

# A gravity study of silicic domes in the Krafla area, N-Iceland

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**Abstract** – *Silicic rocks in Iceland are generally associated with central volcanoes and are often emplaced as domes on or around caldera rims. Some of these domes were formed subglacially while others were erupted under ice-free conditions. A gravity survey was carried out in the area of Krafla in 2007 and 2008 to determine the mean bulk densities of three silicic domes; essential data for meaningful modelling of the emplacement of cryptodomes and lava domes. Such data are scarce. Profiles were measured over three formations: Hlíðarfjall, made of rhyolite, 310 m high, 2 km long and formed under ice 90 000 years BP, Hrafninnuhryggur, made of rhyolite, 80 m high, 2.5 km long and formed subglacially 24 000 years BP and Hraunbunga made of dacite, 125 m high and 1.8 km long, formed under ice-free conditions 10 000 years BP. Mean bulk density for each formation was obtained by the Nettleton method. Mean bulk density and volumes obtained were; Hlíðarfjall: 1600–1800 kg m<sup>-3</sup>, 0.143 ± 0.014 km<sup>3</sup>; Hrafninnuhryggur: 1575–1875 kg m<sup>-3</sup>, 0.021 ± 0.002 km<sup>3</sup>; Hraunbunga: 1750–1775 kg m<sup>-3</sup>, 0.040 ± 0.004 km<sup>3</sup>. The results show that all the domes have low densities, reflecting both low grain-density and high porosity. The density values are significantly lower than those of the surroundings, creating a density contrast possibly sufficient to drive the ascent of silicic magma. Furthermore, results from forward gravity modelling demonstrate that these formations are neither buried by younger volcanic eruptives nor are any roots detected. The domes studied were therefore emplaced by a dike to the surface.*

## INTRODUCTION

Rhyolite magma can rise due to buoyancy forces and either form a cryptodome in the shallow crust or rise to the surface, where it erupts. Due to its high viscosity and resistance to flow it often accumulates and forms a lava dome over the vent. In volcanology, a dome is defined as an accumulated silicic melt of high viscosity. The term is used to describe any dome, whether it is on the surface or not. A dome can actively deform adjacent strata and break through the surface. The term coulee is used for a lava dome where some lateral flow away from the vent has occurred (Fink and Anderson, 2000).

Worldwide, domes are associated with viscous, silicic magma. The occurrence of domes could therefore be expected in areas of silicic volcanism, i.e. subduction zones, rather than in areas where basaltic vol-

canism is dominant, i.e. divergent rift zones and hot spots. However, dome formations are known in areas of basaltic volcanism, e.g. in Krafla, Iceland. Worldwide, dikes feed many silicic domes (Fink and Anderson, 2000). These domes tend to occur in groups, that are either in linear or echelon arrays (Fink and Anderson, 2000), e.g. in Long Valley, California.

Silicic rocks in oceanic crust are very rare and it seems likely that the oceanic crust has to reach a certain thickness before silicic domes can develop. This can be argued from studies of seismic data for Iceland (e.g. Menke, 1999) and the geographical distribution of silicic domes and nunataks in Iceland (Jónasson, 2007). Geological settings in Iceland are very different from those of a subduction zone where domes are common. Iceland is a ridge-centered hotspot island, situated astride the Mid-Atlantic Ridge. The

geology of Iceland is characterised by the interaction of spreading at the mid-ocean plate boundary and the hotspot, centered in east-central Iceland under the Vatnajökull icecap (Wolfe *et al.*, 1997). The divergent plate boundary is marked by a chain of active central volcanoes traversing Iceland, resulting from plate rifting and volcanism induced by upwelling of the hotspot. Central volcanoes are defined by frequent eruptions from a central area (Walker, 1963; Sæmundsson, 1978). Volcanism in the neovolcanic zone results in elongated volcanic systems, consisting of a central volcano and a transecting fissure swarm (Sæmundsson, 1978, 1979). A geothermal field is often associated with the central volcano. Furthermore, silicic rocks in Iceland are generally associated with central volcanoes (Jónasson, 2007) and most central volcanoes have only produced minor amounts of silicic rock in a few formations (Jóhannesson and Sæmundsson, 1999). No dome eruption has been observed with modern monitoring equipment in Iceland while the geological record contains many silicic tephra layers, lavas and dome formations (Jóhannesson and Sæmundsson, 1999; Larsen, 2000). Domes in Iceland generally occur at or near the caldera rims of an active central volcano. The sides of the underlying magma chamber are thought to represent the best conditions for the formation of silicic melts due to cooling of the hydrothermal system (Jónasson, 1994). The central volcano Krafla, situated in the NVZ (Northern Volcanic Zone), has an ice-free caldera surrounded by subglacially formed silicic domes Hlíðarfjall, Hrafn-tinnuhryggur, Jörundur and Rani (not studied here), all located close to the caldera rim. (Sæmundsson, 1991). The Krafla area is both easily accessible and one of the most intensely studied volcanic areas in northern Iceland, due to the geothermal power plant situated above the caldera's shallow magma chamber and the recent volcano-tectonic episode, the Krafla fires, in 1975–1984 (e.g. Einarsson, 1991; Buck *et al.*, 2006). For these reasons the Krafla region was chosen as a study area to examine Icelandic domes in an active central volcano. The determination of the vent structure can shed light on how these domes were emplaced, e.g. whether they were formed by a dike-fed eruption or by a more forceful emplacement displac-

ing surrounding strata in the process. Buoyancy is important in driving magma through the crust, and therefore density data are necessary for meaningful modelling of the emplacement of cryptodomes and lava domes. The aim of the present work was therefore to determine poorly known bulk density values for domes and to investigate whether the domes have roots. Rock samples were also collected and their density measured to further constrain the results.

## GEOLOGICAL SETTINGS

### The Krafla volcanic system

The Krafla volcanic system (Figure 1) is located in the Northern Volcanic Zone (NVZ). The NVZ consists of several elongated closely spaced volcanic systems, amongst which the Krafla and Askja volcanic systems are most active. The Krafla volcanic system consists of a central volcano and a transecting fissure swarm. The Krafla caldera is approximately 10 km wide, transected by a 100 km long and N10°E trending fissure swarm (Sæmundsson, 1991). Around the caldera a number of concentric fissures have erupted hyaloclastites, lavas and rhyolite (Sæmundsson, 1991). A powerful geothermal system lies inside the caldera, harnessed by a geothermal power station operated since 1977. The Krafla caldera began forming about 100 000 years BP (Sæmundsson, 1991). Due to the intensive volcanism, stratigraphic build up has been relatively fast, both during periods of ice-free conditions and periods when ice covered the land. In the geological strata of the Krafla caldera there is evidence of two main warm periods. The silicic rocks are concentrated around the caldera rim and away from the central part of the fissure swarm (Sæmundsson, 1991).

### The Heiðarsporður volcanic system

Heiðarsporður is a small volcanic system located south of Krafla. Its topographic expression is a low and broad ridge, about 15 km long and 3 km wide, extending from the Krafla central volcano in the north towards the Bláfjall ridge and in the south to the Fremrinámur central volcano. This volcanic system was active for a relatively short time (1000 years) in the early Holocene and was built up in several small

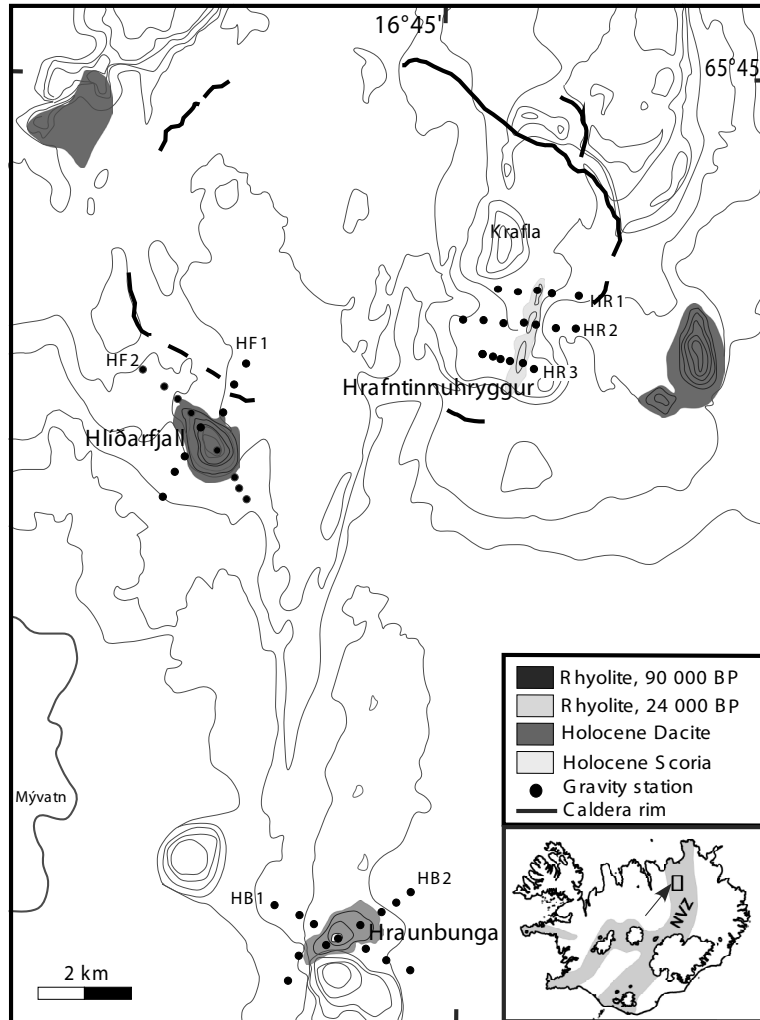


Figure 1. Map of the Krafla and Heiðarsporður areas showing the main outcrops of silicic volcanic rocks together with the approximate location of the inferred caldera (dot-dashed contour) of the Krafla volcanic system. The inset map shows the location of the survey area in the Northern Volcanic Zone (NVZ), with neo-volcanic zones shaded. Map redrawn from Jónasson (1994) with the geology based on maps of Sæmundsson (1991). Gravity stations of this survey are shown with black dots. – *Einfaldað jarðfræðikort af Kröflu- og Heiðarsporðs eldstöðvakerfunum. Kortið sýnir helstu síru myndanirnar á svæðinu og Kröflu öskjuna. Litla Íslandskortið sýnir legu mælisvæðisins í nyrðra gosbeltinu (NVZ); gosbeltin eru sýnd grá. Þyngdarmælingarpunktur þessarir rannsóknar eru sýndar með svörtum doppum.*

eruptions (Sæmundsson, 1991), including the formation of Hraunbunga, a small dacitic dome or coulee.

### Geological framework of studied formations

In this study three well-defined domes were surveyed, Hlíðarfjall, Hrafninnuhryggur and Hraunbunga (Figure 1):

1. Hlíðarfjall (rhyolite, 310 m high, 2 km long) formed 90 000 years BP, parallel to the Krafla caldera rim on the southwest side (Sæmundsson, 1991; Sæmundsson *et al.*, 2000).
2. Hrafninnuhryggur (rhyolite, 80 m high, 2.5 km long) formed 24 000 years BP, located 0.5–1 km inside and sub-parallel with the eastern caldera rim of Krafla (Sæmundsson, 1991; Sæmundsson *et al.*, 2000).
3. Hraunbunga (125 m high, 1.8 km long), a dacitic coulee erupted from a short fissure formed 10 000 years BP in the Heiðarsporður volcanic system (Sæmundsson, 1991).

Hlíðarfjall and Hrafninnuhryggur are short, steep ridges that may be regarded as subglacial equivalents of lava domes. Hlíðarfjall together with the domes Jörundur and Rani are parallel to the Krafla caldera rim and may, on the basis of composition and age, be interpreted to represent a common short-lived phase in Krafla's history. It has been suggested that these rhyolite eruptions were caused by the emplacement of a ring dike (Jónasson, 1994) but the activity may have been more limited and localised, associated with occasional rhyolitic dike intrusions. Hrafninnuhryggur has a different composition and age and is parallel to the tectonic trend in the caldera and subparallel with the eastern caldera rim (Sæmundsson, 1991). Hraunbunga is a dacitic coulee in the Heiðarsporður volcanic system; one of the few silicic domes in Iceland not associated with a central volcano (Jónasson, 2007).

## METHODS AND DATA

In general, silicic rocks have lower densities than those of a more basaltic composition. Measuring a gravity profile over a rhyolite dome surrounded by

basaltic lava should demonstrate a significant density contrast. The form of gravity anomalies associated with outcropping surface formations can often be used to determine whether they are partly buried by younger formations or not (Figure 2). Knowledge of past geological processes at the observation site also gives an idea of what can be expected under the surface. Data from boreholes that reach to just over 2 km depth in the Krafla caldera demonstrate that bedrock in the region consists predominantly of basalt, with suites of layered piles of alternating lava and units of hyaloclastite down to 2000 meters, where granophyre becomes dominant at the bottom (Gudmundsson *et al.*, 2008; Arnadottir *et al.*, 2009).

### The gravity surveys

In Iceland, gravity studies aimed at determining bulk density of individual topographic features have been done on hyaloclastite tindars (hyaloclastite ridges), tuyas and lava flows but not on silicic formations. This study will attempt to fill that gap. The Nettleton method has proved to be useful for density determinations of hyaloclastite and lava formations (Schleusener *et al.*, 1976; Gudmundsson and Milsom, 1997; Gudmundsson *et al.*, 2001; Gudmundsson and Högnadóttir, 2004; Schopka *et al.*, 2006), this should also be the case for rhyolite domes. Density measurements of rock samples have been made for most types of Icelandic rock (Pálsson *et al.*, 1984; Gudmundsson and Högnadóttir, 2004). A knowledge of rock densities is necessary for applying the Bouguer anomaly and the Nettleton method (e. g. Kearey *et al.*, 2002).

The mean bulk density of the surface bedrock in the Krafla caldera was obtained by Johnsen (1995) by applying the Parasnis method (Parasnis, 1973) to the entire Krafla caldera. In the Bouguer reduction we use his value of 2500 kg m<sup>-3</sup> as our background density. The reason is that this density best represents the surroundings of the domes, i.e. the bedrock in the Krafla area. A total of 48 gravity stations along nine profiles were measured (Figure 1) over the three dome formations. Observations were carried out in the autumn of 2007 and the spring of 2008, during five days.

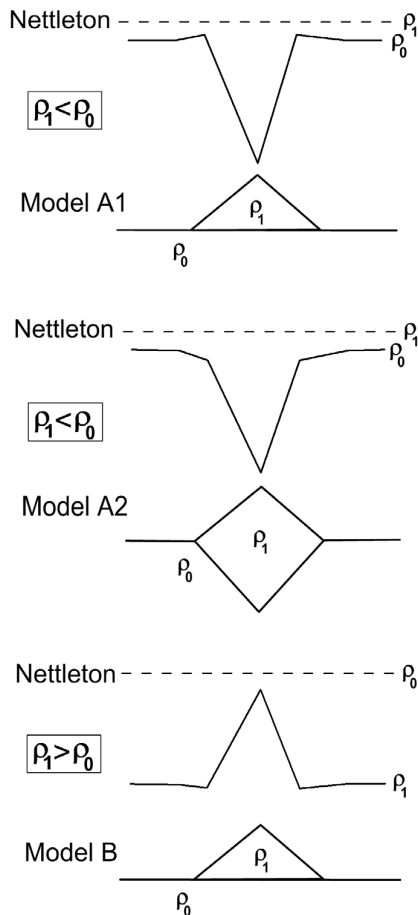


Figure 2. Three cases of expected Bouguer anomaly from a topographic formation. A1: Formation has no crustal root and a density ( $\rho_1$ ), significantly less than the reduction density ( $\rho_0$ ). A2: Formation has a topographic root and density  $\rho_1 < \rho_0$ . Note the difference in the form of the anomaly flanking the formation for A1 and A2. B: No root but formation density higher than reduction density ( $\rho_1 > \rho_0$ ). – *Bouguer þyngdarsvið frá fjalli. A1: Fjallið hefur ekki rót og eðlismassi fjallsins ( $\rho_1$ ) er lægri en sá eðlismassi sem notaður er til að reikna Bouguer leiðréttingu ( $\rho_0$ ). A2: Fjallið hefur lágan eðlismassa og rót sem nær niður í jarðskorpuna. B: Engin rót en eðlismassinn ( $\rho_1$ ) er hærri en viðmiðunar eðlismassinn ( $\rho_0$ ).*

The gravity field was measured along profiles, preferably perpendicular to the strike of the formation, and gravity stations were placed at 0.2–0.5 km intervals. Gravity readings were made using a Lacoste and Romberg (G-445) gravimeter. A kinematic GPS Trimble 5700 was used for elevation measurements at each station. All surveys were carried out on foot and all equipment carried by two surveyors. A combined Bouguer and topographic correction was calculated by direct integration of a topographic model with a pixel size of 25 m (Gudmundsson and Milsom, 1997; Gudmundsson and Högnadóttir, 2004). A Bouguer anomaly was then obtained by subtracting the correction from the free air anomaly.

The accuracy of a gravity survey is limited by the gravimeter, terrain corrections and the accuracy in measured elevation. The gravity meter has an accuracy of 0.01 mGal (LaCoste and Romberg Inc., 1979). The elevation accuracy in this study is equal to or better than 0.5 m which causes a 0.1 mGal error in the Bouguer anomalies. The combined accuracy of the random uncertainty due to terrain and Bouguer corrections (resulting from integration of the elevation model) are minor and is considered to be better than 0.1 mGal. Total accuracy for measurements and processing is therefore 0.2 mGal (Agustsdóttir, 2009).

### Rock samples

Rock samples were gathered from each formation. Usually five representative samples for density determination were collected at important gravity stations along the survey profiles. A total of 95 samples were collected at 15 sites. The dry and wet densities of these samples were obtained in the laboratory from the difference in their weight in air and when submerged in water.

### Nettleton's method

A two-step approach is adopted here to determine the best density and study the roots of the domes:

1. Nettleton's method, used to determine the most likely bulk density of a formation and/or to indicate whether a dome is partly buried in younger formations.

2. Forward modelling, where details of dome form are examined, including the possible existence of a root extending into the crust, and whether the assumption used in Nettleton's method of a single bulk density of a formation is valid.

Nettleton's method (Nettleton, 1976; Kearey et al., 2002) of density determination involves taking gravity observations over an isolated topographic prominence. Field data is reduced using a series of different densities for the Bouguer and terrain corrections. The density that provides a Bouguer anomaly with the least correlation with the topography is taken to represent the mean bulk density of the topographic formation (Kearey et al., 2002). The Nettleton method works where formations are not buried or where formation and surroundings have the same density. A Nettleton profile determines the mean bulk density of an entire mountain, but can give a misleading result if the formation is partly buried in lava or sediments.

It is common that the density obtained from Nettleton's method is less than the mean density of rock samples from the same formation, especially in fractured and porous rock. This discrepancy arises because 5–10 cm diameter rock samples do not include the volume occupied by large fractures or voids. Thus, a systematic difference is to be expected between the two methods. However, the overestimation of bulk density found using the mean of the densities of rock samples, is likely to be similar for porous and fractured rocks, regardless of composition. This is supported by comparisons of Nettleton profiles and rock samples (Agustsdottir, 2009). The accuracy of estimating the bulk density in this study by Nettleton's method is considered to be  $\pm 100 \text{ kg m}^{-3}$  (Agustsdottir, 2009). Figure 3 shows the Nettleton's profile over Hlíðarfjall. We note a slight local rise in Bouguer anomaly immediately adjacent to the formation (Figure 2). Comparing Figure 2 with Figure 3 we conclude that this dome has insignificant roots.

### Gravity forward modelling

Forward, 2.5-D gravity models are generated using the GravMag software (Pedley et al., 1997), using the background density  $2500 \text{ kg m}^{-3}$  (Johnsen, 1995) and

the density values obtained for each formation with the Nettleton method. The model profiles are constructed by subtracting a regional field obtained as the linear fit (since all the profiles are short) that best represents the mean trend of the Bouguer anomaly at the location of the profile. Bodies are assumed to strike perpendicular to the survey line and a finite strike length can be assigned, i.e. the true length of the formation perpendicular to strike can be used as the length of the modelled body.

## RESULTS

### Density values

The main results are that all the domes are of low density, reflecting both low grain-density and high porosity (Table 1). Table 1 also shows that the dome's density values are significantly smaller than those of the surroundings. Table 2 shows the volume and mass of the formations.

Table 1. Mean bulk densities ( $\bar{\rho}$ ) for each profile (Figure 1), determined by the Nettleton method ( $\rho_N$ ) and rock samples ( $\rho_s$ ). The density of the surroundings are from Johnsen (1995). – *Meðaleðlismassi ákvarðaður með aðferð Nettletons fyrir hvert snið á 1. mynd og út frá grjótsýnum ( $\rho_s$ ). Eðlismassi umhverfisins (bakgrunns-eðlismassi) samkvæmt Johnsen (1995).*

Location	$\rho$ [ $\text{kg m}^{-3}$ ]			
	profile	$\rho_N$	$\rho_s$	$\bar{\rho}$
Hlíðarfjall	HF1	1600	2060	1700
	HF2	1800	2060	
Hrafninnuhr.	HR1	1575	1750	1692
	HR2	1875	1750	
	HR3	1625	1750	
Hraunbunga	HB1	1775	1950	1763
	HB2	1750	1950	
Surroundings				2500

### Gravity models

Gravity models for all the formations show consistent results. Therefore only one selected profile from each formation is presented. Three models are presented for Hlíðarfjall and Hrafninnuhyggur, four for Hraunbunga. The three models are defined as:

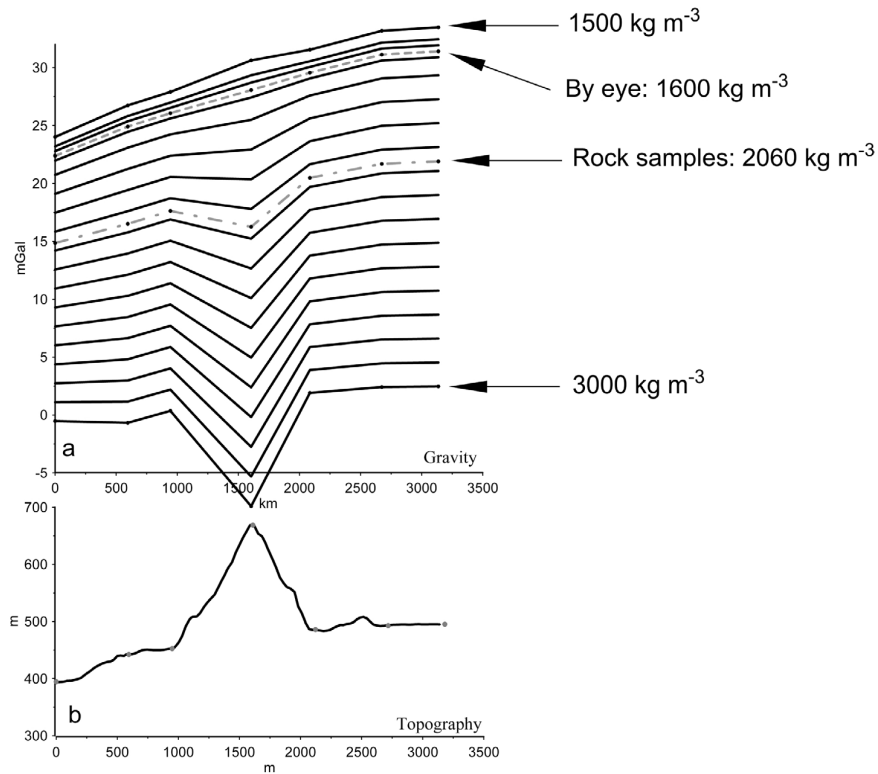


Figure 3. Nettleton's method used to determine the bulk density of Hlíðarfjall (survey line HF1). Gravity reductions have been performed using densities ranging from 1500–3000 kg m<sup>-3</sup> (a). The dot-dash line represents the density determined by the rock samples. The fine dashed line show the best fit density determined by eye. The lower figure (b) represents the topography along the profile, where the dots represent observed gravity stations. – Aðferð Nettletons notuð til að ákvarða meðaleðlismassa Hlíðarfjalls (snið HF1). Þyngdargögnin hafa verið leiðrétt fyrir eðlismassa á bilinu 1500–3000 kg m<sup>-3</sup> (a). Punkta-brotalínan sýnir eðlismassa grjótsýna. Fíngerða brotalínan sýnir eðlismassann sem hefur minnsta fylgni við lögun fjallsins. Neðri myndin (b) sýnir landslag eftir sniðinu þar sem punktarnir sýna hvar mælt var.

Table 2. The volume of the formations, estimated from the digital elevation model using Surfer 8.0®. Mass of each formation is calculated using these volumes and the densities obtained from Nettleton's method (Table 1). – Rúmmál jarðmyndana var metið út frá hæðarlíkani með Surfer 8.0®. Massi hvers myndunar var reiknaður með því að nota rúmmálin og svo eðlismassann sem fékkst með aðferð Nettletons (tafla 1).

Locality	volume (km <sup>3</sup> )	mass min (10 <sup>9</sup> kg)	mass max (10 <sup>9</sup> kg)
Hlíðarfjall	0.143±0.014	229±23	272±27
Hrafninnuhr.	0.021±0.002	34±3	40±4
Hraunbunga	0.040±0.004	72±7	76±8

- a. The dome is strictly a surface formation without a root extending down into the crust.
- b. Same as *a* but a narrow dyke extends downwards into the crust.
- c. The dome is modeled as the top of a partly buried formation.

All gravity models of type *b* are shown with the maximum possible width of the feeder dike, 20–25 m. Insertion of a wider feeder results in a significant effect on the shape of the calculated anomaly and divergence between model and data.

#### *Hlíðarfjall – profile HF1*

The HF1 profile is 3137 meters long from SW-NE, and measured across the subglacially formed rhyolite dome Hlíðarfjall (Sæmundsson, 1991).

Hlíðarfjall is clearly a surface structure (Figures 2 and 4a), and is not buried by younger volcanic eruptives. This model fits very well to the data. Furthermore, Hlíðarfjall is likely to be a vent-formed structure (Figure 4a,b), i.e. formed by a dike or vent to the surface. It is not possible to distinguish between models *a* and *b* for Hlíðarfjall. On the other hand, model *c* shows that Hlíðarfjall does not have significant roots (Figure 4c).

#### *Hrafninnuhryggur – profile HR2*

The HR2 profile is 2264 meters long and is the middle profile, measured over Hrafninnuhryggur from West to East. Models *a*, *b* and *c* are constructed in the same way as for Hlíðarfjall. Model *a* in Figure 5 shows Hrafninnuhryggur and a hyaloclastite ridge to its east. The model suggests that Hrafninnuhryggur is likely to be a surface formation like Hlíðarfjall (Figure 4), i.e. it is not buried by younger volcanic eruptives (Figure 5), nor does it have gravitationally significant roots (Figure 5c). Hrafninnuhryggur is likely to be emplaced as a vent-forming dome but the vent or any underlying dike cannot be distinguished, neither by model *a* nor model *b*.

It is difficult to determine the depth of the hyaloclastite ridge to the west of Hrafninnuhryggur due to the sparsity of gravity stations around it. Furthermore,

the density of the hyaloclastite ridge is quite low compared to values from elsewhere (e.g. Gudmundsson and Högnadóttir, 2004). The density value chosen ( $1500 \text{ kg m}^{-3}$ ) gives a plausible depth for the ridge, a higher and more conventional value demands larger depths of the ridge than the data set allows.

#### *Hraunbunga - profile HB2*

The HB2 profile is 2965 meters long and is measured from NE to SW over the coulee Hraunbunga. The simplest model is shown in Figure 6a. A slightly better fit is obtained when density consistent with a silicic scoria cone is used for the top of Hraunbunga (Figure 6b). The scoria was observed in the field and is consistent with geological maps (e.g. Sæmundsson, 1991).

Hraunbunga does not have gravitationally significant roots (Figure 6a), nor is it buried by younger volcanic eruptives (Figure 6c). Consequently, Hraunbunga is a surface formation and most likely a vent-formed dome/coulee. It is not possible to distinguish between model *b* (Figure 6b) and model *c* (Figure 6c), but they demonstrate clearly that Hraunbunga could have formed from a dike to the surface. Consequently, the results from Hraunbunga suggest similar emplacement mechanisms as for Hrafninnuhryggur and Hlíðarfjall.

The density of the flanks of Hraunbunga is possibly underestimated by the Nettleton method. They are dacite lavas, and the models (Figure 6) show deviations from the observed anomaly over the shoulders of Hraunbunga.

## DISCUSSION

### Density values

The densities determined by the Nettleton method are essentially the same for Hlíðarfjall and Hrafninnuhryggur while there is considerable difference in the values obtained from samples. Since both formations are subglacially-formed rhyolitic domes and should have similar density, we argue that the Nettleton method is more reliable than the mean of the samples. It appears that sampling was somewhat biased towards the more coherent and less vesicular part of the rocks at Hrafninnuhryggur. Marginally higher

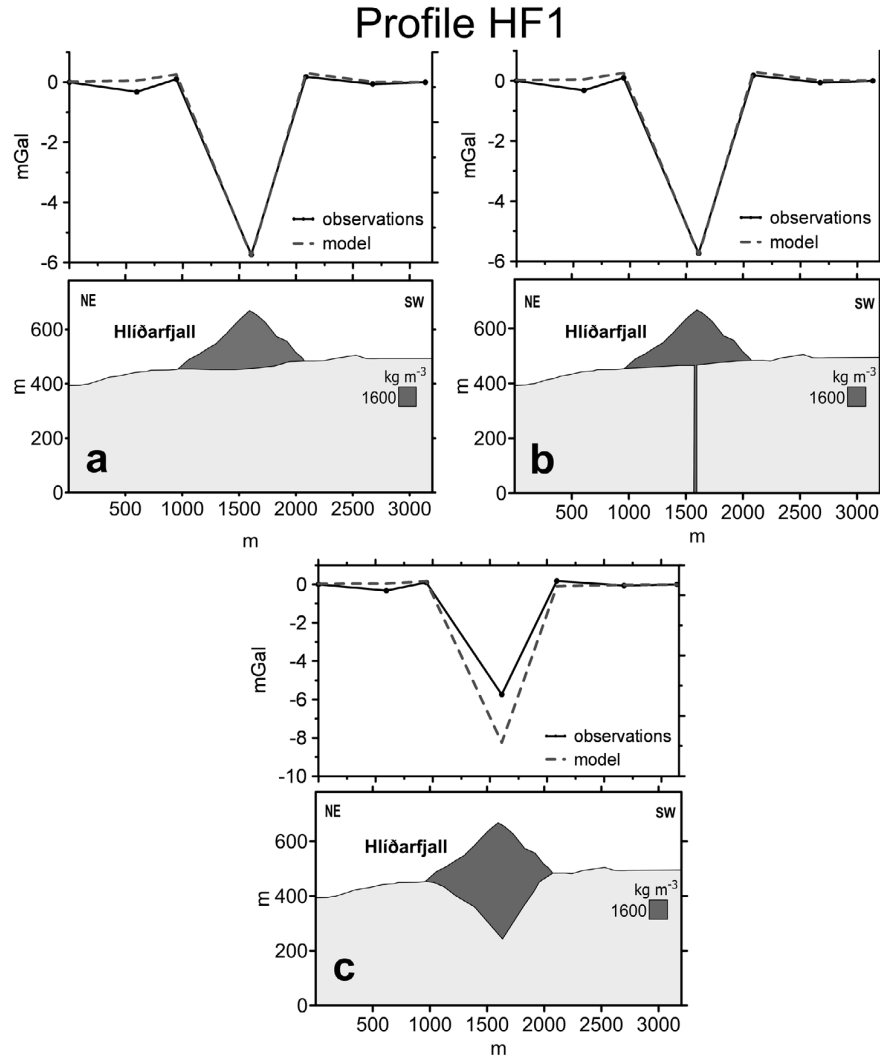


Figure 4. Three different models for the profile HF1, measured over Hlíðarfjall from NE to SW. For profile location see Figure 1. Background density is  $2500 \text{ kg m}^{-3}$ . Maximum dike width is 20 m. – *Sniðið HF1 var mælt yfir Hlíðarfjall frá NA til SV. Til glöggvunar á staðsetningu sniðsins sjá 1. mynd. Bakgrunns eðlismassinn er  $2500 \text{ kg m}^{-3}$  og mesta breidd gangs er 20 m.*

values of Nettleton's density are found for Hraunbunga. This observation is in accordance with what is to be expected since the density of dacite is slightly higher than that of rhyolite. Moreover parts of Hraunbunga are lava that has flowed a short distance. Hraun-

bunga was probably cooled over a longer period of time than were the subglacial formations. Thus, the lava of Hraunbunga may have been more degassed and therefore with lower porosity and higher bulk density when it solidified, compared to both Hlíðar-

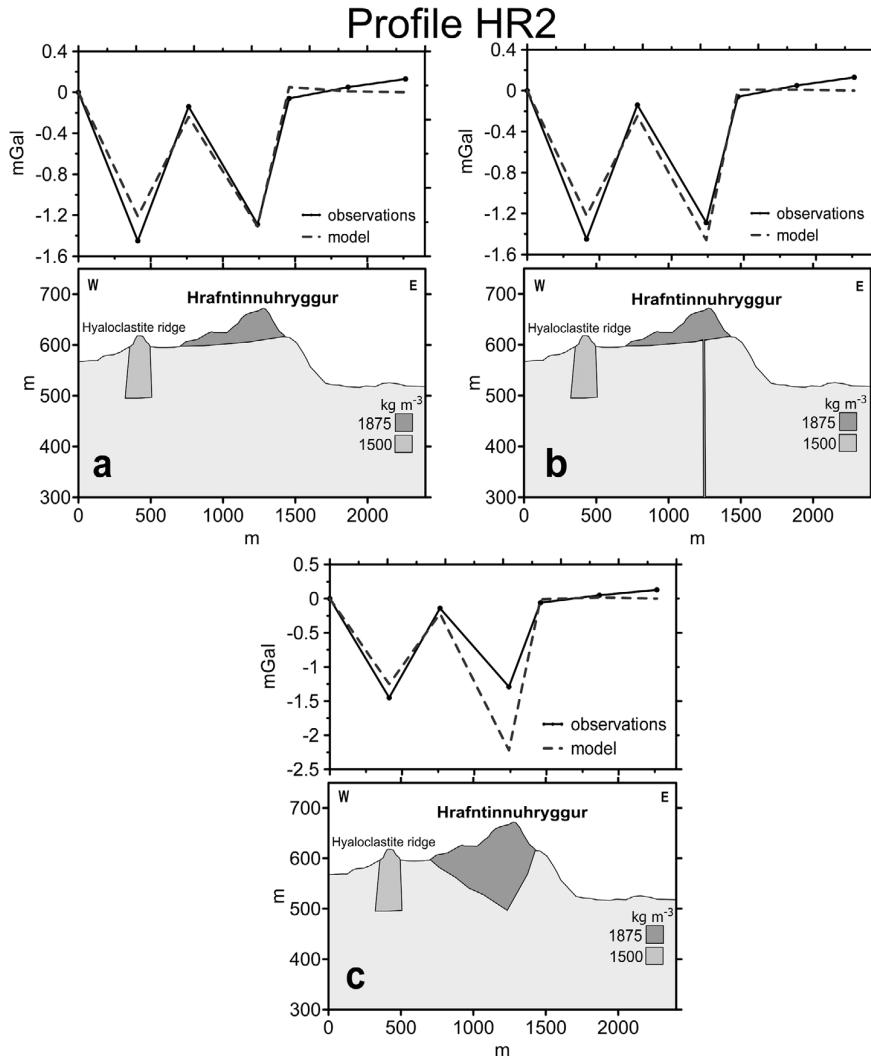


Figure 5. Three different models for profile HR2, measured across Hrafninnuhryggur from W to E. Background density is  $2500 \text{ kg m}^{-3}$ . Maximum dike width is 20 m. – Þrjú mismunandi líkön fyrir sniðið HR2, sem mælt var yfir Hrafninnuhrygg frá V til A. Bakgrunns eðlismassinn er  $2500 \text{ kg m}^{-3}$  og mesta breidd gangs er 20 m.

fjall and Hrafninnuhryggur. The results obtained here are a good addition to previous gravity studies on densities of Icelandic rocks (Gudmundsson *et al.*, 2001; Gudmundsson and Högnadóttir, 2004).

All the studied domes have low densities, reflecting both low grain-density and high porosity. The domes' density values are significantly smaller than

those of the surroundings, creating a density contrast possibly sufficient to drive the ascent of rhyolite magma to the surface by the action of a buoyancy force.

#### Gravity models

A gravity survey using Nettleton's method requires well placed observation points. In this study obser-

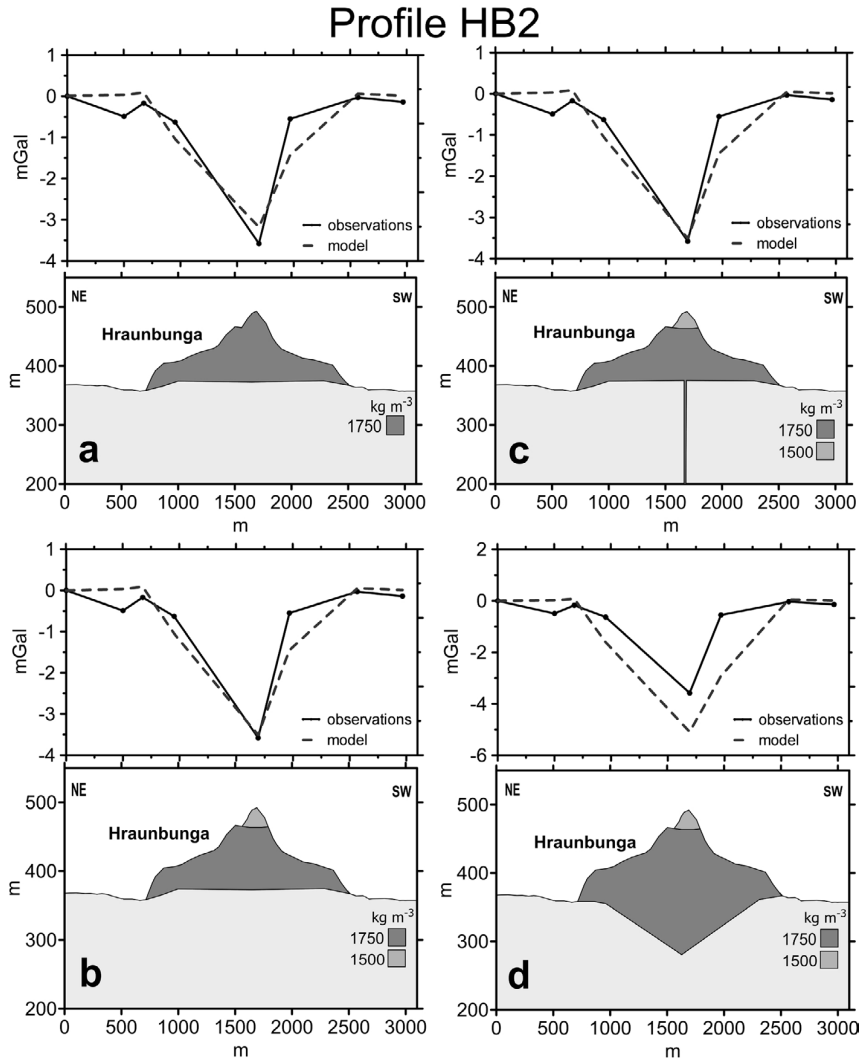


Figure 6. Four different models for the profile HB2, measured across Hraunbunga from NE to SW. Background density is  $2500 \text{ kg m}^{-3}$ . Maximum dike width is 20 m. – Fjögur líkön fyrir sniðið HB2 sem mælt var yfir Hraunbungu frá NA til SV. Bakgrunns eðlismassinn er  $2500 \text{ kg m}^{-3}$  og mesta breidd gangs er 20 m.

vation points were carefully placed with reference to surface geology. For formations with steep slopes like Hlíðarfjall and Hrafninnuhryggur it is only possible to place an observation point at the top and then further points at each side of the foot of the formation. Therefore, for a single profile, one observation

point controls the anomaly and thus the bulk density. However, each formation is crossed by more than one profile and all profiles give similar results for density, indicating that our results are robust. Moreover, the Hraunbunga profile is controlled by three data points measured on the gentle slope of the formation.

The main results from gravity models are the constraints placed on the basal structure of the studied formations; Hlíðarfjall, Hraunbunga and Hrafninnuhryggur. The models show that they are neither buried by younger volcanic eruptives nor are roots with a density contrast with the surroundings detected. The formations studied were therefore emplaced as dike-fed domes, i.e. by the extrusion from a dike onto the surface or the ice-bedrock interface. This idea is in agreement with Jónasson (1994, 2005, 2007) who states that Icelandic rhyolites are rather liquid and therefore erupt more quickly than a more viscous magma. This rules out processes such as stoping, where a magma body forces its way upwards as a massive block, displacing and deforming the surrounding country rock in the process. When reaching the surface, such a forcefully emplaced body is likely to leave rotated and disrupted country rock with the rhyolites extending some distance into the bedrock. Thus, the models, and as far as can be seen also the surface geology, indicate emplacement through dike intrusion to the surface followed by eruption. However, the high viscosity of the magma and confinement in a glacier leads to the formation of a steep dome (Hlíðarfjall and Hrafninnuhryggur). No structural difference is seen between the domes formed during the last glaciation and in the Holocene dome Hraunbunga. We conclude therefore that the three domes were formed in a similar way. The domes have been erupted through a narrow dike (on the order 5–10 m) reaching to the surface. Maximum width of a dike before it starts to register a gravity anomaly of its own that can be distinguished from that of the overlying dome is 20–25 m. Our results are in broad agreement with that of Tuffen and Castro (2008) who studied Hrafninnuhryggur and found evidence of a feeder dike at the surface with a thickness ranging from 2 m to slightly more than 10 m. However, our results suggest that the implied structure shown on their Figure 13 (p. 365, Tuffen and Castro, 2008) should be modified with a narrow dike and flat or semi-flat dome-bedrock contact, as indicated in the gravity model on Figure 5b.

## CONCLUSIONS

- All the studied formations, Hlíðarfjall, Hraunbunga and Hrafninnuhryggur, are neither buried by younger volcanic eruptives nor were any roots detected. The results are consistent with a flat or semi-flat dome-bedrock contact.
- All dome formations studied are emplaced by a dike to the surface. A dike width of 5–10 m is likely and maximum possible dike width is 20–25 m.
- All the domes have low densities (1600–1800 kg m<sup>-3</sup>), reflecting both low grain-density and high porosity.
- The domes display a significant density difference between the formations studied and the surroundings.

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## Þyngdarmælingar á súrum gúlum á Kröflusvæðinu

Súrt berg á Íslandi tengist allajafnan megineldstöðvum og mynda gúla á eða í kringum öskjurima. Sumir þessara gúla hafa myndast á jökulskeiðum en aðrir á hlýskeiðum. Þyngdarmælingar voru gerðar á Kröflusvæðinu 2007 og 2008, til þess að ákvarða meðal-eðlismassa þriggja súrra gúla. Eðlismassagögn eru forsenda líkanagerðar sem eykur skilning á myndun hraungúla og leynigúla. Snið voru mæld yfir þrjú gúla. (1) Hlíðarfjall er líparítgúll, 310 m hár, 2 km langur og myndaður undir jökli fyrir um 90 þúsund árum. (2) Hrafninnuhryggur er líparít- og hrafninnugúll, 80 m hár og 2,5 km langur myndaður fyrir um 24 þúsund árum. (3) Hraunbunga er

dasít hraungúll, 125 m hár, 1,8 km langur, myndaður á íslausu landi fyrir um 10 þúsund árum. Eðlismassar og rúmmál gúlanna: 1) Hlíðarfjall: 1600–1800 kg m<sup>-3</sup>, 0,143±0,014 km<sup>-3</sup>; 2) Hraftinnuhryggur: 1575–1875 kg m<sup>-3</sup>, 0,021±0,002 km<sup>-3</sup>; 3) Hraunbunga: 1750–1775 kg m<sup>-3</sup>, 0,040±0,004 km<sup>-3</sup>. Allir gúlarnir hafa lágan eðlismassa, sem endurspeglar lágan kornaeðlismassa og háan poruhluta. Eðlismassi gúlanna er mun lægri en umhverfisins, sem skapar hugsanlega nógu mikinn eðlismassamun til að súr kvika geti risið í skorpunni. Niðurstöður þyngdarlíkana sýna að gúlarnir eru hvorki grafnir af yngri gosofnum né hafa þeir rætur. Efni allra gúlanna barst til yfirborðs eftir gangi sem í mesta lagi var um 20 metra þykkur en kann að hafa verið mun mjórri. Mælingar benda ekki til þess að umtalsverð snörun eða tilfærsla á aðliggjandi bergi hafi orðið þegar gúlarnir mynduðust.

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