Hæðar- og þyngdarmælingar á utanverðum Reykjanesskaga

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Ágrip
Á utanverðum Reykjanesskaga hefur allt frá 1976, verið fylgst með breytingum í hæð og þyngd á háhitasvæðunum í Svartsengi, Eldvörpum og á Reykjanestá. Í Svartsengi hefur land sigið um allt að 237 mm frá 1976 og fram til 1999. Það samsvarar 10 mm sigi á ári. Sighraðinn var mestur fyrst eftir að virkjunin þar var tekinn í notkun 1975, eða 14 mm/ári fram til 1987, þá minnkaði hann í 7 mm/ári fram til 1992. Frá 1992 og fram til 1999 jókst sigið aftur í sem samsvarar 14 mm/ári. Sigskálin í Svartsengi hefur meginstefnur í NNA-SSV og nær að Elvörpum í SSV þar sem sigið hefur verið 4-10 mm/ári. Yst á Reykjanesi hefur sigið verið um 6 mm/ári. Sigið í Svarstengi breytist línulega með þrýstingi í borholum, sem bendir til að sigið stafi fyrst og fremst af samþjöppun poruhluta bergsins. Þyngdarmælingarnar sýna litla breytingu. Þær hafa einkum verið gerðar í og umhverfis virkjanasvæðið í Svartsengi, þar sem mesta þyngdarbreytingin er um 5 µgal/ári. Út frá samanburði á þyngdarbreytingunum og massatöku svæðisins, má reikna að á Svartsengissvæðinu er náttúrlegur endunnýjanleiki jarðhitavökvans um 70% af heildar massatökunni.

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.
Svartsengi geothermal field has shown considerable changes in elevation and gravity, due to exploitation. The mean maximum subsidence rate in Svartsengi is 10 mm/year and the maximum 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.

Subsidence

Some 220 bench marks 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. 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.

The maximum subsidence measured during 1975-1999 is at a point just north of Svartsengi borefield, or 237 mm from 1976 to 1999 (Fig. 1). This averages to 10 mm/year. Since different parts of the survey area have been measured each year it is practical to use the subsidence rate in mm/year rather then total subsidence between surveying periods. Fig. 2 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. 3. 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. 3, the maximum subsidence (14 mm/year) has moved about 1.5 km west of the borefield.

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, 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.

Fig. 4 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.

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. The gravity reference point prior to 1986 is a point at Keflavik Airport, but since 1986 it has been a point in Reykjavik. 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 (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, 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. 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. 1 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. 5. 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. 5.

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:

$$\Delta m = \left(\frac{1}{2\pi G}\right) \int \Delta g \, ds$$

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. 5, 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, means that there is about 70% annual recharge of the geothermal system in Svartsengi.

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 suggest that the two fields have a common origin. This is further confirmed by a resistivity survey in the area. 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 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.

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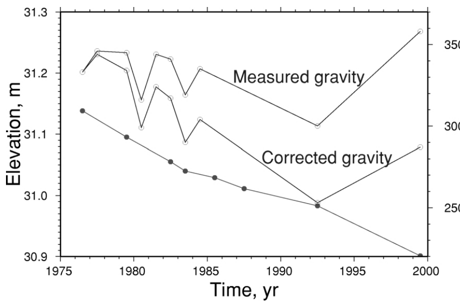

Figure 1. Elevation (filled circles) and gravity variation with time at benchmark SN-H2, located within the borefield at Svartsengi geothermal plant

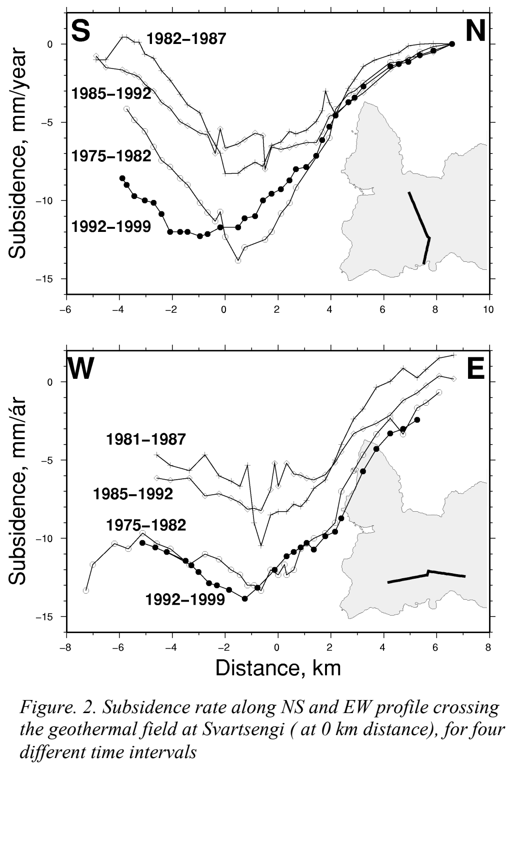

Figure. 2. Subsidence rate along NS and EW profile crossing the geothermal field at Svartsengi (at 0 km distance), for four different time intervals

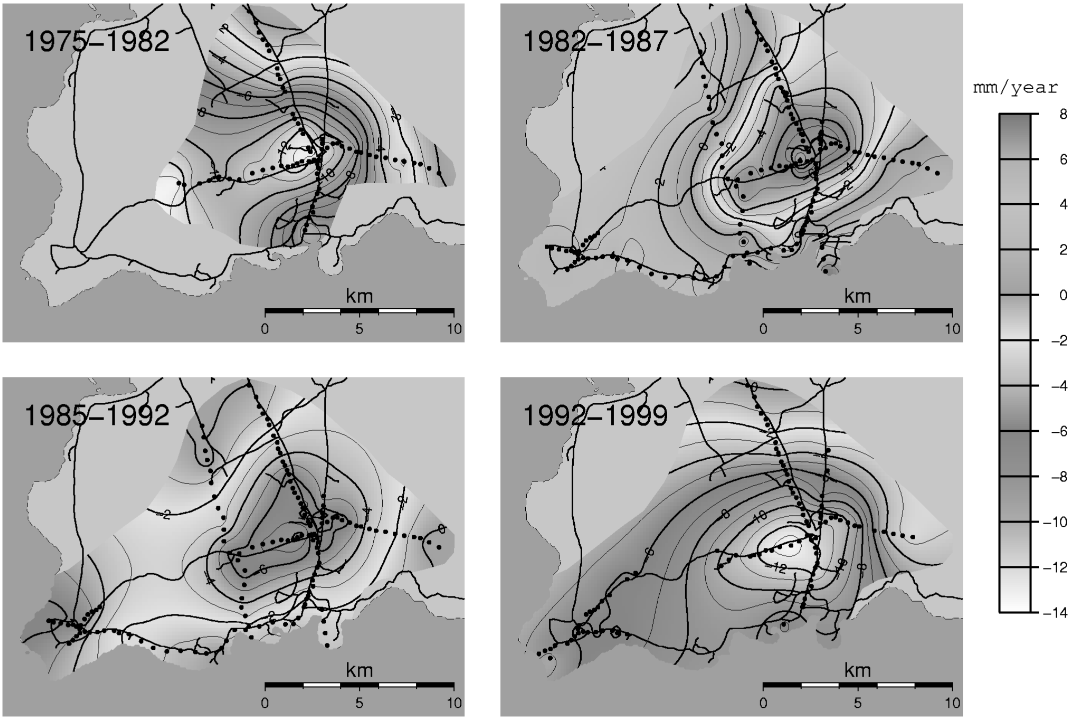

Figure 5. Subsidance rate at the outer part of the Reykjanes peninsula for four time intervals. Bench marks are shown by solid circles, roads are shown by thick lines, contour intervals are 1mm/year

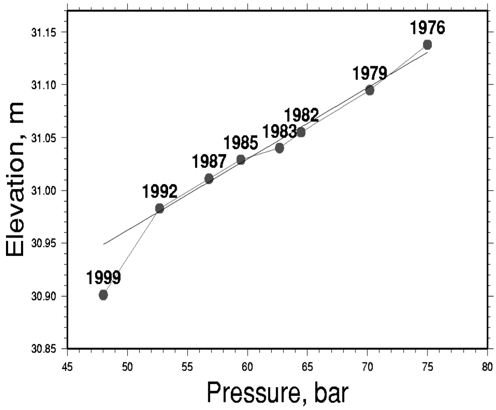

Figure 4. Elevation at a bench mark SN-H2 within the borefield at Svartsengi and pressure in boreholes at 900 meters depth within the reservoir.

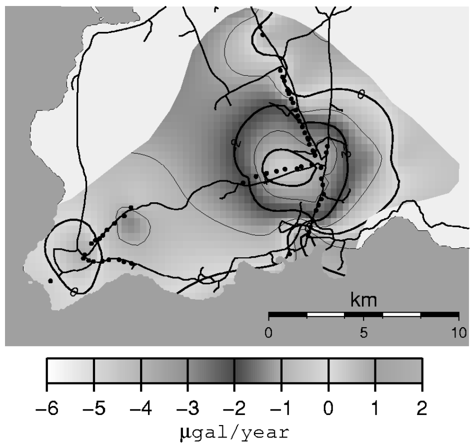

Figure 5. Mean gravity variation (µgal/year) from 1975 to 1999. Only points measured in 1999 and at least two times earlier are used.