni > 250 ppm) corresponding to each trend recognized in the Ni-Ti diagram must have had the following approximate TiO₂-contents (wt.%) : USC: 0.9; USG: 1.3; USI: 1.45; USD + USF: 1.35 to 2.1; USH: 2.1; USE:2.25. Thus, primary contents of TiO₂ and other low partition coefficient elements appear to have differed by a factor of about 2.5.

The almost parallel offset of chondrite-normalized REE patterns to higher absolute values with increasing Ti-contents (Fig. 7) suggests that these primary differences are due to different degrees of partial melting of a uniform source. The results of straightforward batch melting calculations are shown in Fig. 11. We assumed a mantle with heavy REE Yb fixed at 2x chondritic abundances (as typical of primitive mantle nodules; Jagoutz et al., 1979), and used commonly accepted values for mineral/liquid partition coefficients. Specific values selected were mainly taken from Fujimaki et al. (1984).

Successful matches to the patterns of relatively unfractionated transitional tholeiites from formations USD, USF, USG, and USI require a spinel-lherzolite source that was only slightly depleted in Th, Ta, La, and Ce and slightly enriched in the Nd-Tb group (Fig. 11A). The estimated melting range is 8 to 15%. The model suggests an almost primordial character of the source. However, the Sr-, Nd-, and Pb isotope characteristics of these



Figure 5. Variation of alteration-sensitive elements and volatile components as a function of degree of secondary oxidation of iron in tholeiitic flows and dikes of the upper series.

rocks given by Taylor and Morton (this volume) are inherited from a time-integrated depleted mantle source. This demands that the source of the transitional tholeiites once must have been more strongly depleted and has been moderately enriched in a later event.

The significantly lower $(La/Yb)_N$ ratios of lavas of formation USC requires a slightly more Th, Ta, LREE-depleted spinel-lherzolite mantle source. Calculations further indicate that degrees of melting were generally larger (14–20%) than for the overlying lava formations (Fig. 11B). The slightly enhanced Th and Ta concentrations of USC lavas are most readily explained by mixing with a crustal component.

A most interesting result followed from the attempts to model the complex Th-Ta-REE patterns of the tholeiitic dikes D5 and D6 that intrude the lower series (Fig. 11C). The low $(Sm/Yb)_N$ ratios, significant negative Eu-anomalies, and high Yb abundances indicate that these dikes were formed by small degrees of melting of an extremely depleted (La_N = 0.2) shallow plagioclase-lherzolite mantle source. The enhanced abundances of Th, Ta, La, and Ce, and especially the negative Ta-anomalies and higher ${}^{87}Sr/{}^{86}Sr$ ratios (Taylor and Morton, this volume) can be attributed to interaction of strongly depleted magmas with crustal material. This is further illustrated by the fact that in the Hf/3-Ta-Th diagram dikes D5 and D6 lie on a mixing line connecting supracrustal material and very depleted N-MORBs (Fig. 9). Interestingly, the extremely depleted mantle source inferred for the unadulterated tholeiitic precursor magmas of dikes D5 and D6 may have been more than just a local feature. Indeed, the strongly depleted tholeiites drilled during DSDP Leg 81 at Site 533 on the Rockall Plateau (Joron et al., 1984) fairly well match the calculated 5% batch melt of such source (Fig. 11C).

Whatever the uncertainties attached to model calculations, it is obvious that the Hole 642E tholeiites bear the record of a changing mantle source composition with time. These findings fit into several models of mantle heterogeneity and mantle evolution. The occurrence of strongly depleted tholeiites on both the Vøring and Rockall Plateau might indicate that an extremely depleted shallow mantle beneath thinned continental crust was a regional feature in the area of the future North Atlantic Ocean. This strong depletion might be an old feature, but it might as well be a younger event related to migration of small amounts of melt into the stretched crust just prior to continental break-up. Isotopic data (Taylor and Morton, this volume) require that the mantle source of the formations making up the largest part of the lava pile (Fig. 11A) was originally less enriched in Th-Ta-LREE. But again, there are few constraints on the nature and timing of the enrichment process. It might result from migration of cognate enriched fluids within depleted mantle, or might attest to influx of enriched mantle plume material. At any rate,

Table 4. Analyses of selected whole-rock compositions of tholeiitic lava flows and volcaniclastic sediments from Hole 642E. All data are on a H_2O -and CO_2 -free basis and normalized to sum 100%. Major-element oxides in wt.%, trace elements in ppm.

Lith. unit Core-section Interval (cm) Chem. group Depth (mbsf)	D1 9R-2 39-41 USI 367.9	F11 15R-3 121-123 USI 409.6	F18 19R-2 38-40 USG 443.0	F26 23R-3 137-139 USH 486.4	F46 38R-2 91-93 USF 609.9	F59 54R-3 86-88 USF 740.8	F62 59R-3 69-71 USE 775.0
SiO2	49.01	49.52	49.25	49.64	49.06	49.41	48.90
TiO2	1.51	1.48	1.37	2.47	2.21	1.85	2.73
A12 03	15.24	15.53	15.04	15.25	15.08	14.72	13.93
Fe2 03	4.59	4.64	4.63	6.99	5.20	4.38	6.19
FeO	6.98	6.35	6.31	5.69	6.53	7.40	7.54
MnO	0.18	0.20	0.17	0.27	0.15	0.21	0.20
MgO	8.78	8.34	8.45	8.33	8.01	8.09	7.50
CaO	11.41	11.47	12.49	7.85	10.91	11.50	9.79
Na ₂ O	2.04	2.21	2.06	3.03	2.50	2.16	2.70
K ₂ O	0.12	0.12	0.11	0.18	0.13	0.11	0.24
P2 O5	0.13	0.13	0.11	0.30	0.22	0.17	0.26
Sc	39.8	39.8	41.5		40.8	40.6	43.9
v	305	317	308	376	347	338	436
Cr	262	374	317	74	311	313	264
Co	44	52	49	48	46	45	40
Ni	155	148	109	87	122	135	98
Cu	175	150	89	130	102	113	283
Zn	98	91	79	155	102	114	140
Rb	5	2	5	4	3	3	6
Sr	145	201	199	212	240	215	232
Y	27	26	21	56	32	30	40
Zr	85	83	74	141	128	108	161
Nb	3	5	6	9	8	6	11
La	4.7	4.7	4.1		7.2	6.4	9.5
Ce	13.4	12.9	11.7		20.0	17.3	26.9
Nd	10.0	9.8	9.3		15.2	13.5	20.3
Sm	3.28	3.12	2.79		4.73	4.07	5.86
Eu	1.22	1.22	1.14		1.72	1.51	2.09
ть	0.71	0.67	0.61		0.95	0.89	1.22
Yb	2.48	2.29	1.93		2.81	2.68	3.9
Lu	0.38	0.35	0.28		0.41	0.39	0.56
Hf	2.2	2.02	1.85		3.24	2.76	4.22
Та	0.32	0.33	0.31		0.52	0.45	0.71
Th	0.48	0.44	0.40		0.65	0.64	1.09

"plume-type" E-MORB volcanism in the immediate vicinity of the Vøring Plateau is indicated by the volcaniclastic sediments.

STRATIGRAPHIC DISTRIBUTION OF MAGMA FORMATIONS AND THEIR INTERNAL VARIATIONS

The stratification of the lava sequence into seven chemical formations based on early post-cruise shore-based studies (Eldholm, Thiede, Taylor, et al., 1987) is supported by the complete data set presented here. The grouping in different formations is clearly illustrated by binary Ni-Ti diagrams and by REE patterns (Figs. 10 and 11). Flows of the lowermost formation USC (F105-F103A, + F98; 1087-1049 mbsf and 1012-1016 mbsf) are the least enriched (TiO₂ < 1.3 wt.%) and the least fractionated (180-100 ppm Ni; Fig. 10A). Lava flows of formations USD and USF (1049-521 mbsf, F103-F30) form a cluster around $TiO_2 = 1.85$ wt.% and Ni = 95 ppm with a range of 1.6-2.3 wt.% TiO2 and 120-70 ppm Ni (Figs. 10A, 10B). The lowermost six flows (F103-F99; USD1) are less differentiated than the rest of those formations (Ni > 100 ppm and Cr > 240 ppm) and also differ by having lower Sr contents of less than 200 ppm (Bochum values). Above Unit F98, which is the latest and most differentiated flow of USC-type, the following succession of flows (USD and USF) is more or less uniform with increasing TiO₂ at a constant degree of differentiation. However, the uniform succession is interrupted in places by the occurrence of single, less-differentiated flows (F91, F82, and F46). Flows of

formation USF above F46 are in general more enriched in TiO_2 than below and are compositionally more uniform (USF 2 in Fig. 10B). We therefore may divide formation USF into USF1 (799-607 mbsf) and USF2 (607-522 mbsf).

Formation USG starts at 521 mbsf with the compositionally mixed flow F29 (Fig. 10C). The sample analyzed in the U.K. is lower in magmaphile elements than any flow below in the upper series, except for flows of formation USC. With a TiO2 content of 1.44 wt.% it is clearly of USG character. On the contrary, Sample 104-642E-27R-4, 103-105 cm analyzed at Bochum and Leuven (Table 5) shows decoupled trace-element characteristics. While low Y and Zr values indicate USG type, high V (409 ppm) and TiO₂ contents (1.94 wt.%) show relict USF2 affinities. The unusual composition of F29 is underscored by its peculiar REE pattern (dashed line in Fig. 7A). In contrast to chemical unit USG defined in Eldholm, Thiede, Taylor, et al. (1987), formation USG clearly encompasses flows F29 to F16 (521-418 mbsf; Fig. 10C). This section of the lava pile is marked by a number of low-Ti flows (1.34-1.86 wt. % TiO₂, 20-30 ppm Y) with a wide range of Ni values (140 to 50 ppm) and varying in character from aphyric olivine-tholeiite to phyric (20 volume %) cumulus-textured plagioclase-tholeiite. Episode USG is formed by a sequence of flows that at first became less differentiated with time (F29-F25). After a major break in local magmatic activity, indicated by 2 m-thick sediment Unit S12, increasingly differentiated lavas erupted (F24-F20A) and were followed, once again, by more mafic compositions at the end of the for-

Table 4 (continued).

Lith. unit Core-section Interval (cm) Chem. group Depth (mbsf)	F82 71R-4 12-14 USD 888.7	F89 77R-3 99-101 USD 935.4	F104A 91R-2 75-77 USC 1064.3	F105 93R-3 39-41 USC 1073.0	S16 27R-2 48-50 511.1	S21 42R-1 72-76 649.7	S40 86R-2 0-2 1016.5
SiO ₂	49.41	49.26	48.92	48.93	51.00	53.68	50.32
TiO2	1.56	2.11	1.27	1.03	3.20	3.59	1.87
A12 O3	15.48	14.25	15.02	15.04	14.73	12.60	15.09
Fe2 03	4.79	5.77	6.50	3.65	18.38	15.93	12.99
FeO	6.27	7.39	5.71	7.36	1.05	4.11	2.81
MnO	0.16	0.21	0.22	0.20	0.13	0.09	0.12
MgO	8.62	7.09	9.23	10.67	4.91	3.69	8.07
CaO	11.31	11.06	11.07	10.90	3.52	1.88	4.93
Na ₂ O	2.27	2.55	2.16	1.88	1.98	1.67	2.74
K2 O	0.09	0.11	0.13	0.24	0.96	2.53	0.82
P2 O5	0.13	0.20	0.09	0.09	0.13	0.23	0.24
Sc	41.0	44.9	45.1	41.9	37.3	30.8	44.6
v	320	372	304	272	236	212	310
Cr	322	146	215	360	93	39	250
Co	48	37	53.4	52	28	27.7	51
Ni	151	78	98	158	76	60	91
Ću	137	93	99	141	95	301	1017
Zn	94	107	84	73	84	84	93
Rb	3	3	5	15	21	71	12
Sr	194	226	219	186	198	122	169
Y	27	33	22	20	52	62	49
Zr	92	124	75	62	217	307	116
Nb	5	7	5	2	21	31	7
La	4.7	6.9	3.3	2.81	15.5	30.2	13.2
Ce	13.5	17.9	9.2	7.1	40.8	76.	30.7
Nd	10.8	12.5	7.5	5.9	25.1	51.	21.3
Sm	3.45	4.47	2.39	2.14	6.55	12.4	5.89
Eu	1.31	1.55	0.94	0.81	2.19	3.76	2.04
ть	0.77	0.85	0.57	0.47	1.35	2.15	1.31
Yb	2.64	2.87	2.35	1.77	3.84	5.5	3.69
Lu	0.38	0.45	0.32	0.26	0.49	0.71	0.51
Hf	2.35	2.92	1.92	1.49	5.3	8.1	3.02
Ta	0.31	0.43	0.25	0.17	1.51	2.45	0.42
Th	0.45	0.59	0.59	0.33	1.77	2.85	0.73

mation (F19-F16). Flow F16, like F29, seems to be transitional between formations USG and USI (Fig. 10C) which is slightly more enriched in magmaphile elements (25-35 ppm Y, 80-120 ppm Zr).

Formation USI (F15–D1, possibly F3 to F0 as well; 418–366 mbsf), like USG, covers a wide range of Ni-contents suggesting large differences in degree of differentiation. It starts with the most mafic flows at the base (F15–F11), evolves to more differentiated compositions (F9–F6) and, like formation USG, again ends with mafic magmas (F4–D1). Units D1, D2, and D3, which were interpreted aboard ship as dikes, do not deviate chemically from the flows they are thought to have intruded. This might imply that these units are actually flows. The boundary zones, originally identified as chilled margins, might be tectonic contacts that have been preferrentially leached by alteration fluids. Because of the intense alteration of the uppermost flow Units F3, F1, and F0, we conclude that their high Ti contents of 2.11–3.03 wt.% are probably not primary, especially as yttrium contents are as low as 10–15 ppm.

The two formations so far excluded from the stratigraphic discussion (USE: F64-F62, 799-771 mbsf; USH: F26, 486-490 mbsf) are only represented by 3 and 1 flows respectively (Figs. 10B and 10C). They are erratically located within chemically uniform successions of flows. They represent individual magmatic events, possibly derived from magmatic activity of different composition at some distance. Both units are highly enriched in magmaphile elements, which cannot be explained by higher degrees of differentiation but must be a primary feature (F26:

2.47-2.94 wt.% TiO₂, 87 ppm Ni; F62-F64: 2.4-2.88 wt.% TiO₂, 123-73 ppm Ni; Figs. 4, 6, and 7).

The style of compositional variation within single formations is used to distinguish two types of formations (Fig. 10D). Flows within formations USC, USG, USI, and USE follow diffuse trends of Ni depletion being accompanied by enrichment of Ti. These might be related to crystal fractionation processes in steady-state magma chamber systems that are constantly replenished by magma of uniform composition (O'Hara and Mathews, 1981). Formations USD and USF, on the contrary, form clusters. Subsequent flows within these formations can often only be connected by tie lines running oblique to fractionation trends. This effect can only be explained as the result of mixing of magmas with differences in primary trace-element composition as well as in the degree of differentiation. This may indicate the existence of several closely spaced contemporaneous magma chambers and magma supply systems that were replenished by pulses of magma of slightly different chemical composition.

VOLCANICLASTIC SEDIMENTS

Fifty-three dominantly basaltic, lithic vitric tuff beds are interlayered with the lava flows, making up about 4% of the upper series (Fig. 2). They are strongly altered as expressed by intense red coloration and almost complete replacement by secondary sheet silicates and less often zeolites (analcite and heulandite). Chemical alteration led to a marked gain of ferric iron, water, Na, K, Rb, and Cu, as well as loss of Ca and Sr (Table 5). Some beds show an erratic variation of P and Y; it appears to be

Figure 6. Variation of trace elements in the least-altered upper series tholeiites as a function of Ti-content. Symbols for Bochum University data as in Fig. 4. For elements for which systematic interlaboratory differences are apparent (Rb, Sr, V), data from UK labs are outlined as fields.

related to alteration, but a specific cause has as yet not been identified.

The tuff beds can be divided into an upper (325-740 mbsf) and lower group (740-1189 mbsf) (Fig. 2). The volcaniclastic units of the upper group are thicker (up to 7 m) and more common with about one unit for every two lava flows. They may show repetitive fining-upward sequences, internal erosional surfaces, and reworking. Microfossils occur in trace, more rarely in mi- nor amounts especially in the uppermost units. Pumiceous, presumably chemically more differentiated lapilli are rare but may form individual beds up to 10 cm in thickness in a few units of the upper group (S4, S9, S12).

Incompatible element concentrations of the basaltic sediments are higher than those of the lavas (Fig. 10D; 2.7–3.8 wt.% TiO₂). The chondrite normalized REE patterns are uniformly concaveupward with (La/Sm)_N = 1.5–2.2 and (La/Yb)_N = 2.0–2.5 in contrast to the convex-upward shape of the patterns of all lava flows [(La/Sm)_N < 1] (Fig. 7). This pattern difference suggests a more enriched mantle source for the tuff beds which compositionally represent slightly more differentiated (90–60 ppm Ni, 200–40 ppm Cr) ferrobasaltic magmas. Similar basalts occur in East Iceland, Jan Mayen Fracture Zone, and in Site 342 (DSDP Leg 38) on the Vøring Plateau (Gibson et al., 1982; Neumann and Schilling, 1984; Schilling, 1976). These volcaniclastic units are also chemically similar to lower Eocene tuffs of the Balder Formation and equivalents (e.g., tuffs of the Ølst Formation, Denmark, Fig. 12), that are widespread throughout the North Sea and increase in thickness to the northwest (Knox and Morton, 1983).

The tuff beds in the lower group of the upper series are thinner (generally less than 10 mm; Fig. 2) and petrographically more uniform. They are less differentiated (91 ppm Ni, 250 ppm Cr) and less enriched in incompatible elements (Fig. 10D; TiO₂ = 1.8 wt.%). White mica and tectonically deformed undulose quartz are present in most units. Unit S31 (870 mbsf) additionally contains traces of aegirine-augite while Unit S41 (1028.7 mbsf) contains ferro-augitic (?) clinopyroxene. Microfossils are rare in sediments in the lower group of the upper series and have been identified in Unit S33 only (911.2 mbsf). Allowing for the strong alteration that has affected all sediments, major and minor element concentrations are similar to those of the lava flows within which they are interlayered (Fig. 10D). However, like the tuffs of the upper group, these lower tuff units also exhibit an enriched chondrite normalized REE pattern with $(La/Sm)_N =$ 1.4 and $(La/Yb)_N = 2.2$ and therefore cannot be derived from the same magma source as the lavas. They stratigraphically may resemble the quartz-mica-bearing and rarely also aegirine-bearing tuff beds of the Sele Formation that underlies the Balder Formation (Knox and Morton, 1983).

The mode of eruptive origin and emplacement of these tuff beds is a matter of debate. Repetitive fining-upward sequences, internal erosional surfaces and reworking are clear indications

Figure 7. Chondrite normalized rare-earth element (REE) patterns of samples of the upper series, Hole 642E. (A) tholeiitic lava flows of chemical groups USE (flow F62), USD + USF, and USG. Flow F29 (dashed pattern) has higher La/Yb ratio than other USG samples. The positive Eu-anomaly of USG samples is most likely due to accumulation of plagioclase phenocrysts. (B) tholeiitic lava flows of chemical groups USI and USC. Group USI samples fall in the lower range of groups USD + USF field. Group USC samples, forming the base of the upper series, have consistently lower La/Yb ratios than samples from the other chemical groups. The tholeiitic dikes D5 and D6 that intrude the lower series lavas have markedly different and complex REE patterns. (C) volcaniclastic sediment layers of the upper series. Variable REE patterns reflect different petrogenetic and alteration history of the individual beds. In contrast to the tholeiitic flows, all sediment layers show a pronounced LREE enrichment.

that these sediment units do not represent primary pyroclastic deposits. They have been reworked by shallow marine or fluvial activity and their thickness can therefore not be used for correlation. Chemical similarities suggest they may be correlated over several hundred kilometers with the tuff beds of the Balder Formation in the marine basins of the North Sea. Only eruptions of Plinian-type would be able to generate such widespread deposits (Fisher and Schmincke, 1984). The few pumice layers of more differentiated composition are undoubtedly of Plinian origin. However, the petrographic data are not very convincing evidence for a Plinian origin of the ferrobasaltic layers. Most of the units contain formerly glassy sideromelane shards and ta-

Figure 8. Variation of chondrite normalized ratios $(La/Sm)_N$ and $(La/Yb)_N$ of Vøring Plateau tholeiites and volcaniclastic sediments compared to variation observed in other rocks from the North Atlantic Ocean. Fae = Faeroe Islands. KoR = Kolbeinsey Ridge. MAR 49-62 = segment of Reykjanes Ridge, degrees north. MR 73-74 = segment of Mohns Ridge, degrees north. MR 120-240 = Mohns Ridge between 120 and 240 km north of Jan Mayen Fracture Zone. KnR = Knipovich Ridge. RR = Reykjanes Ridge from 62.2°N to Reykjanes Peninsula. RP = Reykjanes Peninsula. E-ICE = Eastern Iceland, Miocene flows. JMFZ = less than 100 km north and south of Jan Mayen Fracture Zone along Mohns and Kolbeinsey Ridge. Data are from Schilling and Noe-Nygaard (1974), Schilling et al. (1983), Gibson et al. (1982), and Neumann and Schilling (1984).

chylitic to microcrystalline clasts in approximately equal amounts. Shards are predominantly arcuate rather than angular, but average vesicularity of the shards is rather small for Plinian-type eruptions (< 50 volume %). Hydroclastic processes most likely influenced the eruptions, and a more local derivation (< 100 km) of the tuff beds is therefore favored. The internal structure of accretionary lapilli found in two of the tuff beds (S10 at 447-450 mbsf, S21 at 650 mbsf) is evidence for subaerial distribution of the fine-grained tephra by drifting ash clouds prior to aquatic redeposition as indicated by sediment structures (R. Schumacher, pers. comm.).

SUMMARY: RECONSTRUCTION OF THE VØRING PLATEAU THOLEIITIC MAGMATISM

During the initial stages of continental break-up at the Vøring Plateau in the early Tertiary, melting of a strongly depleted, shallow plagioclase-lherzolite subcontinental mantle led to formation of magmas with strongly depleted, ocean floor tholeiitic character. Assimilation and fusion of the overlying continental crust by basic magmas contributed to hybrid magmas of the lower series drilled at Hole 642E.

The onset of upper series volcanic activity of transitional tholeiitic character is marked by an erosional unconformity in sediment unit S43 at 1089 mbsf (Section 104-642E-94R-5, 93 cm). Sample 104-642E-94R-4, 126–128 cm, representing the uncompacted sediments of Unit S43 above the unconformity, exhibits tholeiitic affinities (high Cr and Ni, low Nb, Zr, and Y). In contrast, the compacted sediments below the unconformity (Sample 104-642E-95R-1, 134–137 cm) show the calc-alkaline peraluminuous character of the lower series (Table 5).

The basal formation USC (5 volume % of total sequence) comprises relatively unfractionated transitional tholeiites, possibly reflecting shorter magma reservoir residence times due to

Figure 9. Distribution of Hole 642E volcanic rocks and volcaniclastic sediments in the Hf-Ta-Th diagram (Wood, 1980). Crosses = ferrobasaltic volcaniclastic sediments. Filled circles = upper series tholeiites. Open circles = upper series tholeiites affected by crustal assimilation. Filled triangles = tholeiitic dikes D5 and D6 intruded in lower series, strongly affected by crustal contamination. Open triangles = basaltic andesites of lower series. Filled star = average of seven lower series dacites. Compositional field of crustal rocks from the Caledonides (dotted ellipse near Th-apex) includes data for Moine schist, Torridonian sandstone, Paleozoic slates, and Precambrian amphibolites (Wood, 1980; Thompson, 1982; Thompson et al., 1986). Shaded field near Hf-apex covers strongly depleted N-MORBs from Sites 553 and 555, DSDP Leg 81 (Joron et al., 1984).

rapid crustal extension. The USC flows were derived from a depleted spinel-lherzolitic mantle source. Possibly, the source had been enriched in Th-Ta-LREE to some extent prior to magma generation. Model calculations indicate that USC lavas were formed by the highest degrees of partial melting (15–20%) for lavas of the upper series.

Lack of replenishment of the USC magma system led to decreasing volcanic activity while nearby a new set of magmatic systems (USD + USF) developed. Lavas from these formations represent the most voluminous part (65 vol.%) of the lava pile drilled at Hole 642E, and were formed by melting of a mantle zone that had been slightly enriched as compared to the source of the USC lavas. Flows F103 through F99 of formation USD are considered to represent an initial phase of USD, in which magma systems were established. The chemistry of subsequent flows is not controlled by simple fractionation processes, and the magmas still show USC affinities with low Sr contents and high abundances of compatible elements. USD and USF magmas cover a wide compositional range with respect to abundances of incompatible elements (e.g., 1.6-2.3 wt.% TiO2). This may indicate the open character of these USD/USF magma systems as well as their replenishment by heterogeneous primary magmas derived by variable degrees (8-15%) of batch partial melting. Decreasing average contents of Ni and increasing contents of Ti with time indicate that replenishment was not matching the extent of fractionation so that these reservoirs continuously progressed to higher degrees of differentiation. A major interruption in volcanic activity seems to be marked by thorough alteration of flows F46-F48 (607-630 mbsf). The generally lower Ni contents of the succeeding 17 flows indicate that fractionation meanwhile had proceeded without enough replenishment with new primitive magma. Because of the associated effect of constant cooling and final lack of recharge, the USF magma systems died with flow F30 at 521 mbsf. The major

break in eruptive activity at the Vøring Plateau at this point is marked by the intense alteration of flows F30 through F33 (521– 530 mbsf) and the presence of the 1.5-m-thick sedimentary Unit S17 on top of flow F30.

The younger low-Ti magmas of the USG magmatic episode (representing 12.9 volume % of the total pile) are derived by higher degrees of partial melting (ca. 15%) than magmas of the previous episodes. The very first flow F29 is chemically heterogeneous and still bears chemical fingerprints of old magma, e.g., high Ti and Zr, Hf of USF episodes.

Magmas of the USI formation (12.7 volume %) are again of slightly more HFS- and REE-enriched character (approx. 12% partial melting) and, together with formation USG, represent two short-lived, "closed" magma systems at the end of the volcanic activity at Site 642.

Formations USE and USH, which only represent 3.2 and 0.8 volume % of the magmas erupted, are evidence for contemporaneous development of magma systems of more alkalic nature at some distance from Site 642.

The volcaniclastic sediments interlayered with the lava flows are genetically not related, and a more LREE-enriched mantle source is required to explain their ferrobasaltic chemistry. Their increasing thickness as well as the more common and intense reddening of flow-tops in the upper half of the upper series may be due to decreasing activity of extrusive volcanism.

The chemistry of basaltic magmas drilled at Site 642 indicates that four compositionally different mantle sources have to be assumed. A strongly depleted plagioclase-lherzolite source for the tholeiitic dikes of the lower series; a moderately depleted spinel-lherzolite source for the transitional tholeiites at the base of the upper series; a slightly enriched, originally depleted, MORB source for the overlying lava formations; and, finally, a LREE-enriched source for the interlayered volcaniclastic sediments.

ACKNOWLEDGMENTS

We are grateful to all those who through their careful work in the various laboratories at Bochum, Leuven, Newcastle, London, and Waterloo provided us with a valuable set of geochemical data. The chapter on volcaniclastic sediments benefitted from discussions with H.-U. Schmincke and R. Schumacher. We thank G. Wörner and M.J.F. Flower for constructive comments. Financial aid by various national scientific foundations made this work possible. We owe special thanks to the Deutsche Forschungsgemeinschaft (DFG) for its support through grants Schm 250/28-12 and 28-13, and to the Belgian Interuniversity Institute for Nuclear Sciences (IIKW-grants). A. C. Morton and L. M. Parson acknowledge the approval to publish of the Directors, B.G.S. and I.O.S (NERC).

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Date of initial receipt: 8 February 1988 Date of acceptance: 5 December 1988 Ms 104-135

Figure 10. Variation of high-partition coefficient element Ni *versus* low-partition coefficient element Ti. (A) flows of formations USC, USD1, and USD2. (B) flows of formations USE, USF1, and USF2. (C) flows and dikes of formations USG, USH, and USI; subsequent flows are connected by tie-lines. (D) Simplified crystal fractionation trends shown by magmas of formations USC, USG, USI, and USE; data for volcaniclastic sediments 6–26 and S40–S43 and dikes D5 and D6 are included. See text for further explanation.

05R-3	07R-2	07R-2	07R-3	09R-2	10R-1	10R-1	10R-2	11R-1
132-134	78-80	115-117	13-15	39-41	50-60	147-149	35-40	113-115
339.2	359.2	359.5	360.4	367.9	375.9	379.3	380.1	383.6
S5	F2	S6	F3	D1	D2	F3A	D3	F4
	USI		USI	USI	USI	USI	USI	USI
42.80	51.80	50.90	46.00	47.80	48.00	49.90	48.30	48.20
3.83	1.99	3.01	2.27	1.47	1.48	1.66	1.58	1.85
17.91	15.98	13.06	18.54	14.86	15.10	16.54	15.87	14.20
18.35	15.75	15.93	16.72	4.48	4.66	14.11	5.27	6.89
1.91	1.63	2.14	1.46	6.81	6.60	1.86	5.51	5.98
0.07	0.06	0.07	0.09	0.18	0.18	0.09	0.14	0.18
1.89	2.83	3.36	1.95	8.56	8.36	3.22	7.88	7.62
1.20	1.20	1.77	1.28	11.31	11.49	1.29	11.52	11.40
1.71	1.78	1.72	1.70	1.99	1.95	1.84	2.22	2.24
0.64	1.59	1.35	0.85	0.12	0.13	1.27	0.16	0.17
0.11	0.02	0.08	0.07	0.13	0.13	0.09	0.14	0.16
8.14	4.34	5.52	8.40	1.99	2.00	7.57	2.20	1.49
0.29	0.25	0.24	0.41	0.14	0.27	0.44	0.15	0.16
98.85	99.22	99.15	99.74	99.84	100.35	99.88	100.94	100.54
0.05	0.04	0.01		0.04	0.03	0.05	0.03	0.00
0.12	0.05	0.02		0.01	0.01	0.08	0.01	0.01
		37.8		39.8	40.2		41.6	
91.	152.	129.		297.	291.	264.	314.	356.
39.	117.	48.		267.	274.	152.	266.	227.
40.	39.	35.		51.6	52.6	36.	50.3	48.

151.

171.

141.

26.

83.

3.

4.7

13.4

10.0

3.28

1.22

0.71

2.48

0.38

2.20

0.32

0.48

<0.08

96.

5.

149.

148.

103.

135.

26.

83.

5.

14.1

10.7

3.36

1.26

0.74

2.58

0.39

2.22

0.33

0.53

0.1

4.8

3.

114.

161.

73.

34.

65.

17.

97.

5.

142.

146.

105.

144.

26.

86.

5.

5.2

14.1

10.8

3.44

1.31

0.74

2.47

0.38

2.31

0.33

0.51

<0.1

2.

103.

139.

103.

205.

104.

31.

6.

9.

Table 5. Major and trace elements of whole rocks from Hole 642E. Major-element oxides S and Cl expressed in wt.%, all other elements in ppm. For samples analyzed for rare-earth elements, the listed Cr and Co data were obtained by neutron activation analysis. Listed Cr and Co data for the remaining samples were determined by X-ray fluorescence analysis

05R-3

94-96

338.8

391.

82.

201.

102.

44.

59.

114.

9.

9.

90.

80.

94.

59.

30.

96.

50.

13.6

4.65

2.4

6.1

0.77

2.23

2.8

0.77

6.9

23.9

287.

130.

328.

115.

206.

131.

34.

55.

27.

280.

31.

F1

USI

41.50

2.66

20.42

17.93

1.92

0.13

1.12

1.00

1.37

0.54

0.12

9.56

0.78

99.05

0.03

0.04

495.

270.

52.

99.

174.

216.

17.

45.

14.

9.

150.

04R-1

58-59

326.8

S4

40.50

23.30

13.63

2.32

0.09

0.99

0.90

1.71

0.56

0.13

0.77

11.48

98.86

0.07

0.20

267.

46.

39.

132.

152.

103.

16.

44.

15.

12.

175.

2.48

Core-Sect

Lith.Unit

Chem.Group

Interval

Mbsf

SiO2

TiO2

A12 03

Fe2 03

FeO MnO

MgO

CaO

K2 O

P2 05

H₂O

CO2

TOT

S

C1

Sc

Cr

Co

Ni

Cu

Zn

Rb

Sr

Zr

Nb

La

Ce

Nd

Sm

Eu

Tb

Yb

Lu Hf

Ta

Th

U

Y

v

Na₂O

03R-1

14-18

323.3

S3X

60.30

15.48

1.05

1.68

6.50

0.14

1.63

4.02

3.91

2.92

0.44

1.04

0.15

99.26

0.06

0.02

14.5

45.

4.

15.4

18.

19.

168.

109.

313.

919.

114.

58.

12.1

3.16

1.92

1.06

0.89

4.8

1.7

6.8

19.7

65.

20.

52.7

Core-Sect Interval	12R-1 85-87	13R-1 41-43	14R-1 132-134	15R-1 81-83	15R-3 121-123	15R-5 8-10	15R-5 48-50	16R-1 62-64	16R-2 138-140	18R-1 94-96	19R-2 38-40	19R-5 23-25
Mbsf Lith.Unit Chem.Group	392.6 F6 USI	396.2 F7 USI	402.3 F8 USI	406.2 F9 USI	409.6 F11 USI	412.8 F12 USI	412.2 F13 USI	416.1 F15 USI	418.5 F16 USG	434.1 F17 USG	443.0 F18 USG	449.0 S10
SiO2	49.00	48.20	48.80	48.70	48.80	48.80	47.40	48.10	45.90	48.60	48.70	49.80
TiO ₂	2.08	1.97	1.84	1.71	1.46	1.57	1.71	1.58	1.38	1.38	1.35	3.24
A12 O3	14.87	14.53	17.50	15.22	15.30	15.11	14.97	14.90	14.43	14.68	14.87	13.13
Fe ₂ O ₃	15.21	5.89	5.68	6.61	4.57	5.68	10.34	5.04	3.72	3.58	4.58	17.49
FeO	1.96	6.30	3.87	4.58	6.26	5.82	3.75	6.16	6.18	7.26	6.24	0.90
MnO	0.09	0.28	0.12	0.14	0.20	0.19	0.14	0.16	0.37	0.18	0.17	0.08
MgO	2.90	7.35	5.50	7.51	8.22	7.81	6.88	8.10	7.94	8.74	8.30	3.23
Na	1.01	10.44	9.31	9.90	11.40	10.64	9.44	10.71	13.45	11.87	12.30	1.60
Na ₂ O	2 19	2.01	0.50	2.00	2.18	2.40	2.59	2.29	1.00	1.99	2.04	1.69
R20	0 14	0.14	0.50	0.20	0.12	0.15	0.58	0.09	0.07	0.22	0.11	0 10
P2 05	5 92	1 37	2 72	2 59	1 63	1 64	1 99	1 49	1 71	1 74	1 51	6 15
CO.	0.60	0.38	0.33	0.59	0.12	0 19	1.00	0 31	1 00	0.07	0.14	0.15
TOT	98.22	99.64	99.06	100.62	100.45	100.24	100.35	99.08	99.14	100.43	100.53	99.33
s	0.04	0.00	0.04	0.04	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.04
C1	0.03	0.01	0.01	0.02	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.03
Sc	22.2	12.22	222	1000	39.8	122		40.6	2.22	41.0	41.5	26.6
v	221.	379.	355.	349.	312.	327.	347.	331.	288.	282.	308.	152.
Cr	103.	108.	182.	341.	379.	335.	316.	325.	306.	331.	317.	50.
Co	35.	53.	39.	43.	49.6	51.	52.	48.9	40.	50.9	48.6	16.6
Ni	57.	83.	85.	127.	146.	136.	137.	144.	127.	132.	109.	68.
Cu	132.	115.	131.	88.	148.	136.	246.	110.	136.	98.	89.	168.
Zn	161.	119.	116.	100.	90.	99.	90.	92.	84.	77.	79.	105.
Rb	62.	4.	11.	4.	2.	7.	13.	2.	5.	5.	5.	57.
Sr	87.	199.	176.	170.	198.	244.	222.	229.	220.	250.	199.	78.
Y	37.	33.	24.	29.	26.	24.	41.	26.	24.	22.	21.	51.
Zr	118.	113.	108.	96.	82.	87.	94.	93.	79.	11.	74.	303.
ND	8.	5.	7.	6.	5.	5.	6.	8.	6.	6.	6.	36.
La					4.7			5.0		4.4	4.1	25.2
Ue Nd					12.9			13.4		12.1	11.7	25 0
Nu Cm					9.0			10.1		9.4	9.3	35.0
ош Бл					3.12			3.30		1 16	2.19	2 57
љu Th					0.67			0.72		1.10	0.61	1 31
Yh					2 29			2 36		2 1	1 92	3 4
Lu					0.35			0.36		0.32	0.28	0.51
Hf					2.02			2.27		1.96	1.85	6.1
Та					0.33			0.37		0.31	0.31	2.17
Th					0.44			0.45		0.42	0.40	2.53
U					<0.1			0.11		<0.1	<0.1	0.65
Чо					0.92			0.11				0.00
					0.94							

Table	5	(continued).

Core-Sect Interval Mbsf Lith.Unit Chem.Group	20R-4 49-51 456.9 F19 O USG	21R-2 134-136 465.5 F20A USG	21R-4 47-49 467.7 F21 USG	22R-2 120-122 472.0 F22 USG	22R-4 148-150 475.3 F23 USG	22R-6 118-120 478.1 F24 USG	23R-1 112-114 480.9 S12	23R-2 144-146 482.9 F25 USG	23R-3 137-139 486.4 F26 USH	25R-3 58-60 495.0 F27 USG	26R-5 88-90 504.9 F28 USG	27R-2 48-50 511.1 S16
SiO	48.60	48.60	48.70	48 10	48 70	48 40	51 50	49.10	47.80	48.30	48.10	47 90
TiO	1.48	1.70	1.81	1.41	1.45	1.51	2.71	1.27	2.38	1.33	1.37	3.01
A1.0.	16.09	18.28	18.46	16.19	16.44	16.36	12.77	13.69	14.68	17.04	15.26	13.83
Fer Or	5.25	5.50	6.19	4.38	4.62	4.92	14.24	11.03	6.73	4.67	4.23	17.26
FeO	5.10	4.88	4.09	5.98	5.72	5.78	1.95	3.88	5.48	5.05	6.73	0.99
MnO	0.19	0.23	0.19	0.20	0.17	0.17	0.14	0.08	0.26	0.22	0.18	0.12
MgO	8.28	6.39	6.37	7.73	7.38	7.37	3.71	7.91	8.02	7.83	7.38	4.61
CaO	10.51	9.68	8.73	10.96	11.86	12.00	1.57	4.11	8.32	11.73	12.60	3.99
Na ₂ O	2.35	2.77	2.82	2.25	2.17	2.23	1.80	2.32	2.92	2.15	2.07	1.86
K ₂ O	0.14	0.11	0.15	0.07	0.07	0.07	1.40	1.16	0.17	0.06	0.10	0.92
P2 O5	0.13	0.16	0.16	0.12	0.12	0.13	0.13	0.40	0.29	0.11	0.12	0.12
H ₂ O	1.69	1.56	2.03	1.66	1.23	1.48	6.84	5.00	2.29	1.74	0.71	4.56
CO ₂	0.35	0.35	0.34	0.18	0.19	0.23	0.72	1.02	0.60	0.18	0.15	0.54
TOT	100.16	100.21	100.04	99.23	100.12	100.65	99.48	100.97	99.94	100.41	99.00	99.71
S	0.00	0.00	0.00	0.00	0.00	0.03	0.06	0.04	0.04	0.00	0.01	0.01
C1	0.01	0.01	0.01	0.01	0.01	0.01	0.07	0.04	0.02	0.01	0.01	0.03
Sc				37.9	39.8						41.9	37.3
V	335.	337.	357.	292.	305.	305.	161.	248.	362.	308.	289.	222.
Cr	304.	38.	41.	209.	232.	251.	42.	121.	71.	193.	195.	84.
Co	48.	47.	40.	44.8	45.2	36.	28.	64.	46.	41.	50.5	37.6
Ni	107.	54.	53.	91.	93.	100.	72.	129.	84.	107.	104.	71.
Cu	177.	91.	114.	128.	106.	46.	160.	123.	125.	188.	145.	89.
Zn	93.	96.	94.	84.	87.	85.	181.	111.	149.	86.	82.	79.
Rb		4.	1.	4.	3.	5.	52.	25.	4.	3.	4.	20.
Sr	208.	240.	235.	202.	208.	174.	66.	131.	204.	202.	216.	186.
Y	20.	22.	22.	22.	22.	25.	48.	52.	54.	21.	20.	49.
Zr	78.	92.	96.	71.	71.	75.	194.	72.	136.	63.	69.	204.
Nb	4.	6.	5.	3.	4.	6.	16.	5.	9.	4.	4.	20.
La				4.0	4.1						4.4	15.5
Ce				10.6	11.8						12.0	40.8
Nd				8.4	9.5						8.5	25.1
Sm				2.75	2.93						2.87	6.55
Eu				1.09	1.19						1.14	2.19
ть				0.58	0.64						0.62	1.35
Yb				1.89	2.15						2.09	3.84
Lu				0.28	0.31						0.30	0.49
Hr				1.73	1.88						1.87	5.3
Ta				0.31	0.32						0.32	1.51
Th				0.34	0.43						0.41	1.77
U				<0.1	(0.15						(0.15	0.53

Core-Sect Interval Mbsf Lith.Unit Chem.Group	27R-4 103-105 514.9 F29 USG	28R-3 126-128 521.3 S17	28R-4 5-6 523.2 F30 USF	28R-4 86-88 524.5 F32 USF	28R-4 134-136 526.4 F33 USF	29R-1 6-8 527.0 F34 USF	29R-1 105-107 530.2 F35 USF	30R-4 31-33 540.0 F36 USF	31R-2 36-38 548.2 F37 USF	32R-3 55-57 559.3 F37A USF	33R-2 42-44 566.2 F38 USF	33R-4 36-38 571.6 F38 USF
SiO ₂ TiO ₂ Al ₂ O ₃ FeO MnO MgO CaO Na ₂ O K ₂ O P ₂ O ₅ H ₂ O CO ₂	47.60 1.88 16.24 7.29 5.02 0.18 7.33 8.73 2.58 0.22 0.17 2.00 0.35	46.80 3.73 14.23 19.18 0.97 0.07 2.39 1.39 1.89 1.01 0.05 6.21 0.49	50.00 2.26 15.86 7.79 3.70 0.27 6.70 7.05 3.11 0.88 0.24 2.31 0.81	$\begin{array}{r} 47.50\\ 2.18\\ 15.49\\ 6.15\\ 4.33\\ 0.34\\ 7.81\\ 8.25\\ 2.91\\ 0.31\\ 0.23\\ 2.55\\ 0.53\end{array}$	48.50 1.97 14.90 5.75 5.92 0.17 7.40 10.44 2.52 0.23 0.18 1.25 0.22	47.60 2.10 13.65 8.71 4.80 0.12 7.59 7.68 2.77 0.60 0.25 2.28 0.33	48.60 2.23 14.21 9.09 4.55 0.08 7.91 6.89 2.95 0.75 0.23 2.20 0.37	48.80 2.02 13.71 4.42 8.18 0.20 7.34 11.20 2.25 0.16 0.17 1.01 0.12	$\begin{array}{r} 48.30\\ 1.82\\ 14.90\\ 6.17\\ 5.36\\ 0.20\\ 7.96\\ 10.84\\ 2.42\\ 0.35\\ 0.17\\ 1.40\\ 0.33\end{array}$	48.90 1.81 14.75 4.63 6.15 0.15 7.63 12.27 2.22 0.15 0.16 1.01 0.13	48.10 2.19 13.39 9.32 4.39 0.13 7.57 9.26 2.34 0.81 0.20 1.42 0.18	48.00 2.17 13.76 6.63 6.19 0.15 7.22 10.86 2.33 0.20 0.21 1.30 0.18
TOT S	99.59	98.41	100.98	94.25	99.45	98.48	100.06	99.58	0.03	99.96	99.30	99.20
Sc V Cr Co Ni Cu Zn Rb	47.3 396. 93. 55.6 75. 70. 126. 2.	32.9 306. 93. 35.4 77. 410. 86. 43.	399. 186. 45. 97. 109. 168. 22.	375. 191. 39. 91. 252. 173. 4.	363. 183. 48. 86. 171. 94. 7.	350. 178. 39. 77. 329. 81. 13.	373. 168. 39. 77. 508. 99. 19.	43.5 354. 295. 48.7 96. 128. 100. 2.	346. 292. 45. 108. 69. 103. 4.	45.1 333. 322. 47.8 96. 84. 95. <2.	365. 173. 42. 88. 197. 104. 21.	362. 204. 39. 88. 184. 103. 6.
Sr Y Zr Nb La Ce Nd Sm Eu Tb Yb	202. 23. 91. 5. 4.8 13.6 10.2 3.28 1.38 0.73 2.03	128. 50. 222. 20. 21.5 47.6 24.2 6.02 1.95 1.32 5.8	222. 38. 124. 6.	200. 39. 127. 5.	214. 32. 110. 8.	247. 45. 123. 8.	232. 37. 131. 7.	215. 34. 113. 8. 7.1 18.8 14.8 4.51 1.66 0.92 2.98	191. 26. 104. 7.	$213. \\ 28. \\ 104. \\ 3. \\ 5.9 \\ 17.0 \\ 13.0 \\ 4.09 \\ 1.53 \\ 0.84 \\ 2.69$	238. 36. 127. 8.	200. 34. 126. 5.
Lu Hf Ta Th U	0.26 2.46 0.35 0.41 <0.15	0.81 5.7 1.58 1.91 1.0						0.45 3.05 0.49 0.74 <0.15		0.40 2.79 0.41 0.56 0.17		

Table 5 (continued).

	25D 0	250 0	250 2	25D 4	26D 1	260.0	270 9	200.0	200 4	400.1	410 1	410.0
Core-Sect	35R-2	35R-2	35R-3	35K-4	30R-1	30R-2	378-2	38K-2	38R-4	40R-1	41R-1	41R-2
Mhaf	5-5	108-110	48-50	500 1	143-145	114-110	42-44	91-93	9-11	11-19	4-0	26-28
MOSI	503.1	564.1	565.9	D09.1	592.8	594.0	507.0	609.9 EAC	014.7	020.7	030.0	641.5
Cham Chaun	FSS	519	F40	F41 UCE	F43	F44	F4D UCE	F40	F47	F48	F49A	FDU
chem.Group	051		031	035	055	035	035	035	035	05F	USF	USF
SiO2	48.30	47.60	47.70	48.10	48.10	48.40	49.00	47.60	46.90	48.00	48.40	47.50
TiO ₂	2.26	3.51	2.03	1.88	1.77	1.99	2.10	2.14	1.80	1.70	1.86	1.81
A12 O3	13.80	12.45	14.45	15.10	15.19	14.65	14.78	14.63	11.58	15.23	14.12	15.63
Fe2 03	5.14	18.60	11.38	5.98	7.73	6.54	4.71	5.05	12.50	4.41	5.97	6.37
FeO	7.06	1.36	1.72	5.56	4.40	5.43	6.81	6.34	3.96	5.85	5.95	5.18
MnO	0.23	0.10	0.15	0.14	0.12	0.12	0.29	0.15	0.08	0.15	0.21	0.18
MgO	7.25	5.53	7.18	7.30	7.73	7.71	7.69	7.77	10.62	8.15	7.64	9.24
CaO	10.65	3.85	10.44	10.15	9.98	9.63	10.71	10.85	4.92	10.94	11.01	6.81
Na ₂ O	2.43	2.04	2.38	2.41	2.39	2.54	2.40	2.43	2.27	2.30	2.30	2.74
K2 0	0.16	0.96	0.18	0.37	0.16	0.47	0.18	0.13	1.39	0.12	0.08	0.57
P2 O5	0.20	0.34	0.18	0.17	0.16	0.17	0.20	0.21	0.21	0.16	0.17	0.17
H ₂ O	1.05	4.24	1.19	1.53	1.44	1.50	1.29	1.49	3.25	1.81	1.45	3.17
CO ₂	0.19	0.38	0.27	0.25	0.24	0.21	0.18	0.21	1.08	0.17	0.19	0.82
TOT	98.72	100.96	99.25	98.94	99.41	99.36	100.34	99.00	100.56	98.99	99.35	100.19
S	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.04
C1	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01
Sc	44.1	30.0					41.1	40.8			41.6	
v :	365.		333.	319.	294.	319.	340.	337.	241.	313.	353.	330.
Cr	182.	58.	146.	148.	154.	149.	252.	310.	239.	315.	135.	234.
Co	49.5	35.1	40.	36.	44.	40.	46.8	46.6	45.	45.	49.8	45.
Ni	87.		82.	87.	84.	79.	88.	118.	104.	121.	87.	90.
Cu	196.		107.	86.	164.	181.	193.	99.	147.	109.	137.	71.
Zn	113.		99.	102.	76.	86.	102.	99.	80.	94.	101.	105.
Rb	4.		7.	15.	8.	10.	4.	3.	30.	3.	6.	<2.
Sr	230.		224.	225.	223.	222.	215.	233.	139.	213.	249.	185.
Y	33.		34.	31.	31.	28.	31.	31.	46.	24.	28.	26.
Zr	129.		113.	104.	99.	12.	122.	124.	113.	97.	102.	102.
Nb	7.		7.	5.	5.	6.	6.	8.	8.	5.	6.	5.
La	7.6	27.9					6.8	7.2			5.6	
Ce	21.4	67.8					19.1	20.0			15.9	
Nd	16.2	49.0					15.2	15.2			13.4	
Sm	5.06	12.0					4.66	4.73			3.95	
Eu	1.82	3.49					1.67	1.72			1.51	
Tb	1.03	2.18					0.97	0.95			0.85	
Yb	3.27	7.4					2.79	2.81			2.62	
Lu	0.49	1.01					0.41	0.41			0.39	
Hf	3.55	6.8					3.25	3.24			2.62	
Та	0.55	2.16					0.49	0.52			0.41	
Th	0.78	2.65					0.66	0.65			0.59	
U	0.2	1.12					0.12	0.12			<0.15	

Core-Sect Interval Mbsf Lith.Unit Chem.Group	41R-3 110-112 645.3 F51 USF	42R-1 72-76 649.7 S21	42R-2 57-59 651.3 F52 USF	45R-1 30-32 676.4 S22	45R-5 62-64 682.9 F53 USF	50R-1 118-120 712.3 F56 USF	52R-1 90-92 718.3 F57A USF	54R-1 117-119 733.7 F58A USF	54R-2 73-74 739.1 S26	54R-3 86-88 740.8 F59 USF	56R-1 22-24 754.2 F60 USF	58R-1 104-106 764.5 F61 USF
SiO2	47.60	49.60	47.80	53.10	48.50	48.90	48.60	48.70	46.60	48.20	47.40	48.30
TiO2	1.73	3.32	2.05	2.31	1.83	1.91	1.97	1.61	2.82	1.80	1.82	1.78
Al2 O3	14.46	11.64	15.12	13.40	13.82	15.29	14.50	14.22	14.92	14.36	14.37	15.04
Fe2 03	7.20	14.72	5.88	13.95	4.07	5.29	5.92	3.60	18.23	4.27	8.08	5.88
FeO	5.33	3.80	5.29	0.99	8.55	5.60	6.07	8.09	0.73	7.22	5.59	5.66
MnO	0.15	0.08	0.17	0.12	0.20	0.21	0.16	0.21	0.18	0.20	0.16	0.18
MgO	8.84	3.41	7.78	3.69	7.41	8.00	7.91	7.85	4.01	7.89	9.37	8.52
CaO	9.45	1.74	10.53	1.44	11.12	10.01	10.24	11.47	4.16	11.42	8.36	9.31
Na ₂ O	2.37	1.54	2.42	2.03	2.20	2.57	2.70	2.18	1.53	2.11	2.44	2.36
K2 O	0.23	2.34	0.15	1.54	0.16	0.16	0.21	0.12	1.58	0.11	0.26	0.44
P2 O5	0.17	0.21	0.19	0.07	0.18	0.18	0.19	0.15	0.36	0.17	0.17	0.18
H ₂ O	1.85		1.47	7.11	1.09	1.60	1.58	1.11	4.79	1.35	2.31	1.89
CO ₂	0.32	and the second	0.20	0.54	0.30	0.26	0.21	0.21	0.35	0.16	0.30	0.30
TOT	99.70	92.40	99.05	100.29	99.43	99.98	100.26	99.52	100.26	99.26	100.63	99.84
S	0.00	0.01	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C1	0.01	0.04	0.01	0.05	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
Sc		30.8			40.7	44.4		40.7	38.3	40.6		
V	319.	212.	353.	185.	348.	369.	385.	324.	204.	330.	337.	341.
Cr	193.	39.	285.	28.	174.	231.	111.	281.	199.	318.	233.	262.
Co	45.	27.7	42.	27.	50.5	48.7	45.	49.4	43.7	48.8	54.	43.
Ni	74.	60.	103.	65.	99.	89.	71.	104.	87.	132.	99.	100.
Cu	97.	301.	205.	118.	70.	128.	180.	149.	101.	110.	72.	88.
Zn	104.	84.	115.	130.	97.	106.	106.	90.	66.	111.	97.	101.
Rb	3.	71.	8.	68.	2.	3.	5.	4.	19.	3.	5.	4.
Sr	204.	122.	209.	100.	129.	259.	206.	212.	198.	210.	207.	256.
Y	29.	62.	37.	32.	29.	25.	29.	26.	48.	29.	31.	28.
Zr	97.	307.	120.	236.	105.	110.	115.	91.	175.	105.	107.	108.
Nb	7.	31.	8.	38.	6.	6.	6.	3.	15.	6.	6.	6.
La		30.2			6.3	5.7		5.1	16.2	6.4		
Ce		76.			17.3	15.5		13.7	37.5	17.3		
Nd		51.			13.3	12.0		12.4	24.0	13.5		
Sm		12.4			3.99	3.81		3.53	6.49	4.07		
Eu		3.76			1.48	1.44		1.33	2.16	1.51		
ть		2.15			0.86	0.77		0.78	1.38	0.89		
Yb		5.5			2.74	2.38		2.51	5.2	2.68		
Lu		0.71			0.39	0.38		0.37	0.71	0.39		
Hf		8.1			2.71	2.67		2.31	4.8	2.76		
Ta		2.45			0.43	0.41		0.33	1.08	0.45		
Th		2.85			0.57	0.60		0.49	1.32	0.64		
U		0.94			<0.15	<0.15		<0.15	0.29	<0.15		

Core-Sect	59R-3	60R-2	61R-2	61R-2	62R-1	64R-1	64R-5	65R-1	65R-1	66R-3	67R-1	67R-2
Interval	69-71	7-9	12 - 14	128-130	102-104	95-97	60-63	23-25	104-106	143-145	81-83	77-79
Mbsf	775.0	784.1	797.3	801.5	806.4	811.9	821.3	822.9	827.0	839.8	841.4	845.5
Lith.Unit	F62	F63	F64	F65	F66	F67	F69	F70	F71	F72	F73	F74
Chem.Group	USE	USE	USE	USD	USD	USD	USD	USD	USD	USD	USD	USD
SiO2	47.60	47.20	47.50	48.60	48.30	48.70	48.60	48.50	46.50	48.80	48.60	48.40
TiO ₂	2.66	2.31	2.72	1.81	1.83	1.81	1.82	1.92	1.89	2.00	2.11	2.10
A12 03	13.56	14.64	14.08	15.79	14.43	13.72	14.04	14.77	13.96	14.71	14.33	13.92
Fe ₂ O ₃	6.03	7.60	6.58	5.34	8.13	4.16	8.24	4.61	9.14	5.33	9.12	6.47
FeO	7.34	5.25	6.71	5.71	4.82	8.12	4.52	5.96	4.83	6.19	4.03	6.40
MnO	0.19	0.28	0.32	0.28	0.17	0.22	0.13	0.19	0.17	0.23	0.12	0.22
MgO	7.30	8.67	7.34	7.66	7.14	7.27	8.01	8.12	8.11	7.54	7.16	8.06
CaO	9.77	7.76	9.30	9.22	9.98	11.35	9.73	10.24	9.58	11.24	7.32	9.53
Na ₂ O	2.63	2.69	2.57	2.71	2.30	2.16	2.68	2.64	2.35	2.47	2.94	2.70
K ₂ O	0.23	0.34	0.12	0.18	0.71	0.13	0.45	0.19	0.31	0.18	0.54	0.20
P2 O5	0.27	0.22	0.27	0.17	0.14	0.16	0.16	0.18	0.12	0.18	0.19	0.20
H ₂ O	1.28	2.68	1.58	1.62	1.64	0.83	1.81	2.27	1.62	1.20	2.81	1.62
CO ₂	0.19	0.53	0.20	0.29	0.24	0.16	0.33	0.37	0.29	0.22	0.83	0.62
TOT	99.05	100.17	99.29	99.38	99.83	98.79	100.52	99.96	98.87	100.29	100.10	100.44
S	0.00	0.04	0.00	0.01	0.00	0.00	0.04	0.04	0.00	0.00	0.04	0.01
Cl	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.02	0.02
Sc	43.9			37.5		42.6				45.3		
v	424.	394.	428.	319.	329.	336.	315.	370.	341.	371.	346.	360.
Cr	256.	252.	128.	61.	203.	194.	177.	204.	215.	233.	106.	107.
Co	47.3	39.	45.	53.1	44.	49.9	48.	42.	46.	47.9	43.	45.
Ni	95.	119.	71.	80.	97.	94.	103.	100.	90.	79.	77.	77.
Cu	275.	103.	356.	384.	162.	154.	109.	106.	213.	117.	230.	203.
Zn	136.	144.	141.	119.	92.	96.	109.	99.	116.	112.	200.	118.
Rb	6.	5.	4.	6.	14.	5.	12.	6.	9.	4.	14.	6.
Sr	226.	194.	216.	246.	255.	235.	171.	186.	209.	239.	189.	211.
Y	39.	29.	41.	29.	27.	30.	30.	27.	21.	27.	35.	30.
Zr	157.	132.	159.	106.	104.	104.	105.	111.	108.	107.	123.	122.
Nb	11.	8.	9.	6.	6.	7.	11.	5.	8.	6.	5.	6.
La	9.5			6.6		6.6				6.8		
Ce	26.9			18.1		17.6				18.7		
Nd	20.3			14.1		11.9				13.6		
Sm	5.86			4.13		4.05				4.16		
Eu	2.09			1.53		1.49				1.58		
Tb	1.22			0.86		0.88				0.86		
Yb	3.9			2.31		2.92				2.6		
Lu	0.56			0.32		0.42				0.38		
Hf	4.22			2.96		2.7				2.91		
Ta	0.71			0.44		0.44				0.48		
Th	1.09			0.65		0.67				0.73		
U	<0.15			<0.15		0.14				<0.15		

Core-Sect	68R-1	68R-2	69R-2	69R-4	70R-2	71R-1	71R-4	72R-2	73R-3	75R-1	75R-2	76R-1
Interval	79-81	19-21	70-72	5-7	14-16	142-144	12-14	42-44	63-65	29-31	84-86	134-136
MOSI Lith Unit	840.0	830.2	870.1	871.0	879.0	881.7	888.7	893.2	891.0	911.1	917.5	919.5
Chem.Group	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD	USD
SiO2	48.80	48.70	48.70	48.90	48.90	48.70	48.20	48.10	49.20	48.70	46.30	48.10
TiO ₂	1.79	1.83	1.57	2.00	2.09	2.15	1.52	1.84	1.78	1.71	1.89	1.68
Al ₂ O ₃	14.39	13.84	15.33	13.66	14.55	14.52	15.10	14.80	14.09	16.95	13.96	14.41
Fe ₂ O ₃	5.81	6.54	5.35	5.12	5.75	6.01	4.67	8.07	5.58	8.02	9.10	5.84
FeO	5.68	5.64	6.00	7.67	6.23	5.92	6.02	4.62	6.85	2.65	5.30	6.22
MnO	0.24	0.18	0.16	0.22	0.25	0.29	0.16	0.18	0.21	0.09	0.17	0.18
MgO	7.97	8.06	7.79	7.26	7.44	7.15	8.41	7.63	7.15	6.99	8.57	7.96
CaO	10.04	10.65	10.97	11.08	10.83	10.29	11.25	9.39	11.27	8.10	8.90	11.06
Na ₂ O	2.50	2.44	2.16	2.33	2.31	2.60	2.21	2.41	2.31	2.75	2.50	2.28
K ₂ O	0.26	0.10	0.10	0.10	0.09	0.12	0.09	0.65	0.09	0.96	0.43	0.10
P2 O5	0.17	0.17	0.14	0.19	0.19	0.20	0.13	0.21	0.17	0.13	0.15	0.16
H ₂ O	1.53	1.73	1.45	1.02	1.25	1.40	1.62	1.63	1.03	2.82	1.63	1.45
CO ₂	0.26	0.41	0.25	0.17	0.18	0.26	0.17	0.27	0.13	0.57	0.29	0.20
TOT	99.44	100.29	99.97	99.72	100.06	99.61	99.55	99.80	99.86	100.44	99.19	99.64
S	0.00	0.04	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.04	0.00	0.00
Cl	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01
Sc			38.9	44.5	46.8		41.0		43.2			42.1
v	359.	367.	318.	366.	391.	392.	312.	348.	348.	299.	369.	340.
Cr	177.	291.	280.	156.	182.	183.	328.	165.	151.	217.	251.	244.
Co	46.	45.	48.9	48.6	46.8	47.	47.9	43.	48.1	36.	52.	48.3
NI	90.	83.	103.	80.	85.	81.	147.	88.	84.	96.	114.	104.
Cu	159.	117.	77.	142.	193.	182.	134.	317.	148.	90.	145.	143.
Zn	102.	110.	87.	108.	127.	115.	92.	89.	107.	93.	101.	72.
RD	9.	150	4.	8.	5.	3.	3.	8.	2.	10.	1.	3.
Sr V	204.	159.	190.	204.	300.	217.	189.	193.	202.	190.	221.	213.
1	105	105	20.	33.	31.	32.	20.	37.	31.	24.	33.	29.
21 Nb	105.	105.	91.	117.	122.	125.	90.	110.	100.	100.	120.	99.
Lo	0.	1.	1 9	6.9	6.9	1.	J. 7	5.	5 7	4.	1.	5.3
Co			14.9	10.0	10.0		12 5		16 2			14 5
Nd			10 9	13 5	14.6		10.9		12 1			12 0
Sm			3 49	4 42	A AA		3 45		3 94			3.75
En			1 32	1 57	1 62		1 31		1 46			1 39
Th			0.77	0.97	0.95		0.77		0.88			0.81
Yb			2.57	3.18	3.09		2.64		3.06			2.62
Lu			0.36	0.45	0.45		0.38		0.45			0.37
Hf			2.34	2.95	3.11		2.35		2.71			2.52
Та			0.33	0.42	0.44		0.31		0.36			0.33
Th			0.52	0.65	0.72		0.45		0.61			0.52
U			<0.15	<0.15	0.14		<0.1		<0.1			<0.15
Ta Th U			0.33 0.52 <0.15	0.42 0.65 <0.15	0.44 0.72 0.14		0.31 0.45 <0.1		0.36 0.61 <0.1			

Core-Sect Interval Mbsf Lith.Unit Chem.Group	76R-2 122-124 923.9 F88 USD	77R-3 99-101 935.4 F89 USD	78R-2 32-34 937.7 F90 USD	79R-1 26-28 944.3 F91 USD	79R-2 26-28 957.0 F92 USD	80R-1 12-14 964.2 F93 USD	81R-1 96-98 972.7 F94A USD	83R-1 26-28 979.0 F95 USD	84R-1 11-13 996.2 F96 USD	85R-3 95-97 1001.6 F97 USD	86R-1 34-36 1014.4 F98 USD	86R-2 0-2 1016.5 S40
Si0.	47.40	48.60	48.10	48.00	47 60	48 70	48.40	47.70	48.30	48.20	48.70	48.50
TiO	1.65	2.08	1 99	1.83	1 75	1 71	1.72	1.64	1.87	1.78	1.56	1.80
A1.02	14.78	14.06	14.46	14.63	14.36	15.15	14.53	14.59	14.88	13.92	15.06	14.55
Fee Oa	6.03	5.69	5.86	7.59	5.41	4.79	6.50	8.83	5.36	3.90	5.68	12.52
FeO	5.11	7.29	6.24	4.62	6.64	6.17	6.03	4.25	5.44	7.88	6.52	2.71
MnO	0.36	0.21	0.18	0.16	0.17	0.26	0.22	0.10	0.21	0.23	0.25	0.12
MgO	8.84	7.00	7.06	8.93	8.96	7.29	7.41	8.29	7.49	7.21	7.26	7.78
CaO	9.50	11.19	11.21	9.39	9.08	12.02	11.14	8.44	11.29	11.65	11.18	5.30
NavO	2.44	2.52	2.39	2.63	2.51	2.23	2.39	2.64	2.47	2.17	2.27	2.64
K ₂ O	0.14	0.11	0.10	0.18	0.21	0.08	0.25	0.33	0.16	0.15	0.10	0.79
Pa Os	0.15	0.20	0.19	0.16	0.17	0.16	0.19	0.13	0.18	0.17	0.14	0.23
H ₂ O	2.54	1.11	1.14	2.44	2.22	1.39	1.00	2.22	1.25	1.08	1.12	1.76
CO ₂	0.39	0.22	0.24	0.32	0.29	0.15	0.16	0.46	0.20	0.15	0.20	0.43
TOT	99.33	100.28	99.16	100.88	99.37	100.10	99.94	99.62	99.10	98.49	100.04	99.13
S	0.04	0.00	0.00	0.04	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.01
C1	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Sc		44.9	44.2			44.3						44.6
v	334.	367.	359.	342.	336.	339.	333.	309.	363.	343.	316.	299.
Cr	235.	140.	218.	258.	226.	293.	236.	133.	183.	174.	127.	165.
Co	49.	47.1	47.1	50.	46.	45.8	43.	43.	38.	41.	40.	50.4
Ni	112.	77.	91.	134.	114.	81.	93.	94.	94.	94.	74.	88.
Cu	210.	92.	149.	116.	122.	176.	75.	94.	162.	147.	202.	980.
Zn	101.	106.	110.	115.	121.	90.	94.	75.	105.	84.	94.	90.
Rb	6.	3.	3.	2.	3.	3.	5.	12.	2.	9.	4.	12.
Sr	170.	223.	221.	174.	198.	211.	205.	177.	227.	207.	186.	182.
Y	24.	33.	31.	27.	28.	32.	35.	33.	27.	30.	29.	47.
Zr	97.	122.	117.	106.	101.	101.	112.	97.	113.	107.	94.	112.
Nb	7.	7.	6.	6.	6.	5.	6.	5.	7.	6.	6.	7.
La		6.9	6.9			5.5						13.2
Ce		17.9	19.7			14.8						30.7
Nd		12.5	14.7			11.7						21.3
Sm		4.47	4.54			3.90						5.89
Eu		1.55	1.66			1.41						2.04
Tb		0.85	0.96			0.83						1.31
Yb		2.87	3.04			2.75						3.69
Lu		0.45	0.44			0.40						0.51
HI		2.92	3.16			2.55						3.02
Ta		0.43	0.47			0.36						0.42
Th		0.59	0.69			0.52						0.73
U		(0.15	(0.15			(0.15						0.18

Core-Sect Interval Mbsf	86R-3 37-40 1020.9	86R-4 29-32 1024.3	87R-1 4-6 1027.7	87R-1 103-105 1028.7	87R-2 44-46 1029.7	88R-2 63-65 1043.8	89R-1 112-114 1045.2	90R-2 16-18 1050.8	90R-3 128-130 1057.3	91R-2 75-77 1064.3	93R-3 39-41 1073.0 F105	93R-4 127-130 1073.9
Chem.Group	USD	USD	USD	541	USD	USD	USD	USC	USC	USC	USC	USC
SiO2	48.30	48.80	48.60	49.30	48.30	48.80	48.50	48.60	47.90	48.00	46.80	48.30
TiO ₂	1.82	1.71	1.64	1.73	1.70	1.40	1.58	1.26	1.23	1.25	0.99	1.16
Al ₂ O ₃	15.37	13.87	15.19	12.64	14.12	14.56	15.52	15.20	14.78	14.74	14.39	15.14
Fe ₂ O ₃	6.69	6.51	5.04	14.32	5.58	5.91	5.92	4.01	6.60	6.38	3.49	3.59
FeO	5.04	6.11	6.33	1.35	6.56	4.78	4.67	6.38	4.64	5.26	7.04	6.81
MnO	0.28	0.19	0.21	0.13	0.18	0.23	0.34	0.18	0.19	0.22	0.19	0.21
MgO	8.16	8.00	7.42	6.06	7.53	8.54	7.79	8.62	9.16	9.06	10.21	9.23
CaO	8.25	10.67	11.10	4.94	11.60	11.83	11.49	12.16	10.86	10.86	10.69	12.13
Na ₂ O	2.88	2.40	2.36	2.45	2.33	2.17	2.44	1.79	2.02	2.12	1.80	1.87
K2 O	0.21	0.30	0.21	0.55	0.10	0.15	0.14	0.09	0.23	0.13	0.23	0.13
P2 O5	0.18	0.16	0.16	0.07	0.16	0.12	0.15	0.11	0.11	0.09	0.09	0.11
H ₂ O	2.24	1.36	1.52	5.19	1.12	1.35	1.86	1.71	2.68	1.52	3.51	1.91
CO ₂	0.46	0.11	0.15	0.87	0.13	0.41	0.14	0.17	0.51	0.29	0.21	0.06
TOT	99.88	100.19	99.93	99.60	99.41	100.25	100.54	100.28	100.91	99.92	99.64	100.65
S	0.04	0.04	0.00	0.05	0.00	0.03	0.04	0.00	0.04	0.01	0.00	0.04
C1	0.02	0.01	0.02	0.03	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01
Sc			42.3		50.4			44.5		45.1	41.9	
v	347.	339.	312.	298.	376.	311.	344.	303.	292.	304.	260.	287.
Cr	253.	240.	256.	135.	148.	315.	304.	303.	281.	215.	339.	344.
Co	43.	46.	52.9	39.	60.7	41.	38.	147.	42.	53.4	53.5	43.
Ni	112.	117.	109.	93.	83.	118.	123.	110.	115.	98.	151.	164.
Cu	351.	253.	168.	119.	70.	133.	264.	150.	119.	99.	135.	128.
Zn	127.	103.	98.	77.	106.	90.	114.	82.	88.	84.	70.	91.
Rb	5.	9.	3.	17.	6.	6.	5.	2.	12.	5.	14.	4.
Sr	181.	159.	194.	94.	175.	160.	176.	164.	127.	219.	178.	116.
Y	23.	30.	27.	38.	31.	28.	24.	22.	24.	22.	19.	23.
Zr	114.	108.	101.	137.	97.	85.	95.	69.	70.	75.	59.	71.
Nb	3.	6.	5.	14.	5.	6.	3.	4.	4.	5.	2.	4.
La			6.5	1 78 BOX	6.	202		3.4		3.3	2.81	
Ce			17.3		16.3			9.		9.2	7.1	
Nd			12.8		12.4			7.3		7.5	5.9	
Sm			3.75		3.76			2.6		2.39	2.14	
Eu			1.33		1.38			0.96		0.94	0.81	
Tb			0.77		0.85			0.56		0.57	0.47	
Yb			2.46		2.89			2.14		2.35	1.77	
Lu			0.35		0.39			0.32		0.32	0.26	
Hf			2.62		2.51			1.59		1.92	1.49	
Та			0.51		0.55			17. 2. 7. 7. 18.		0.25	0.17	
Th			0.94		0.56	<u>.</u>		0.32		0.59	0.33	
U			0.19		<0.15			<0.2		<0.15	<0.15	

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Core-Sect	93R-4	94R-4	95R-1
Interval	135-138	126-128	134-137
Mbsf	1074.0	1088.4	1091.5
Lith.Unit	F105	\$43	\$43
Chem.Group	USC	UPPER S.	LOWER S.
SiO2	48.00	42.50	51.60
TiO2	0.80	1.31	1.62
Al2 03	13.18	25.45	16.61
Fe2 O3	5.16	15.27	15.90
FeO	5.75	1.03	0.97
MnO	0.13	0.09	0.03
MgO	11.93	0.41	0.71
CaO	9.96	0.78	1.07
Na ₂ O	1.74	0.92	0.95
K2 O	0.08	0.79	2.71
P2 O5	0.06	0.12	0.43
H ₂ O	3.18	11.51	6.11
CO2	0.19	0.39	0.38
TOT	100.16	100.57	99.09
S	0.04	0.04	0.05
C1	0.01	0.06	0.03
v	213.	275.	103.
Cr	305.	206.	85.
Co	60.	85.	33.
Ni	171.	313.	97.
Cu	366.	38.	105.
Zn	66.	206.	101.
Rb	6.	50.	245.
Sr	99.	37.	64.
Y	13.	19.	99.
Zr	49.	131.	291.
Nb	4.	7.	24.

Figure 11. Modeling of source compositions and degree of partial melting of the tholeiitic rocks of Hole 642E. (A) relatively unfractionated flows of groups USD, USF, and USG could have been formed by 8 to 10% batch partial melting of a spinel lherzolite mantle source that was only slightly depleted in Th, Ta, La, and Ce, and slightly enriched in Nd, Sm, Eu, and Tb. (Modal source composition: 60% OLIV, 25% OPX + SPINEL, 15% CPX; melting proportions: 0.7 CPX, 0.3 OPX + SPINEL.) (B) Group USC flows at the transition from lower to upper series apparently derived from a moderately depleted spinel-lherzolite mantle source. The slightly enhanced Th and Ta abundances are most likely due to mixing with a crustal component [same modal source composition and melting proportions as in (A)]. (C) the complex Th-Ta-REE pattern of tholeiitic dikes D5 and D6 most likely reflects mixing of a melt derived from a strongly depleted, shallow plagioclase-lherzolite mantle source with Th-LREE enriched melts originating from crustal anatexis. The continental crustal signature is clearly reflected in the negative Taanomaly. The unusually high Yb abundances of D5 and D6 point to rather small (less than 5%) degrees of partial melting. (Mantle source composition: 60% OLIV, 20% OPX, 10% CPX, 10% PLAG; melting proportions: 0.15 OPX, 0.25 CPX, 0.6 PLAG.) The filled hexagons are the average concentrations of tholeites of Hole 553A, DSDP Leg 81, Rockall Plateau (Joron et al., 1984). The good match to the 5% model batch melt composition suggests that the strongly depleted mantle source inferred for D5 and D6 at the Vøring Plateau was more than just a local feature.

Figure 12. MORB-normalized variation of hygromagmaphile elements in volcaniclastic sediment units of the upper series, Hole 642E. The least-enriched Unit S40 is situated in the lower sediment group of the upper series. Compositional range of the Eocene ash layers in the Olst Formation of Denmark and Miocene tuffs drilled in the IRDP drill hole in eastern Iceland (Schmincke et al., 1982) are given for comparison. MORB normalization values are from Pearce et al. (1984).