Thickness, Composition and Physical Properties of Crust in Iceland's Neovolcanic Zone

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Abstract

We report the results of an ongoing effort to use petrologic data to estimate the thickness, composition and physical properties of crust in the neovolcanic zone of Iceland. The objectives are to constrain the depths of magma chambers, calculate geothermal gradients, and resolve discrepancies in the interpretation of geophysical data (primarily gravity and seismic). 1788 whole rock analyses and 170 glass analyses of erupted Icelandic lavas from the neovolcanic zone have been compiled from published papers. Variation diagrams indicate that Icelandic magmas evolved primarily by crystallization of Ol-Cpx-Plag, whereas the most primitive magmas evolved by crystallization of Ol alone. Phase equilibrium constraints were used to quantitatively estimate the pressure of crystallization along the Ol-Cpx-Plag cotectic and hence the depths of the magma chambers. The latter occur at 20±6.2 km, and the average temperature of magma in the chambers is 1207±26°C (also estimated from phase equilibrium constraints). The results suggest magma chambers located at the base of the crust indicating that the latter is ~20 km thick along the neovolcanic zone in agreement with estimates based on geophysical studies. It is argued that the average composition of erupted lavas provides an accurate estimate of crustal composition because magma evolution occurs in sub-crustal chambers. A representative geothermal gradient was calculated using the average crust composition and surface heat flow measurements. The calculated gradient is consistent with the periodic presence of shallow intracrustal magma chambers at ~5 km depth that have been detected seismically, with hydrothermal circulation in the uppermost 3 km of the crust, and with temperatures of ~1200°C at the base of the crust. The geotherm was used to calculate a density-depth profile for average crust. Densities decrease with depth if a low-pressure mineralogy is used for the crust. This density inversion can be avoided by assuming either that the crust varies in composition (becoming richer in MgO) with depth, or that the composition is uniform and the mineralogy changes to that of a low-P, high-T granulite at 20 km. The latter model involves fewer ad hoc assumptions and provides a close match to accepted densities and seismic velocities for the lower crust. The calculated density contrast between crust and mantle, Δρ, is 150 kgm-3 assuming a mantle density of 3300 kgm-3, whereas VP is calculated as 6.95 kms-1 at the base of the crust.

Setting and Location

Iceland is located along the Mid-Atlantic Ridge (MAR). Active rifting occurs in the Northern Volcanic Zone (NVZ), the Western Volcanic Zone (WVZ), and the Eastern Volcanic Zone (EVZ) (Figure 1). Whole Rock and Glass samples are available at many volcanic centers and analyses have been compiled from published work (Figure 2, Table 1).

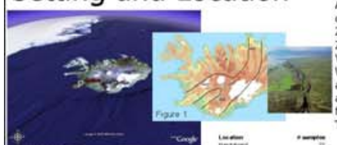


Figure 1

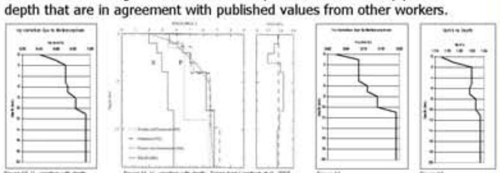
Figure 2

Location	# samples	Reference
Herdubreid	22	Moore and Calk, 1991
Hlodufell	19	Moore and Calk, 1991
Raudafell	12	Moore and Calk, 1991
Efstadalsfjall	30	Moore and Calk, 1991
Kalfstindar	10	Moore and Calk, 1991
Geitafell	12	Moore and Calk, 1991
Kistufell	10	Breddam, 2002
Bondholshraun	5	Slater et al., 2001
Borgarhraun	6	Slater et al., 2001
Langavitigraun	3	Slater et al., 2001
Blafjall Ridge	19	[illegible], 1995
Halar	3	[illegible], 1995
Seljahalli	4	[illegible], 1995
Reykjanes Ridge	612	Hilton et al., 2000; Michael, 1995; Ryan and Langmuir, 1987; Christie et al., 1986; Fornari et al., 1988; [illegible]; Sigurdsson, 1981; Cohen et al., [illegible]; Wood et al., 1979; and Hermes and Schilling, 1976
Kolbeinsey Ridge	94	Michael, 1995; Fornari et al., 1988; Sigurdsson, 1981; Delaney et al., 1978

Table 1. Neovolcanic zone glass analyses.

Geophysical Applications

Knowledge of crustal thickness, surface heat flow values, and T at the base of the crust allows calculation of a representative neovolcanic zone geothermal gradient (Figure 8). Using the geothermal gradient, a model is developed providing for change in mineral assemblage with depth due to changing metamorphic facies where the average crustal composition is held constant. This crustal model gives calculated density and seismic velocity profiles with depth that are in agreement with published values from other workers.



Compositions

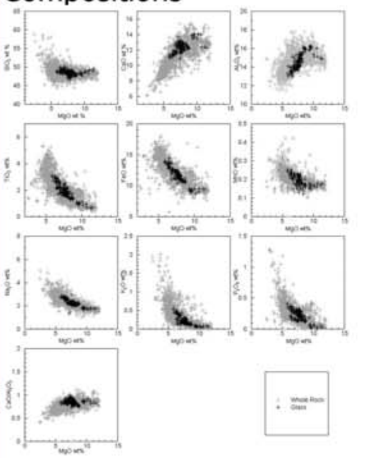


Figure 3. Variation diagrams plotting whole rock and glass analyses for samples from the Iceland neovolcanic zone. These diagrams demonstrate the importance of using glass analyses in petrologic calculations rather than whole-rock analyses as is typically done. Qualitatively, the glass analyses better illustrate the paths of crystallization. Quantitatively, there is far less deviation from the trend line in the data.

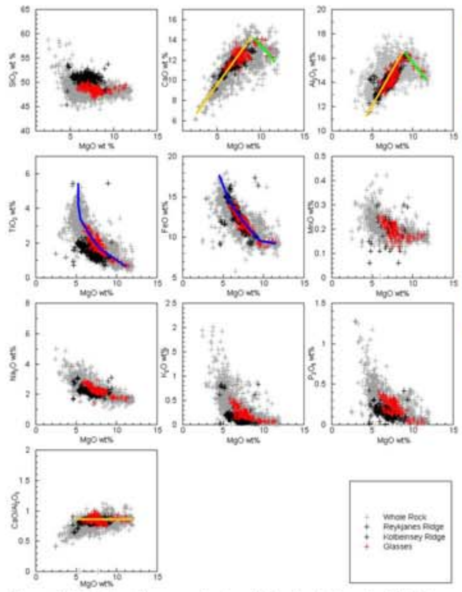


Figure 4. Variation diagrams showing Icelandic whole rock, MAR glass, and Icelandic glass analyses.

The plots of CaO vs. MgO and Al_2O_3 vs. MgO show that olivine crystallized alone from initial melts until plag and cpx also began to crystallize from the melt at ~9% MgO.

The decrease in CaO and Al_2O_3 with decreasing MgO could be due to the crystallization of plagioclase and cpx, or plagioclase alone. The plot of CaO/Al_2O_3 vs. MgO shows this ratio remains constant throughout the crystallization history indicating crystallization of both plag and cpx.

TiO_2 vs. MgO and FeO vs. MgO plots show that there are no Fe or Ti oxides crystallizing until late in the the evolutionary history. This has implications regarding fO_2 studies.

The knowledge that olivine crystallized alone from the most primitive melt allows calculation of a primary magma through olivine addition. The calculated primary magma from this work is shown below along with that of Korenga and Kelleman (2000). The later results were obtained through calculations involving whole rock analyses while the results of this work were obtained using glass analyses only.

Oxide (wt%)	SiO2	TiO2	Al2O3	Fe2O3	FeO	CaO	MgO	MnO	K2O	Na2O	P2O5	Total
Kolbeinsey Ridge	50.67	1.28	14.14	1.35	12.08	11.62	6.96	0.19	2.21	0.19	0.12	99.42
Reykjanes Ridge	50.79	1.44	14.04	1.34	12.34	11.70	6.92	0.21	2.09	0.12	0.14	99.59
Most Felsic WR	72.3	0.22	12.1	0.4	1.4	1	0.09	0.05	3.5	4.9	0.04	96.00
Average WR	48.84	2.13	14.43	1.42	10.86	11.13	7.04	0.20	0.41	2.39	0.24	99.10
Most Mafic WR	49.78	1.63	11.78	3.32	6.05	11.99	11.06	0.18	0.69	2.02	0.24	98.74
Calculated Parent Magma (Ol Fo88)	47.05	1.78	12.06	1.19	11.47	9.30	14.45	0.17	0.34	2.00	0.20	100.01
Korenga and Kelleman (2000) (Ol Fo88)	46.5	1.48	13.1	0.7	11.8	9.8	14.4	0.17	0.18	1.79	0	99.92
Most Felsic Glass	49	3.09	13.3	0	13.8	11.2	5.82	0.25	0.54	2.73	0.41	100.14
Average Glass	48.45	1.84	14.57	0.00	11.53	12.35	7.99	0.19	0.21	2.22	0.21	99.55
Most Mafic Glass	48.54	0.61	14.48	0	8.91	12.85	12.07	0.17	0.05	1.5	0.01	99.19

Table 2. Major element compositions for neovolcanic zone crustal whole rocks and glasses, Kolbeinsey Ridge samples, Reykjanes Ridge samples, and calculated parent magmas.

Magma Chamber Depth; Crustal Thickness Determination

The evidence for ol-plag-cpx cotectic crystallization from melt allows calculation of the P and T of magma evolution using the method of Yang et al. (1996). The change in equilibrium compositions with increasing pressure is represented by the shifting cotectic in the olivine, quartz, diopside ternary diagram (Tormey et al., 1987). This method was used to quantitatively determine the pressures at which the magmas that sourced the samples were in equilibrium. These pressures correspond to the depths of magma chambers where melt evolution occurs.

Volcanic Center	Ave. P (kb)	Ave. z (km)	Ave. T (C)
Herdubreid	4.3±1.0	15.0	1193±8.5
Hlodufell	3.9±0.8	14.0	1185±7.5
Raudafell	5.4±1.1	19.0	1201±7.5
Efstadalsfjall	5.0±1.7	18.0	1199±11
Kalfstindar	7.6±0.4	27.0	1217±3.0
Geitafell	4.4±0.8	15.0	1187±5.8
Kistufell	4.4±1.0	15.3	1210±5.4
Bondholshraun	6.0±0	21.0	1214±1.0
Borgarhraun	7.0±2.1	24.5	1223±9.7
Langavitigraun	7.3±0.6	25.7	1227±4.2
Blafjall	6.2±0.6	22.0	1211±4.0
Halar	5.3±0.8	19.0	1206±7.7
Seljahalli	8.1±9.5	28.6	1221±7.7

Table 4. Pressures P, temperatures T, and depths z of magma evolution for sampled volcanic centers in the neovolcanic zone.

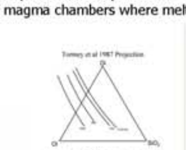
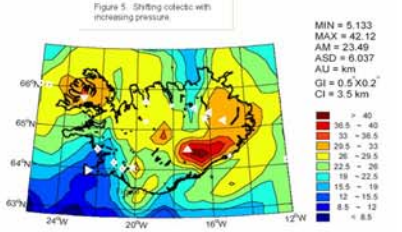


Figure 5. Shifting cotectic with increasing pressure



Gravimetry results showing agreement between geophysically and petrologically derived crustal thickness estimates (Leftwich et al., 2005)

Figure 7

Discussion

From glass compositions it is possible to reliably determine the crystallization history, primary melt composition, depth and temperature of magma equilibration, geothermal gradient, crustal mineral assemblage model, seismic velocity profile, and density profile in the Iceland neovolcanic zone through relatively uncomplicated petrologic calculations.

Conclusions

- Crustal thickness in the neovolcanic zone is ~20 km with a temperature of ~1200° C at the base of the crust.
- Any petrologic calculations should be based on analyses of volcanic glasses rather than whole rock compositions.
- A model of changing mineralogy with depth along the determined geothermal gradient allows calculation of V_p and ρ that are in agreement with published geophysical studies.
- Primary melt is calculated to contain 14.45% MgO.

Future Work

- Glass samples from the adjacent Reykjanes and Kolbeinsey Ridges as well as Icelandic glass samples are being analyzed in order determine the trends in composition and to calculate the oxidation state of magmas erupted in MORB and OIB settings in this region.
- In addition, mantle potential temperatures beneath the adjacent Reykjanes and Kolbeinsey Ridges as well as beneath Iceland will be calculated from olivine-melt thermometer described by Putirka (2005), using glass analyses rather than whole rock compositions.