Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

ELEVATION AND GRAVITY CHANGES AT GEOTHEMAL FIELDS ON THE REYKJANES PENINSULA, SW ICELAND

Hjalmar Eysteinsson
Orkustofnun, Grensasvegi 9, 108 Reykjavik, Iceland

Keywords: Elevation, gravity, geothermal

ABSTRACT

On the outer part of the Reykjanes Peninsula in SW Iceland are three high temperature geothermal fields, Svartsengi, Eldvorp and Reykjanes. These have been monitored with precise elevation and gravity measurements since 1976. In Svartsengi a power plant has been in operation since 1975 with an annual 8 Mt (10^9 kg) production. The Eldvorp geothermal field west of Svartsengi has not been utilised, and is connected to the Svartsengi field. The third field is on the tip on the Reykjanes Peninsula where the Mid-Atlantic Ridge comes onshore. A geothermal field with minor productivity but great potential.

At Svartsengi, land has subsided over an area of 100 km^2, which is much more extensive than the borefield, where the subsidence is highest, i.e. 237 mm from 1976 to 1999. This corresponds to 10 mm/year. Subsidence rate was highest right after the exploitation started in Svartsengi in 1975 or 14 mm/year, but decreased to 7 mm/year during the time period from 1987 to 1992. From 1992 to 1999 the subsidence rate has increased again to 14 mm/year. The subsidence bowl in Svartsengi has a NNA-SSW direction, extending to the Eldvorp geothermal field where the subsidence has been 4-10 mm/year. At the Reykjanes geothermal field the subsidence rate has been around 6 mm/year since 1986. The subsidence at Svartsengi varies linearly with observed pressure decrease as observed at 900 meter depth in boreholes, indicating that the subsidence is mainly due to compaction of pores space in the rock matrix.

Gravity measurements on the outer part of the Reykjanes Peninsula show little changes. Those measurements have mainly been focused around the Svartsengi field, where the average maximum gravity reduction, after corrections for subsidence, is 5 µgal/year. Calculations using Gauss law for the integrated gravity change indicates that the geothermal field in Svartsengi has 70% natural recharge

1. INTRODUCTION

The purpose of monitoring elevation and gravity changes in geothermal fields is to observe the environmental effects caused by utilisation. When geothermal fluid is drawn out of the geothermal reservoir the effect is decreasing pressure, which due to compression of rock matrix causes land subsidence. If the fluid is not recharged at the same rate as is drawn out of the reservoir, it causes gravity decrease due to loss of mass. Thus measurements of elevation and gravity changes with time give valuable information on the changes that occur in the reservoir during exploitation. They also yield information on the lateral extension of the geothermal reservoir.

Elevation and gravity monitoring is applied on all the utilised high temperature areas in Iceland. Apart from the Reykjanes area the others are the Hengill field in SW Iceland, where a powerplant has been in operation at Nesjavellir since 1990. The third area is Krafla in north Iceland were a powerplant has been in operation since 1976. Out of those the Svartsengi geothermal field is the only one which has shown considerable changes in elevation and gravity, due to exploitation. In the other two areas, the main changes are due to natural changes related to magma inflow to the crust and related tectonics. The mean maximum subsidence rate in Svartsengi is 10 mm/year and the gravity reduction (corrected for elevation changes) is 5 µgal/year. Compared to other areas in the world those are not high values. Allis and Hunt (1986) reported subsidence rate at Wairakei geothermal field, New Zeeland, up to 450 mm/year and up to 11 m total subsidence, and maximum gravity reduction of 80 µgal/year. In Cerro Prieto geothermal field, Mexico, Glowacka (1999) reported subsidence rate up to 126 mm/year, with the average of 100 mm/year during the last two decades. In the Bulalo geothermal field, Philippines, Andres and Pedersen (1993) reported reduced gravity up to 26 µgal/year. Mossop and Segall (1997) reported 48 mm/year subsidence at the Geyers field in California, USA, with a total of 1.09 meters subsidence since 1973. In recent years the surface deformation of geothermal fields have been monitored by spaceborne interferometric synthetic aperture radar (SAR). Vadon and Sigmundsson (1997) found by SAR techniques that the maximum subsidence rate in Svartsengi is about 20 mm/year from 1992 to 1995 which is comparable to the ground geodetic surveys between 1992 and 1999. Massonnet et al. (1997) found from SAR technique a subsidence rate of 19 mm/year in the East Mesa geothermal field, in south California USA, which is very much comparable to the land observation of 18 mm/year.

The three geothermal fields on the outer part of the Reykjanes Peninsula are shown on Fig. 1 along with the location of benchmarks and boreholes. The powerplant at Svartsengi started operation in 1976, and is now producing 125 MW_{th} and 45 MW_e for 16.000 persons in nearby communities. The productive area, as delineated by 7 productive wells, is within 1 km^2. The average mass flow rate in 1998 was 226 kg/s, whereof 28 k/s is reinjected into the reservoir. The steam fraction is 32% at 5.5 bar separation pressure (see Fig. 2). One deep drillhole is located in Eldvorp but it is not being utilised. Eldvorp and Svartsengi are related, if not the same geothermal field. Several drillholes are in the Reykjanes geothermal field with minor production, however there is a great potential for utilising geothermal energy there.

2. SUBSIDENCE

Some 220 bench marks (Fig. 1) have been used in the outer part of the Reykjanes Peninsula for motoring subsidence after production started in Svartsengi in 1976 (Eysteinsson 1993, Thorbergssson and Vigfusson 1999). Out of them 190 have been levelled more then once. There have been 10 levelling surveys from 1975 to 1999 (see Table 1). Not every benchmark was measured in each survey. The initial strategy was to measure some part of the network every year or so. This led to difficulties in comparing the result from one survey to another and since 1992 the strategy has been to measure the whole network in each survey but with longer time between surveys. Due to construction work in the area some benchmarks have been destroyed, and new roads have led to new benchmarks with easier accessibility than older closeby benchmarks which are therefore not longer in use. The reference point in all the levelling surveys (except in 1986) is the northernmost point on the SE-NW profile, some 8.6 km NW from Svartsengi powerplant. In 1999 57 points where selected for GPS survey, evenly distributed around the survey area. Out of those about 15 new points where selected along a new survey line (Njarðvik-Hafnir-Reykjanes, see Fig. 1). It is necessary to measure both with GPS and conventional levelling survey once at the same time in order to get continuity with time for subsidence. This is because the levelling method measures height above see level (i.e. the geoid), while the GPS method measures height above a ellipsoidal surface.

The maximum subsidence measured during 1975-1999 is at a point just north of Svartsengi borefield, or 237 mm from 1976 to 1999 (Fig. 3). This averages to 10 mm/year. Since different parts of the survey area have been measured each year (see Table 1) it is practical to use the subsidence rate in mm/year rather then total subsidence between surveying periods. Fig. 4 shows mean subsidence rate along two profiles (NS and EW) crossing the geothermal field in Svartsengi (i.e. at 0 km on the figure), for 4 different time intervals. For the first time period (1975-1982), the maximum subsidence rate after the exploitation of the powerplant started, was 14 mm/year, with the maximum located right at the middle of the borefield. The maximum subsidence in the following 10 years (1982-1987 and 1985-1992) reduced to 7-8 mm/year, with its maximum again within the borefield. From 1992 to 1999 the subsidence rate has increased again to 14 mm/year and the subsidence maximum has moved further to west and south, outside the borefield. This change in subsidence rate with time is shown on the four maps in Fig. 5. After six years from the start of utilisation of the powerplant, a well developed subsidence bowl has formed with the centre at the borefield. After that, i.e. between 1982 and 1987, an E-W elongated subsidence ellipse is formed, with the maximum subsidence within borefield in Svartsengi, and another just east of the Eldvorp geothermal field (1982-1987). Note the increased elevation at numerous points around the main subsidence area, especially close to the town of Grindavik. This might indicate that the levelling reference point is really subsiding as well. In the next time frame (1985-1992) the centre of the subsidence ellipse has moved about 1 km west of the main borefield. During this time interval an increased subsidence is seen on the Reykjanes geothermal field. During the last time interval presented on Fig. 5, the maximum subsidence (14 mm/year) has moved about 1.5 km west of the borefield. The reason for this westerly shift of the maximum subsidence location, away from the main borefield, is not known, but probably shows that the main upflow zone of geothermal water is just west of the main borefield. This is in agreement with newly drilled borhole located between Svartsengi and Eldvorp (was drilled as a injection hole, see Fig. 1) and is a few degrees hotter then other drillholes in the area (but with similar pressure).

From the subsidence bowl in Fig. 5 it is possible to calculate the volume change due to subsidence. Table 2 shows the calculated volume change per year, for each time interval on Fig. 5. In the calculations we have restricted the volume calculations within 8.6 km radius from the borefield (i.e. distance to the reference point). The integrated volume change due to subsidence, from 1976 to 1999 is about 0.02 km^3. Assuming density of 820 kg/m^3 of the geothermal water, the cumulative mass withdrawal from the reservoir from 1976 to 1999 is 0.19 km^3 (see Fig. 2), or an order of magnitude higher then the total calculated volume change due to subsidence. This must mean that at least 10% of the geothermal water used is not being recharged into the geothermal system, that is assuming all subsidence to be due to the utilisation in Svartsengi.

The Reykjanes geothermal field has been surveyed 4 times, but not all the points where levelled each time. Therefore there is a limited number of data points from that area. Fig. 6 shows the subsidence at a point in the centre part of the Reykjanes geothermal field. The maximum subsidence rate is about 6 mm/year and has been more or less constant since 1986.

Fig. 7 shows that there is a strong linear relation between subsidence (at a benchmark within the borefield in Svartsengi) and the pressure at 900 meters depth, as measured in drillholes. From 1976 to 1992 the subsidence is 67mm/MPa, but between 1992 and 1999 it is 175 mm/MPa. Assuming that the subsidence is due to closing and compaction of pore space in the rock matrix, the figure shows that the strength of the pores within the rock matrix is linearly related to the fluid pressure.

3. GRAVITY CHANGES

The gravity field in Svartsengi has been monitored since 1976 (Johnsen 1983, Eysteinsson 1993). Just like in the levelling surveys, the whole area was not measured at the same time (except for the last two surveying periods) but rather, parts of the area were surveyed at different times. Out of a total of 227 benchmarks ever measured in the area, between 30 and 190 benchmarks were measured in each of the 11 surveys. Table 3 lists the number of measured points in each survey as well as short descriptions on survey location. The gravity reference point prior to 1986 is a point at Keflavik Airport (now lost), but since 1986 it has been a point in Reykjavik. Both those points are in the ISGN71/V85 reference system (Thorbergsson et al. 1993). The point in Reykjavik has proven to be stable by ties to an other point in Reykjavik which has been measured with absolute gravimetry twice since 1985 (Torge et al. 1992, Eysteinsson 1998). In each survey every point is usually measured twice (back and forth), except for the first two surveys (1976 and 1979) when each point was usually measured once.

In each survey a local reference point is tied to main base point by 1-3 ties. Other points are then tied to this local reference point. The data is corrected for tidal variations (using tidal coefficient found from gravity time series measured in Reykjavik, (Eysteinsson unpublished data)),

height of the gravity meter from the benchmark, and daily drift of the meter. For points measured more than once, it is possible to estimate the error as the maximum variation from it's mean after all corrections. In Table 3 we give the mean and maximum error for each survey. This error is generally 5-25 μgal, thus the estimated error for each point is twice or 10-50 μgal (i.e. error at each point plus error of local reference point).
Fig. 3 shows the measured and free air corrected gravity due to subsidence (0.308 mgal/meter) at a point close to the power plant in Svartsengi. The fluctuation of the gravity is largely due to error in measurements. The corrected gravity shows a gravity reduction of about 60 μgal over 23 years or less then 3 μgal/year. The general trend is that the gravity is decreasing, at least until 1992. From 1992 to 1999 there is some gravity increase, or 30 μgal on the average. This increase is just marginally within error bars and there is a considerable scatter Due to the little variation in gravity with time (maximum difference at a point is 125 μgal), compared to the error in the measurements, it is not worth while comparing the gravity variation from one survey to another. Instead we take the average time variation (i.e. the gradient) at those points measured in the 1999 survey and have also been measured at least in two earlier surveys. This makes total of 59 points. The result is shown on Fig. 8. The maximum gravity reduction is 5 μgal/year, located about 1 km west of the powerplant, at the same place as the maximum subsidence. No gravity change is seen at the Reykjanes geothermal field. Some considerable gravity reduction was seen in the area close to the Eldvorp geothermal field in the 1992 survey. Those points where not measured in the 1999 survey and are therefore not presented on Fig. 8.

It is possible to estimate the total mass change in the geothermal reservoir at Svartsengi due to the gravity changes, by applying Gauss law which becomes:

$$\Delta m = (\tfrac{1}{2}\pi G) \oint \Delta g \, ds \qquad (1)$$

where G is the gravitational constant ($6.67 \cdot 10^{-11}$ Nm^2/kg^2), Δg is the gravity change (m/s^2) in a surface area ds (Hammer 1945). Applying this formula to the mean annual gravity change in Fig. 8, and restricting the area to 5 km radius around the borefield (78 km^2) gives 2.6 Mt/year. Comparing this value to the annual production of about 8 Mt (Fig. 2) means that there is about 70% annual recharge of the geothermal system in Svartsengi.

4. DISCUSSION AND CONCLUSION

The main subsidence on the outer part of the Reykjanes Peninsula is at Svartsengi. The centre of maximum subsidence was initially in the borefield and the subsidence was 14 mm/year (from 1976-1982). Between 1982 and 1992 the maximum subsidence was 6-8 mm/year and it's centre has moved about one km to the west of the main borefield. Between 1992 and 1999 the subsidence increased again to 14 mm/year and the centre of the maximum is now about 1.5 km west of the borefield in Svartsengi. The reason for this increasing subsidence is not known, but there is evidence from SAR measurements (Vadon and Sigmundsson 1997) that it has mainly occurred during a short time in 1992 and 1993. According to their findings the average subsidence rate between 1992 and 1993 was 25 mm/year, and 9 mm/year between 1993 and 1995 which is much more comparable to the levelling data between 1982 and 1992. It is expected that in the near future, the SAR measurements, along with GPS measurements at limited number of bench marks, will succeed conventional elevation measurements. This will reduce the high cost of ground geodetic measurements.
The subsidence bowl around the Svartsengi field is connected to the Eldvorp geothermal field. That, along with the fact that those two geothermal systems are pressure related (Bjornsson and Steingrimsson 1991), suggest that the two fields have a common origin. This is further confirmed by a resistivity survey in the area (Karlsdottir 1998). The subsidence at Reykjanes has been steady since 1986 with a maximum of 6 mm/year. The total integrated subsidence volume around Svartsengi is 10% of the total volume of fluid subtracted from the reservoir. Although the fluid production for the power plant at Svartsengi has been explained as the cause of the subsidence, another possible source could be a reduced pressure in a solidifying magma chamber within the crust beneath Svartsengi (Vadon and Sigmundsson, 1997).

The gravity changes on the outer part of the Reykjanes peninsula are small and mainly limited to the Svartsengi and Eldvorp geothermal areas. The maximum reduction in gravity is located at the same place as maximum subsidence where it is around 5 μgal/year. The integrated gravity reduction is equivalent to 2.4 Mt/year mass loss in the area. This is about 30% of the total mass drawn out of the geothermal field. No gravity change is observed at the Reykjanes geothermal field.

The subsidence at Svartsengi is greater than has been observed in other utilised geothermal fields in Iceland. At Nesjavellir (SW Iceland) small subsidence has been observed over a limited area around the power plant at the rate of 5 mm/year, but recent observations show that the land is rising, probably due to natural tectonic processes in the area. No gravity changes have been observed in the area that could be related to the exploitation of the geothermal field. In Krafla geothermal field (north Iceland) there have been large elevation and gravity changes over the last 25 years due to the volcanic eruption period from 1975 to 1985. In this area land has lifted over 3 meters and in limited area there has been subsidence of over 1 meter. Since 1989, when land lifting reached the peak, and to 1995, land has subsided up to 250 mm. During this period a subsidence bowl is observed around the borefield in Krafla which corresponds to 30 mm/year subsidence, a part of that is probably related to utilisation of that field. Observed gravity changes in Krafla field are only related to tectonics during the eruption period.

.

5. REFERENCES

Andres, R. B. S and J. R. Pedersen (1993). Monitoring the Bulalo geothermal reservoir, Philippines, using precision gravity data. *Geothermics,* 22, 5/6, 395-402.

Allis, R.G and T.H. Hunt (1986). Analysis of exploitation-induced gravity changes at Waiakei Geothermal Field. *Geophysics*, 51, 8, 1647-1660.

Bjornsson, G. and B. Steinngrimsson (1991). *Temperature and pressure in the Svartsengi geothermal system*. Report 91016, National Energy Authority, Reykjavik Iceland.

Eysteinsson , H. (1993). *Levelling and gravity measurements in the outer part of the Reykjanes Peninsula 1992*. Report OS-93029/JHD-08, National Energy Authority, Reykjavik Iceland.

Eysteinsson, H. (1998). *Gravity values at base stations in Reykjavik*. Report HE-98/02-08, National Energy Authority, Reykjavik Iceland.

Glowacka, E. (1999). Surface deformation in the area of Cerro Prieto (B.C., Mexico) ant it relationship with seismicity, local tectonics and fluid extraction. *Geothermia, Rev. Mex. De Geoenergia*. 15, 1, 39-46.

Hammer, S. (1945). Estimating ore masses in gravity prospecting. *Geophysics*. 10. 50-62.

Johnsen, G. V. (1983). *Gravity measurements in the Svartsengi area*. Report OS-83083/JHD-15, National Energy Authority, Reykjavik Iceland.

Karlsdottir, Ragna (1998). *TEM resistivity survey in Svartsengi, 1997*. Report OS-98025, National Energy Authority, Reykjavik Iceland, 43p.

Massonnett, D., T. Holzer and H. Vadon (1997). Land subsidence caused by the East Mesa geothermal field, California, observed using SAR interferometry. *Geophys. Res. Letters*, 24, 8, 901-904.

Mossop, A. and P. and Segall (1997). Subsidence at the Geysers geothermal field, N. California from comparison of GPS and levelling surveys. *Geophys. Res. Letters*, 24, 14, 1839-1842.

Torge, W., R. Grote, R. H. Roder, M. Schnüll and H.-G. Wenzel (1992). *Introduction of absolute gravimetric techniques into a high-precision gravity and vertical control system in northern Iceland*. Deutsche Geodätische Kommission, B, Nr. 297, ISBN 3 7696 8581 4.

Vadon, H. and F. Sigmundsson (1997). Crustal deformation from 1992 to 1995 at the Mid-Atlantic Ridge, southwest Iceland, mapped by Satellite Radar Interferometry. *Science,* 275, 193-197.

Thorbergsson, G., I. Th. Magnusson and G. Palmason (1993). *Gravity data and a gravity map of Iceland*. Report OS-93027/JHD-07, National Energy Authority, Reykjavik Iceland.

Thorbergssson, G. and G. H. Vigfusson (1999). Levelling- and GPS measurements in the outer part of the Reykjanes Peninsula 1999. Report OS-99065, National Energy Authority, Reykjavik Iceland.

Table 1. Elevation surveys on the outer part of the Reykjanes Peninsula

Year of survey	Number of points	Survey lines
1975	12	Gr-Sv.
1976	19	Sv.-Nj
1979	45	El-Sv.-SvE.
1982	115	Gr-Sv.-Nj; Sy-El-Sv.-SvE; Sv-SvN; Hu-El-ElN
1983	104	Gr-Sv-Nj; Gr-Hu-Re
1985	100	Hu-Gr-Sv-Nj; Sv-SvN; El-Sv-SvE; Hu-El-ElN
1986	36	Hu-Re;
1987	70	Hu-Gr-Sv-Nj; Sv-SvE
1992	193	Gr-Sv-Nj; Gr-Hu-Re; Re-Sy-El-Sv-SvE; Sv-SvN; Hu-El-ElN
1999	115	Gr-Sv-Nj; Gr-Hu-Re; Re-Sy-El-Sv-SvE; Sv-SvN; Hu-El-ElN GPS: at selected points.

Gr: Grindavik; Sv: Svartsengi; SvN: along road north of Sv., SvE: East of Sv.,El: Eldvorp; ElN: North of Eldvorp, Hu: Husatoftir, Re: Reykjanes, Sy: Syrfell, Ha: Hafnir.

Table 2. Volume change due to subsidence

Time interval	**km^3/year**
1976-1982	$1.08 \cdot 10^{-3}$
1982-1987	$0.34 \cdot 10^{-3}$
1985-1992	$0.51 \cdot 10^{-3}$
1992-1999	$1.11 \cdot 10^{-3}$

Table 3. Gravity surveys on Reykjanes Peninsula

Year of survey	**Numb er of points**	**Mean/max error (μgal)**	**Survey lines**
1976	32	10/42	Gr-Sv-Nj, Sv-SvN
1977	43	6/26	Gr-SvNj, Sv-SvN
1979	47	3/11	El-Sv-SvE
1980	57	4/10	Gr-Sv-Nj, El-Sv-SvE
1981	16	?/?	Around Sv.
1982	54	5/17	Gr-Sv-Nj, Hu-El
1983	116	3/13	Gr-Sv-Nj, Hu-El-ElN, Gr-Hu-Re-El
1984	18	5/11	Around Sv.
1986	70	3/9	Hu-Re-El
1992	188	9/30	Gr-Sv-Nj, Re-El-Sv-SvN, Sv-SvN, Gr-Hu-Re, Hu-El-ElN
1999	116	6/20	Gr-Sv-Nj, Re-El-Sv, Sv-SvN, Gr-Hu-Re, SvN-ElN-Ha-Re

Gr: Grindavik; Sv: Svartsengi; SvN: along road north of Sv., SvE: East of Sv.,El: Eldvorp; ElN: North of Eldvorp, Hu: Husatoftir, Re: Reykjanes, Sy: Syrfell, Ha: Hafnir.

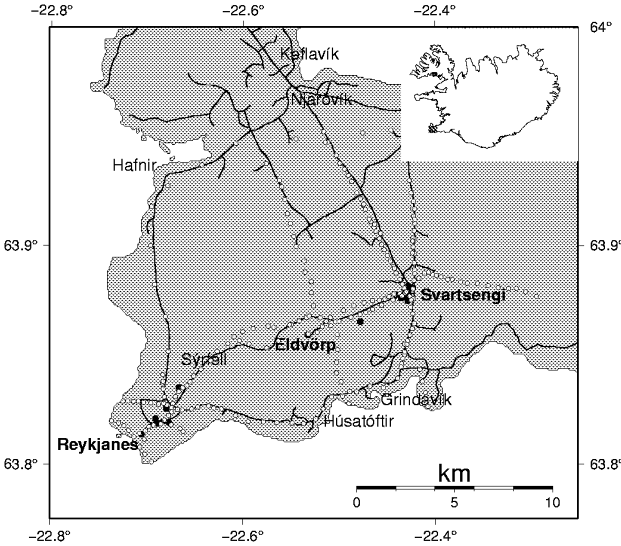

Figure 1. *Map showing the three geothermal fields on the outer part of the Reykjanes Peninsula, i.e. Svartsengi, Eldvorp and Reykjanes. Open circles show location of bench marks used for precise levelling and gravity measurements. Black dots show location of deep boreholes, and lines location of roads*

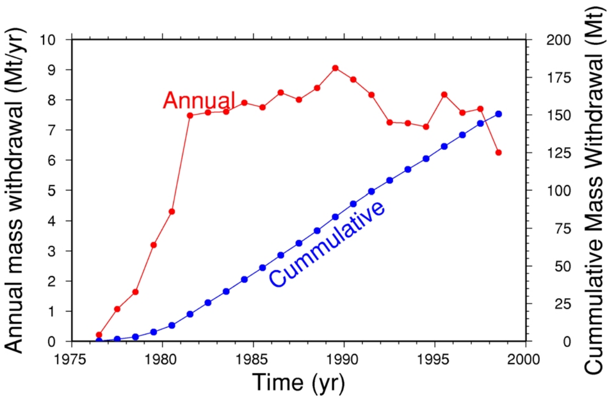

Figure 2. Annual and cumulative mass discharge from the geothermal borefield in Svartsengi

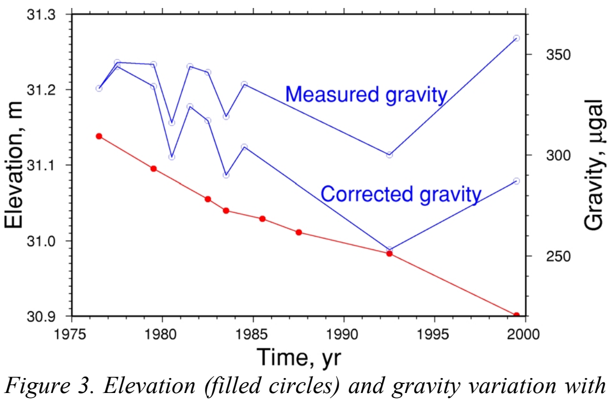

Figure 3. Elevation (filled circles) and gravity variation with time at benchmark SN-H2, located within the borefield at Svartsengi geothermal plant

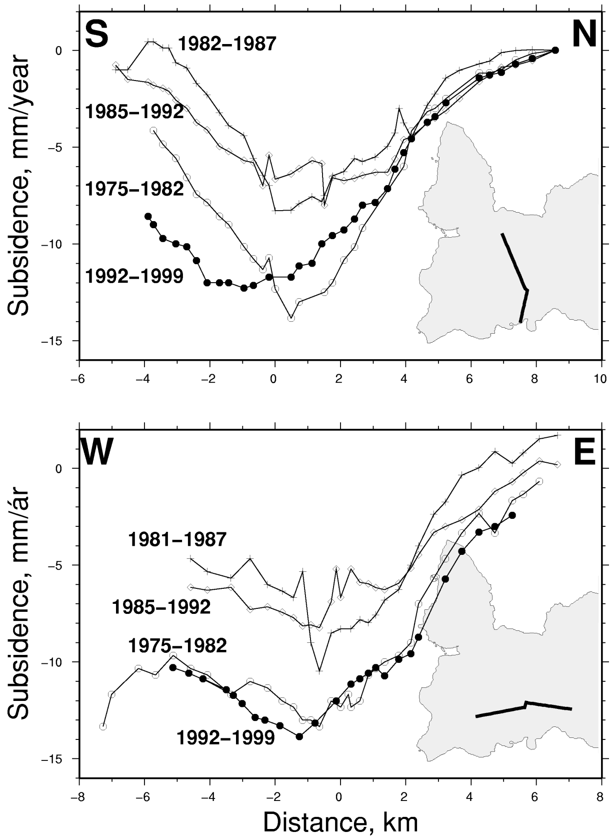

Figure. 4. Subsidence rate along NS and EW profile crossing the geothermal field at Svartsengi (at 0 km distance), for four different time intervals

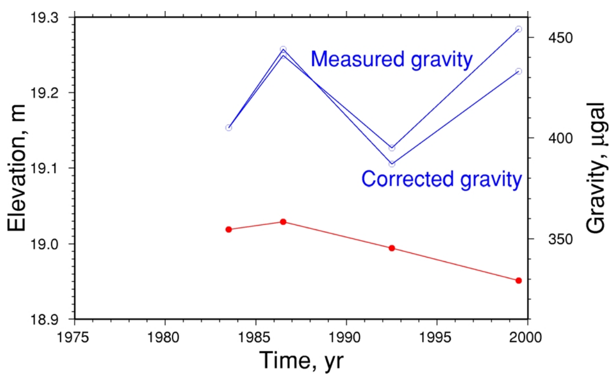

Figure 6.. Elevation (filled circles) and gravity (open circles) variation with time at benchmark RN07, located in the central part of the Reykjanes geothermal field

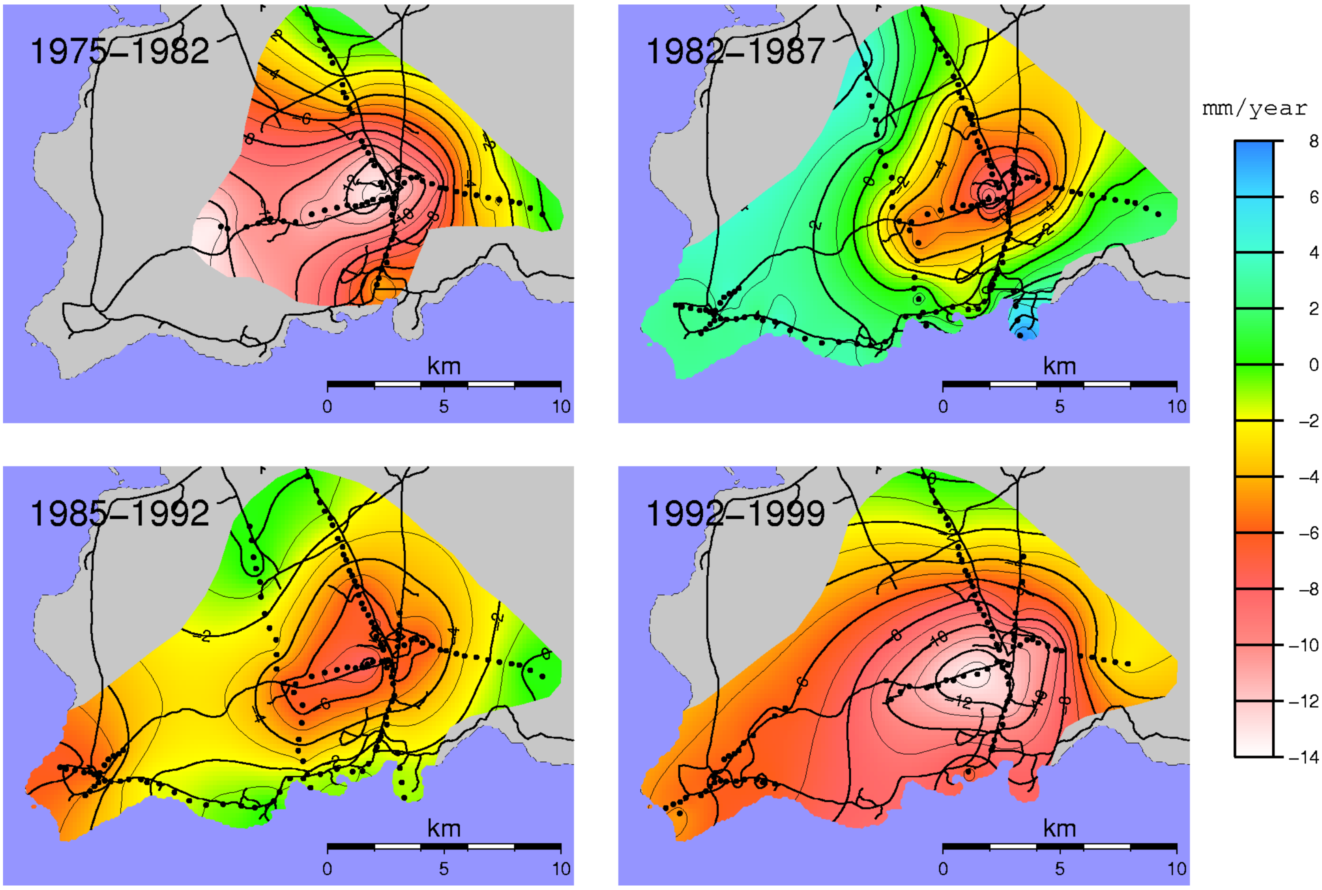

Figure 5. Subsidance rate at the outer part of the Reykjanes peninsula for four time intervals. Bench marks are shown by solid circles, roads are shown by thick lines, contour intervals are 1mm/year

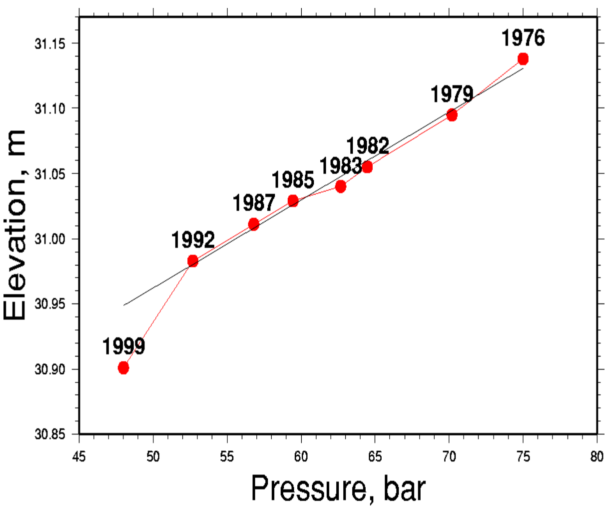

Figure 7. Elevation at a bench mark SN-H2 within the borefield at Svartsengi and pressure in boreholes at 900 meters depth within the reservoir.

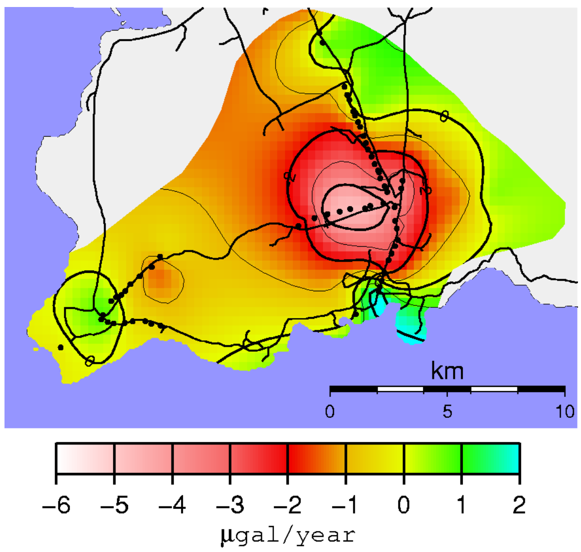

Figure 8. Mean gravity variation (μgal/year) from 1975 to 1999. Only points measured in 1999 and at least two times earlier are used.