

Volcanic systems and calderas in the Vatnajökull region, central Iceland: Constraints on crustal structure from gravity data

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Received 28 April 2006; received in revised form 26 July 2006; accepted 5 September 2006

Abstract

A Bouguer anomaly map is presented of southern central Iceland, including the western part of Vatnajökull and adjacent areas. A complete Bouguer reduction for both ice surface and bedrock topography is carried out for the glaciated regions. Parts of the volcanic systems of Vonarskarð-Hágöngur, Bárðarbunga-Veiðivötn, Grímsvötn-Laki, and to a lesser extent Kverkfjöll, show up as distinct features on the gravity map. The large central volcanoes with calderas: Vonarskarð, Bárðarbunga, Kverkfjöll and Grímsvötn, are associated with 15–20 mGal gravity highs caused by high density bodies in the uppermost 5 km of the crust. Each of these bodies is thought to be composed of several hundred km³ of gabbros that have probably accumulated over the lifetime of the volcano. The Skaftárkatlar subglacial geothermal areas are not associated with major anomalous bodies in the upper crust. The central volcanoes of Vonarskarð and Hágöngur belong to the same volcanic system; this also applies to Bárðarbunga and Hamarinn, and Grímsvötn and Þórðarhryna. None of the smaller of the two volcanoes sharing a system (Hágöngur, Hamarinn and Þórðarhryna) is associated with distinct gravity anomalies and clear caldera structures have not been identified. However, ridges in the gravity field extend between each pair of central volcanoes, indicating that they are connected by dense dyke swarms. This suggests that when two central volcanoes share the same system, one becomes the main pathway for magma, forming a long-lived crustal magma chamber, a caldera and large volume basic intrusive bodies in the upper crust. Short residence times of magma in the crust beneath these centres favour essentially basaltic volcanism. In the case of the second, auxiliary central volcano, magma supply is limited and occurs only sporadically. This setting may lead to longer residence times of magma in the smaller central volcanoes, favouring evolution of the magma and occasional eruption of rhyolites. The eastern margin of the Eastern Volcanic Zone is marked by a NE–SW lineation in the gravity field, probably caused by accumulation of low density, subglacially erupted volcanics within the volcanic zone. This lineation lies 5–10 km to the east of Grímsvötn.

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Keywords: Bouguer anomaly; Glaciers; Seismics; Volcanism; Intrusive complexes; Geothermal activity

1. Introduction

Volcanic systems and central volcanoes are fundamental units of the volcanic zones in Iceland. The systems range from 30 to 180 km in length, are 10–20 km wide, elongated along the volcanic zones and defined on the basis of common petrological characteristics as tectonic units consisting of a fissure swarm and one or two central volcanoes (Jakobsson, 1979; Saemundsson, 1978, 1979). The central volcanoes occur where magma supply is highest on each

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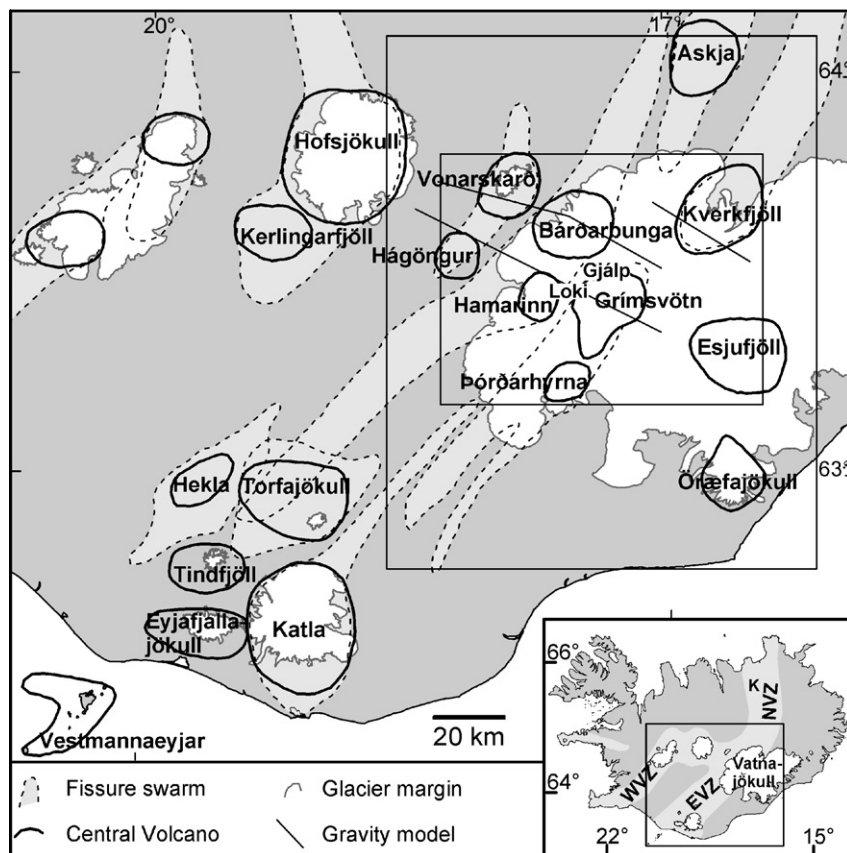


Fig. 1. South and central Iceland, active volcanic systems and central volcanoes (after Jóhannesson and Saemundsson, 1998). The outer square marks the survey area with the western part of Vatnajökull and its surroundings (Figs. 2, 3 and 5) while the inner square demarks the area shown in Fig. 4. The location of the three forward model sections in Figs. 7–9 is indicated. Abbreviations on Iceland map: EVZ: Eastern Volcanic Zone, WVZ: Western Volcanic Zone, NVZ: Northern Volcanic Zone, K: Krafla central volcano.

system. They have often developed calderas and the magmas erupted may range from basalts to rhyolites while only basalts are erupted on the fissure swarms (e.g. Jakobsson, 1979; Saemundsson, 1979; Gudmundsson, 1995).

The distribution of central volcanoes on the volcanic zones is not even. Notable clusters occur near the southern tip of the Eastern Volcanic Zone and in eastern central Iceland, which is for the most part covered by the western part of the Vatnajökull glacier (Fig. 1). This area is notable for having the highest eruption frequency in Iceland and, due to ice melting by geothermal and volcanic activity, being the source of large jökulhlaups (e.g. Thorarinsson, 1974; Thorarinsson and Saemundsson, 1979; Björnsson and Einarsson, 1990; Larsen et al., 1998). The centre of the Iceland mantle plume has been identified as lying under the northwestern part of Vatnajökull (Wolfe et al., 1997), coinciding with the greatest crustal thickness in Iceland of about 40 km (Darbyshire et al., 1998).

The extensive ice cover and the resulting limited exposure of rocks has resulted in much less detailed knowledge of the geology of this area compared to other parts of the volcanic zone. The large central volcanoes of Þórðarhryna, Grímsvötn, Bárðarbunga and Kverkfjöll are to a large degree ice covered and conventional geological mapping is not possible. Extensive radio echo soundings in the 1980s and the early 1990s have revealed the bedrock topography of the western part of Vatnajökull in considerable detail (Björnsson, 1988; Björnsson and Einarsson, 1990; Björnsson et al., 1992). These data have made feasible other geophysical surveys aimed at studying crustal structure.

In this contribution we report the results of a gravity survey of the part of the Eastern Volcanic Zone covered by Vatnajökull. We present a detailed Bouguer anomaly map that reveals anomalies associated with central volcanoes and fissure swarms in the area. We compile forward models (2.5-D) of crustal structure of the central volcanoes Vatnarskarð, Bárðarbunga, Kverkfjöll and Grímsvötn, analyse the anomalies associated with fissure swarms and discuss the implications for the crustal structure in the region.

2. Geological setting

The Eastern Volcanic Zone north of Torfajökull and south of Askja is partly covered by Vatnajökull (Fig. 1). The western part of the volcanic zone is ice free, including hyaloclastite ridge complexes and fissure swarms (e.g. Jóhannesson and Saemundsson, 1998). The ice cover of Vatnajökull has made the definition of the volcanic systems in the area less certain than elsewhere. Five volcanic systems have been identified with certainty (Vonarskarð-Hágöngur, Bárðarbunga-Veiðivötn, Grímsvötn-Laki, Askja and Kverkfjöll) while the existence of the sixth (Loki) as a distinct system is less certain (Jóhannesson, 1984; Björnsson and Einarsson, 1990).

Vonarskarð-Hágöngur lies furthest to the west of the volcanic systems belonging to the central Iceland part of the Eastern Volcanic Zone. It lies fully outside the margins of Vatnajökull. The main central volcano is Vonarskarð-Tungnafellsjökull (hereafter referred to as Vonarskarð). Considerable rhyolite formations occur in Vonarskarð, mainly close to an inferred caldera fault (Saemundsson, 1982). A swarm of hyaloclastite ridges extends towards southwest from Vonarskarð, towards the rhyolite domes of Hágöngur, the second central volcano on the system. Both Vonarskarð and Hágöngur have a geothermal area.

The second volcanic system in the area is Bárðarbunga-Veiðivötn. It is some 180 km long with fissure swarms extending from Bárðarbunga both to the northeast and the southwest. The southwest swarm intersects the large Torfajökull central volcano (Jóhannesson and Saemundsson, 1998). During the Holocene, large fissure eruptions have occurred repeatedly on this swarm (Larsen, 1984). The large central volcano of Bárðarbunga is mostly covered by Vatnajökull, but radio echo soundings have revealed an 80 km² ice-filled caldera where ice thickness is over 800 m in places (Björnsson, 1988; Björnsson and Einarsson, 1990). A presumed second central volcano is Hamarinn, 15 km southwest of Bárðarbunga. Considerable volcanic activity has taken place on the system during historical times, including several eruptions on the ice-covered part of the swarm north of Bárðarbunga (Larsen et al., 1998).

The Grímsvötn-Laki system includes the large ice-covered central volcanoes of Grímsvötn and Þórðarhyrna. Grímsvötn is the most active volcano in Iceland with about 75 eruptions known on the system over the last 1100 years, mostly occurring within the Grímsvötn caldera (Larsen, 2002; Larsen et al., 1998). The last eruptions occurred in 1998 and 2004. Grímsvötn is also one of the most powerful geothermal areas on earth (e.g. Björnsson and Gudmundsson, 1993). The geothermal heat sustains a lake within the composite caldera. This lake is drained subglacially towards south in semi-periodic jökulhlaups in the river Skeiðará (e.g. Thorarinsson, 1974; Björnsson, 1988; Gudmundsson et al., 1995). A combined gravity and magnetic survey of Grímsvötn (Gudmundsson and Milsom, 1997) revealed the existence of a 400 km³ intrusive complex in the upper crust underneath the volcano. This complex was found to be essentially non-magnetic, suggesting temperatures at or above the Curie point. A block of lower density than the surroundings, about 2 km thick, was found underneath the main Grímsvötn caldera. This body is considered to be partly a caldera fill, and partly a consequence of displacement of low density rocks to greater depth by subsidence during the formation of the caldera (Gudmundsson and Milsom, 1997). A teleseismic study of Grímsvötn carried out in 1998 and 1999 gave similar results on upper crustal structure (Alfaro et al., in press). Rock outcrops are limited to the 200–300 m high upper part of the southern caldera fault in Grímsvötn where basaltic hyaloclastites are exposed. A second central volcano on the system is Þórðarhyrna. In contrast to Grímsvötn, extensive rhyolite exposures occur in nunataks in the Þórðarhyrna area (Noe-Nygaard, 1952; Jóhannesson and Saemundsson, 1998). To the south of the glacier the fissure swarm includes the 25 km long Laki fissure from 1783.

To the northwest of Grímsvötn two geothermal areas occur, beneath the Skaftárkatlar ice cauldrons (e.g. Björnsson, 1988). These are two, 2–3 km wide and about 100 m deep depressions in the glacier sustained by geothermal activity. They are located on the Loki ridge, a broad ridge in the bedrock that trends towards east from Hamarinn. Björnsson and Einarsson (1990) suggest that the geothermal areas mark the centre of a separate volcanic system, Loki, in between the large Bárðarbunga and Grímsvötn systems. Unlike the other systems, a distinct geochemical signature has not been established for the Loki system. A few kilometres to the east of Skaftárkatlar, between the central volcanoes of Grímsvötn and Bárðarbunga is Gjálpi, the site of subglacial eruptions in 1938 and 1996, both of which lead to massive jökulhlaups (Gudmundsson et al., 1997, 2004; Gudmundsson and Björnsson, 1991; Björnsson, 1988). The isotopic signature of magma erupted in 1996 suggests that Gjálpi is a part of the Grímsvötn system (Sigmarsson et al., 2000) while seismic activity associated with the 1996 eruption point to magma drainage towards south from Bárðarbunga (Einarsson et al., 1997).

In the northern part of the research area the fissure swarm of Askja extends southwards under the broad outlet lobe of Dyngjufjökull, east of Bárðarbunga. The subglacial part of the system is expressed by a few bedrock ridges (Björnsson and Einarsson, 1990).

On the eastern margin of the volcanic zone is the large central volcano of Kverkfjöll. Its northern part is a prominent mountain massif that rises over 1000 m above its surroundings. The northern massif has a shallow caldera, mostly filled with ice. The southern part of Kverkfjöll is fully subglacial and has a caldera that was first identified on Landsat images of the area (Thorarinsson et al., 1973). Volcanic eruptions in Kverkfjöll have caused large jökulhlaups in the river Jökulsá á Fjöllum in pre-historic times (Carrivick et al., 2004).

The Kverkfjöll and Grímsvötn-Laki systems are considered to mark the boundary of the Eastern Volcanic Zone under Vatnajökull. However, active volcanism occurs further to the east. The largest composite stratovolcano in Iceland, Öraefajökull, is located on the southeast coast and to the northeast of Öraefajökull is the much eroded Esjufjöll central volcano. Öraefajökull has erupted twice in historic times, including the large plinian eruption of 1362 (Thorarinsson, 1958). Esjufjöll is suspected still to be active (e.g. Björnsson and Einarsson, 1990) but no confirmation exists of volcanic eruptions in the Holocene.

3. Crustal structure

Studies of crustal structure of the Vatnajökull region have been few. Pálmason (1971) studied the upper crustal structure to the west and northwest of Vatnajökull, and the 1977 RRISP profile traversed the same region (Gebrande et al., 1980; Menke et al., 1996). The only seismic profile that crossed Vatnajökull itself (the ICEMELT profile) was shot in 1996, at a station spacing of 5 km (Darbyshire et al., 1998). A thickness of 4–6 km for the upper crust ($V_p < 6.5 \text{ km s}^{-1}$) was obtained for northwest Vatnajökull. The depth to Moho was estimated as 40 km under the northwest margin of the glacier. However, the Moho depth decreased to 25–30 km near the edges to the west, south and east according to the combined interpretation of seismic and gravity data (Darbyshire et al., 2000).

The Bouguer gravity anomaly in Iceland is dominated by a central low (see Fig. 3) that bottoms out near the northwest margin of Vatnajökull (Eysteinsson and Gunnarsson, 1995; Kaban et al., 2002). The low is considered to mainly reflect crustal thickness but a low density mantle may also be a contributing factor (e.g. Darbyshire et al., 2000).

The combination of glacial cover, concentration of central volcanoes and the highest eruption frequency of any region in Iceland make the western part of Vatnajökull very worthy of further study. Among the questions that arise are:

1. What is the crustal structure associated with volcanic systems and central volcanoes in this region? In particular, what is the connection between two central volcanoes that belong to the same volcanic system?
2. What is the crustal structure associated with the calderas found in the large central volcanoes in this region?
3. Is the eastern margin of the Eastern Volcanic Zone under Vatnajökull a boundary that can be detected on gravity maps? If so, what can be learned about the nature of this boundary under the glacier?

In the following, we will concentrate on the upper crustal structure of the region with emphasis on the central volcanoes, the associated fissure swarms and connections between the central volcanoes.

4. Data

The gravity data used in this work have been collected over more than three decades (Fig. 2). The data sources can be listed as follows:

1. Four profiles with 40 gravity stations on Vatnajökull surveyed in 1971 (Thorbergsson, 1971). Elevation control was obtained through optical levelling.
2. Data with about 8 km point spacing, obtained during the regional survey of Iceland in 1968–1971 and 1985 (Thorbergsson et al., 1993). Elevation was measured using optical levelling or inertial navigation systems aboard helicopters.

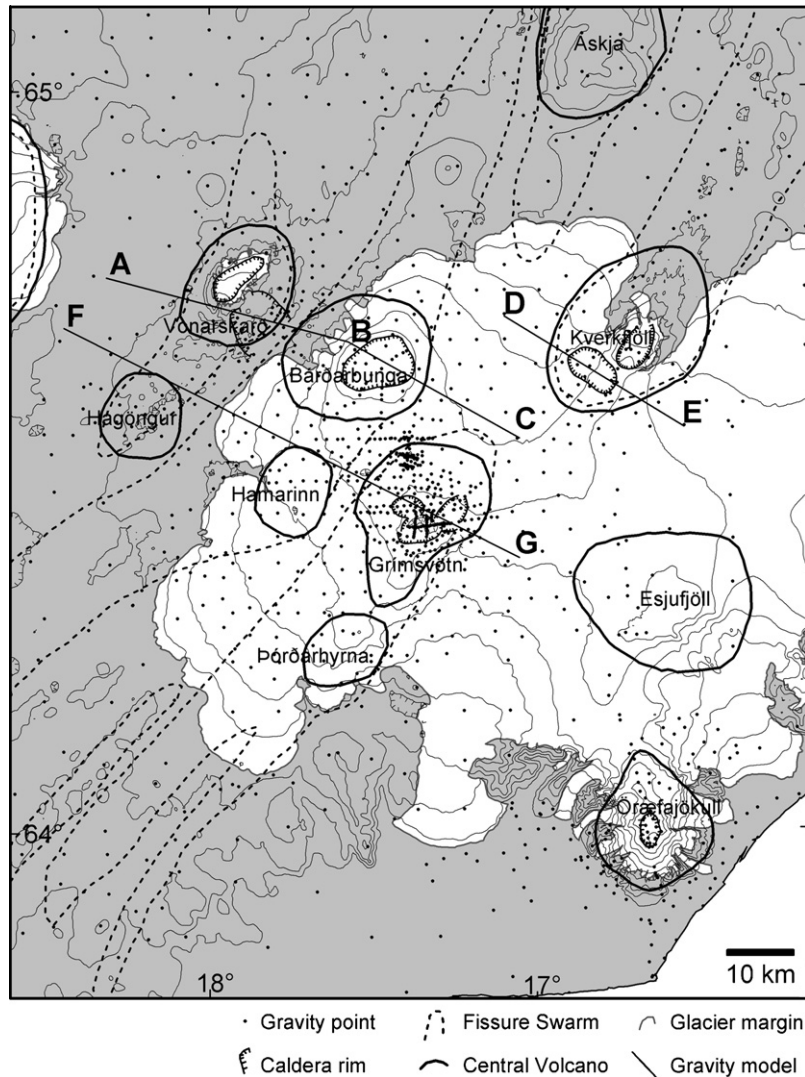


Fig. 2. The survey area is 120 km × 150 km across. Approximate boundaries of volcanic systems and central volcanoes are according to Jóhannesson and Saemundsson (1998). Gravity stations are shown as dots.

3. A gravity survey of Grímsvötn in 1988, with 181 stations at 1–1.5 km spacing (Gudmundsson and Milsom, 1997). Elevation was measured through a combination of optical and precision barometric levelling.
4. Surveys conducted in 1994–2000 on western Vatnajökull, at its northwestern margin and around Öraefajökull, in total comprising about 590 gravity stations. Elevation control was obtained from submeter DGPS.

Accuracy of elevation for stations in the 1971, 1988 and the 1994–2000 surveys is considered to be about 2 m, and 1 m for the 1985 survey (Thorbergsson et al., 1993; Gudmundsson and Milsom, 1997; Gudmundsson and Högnadóttir, 2001). All surveys were tied to the ISGN71 base network (Thorbergsson et al., 1993), the majority to base 2023 on Grímsfjall or base 5258 at Hald west of Vatnajökull. A complete Bouguer Anomaly has been obtained by integrating the gravitational effects of digital elevation models (DEMs) of both ice surface and bedrock (Björnsson, 1988; Björnsson and Einarsson, 1990; Björnsson et al., 1992; H. Björnsson and F. Pálsson, pers. communication). In order to minimize possible bedrock elevation errors on Vatnajökull, gravity stations were chosen to coincide with radio-echo survey lines from the 1980s and 1990s. For each station the Bouguer reduction is applied to a 100 km × 100 km area with the station at its centre. Surface DEMs have been compiled for every survey year, thus taking into account rapid changes in ice

surface elevation due to lake level fluctuations in Grímsvötn (Gudmundsson et al., 1995; Björnsson, 2003), glacier surges (Björnsson et al., 2003); and volcanic eruptions (Gudmundsson et al., 2004).

5. Bouguer anomaly map

A bedrock reduction density of 2600 kg m^{-3} was used in the compilation of the gravity map of Iceland by Thorbergsson et al. (1993) but 900 kg m^{-3} for ice in regions where glacier thickness was known. Kaban et al. (2002) obtained a best fitting reduction density of 2520 kg m^{-3} for bedrock using admittance between topography and gravity. These mean densities do not take into account regional differences; the density of the uppermost crust is lower within the volcanic zones than in the older Tertiary regions. Our survey area in central Iceland mostly lies within the volcanic zone where low density hyaloclastites, pillow lava and breccias make up a large part of the uppermost crust. Pálmason (1971) conducted extensive seismic refraction surveys in Iceland and defined this uppermost part of the crust in the volcanic zones as seismic layer 0, with low seismic velocities ($V_p = 2.5\text{--}3.0 \text{ km s}^{-1}$), a thickness of $0.5\text{--}1.0 \text{ km}$ and a mean density of 2300 kg m^{-3} . In the southeastern-most part of the surveyed area the uppermost crust is somewhat older (Jóhannesson and Saemundsson, 1998) and denser. We therefore adopt a reduction density of 2400 kg m^{-3} for our Bouguer anomaly map (Fig. 3).

The Bouguer anomaly (Fig. 3) is dominated by the centre of Iceland gravity low which has a minimum between Bárðarbunga and Kverkfjöll. Superimposed on this main low are gravity highs associated with the large central volcanoes. These are Grímsvötn, Bárðarbunga, Vonarskarð and Kverkfjöll. In contrast, the other three central volcanoes within the Eastern Volcanic Zone, Hágöngur, Hamarinn and Þórðarhyrna have much less distinct gravity signatures. An unclear gravity low may, however, be linked to Þórðarhyrna. An interesting feature of the map is that ridges in the gravity field connect the two volcanoes that belong to the same volcanic system. These pairs are Vonarskarð–Hágöngur, Bárðarbunga–Hamarinn, and somewhat less distinctly, Grímsvötn and Þórðarhyrna.

The two large central volcanoes to the east of the Eastern Volcanic Zone, Esjufjöll and Örafajökull, are also associated with gravity highs. Esjufjöll and Örafajökull lie outside the Eastern Volcanic Zone and the former is poorly covered by existing data. We will therefore largely exclude these two volcanoes from our analysis.

Fig. 4 is a closeup of western Vatnajökull, with the Bouguer gravity anomaly in colour and 200 m bedrock elevation contours superimposed. The Skaftárkatlar geothermal area, lying between Grímsvötn and Hamarinn, is a region with no clear gravity anomalies associated with them, and Gjalp is located at the northern margin of the Grímsvötn gravity high.

Fig. 5 shows the absolute value of the horizontal gravity gradient in the survey area. Lineations in horizontal gravity gradients are caused by lateral changes in density and thus often delineate structural boundaries (e.g. Dobrin and Savit, 1988; Kaban et al., 2002). The most prominent features in Fig. 5 are the steep gradients associated with the central volcanoes (Bárðarbunga, Grímsvötn, Kverkfjöll and Esjufjöll). A clear NE–SW lineation coincides with the eastern boundary of the active volcanic zone from the southwest corner of the map to Kverkfjöll. Comparison with the Bouguer anomaly map (Fig. 3) shows that the lineation is a step in the field with lower values within the volcanic zone than on its eastern boundary.

An elliptical feature with a long axis trending northwest-southeast, extends from the eastern margin of Hofsjökull to the western part of Esjufjöll (Fig. 5). It is the largest feature on the map with a long axis of 120 km . Its margins on the southwest lie south of Þórðarhyrna and the northern margin, less clearly defined, is south of Askja. Comparison with the Bouguer anomaly map (Fig. 3) shows that the elliptical feature marks local steepening of the gradient down towards the bottom of the main gravity low. This may reflect rapid thickening of the crust underneath this boundary. This was the interpretation of Darbyshire et al. (2000). Alternatively, this feature may be related to changes in the density layering of the crust relative to the surroundings. This anomaly will not be considered further here.

6. Forward modelling

The gravity anomalies can be used to map the size and extent of anomalous bodies. Due to the nature of the gravity field, solutions for the source of gravity anomalies are inherently non-unique. Constraints from geology and other geophysical methods are therefore important. The extensive seismic work of Pálmason (1971) and its subsequent refinement (Flóvenz, 1980; Flóvenz and Gunnarsson, 1991) defined the upper crustal structure and later work has not altered that picture. Geological mapping of eroded and extinct volcanic centers provides further constraints on subvolcanic structure of central volcanoes. The eroded older centres are characterized by predominantly basaltic major

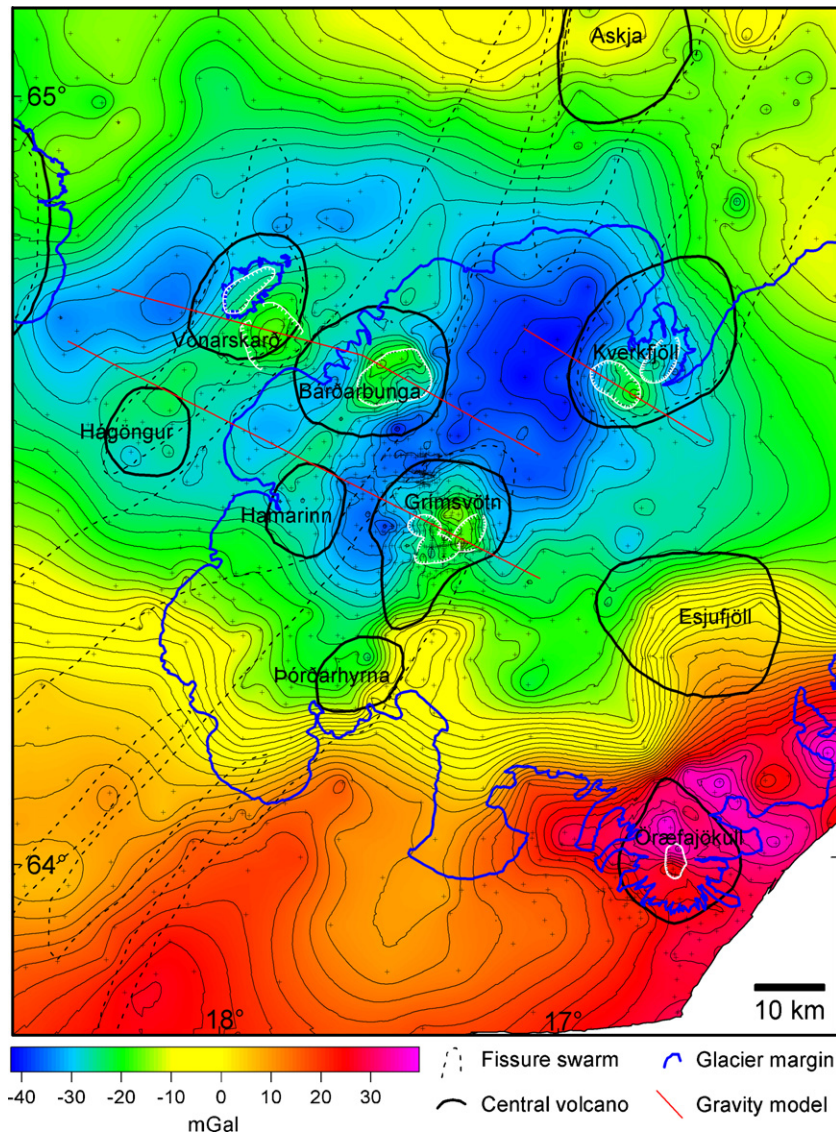


Fig. 3. Bouguer anomaly map of the survey area using reduction densities of 900 kg m^{-3} for ice and 2400 kg m^{-3} for bedrock. Contour interval 2 mGal.

intrusions and dense swarms of dykes and inclined sheets (Saemundsson, 1979; Gudmundsson, 1995). These centres give rise to 5–15 mGal gravity highs and appear as protrusions of seismic layer 3 (Pálmason, 1971) that has a density and seismic velocity similar to gabbro, although considered to be mainly composed of thermally altered, very low porosity basalts (Pálmason, 1971; Flóvenz and Gunnarsson, 1991). Seismic refraction work across the Krafla central volcano in north Iceland (location denoted with K on Iceland map in Fig. 1) suggests that large contrasts in velocity and density are to be sought in the upper crust (Brandsdóttir et al., 1997). In the study area, hard constraints are lacking, but general knowledge of the stratigraphy of the volcanic strata, combined with seismic velocity–density systematics can be used to narrow the range of plausible models.

Fig. 6 shows P-wave velocity–density systematics according to several models, the P-wave velocity layering of the upper crust in Iceland and the expected density layering. The main indication of this is that a positive contrast of $100\text{--}300 \text{ kg m}^{-3}$ is to be expected between a gabbroic intrusion and the crust at 1–4 km depth. Since most of the survey area is covered with several hundred metres of ice, no details are available to constrain any crustal models further than applying the general crustal density layering shown in Fig. 6.

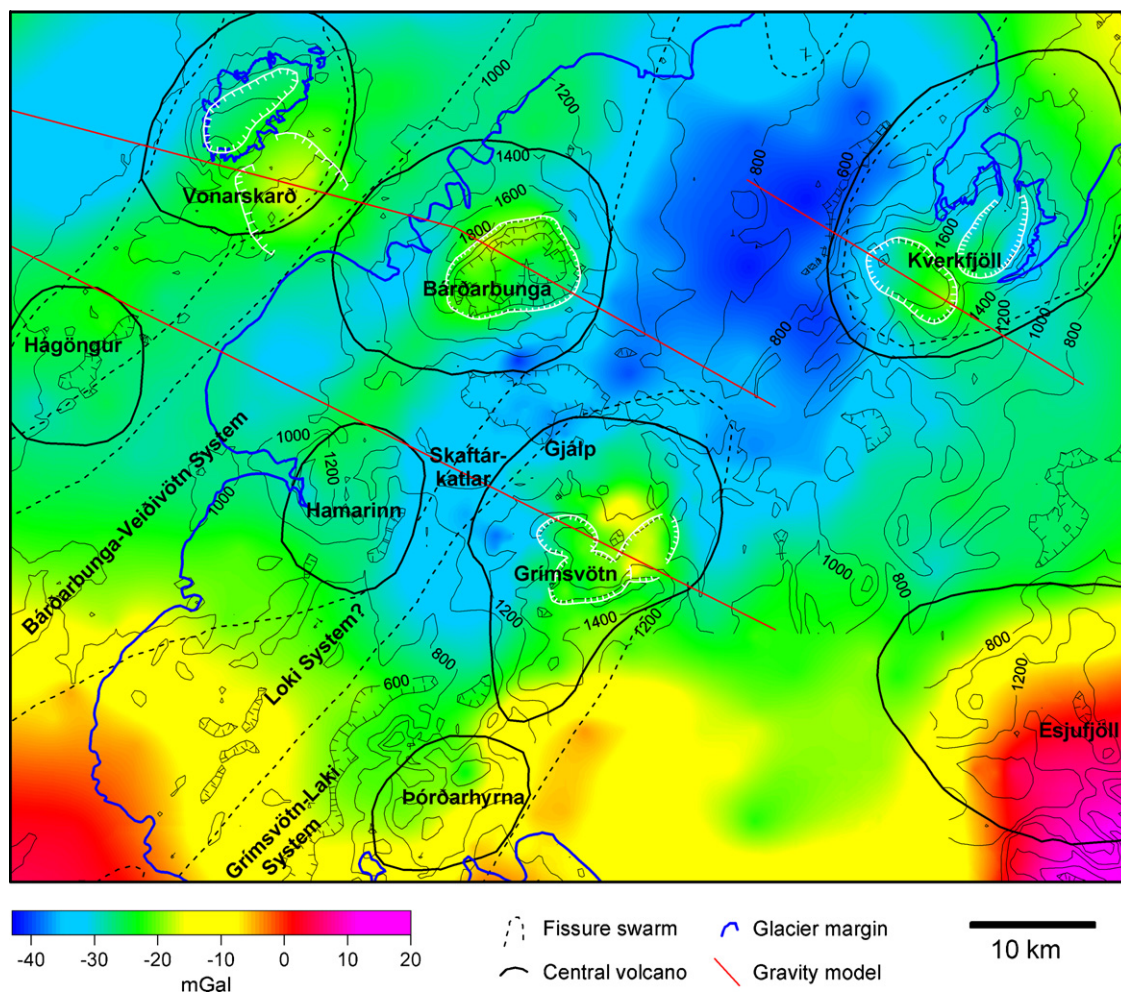


Fig. 4. Bouguer anomaly (colour coded) with 200 m bedrock elevation contours in western Vatnajökull (Björnsson et al., 1992).

In our approach, anomalous bodies are considered to be confined to the about 5 km thick upper crust. A single density contrast of $+200 \text{ kg m}^{-3}$ is used for the dense subvolcanic intrusions. A complication worth mentioning is that the edifices of the large central volcanoes are expected to have average density lower than the reduction density of 2400 kg m^{-3} (Gudmundsson and Milsom, 1997). Where a subvolcanic intrusion causes a gravity high, the use of a too high reduction density for the topography leads to a smaller gravity anomaly and hence to a source body that is too small. However, a density contrast of $+200 \text{ kg m}^{-3}$ for subvolcanic intrusions, may lead to an underestimation of the true contrast in the uppermost 1–2 km of the crust. This on its own would lead to a modelled source body that is too large. These two effects may partly offset one another but their relative importance cannot be estimated with the presently available data. These possible complications imply that our forward models are only capable of revealing large scale features. Three model sections roughly perpendicular to strike are produced (see Figs. 2–4 for location). The first model (Fig. 7) is 65 km long and crosses the central volcanoes of Vonarskarð and Bárðarbunga. The second model crosses southern Kverkfjöll (Fig. 8). The third model section (Fig. 9) runs across the whole volcanic zone. It is 75 km long and crosses Grímsvötn, the Skaftárkatlar geothermal areas and the fissure swarms associated with Bárðarbunga and Vonarskarð–Hágöngur.

The modelled profiles are constructed by subtracting a regional field obtained as the second-order polynomial that best fits the Bouguer anomaly map. 2.5-D forward models are generated using the Gravmag software (Pedley et al., 1997). Bodies are assumed to strike perpendicular to the survey line and a finite strike length can be assigned.

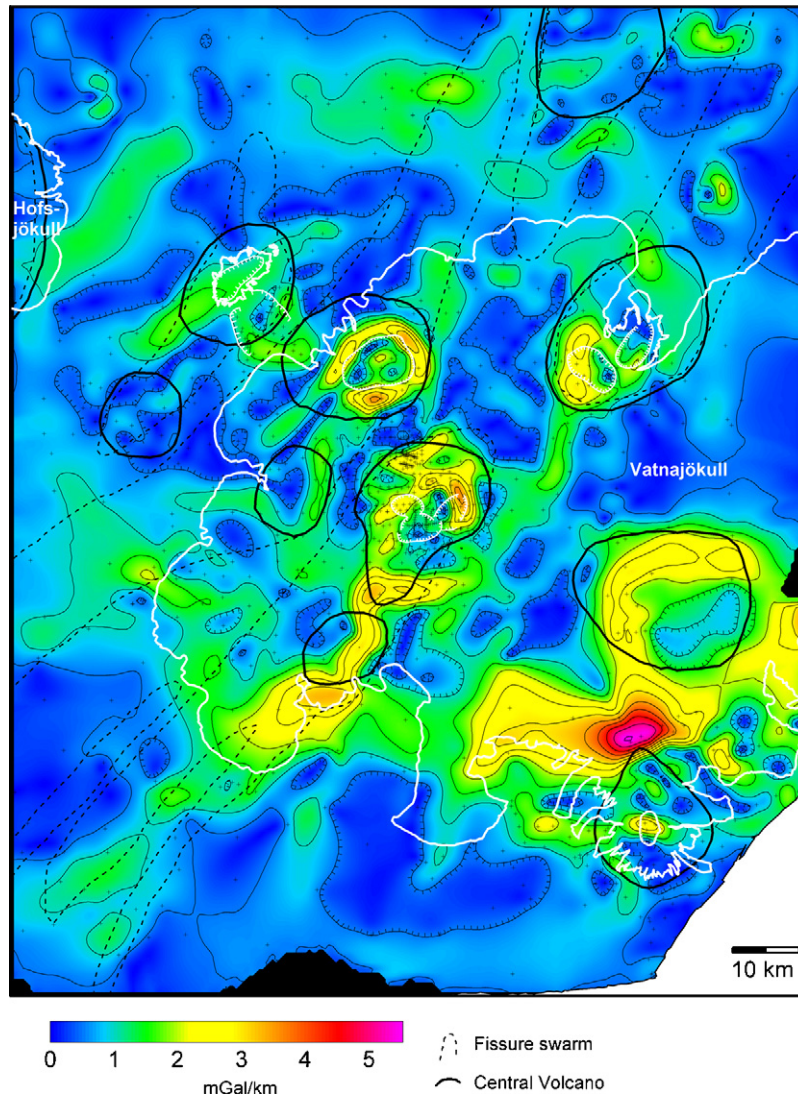


Fig. 5. Magnitude of horizontal gradient of the Bouguer anomaly. Steep gradients delineate the margins of the high density bodies underlying the large central volcanoes, some fissure swarms, and the eastern margin of the volcanic zone. Glacier margins are shown as white lines.

Table 1
Half strike lengths of model bodies

Model	Body	$\Delta\rho$ (kg m^{-3})	Half strike (km)
Fig. 7: ABC	Vonarskarð	200	4
Fig. 7: ABC	Bárðarbunga	200	4
Fig. 7: ABC	East of Bárðarbunga	−200	3
Fig. 8a: DE	Kverkfjöll	200	4
Fig. 8b: DE	Kverkfjöll	200	4
Fig. 8b: DE	Kverkfjöll-massif	−100	4
Fig. 9: FG	Fissure swarm west	100	10
Fig. 9: FG	Fissure swarm east	100	10
Fig. 9: FG	Skaftárkatlar	−50	4
Fig. 9: FG	Skaftárkatlar	100	4
Fig. 9: FG	Grímsvötn	200	4

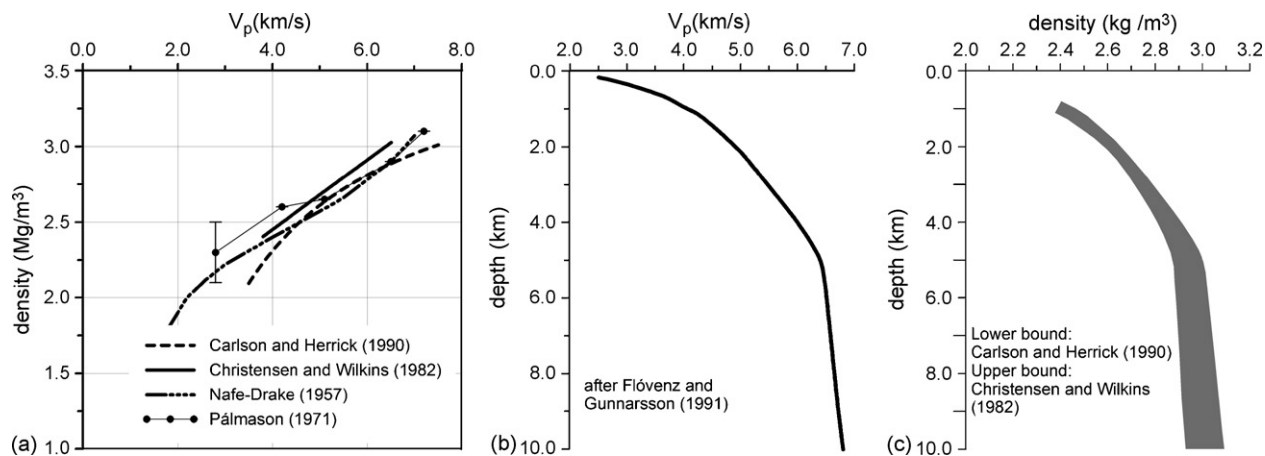


Fig. 6. (a) Density-P-wave velocity systematics (Nafe and Drake, 1957; Pálmason, 1971; Christensen and Wilkins, 1982; Carlson and Herrick, 1990). (b) The velocity-depth profile down to 10 km depth for uneroded Icelandic crust (Flóvenz and Gunnarsson, 1991). (c) The most likely density-depth profile of the Icelandic crust based on the velocity–density systematics. The two models of Carlson and Herrick (1990) for oceanic crust and Christensen and Wilkins (1982) from eastern Iceland provide respectively the lower and upper bound for the density profile.

6.1. Section Vonarskarð-Bárðarbunga

Both central volcanoes are associated with high density bodies in the upper crust (Fig. 7). The body underlying Vonarskarð is up to 4 km thick and over 15 km wide. If it is taken as roughly circular in form (see form of anomaly in Figs. 3 and 4) with a diameter of 17 km and height of 3 km, its volume is 600–700 km³. For Bárðarbunga, a similar body is obtained, about 12 km in diameter and with a volume of 300–400 km³. By analogy with the eroded centres (e.g. Saemundsson, 1979), these bodies are thought to be mainly large gabbroic intrusions.

At Bárðarbunga the gravity anomaly has clear associations with the caldera rims. Under the western rim the high density body, 3–5 km wide and 2 km high, extends upwards to the glacier base. A similar body, but only 1 km wide, is located under the southeast caldera rim. These bodies may be a swarm of inclined sheets or dykes, a ring dyke or a mixture of such intrusions. Under the centre of the caldera a body of neutral density is located, about 2 km high. It presumably represents a subsided block, caldera fill or a mixture of both. A magma chamber would most likely be

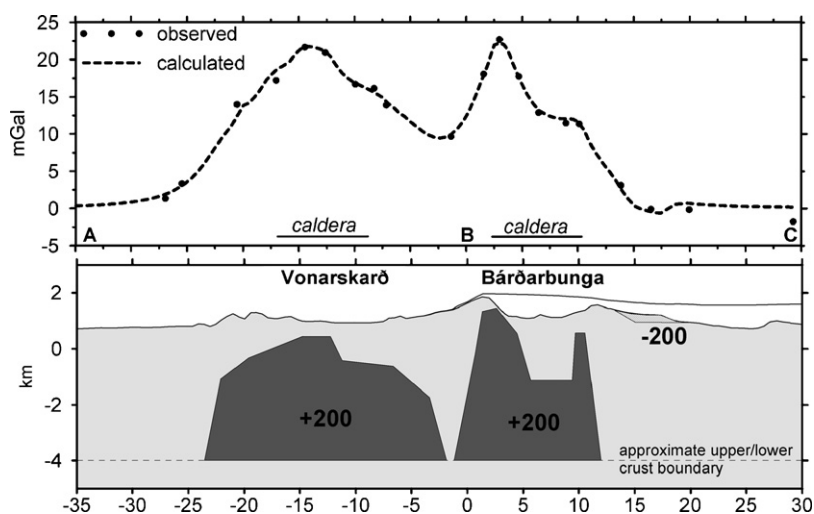


Fig. 7. A forward 2.5-D gravity model section over Vonarskarð and Bárðarbunga (ABC in Fig. 2). The regional field has been removed with a second-order polynomial. The numbers within the bodies are the deviation of densities from the background in kg m⁻³. The half-strike lengths of the bodies are given in Table 1.

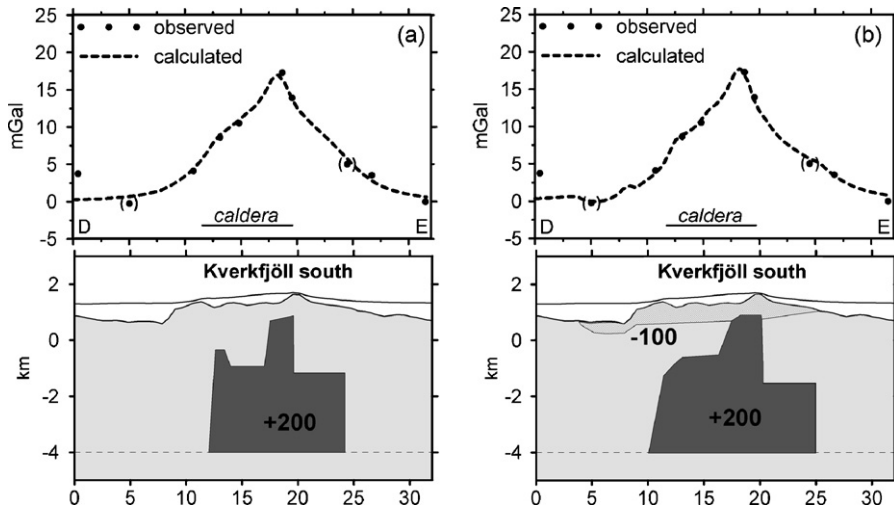


Fig. 8. A forward 2.5-D gravity model section over southern Kverkfjöll (DE in Fig. 2). Regional field removed in the same way is in section ABC. The numbers within the bodies are the deviation of densities from the background in kg m^{-3} . The half-strike lengths of the bodies are given in Table 1.

represented by a neutral or low density body. If one exists at present under Bárðarbunga, a likely place would be at the bottom of this neutral region, under the southeastern part of the caldera. A small low density body is required near the surface in the southeast slopes. Its existence suggests that the actual density contrast between the intrusions and low density shallow crustal material making up the edifice is underestimated in the model.

6.2. Section Kverkfjöll

Data coverage for the northern part of the Kverkfjöll massif is too sparse for meaningful gravity modelling. However, data coverage is sufficient to show that the main gravity high and hence the crustal anomaly is associated with the southern caldera (Fig. 8). Two possible models are presented in Fig. 8. In (a) a single density contrast is applied, while in (b) the edifice has a slightly lower density than the surroundings. The models are similar in showing a 12–15 km wide and 2.5–3 km high body of high density in the upper crust associated with the caldera. The volume of this body

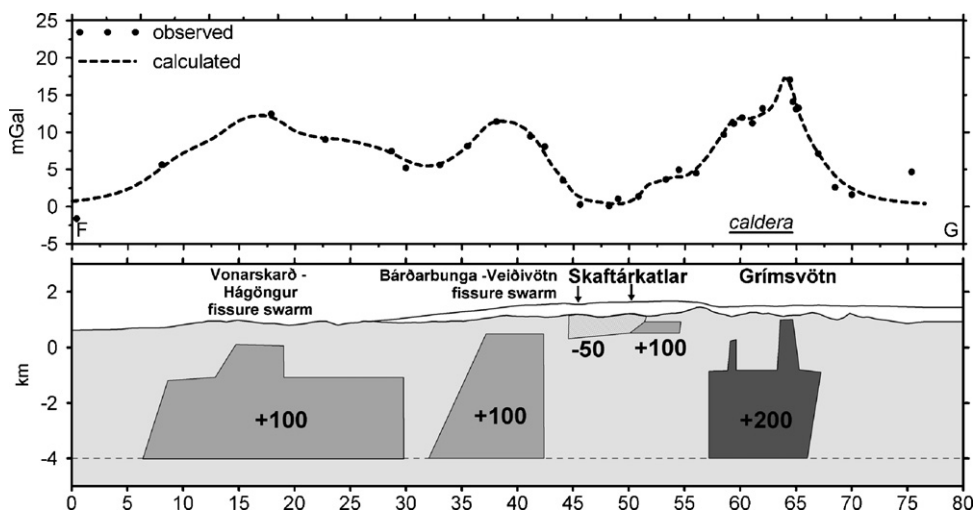


Fig. 9. A forward 2.5-D gravity model section across the volcanic zone, crossing Hágöngur, the Bárðarbunga-Veiðivötn fissure swarm, Skaftárkatlar and Grímsvötn (FG in Fig. 2). Regional field removed in the same way as in sections ABC and DE. The numbers within the bodies are the deviation of densities from the background in kg m^{-3} . The half-strike lengths of the bodies are given in Table 1.

is 200–300 km³. As with Bárðarbunga, a high density body (swarm of inclined sheets/dykes or a ring dyke) underlies the eastern margin of the caldera.

6.3. Section Vonarskarð–Hamarinn fissure swarm—Grímsvötn

This is the longest of the sections and crosses the whole of the Eastern Volcanic Zone (Fig. 9). The model of Grímsvötn is essentially the same as presented by Gudmundsson and Milsom (1997), with about 300 km³ high density body between 2 and 5 km depth. A dyke complex marks the eastern margin of the caldera with a much smaller body, apparently of the same nature, under the western margins. This model reproduces the main features of previous studies. However, the body of neutral density at 0–2 km depth underlying the Grímsvötn caldera (Fig. 9) is a simplification of the actual structure. Gudmundsson and Milsom (1997) and Alfaro et al. (in press) showed a low density/low P-wave velocity body at this location, with a thickness of about 2 km.

The profile crosses the powerful geothermal area of Skaftárkatlar 15 km to the northwest of Grímsvötn. Each of the two cauldrons (katlar) has created an independent ice drainage basin and water accumulates underneath both cauldrons, which drain every 2–3 years (e.g. Björnsson, 1988). The combined thermal power of these two areas is in the range of 1000 MW (Björnsson, 1988). As suggested by the Bouguer anomaly map (Figs. 3 and 4) no high density upper crustal bodies can be associated with Skaftárkatlar. As with other high temperature geothermal areas Skaftárkatlar must derive their energy from hot rocks at shallow depth. The model indicates that dense intrusions have not accumulated in sufficient quantity to register in the gravity field. Some irregularities in the density of the uppermost kilometre of the crust apparently occur at and in the vicinity of Skaftárkatlar, although the implication of this is unclear.

The two fissure swarms of Bárðarbunga–Veiðivötn and Vonarskarð–Hágöngur, show up as 10 mGal gravity highs (Fig. 9). These highs cannot be an artifact of anomalously high bedrock density, since they do not correlate well with bedrock elevation. Geometry of possible sources for these highs are shown as bodies with a density contrast of +100 kg m⁻³. Using a plausible density of 2700–2750 kg m⁻³ for the normal upper crust in this region and assuming a density of 2950 kg m⁻³ for intrusive basalt, the +100 kg m⁻³ contrast would imply that intrusions make up 40–50% of the volume within these bodies.

7. Discussion

Our Bouguer anomaly map (Figs. 3 and 4) represents the first detailed gravity map of a substantial part of the volcanic zones in Iceland. Several earlier maps of comparable station spacing (e.g. Brown et al., 1991; Hersir et al., 1990; Foulger and Field, 2000; Gudmundsson and Milsom, 1997) have mostly covered single volcanic centres and not given a clear indication of crustal anomalies connecting central volcanoes and fissure swarms. Direct comparison of the results obtained here with other areas is therefore difficult and it is not clear whether they apply elsewhere in the volcanic zones in Iceland. The main features observed are shown in Fig. 10.

7.1. Large central volcanoes with calderas

A clear result of the present study is that the large central volcanoes of Vonarskarð, Bárðarbunga, Kverkfjöll and Grímsvötn are associated with major density anomalies located in the upper crust. As the forward models show, the overall structure of these volcanoes is similar: Beneath them are high density bodies with a volume of several hundred km³ in the upper crust between 1 and 5 km depth. These bodies have considerably greater extent than the calderas above them. Bodies of this type are commonly found underneath basaltic and andesitic volcanoes and calderas in a variety of tectonic settings (e.g. Williams and Finn, 1985; Rymer and Brown, 1986). It is argued here that these bodies are predominantly basic intrusives which conforms with field evidence from extinct eroded centres in Iceland and elsewhere (e.g. Bott and Tuson, 1973; Saemundsson, 1979). For ocean island settings these bodies are commonly interpreted as gabbroic cumulates from an overlying magma chamber (e.g. Melengre et al., 1999; Ablay and Kearey, 2000). This may be a contributing factor for the central Iceland volcanoes.

A further conclusion that may be drawn from the present study is that the generally high density of the upper crust under the calderas implies that molten magma occupies only a small fraction of the space in the roots of these volcanoes. A magma chamber at a few kilometres depth has been inferred from ground deformation at Grímsvötn (Sturkell et al.,

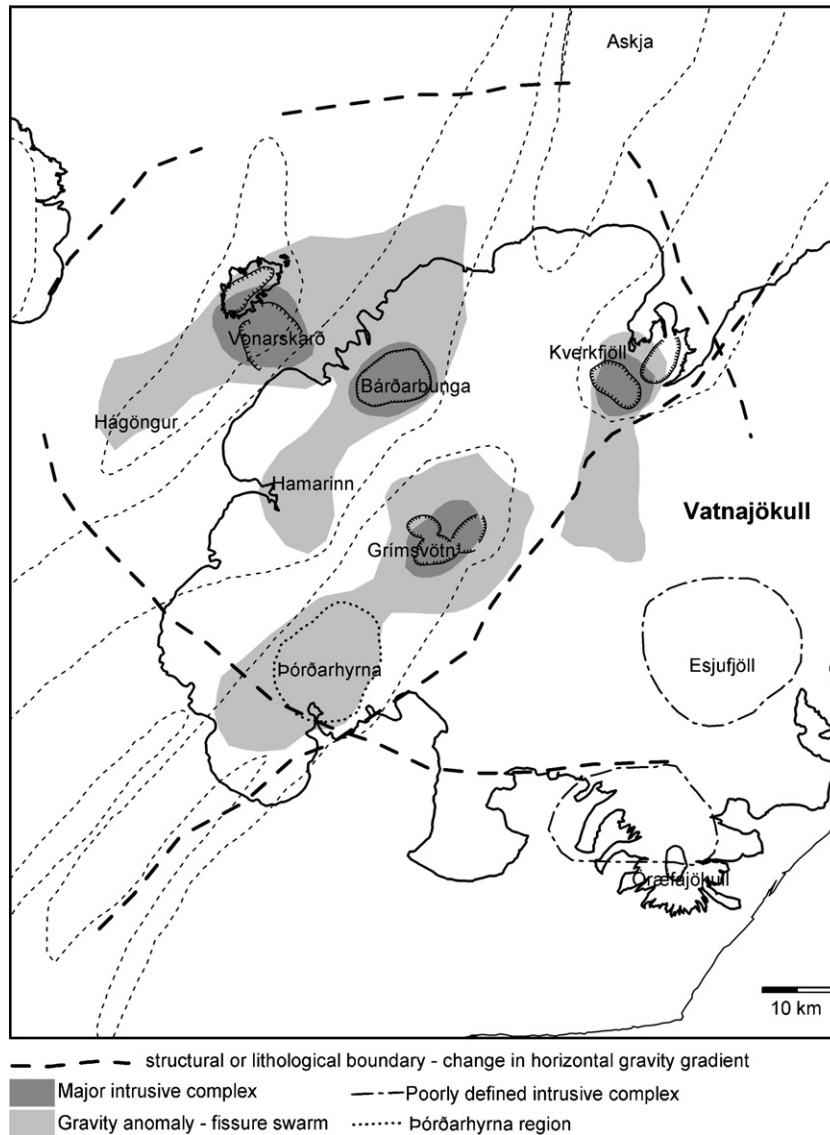


Fig. 10. Map of the survey area outlining intrusive complexes underneath the large central volcanoes, dense fissure swarms between central volcanoes on the same system, margin of the Eastern Volcanic Zone and the large elliptical feature apparent on the horizontal gravity gradient map (Fig. 5).

2003) but similar data are lacking from other volcanoes in the region. Our data do not provide strong constraints on magma storage. The density of basaltic magma is $2650\text{--}2700\text{ kg m}^{-3}$ (Spera, 2000), similar to average crustal density at 1–3 km depth and considerably less than the high densities imaged here at 2–5 km depth underneath the volcanoes. For a fully molten rhyolite body the density would be close to 2300 kg m^{-3} . Thus, at least within the well-developed volcanoes, a magma chamber would contribute to a local gravity low. This suggests that the most likely location for a magma chamber in Grímsvötn is underneath the caldera, in Bárðarbunga under the southeast part of the caldera and in Kverkfjöll under the western part of the caldera. However, it is unclear whether shallow magma chambers exist at present beneath the latter two volcanoes.

Very prominent in Grímsvötn and Bárðarbunga but also seen in Kverkfjöll, are gravity highs associated with the caldera faults. These are caused by upwards protrusions from the main high density bodies. This type of structure has been observed on volcanoes in the Cascades in the USA (e.g. Gettings and Griscom, 1988) and to some extent in Askja and Krafla (Brown et al., 1991; Foulger and Field, 2000). Grímsvötn is the most active and best known of

the volcanoes studied here and observed eruptions within the caldera occur along the caldera fault (Gudmundsson and Björnsson, 1991). If that is a common behaviour, it explains the existence of these high density bodies under caldera margins as cone sheets, dykes and other shallow intrusions. At Vonarskarð the relation between shallow high density bodies and caldera faults is not apparent. This may be a reflection of the higher age of Vonarskarð (Saemundsson, 1982); intrusive events occurring after caldera faults have ceased to be the obvious pathways for magma could obscure a previous relationship between caldera faults and intrusions.

7.2. Small or caldera-free central volcanoes

In contrast to the large central volcanoes the gravity signature associated with the central volcanoes of Hágöngur, Hamarinn and Þórðarhyrna is indistinct. Hágöngur and especially Þórðarhyrna have rhyolite exposures while only basalts are seen in the exposed part of Hamarinn. An unclear gravity low associated with Þórðarhyrna may be caused by the rhyolites (Fig. 10). All three have two things in common. They share a fissure swarm with a larger central volcano and they lie farther to the south of the two central volcanoes. Further, all three lack clear caldera structures, although a shallow depression that may be a caldera occurs in Hamarinn (Saemundsson, 1982; Björnsson and Einarsson, 1990). The fact that two central volcanoes develop on the same system may be an indicator of high magma supply, at least during some periods of the lifetime of these systems. However, it seems that one of the two becomes dominant and serves as the main conduit for magma on the system. The dominant one develops a semi-permanent magma chamber in the upper crust, leading to caldera formation, often with repeated collapses creating composite or nested calderas. In contrast, for the smaller volcano, magma supply is only sporadic, precluding the formation of long-lived magma chambers. However, the rhyolite exposures show that residence of magma in the crust occurs occasionally. As pointed out above, a possible explanation for the gravity highs linking the two central volcanoes on these three systems is that they are caused by dyke swarms (Fig. 10). This may indicate that the smaller centre is fed by lateral magma flow from the larger one. For a highly active centre, residence times of magma in the crust may be short, largely precluding formation of rhyolite. In contrast, the more sporadic magma supply for the small centre may favour longer residence times of isolated magma batches in the crust increasing the possibility of evolved magma forming. This would fit the sharp contrast in volume of basic subvolcanic intrusions between the pairs of volcanoes, and the widespread occurrence of rhyolite in Þórðarhyrna while no rhyolite is observed at Grímsvötn.

7.3. Eastern margin of the volcanic zone

The NE–SW lineation apparent on the horizontal gradient map (Figs. 5 and 10), coincides with the eastern margin of the volcanic zone, and extends from the southwest margin of the study area, to the east of Grímsvötn through Kerkfjöll. To the north of Kerkfjöll this lineation is not apparent but data coverage at that margin of the study area is rather poor. The lineation is caused by steeper than average gradient in the Bouguer anomaly field, with lower values on the western side, within the volcanic zone. A likely explanation for this is a low-density uppermost crust within the volcanic zone, composed to a considerable degree of subglacially-formed volcanics. Such rocks are abundant on the surface both to the north and the south of Vatnajökull (Jóhannesson and Saemundsson, 1998). Apparently this boundary lies 5–10 km east of Grímsvötn.

In Fig. 10, a local gravity high is marked, that extends to the south from Kerkfjöll. This high appears as a step in the Bouguer anomaly (Figs. 3 and 4). It trends out of the volcanic zone but coincides with a bedrock ridge complex (Björnsson and Einarsson, 1990) and magnetic high that stretches from Kerkfjöll towards Esjufjöll (Jónsson et al., 1991). This combination indicates that Brunhes volcanism created these subglacial ridges to the east of the main margin of the Eastern Volcanic Zone.

8. Conclusions

Our gravity map has revealed new information on the shallow crustal structure, volcanic systems and central volcanoes in central eastern Iceland. Lessons drawn from the data include:

1. Where the volcanic systems in the area have two central volcanoes, one is dominant, acting as the main conduit for magma to the surface. The larger of the two volcanoes develops large calderas, long-lived shallow magma

chambers and major intrusive bodies in the upper crust. It is suggested that short residence times of magma in the crust cause these volcanoes to erupt predominantly basalts. Bárðarbunga, Kverkfjöll, Grímsvötn and the older Vonarskarð belong to this category.

2. The second central volcano on a volcanic system is auxillary to the main volcano, and its magma supply is limited and sporadic. This may occasionally lead to long residence times of magma in the crust, favouring the formation of evolved magma. This may explain rhyolites in Þórðarhyrna and Hágöngur.
3. The two central volcanoes on a system are connected with gravity highs that may be caused by higher than average percentage of basic intrusives. These intrusives may have formed by lateral flow of magma from the main central volcano to the auxillary volcano.
4. The margin of the Eastern Volcanic Zone appears as a lineation in the horizontal gradient of the Bouguer anomaly field, lying 5–10 km east of Grímsvötn and just east of Kverkfjöll. It is suggested that this is caused by accumulation of low density subglacially erupted volcanics inside the volcanic zone.

Acknowledgements

Fieldwork during the campaigns on Vatnajökull in 1994–2000 was done with the assistance of the many volunteers of the Iceland Glaciological Society. K. Langley took part in fieldwork to the west and north of the glacier in 1998. Logistical support was provided by the Iceland Glaciological Society and the National Power Company of Iceland. Access to unpublished bedrock data on southern Vatnajökull was granted by H. Björnsson and F. Pálsson of the Institute of Earth Sciences University of Iceland, and is greatly appreciated. Useful comments by P. Einarsson, W. Jacoby and J. Behrendt improved the quality of this paper. Financial support was provided by the University of Iceland Research Fund.

References

- Ablay, G.J., Kearey, P., 2000. Gravity constraints on the structure and volcanic evolution of Tenerife, Canary Islands. *J. Geophys. Res.* 105, 5783–5796.
- Alfaro, R., Brandsdóttir, B., Rowlands, D.P., White, R.S., Gudmundsson, M.T. Structure of the Grímsvötn central volcano under the Vatnajökull ice cap, Iceland. *Geophys. J. Int.*, in press.
- Björnsson, H., 1988. Hydrology of ice caps in volcanic regions. *Soc. Sci. Isl.* 45, 139pp.
- Björnsson, H., 2003. Subglacial lakes and jokulhlaups in Iceland. *Global Planetary Change* 35, 255–271.
- Björnsson, H., Einarsson, P., 1990. Volcanoes beneath Vatnajökull, Iceland: Evidence from radio echo-sounding, earthquakes and jokulhlaups. *Jökull* 40, 147–168.
- Björnsson, H., Pálsson, F., Gudmundsson, M.T., 1992. Vatnajökull, Northwestern part, 1:100,000, Subglacial surface. National Power Company and Science Institute, University of Iceland.
- Björnsson, H., Gudmundsson, M.T., 1993. Variations in the thermal output of the subglacial Grímsvötn Caldera, Iceland. *Geophys. Res. Lett.* 20, 2127–2130.
- Björnsson, H., Pálsson, F., Sigurdsson, O., Flowers, G.E., 2003. Surges of glaciers in Iceland. *Ann. Glaciol.* 36, 82–90.
- Bott, M.H.P., Tuson, J., 1973. Deep structure beneath the Tertiary volcanic regions of Skye, Mull and Ardnamurchan, North-west Scotland. *Nature* 242, 114–116.
- Brandsdóttir, B., Menke, W., Einarsson, P., White, R.S., Staples, R.K., 1997. Faroe-Iceland Ridge Experiment. 2. Crustal structure of the Krafla central volcano. *J. Geophys. Res.* 102, 7867–7886.
- Brown, G.C., Everett, S.P., Rymer, H., McGarvie, D.W., Foster, I., 1991. New light on caldera evolution—Askja, Iceland. *Geology* 19, 352–355.
- Carlson, R.L., Herrick, C.N., 1990. Densities and porosities in the oceanic crust and their variations with depth and age. *J. Geophys. Res.* 95, 9153–9170.
- Carrivick, J.L., Russell, A.J., Tweed, F.S., 2004. Geomorphological evidence for jokulhlaups from Kverkfjöll volcano, Iceland. *Geomorphology* 63, 81–102.
- Christensen, N.I., Wilkens, R.H., 1982. Seismic properties, density, and composition of the Icelandic crust near Reyðarfjörður. *J. Geophys. Res.* 87, 6389–6395.
- Darbyshire, F.A., Bjarnason, I.T., White, R.S., Flóvenz, Ó.G., 1998. Crustal structure above the Iceland mantle plume imaged by the ICEMELT refraction profile. *Geophys. J. Int.* 135, 1131–1149.
- Darbyshire, F.A., White, R.S., Priestley, K.F., 2000. Structure of the crust and uppermost mantle of Iceland from a combined seismic and gravity study. *Earth Planet. Sci. Lett.* 181, 409–428.
- Dobrin, M.B., Savit, C.H., 1988. *Introduction to Geophysical Prospecting*. McGraw-Hill, New York, 867 pp.
- Einarsson, P., Brandsdóttir, B., Gudmundsson, M.T., Björnsson, H., Sigmundsson, F., Grönvold, K., 1997. Center of the Iceland hotspot experiences volcanic unrest. *Eos* 78 (35), 369–375.

- Eysteinnsson, H., Gunnarsson, K., 1995. Maps of gravity, bathymetry and magnetics for Iceland and surroundings. Orkustofnun, OS-95055/JHD-07. 39 pp. with 4 maps.
- Flóvenz, Ó.G., 1980. Seismic structure of the Icelandic crust and the relation between body wave velocity and the alteration of the basaltic crust. *J. Geophys.* 47, 211–220.
- Flóvenz, Ó.G., Gunnarsson, K., 1991. Seismic crustal structure in Iceland and surrounding area. *Tectonophysics* 189, 1–17.
- Foulger, G.R., Field, P.R., 2000. Comparison of local earthquake tomographic crustal models with gravity data for the Hengill-Grensdalur and Krafla areas. *Jökull* 48, 29–48.
- Gebrande, H., Miller, H., Einarsson, P., 1980. Seismic structure of Iceland along RRISP-profile I. *J. Geophys.* 47, 239–249.
- Gettings, M.E., Griscorn, A., 1988. Gravity model studies of Newberry volcano, Oregon. *J. Geophys. Res.* 93, 10109–10118.
- Gudmundsson, A., 1995. Infrastructure and mechanics of volcanic systems in Iceland. *J. Volcanol. Geoth. Res.* 64, 1–22.
- Gudmundsson, M.T., Björnsson, H., 1991. Eruptions in Grímsvötn 1934–1991. *Jökull* 41, 21–46.
- Gudmundsson, M.T., Björnsson, H., Pálsson, F., 1995. Changes in jökulhlaup sizes in Grímsvötn, Vatnajökull, Iceland, 1934–1991, deduced from in situ measurements of subglacial lake volume. *J. Glaciol.* 41, 263–272.
- Gudmundsson, M.T., Milsom, J., 1997. Gravity and magnetic studies of the subglacial Grímsvötn volcano, Iceland: implications for crustal and thermal structure. *J. Geophys. Res.* 102, 7691–7704.
- Gudmundsson, M.T., Sigmundsson, F., Björnsson, H., 1997. Ice-volcano interaction of the 1996 Gjálp subglacial eruption, Vatnajökull, Iceland. *Nature* 389, 954–957.
- Gudmundsson, M.T., Th. Högnadóttir, 2001. Gravity surveying 1988–2001: Central volcanoes in the Eastern Volcanic Zone and hyaloclastite regions in the Western Volcanic Zone. Science Institute, University of Iceland, RH-22-2001, 57 pp.
- Gudmundsson, M.T., Sigmundsson, F., Björnsson, H., Högnadóttir, Th., 2004. The 1996 eruption at Gjálp, Vatnajökull ice cap, Iceland: efficiency of heat transfer, ice deformation and subglacial water pressure. *Bull. Volcanol.* 66, 46–65.
- Hersir, G.P., Björnsson, G., Björnsson, A., 1990. Eldstöðvar og jarðhiti á Hengillssvæði, jarðeðlisfræðileg könnun. (Geophysical surveying of volcanoes and geothermal heat in the Hengill region). Orkustofnun, OS90031/JHD-06, 93 pp.
- Jakobsson, S.P., 1979. Outline on the petrology of Iceland. *Jökull* 29, 57–73.
- Jóhannesson, H., 1984. Grímsvatnagos 1933 og fleira frá því ári (the 1933 Grímsvötn eruption). *Jökull* 34, 151–158.
- Jóhannesson, H., Saemundsson, K., 1998. Geological map of Iceland, 1:500,000, Bedrock geology. Icelandic Institute of Natural History.
- Jónsson, G., Kristjánsson, L., Sverrisson, M., 1991. Magnetic surveys of Iceland. *Tectonophysics* 189, 229–247.
- Kaban, M.K., Flóvenz, Ó.G., Palmason, G., 2002. Nature of the crust-mantle transition zone and the thermal state of the upper mantle beneath Iceland from gravity modeling. *Geophys. J. Int.* 149, 281–299.
- Larsen, G., 1984. Recent volcanic history of the Veidivötn fissure swarm, southern Iceland—an approach to volcanic risk assessment. *J. Volcanol. Geoth. Res.* 22, 33–58.
- Larsen, G., 2002. A brief overview of eruptions from ice-covered and ice-capped volcanic systems in Iceland during the last 11 centuries: frequency, periodicity and implications. In: Smellie, J.L., Chapman, M.G. (Eds.), *Ice-volcano Interaction on Earth and Mars*, vol. 202. *Geol. Soc. Lond. Spec. Publ.*, pp. 81–90.
- Larsen, G., Gudmundsson, M.T., Björnsson, H., 1998. Eight centuries of periodic volcanism at the center of the Iceland hot spot revealed by glacier tephrostratigraphy. *Geology* 26, 943–946.
- Melengreu, B., Lénat, J.-F., Froger, J.-L., 1999. Structure of Réunion Island (Indian Ocean) inferred from the interpretation of gravity anomalies. *J. Volcanol. Geoth. Res.* 88, 131–146.
- Menke, W., Brandsdóttir, B., Einarsson, P., Bjarnason, I.T., 1996. Reinterpretation of the RRISP-77 Iceland shear-wave profiles. *Geophys. J. Int.* 126, 166–172.
- Nafe, J.E., Drake, C.L., 1957. Variation with depth in shallow and deep water marine sediment of porosity, density and the velocities of compressional and shear waves. *Geophysics* 22, 523–553.
- Noe-Nygaard, A., 1952. A group of liparite occurrences in Vatnajökull, Iceland. *Folia Geographica Danica*, Tom I, no. 3, 59 pp.
- Palmason, G., 1971. Crustal structure of Iceland from explosion seismology. *Soc. Sci. Isl.* 40., 171pp.
- Pedley, R.C., Busby, J.P., Dabek, Z.K., 1997. Gravmag User Manual. British Geological Survey, 73 pp.
- Rymer, H., Brown, G.C., 1986. Gravity fields and the interpretation of volcanic structures: geological discrimination and temporal evolution. *J. Volcanol. Geoth. Res.* 27, 229–254.
- Saemundsson, K., 1978. Fissure swarms and central volcanoes in the neovolcanic zones of Iceland. *Geol. J. Spec. Issue* 10, 415–432.
- Saemundsson, K., 1979. Outline on the geology of Iceland. *Jökull* 29, 7–28.
- Saemundsson, K., 1982. Öskjur á virkum eldfjallsvæðum á Íslandi [Calderas within the active volcanic zones in Iceland] In: Þórarinnssdóttir, H., Ó.H., Óskarsson, S., Steinthórhsson, Th. Einarsson (Eds.), *Sögufélag*, Reykjavík, pp. 221–239.
- Sigmarsson, O., Karlsson, H.R., Larsen, G., 2000. The 1996 and 1998 subglacial eruptions beneath the Vatnajökull ice sheet in Iceland: contrasting geochemical and geophysical inferences on magma migration. *Bull. Volcanol.* 61, 468–476.
- Spera, F.J. 2000. Physical properties of magma. In: Sigurdsson (chief Ed.): *Encyclopedia of Volcanoes*, Academic Press, pp. 171–190.
- Sturkell, E., Einarsson, P., Sigmundsson, F., Hreinsdóttir, S., Geirsson, H., 2003. Deformation of Grímsvötn volcano, Iceland: 1998 eruption and subsequent inflation *Geophysical Research Letters* 30, Art. No. 1182.
- Thorarinsson, S., 1958. The Öræfajökull eruption of 1362. *Acta Nat. Isl.* 2 (2), 1–99.
- Thorarinsson, S. 1974. Vötnin Stríð. The swift flowing rivers: The history of Grímsvötn jökulhlaups and eruptions. Menningarsjóður, Reykjavík, 254 pp.
- Thorarinsson, S., Saemundsson, K., Williams, R.S., 1973. ERTS-1 image of Vatnajökull: Analysis of glaciological, structural and volcanic features. *Jökull* 23, 7–17.
- Thorarinsson, S., Saemundsson, K., 1979. Volcanic activity in historical time. *Jökull* 29, 29–32.

- Thorbergsson, G., 1971. Gravity Survey on Vatnajökull in Southeastern Iceland in 1971. National Energy Authority, Iceland, 12 pp.
- Thorbergsson, G., Magnússon, I.Þ., Pálmason, G., 1993. Gravity data and gravity map of Iceland. Report: National Energy Authority OS-930027/JHD-07, 38 pp. + 1 map.
- Williams, D.L., Finn, C., 1985. Analysis of gravity data in volcanic terrain and gravity anomalies and subvolcanic intrusions in the Cascade Range, USA. In: Hinze, W.J. (Ed.), *The Utility of Regional Gravity and Magnetic Maps*. SEG, Tulsa, pp. 361–374.
- Wolfe, C.J., Bjarnason, I.T., VanDecar, J.C., Solomon, S.C., 1997. Seismic structure of the Iceland mantle plume. *Nature* 385, 245–247.