Shallow Structures beneath Heimaey and Surtsey from Local Gravity Data

By

B.R. CAMERON, F.S. CRANMER and G.R. FOULGER

Dept. of Geological Sciences
University of Durham
Durham, DH1 3LE, UK

ABSTRACT

In July and August 1989, local gravity surveys of the islands and Heimaey and Surtsey were conducted. Networks of 42 points on Heimaey and 41 points on Surtsey were surveyed for height and measured using a LaCoste and Romberg gravimeter. The data were reduced in the conventional way to obtain Bouguer anomaly maps of the islands. The average density of the material above sea level was 2250 kg/m^3 for Heimaey and 2000 kg/m^3 for Surtsey. This indicates that Surtsey is composed of material with a higher percentage of hyaloclastites than Heimaey.

On Heimaey, negative anomalies associated with Eldfell, Helgafell and Sæfell indicate that their summit conduits evacuated most of their lava at the end of their last eruptions and are now filled with low density ash and tephra. The relatively high densities on the flanks indicate increased percentage of lava flows there. A gravity high over Stórhöfdi indicates that this summit conduit was filled with magma at the end of its last eruption, which froze in the pipe to form a massive, high density core. The relatively low density flanking material indicates material with a higher percentage of hyaloclastites than the core.

On Surtsey, gravity lows associated with the tuff hills north of the eruptive vents Surtur I and Surtur II suggest that these hills have cores of low density tephra accumulations containing large cavities. Higher density bodies underly Surtur I and Surtur II which indicates that these vents are plugged with more massive material.

INTRODUCTION

The Westmann Islands are a 30 km long volcanic archipelago that is the continuation of the southwards propagating Eastern Volcanic Zone of Iceland. Heimaey is the largest, and contains rocks at least 5400 years old (Jakobsson, 1968). Surtsey is the youngest, and erupted out of the sea during the period 1963 to 1967 (Jakobsson and Moore, 1982).

In July and August 1989 local gravity surveys were made of these, the two largest islands. Since there had been no previous detailed gravity surveys there, it was necessary to also establish a network of geodetic stations at which the gravity measurements could be made.

The aim was to investigate the near-surface crustal structure with particular reference to the volcanoes og Eldfell and Helgafell on Heimaey, and the tuff hills and eruptive vents (Surtur I and Surtur II) of Surtsey.

FIELD MEASUREMENTS

Surveying

A Pentax Electronic Theodolite and a Sokkisha Red Mini EDM were used to determine the heights of the stations where gravity measurements were to be made.

The method of theodolite tacheometry was employed (Bannister and Raymond, 1984).

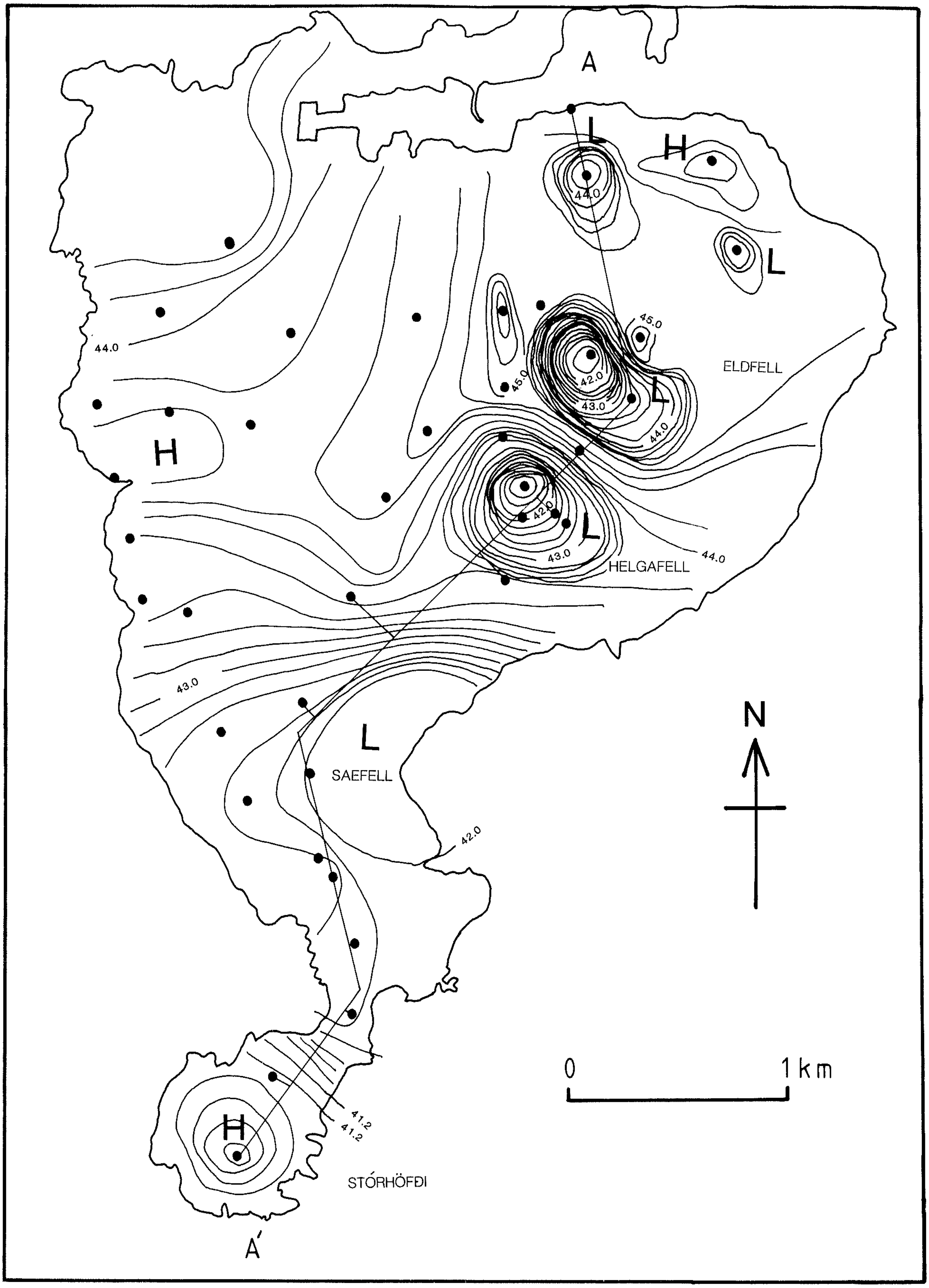

Fig. 1. Bouguer anomaly map of Heimaey. Black dots indicate survey points.

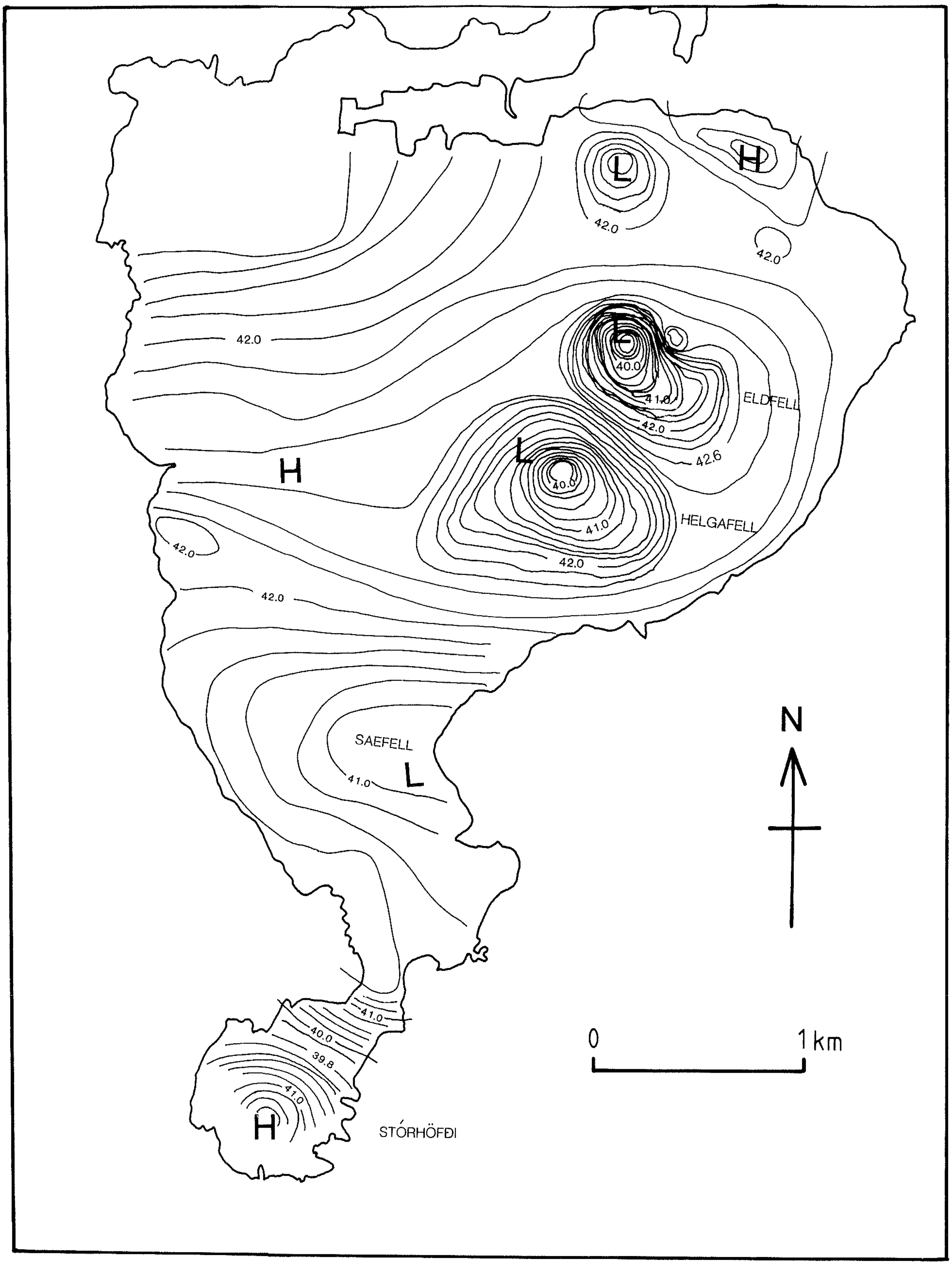

Fig. 2. Bouguer anomaly map of Heimaey. A regional gradient of 0.5 mgal/km increasing to the north has been removed.

This involves measuring the vertical angle and direct distance between points, and using simple trigonometry to determine the relative heights of the stations. By tying to a point of known height above sea level, the heights of all the survey points above mean sea level

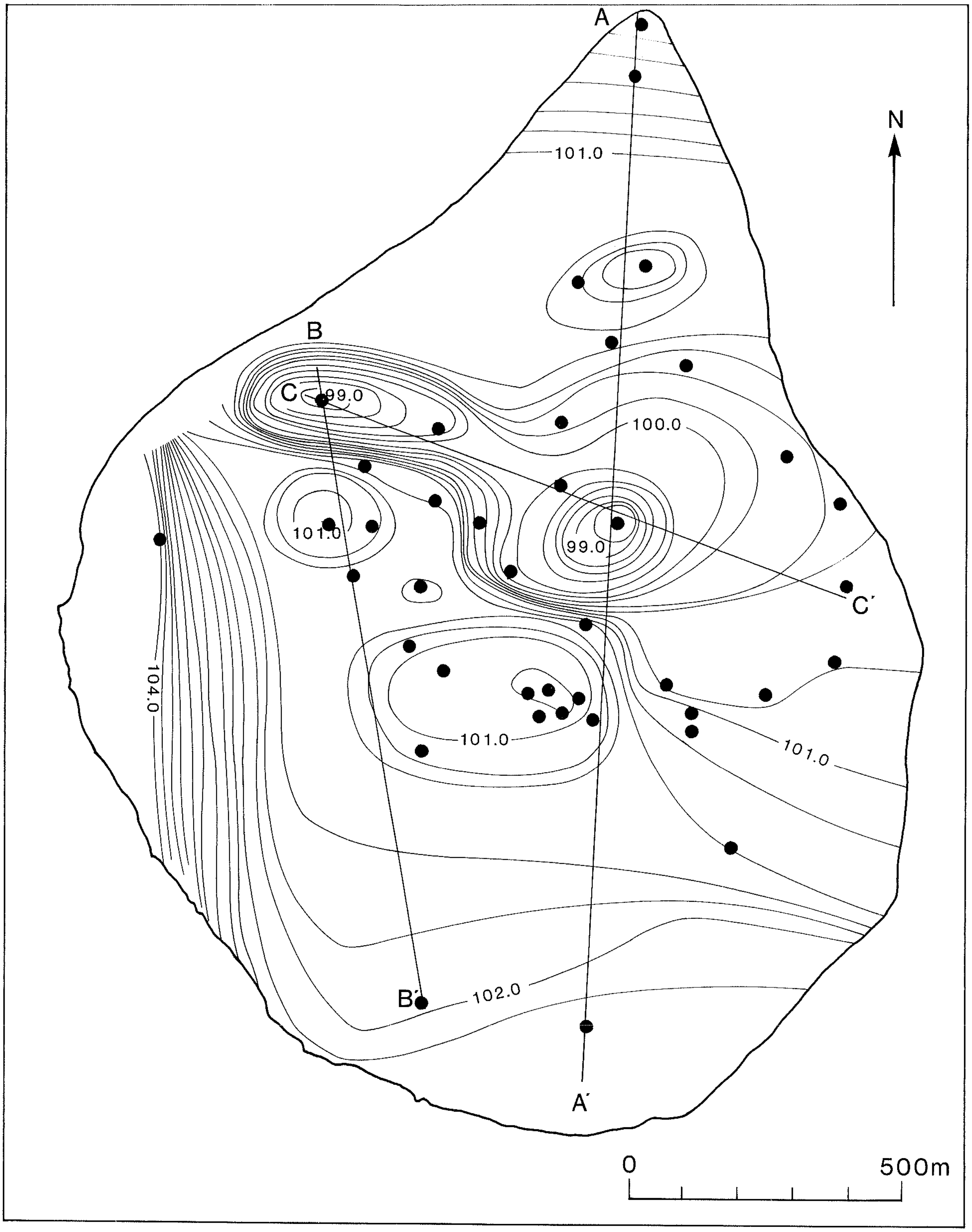

Fig. 3. Bouguer anomaly map of Surtsey. Black dots indicate survey points.

were determined. The latitudes of the points were determined by plotting the stations on large-scale maps, calculating their coordinates in the local coordinate systems of Heimaey (Ólafur Ólafsson, pers. comm.) and Surtsey (Sjómaelingar Íslands, 1985), and converting to geodetic coordinates (Ólafur Ólafsson, pers. comm., Sjómaelingar Íslands, 1985).

A network of 42 points was measured on Heimaey, which was tied to several bench-

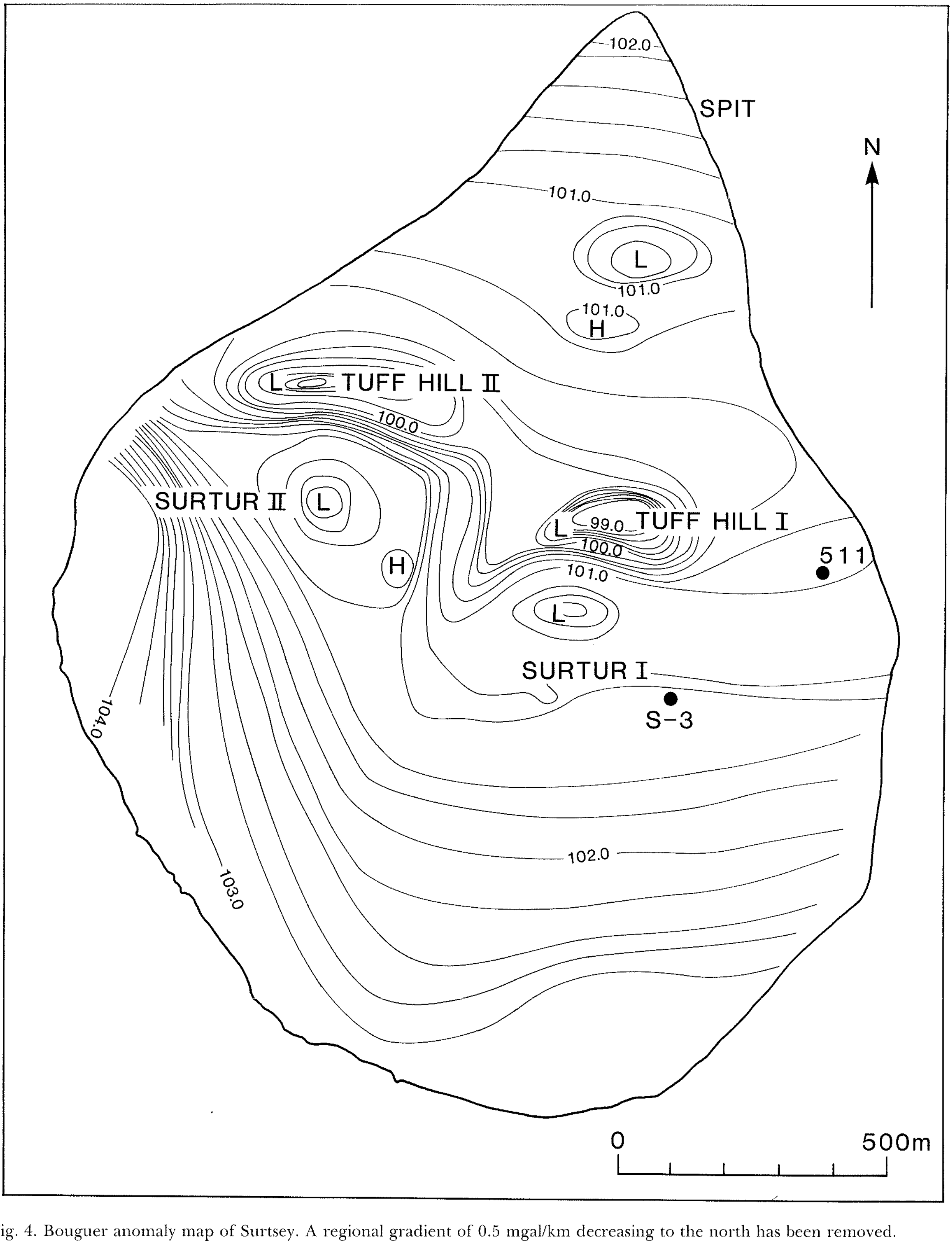

Fig. 4. Bouguer anomaly map of Surtsey. A regional gradient of 0.5 mgal/km decreasing to the north has been removed.

marks in the town (Fig. 1). On Surtsey, a network of 41 points was surveyed (Fig. 3) and tied to point 511 (Moore, 1982). The points were marked by yellow painted crosses and/or nails.

Gravity

A LaCoste and Romberg standard model G Gravimeter was used to measure gravity at the stations. The gravimeter was levelled using a concave levelling plate on top of the station or as close to it as possible. The difference in height (if any) between the station and gravimeter position was measured. Terrain around the stations was estimated for compartments B and C (out to a total of 36 m from the stations). Tie backs to a base station were made at intervals of no more than 2 hours to enable gravimeter drift to be calculated.

It is desriable in surveys of this kind to tie all measurements to a station where absolute gravity is known. There was an absolute gravity station on Heimaey at the old airport terminal building, but unfortunately this was destroyed when the new terminal was built. A new base at the airport control tower was therefore used, and all station readings were made relative to this base, although the absolute value of gravity is not yet known there (Fig. 1).

On the island of Surtsey, no previous gravity measurements had been made, and all readings were made relative to a base at station S-3 (Fig. 4), which is close to the new hut in the west, and at a surveying station of Tryggvason (1972).

REDUCTION OF DATA

The Bouguer anomaly was calculated using the formula:

$$BA = g_{obs} - g_{\varnothing} + FAC - BC + TC$$

where BA is the Bouguer anomaly, g_{obs} is the observed value of gravity after correcting for gravimeter drift, $g_{\varnothing}$ is theoretical gravity at latitude $\varnothing$, FAC is the Free Air correction, BC is the Bouguer correction and TC is the terrain correction. The value of observed gravity was obtained by correcting the raw gravity measurements for drift. Gravimeter drift was typically less than 0.05 mgal/hour. Theoretical gravity was calculated using the IGRF formula:

$$g_{\varnothing} = 9.780318(1 + 5.3024x10^{-3}\sin^2\varnothing + 5.9.10^{-6}\sin^2 2\varnothing)$$

The equation used to make the Free Air correction was:

$$FAC = 0.3085h$$

where h is the height of the station above mean sea level. The Bouguer correction was made using the formula:

$$BC = 4.188.10^{-5}\rho h$$

where ρ is the average density of the material above sea level.

The terrain correction for each station was assessed by estimating the average height in compartments for zones D to M using available topographic and bathymetric maps, and summing the correction factors given in the Hammer chart (Hammer, 1939) for all zones estimated both in the field and from the map (i.e. zones B to M).

$$TC = \rho \sum_{i=B}^{M} HTF_i$$

HTF is the Hammer terrain factor. In considering the terrain corrections for those segments that were mostly in the sea, the volumes above and below sea level were compensated for separately, and a correction was made for the presence of the sea layer, which was taken to have a density of 1000 kg/m^3.

In order to make the Bouguer and terrain corrections, the value of the average density for the material above sea level is required. Three methods were used to obtain estimates for the average rock density of the islands:

(a) Direct measurement of the volumes and masses of samples of rock, from which the density is calculated. This method has the drawback that the densities obtained may not accurately reflect those of larger rock masses.

(b) Nettleton's Method (Dobrin and Savit, 1988, p 557–558). This involves calculating Bouguer anomaly profiles for a number of stations that traverse a topographical feature, using a series of densities. The density that yields a Bouguer anomaly profile that shows least correlation with the topography is taken to be the average density of the feature. This method may be untrustworthy, in particular in Iceland, because in a young volcanic environment topographic features may be directly attributable to lateral variations in structure and density.

(c) The least squares method. This involves rearranging the Bouguer anomaly equation into density dependent and independent parts to form the equation of a line whose gradient is the density:

$$g_{obs} - g_{\varnothing} + FAC = BA_{ave} + \delta BA + \rho(0.04191h - \sum_{i=B}^{M} HTF_i)$$

BA_{ave} is the average Bouguer anomaly and δBA is the deviation from this for a particular station. A graph may then be drawn, whose gradient is the average density of the material above sea level, and whose intercept is BA_{ave}. This is a robust method of determining average density over a survey area, that has some statistical foundation.

The average Bouguer density used for Heimaey was 2250 kg/m^3. This was decided on the basis of the following density determinations:

i) Direct measurement – 2230 kg/m^3
ii) Nettleton's method – 2350 kg/m^3
iii) Least squares method – 2170 kg/m^3

The average Bouguer density chosen for Surtsey was 2000 kg/m^3. This value was a reasonable mid value of the following determinations:

i) Direct measurements:
  Lava – 2230 kg/m^3
  Basic glomerobreccia – 2160 kg/m^3
  Palagonitised tuff – 1850 kg/m^3
  Sedimentary xenolith – 2420 kg/m^3
ii) Nettleton's method – 2200 kg/m^3
iii) Least squares method – 1880 kg/m^3

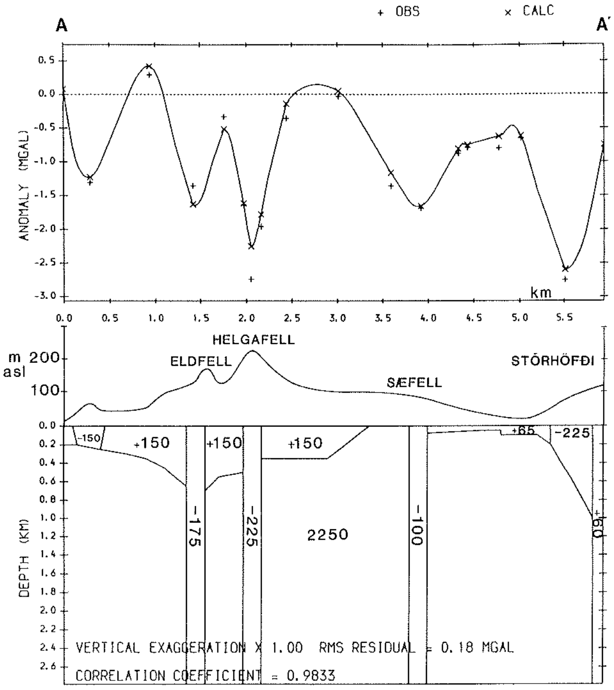

Fig. 5. Profile AA' (c.f. Fig. 1), running NS through Heimaey. Upper part of Figure indicates field (+) and theoretical (×) gravity values. Lower part of Figure illustrates the structure modelled. The densities of the bodies are indicated in kg/m^3. The topography is indicated above the lower part of the Figure.

RESULTS

Bouguer anomaly maps of Heimaey and Surtsey are presented in Figs 1 to 4. The data are tabulated in Tables 1 and 2. An error analysis was performed (Table 3), and the estimated error in the calculated values of the Bouguer anomaly is 0.3 mgal, or about one contour interval in Figs. 1 to 4.

INTERPRETATION

Method

After removing the island-wide gravity trend (the "regional"), the program GRAVN (Bott, 1986) was used to model the gravity profiles along various sections of the Bouguer anomaly maps. Bodies are defined by the coordinates of their corners and their density contrasts with the background material are declared. The program decomposes each body into a set of semiinfinite slabs with sloping ends and calculates and sums the gravity contributions due to each slab and each body. The resultant theoretical profile may be plotted on a graphics computer screen, and the true values obtained by processing the field data superimposed. The model is progressively adjusted until a good fit to the field data points is obtained. When this has been achieved, a candidate interpretation has been established. It should be borne in mind, however, that in theory, an infinite number of structures could be found to fit the observed gravity field. This is known as the ambiguity problem. In the models presented below, effort was made to arrive at geologically reasonable solutions.

Heimaey

The island-wide gradient over Heimaey was found to be 0.5 mgal/km, increasing to the north. This result is in agreement with the results of 4 gravity measurements reported by Einarsson (1954). Such a gradient is in the opposite direction to the regional gravity trend of Iceland which is bowl shaped with a central low in the middle of Iceland. This discrepancy points towards the existence of structure on the scale of 5 km or more, that overprints the regional gradient of Iceland.

A Bouguer gravity map of Heimaey with the regional removed is presented in Fig. 2. This map is dominated by 3 narrow, steep anomalies, with amplitudes of approximately 2 mgal, in the areas of Eldfell, Helgafell and Stórhöfdi. A broader gravity low was detected

TABLE 1
Gravity data from Heimaey.

1	STATION	HEIGHT		LATITUDE		T.C.	BOUGUER ANOMALY
2		m	degs	mins	secs		mgals
3	L1	120.896	63	23	28.3	2.491	41.81743
4	M1	54.967	63	23	40.9	0.8823	41.04887653
5	M2	13.565	63	23	49.94	0.2709	42.34997626
6	M3	38.636	63	24	1.895	0.5201	42.39790172
7	M4	51.168	63	24	11.91	0.6549	42.40622044
8	T1	46.789	63	24	14.82	0.572	42.52087138
9	M6	40.702	63	24	24.83	0.403	42.31037171
10	M7	66.204	63	24	35.49	0.5694	42.44268465
11	Z8	70.496	63	24	54.87	0.4961	43.58199809
12	Z6	67.512	63	24	56.48	0.69	43.75726783
13	Z4	47.945	63	25	6.818	0.505	43.79164077
14	Z2	38.384	63	25	15.22	0.3913	44.40993141
15	s7692	32.155	63	25	41.38	0.4201	44.38804415
16	s7693	25.129	63	25	27.17	0.2931	43.98602443
17	s132	26.461	63	25	52.68	0.9093	43.52337259
18	s7802	57.786	63	26	4.635	0.9188	45.43163004
19	s7804	93.01	63	25	50.75	1.3859	44.36985569
20	s7800	66.656	63	26	3.343	0.7544	43.68686246
21	shore	0	63	26	13.36	0.7906	45.13982822
22	E2	117.032	63	25	34.92	1.4131	41.71446967
23	E4	135.611	63	25	41.38	1.709	43.04403451
24	E5	92.705	63	25	34.92	0.9291	45.20983251
25	V	73.622	63	24	28.38	0.7056	41.90494765
26	F1	81.719	63	24	39.69	0.586	42.44334226
27	F2	98.143	63	24	56.16	0.5721	43.97359006
28	s111	39.319	63	25	25.88	0.3518	44.45849489
29	s103	56.493	63	25	23.94	0.3895	44.30448782
30	s101	47.705	63	25	37.83	0.3594	44.00892489
31	s7606	39.031	63	25	40.41	0.3595	44.4761089
32	s222	35.859	63	25	42.99	0.4254	45.51713908
33	s226	48.773	63	25	41.38	0.545	44.88486342
34	F4	89.85	63	25	11.99	0.5791	44.53597211
35	R14	84.968	63	25	22.65	0.6515	44.72988054
36	R5	72.592	63	25	28.46	0.7901	45.10192845
37	HELGA1	156.573	63	25	21.03	2.8103	43.74596895
38	R7	112.225	63	25	18.12	1.0034	44.06974595
39	HELGA2	138.038	63	25	8.756	1.9183	42.56303017
40	R9	118.23	63	25	6.172	1.0978	42.57261904
41	R11	109.26	63	24	59.07	0.9138	43.64348483
42	HELGA4	175.757	63	25	8.433	3.3343	43.23993761
43	HELGATOP	227.039	63	25	12.31	6.1346	41.45506725
44	OB	108.85	63	25	1.973	0.7906	
45							

around Saefell. In the cases of Eldfell, Helgafell and Saefell, the summits of the mountains are associated with gravity lows. The opposite case was true of Stórhöfdi, where the mountain summit gave a high gravity value when compared with the flanks.

It is to be expected that gravity decreases with height, and the possibility was considered that the negative anomalies observed over Eldfell, Helgafell and Saefell resulted from too high a density having been used to make the Bouguer and terrain corrections. (This is equivalent to testing the hypothesis that the anomalies observed were all due to lateral variations in density in the material above sea level). It was found that densities as low as 1000 kg/m^3 for the material above sea level would be required to account for the observations. It was therefore concluded that density variations exist also in the material below sea level.

A N-S trending profile passing through all the major anomalies was modelled (profile A A', Fig. 1). The results of this modelling are shown in Fig. 5. The correlation coefficient between the observed and theoretical values was better than 0.98. The anomalies observed over Eldfell, Helgafell and Saefell may be explained by low density pipes extending from the surface down to 3 km depth, flanked by higher density bodies of shallower extent (extending from the surface to 0.5–1.0 km depth). The density contrasts used are shown in Fig. 5. These are typically -100 kg/m^3 between the low density bodies and the background, and $+200$ kg/m^3 between the high density bodies and the background. This corresponds to a density contrast of about 300 kg/m^3 between the high and low density bodies. The anomaly in the Stórhöfdi area was modelled as a relatively high density pipe beneath the centre of the hill and low density bodies on the flanks.

It was a somewhat surprising result that the central cores of Eldfell, Helgafell and Saefell are associated with low density bodies. It is suggested that these bodies represent columns of tephra, and probably contain sizeable cavities also. This may indicate that the summit conduits of Eldfell, Helgafell and Saefell evacuated most of their lava towards the end of their respective eruptions. The higher density flanking bodies may exhibit higher densities because of lava flows, many of which are visible at the surface.

The relatively high density pipe modelled beneath the summit of Stórhöfdi suggests a contrasting eruptive history. The summit conduit of this volcano was not evacuated at the end of the eruption, but filled with magma that later crystallised and solidified in the pipe to form high density core. The relatively low density flanking material probably contains a relatively high proportion of pumice and hyaloclastites.

To the north of Eldfell, the part of the volcano that crumbled away is modelled as a low density slab. This could represent a sector collapse of the volcano with the low density attributed to the fractured and unconsolidated nature of the tephra. The area to the east of Helgafell were the 1.9 km long fissure opened up at the start of the 1973 Eldfell eruption (Jakobsson et al., 1973), is characterised by relatively low density material.

A schematic cross section of Heimaey is presented in Fig. 9, that illustrates the structure along the profile modelled. The relatively large depths to which the structures appear to extend was also surprising. Because of the ambiguity problem in gravity interpretation, there is a trade-off between density contrast and extent, and it is possible that the anomalies may also be interpreted as shallower bodies with greater density contrasts. Drilling on Heimaey shows that at least 1 km of sediments overly the basalt basement (Björnsson, 1967).

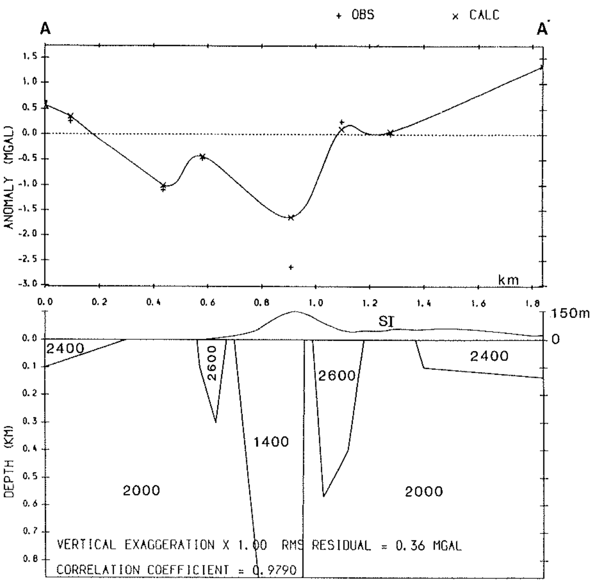

Fig. 6. AA' (c.f. Fig. 2), running NS through Surtur I in Surtsey. Caption as for Fig. 5. SI indicates the position of Surtur I.

Surtsey

An island-wide Bouguer anomaly trend of 0.5 mgal/km, decreasing northwards over the island (1.8 km) was removed. This trend is similar to that of Iceland as a whole (Einarsson, 1954), although opposite to that of Heimaey. Structure on a scale of kilometers is doubtless responsible for the undulatory regional gravity trend along the archipelago.

After the regional is removed (Fig. 4), the gravity map of Surtsey is dominated by a general gravity trough, approximately 2.5 mgal deep, crossing the island from east to west and containing the tuff hills north of their eruptive vents Surtur I and Surtur II. This general low may be subdivided into several narrow anomalies up to approximately 2 mgal in amplitude and 1–200 m in diameter. Two such anomalies are associated with the tuff hills, and another two with Surtur I and Surtur II. A fifth negative anomaly was observed north of the easternmost tuff hill.

As with the Heimaey data, different Bouguer densities were tried, to see whether the anomalies that correlated with topography could be explained by lateral density variations in the material above sea level. It was found that densities of as low as 500 kg/m^3

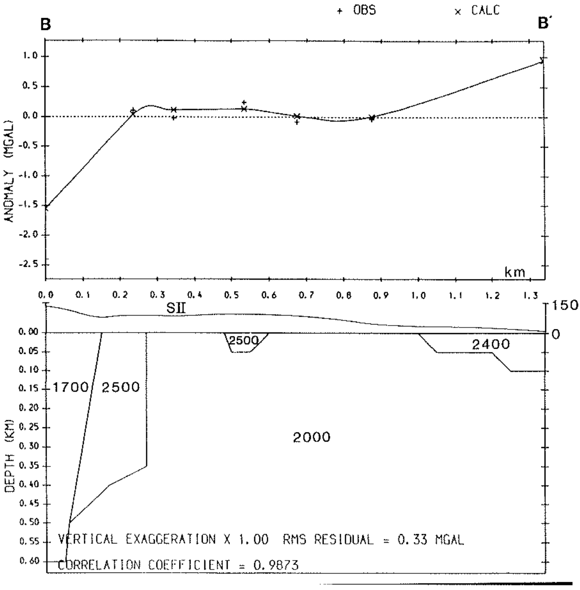

Fig. 7. Profile BB' (c.f. Fig. 2), running NS through Surtur II in Surtsey. Caption as for Fig. 5. SII indicates the position of Surtur II.

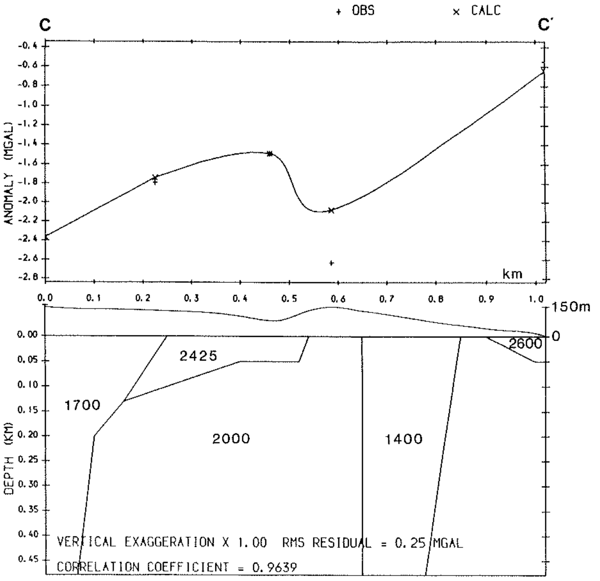

Fig. 8. Profile CC' (c.f. Fig. 2), running EW through the tuff hills in Surtsey. Caption as for Fig. 5.

would be necessary to explain the anomalies by this. These are geologically unreasonable, and it was concluded that density variations extending deeper than sea level were necessary to explain the observations.

Three profiles that sampled the main anomalies were chosen for computer modelling of the subsurface features. Two profiles (AA' and BB', Fig. 3) run approximately N-S through the tuff hills and Surtur I and Surtur II, and a third runs E-W across the tuff hills (CC', Fig. 3). Structures were modelled that fitted the observed data with correlation coefficients better than 0.95.

Profile AA' lies in the east of the island and traverses Surtur I, the tuff hill to the north of it and the negative anomaly to the north of that. Between the three gravity lows, the Bouguer anomaly had rather higher values. This profile was modelled by a structure involving a low density pipe extending from the surface to 1 km depth beneath the tuff hill, with higher density bodies extending from the surface down to 300 and 600 m depth on its flanks (Fig. 6). The body to the south of the tuff hill partially underlies Surtur I. Relatively high density, shallow bodies (up to 150 m in thickness) at the extreme north and south ends of the island were necessary to account for the general increase in Bouguer anomaly away from the central trough.

Alternating high and low density bodies in the vicinity of the tuff hill and Surtur I were necessary to model the steep Bouguer anomaly gradients observed. The low density core of the tuff hill had a density contrast of −600 kg/m^3 with the background material. The high density bodies flanking the tuff hill had contrasts of +600 kg/m^3 with the background whereas in the case of the distal bodies it was +400 kg/m^3.

Profile BB' traverses Surtur II and its associated tuff hill to the north (Fig. 7). A similar structure was necessary to model this profile, with a vertical low density central pipe extending from the surface to 600 m depth. A flanking high density body extending from the surface to a depth of 4–500 m in the vicinity of Surtur II was necessary to model the steep gravity gradient. The density constrasts of these bodies with the background material were −300 kg/m^3 for the low density pipe, and +500 kg/m^3 for the high density body in the vicinity of Surtur II. A shallow (100 m) high density body at the far south of the island was necessary to explain the increase in Bouguer anomaly there.

An east-west profile passing through the tuff hills is shown in Fig. 8, and is reasonably well modelled with the same structure obtained by modelling the two north-south profiles (Figs. 6 and 7).

The low density pipes beneath the summits of the tuff hills probably represent ash accummulations of particularly low density from the phreatic eruptions, and large cavities may also

TABLE 2
Gravity data from Surtsey.

1	STATION	HEIGHT		LATITUDE		T.C.	BOUGUER ANOMALY
2		m	degs	mins	secs		mgals
3	base	41.172	63	18	3.077	0.6455	101.5844579
4	np	2.527	63	18	43.84	0.532	102.1491814
5	n1	6.836	63	18	40.8	0.4405	101.7615594
6	th	4.646	63	18	29.48	0.3815	100.4060145
7	wp	3.661	63	18	28.44	0.6335	100.8141374
8	s7	4.41	63	18	25.31	0.8735	101.0186802
9	n2	5.253	63	18	23.78	0.795	100.6601136
10	du1	5.75	63	18	18.16	0.965	100.5326848
11	du2	8.634	63	18	15.28	0.837	100.7383513
12	sw	15.875	63	18	10.46	0.609	100.95082
13	s607	22.82	63	18	6.127	0.615	101.195306
14	s1	27.122	63	18	4.201	0.4785	101.0562995
15	base	41.172	63	18	3.077	0.6455	101.5853114
16							
17	base						
18	du3	36.636	63	18	2.034	0.5215	101.5373469
19	base						
20							
21	base						
22	sdh1	57.854	63	18	5.003	0.6215	101.1070028
23	du4	67.567	63	18	8.454	1.058	101.74817
24	du5	60.287	63	18	2.917	0.7915	101.4990841
25	j518	68.088	63	18	3.238	0.9365	101.190798
26	c1	63.956	63	18	4.04	0.9185	101.3688503
27	j517	65.604	63	18	4.682	0.9005	101.1285025
28	j519	61.865	63	18	3.077	0.7985	101.2130072
29	c2	65.907	63	18	4.441	0.8415	101.1733849
30	du6	67.073	63	18	5.485	0.921	101.2574288
31	du7	84.577	63	18	6.929	1.152	101.4242362
32	base						
33							
34	base						
35	c3	101.718	63	18	11.26	1.401	101.7513341
36	c4	88.869	63	18	14.23	1.1	101.4771049
37	c5	93.026	63	18	14.31	1.115	101.0816472
38	du8	91.879	63	18	13.35	2.253	104.4483797
39	du10	96.08	63	18	17.84	1.305	101.6136132
40	du9	98.559	63	18	15.92	1.555	101.6983137
41	ws1	102.422	63	18	10.62	1.5175	101.9276631
42	ws2	51.013	63	18	0.67	0.608	101.4767251
43	ws3	21.02	63	17	45.99	0.363	102.4088575
44	base						
45							
46	base						
47	du12	137.236	63	18	21.7	4.2645	99.12217724
48	du11	129.551	63	18	20.09	2.744	99.72203408
49	rf14	111.105	63	18	14.47	1.5555	100.8327949
50	du14	129.556	63	18	11.5	2.8555	100.1085952
51	du15	152.228	63	18	14.39	3.997	98.87237458
52	du16	86.372	63	18	16.72	1.6055	100.0100882
53	vi	40.734	63	18	20.33	1.0935	100.4630428
54	base						
55							
56	base						
57	ws4	22.99	63	17	55.06	0.4455	101.8690912
58	ws5	22.879	63	17	44.63	0.409	102.8393265
59	base						

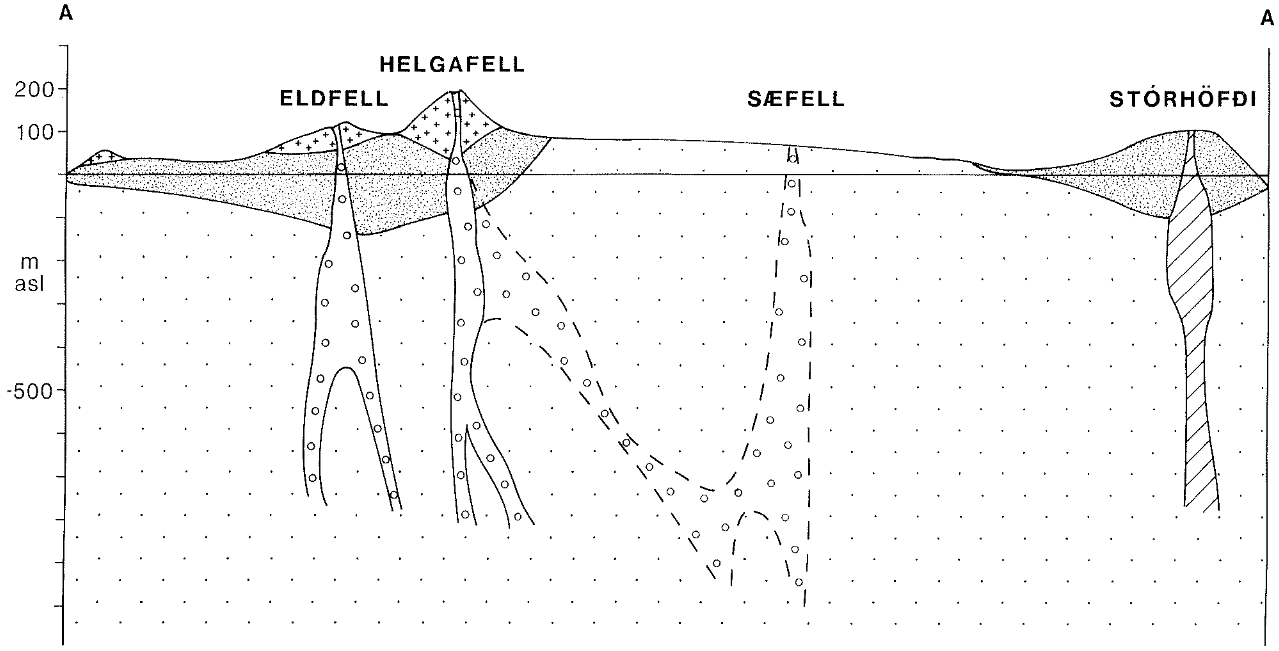

Fig. 9. Schematic cross section of Heimaey illustrating the structure along Profile AA', which traverses Helgafell, Eldfell, Saefell and Stórhöfdi.

be present. The western tuff hill (modelled with a pipe of density contrast -300 kg/m^3) appears to have a slightly higher density than the eastern one (modelled with a pipe of density contrast $+600$ kg/m^3). This may indicate higher density of the eruptive material from Surtur II than Surtur I, and/or fewer cavities. The high density bodies in the vicinity of the Surtur I and Surtur II vents probably represent basaltic material more massive than that comprising the tuff hills. This may be attributable to higher percentage of magma that has solidified in situ, forming a plug-like structure. The minor gravity lows centred on Surtur I and Surtur II may indicate that the high density material is offset to the north of the vents, and slightly lower values of gravity over the vents themselves result from the collapse of near surface material.

This interpretation is consistent with the facts that eruptions occurred from the south flank of the tuff hill north of Surtur I in December 1966 – January 1967 (Jakobsson and Moore, 1982), and the vent of Surtur II has suffered a major collapse in the top part.

The (slightly lesser) high density body modelled in the south of the island corresponds to the lava field there, that was erupted in August 1966 to January 1967 (Jakobsson and Moore, 1982). In the north of the island, the spit is underlain by relatively high density material. This probably represents lava which has been crushed and compacted by the sea to form the spit that exists there now.

A schematic NS cross section is presented in Fig. 10 that illustrates the structure along Profile AA', which traverses Surtur I and it's associated tuff hill.

As in the case of Heimaey, we were surprised at the large depth to which the structures modelled appeared to extend. Models involving larger density contrasts and shallower structures may also fit the data, though densities greatly lower than those modelled here could only be accounted for by large cavities.

CONCLUSIONS

The Bouguer gravity anomaly maps of Heimaey and Surtsey exhibit island-wide trends that increase to the north in the case of Hei-

TABLE 3
Error analysis.

Error source	Error	mgal equivalent
Gravimeter readings	0.02 mgal	0.02
Altitude	0.05 m	0.01
Latitude	1.0	0.02
Density	200 kg/m^3	0.26
Time	1 min	0.0004
	Total	0.31 mgal

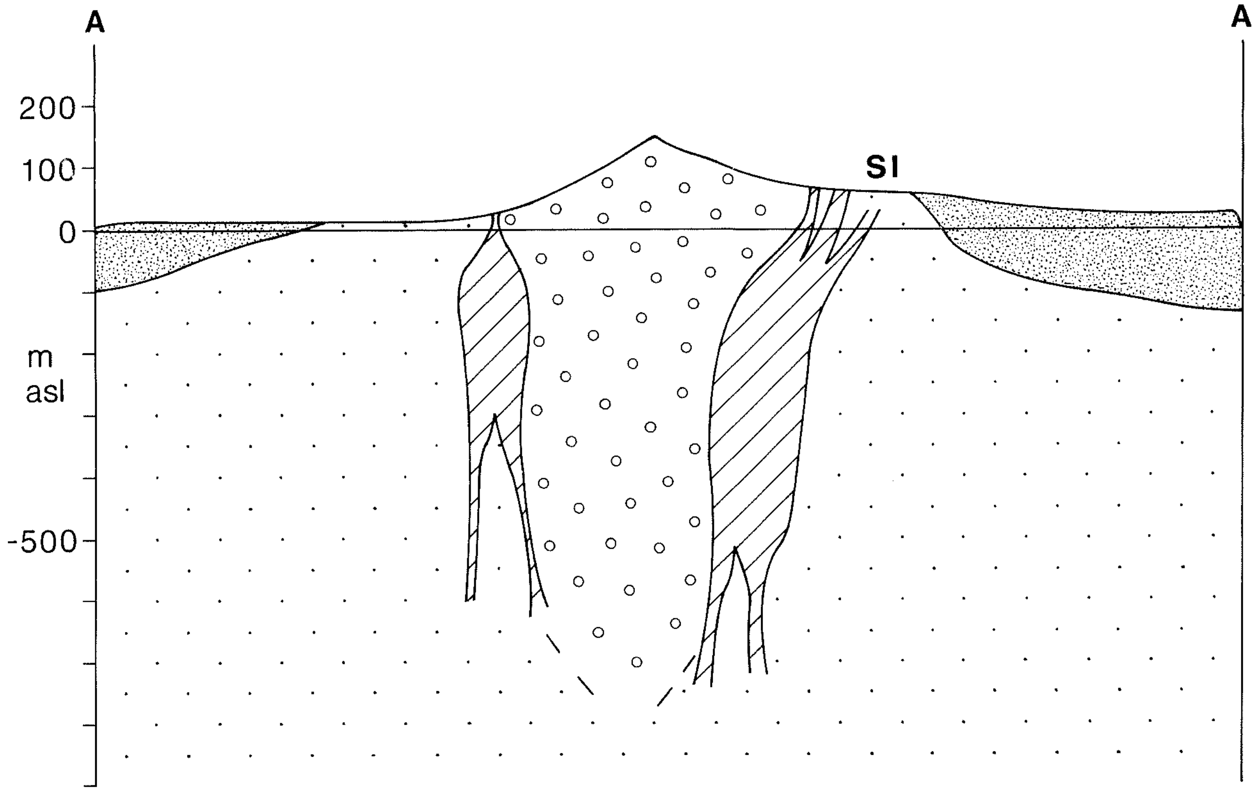

Fig. 10. Schematic cross section of Surtsey illustrating the structure along Profile AA', which traverses Surtur I and it's associated tuff hill.

maey and to the south in the case of Surtsey. These trends reflect variation of structure along the archipelago on a scale of kilometers. The average density to the material above sea level was 2250 kg/m^{-3} for Heimaey and 2000 kg/m^{-3} for Surtsey. Surtsey is on average less dense than Heimaey, probably because Surtsey is younger, less compacted, and composed of material with a higher percentage of hyaloclastites than Heimaey.

On Heimaey, negative anomalies with amplitudes up to approximately 2 mgal, and a few hundred metres in lateral extent associated with Eldfell, Helgafell and Saefell were interpreted as low density pipes extending from the surface down to 3 km depth, flanked by higher density bodies a few hundred metres in thickness. Density contrasts of about -300 kg/m^{-3} were required. These pipes may have formed because the summit conduits evacuated most of their lava at the end of their last eruptions and became filled with low density ash and tephra. Higher densities on the flanks indicate an increased percentage of lava flows. A gravity high over Stórhöfdi was modelled as a relatively high density pipe. This may indicate that the summit conduit did not evacuate at the end of the eruption, but filled with magma that later froze in the pipe to form a massive, high density core. The relatively low density flanking material indicates material with an increased percentage of pumice and hyaloclasties.

A general EW trending gravity trough approximately 2.5 mgal deep traverses Surtsey. Within this are several negative anomalies of up to 2 mgal in amplitude and 1–200 m in diameter. Four of these are associated with Surtur I and Surtur II and their corresponding tuff hills. The data suggest that the tuff hills have very low density cores extending from the surface to 1 km depth, with shallower, higher density bodies on their flanks, in the vicinity of Surtur I and Surtur II. The cores of the tuff hills are probably composed of unusally low density tephra, perhaps containing large cavities. Higher densities associated with Surtur I and Surtur II indicate magma that has solidified in situ, although slight gravity lows centred on the vents themselves suggest that the high density material is offset to the north. The vents themselves may have slightly depressed near surface densities as a result of the collapse of near surface material.

ACKNOWLEDGEMENTS

We would like to thank the many people and institutions who made this work possible, in particular Sveinn Jakobsson, Gunnar Thorbergsson, John Norrman, Ólafur Ólafsson, David Toll, and the Land Survey Department of the North East London Polytechnic, who kindly lent us the surveying equipment. Mr. G.R. Oates, BP International Ltd., Amerada Hess Ltd., University College, Durham, St. Mary's College, Durham, and Roedean School (SA) kindly made financial contributions to the project.

References:

Bannister, A. and S. Raymond, 1984: Surveying, 5th ed. Longman, 510 pp.

Bott, M.H.P., 1968: GRAVN, Unpublished computer program. University of Durham.

Björnsson, S., (Ed.) 1967: Iceland and mid-ocean ridges. Report of a symposium, Soc. Sci. Islandica, 38.

Dobrin, M.B. and C.H. Savit, 1988: Introduction to geophysical prospecting, 4th ed. McGraw-Hill, 867 pp.

Einarsson, T., 1954: A survey of gravity in Iceland. Soc. Sci. Islandica, 30, 22 pp.

Jakobsson, S.P., 1968: The geology and petrography of the Westmann Islands, Surtsey Res. Progr. Rep. IV, pp. 16.

Jakobsson, S.P., A.K. Pederson, J.G. Ronsbo, L. Melchio and G. Larson, 1973: Petrology of mugearite-hawiite: Early extrusives in the 1973 Heimaey eruption, Iceland. Lithos, 6, 203–14.

Jakobsson, S.P. and J.G. Moore, 1982: The Surtsey research drilling project of 1979. Surtsey Res. Progr. Rep. IX, 76–93.

Hammer, S., 1939: Terrain corrections for gravimeter stations. Geophysics, 4, 184–194.

Moore, J.G., 1982: Tidal and levelling measurements on Surtsey, July–August 1979. Surtsey Res. Progr. Rep. IX, 98–101.

Sjómaelingar Íslands, 1985: Bathymetric map SV-146.

Tryggvason, E., 1972: Precision levelling in Surtsey. Surtsey Res. Progr. Rep. VI, 158–162.