P-03-42

Forsmark site investigation

Regional gravity survey in the Forsmark area, 2002 and 2003

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April 2003

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Contents

1 Introduction

This document reports the data gained in the project *PLU Forsmark – Gravimetri* carried out according to activity plan AP PF 400-02-26 (SKB internal controlling document). A regional gravity survey has been carried out in the Forsmark area during the autumn 2002 and the winter 2003 (Figure 1-1).

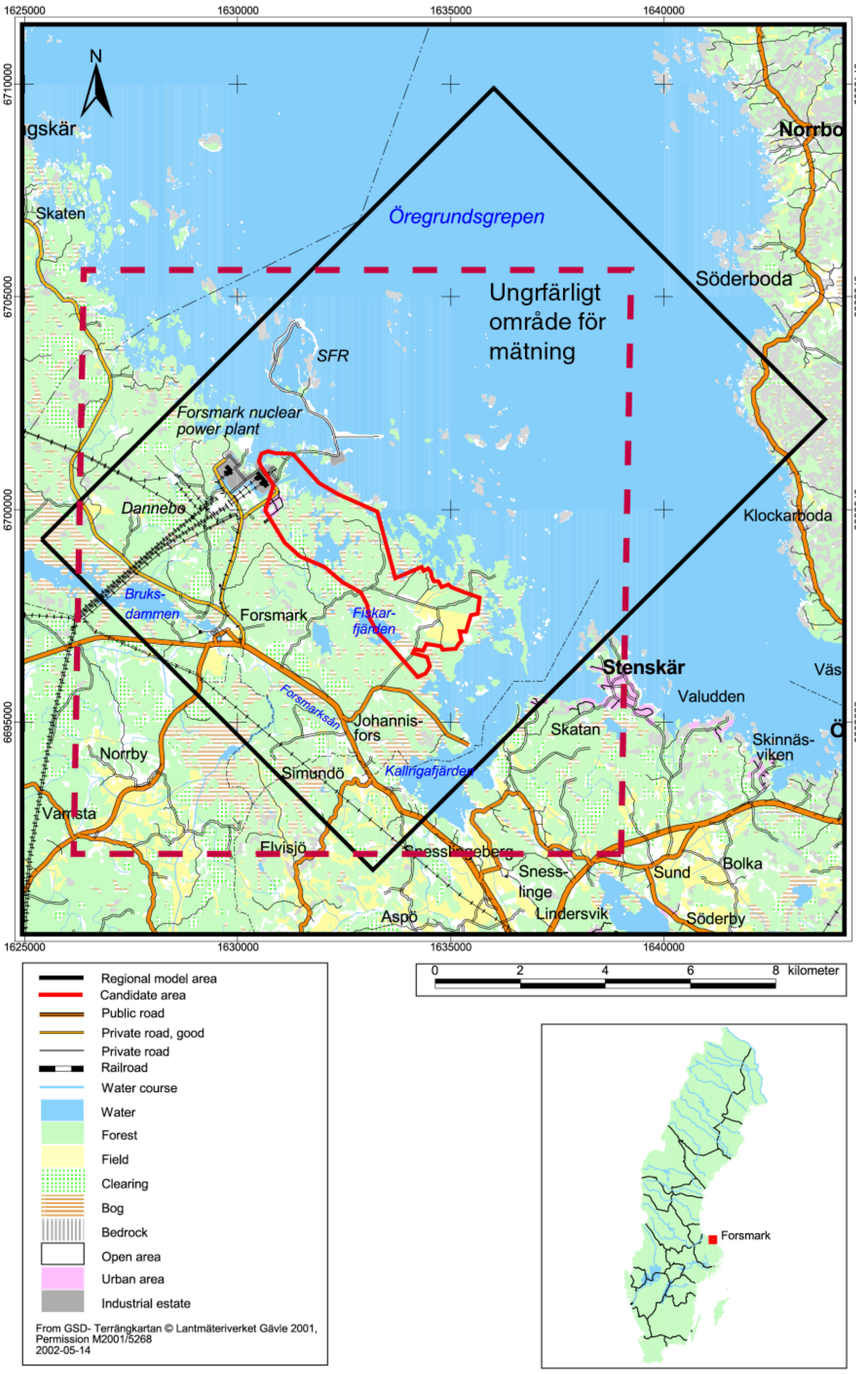

Figure 1-1. *Map over the Forsmark area. The dashed red line marks the investigated area.*

During the autumn, measurements were made at 243 stations, in sea areas and along available roads, and during the winter at 98 stations, mostly on ice and in forest areas. The gravity measurements were made during three periods. In early September, most of the sea areas were measured. During late October, measurements were carried out in a restricted area in the bay Kallrigafjärden and along roads on the mainland. Minor control measurements of station elevations were made in early December. The measurements in the winter period were concentrated to two areas in the strait Öresundsgrepen, near to the mainland, and to some minor areas on the mainland. The gravity survey includes parts of the topographic map-sheets 12I Östhammar and 13I Österlövsta.

Earlier measurements in the area, with a point-distance around 2 km, have been made by the Geological Survey of Sweden (SGU), predominantly during 1999, and by the National Land Survey of Sweden (LMV).

2 Objective and scope

Measurements of the acceleration due to the earth's gravity field provide an insight into bedrock structures beneath the surface. The gravity effects which depend on latitude, elevation, topography and earth tides are normally removed, leaving the effect due to the mass of rock bodies, i.e. the density distribution in the crust and mantle. By determining the densities of the constituent rocks, the size, shape and orientation of the different rock units can possibly be revealed.

The best interpretation results will be provided by an integration of gravity with magnetics and other geophysical data, together with petrophysics and bedrock information. To reduce gravity data to the so-called Bouguer anomaly, knowledge of the elevation, or orthometric height, of the gravity station is of crucial importance. This means that the orthometric height of each station must be determined with high accuracy. The Bouguer anomaly of an area describes the mass-distribution mainly in the crust. Locally, the anomaly is negative over, for instance, granitic rocks, due to their low density, and positive over more dense rocks, such as gabbro.

The scope was to make measurements during the autumn 2002 at totally 238 stations (Figure 2-1a); 145 stations along roads, 90 at islets and along the coast and at three stations in forest areas. The aim was to have, where possible, a station distance of 0.5 to 0.8 km along the roads and in sea areas. For the additional measurements – in the winter period 2003 – 98 stations were planned (Figure 2-1b); 18 stations along roads, 61 mostly on ice in sea and coastal areas and 19 in forest areas. These additional measurements were planned for a station distance down to 0.3 km.

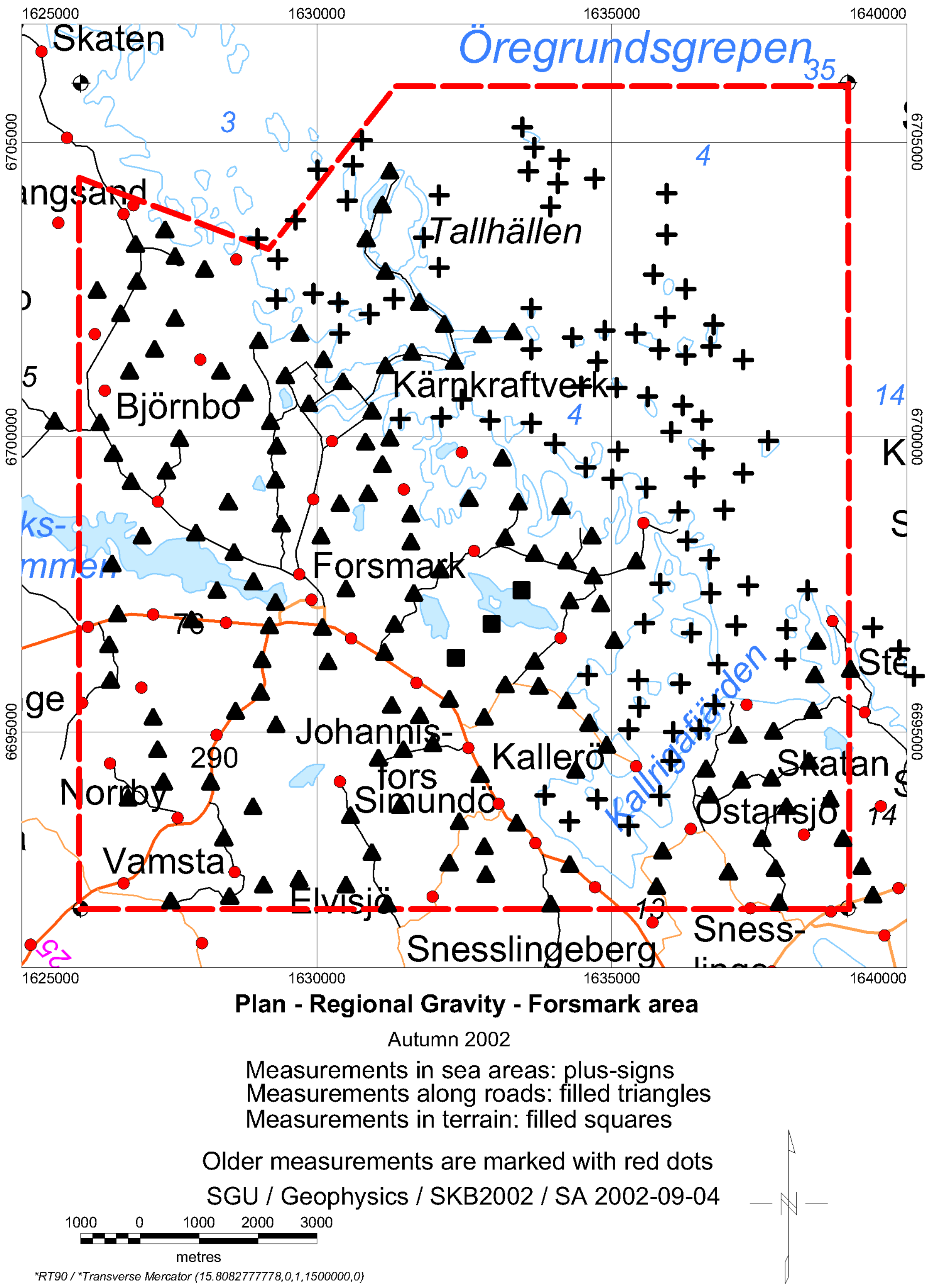

Figure 2-1a. *Plan for the gravity survey in the Forsmark area, autumn 2002.*

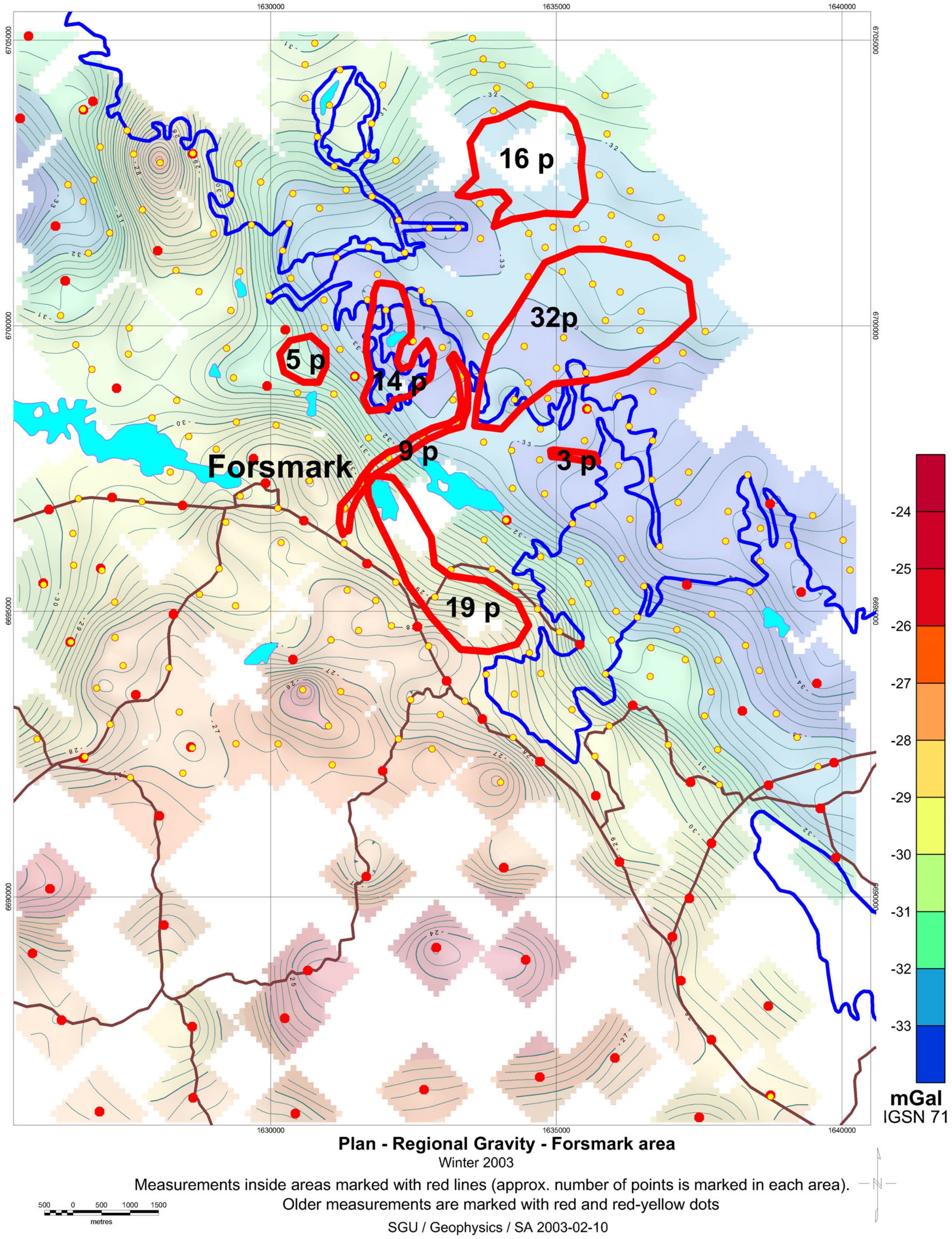

Figure 2-1b. Plan for the gravity survey in the Forsmark area, winter 2003.

3 Equipment

3.1 Description of equipment

The gravity measurements were carried out using LaCoste & Romberg land gravity meters (G-788 and G-1059), see Figure 3-1. Height determinations were made using two GPS-receivers, one reference station and one rover (Figure 3-2), as well as a stationary barometer and two altimeters. The GPS-equipment, Trimble 4700, makes use of dual frequency receivers, which allows correction of ionospheric disturbances. The method for fast-static surveying and post processing has been applied. The plane co-ordinates, x and y, have been determined with a small GPS-receiver (handhold for absolute positioning) and/or with the Trimble 4700 equipment. For the measurements on ice, the depth of the sea was determined with an echo sounder. The equipment used is described in /Aaro, 2001/.

Figure 3-1. *Measurements with LaCoste & Romberg land gravity meter.*

Figure 3-2. *High precision GPS-system used by SGU. The receiver with the antenna on the tripod is used as the reference station and the receiver in the car as a rover. The antenna for the rover is situated on the roof of the car.*

4 Execution

The gravity survey started September 2, 2002 in the sea areas (Figure 4-1a), where 74 stations were measured. In the restricted bay Kallrigafjärden, measurements at 18 stations were carried out during rather cold weather-conditions in the end of October. This provided totally 92 stations in sea areas, two more than planned.

Measurements during autumn 2002 along available roads were made during two short periods in connection with the sea measurements. Totally, 151 stations were measured including re-measurements of ten older stations; five stations less than planned. Some stations were omitted because of inaccessible roads. The planned measurements in forest areas were excluded in the autumn due to practical problems. Some of these stations were measured during the winter period, 2003. During the winter period (Figure 4-1b), measurements were carried out according to plan.

For the gravity measurements, three local base-points (UPP18501, UPP39601 and UPP39602) were established close to and inside the investigated area. UPP18501 (Figure 4-2a) was used during the autumn and the others (Figures 4-2b and 4-2c) during the winter period. All local base-points were connected to system RG 82 (Rikets tyngdkraftssystem 1982) at Östhammar, point Östhammar A /Haller and Ekman, 1988/. The system RG 82 is still not completely connected to the older system, RG 62, which is equal to the European Calibration System 1962 (ECS 62). All older measurements are based on the RG 62 system /Pettersson, 1967/. SGU recalculates all g-values adopted from the network based on RG82 to the older system, using the term 14.60 mGal.

Figure 4-1a. *Gravity measurements on an islet in the strait Öregrundsgrepen.*

Figure 4-1b. *Gravity measurements on ice in the strait Öresundsgrepen. The ice thickness was approximately 40 cm. This is sufficient for good quality measurements during calm days.*

Figure 4-2a. *The local base-point UPP18501, Lill Vamsta, on map-sheet 12I Östhammar. The base-point is connected to RG82 using point "Östhammar A" with the g-value 981908.210 mGal /Haller and Ekman, 1988/. Two connections were made giving very small difference in the g-value, below 0.01 mGal.*
The base-point UPP18501 has the following parameters:
x/y (RT90): 6692764 m / 1625910 m
H (RH70): 19.13 m
g-value (RG 82): 981 911.63 mGal
g-value (ECS 62): 981 926.23 mGal

Figure 4-2b. *The local base-point UPP39601, 1 km south of the reactors 1 and 2 at Forsmark. Map-sheet 12I Östhammar. The base-point is connected to RG82 using point "Östhammar A" with the g-value 981908.210 mGal /Haller and Ekman, 1988/. Two connections were made with the gravity meter in damped mode. The difference in the g-value was 0.04 mGal.*
The base-point UPP19601 has the following parameters:

x/y (RT90): 6699888 m / 1630696 m
H (RH70): 5.30 m
g-value (RG 82): 981 915.75 mGal
g-value (ECS 62): 981 930.35 mGal

Figure 4-2c. *Local base-point UPP39602, in the south-eastern part of the nature reserve Kallriga-fjärden. Map-sheet 12I Östhammar. The base-point is connected to RG82 using point "Östhammar A" with the g-value 981908.210 mGal /Haller and Ekman, 1988/. Two connections were made with the gravity meter in damped mode. The difference in the g-value was 0.03 mGal. This base-point was mostly used for the measurements on ice inside and north-east of the reserve.*
The base-point UPP19602 has the following parameters:

x/y (RT90): 6698697 m / 1634272 m
H (RH70): 1.80 m
g-value (RG 82): 981 915.07 mGal
g-value (ECS 62): 981 929.67 mGal

For the high precision GPS, three different sites (internal id number 0605, 0606 and 8505) for the reference station were used. Sites 0605 and 0606 were used during the period 020905–020906 and 030225–030303, respectively, at Stora Asphällan (6701428/1632344 and 6701393/1632351). Site 8505 was used during the period 021028–021031 and 030213–030214, at Norrby (6693463/1627553). The sites 0605 and 0606 are almost at the same place, the former used during the autumn period and the latter during the winter period. The reason for entirely different places is to avoid too long baselines, i.e. distances between reference station and rover. For most of the gravity stations, baselines are less than 10 km with a maximum of 12 km. The elevations for the reference-stations were taken from benchmarks with heights in system RH70, established by the National Land Survey of Sweden (LMV). All heights derived from the GPS- measurements were corrected using a LMV geoid-model with corrections for land uplift, SWEN98L. The geoid-model SWEN98 is referred to in /Ekman, 1998/. Due to poor satellite configuration during some short periods, control measurements were carried out after the preliminary compilation of data, which according to barometric data showed some errors in the station heights (see Figure 4-3).

The sea level height was checked every morning and evening during the period of sea measurements. The height of the sea was levelled from benchmark Igelgrundet, LMV number 138 RA 0602. During the winter period, the height of the ice-surface was measured with high-precision GPS and also checked against sea-level data from the SMHI. The highest sea/ice level was 0.0 metre (020905) and lowest –0.4 metre (0302226).

The gravity survey has followed the method description for gravity measurements ("Metodbeskrivning för Gravimetri", SKB MD 212.003). Se also /Aaro, 2001/.

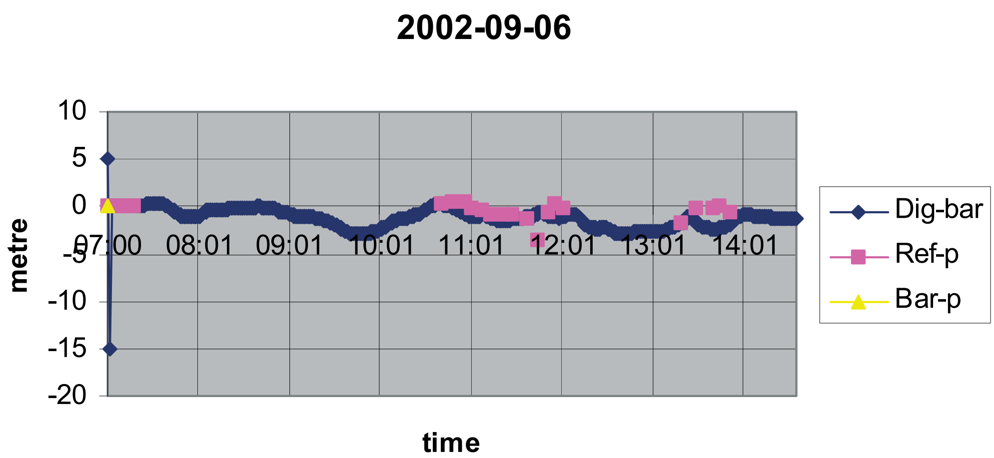

Figure 4-3. *Compiled barometer data together with, in this case, height determinations obtained by high precision GPS. The blue line is the registration, each 10 sec, from the stationary barometer. The red dots represent the recalculated GPS and altimeter heights. One point measured 11.44 deviates considerably from the other points. This point has low GPS-quality and the control measurement indicated an elevation error greater than 2 m.*

4.1 Preparations

In order to check the instrument, drift gravity readings were taken at some of the base-points every morning and evening during the periods of measurement. The drift of the gravity meters was below 0.2 mGal, except for two days when the drift was a little bit higher, up to 0.5 mGal. For regional measurements, these drift-values are acceptable.

4.2 Execution of tests measurements

During the measurements along roads in the investigated area, some of the older measurements were re-measured. In most cases, the difference in Bouguer anomaly value was around 0.1 mGal. The highest difference was 0.4 mGal, which was due to an error in height. The point was measured 1999 and the height was determined with altimeters.

The control measurements of station elevations indicate very small divergences, standard deviation 0.1 metre, for GPS-measured points which were not clearly observed as outliers in the barometric data. The latter station elevations have been corrected. The control measurements include totally 18 stations.

4.3 Data handling

The treatment of data has followed the normal routines used by SGU /Aaro, 2001/. One exception is the handling of negative station-heights. For points in the sea area with negative heights, the gravity reading was recalculated in such a way that it was possible to give the station a zero height. Otherwise, the adapted computer system does not function.

The steps are as follows:

1. Compilation of GPS-data during the field measurements, using GPSurvey 2.35 (Trimble software).
2. Digitising of protocols.
3. Calculation of position for the GPS-reference-stations using SWEPOS data. This calculation gives the geographical co-ordinates as well as the ellipsoidal heights of the reference station. The height from the levelling is, from experience, better than the calculated height and is, in this case, adapted.
4. Calculation of the co-ordinates for the gravity stations. This calculation is based on the results of clause 2.
5. Calculation of heights using altimeter data.
6. Compilation of data from the stationary barometer together with GPS- and altimeter data (one example of a diagram used can be seen in Figure 4-3).
7. Calculation of the g-value for the base-points.

8. Calculation of the g-value, Bouguer anomaly etc of each gravity station.

9. Calculation of terrain correction using 500 m x 500 m DTM and 50 m x 50 m DTM. The primary data file is now related to the European Calibration System 1962 (ECS 62). The file used for the Oasis-software is recalculated to IGSN 71, which is almost identical with RG 82.

10. Data analyses with Oasis-software.

5 Results and data delivery

The resulting data files in the GRAVIA-format and in a format adapted for Oasis-software as well as for SICADA have been delivered to SKB. The gravity data in the former file is in ECS 62 and in the two latter in IGSN 71 (RG82). The Bouguer anomaly value for each point is terrain-corrected using 50 m x 50 m DTM.

The format-description with comments is presented in Appendix 1. For the two other delivered files, the format is described in the head of each file.

The SICADA reference to the activity presented in this report is Field note Forsmark 37.

A Bouguer anomaly map over the investigated area can be seen in Figure 5-1.

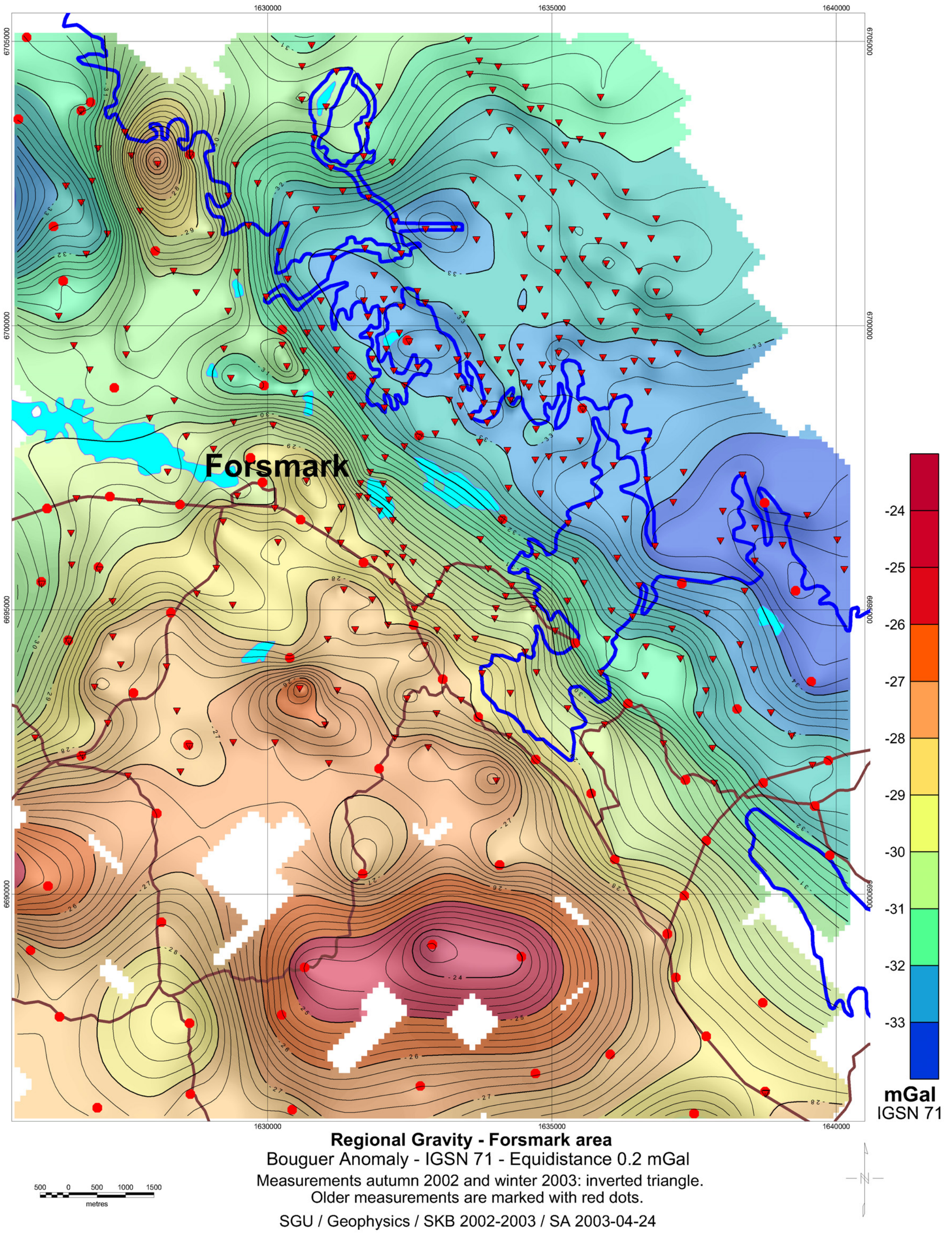

Figure 5-1. *The Bouguer anomaly map over the investigated area. The map is based on all available gravity points. All measurements are terrain-corrected using a 50 m x 50 m digital terrain model (DTM) from the National Land Survey of Sweden (LMV).*

6 References

Aaro S, 2001. Kvalitetshandbok – Geologisk informationsproduktion – Tyngdkraftskartläggning, SGU.

Ekman M, 1998. Jordellipsoider, geoider, koordinatsystem, höjdsystem och tyngdkraftssystem i Sverige genom tiderna. Lantmäteriet 1998:4.

Haller L Å, Ekman M, 1988. The fundamental gravity network of Sweden. Lantmäteriet 1988:16.

Pettersson L, 1967. The Swedish first order gravity network. Rikets allmänna kartverk. Meddelande nr A 35.

Appendix 1

The GRAVIA-format

001–008	point ID	a8
009–011	mapsheet	a3
012–013	measurement-year	i2
014–015	month	i2
016–017	day	i2
018–019	98 if base point, else ‘null’	a2
020–027	theoretical g-value – 980000 (mGal)	f8.3
028–029	normally 98, else ‘B ‘ if there is a ‘B ‘ the g-value has been calculated using the Bouguer anomaly and the orthometric height.	a2
030–037	g-value – 980000 (mGal)	f8.3
038–043	tidal correction (mGal)	f6.3
044–049	water depth (m) for sea/lake point	f6.1
050–054	terrain correction (mGal)	f5.2
055–055	normally ‘null’, else ‘C’ If there is a ‘C” the g-value has been corrected because of round-off problems.	a1
056–063	free-air anomaly (mGal)	f8.3
064–071	Bouguer anomaly (mGal)	f8.3
072–073	latitude (deg)	i2
074–078	latitude (min)	f5.2
079–080	longitude (deg)	i2
081–085	longitude (min)	f5.2
086–092	x-coordinate in the Swedish system (RT38/90) approx N-S	i7
093–099	y-coordinate in the Swedish system (RT38/90) approx E-W	i7
100–106	orthometric/normal height (m)	f7.2
107–107	quality parameter for orthometric/normal height	a1
108–108	quality parameter for gravity reading	i1
109–109	quality parameter for coordinates	i1
110–111	comments	a2
112–114	podheight (cm)	i3
115–121	discrepancy between measured and interpolated heights (only for points corrected with 50 m x 50 m DTM)	f7.2
122–126	terrain correction from 0 to 3.52 km (only for points corrected with 50 m x 50 m DTM)	f5.2

Comments to the GRAVIA-format

point ID:	If the first four characters are;		
	LMV.:	Point owned	by the National Land Survey of Sweden.
	LUTH:	-”-	by the Luleå. University of Technology
	numerical (map 23K):	-”-	by the Boliden Company.
	ZNGR:	-”-	by the Zinkgruvan
	MINB:	-”-	by the Univ of Uppsala
	FJF :	-”-	by the Univ of Uppsala
	etc.		
	If character seven and eight are;		
	01, 02, 03 or 04		Point is used as a base-point

theoretical g-value: Formula 1930.

g-value: European Calibration System 1962 (ECS62)

terrain correction: Spherical correction using density 2670 SI.
0–20 km: 500 m x 500 m DTM (LMV-data).
If 50 m x 50 m DTM used then
0–3.52 km 50 m x 50 m DTM
3,52–20 km 500 m x 500 m DTM
20km–166.7 km: 5’ x 10’ grid (c. 9 km x 9 km)

Bouguer anomaly: ECS62 and formula 1930. Bouguer density 2670 SI.
Spherical Bouguer correction since 1971.
Transformation from ECS62/1930 to IGSN71/1980:
IGSN71=ECS62–14.6–(–16.3+13.7(sin(latitude))**2) mGal

latitude/longitude: Bessel 1841.
Since there are only two decimals the precision in N-S is c. 20 m and in E-W c. 10 m. Normally the errors in x- and y-coordinates are larger (see below). After May 2000, when the Selective Availability (SA) was removed, the absolute positioning with GPS became better than 10 m.

quality/height:	1:	± 0.05 m	Benchmark or levelling with good control.
	2:	± 0.2 m	Height point or levelled lake-surface.
	3:	± 3 m	Height curve or lake-surface.
	5:	± 0.2 m	Levelling from benchmark, with some control.
	6:	± 0.2 m	Levelling from height point, with some control.

	7:	± 3 m	Levelling from height curve to height curve.
	8:	± 2 m	1995–. Height determined with field-barometer(s). Control against reference-points and height curves.
	8:	± 2 m	1998–. Height determined with field-barometer(s). Strategic reference-points and control against a stationary barometer. Disturbed weather conditions.
	B:	± 1 m	1998–. Height determined with field-barometers. Strategic reference-points and control against a stationary barometer. Good weather conditions.
	9:	± 0.2 m (67%)	Height determined with static GPS.
	p:	± 0.2 m (95%)	Height determined with static GPS.
	q:	± 0.5 m (95%)	Height determined with static GPS.
	r:	± 1.5 m (95%)	Height determined with static GPS.
	D:	± 0.5 meter	Uncorrected sea level.
	H:	± 0.1 m	Corrected sea level.
quality/g-det.	1:	± 0.04 mGal	Good reading.
	2:	± 0.1 mGal	Bad reading due to traffic, seismic activity etc.
	3:	± 0.04 mGal	Damped gravity meter. Good reading.
	4:	± 0.5 mGal	Damped gravity meter. Bad reading.
quality/coord.	0:	± 100 m	1993–. Map scale 1 : 100 000.
	1:	± 10 m	Map-scale 1 : 10 000.
	2:	± 20 m	Map-scale 1 : 20 000.
	5:	± 50 m	Map-scale 1 : 50 000.
	7:	± 200 m	Map-scale larger than 1 : 100 000.
	9:	± 100 m	–1992. Map scale 1 : 100 000.
	9:	± 70 m	1995–. Absolute GPS.
	9:	± 10 m	2000-05-02–. Absolute GPS.
	d:	± 3 m	Static GPS. The relatively seen large error is due to the displacement between the GPS-antenna and the gravity meter.