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DIVERSITY OF PLUTONIC ROCKS IN THE OCEANIC CRUST: THE THVERARTINDUR CENTRAL VOLCANIC COMPLEX, SE ICELAND

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Abstract. Iceland, with the plate boundary exposed on land, represents a natural laboratory for observing the petrology and tectonics of the mid-ocean ridge environment interacting with a deep mantle plume. The specific chemical characteristics of Icelandic igneous rocks, such as high abundance of incompatible trace elements, high $^{87}Sr/^{86}Sr$, low $^{143}Nd/^{144}Nd$ and radiogenic Pb contents result from plume influences on the magma generation and its subsequent evolution in crustal magma chambers inside the anomalously thick Icelandic crust (8—20 km) and interaction with the altered old crust.

The Tertiary Thverartindur central volcanic complex in SE Iceland offers 2-km-deep erosional sections and exhibits a large variety of intrusive rocks from ultramafic, through olivine- and quartz-tholeiites, hybrid rocks to acid in the chemical composition. Wehrlitic ultramafic rocks consist of olivine (Fo_{69-91}) and/or clinopyroxene ($En_{42-45}Fs_{12-14}Wo_{42-43}$). Gabbros are fine- to very coarse-grained, melano- to leucocratic with plagioclase (average An_{45-65}) and clinopyroxene (average $En_{40-43}Fs_{15-25}Wo_{35-42}$; 80—95 vol%), magnetite and/or ilmenite ($<10\%$) with minor olivine, quartz, apatite, hornblende, biotite, and alteration minerals. Hybrid rocks consist of plagioclase (An_{26-72}), clinopyroxene ($En_{32-39}Fs_{19-28}Wo_{39-41}$), magnetite, ilmenite, and quartz with minor hornblende, apatite, epidote, sphene, zircon, and alteration minerals. They clearly exhibit different generations of minerals and abridge the compositional gap between quartz-tholeiite and granite. Granitic rocks display granophyric textures, contain up to 60 vol% quartz and 20—60 vol% feldspar with 10—16 vol% normative orthoclase, and define a distinctive evolutionary trend from 65 to 80 wt% SiO_2.

This rock diversity is a result of multiple magmatic processes: (i) fractional crystallization in the probably refilled crustal magma chamber; (ii) mixing between basic and acid magmas, and mixing of earlier formed crystals with more evolved basic magma. The Fe—Ti-enrichment accompanied by Si-decrease in quartz-tholeiitic gabbros can most easily be explained by a 50—70% crystallization of an olivine-tholeiitic composition in NNO oxygen buffer following the equilibrium/fractional crystallization path.

Key words: oceanic crust, petrology, central volcano, plutonic rocks, magmatic processes, Iceland.

INTRODUCTION

Iceland is a part of the oceanic crust representing a combination of the oceanic ridge and the Icelandic hot spot which has been active since before the opening between Greenland and Norway. In general, the rock formations get younger towards the centre of the island, but as the

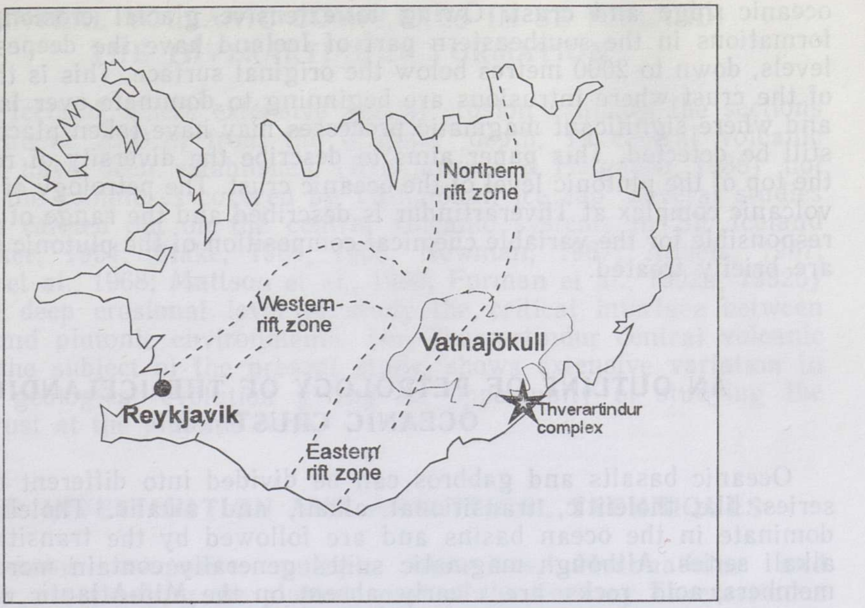

Fig. 1. Sketch map of Iceland. Neovolcanic (active rifting) zones and Tertiary Thverartindur central volcanic complex are shown.

relative positions of the plume centre and the plate boundary in Iceland have changed in the course of time, there has occurred a series of ridge jumps and ridge propagation episodes.

The Icelandic crust is thicker than normally on the oceanic ridges, reflecting higher magmatic production rates due to higher mantle temperatures (White & McKenzie, 1989), and the range of rock types is more varied. The estimated thickness of the crust in Iceland varies from 8 to over 20 km being anomalously thick compared to that of 3—8 km for a normal oceanic crust. At present, the spreading activity is confined to the Western, Eastern, and Northern neovolcanic (rift) zones (Fig. 1). The tectonic activity of the main rift zones is concentrated in elongated segments while the volcanic activity is confined to the main rift zones and to certain off-rift volcanic systems. Each volcanic/tectonic system is composed of a set of parallel eruptive ridges or fissures, constituting a fissure swarm that varies in length from 17 to 105 km, in width from 5 to 30 km (Jakobsson, 1979). The life span of such systems may vary from 300 000 to 500 000 years. These swarms may in time develop a central volcano the lifetime of which is from about 300 000 to 1 000 000 years (Saemundsson, 1979). This kind of a volcano is topographically elevated relative to the surroundings due to increased magma extrusion at one site. Shield volcanoes or lava shields of different sizes (up to 15 km^2) are found randomly within the volcanic rift zones. It is important to mention that the volcanic morphology is greatly dependent on whether the eruption occurs under ice or subaerally. The half-spreading rate is 10 mm/yr in Iceland, while those for southern zones of the Atlantic are 11—12 mm/yr for the Azores and 15 mm/yr for the Kane Fracture Zone.

Iceland, where the Mid-Atlantic plate boundary is exposed on land, gives a unique opportunity to study the structure and composition of an oceanic ridge and crust. Owing to extensive glacial erosion, the rock formations in the southeastern part of Iceland have the deepest erosion levels, down to 2000 metres below the original surface. This is the section of the crust where intrusions are beginning to dominate over lava flows, and where significant magmatic processes may have taken place and can still be detected. This paper aims to describe the diversity of rocks near the top of the plutonic level of the oceanic crust. The petrology of a central volcanic complex at Thverartindur is described and the range of processes responsible for the variable chemical composition of the plutonic formation are briefly treated.

AN OUTLINE OF PETROLOGY OF THE ICELANDIC OCEANIC CRUST

Oceanic basalts and gabbros can be divided into different magmatic series like tholeiitic, transitional alkali, and alkalic. Tholeiitic rocks dominate in the ocean basins and are followed by the transitional and alkali series. Although magmatic suites generally contain more evolved members, acid rocks are clearly absent on the Mid-Atlantic ridge. The evolved compositions characterize the Atlantic islands (e.g. Iceland, Azores, Canaries). Specific chemical features allow us to distinguish normal oceanic basalts, MORBs, from oceanic island basalts, OIBs.

In Icelandic rift zones olivine- and quartz-tholeiites are the dominant eruptive products. Olivine tholeiites can be erupted randomly within the rift zones but the more evolved parts of the tholeiitic suites (quartz-tholeiites), having high iron and low magnesium contents compared to typical MORBs, are mainly confined to the volcanic/tectonic swarms. There has been much discussion on whether these two types of basic rocks are related to each other by simple fractional crystallization or whether they are derived from different magma batches and have different fractional crystallization histories. Alkalic and transitional rocks, similar to those observed for oceanic islands, are confined to the off-rift volcanism. Alkali rocks appear in two areas, the Vestmann Islands in southern Iceland, and Snaefellsness volcanic system in western Iceland (Steinthorsson et al., 1985). The Austurhorn Tertiary volcanic complex in southeastern Iceland is believed to represent transitional alkali series (Furman et al., 1992a, 1992b).

There are 29 volcanic systems currently active in Iceland; four of these are alkaline, seven are transitional and the rest are tholeiitic. Acid and intermediate rocks form 9% of the erupted products being associated particularly with the central volcanoes (Saemundsson, 1979).

The high abundance of incompatible trace elements, high $^{87}Sr/^{86}Sr$, low $^{143}Nd/^{144}Nd$ and radiogenic Pb contents (O'Nions et al., 1977; Hemond et al., 1993) and additionally, a light oxygen enrichment of rocks in volcanic centres of the rift zones (Condomines et al., 1983) are distinctive features of Icelandic rocks. These features have been explained by two different processes which are not necessarily mutually exclusive. Firstly, chemical and isotopic heterogeneities may exist in the mantle (e.g. Zindler et al., 1979). Secondly, ascending magmas may interact with the old, hydrothermally altered crust (e.g. Oskarsson et al., 1982; Nicholson et al., 1991). Oxygen isotope results (Hemond et al., 1993) distinguish two groups, like quartz-tholeiites and more evolved rocks with low $\delta^{18}O$ values resulting from interactions with the hydrothermally altered Icelandic crust that contrasts with picrites, olivine-tholeiites, and alkali basalts with a normal mantle $\delta^{18}O$ compositions.

CENTRAL VOLCANIC COMPLEXES IN SE ICELAND: THE THVERARTINDUR FORMATION

In SE Iceland, where extensive glacial erosion exhumes the sections down to about 2000 m from the original depth, 19 central volcanic complexes have been established (Kristjansson & Helgason, 1988) not including the complexes covered by Vatnajökull ice cap. Several studies have been carried out on the central volcanic systems in SE Iceland (e.g. Walker, 1964; Blake, 1964, 1966; Newman, 1967; Annels, 1967; Moorbath et al., 1968; Mattson et al., 1986; Furman et al., 1992a, 1992b) using the deep erosional level to study the critical interface between volcanic and plutonic environments. The Thverartindur central volcanic complex, the subject of the present study, shows extensive variation in rock and geological evolution giving an opportunity of studying the oceanic crust at the plutonic level.

FIELD INVESTIGATION AND ANALYTICAL TECHNIQUES

Two major composite multiple intrusives, Hvannadalur and Fellsadalur, representing the plutonic part of the Tertiary Thverartindur central volcanic complex, were mapped during the 1993/94 field seasons. Rock samples were collected to cover the variation in rock subtypes, then representative samples were selected to characterize chemical features of the main rock units. The analyses of major and trace elements were performed by ICP, Rb was analysed using AAS (Nordic Volcanological Institute, University of Iceland), and 28 samples were analysed for Nb, Ga, and repeatedly for Sr and Rb using X-ray fluorescence technique at the Institute of Geology in Estonia. For preliminary petrological testing and some calculations, the NewPet and CSS computer software were employed.

Sixteen samples were selected for electron microprobe study. The analyses were performed on an ARL-SEMQ instrument at Nordic Volcanological Institute. The analytical conditions for olivine, oxides, and clinopyroxene were: beam potential 15 kV, sample current 80 nA, and the counting times of 10 seconds for peak and 4 seconds for the background. Plagioclase was analysed at 15 kV and 25 nA, with the counting times of 20 seconds (peak) and 4 seconds (background). Natural minerals and metals were used as standards.

DIVERSITY OF ROCK TYPES OF THE THVERARTINDUR COMPLEX

The Thverartindur area (Fig. 1) is dominated by late Tertiary plateau basalts and hyaloclastites exhibiting a shallow regional dip towards NNE. Only a few age determinations have been made on the plutonic rock suites in SE Iceland. These estimations give a time span of 2.2—7 Ma (Gale et al., 1966; Moorbath et al., 1968), where the granophyres from the Hvannadalur pluton display the youngest age of about 2.2 Ma. The distance from the present rift zone gives the expected age of slightly less than 7 Ma. The estimated age of granitic rocks implies a long-living magmatic system which probably continued magmatic evolution long after the main rifting episode had ceased or a rift jump did occur.

The Hvannadalur and Fellsadalur gabbro-granophyric intrusions located in deep glacial valleys are believed to be related to a common shallow magma chamber (Bromann & Soesoo, 1994). The gabbro intrusions consist of multiple subparallel 15—80-m-thick melanocratic to leucocratic

Table I

Representative whole-rock chemical analyses of ultramafic rocks, olivine-, and quartz-tholeiitic gabbros, hybrid and granitic rocks. For each major rock unit, the representative dyke composition is presented to show the restricted modification of liquid composition within the plutonic formation

Elements	Samples																
	Ultramafic rocks			Olivine-tholeiitic gabbros				Quartz-tholeiitic gabbros				Hybrid rocks			Granitic rocks		
	F063	F065	dyke	F044	F045	F081	dyke	F047	F079	H012	dyke	F046	F048	dyke	F043	F080	dyke
SiO_2	37.24	42.00	47.24	51.32	49.07	47.41	47.33	48.44	50.87	47.00	47.17	49.98	55.20	58.57	71.16	71.38	73.18
TiO_2	0.81	0.74	1.06	1.64	1.44	1.99	1.99	3.52	2.78	4.11	3.60	1.94	2.11	1.77	0.58	0.59	0.40
Al_2O_3	5.76	6.71	10.08	16.39	15.47	16.11	16.40	12.31	14.43	14.80	13.55	19.54	14.25	13.66	13.25	12.96	13.10
FeO	19.07	19.32	10.17	9.18	9.43	12.48	12.08	15.59	12.50	14.19	15.93	9.07	12.71	11.63	5.21	4.63	4.78
MnO	0.24	0.29	0.15	0.16	0.15	0.19	0.18	0.24	0.22	0.26	0.29	0.15	0.28	0.24	0.16	0.14	0.05
CaO	4.24	6.59	7.09	12.32	14.03	11.46	10.83	10.24	10.05	10.40	9.72	12.31	6.97	7.09	2.70	2.31	1.84
MgO	31.85	23.75	22.98	5.74	7.77	7.21	7.85	5.34	5.27	4.81	5.02	3.40	2.51	2.24	0.27	0.27	0.31
Na_2O	0.32	0.32	0.51	2.55	2.30	2.63	2.33	3.18	2.97	3.09	3.56	2.82	3.77	2.85	4.28	4.88	3.78
K_2O	0.12	0.05	0.31	0.36	0.14	0.20	0.57	0.62	0.48	0.72	0.52	0.41	0.92	0.97	2.13	2.45	2.32
P_2O_5	0.07	0.04	0.10	0.23	0.07	0.14	0.31	0.37	0.30	0.48	0.49	0.26	1.15	0.86	0.09	0.12	0.09
Total	99.72	99.81	99.69	99.89	99.87	99.82	99.87	99.85	99.87	99.86	99.85	99.88	99.87	99.88	99.83	99.89	99.89
Ba	13	9	15	63	38	52	176	119	119	114	158	80	209	206	432	477	473
Co	124	118	98	45	49	60	71	69	56	67	82	38	43	32	0	8	b.d.
Cr	727	480	1392	50	84	220	202	9	32	42	29	27	8	12	16	18	7
Cu	516	331	84	194	190	584	85	115	84	39	81	97	20	14	18	17	4
Ni	995	423	834	59	63	113	124	26	31	46	38	28	11	4	15	31	2
Sc	22	29	21	36	49	36	30	45	40	38	41	26	22	26	12	11	7
Sr	67	95	96	245	239	251	296	231	258	285	234	294	269	185	159	146	106
V	209	214	321	300	344	349	278	554	325	454	448	269	137	66	155	123	b.d.
Y	10	10	16	28	18	19	27	45	37	32	49	28	72	98	101	100	102
Zn	111	125	98	82	71	64	85	130	119	149	125	82	154	151	157	119	38
Zr	44	39	55	117	50	90	161	198	176	161	250	124	334	494	695	569	797
Rb	3.5	2	10	4	2.5	2	6	8.3	8.7	2	10	6	14.9	17	48.6	50	36
Ga	7	5	n.a.	14	13	n.a.	n.a.	14	16	14	n.a.	15	16	n.a.	21	46	n.a.
Nb	b.d.	b.d.	n.a.	3	b.d.	n.a.	n.a.	6	5	6	n.a.	3	17	n.a.	52	18	n.a.
Y/Zr	0.238	0.266	0.291	0.240	0.365	0.209	0.168	0.226	0.211	0.198	0.196	0.225	0.214	0.198	0.146	0.179	0.128
Mg#	0.75	0.69	0.80	0.53	0.59	0.51	0.51	0.38	0.43	0.38	0.36	0.40	0.26	0.25	0.08	0.12	0.10

Mg# = Mg/Mg+Fe; F, Fellsadalur; H, Hvannadalur pluton; n.a., not analysed; b.d., content below detection limit.

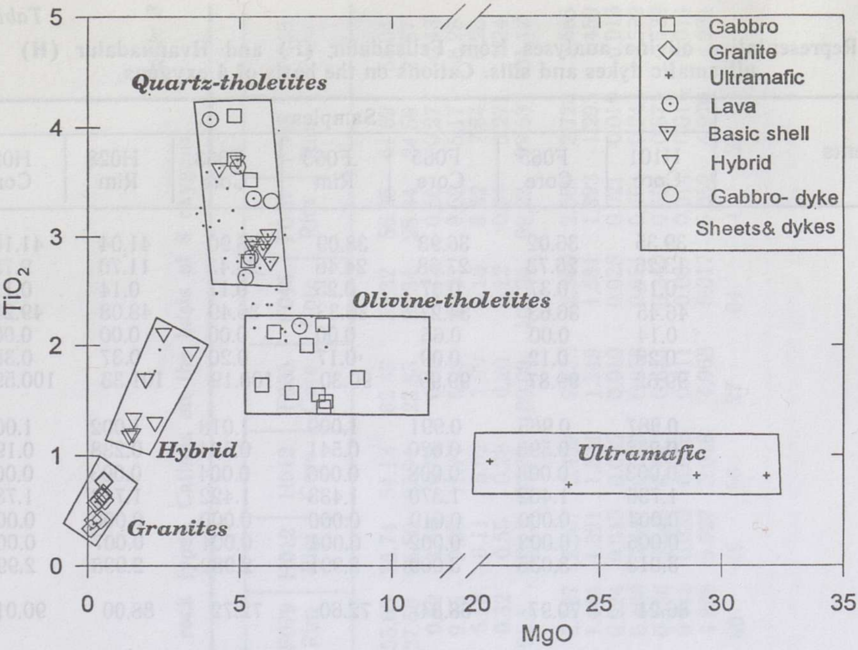

Fig. 2. Olivine- and quartz-tholeiites, ultramafic and hybrid rocks, and granites distinguished on the MgO—TiO_2 classification diagram. Note that the dyke compositions occupy the space between olivine- and quartz-tholeiitic gabbros showing gradual change in magma chemistry in the evolutionary context.

sills, which are cut by 0.5—3-m-thick ultramafic sills. Granophyric rocks, surrounding the gabbro bodies, are enveloped by a very fine-grained basic intrusive rock type separating the intrusions from the surrounding lavas. The multiple emplacement history of gabbroic sills is supported by compositionally and texturally different gabbros and ultramafic xenoliths and chilled margins between sills. The mafic part of the intrusions has all characteristics of sills, emplaced most probably from a common magma chamber, and the granophyres form a huge body (up to 3—4 km^3) accompanied by some sheets propagating from the top of the acid body.

The **Thverartindur gabbros** (Table 1) are fine- to very coarse-grained, melano- to leucocratic plagioclase (average An_{45-65}), and clinopyroxene (Cpx; average $En_{40-43}Fs_{15-25}Wo_{35-42}$; 80—95 vol%), magnetite and/or ilmenite (<10%) rocks containing minor olivine, quartz, apatite, hornblende, biotite, and alteration minerals, such as iddingsite, calcite, and chlorites as an accessory phase. They do not exhibit cumulate textures and there is compositional overlapping of the minor and major intrusive units as shown in Fig. 2. Whole-rock major element composition and normative mineralogy separate the gabbros into olivine- and quartz-tholeiitic units (Fig. 2) with the Mg# number ranging from 39 to 61.

Representative olivine, plagioclase, and clinopyroxene analyses are presented in Tables 2, 3, and 4. In Fig. 3, the En, Wo, Fs, and An components in clinopyroxene and plagioclase are shown. The Zr content in the whole-rock chemistry is used as an evolutionary index distinctively separating the rock units defined. It is significant that there is no clear difference between quartz- and olivine-tholeiitic gabbros expressed in the mineral compositions (Fig. 3). Slight trends are displayed by the Fs component in Cpx and the An component in plagioclase, which show some Fe-enrichment and Ca-depletion, respectively. One olivine-tholeiitic sample,

Table 2

Representative olivine analyses from Fellsadalur (F) and Hvannadalur (H) ultramafic dykes and sills. Cations on the basis of 4 oxygens

Elements	Samples						
	H101 Core	F065 Core	F065 Core	F063 Rim	F063 Core	H028 Rim	H028 Core
SiO_2	39.35	36.02	36.93	38.09	38.90	41.04	41.10
FeO	13.26	26.73	27.68	24.46	24.43	11.70	9.75
MnO	0.14	0.37	0.37	0.25	0.17	0.14	0.11
MgO	46.45	36.63	34.27	36.33	36.49	48.08	49.25
CaO	0.14	0.00	0.65	0.00	0.00	0.00	0.00
NiO	0.28	0.12	0.09	0.17	0.20	0.37	0.38
Total	99.62	99.87	99.99	99.30	100.19	101.33	100.59
Si	0.987	0.965	0.991	1.009	1.018	1.002	1.002
Fe^{2+}	0.278	0.598	0.620	0.541	0.534	0.238	0.198
Mn	0.003	0.008	0.008	0.006	0.004	0.003	0.002
Mg	1.736	1.462	1.370	1.433	1.422	1.748	1.788
Ca	0.004	0.000	0.019	0.000	0.000	0.000	0.000
Ni	0.006	0.003	0.002	0.004	0.004	0.007	0.007
Sum	3.013	3.035	3.009	2.991	2.982	2.998	2.998
Fo#	86.21	70.97	68.84	72.60	72.72	88.00	90.01

FE081, exhibits two distinctive generations of Cpx although no plausible chemical characteristics indicate the hybridizational (mixing) origin of this gabbro. A remarkable feature of Thverartindur gabbros is the lack of Ca-poor pyroxene and exsolutions. Clinopyroxenes are usually rather uniform in composition. Quartz-tholeiitic gabbros yield Cpx with the Fe—Mg mineral/bulk partitioning coefficients expected from growth under equilibrium conditions.

Ultramafic sills and dykes are medium- to coarse-grained (Table 1) and consist of olivine (Fo_{69-91}) and/or clinopyroxene ($En_{42-45}Fs_{12-14}Wo_{42-43}$) (see also Tables 2, 4). Minor minerals are plagioclase (An_{59-70}), magnetite, ilmenite, Cr-spinel, and chromite. The ultramafic rocks are sometimes slightly nepheline-normative containing 37—44 wt% SiO_2. K_2O and Na_2O contents are usually low between 0.05—0.5 wt% and 0.32—0.73 wt%, respectively. Mg# numbers vary from 69 to 83.

Hybrid rocks abridge the compositional gap between normal quartz-tholeiitic gabbros and granite, and are represented by clearly different mineral generations suggesting that they are hybrids (Table 1; Fig. 2). They consist of plagioclase (An_{26-72}), clinopyroxene ($En_{32-39}Fs_{19-28}Wo_{39-41}$), magnetite, ilmenite, and quartz with minor hornblende, apatite, epidote, sphene, zircon, and alteration minerals (see Tables 3, 4). Frequently, this rock type exhibits compositionally different plagioclase and/or clinopyroxene with normal and reverse zoning in the same sample. They have high K and Na contents, 0.4—2.9 wt% and 2.39—5.2 wt%, respectively. There appear to be two types of hybrid rocks differing in the chemical composition, mineralogy, and clinopyroxene composition. The intermediate to acid type (54—65 wt% of SiO_2) may be explained by the mixing of basic and acid magmas. A more basic type of hybrid rocks (49—55 wt% of SiO_2) is abundant in the Fellsadalur intrusion. This could be explained by the mixing of solid crystals with the evolved basic liquid.

Table 3

Representative plagioclase analyses from Fellsadalur (F) and Hvannadalur (H) rock types. Cations on the basis of 8 oxygens

Elements	Samples																		
	F065 Core	F065 Rim	F045 Rim	F045 Core	F045 Core	F081 Core	F081 Rim	F081 Core	F047 Rim	F047 Core	F079 Core	F079 Rim	H012 Rim	H012 Core	F035 Core	F046 Core	F046 Rim	F048 Rim	F048 Core
SiO_2	49.43	50.72	52.61	54.76	52.02	50.35	55.11	53.65	54.79	55.95	55.23	55.65	55.74	54.13	62.33	52.32	56.25	61.39	58.04
Al_2O_3	31.28	31.46	29.77	29.13	30.81	30.23	27.37	28.92	27.37	25.79	27.98	27.58	25.50	27.94	23.85	29.34	25.84	24.59	27.87
FeO	0.62	0.71	0.74	0.68	0.67	0.54	0.53	0.70	0.72	0.69	0.71	0.62	1.16	0.65	0.26	0.73	0.56	0.27	0.43
CaO	12.61	13.38	12.41	11.50	12.78	14.76	10.75	11.83	11.28	11.64	10.40	9.45	9.06	11.77	5.46	13.37	9.52	5.17	8.28
Na_2O	4.73	4.10	4.34	5.09	4.22	3.31	5.36	5.15	5.51	5.93	4.84	5.18	6.11	5.02	7.99	4.18	6.82	7.84	6.26
K_2O	0.15	0	0.17	0.22	0.17	0.17	0.16	0.18	0.20	0.16	0.11	0.32	0.55	0.28	0.20	0.12	0.24	0.27	0.24
Total	98.82	100.37	100.04	101.38	100.67	99.36	99.28	100.43	99.87	100.16	99.27	98.8	98.12	99.79	100.09	100.06	99.23	99.53	101.12
Si	2.284	2.302	2.387	2.444	2.348	2.315	2.504	2.424	2.485	2.534	2.501	2.527	2.567	2.459	2.755	2.380	2.559	2.728	2.565
Al	1.712	1.692	1.600	1.540	1.647	1.647	1.473	1.548	1.471	1.384	1.501	1.484	1.391	1.504	1.249	1.581	1.393	1.295	1.459
Fe^{2+}	0.024	0.027	0.028	0.025	0.025	0.021	0.020	0.026	0.027	0.026	0.027	0.024	0.045	0.025	0.010	0.028	0.021	0.010	0.016
Ca	0.624	0.650	0.603	0.550	0.618	0.727	0.523	0.572	0.548	0.565	0.504	0.460	0.447	0.573	0.258	0.651	0.464	0.246	0.392
Na	0.423	0.361	0.382	0.440	0.369	0.295	0.472	0.451	0.484	0.520	0.425	0.456	0.545	0.442	0.684	0.369	0.601	0.675	0.536
K	0.009	0.000	0.010	0.013	0.010	0.010	0.009	0.010	0.012	0.009	0.006	0.019	0.032	0.016	0.011	0.007	0.014	0.015	0.014
Sum	5.076	5.032	5.009	5.012	5.018	5.014	5.001	5.032	5.027	5.039	4.964	4.968	5.027	5.018	4.968	5.017	5.052	4.970	4.981
An#	60	64	61	56	63	71	53	56	53	52	54	50	45	56	27	64	44	27	42

Table 4

Representative clinopyroxene analyses from Fellsadalur (F) and Hvannadalur (H) rock types. Cations on the basis of 6 oxygens

Elements	Samples														
	F063 Rim	F063 Core	F065 Core	F065 Rim	F044 Rim	F044 Core	F045 Rim	F045 Core	F081 Rim	F081 Core	F079 Core	F079 Rim	H012 Rim	H012 Core	F048 Core
SiO_2	53.09	53.26	50.62	50.96	53.2	51.57	50.86	51.76	54.31	49.67	51.52	51.39	50.85	51.58	50.64
TiO_5	0.82	0.74	1.09	1.02	0.70	1.02	1.08	1.02	0.33	0.36	0.82	1.05	1.02	1.08	0.49
Al_2O_3	1.64	1.35	1.68	1.02	1.48	2.52	1.74	1.66	2.78	6.96	1.02	1.13	1.31	1.15	0.57
Cr_2O_3	0.36	0.27	0.34	0.01	0	0.01	0	0.01	0.06	0.42	0.05	0	0.01	0.04	0
FeO	6.36	6.99	8.43	10.63	12.27	9.43	9.8	9.58	16.81	19.17	9.86	10.31	9.39	9.39	17.35
MnO	0.13	0.17	0.17	0.28	0.37	0.21	0.28	0.22	0.34	0.17	0.20	0.24	0.23	0.24	0.56
MgO	15.97	15.77	15.78	16.09	13.80	15.28	14.90	14.50	11.74	10.44	15.69	15.12	15.86	16.19	10.59
CaO	21.16	20.68	20.85	19.32	18.13	20.01	20.91	20.15	12.31	12.32	19.78	20.38	20.66	20.45	19.57
Na_2O	0.31	0.25	0.32	0.26	0.28	0.31	0.28	0.33	0.62	0.58	0.32	0.29	0.32	0.29	0.26
Total	99.84	99.48	99.28	99.59	100.23	100.36	99.85	99.23	99.30	100.09	99.26	99.91	99.65	100.41	100.03
Si	1.955	1.970	1.903	1.919	1.984	1.913	1.911	1.945	2.040	1.884	1.939	1.929	1.911	1.920	1.961
Ti	0.023	0.021	0.031	0.029	0.020	0.028	0.030	0.029	0.009	0.010	0.023	0.030	0.029	0.030	0.014
Al	0.072	0.059	0.075	0.046	0.065	0.111	0.077	0.074	0.124	0.313	0.045	0.050	0.058	0.051	0.026
Cr	0.010	0.008	0.010	0.000	0.000	0.000	0.000	0.000	0.002	0.013	0.001	0.000	0.000	0.001	0.000
Fe^{2+}	0.196	0.216	0.265	0.334	0.382	0.292	0.307	0.300	0.527	0.607	0.310	0.323	0.295	0.292	0.561
Mn	0.004	0.005	0.005	0.009	0.012	0.007	0.009	0.007	0.011	0.005	0.006	0.008	0.007	0.008	0.018
Mg	0.876	0.869	0.884	0.903	0.767	0.845	0.834	0.811	0.657	0.590	0.880	0.846	0.888	0.898	0.611
Ca	0.835	0.819	0.839	0.779	0.724	0.795	0.841	0.811	0.495	0.500	0.797	0.819	0.831	0.815	0.811
Na	0.022	0.018	0.023	0.019	0.020	0.022	0.020	0.024	0.045	0.043	0.023	0.021	0.023	0.021	0.020
Total	3.992	3.985	4.035	4.038	3.974	4.014	4.030	4.001	3.910	3.965	4.026	4.026	4.043	4.035	4.022
En	46	46	44	45	41	44	42	42	39	35	44	43	44	45	31
Fs	10	11	13	17	20	15	16	16	31	36	16	16	15	15	28
Wo	44	43	42	39	39	41	42	42	29	29	40	41	41	41	41

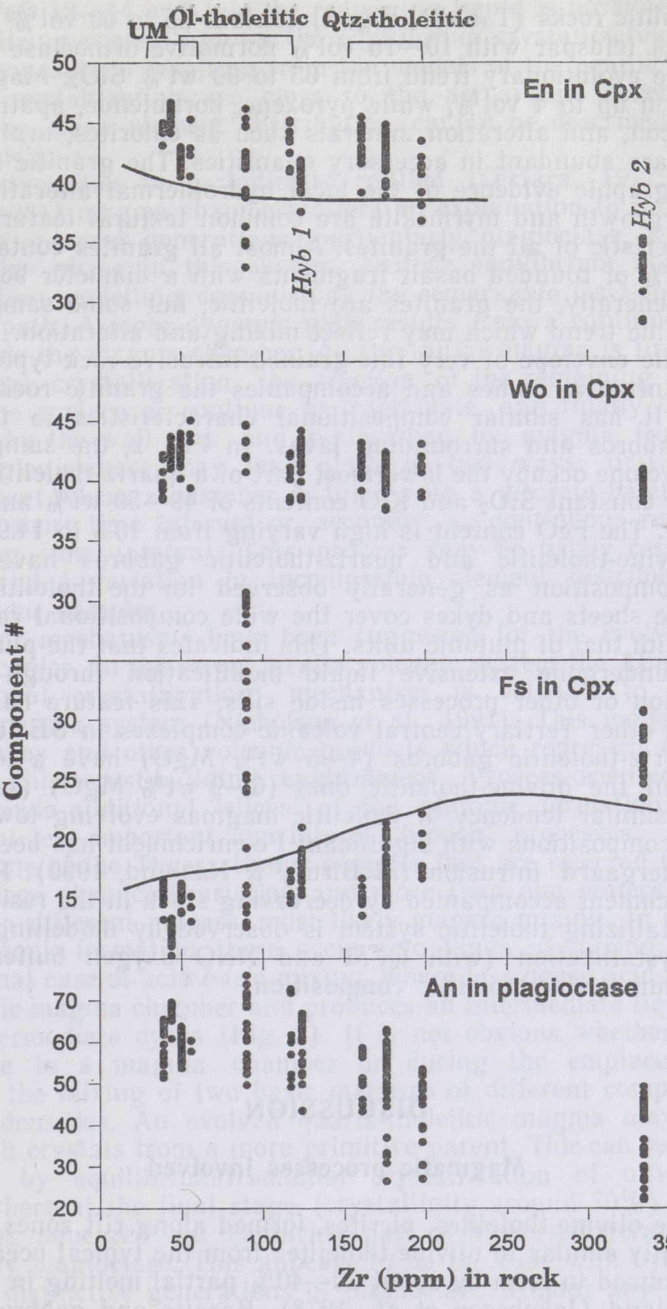

Fig. 3. En, Wo, Fs, and An components in clinopyroxene and plagioclase, respectively plotted against the Zr content in rock (ppm), the latter as an evolutionary index. Two hybrid samples display different origin. The distinctive separation of En, Wo, Fs, and An components in minerals may indicate interactions between different magmas and crystals. Circle size corresponds to an analytical error.

The **granitic rocks** (Table 1; Fig. 2) contain up to 60 vol% quartz and 20—60 vol% feldspar with 10—16 vol% normative orthoclase and define a distinctive evolutionary trend from 65 to 80 wt% SiO_2. Magnetite and ilmenite form up to 4 vol%, while pyroxene, hornblende, apatite, epidote, sphene, zircon, and alteration minerals such as chlorites, uralite, calcite, and pyrite are abundant in accessory quantities. The granitic rocks often show petrographic evidence of the local hydrothermal alteration. Granophyric intergrowth and myrmekite are common textural features, but are not characteristic of all the granites. Almost all granites contain roughly 0.1—10 vol% of rounded basalt fragments with a diameter between 1 to 300 mm. Generally, the granites are tholeiitic, but some samples lie on a calc-alkaline trend which may reflect mixing and alteration.

A **basaltic envelope** of very fine-grained intrusive rock type surrounds the major intrusive bodies and accompanies the granitic rocks in space and time. It has similar compositional characteristics to the quartz-tholeiitic gabbros and surrounding lavas. In Fig. 2, the samples of the basaltic envelope occupy the lowermost part of a quartz-tholeiitic field and have nearly constant SiO_2 and K_2O contents of 49—50 wt% and 0.6 wt%, respectively. The FeO content is high varying from 13.3 to 14.9 wt%.

The olivine-tholeiitic and quartz-tholeiitic gabbros have a similar chemical composition as generally observed for the tholeiitic suites in Iceland. The sheets and dykes cover the wide compositional range which coincides with that of plutonic units. This indicates that the plutonic units have not undergone extensive liquid modification through fractional crystallization or other processes inside sills. This feature has not been observed in other Tertiary central volcanic complexes in SE Iceland.

The quartz-tholeiitic gabbros (4—5 wt% MgO) have a lower silica content than the olivine-tholeiitic ones (6—9 wt% MgO) (see Table 1; Fig. 2). A similar tendency of tholeiitic magmas evolving towards more silica-poor compositions with significant Fe-enrichment has been observed in the Skaergaard intrusion (McBirney & Naslund, 1990). Remarkable Fe—Ti-enrichment accompanied by decreasing silica in the residual liquid in the crystallizing tholeiitic system is observed by modelling the equilibrium crystallization (with QFM and NNO oxygen buffers) of the Thverartindur olivine-tholeiitic composition.

DISCUSSION

Magmatic processes involved

Primitive olivine-tholeiites, picrites, formed along rift zones in Iceland are chemically similar to olivine-tholeiites from the typical oceanic ridges and are assumed to form by about 20—40% partial melting in the mantle beneath Iceland (Jakobsson et al., 1978). Basalts and gabbros, ranging from more evolved olivine-tholeiites to quartz-tholeiites, may be derived by combinations of several magmatic processes:

i) Fractional crystallization in a crustal magma chamber (Biggar, 1983; Oskarsson et al., 1985). This is likely to be an important mechanism of magma evolution but cannot be solely responsible for the wide range of variations described in the Thverartindur complex. The modelling of equilibrium crystallization versus fractional crystallization on two Thverartindur compositions has been performed but it shows significant differences only for Si, Ti, and Fe in the evolving systems. The quartz-tholeiitic compositions may be derived after 50—70% crystallization of olivine-tholeiites. A very high iron—titanium enrichment (TiO_2 up to

4.2 wt%; FeO 13—14 wt%) in the remaining liquid is possible only when the crystallizing system follows the equilibrium crystallization path. The mineral compositions resulting from the models of the equilibrium and/or fractional crystallization are close to the actual one observed in the gabbros. The trace element distribution cannot be described with these simple models.

ii) Fractionation in periodically refilled (O'Hara, 1977; O'Hara & Mathews, 1981) magma chambers offers an explanation to the occurrence of different mineral generations, particularly plagioclase, which is the first liquidus phase in this system. Neither equilibrium nor fractional crystallization modelling does display the remarkable CaO-enrichment of the liquid path. A more dynamic path results from a continued series of cycles inside the magma chamber. As the initial magma is first subjected to fractional crystallization, the fraction of the remaining magma can erupt to the surface or continue to fractionate, and finally become contaminated by the wall rock and replenished by magma from a deeper source. Replenishment may take place in two ways: firstly, as batch replenishment where a chamber is filled with a discrete batch of magma through a short time interval or, secondly, as continuous replenishment over a long time interval. This process may be partly responsible for some restricted variation in incompatible element distribution in the Thverartindur samples.

Different mechanisms have been suggested for the evolution of Icelandic volcanics. In the recent Krafla volcanic system the AFM (assimilation-fractional crystallization) mechanism is believed to control the evolving magma system (Nicholson et al., 1991). This model takes into account lavas and other volcanic products which represent only the top "slice" of this crust-building environment. Process-oriented modelling should include additional "slices" of the plutonic formation, which may contain not less important imprints of "hidden" processes.

iii) Some of the Thverartindur samples that are referred to as hybrid, show a large chemical variation and more than one mineral generation requiring a different process, most likely magma mixing. In the Thverartindur plutonic formation, there occur two kinds of mixing. Firstly, the conventional case of acid-basic mixing, where less dense acid liquid enters into a basic magma chamber and produces an intermediate liquid observed in the intermediate dykes (Fig. 2). It is not obvious whether the mixing took place in a magma chamber or during the emplacement stage. Secondly, the mixing of two basic magmas of different compositions and different densities. An evolved quartz-tholeiitic magma may have been mixed with crystals from a more primitive parent. This can be successfully explained by equilibrium/fractional crystallization of olivine-tholeiitic magma where at the final stage (crystallinity around 70%) the residual liquid was squeezed out capturing part of higher-temperature crystals, most likely plagioclase. This appears to be the case with hybrid samples with two distinctive generations of plagioclase without any smooth compositional change.

CONCLUSIONS

The plume influence in initial magma generation and magmatic evolution in crustal magma chambers inside the anomalously thick Icelandic crust (8—20 km) and later interaction with the altered old crust has created the specific chemistry of Icelandic rocks, such as high abundance of incompatible trace elements, high $^{87}Sr/^{86}Sr$, low $^{143}Nd/^{144}Nd$ and radiogenic Pb contents.

Central volcanic systems along the rift zones modify the oceanic crust producing abundant evolved basaltic, intermediate, and rhyolitic rock types, which are not typical in the normal MORB environment. The Tertiary Thverartindur central volcanic complex in SE Iceland exhibits a large variation of rock types from ultramafic through olivine- and quartz-tholeiites, hybrid rocks to acid in the chemical composition. These rocks are developed as a result of multiple processes: i) fractional crystallization in a probably refilled crustal magma chamber; ii) mixing between basic and acid magmas, and mixing of the captured solidified crystals with more evolved basic magma. However, the Fe—Ti-enrichment accompanied by Si decrease in quartz-tholeiitic gabbros can be most easily obtained by a 50—70% crystallization of the olivine-tholeiitic composition following the equilibrium crystallization path.

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PLUTOONILISTE KIVIMITE MITMEKESISUS OOKEANI KOORES: THVERARTINDURI TSENTRAALNE VULKAANILINE KOMPLEKS KAGU-ISLANDIL

Alvar SOESOO

Islandi saar on osa Põhja-Atlandi ookeani koorest, kus ookeani keskahelik paljandub maismaal. Kagu-Island on läbi teinud ulatusliku glatsiaalse erosiooni, mille tulemusel on võimalik uurida geoloogilisi läbilõikeid, mis algselt olid maetud kahe kilomeetri sügavusele. Thverartinduri vulkaanilise kompleksi plutooniline osa koosneb tholeiitse seeria oliviin- ja kvartsnormatiivsetest gabrodest, hübriidsetest kivimitest ja suhteliselt laialdases mahus graniitsetest kivimitest. Ultraaluselised kivimid on esindatud sillide ja daikidena. Nimetatud kivimitüübid paljanduvad kahe

paljufaasilise intrusioonina ja on geneetiliselt seotud ühise, maapinnalähedase magmakambriga. Kivimitüüpide mitmekesisus on tingitud erinevatest magmaprotsessidest, nagu: 1) fraktsiooniline ja tasakaaluline kristalliseerumine aeg-ajalt uuesti täidetud magmakambris; 2) väga mitmekesine aluselise magma ja happelise magma ning aluselise magma ja kristalliseerunud mineraalide segunemine, mis on arvatavasti aset leidnud nii magmakambris kui ka sillide formeerumise etapil. Kvartsnormatiivsed gabrod on raua- ja titaanirikkad, aga samas sisaldavad vähem ränioksiidi kui primitiivsemad oliviinnormatiivsed gabrod. On modelleeritud oliviinnormatiivse gabro kristalliseerumist Ni-NiO (NNO) ja kvarts—fajaliit—magnetiit (QFM) puhvrites, kusjuures parimad tulemused on saadud tasakaalulisel kristalliseerumisel NNO-puhvris. Pärast oliviin-tholeiitse magma 50—70%-st kristallisatsiooni vastab jääkmagma põhielementidelt kvartsnormatiivsete gabrode koostisele.

РАЗНООБРАЗИЕ ПЛУТОНИЧЕСКИХ ПОРОД В ОКЕАНИЧЕСКОЙ КОРЕ: ТВЕРАТИНДУРСКИЙ ЦЕНТРАЛЬНО-ВУЛКАНИЧЕСКИЙ КОМПЛЕКС В ЮГО-ВОСТОЧНОЙ ИСЛАНДИИ

Алвар СОЕСОО

Исландия представляет собой часть океанической коры на севере Атлантики. Глубоко эродированный Твератиндурский комплекс сложен олевиновым и кварцевым габбро, гибридными и ультраосновными породами и гранитами. Названные породы картографированы на двух многофазных интрузивных массивах. Разнообразие плутонических пород океанической коры обусловлено разными магматическими процессами: фракционной и равновесной кристаллизацией, смешением разных магм, а также магм и кристаллов. Результаты моделирования кристаллизации олевин-нормативного габбро в NNO и QFM кислородных буферах показывают, что после 50—70%-ной кристаллизации остающаяся часть магмы отвечает по составу главных элементов кварцевым габбро.