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22. THE PETROLOGY OF THE LOWER SERIES VOLCANICS, ODP SITE 642[1]

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ABSTRACT

Between 1086.6 and 1229.4 m below seafloor at Site 642 on the Outer Vøring Plateau, a series of intermediate volcanic extrusive flow units and volcaniclastic sediments was sampled. A mixed sequence of dacitic subaerial flows, andesitic basalts, intermediate volcaniclastics, subordinate mid-ocean ridge basalt, (MORB) lithologies, and intrusives was recovered, in sharp contrast to the more uniform tholeiitic T-type MORB units of the overlying upper series. This lower series of volcanics is composed of three chemically distinct groups, (B, A2, A1), rather than the two previously identified. Flows of the dacitic group (B) have trace-element and initial Sr isotope signatures which indicate that their source magma derived from the partial melting of a component of continental material in a magma chamber at a relatively high level in the crust. The relative proportions of crustal components in this complex melt are not known precisely. The most basic group (A2) probably represents a mixture of this material with MORB-type tholeiitic melt. A third group (A1), of which there was only one representative flow recovered, is chemically intermediate between the two groups above, and may suggest a repetition of, or a transition phase in, the mixing processes.

INTRODUCTION

Site 642 was selected for drilling during ODP Leg 104 because it offered an excellent opportunity to test a number of currently available models for the interpretation of the structure and evolution of the volcanic sequences associated with the ocean-continent transition (OCT) at passive margins recently reviewed by (Morton and Parson, 1988). These models deal with both general and specific distribution of continental and oceanic crust at these sites. The identification of continental material at depth beneath Site 642 as reported by Eldholm, Thiede, Taylor, et al. (1987) is of vital importance not only to the positioning of the OCT zone and therefore continental reconstruction, but also for an understanding of the early structuring and evolution of passive volcanic margins, in particular those along the northwestern European margin. The northwestern outer Vøring Plateau (Fig. 1A), like many northeastern Atlantic margins north of 55°N, is characterized by a thick, margin-parallel sequence of basaltic lava flows disposed in a seaward-thickening and seaward-inclined wedge readily mappable on seismic reflection profiler data.

The seismic horizons which characterize these sequences appear to diverge on profiles towards the ocean basin. A shallow section of these so-called dipping reflectors was sampled during Leg 81 of the Deep Sea Drilling Project (DSDP) on the western Rockall Plateau in the northeastern Atlantic (Roberts, Schnitker, et al., 1984). These rocks were found to be plagioclase-clinopyroxene-olivine phyric tholeiites, and are described as highly light rare-earth element (LREE) depleted normal mid-ocean ridge basalt (MORB) in character by Joron et al. (1984). This appears to indicate an advanced stage of rifting or early drifting in progress at the time of their deposition. During Leg 104, a thick sequence of similar lithologies was recovered from Site 642 between 336.9 and 1086.6 m below seafloor (mbsf) (Eldholm, Thiede, Taylor, et al., 1987; Viereck et al., 1988); these are referred to as the upper series volcanics. However, these MORBs are slightly LREE-enriched, and their consistently parallel convex upward REE pattern suggests different degrees of partial melting of a relatively homogeneous mantle source (Eldholm, Thiede, Taylor, et al., 1987).

It is now recognized that these basalts were deposited during a period of extensive extrusive activity which dominated the margin evolution during the final stages of rifting and earliest seafloor spreading (Eldholm, Thiede, Taylor, et al., 1987; Skogseid and Eldholm, 1987). This extrusive period took place over a relatively short time interval of between 2 and 5 m.y., but composite thicknesses of more than 6 km have been recorded for some sections (Hinz, 1981). Equivalents of the dipping reflector sequences onshore can exceed this, reaching 7 km in thickness in the case of the East Greenland Plateau lavas (Nielsen and Brooks, 1981). At their oceanward limit, the smooth dipping seismic reflectors almost invariably give way to the more typically rough and hummocky oceanic basement surface. Dipping seismic horizons typically occur within oceanic crust, but at more widely spaced and irregular intervals (Parson et al., 1986; Larsen and Jakobsdottir, 1988). On some seismic sections, away from the OCT, the flow units are seen to lap onto poorly-defined structural highs, an example of which is particularly well developed at the Vøring Plateau (Skogseid and Eldholm, 1987). An understanding of the geology of this particular high was one of the prime objectives of Leg 104. The basement floor to this sequence has been identified as a readily mapped horizon on seismic records over the western Vøring Plateau, but similar, distinct bases are only recognized over a few other localities of dipping reflector formation elsewhere in the world (unpublished IOS and GGU multichannel seismic data; Parson et al., 1988). This surface on the Vøring Plateau has a local nomenclature, (K), but remained unsampled until ODP Leg 104.

Migrated multichannel seismic profile NH-1 shot by the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) was used to identify a site where the onlapping "feather edge" of the dipping reflector sequence could be readily drilled, and one which would allow a good opportunity to penetrate the underlying basement surface, K. The sampling procedure and analysis of both the sedimentary sequence (0–336.9 mbsf) and the upper se-

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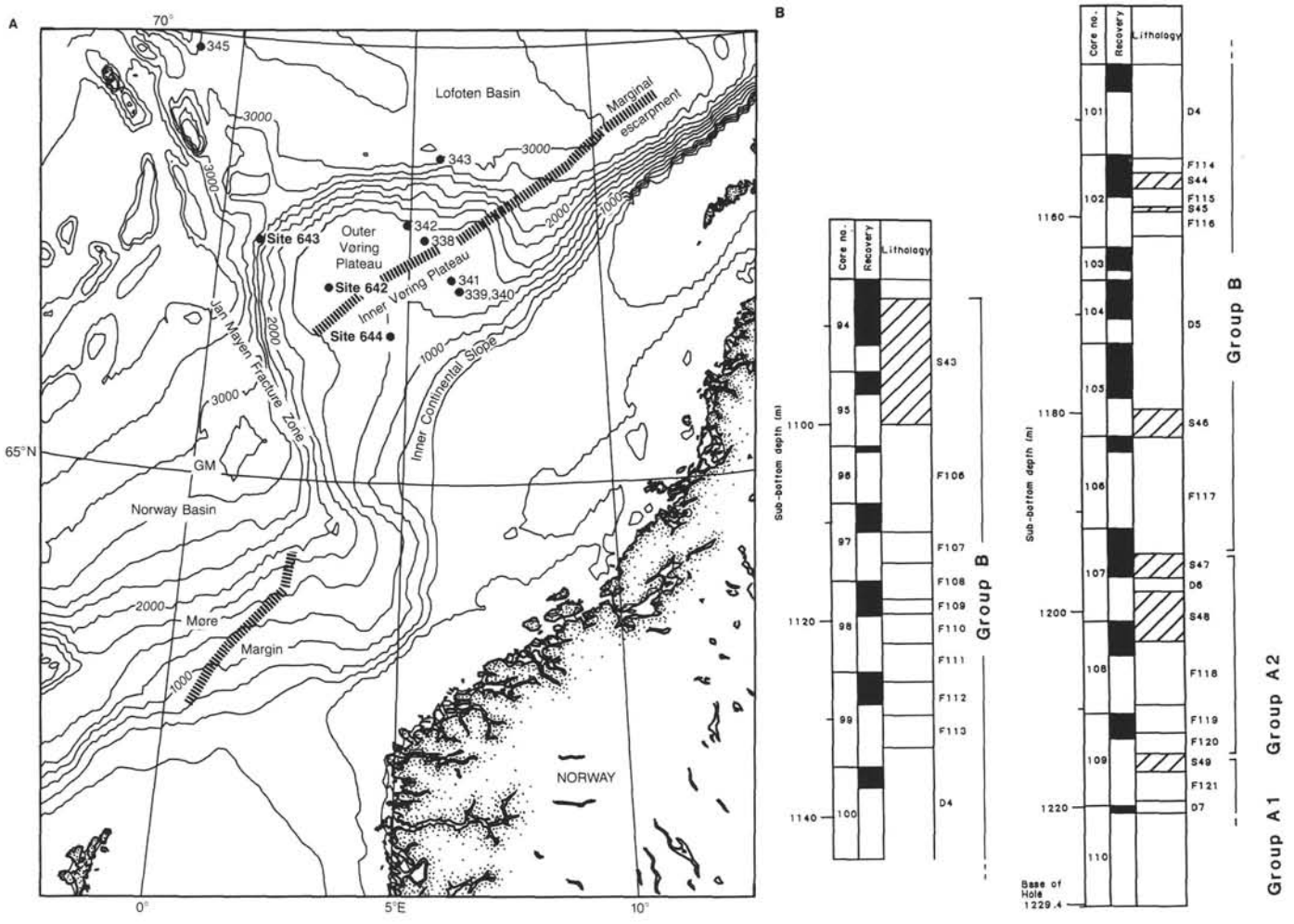


Figure 1. A: Location map for Site 642 on the outer Vøring Plateau. Contour interval 250 m. B: Revised grouping of lower series volcanics (cf. Eldholm, Thiede, Taylor, et al., 1987). Numbered circles locate DSDP and ODP drill sites.

ries volcanics (336.9–1086.6 mbsf) are discussed elsewhere (in general by Eldholm, Thiede, Taylor, et al., 1987, and more specifically by Viereck et al., this volume). Between 1086.6 and 1100.0 mbsf, a thick composite volcaniclastic unit, S43, was recovered. This was composed of several ignimbrite units, and was of intermediate to dacitic composition. It has been tentatively correlated to the seismic horizon K, and is fully discussed in Eldholm, Thiede, Taylor, et al. (1987).

Between 1100.0 and 1229.4 mbsf (terminal depth, Hole 642E), 16 extrusive flow units, 4 dykes, and 6 sedimentary units were identified during shipboard analysis (Fig. 1B). This mixed sequence is referred to as the lower series volcanics. The recovery from this section was only 36%, and, as no well logs were obtained from this section due to the bridging of the hole at around the level of reflector K, estimates of flow number and thickness may be in error. The flow units F106–F121 were originally described as being cut by four intrusions (D4–D7), interleaved with six volcaniclastic sedimentary units (S44–S49). Some doubt exists as to the intrusive status of the dykes D4 and D7.

The flow units were originally separated into two groups based on their major- and trace-element and isotopic compositions (Eldholm, Thiede, Taylor, et al., 1987). F106–F117 (Group B) are a series of andesitic/dacitic peraluminous flows, overlying flows F118–F121 (Group A of Eldholm, Thiede, Taylor, et al., 1987), generally fine-grained to microcrystalline basaltic andesites. The interleaved volcaniclastic sediments S44–S49 are highly altered, but are estimated to be of andesitic or dacitic composition. Within the sedimentary units, there is no clear chemical division analogous to that of the extrusive volcanics within which they are deposited. Two of the four intrusions identified by the shipboard party (D5 and D6), are of similar tholeiitic composition to the upper series apart from an enrichment of LIL elements suggesting some crustal contamination. They are considered to be early intrusives, postdating the deposition of the lower series but preceding the true feeder dykes for the upper series. The remaining two units D4 and D7 were initially described as dykes, due to their unusual apparent thickness, although chilled margins were not recovered. Viereck et al. (1988 and this volume) reinterpreted them as thick, coarsely crystalline flows, as their compositions are very similar to the units into which they "intrude." Although the original interpretation is here favored on grounds of their unusual morphology, (the average flow thickness is only 5.2 m, yet D4 is identified over at least 20.8 m of the section), without further sampling, the question is not resolved.

It is here proposed that the lower group (A of Eldholm, Thiede, Taylor, et al., 1987) should be further subdivided into two groups, Al and A2, following the reappraisal of the chemical analyses of flow F121. It is chemically distinct from flows F118–F120, intermediate between these flows and those of Group B. We will describe and compare the detailed chemical characteristics of the groups below.

ANALYTICAL TECHNIQUES

Wherever possible, samples were taken from each of the geological units recovered from the lower series, and analyzed at a number of laboratories in three countries. Petrographic work was completed at the Institute of Oceanographic Sciences (IOS), United Kingdom; the British Geological Survey (BGS), United Kingdom; Ruhr-Universitaet, Bochum, (FRG); and Waterloo, Canada (CAN). Tables 1–5 are geochemical analyses of lower series volcanics, Site 642. Electron microprobe analyses were carried out at BGS using a Link Systems energy-dispersive X-ray analyzer attached to a Geoscan electron microprobe. Major and trace element data were obtained by X-ray fluorescence spectroscopy and atomic absorption techniques at the University of Newcastle-upon-Tyne (using a Phillips PW1410 system) and at Midland Earth Science Associates in the United Kingdom, as well as at the Ruhr-Universitaet, Bochum, FRG. Rare-earth elements were determined by neutron activation analysis at the University of Waterloo (Canada), Imperial College of Science and Technology, Reactor Centre, (UK), and at the Katholieke Universitet, Leuven, Belgium. Isotope analyses were obtained from the Department of Earth Sciences, Oxford University, United Kingdom. Methods of isotopic analysis are discussed by Taylor and Morton (this volume). A blank instead of a value indicates no analysis, rather than zero content. LAB: analyzing laboratory (see below); D (MBK): depth in meters below reflector K for extrusives. Geochemical analysis sites are identified in Tables 1–4, and techniques are discussed in the captions.

The highly altered state of many of the samples coupled with a locally poor recovery prevented a full analysis being undertaken on every unit. Regrettably, no interlaboratory standardizations were performed but the relative accuracy of the mixed data set appears acceptable and consistent throughout the range of analyses. Flows F106 and F111 were not analyzed due to a lack of satisfactory sample material. Of the remaining flows, analysis of major- and trace-element concentrations confirmed the high degree of alteration throughout (mean loss on ignition was approximately 5%, mean K_2O and CaO were 1.7% and 4.5%, respectively). Nevertheless, the results of all the analyses carried out appear in Tables 1–3, without differentiation between acceptable and nonacceptable alteration states. It would be fair to state that in rigorous comparative work, the majority of these samples would be treated with extreme care or discarded. In practice, however, there are so few data for these rocks that they are all included in the discussion.

COMPARISON OF LOWER SERIES GROUPS A1, A2 AND B

Petrographically the Group B units are composed of perlitic glassy to microcrystalline dacites, plagioclase-hypersthene phyric, with total phenocryst content between 2 and 10%. Plagioclase phenocrysts are with few exceptions weakly normally zoned bytownites, with a mean composition of An_{80} and ranging between An_{64} and An_{84}. Interstitial plagioclase lath compositions are around An_{72}. Pyroxene compositions fall mainly within hypersthene limits (Fig. 2), between En_{44} and En_{46} (Fig. 2 and Table 4).

Additional probe analyses of glass matrices are indicated for flows F109 and F117 in Table 4. Poorly twinned cordierite phenocrysts in Group B make up less than 1% in phenocryst content of flows F116, F117, and D4. Groups A1 and A2 are represented by microcrystalline lithologies with little glassy matrix. Glomerocrysts of bytownite and clinopyroxene dominate the phenocryst phase. No examples of cordierite were identified.

Table 1. Major-element analyses of lower series volcanics, Site 642. All analyses are included despite high levels of alteration. Laboratory key as follows: UKA = University of Newcastle-upon-Tyne; UKB = Midland Earth Science Associates, University of Nottingham; CAN = University of Waterloo, Canada; FGR = Institut fur Mineralogie, Bochum; LOI = loss on ignition.

Unit	Lab	Sample	D(MBK)	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	FeO T	MnO	MgO	CaO	Na_2O	K_2O	P_2O_3	LOI
F107	UKB	97-1- 130–132	12.00	59.05	1.28	15.69	10.28	—	—	0.06	1.60	2.26	2.02	1.03	0.09	6.79
F107	UKA	97-1- 133–135	12.80	59.90	1.26	15.20	9.76	—	—	0.11	1.76	2.44	2.18	1.14	0.14	5.70
F108	UKB	97-2- 129–131	14.90	61.31	1.32	15.22	8.21	—	—	0.20	1.00	3.11	2.16	0.49	0.19	7.03
F108	CAN	98-1- 48–50	16.20	59.40	1.40	17.10	6.95	—	—	0.07	0.81	3.80	2.59	0.54	0.05	0.16
F108	CAN	98-1- 58–60	16.50	58.60	1.20	14.80	9.67	—	—	0.13	1.54	2.78	2.22	1.71	0.18	6.93
F108	UKA	98-1- 60–62	16.80	61.10	1.28	14.80	9.34	—	—	0.12	1.61	2.88	2.31	1.61	0.28	4.92
F109	CAN	98-1- 147–149	17.50	53.00	1.33	16.10	7.64	—	—	0.41	1.01	7.66	2.55	0.45	0.21	8.54
F108	CAN	98-2- 16–18	17.70	57.50	1.41	17.20	7.61	—	—	0.12	0.98	4.95	2.91	0.48	0.09	6.00
F109	FGR	98-2- 69–72	18.00	61.10	1.17	14.61	3.22	5.79	8.68	0.13	1.59	3.02	2.21	1.75	0.20	—
F109	UKB	98-2- 77–79	18.30	59.03	1.26	14.58	10.43	—	—	0.11	1.75	2.90	2.08	1.29	0.18	6.15
F109	CAN	98-2- 81–83	18.60	58.30	1.28	15.30	9.98	—	—	0.21	1.47	2.59	2.13	1.47	0.13	7.54
F110	UKB	99-1- 5–7	20.02	61.03	1.21	14.49	9.13	—	—	0.13	1.50	2.81	2.63	0.81	0.18	5.66
F112	UKB	99-2- 45–47	27.80	63.78	1.38	16.85	5.79	—	—	0.06	0.62	4.64	2.35	1.38	0.61	—
F113	FGR	100-1- 31–33	30.60	67.20	1.20	14.25	4.88	1.62	6.01	0.05	0.43	1.62	1.84	2.94	0.16	—
F113	UKA	100-1- 118–120	32.10	60.40	1.26	16.20	9.44	—	—	0.06	0.88	3.92	2.36	0.52	0.11	3.32
D4	FGR	101-1- 98–100	—	63.00	1.20	14.68	2.65	5.18	7.56	0.10	1.65	3.58	2.38	0.77	0.19	—
D4	UKA	101-1- 109–111	—	64.50	1.15	14.40	7.93	—	—	0.10	1.57	3.48	2.82	0.82	0.18	3.00
D4	UKB	101-2- 25–27	—	59.43	1.45	17.77	10.05	—	—	0.06	1.63	4.57	2.73	0.56	0.19	1.77
F114	CAN	102-1- 13–15	54.50	57.00	1.31	19.10	1.45	—	—	0.02	0.35	3.25	2.48	8.24	0.24	5.85
F114	UKA	102-1- 20–22	54.90	49.00	1.44	17.70	14.90	—	—	0.12	2.40	3.50	2.06	0.64	0.23	5.35
F114	CAN	102-1- 33–35	55.00	48.00	1.43	17.50	11.70	—	—	0.09	2.02	3.18	1.68	0.40	0.25	13.80
F115	FGR	102-1-2 146–40	58.20	61.60	1.42	19.26	0.22	0.42	0.62	0.01	0.16	3.61	1.86	8.59	0.29	—
F115	UKA	102-2- 4–6	58.50	53.20	1.36	16.50	13.80	—	—	0.12	2.98	2.84	1.98	0.34	0.16	5.62
F115	CAN	102-2- 23–25	58.80	60.80	1.26	18.30	0.47	—	—	0.01	0.11	3.14	1.98	8.60	0.28	4.23
F116	CAN	102-2- 68–70	60.50	59.30	1.30	17.90	3.15	—	—	0.01	0.91	4.04	2.68	4.50	0.26	5.85
F116	CAN	102-2- 94–96	60.80	54.50	1.29	16.00	9.09	—	—	0.04	2.76	4.41	2.49	0.37	0.22	8.23
F116	CAN	102-2- 113–115	61.40	60.00	1.12	13.90	8.83	—	—	0.14	1.66	1.19	3.08	0.19	0.19	5.08
F116	UKA	102-2- 114–115	61.70	61.90	1.24	14.20	9.24	—	—	0.15	1.98	3.39	3.13	1.05	0.19	2.83
D5	UKA	104-1- 18–20	—	51.80	1.20	13.30	13.70	—	—	0.23	6.37	10.40	2.52	0.22	0.09	0.25
D5	FGR	105-2- 84–86	—	48.90	1.07	13.28	5.53	7.66	12.64	0.21	8.43	9.84	2.09	0.11	0.10	—
F117	CAN	106-1- 33–35	82.80	59.10	1.37	17.30	5.03	—	—	0.11	1.23	4.64	2.88	2.64	0.16	4.62
F117	UKA	106-1- 86–88	83.00	60.00	1.26	15.30	9.52	—	—	0.16	2.08	3.99	2.88	0.63	0.23	3.16
D6	UKA	107-2- 82–84	—	49.40	1.50	18.20	9.48	—	—	0.16	5.19	7.52	3.61	0.34	0.13	2.25
F118	FGR	108-2- 51–53	103.50	48.90	1.18	17.11	7.23	2.59	9.10	0.16	5.21	7.48	2.98	1.66	0.18	—
F118	UKB	108-2- 55–57	103.60	49.97	1.19	16.97	10.41	—	—	0.18	5.14	7.60	3.27	1.57	0.18	3.24
F119	UKA	109-1- 17–19	109.80	49.50	1.17	17.60	11.30	—	—	0.12	6.11	6.75	3.17	1.20	0.15	2.00
F120	UKB	109-1- 51–52	112.50	47.02	1.24	16.66	13.64	—	—	0.12	5.95	6.51	3.10	0.86	0.17	4.62
F121	FGR	109-2- 79–81	118.00	51.70	1.51	14.87	7.93	3.42	10.63	0.14	3.07	5.66	2.68	2.14	0.19	—
F121	UKA	109-2- 90–92	118.20	55.50	1.32	16.10	10.20	—	—	0.10	3.00	5.57	3.12	2.16	0.18	2.17
D7	FGR	110-1- 28–30	—	54.20	1.33	15.55	7.73	2.68	9.64	0.27	2.33	6.81	2.68	1.33	0.16	—
D7	UKA	110-1- 44–46	—	51.90	1.00	15.80	10.90	—	—	0.24	3.39	8.04	2.68	1.02	0.11	2.27

Table 2. Trace-element abundances of lower series volcanics, Site 642. Laboratory key as for Table 1.

Unit	Lab	Sample	D(MBK)	V	Cr	Co	Ni	Cu	Zn	Rb	Sr	Y	Zr	Nb	Sc	Ba	Li	Pb
F107	UKB	97-1- 130-132	12.00	117.00	116.00	15.00	5.00	12.00	100.00	59.00	102.00	28.00	270.00	20.00	31.00	279.00	—	16.00
F107	UKA	97-1- 133-135	12.80	159.00	65.00	10.00	12.00	13.00	165.00	61.00	119.00	34.00	197.00	20.00	26.00	—	17.00	28.00
F108	UKB	97-2- 129-131	14.90	119.00	76.00	12.00	3.00	10.00	57.00	34.00	158.00	82.00	276.00	23.00	30.00	228.00	—	14.00
F108	CAN	98-1- 48-50	16.20	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F108	CAN	98-1- 58-60	16.50	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F108	UKA	98-1- 60-62	16.80	165.00	68.00	10.00	10.00	12.00	122.00	84.00	143.00	82.00	285.00	19.00	31.00	—	12.00	28.00
F109	CAN	98-1- 147-149	17.50	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F109	CAN	98-2- 16-18	17.70	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F109	FGR	98-2- 69-72	18.80	137.00	58.00	7.00	14.00	8.00	126.00	87.00	148.00	48.00	251.00	16.00	—	407.00	—	—
F109	UKB	98-2- 77-79	18.30	139.00	136.00	21.00	13.00	12.00	123.00	71.00	132.00	51.00	258.00	19.00	30.00	390.00	—	21.00
F109	CAN	98-2- 81-83	18.60	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F110	UKB	99-1- 5-7	20.02	117.00	84.00	10.00	11.00	21.00	112.00	83.00	141.00	47.00	277.00	21.00	27.00	506.00	—	25.00
F112	UKB	99-2- 45-47	27.80	154.00	177.00	29.00	17.00	11.00	109.00	26.00	214.00	118.00	320.00	24.00	34.00	516.00	—	27.00
F113	FGR	100-1- 31-33	30.60	116.00	65.00	3.00	9.00	30.00	75.00	120.00	159.00	43.00	270.00	19.00	—	530.00	—	—
F113	UKA	100-1- 118-120	32.10	160.00	66.00	15.00	18.00	15.00	78.00	20.00	213.00	31.00	324.00	22.00	25.00	—	22.00	20.00
D4	FGR	101-1- 98-100	—	116.00	87.00	7.00	18.00	21.00	117.00	63.00	212.00	48.00	263.00	17.00	—	434.00	—	—
D4	UKA	101-1- 109-111	—	153.00	59.00	13.00	12.00	13.00	115.00	70.00	187.00	43.00	296.00	20.00	16.00	—	21.00	20.00
D4	UKB	101-2- 25-27	—	154.00	78.00	18.00	16.00	16.00	73.00	16.00	230.00	67.00	331.00	24.00	32.00	429.00	—	26.00
F114	CAN	102-1- 13-15	54.50	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F114	UKA	102-1- 20-22	54.90	203.00	85.00	34.00	25.00	26.00	128.00	25.00	134.00	51.00	363.00	24.00	28.00	—	86.00	24.00
F114	CAN	102-1- 33-35	55.00	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F115	FGR	102-1-2 146-40	58.20	120.00	64.00	3.00	16.00	31.00	139.00	201.00	230.00	85.00	322.00	22.00	—	189.00	—	—
F115	UKA	102-2- 4-6	58.50	186.00	68.00	10.00	10.00	15.00	125.00	21.00	115.00	39.00	345.00	22.00	26.00	—	81.00	20.00
F115	CAN	102-2- 23-25	58.80	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F116	CAN	102-2- 68-70	60.50	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F116	CAN	102-2- 94-96	60.80	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F116	CAN	102-2- 113-115	61.40	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F116	UKA	102-2- 114-115	61.70	165.00	63.00	16.00	10.00	15.00	112.00	91.00	183.00	42.00	292.00	20.00	26.00	—	17.00	12.00
D5	UKA	104-1- 18-20	—	461.00	127.00	50.00	58.00	63.00	113.00	4.00	65.00	32.00	68.00	3.00	48.00	—	10.00	—
D5	FGR	105-2- 84-86	—	362.00	268.00	53.00	163.00	65.00	111.00	2.00	121.00	34.00	67.00	1.00	—	71.00	—	—
F117	CAN	106-1- 33-35	82.80	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F117	UKA	106-1- 86-88	83.00	166.00	61.00	15.00	14.00	16.00	122.00	54.00	213.00	47.00	306.00	20.00	29.00	—	36.00	20.00
D6	UKA	107-2- 82-84	—	595.00	206.00	63.00	76.00	86.00	158.00	8.00	107.00	41.00	97.00	4.00	65.00	—	28.00	—
F118	FGR	108-2- 51-53	103.50	229.00	166.00	35.00	11.00	30.00	129.00	44.00	185.00	36.00	127.00	6.00	—	242.00	—	—
F118	UKB	108-2- 55-57	103.60	250.00	261.00	41.00	11.00	21.00	109.00	46.00	144.00	45.00	126.00	8.00	49.00	343.00	—	10.00
F119	UKA	109-1- 17-19	109.80	300.00	165.00	42.00	12.00	25.00	115.00	30.00	160.00	41.00	151.00	8.00	51.001	—	14.00	8.00
F120	UKB	109-1- 51-52	112.50	261.00	235.00	67.00	4.00	28.00	101.00	24.00	165.00	47.00	126.00	7.00	58.00	344.00	—	12.00
F121	FGR	109-2- 79-81	118.00	170.00	89.00	31.00	15.00	28.00	125.00	80.00	198.00	45.00	194.00	12.00	—	382.00	—	—
F121	UKA	109-2- 90-92	118.20	233.00	94.00	29.00	6.00	14.00	156.00	79.00	158.00	43.00	223.00	14.00	44.00	—	42.00	12.00
D7	FGR	110-1- 28-30	—	200.00	108.00	35.00	16.00	14.00	120.00	52.00	145.00	42.00	146.00	9.00	—	280.00	—	—
D7	UKA	110-1- 44-46	—	285.00	152.00	7.00	6.00	17.00	106.00	40.00	136.00	31.00	130.00	8.00	50.00	—	23.00	4.00

No clear indication of tectonic setting of magma types is evident from the variations in clinopyroxene compositions such as proposed by Nisbett and Pearce (1976). A fairly broad spread of analyses throughout volcanic arc and within plate basalts is indicated without clear distinctions between upper and lower series samples (Fig. 3).

The major, trace and rare-earth characteristics of the groups have been summarized in Eldholm, Thiede, Taylor, et al. (1987), but means and ranges have been here recalculated to incorporate additional analyses from more altered lithologies. These calculations appear in Table 5.

Trace-element chemistry of the Group B lavas can be used to differentiate them from Groups A1 and A2 (Tables 1 and 2, and Fig. 4). Zirconium levels in flows F106–F117 (Group B) range between 251 and 363 ppm (A1 and A2: Zr = 126–306 ppm), Group B levels of Vanadium (116–203 ppm) contrast with A1 and A2 (166–300 ppm), and Chromium (B: 58–177 ppm) differentiates A2 (165–235ppm) and A1 (89–94 ppm).

Concentrations of incompatible trace elements niobium, zirconium, Strontium, and Rubidium further support a subdivision of the lower series lavas into the three chemical groups. The Zr/Nb plot (Fig. 5A) indicates the relative enrichment of the Group B lavas in both Zr and Nb with respect to those of Group A2 and a clear separation and clustering into their respective distributions. This separation is bridged by values for F121, the sole sampled representative of Group A1. A plot of Zr against Y (Fig. 5B) again clearly separates Groups B, A2, and A1, and confirms the closer affinity of the Group A2 lavas with the upper series lithologies (hachured in Figs. 5A and 5B) than with Group B lavas. Zr/Y ratios as indicated on the plot suggest a mixing trend between Group A2 and the upper series rocks; Rb/Sr and Zr/Rb plots (Figs. 5C and 5D) confirm this trend, despite wide spreads in both the rubidium values (10–200 ppm) and more surprisingly the yttrium values (25–125 ppm). Ternary discriminant plots such as the Hf/Ta/Th diagram indicate their concentration at the Thorium-rich limit of the volcanic arc basaltic field (Fig. 6).

LREE-enriched patterns of MORB-normalized concentrations are a clear and consistent characteristic of the lower series flows (Fig. 7). They compare well with those published by Morton et al. (1988) for the similar lithologies recovered from deep drilling in the Rockall Trough (Fig. 7), but contrast with the flatter MORB patterns of the upper series (Viereck et al., this volume).

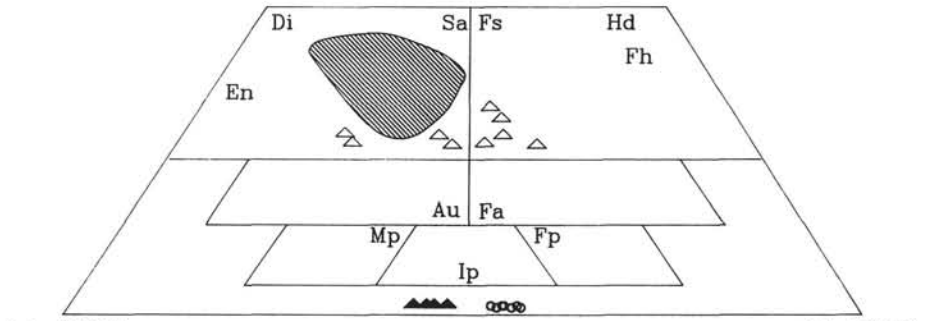
Isotope geochemistry of the lavas presented by Taylor and Morton (this volume) serve to reinforce the tripartite division of the lower series. $^{207}Pb/^{204}Pb$ plots against $^{206}Pb/^{204}Pb$ for the upper series units show a strong correlation with the North Atlantic MORB field. The Group A2 sample (F119) also falls within this field, confirming its closer affinities with the upper series. Pb-isotope ratio plots for A1 and B samples fall outside this field, and occupy a steep trend away from that of the MORB rocks. Initial $^{87}Sr/^{86}Sr$ ratios for Group B range between 0.71225 and 0.71309 (mean of 0.71218), contrasting with the lower values, 0.70947, of the Group A2. Group A1 (one sample, 0.71097) again lies almost exactly between the distributions of A2 and B.

DISCUSSION

The presence of cordierite as a phenocryst phase in at least three of the Group B units is unusual, but not unique. Palaeocene dacites recovered from the northern Rockall Trough have yielded a strikingly similar petrography and composition (Morton et al., 1988) but they are rare in oceanic or transitional

Table 3. Rare-earth element abundances, lower series volcanics, Site 642. Laboratory key as for Table 1, except FGR = Katholieke Universitet, Leuven, Belgium.

Unit	Lab	Sample	D(MBK)	La	Tb	Nd	Gd	Th	Ta	Sm	Yb	Lu	Eu	Ba	Hf	Ce	Ho	U	W
F107	UKB	97-1- 130-132	12.00	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F107	UKA	97-1- 133-135	12.80	23.00	0.78	28.50	—	12.20	1.16	5.66	3.46	0.60	0.92	—	7.23	63.50	1.43	—	48.00
F108	UKB	97-2- 129-131	14.90	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F108	CAN	98-1- 48-50	16.20	—	0.43	16.56	—	11.58	1.36	2.58	1.35	0.17	1.32	149.91	7.99	42.54	—	—	—
F108	CAN	98-1- 58-60	16.50	—	1.36	38.33	9.30	13.04	1.18	8.35	5.21	0.75	1.21	301.49	7.02	79.01	—	—	—
F108	UKA	98-1- 60-62	16.80	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F109	CAN	98-1- 147-149	17.50	—	1.35	41.80	6.98	13.31	1.29	9.10	6.27	0.90	1.55	129.77	7.39	86.24	—	—	—
F109	CAN	98-2- 16-18	17.70	—	0.58	27.82	3.36	14.45	1.45	5.18	2.80	0.36	1.49	154.94	7.71	63.68	—	—	—
F109	FGR	98-2- 69-72	18.00	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F109	UKB	98-2- 77-79	18.30	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F109	CAN	98-2- 81-85	18.60	—	0.78	26.74	—	13.35	1.42	6.11	3.30	0.46	0.87	—	7.43	61.11	—	—	—
F110	UKB	99-1- 5-7	20.02	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F112	UKB	99-2- 45-47	27.80	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F113	FGR	100-1- 31-33	30.60	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F113	UKA	100-1- 118-120	32.10	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
D4	FGR	101-1- 98-100	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
D4	UKA	101-1- 109-111	—	44.30	1.07	46.60	—	14.50	1.34	9.11	4.23	0.65	1.48	—	5.70	107.00	2.27	2.90	14.60
D4	UKB	101-2- 25-27	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F114	CAN	102-1- 13-15	54.50	—	1.70	49.31	10.07	15.80	1.42	10.19	8.24	1.23	1.73	259.47	8.52	105.32	—	—	—
F114	UKA	102-1- 20-22	54.90	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F114	CAN	102-1- 33-35	55.00	—	1.58	53.53	11.21	14.76	1.33	10.85	5.22	0.72	1.73	62.14	8.07	108.36	—	—	—
F115	FGR	102-1-2 146-40	58.20	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F115	UKA	102-2- 4-6	58.50	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F115	CAN	102-2- 23-25	58.80	—	2.00	56.55	—	14.98	1.37	12.48	9.06	1.27	1.74	172.26	8.29	121.95	—	—	—
F116	FGR	102-2- 68-70	60.50	—	1.69	54.63	10.99	15.02	1.34	11.21	8.04	1.19	1.84	161.76	7.98	119.84	—	—	—
F116	CAN	102-2- 94-96	60.80	—	1.29	42.56	—	13.65	1.20	10.36	4.86	0.71	1.43	128.37	7.36	88.14	—	—	—
F116	CAN	102-2- 113-115	61.40	—	1.16	39.80	—	12.17	1.11	9.22	4.58	0.67	1.35	374.64	6.74	86.20	—	—	—
F116	UKA	102-2- 114-115	61.70	36.40	1.41	41.90	—	12.50	1.22	7.98	5.24	0.65	1.39	—	7.37	91.70	5.18	2.80	—
D5	UKA	104-1- 18-20	—	4.93	0.97	8.14	—	1.56	0.25	3.28	4.43	0.69	0.89	—	2.15	8.25	1.49	0.23	24.10
D5	FGR	105-2- 84-86	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F117	CAN	106-1- 33-35	82.80	—	1.03	37.69	—	16.32	1.82	7.95	5.55	0.76	1.66	—	8.71	87.35	—	—	—
F117	UKA	106-1- 86-88	83.00	53.60	1.61	56.40	—	16.00	1.66	11.10	5.06	0.83	1.72	—	9.36	129.00	—	4.77	—
D6	UKA	107-2- 82-84	—	11.50	1.14	9.82	—	1.47	0.25	3.93	5.41	0.80	1.35	—	3.56	14.70	1.74	0.37	12.80
F118	FGR	108-2- 51-53	103.50	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F118	UKB	108-2- 55-57	103.60	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F119	UKA	109-1- 17-19	109.80	20.00	1.20	24.20	—	5.25	0.55	5.67	5.69	0.74	1.50	—	4.52	49.50	2.38	1.41	—
F120	UKB	109-1- 51-52	112.50	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F121	FGR	109-2- 79-81	118.00	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
F121	UKA	109-2- 90-92	118.20	30.70	1.24	36.10	—	8.42	1.01	7.67	5.29	0.74	1.62	—	7.90	75.80	2.26	2.13	16.70
D7	FGR	110-1- 28-30	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
D7	UKA	110-1- 44-46	—	17.20	0.89	22.10	—	4.58	0.53	4.84	3.04	0.50	1.36	—	3.70	42.10	1.40	1.17	15.10



Di Diopside
En Endiopside
Sa Salite
Fs Ferrosalite
Hd Hedenbergite
Fh Ferrohedenbergite
Au Augite
Fa Ferroaugite
Mp Magnesium Pigoenite
Ip Intermediate Pigeonite
Fp Ferriferous Pigeonite

Figure 2. Pyroxene $CaSiO_3/FeSiO_3/MgSiO_3$ discriminant plot. Circles = Group B, Group A2 not analyzed. Triangles = Group A1; filled triangles = dykes D4 and D7. Shaded field covers analyses of upper series and D5 and D6.

regimes outside of arc volcanism. The two sites in the NE Atlantic where the mineral association has been identified are comparable, each suffering two separate phases of superimposed rifting and sedimentation. These unusual lithologies found within the rifts may have formed as a result of melting of upper crustal sediment adjacent to the rising magma source which eventually supplied the material for both the dipping reflector sequence and the new ocean floor. The sediments appear to have accumulated during or after an early failed rifting attempt (and in the examples discussed here the development of sites of Mesozoic

Table 4. Representative microprobe analyses of lower series samples, phenocryst phases, and glass mesostases.

	F112	F117	F109	F117	F117
	642E 99-3-13-15	642E 106-2-94-96	642E 98-2-62-64	642E 106-2-94-96	642E 106-2-94-96
	Plag (core)	Plag	Glass	Glass	Glass
SiO_2	49.07	47.45	66.07	70.05	68.27
Al_2O_3	33.41	32.47	11.42	13.95	13.08
Fe O	0.36	0.52	7.38	1.95	4.79
MgO	0.00	0.00	1.23	0.00	0.54
CaO	16.44	16.89	2.36	2.87	2.91
Na_2O	2.01	1.80	1.12	3.16	3.09
K_2O	0.19	0.12	1.25	1.19	1.15
TiO_2	0.00	0.00	1.30	0.96	1.28
MnO	0.07	0.00	0.09	0.24	0.12
P_2O_5	0.00	0.10	0.00	0.03	0.15
Cr_2O_3	0.00	0.13	0.02	0.08	0.05
Total	101.55	99.48	92.24	94.48	95.43
An	81	83	—	—	—
Ab	18	16	—	—	—
Or	1	1	—	—	—

	D4	F116	F117	D4	F116	F117
	642E 101-2-138-140	642E 102-2-1023	642E 106-2-94-96	642E 101-2-138-140	642E 102-2-102-103	642E 106-2-94-96
	Opx	Opx	Opx	Cord	Cord	Cord
SiO_3	49.63	50.84	49.00	50.33	49.30	49.98
Al_2O_3	3.24	3.59	2.77	33.41	33.22	32.77
Fe O	26.80	24.013	25.01	7.17	7.18	8.00
MgO	17.74	17.46	18.05	9.35	9.11	9.05
CaO	0.50	0.68	0.48	0.02	0.00	0.11
Na_2O	0.29	0.72	0.19	0.28	0.19	0.02
K_2O	0.00	0.13	0.00	0.13	0.15	0.22
TiO_2	0.83	0.57	0.70	0.00	0.07	0.00
MnO	0.21	0.30	0.46	0.36	0.12	0.09
P_2O_5	0.00	0.04	0.00	0.00	0.00	0.10
Cr_2O_3	0.41	0.46	0.39	0.00	0.07	0.00
Total	99.65	98.80	97.05	101.04	99.41	100.34
Wo	1	2	1	—	—	—
En	54	56	56	—	—	—
Fs	45	42	43	—	—	—

basins) and provided a cover for the subsequent melting phase. The migration of the magmatic activity westward to the finally successful Tertiary separation generated progressively less silicic and trace-element-enriched magmas.

The geological setting of Site 642 at the Vøring Plateau is on the upper flanks of a basement high, the surface of which has now been identified as volcanics with a continental component (the Group B lavas). The tholeiitic flow basalts which act as the immediate "cover" to this high are recognized as a sequence of subaerially extruded lavas immediately preceding or contemporaneous with the inception of seafloor spreading. The peraluminous nature of these lower series lavas, although not unusual for volcanic arc basalts (VAB) and documented for sites elsewhere (Clemens and Wall, 1984; Ambruster, 1985), is almost unique in marginal rifting environments. The only other locality at a passive continental margin was recently identified in the northern Rockall Trough by Morton et al. (1988). The geological framework is similar. A failed rift of Mesozoic age (Roberts et al., 1984; Talwani and Eldholm, 1977) was invaded by volcanics during a resurgence of volcanism associated with a later attempt at rifting (in both cases, again, a Tertiary event). In the Rockall example, the failed rift is obvious as the Rockall Trough, but at the Vøring Plateau the magnitude of the basement high has perhaps complicated the setting. The Vøring Basin to the east is a major intracontinental rift feature and the intermediate volcanism could have been associated with the development of a magma source within or on the flanks of this basin. Another possibility is that the volcanism developed during the interval between anomalies 24/25 and 23, and marked a temporary hiatus in the formation of the Norwegian Sea Basin. The successful separation finally took place to the west of both of these sites, but the rifted, thinned, and weakened continental basement of the developing margin was subject to intrusion and volcanism. The volcanism took place following a buildup of a differentiating magma source, which melted and assimilated adjacent continental crust.

The intermediate composition of the lower series volcanics would be one likely to cool and solidify under subaerial conditions close to the source, and therefore unlikely to be responsible for the major part of the Vøring Plateau basement high. Evidence of structural control of the Vøring Plateau at depth is not resolved on existing geophysical data. A model favoring attenuated and probably faulted basement blocks beneath site 642 cut by intermediate volcanics requires testing with further deep seismic reflection profiling.

CONCLUSIONS

1. The lower series volcanics can be subdivided into three chemically distinct Groups, A1, A2, and B. Two of the three Groups, A1 and A2, are related to the third by varying degrees

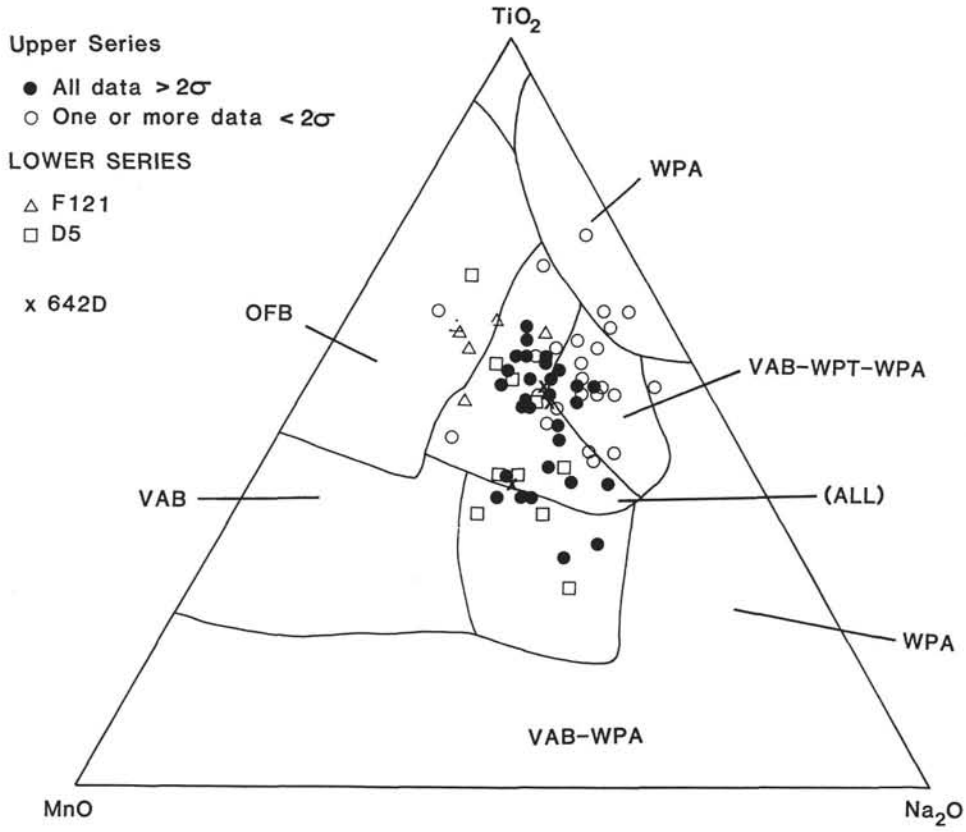


Figure 3. Minor element geochemistry of clinopyroxenes from the basalts of both upper and kower volcanic series, plotted on the discriminant diagram formulated by Nisbett and Pearce (1976). Elemental abundances determined by electron microprobe. OFB = ocean floor basalt; WPA = within-plate alkali; VAB = volcanic arc basalt; WPT = within-plate tholeiite.

of mixing of a MORB mantle source with a melt of intermediate composition, which was probably generated from a combination of primary melt and continental rocks adjacent to this source.

2. This paragenesis is similar to that invoked for a lithological association identified from deep drilling in the north Rockall Trough. This failed rift to the west of the United Kingdom has a similar structural and geological framework to that of the Vøring Plateau, but is without a prominent basement structural high such as forms the core of the Plateau.

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Table 5. Ranges and means of all analyses completed on lower series volcanics, Site 642. Figures in parentheses are only single analyses, not means.

	Group B F106–F117 (27)		Group A2 F118–F120 (4)		Group A1 F121		D4	D7
	range	mean	range	mean	range	mean	mean	mean
SiO_2	48.00–67.20	58.61	47.02–49.97	48.85	51.70–55.50	53.60	62.30	53.10
TiO_2	1.12–1.44	1.26	1.17–1.24	1.19	1.32–1.51	1.42	1.27	1.17
Al_2O_3	13.90–19.26	15.20	16.66–17.60	17.08	14.87–16.10	15.42	15.62	15.65
MnO	0.01–0.41	0.11	0.12–0.18	0.13	0.10–0.14	0.12	0.09	0.25
MgO	0.11–2.76	1.37	5.14–6.11	5.37	3.00–3.07	3.04	1.62	2.65
CaO	1.19–7.66	3.47	6.51–7.60	7.09	5.57–5.66	5.62	3.88	7.43
Na_2O	1.68–3.13	2.37	2.98–3.27	3.13	2.68–3.12	2.90	2.63	2.68
K_2O	0.19–8.59	2.03	0.86–1.66	1.13	2.14–2.16	2.15	0.72	1.17
P_2O_5	0.09–0.61	0.21	0.15–0.18	0.16	0.18–0.19	0.19	0.19	0.14
LOI	0.25–13.80	6.07	2.00–4.62	3.29	—	(2.17)	2.39	2.27
V	116.00–203.00	149.76	229.00–300.00	253.44	170.00–233.00	201.00	141.00	242.50
Cr	58.00–177.00	80.78	165.00–261.00	206.56	89.00–94.00	91.50	74.70	130.00
Co	3.00–34.00	13.87	35.00–67.00	46.87	29.00–31.00	30.00	12.70	36.00
Ni	3.00–25.00	12.94	4.00–12.00	8.44	6.00–15.00	10.50	15.30	11.00
Cu	10.00–31.00	16.71	21.00–30.00	23.12	14.00–28.00	21.00	16.70	15.50
Zn	57.00–165.00	113.28	101.00–129.00	101.56	125.00–156.00	140.50	101.70	113.00
Rb	16.00–120.00	69.55	24.00–46.00	31.25	79.00–80.00	79.50	49.70	46.00
Sr	102.00–230.00	163.70	144.00–185.00	163.50	158.00–198.00	178.00	209.70	140.00
Y	28.00–118.00	56.89	36.00–47.00	41.56	43.00–45.00	(44.00)	52.70	36.50
Zr	251.00–363.00	297.67	126.00–151.00	132.50	194.00–223.00	(208.50)	296.70	138.00
Nb	16.00–24.00	20.69	6.00–8.00	7.19	12.00–14.00	(13.00)	20.30	8.50
Sc	26.00–34.00	30.00	49.00–58.00	52.67	—	(44.00)	24.00	50.00
Ba	189.00–530.00	338.97	242.00–344.00	305.33	—	(382.00)	431.50	280.00
La	23.00–53.60	40.00	—	(20.00)	—	(30.70)	44.30	17.20
Ce	42.54–121.95	94.73	—	(49.50)	—	(75.80)	107.00	42.10
Nd	16.56–56.55	40.89	—	(24.20)	—	(36.10)	46.60	22.10
Sm	2.58–12.48	8.91	—	(5.67)	—	(7.67)	9.11	4.84
Eu	0.92–1.84	1.48	—	(1.50)	—	(1.62)	1.48	1.36
Gd	3.36–11.21	6.73	—	—	—	—	—	—
Tb	0.43–1.70	1.25	—	(1.20)	—	(1.26)	1.07	0.89
Ho	1.43–5.18	3.31	—	(2.38)	—	(2.26)	2.27	1.40
Yb	1.35–9.06	5.09	—	(5.69)	—	(5.29)	4.23	3.04
Lo	0.17–1.27	0.72	—	(0.74)	—	(0.74)	0.65	0.50
Hf	7.23–9.26	7.76	—	(4.52)	—	(7.90)	5.70	3.70
Ta	1.11–1.82	1.36	—	(0.55)	—	(1.01)	1.34	0.53
Th	11.58–15.80	13.86	—	(5.25)	—	(8.47)	14.50	4.58

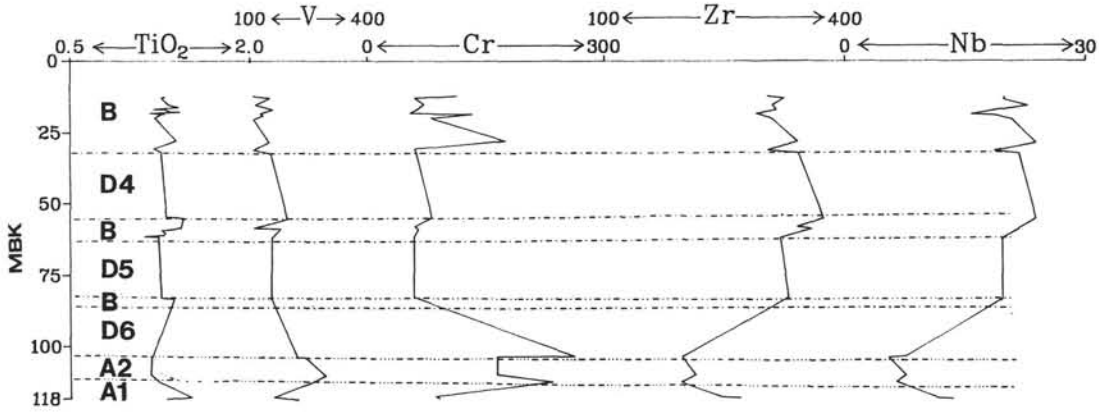

Figure 4. Chemical stratigraphy of lower series flows illustrated using TiO_2, V, Cr, Zr, Nb, and presenting a subdivision into Groups A1, A2, B, and dykes. For discussion, see text. Vertical scale is in meters below seismic reflector K (MBK). Concentration is in % for TiO_2, ppm for V, Cr, Zr, and Nb.

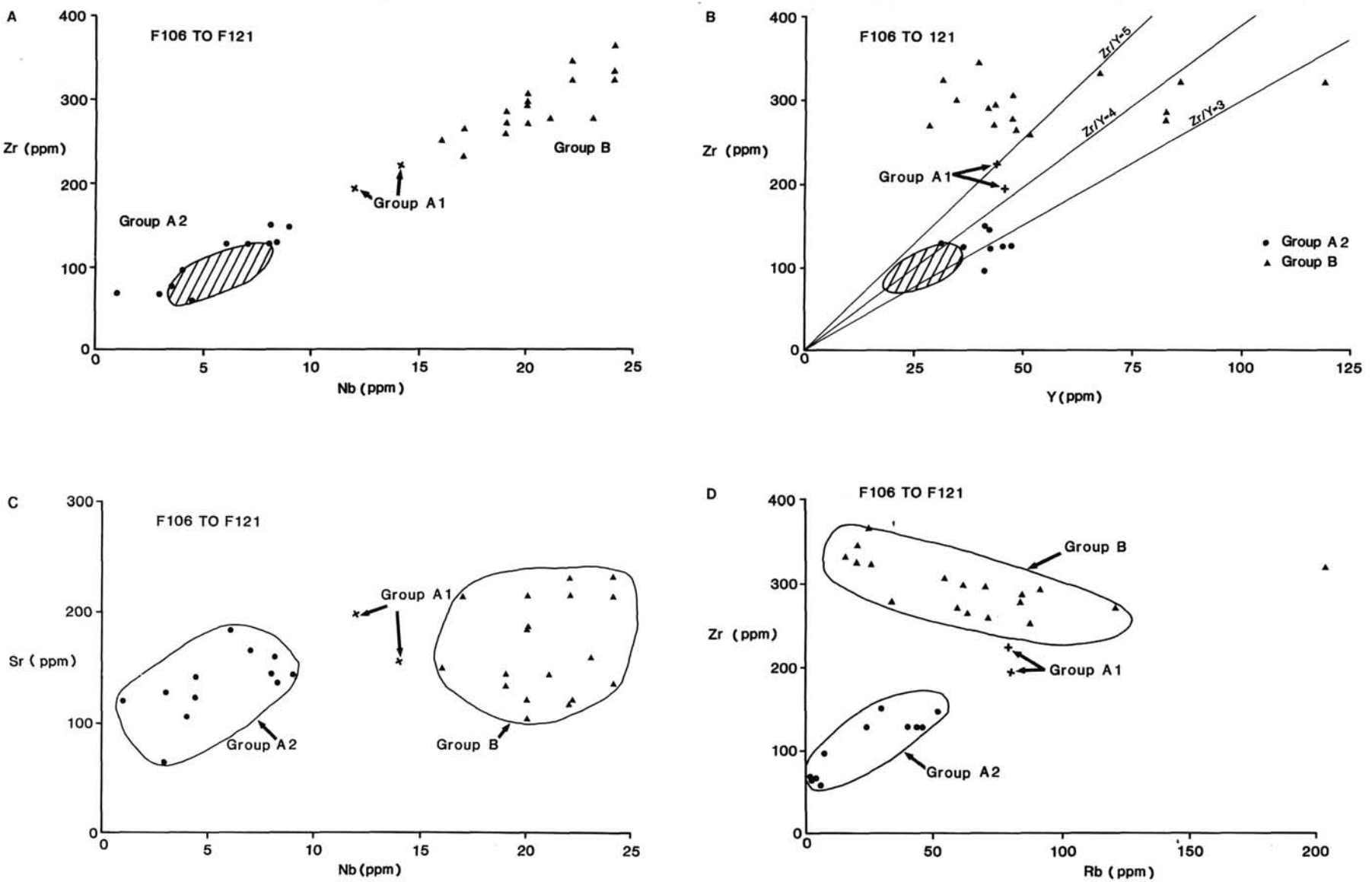

Figure 5. A to D: Two-element discriminant plots. Circles = Group A2, triangles = Group B, Crosses = F121, Group A1. Shaded area is field of upper series flows. A: Zr/Nb, B: Zr/Y, C: Nb/Sr, D: Zr/Rb.

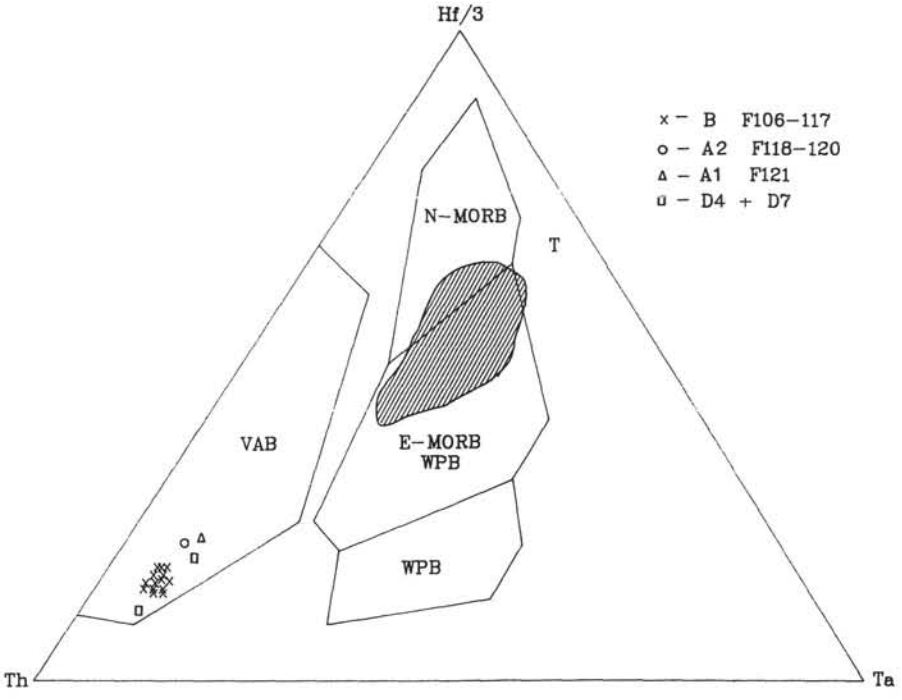

Figure 6. Hf-Ta-Th discrimnant plot for lower series volcanics. Shaded area is field of upper series flows.

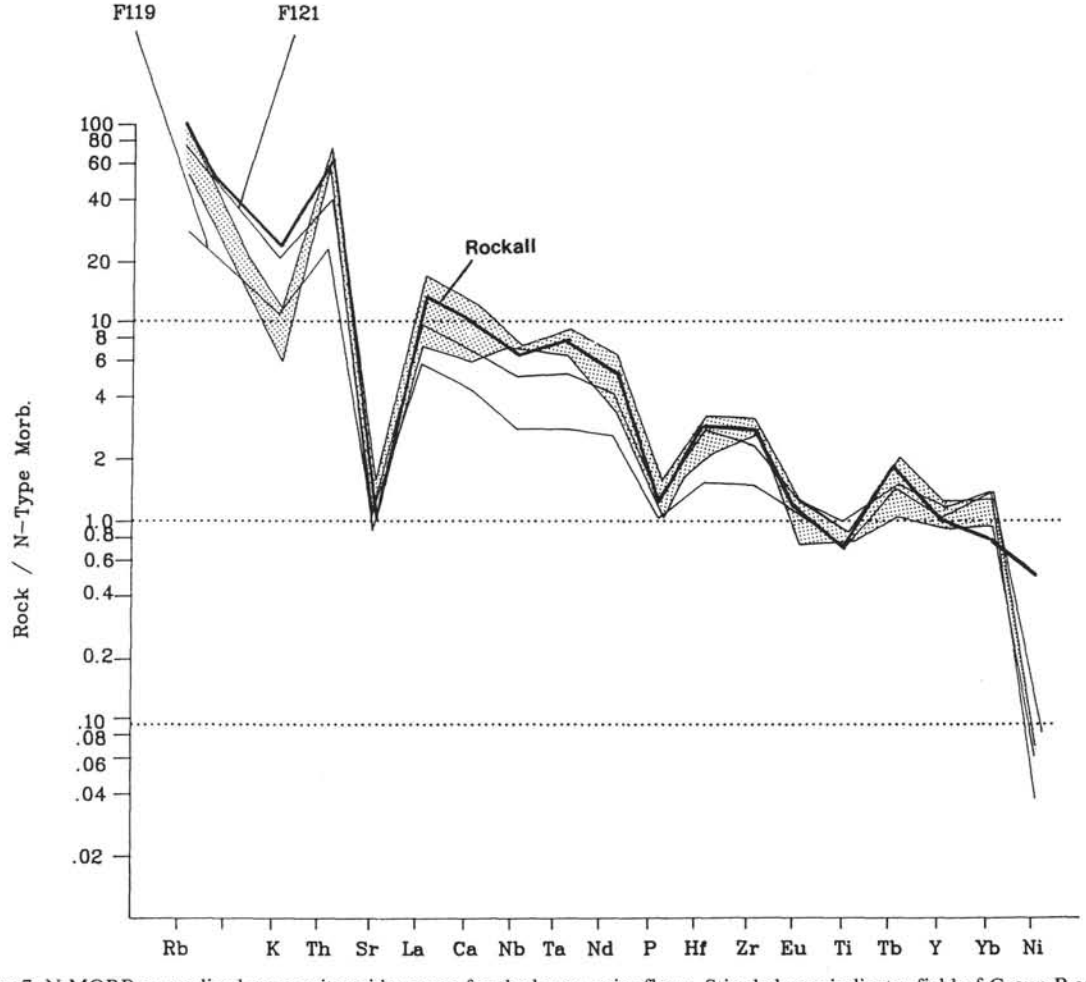

Figure 7. N-MORB normalized composite spidergrams for the lower series flows. Stippled area indicates field of Group B analyses. Additional spidergrams for Group A1 (F121), Group A2 (F119), and dacites from the Rockall Trough (in boldface).