Interpreting Ground Deformation and Microgravity Changes in the Travale-Radicondoli Geothermal Field (Italy)

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Keywords: topographic and micro-gravity monitoring; land subsidence.

ABSTRACT

Since 1973, when industrial exploitation of the Travale-Radicondoli geothermal field started, ground vertical movements have been monitored by means of precise topographic levelling. Up-to-date methods have also been applied (EDM, and GPS).

The elevation changes, detected so far are rather modest and show a regular temporal trend, so that it is possible to make a precise determination and interpretation of the subsidence that has occurred.

Right in the small central area of the field, which has been the most productive for many years, the maximum subsidence rate exceeds 1 cm per year. This can be interpreted as the result of pressure depletion related to poorly connected reservoirs located at different depths. These reservoirs have different rates of pressure stabilisation depending on their exploitation history.

Since 1979, micro-gravity changes have also been monitored by a network of permanent bases that coincide with selected topographic benchmarks used for subsidence monitoring.

The gravity changes, corrected for elevation change effects, are very small and show flat trends. This allows us to make some interesting evaluations in terms of mass balance and is encouraging as regards the sustainability of geothermal production in time.

The on-going monitoring results indicate that the effects on the environment are negligible, which should help in overcoming any resistance on the part of the local community and convince them of the benefits of geothermal development for the region.

1. INTRODUCTION

The Travale-Radicondoli geothermal field (Tuscany, Italy), as a result of its geo-tectonic characteristics and its evolution, has been considered a "test area" for studying dynamics of a geothermal reservoir. Eight different power plants have been installed, six of which are still operating, with a total installed capacity of more than 150 MWe. Besides the normal industrial activity, this area has been the subject of many surveys and has undergone a series of geophysical and geochemical measurements, well tests and reinjection experiments based on different programs and pumping rates.

A few networks for monitoring geophysical and geochemical parameters have been set up. This paper presents the results of the topographic and micro-gravity monitoring program, including an interpretation of these data within the wider context of all the field exploitation data.

For a detailed description of the design, characteristics and properties of the methods and techniques used, and for a critical review and discussion of the data, see also Marchesini et al. (2004).

Renewed exploitation of the Travale-Radicondoli geothermal field began in 1973. The repeat surveys of 2003 fall, therefore, the 30th anniversary of modern industrial activity.

Over the past 30 years a maximum subsidence of 50 cm has been measured; the initial rate being 2.3 cm/year has progressively decreased to the current 1 cm/year.

At present, the average values all over the exploited field are so small that they can only be detected over long intervals between two consecutive precise measurement surveys (3-5 years).

Since 1979, micro-gravity monitoring of the field, through the combined observation of gravity and vertical changes, has been aimed at detecting any mass or density variations, and has thus provided a great deal of information on reservoir dynamics. The results of 12 micro-gravity surveys acquired in 24 years, have shown that the relevant gravity changes were surprisingly small (20-25 μGal) and consistent with very small mass or density variations in the reservoirs.

This particular situation is quite different from the case histories of most geothermal fields, where the reported land subsidence and negative micro-gravity changes are much larger, e.g. Allis and Hunt, (1986); San Andres and Pedersen, (1993); Mossop and Segall, (1997); Tagomori et al., (1997); Glowacka et al., (1999); Bloomer et al., (2001). The only comparable case, as for our knowledge, is related to the Svartsengi geothermal field (Reykjanes peninsula, Iceland). In fact, after 23 years of exploitation, with 24 bar decrease in reservoir pressure, the maximum subsidence is around 25 cm and the micro-gravity maximum decrease of the order of 100 μGal, Eysteinsson (2000).

This information is consistent with the hypothesis that an extensive, thick storage of fluids and thermal energy is present in the Travale-Radicondoli field, connected in some way to the permeable outcrops and receiving conspicuous supplies of recharge water that largely compensate for the effects of production.

2. TOPOGRAPHIC NETWORK AND ELEVATION CHANGES

A network of precise levelling elevation benchmarks was set up for the first time in June 1973 in the Travale-Radicondoli

geothermal field to monitor any vertical topographic changes with time.

The local geothermal power-plant began operations one month later, fed by the first well, T22, which was drilled in a new site north-east of the abandoned Old field, e.g. Cataldi et al., (1970); Burgassi et al., (1975).
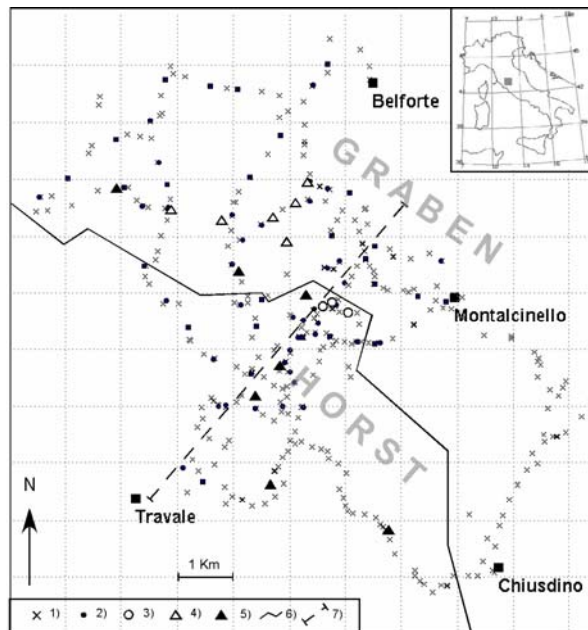

Figure 1: Location of the elevation and micro-gravity networks in the Travale-Radicondoli geothermal field (present status). 1) Topographic benchmark; 2) micro-gravity base; 3) well producing from the Horst reservoir; 4) well producing from the Graben reservoir; 5) well producing from the Deep reservoir; 6) main fault system; 7) profile of section shown in Figure 2.

During the first 5 years, the levelling network covered only the small area spanned by the profile shown in Figure 1, from the Travale carbonate outcrops, across the Old field and the fault system on the south-west border of the Radicondoli Graben (see Figure 2-A).

Since then the topographic network has been progressively widened following the expansion in the geothermal development in to the area between Travale and Belforte; it now covers an area of about 80 km^2 with more than 300 benchmarks; 70% of the levelling lines running along rough country roads, steeply sloping lanes, through woods and thick vegetation.

During the 30 year period, 1973-2003, the network was measured by 18 different levelling surveys. Also GPS (Global Position System) and EDM (Electronic Distance Measurement) methods were applied in 5 surveys, adding further information, e.g. Beinat et al., (1995); Marchesini et al., (2004).

The reference benchmark is sited on metamorphic outcrops, about 15 km north-east of the geothermal area (Palazzo al Piano). The place is unaffected by anthropogenic noise or other disturbances and is considered stable over the entire 30 year period.

Statistical analysis of the results showed that, taking into account instrumental characteristics, local topographic difficulties, seasonal variability of temperature, water content and geo-mechanical characteristics of the ground soils, the detected elevation changes between two different surveys, with respect to an external reference benchmark, have a rms (*root mean square* error) ranging between ±3 and ±6 mm, e.g. Geri et al., (1982, 1984).
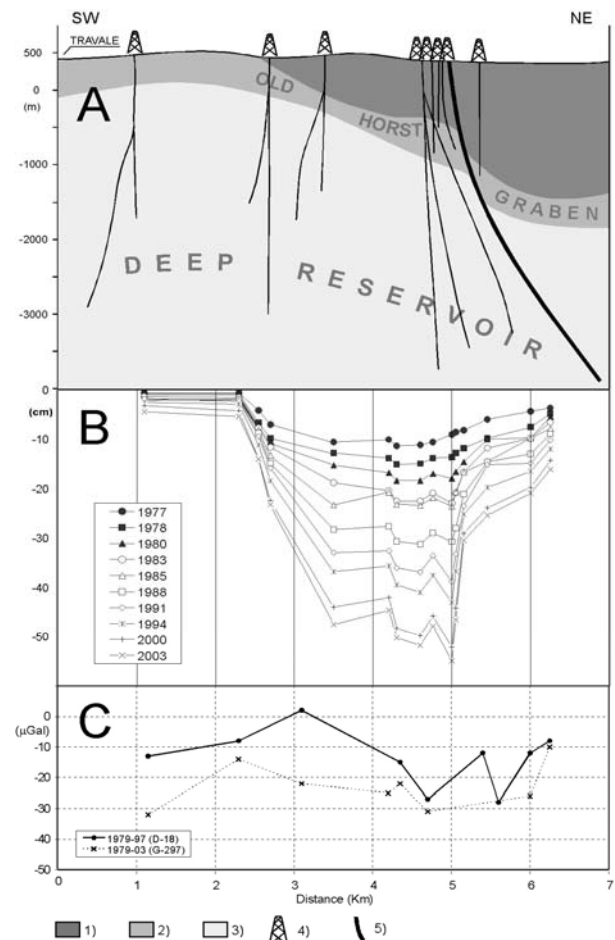

Figure 2: Geological cross section showing the location of the geothermal reservoirs called Old, Horst, Graben and Deep reservoir (A); the elevation changes that have occurred along the profile since 1973 (B); and the micro-gravity changes that have occurred since 1979 (C). 1) Cap rock, 2) carbonate formations; 3) metamorphic basement formations; 4) currently productive well; 5) main fault system.

The maps in Figure 3 were compiled by integrating all the subsidence data acquired during the 18 levelling surveys. The subsidence contours are quite regular and uniformly spaced, and seem to be unaffected by the characteristics of the benchmarks (type of monument, foundation soil, etc.).

As already noted in the previous studies, e.g. Di Filippo et al., (1985); Geri et al., (1984), subsidence rate was higher in the initial period than in subsequent years, yet the levelling network, during the first 5 years, did not cover the area that showed the highest subsidence rate with time. This is also evident in Figure 4, which shows the vertical change with time of a group of benchmarks, relative to their elevation in 1973.

The subsidence trend during the first 10-15 years, depicts a roughly elliptical depression whose longest axis trends NE-SW.
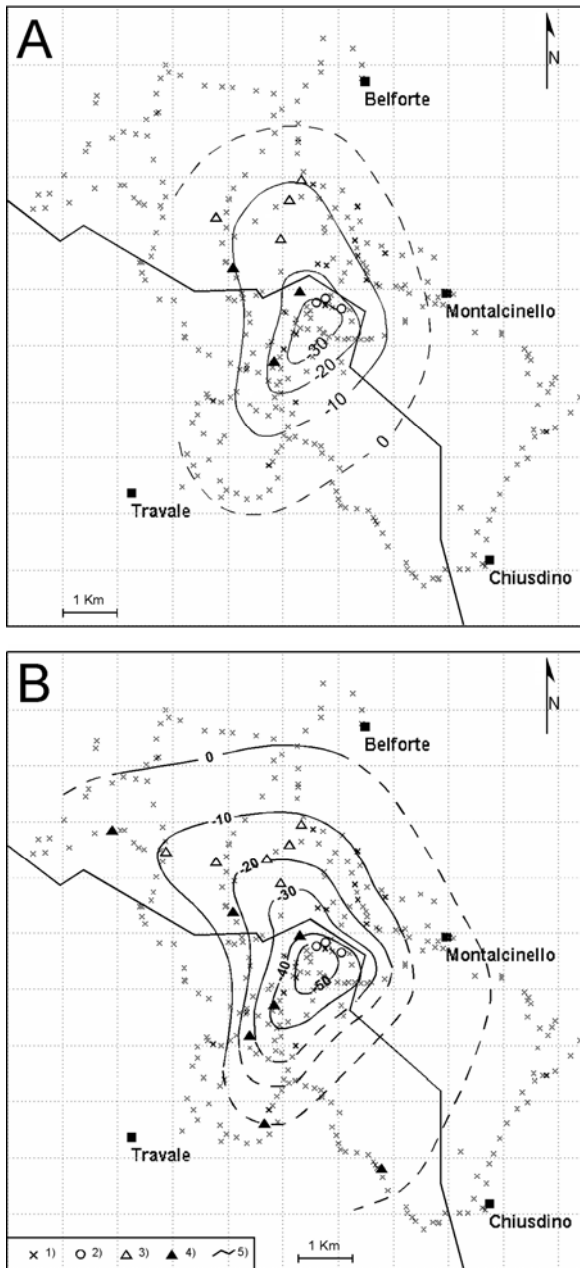
Figure 3: Contour of total elevation changes (cm) that occurred during the first 15 year period 1973-1988 (A); complete 30 year period 1973-2003 (B). 1) Topographic benchmark; 2) well producing from the Horst reservoir; 3) well producing from the Graben reservoir; 4) well producing from the Deep reservoir; 5) main fault system.

Later on, after production began in new Graben areas, another subsidence develops, trending NW-SE. The resulting depression of the entire 30 year period sums up both effects.

This trend can be correlated with the history of the exploitation of the geothermal field, and also with the geological- structural elements that gave origin to the field.

The most important factor seems to be the main fracture and fault systems that opened preferential permeability lines, as revealed by previous surveys, e.g. Celati et al., (1973); Batini et al., (1978); Brogi et al., (2003).

Indeed, the location, shape and intensity of the subsided terrains are good fits of the most productive areas, proportionally to their exploitation rates. The topographic changes in particular highlight the contribution to fluid production, over the last few decades from the fractured and permeable rock formations of the reservoirs at various depths (see Figures 2 and 3).

3. MICROGRAVITY MONITORING AND RESIDUAL GRAVITY CHANGES

In 1979 a permanent micro-gravity network was established in the Travale-Radicondoli geothermal field designed to obtain a robust and accurate net. At the beginning it consisted of 32 bases, utilized also for the levelling purposes. Since 1997, following the development of new exploited areas, the bases number has been raised to 60.

The siting of reliable reference points was of particular concern: 3 remote bases were therefore set up, some 15 to 20 km from the geothermal field, located in geologically stable sites, and unaffected by anthropogenic disturbances.

One of them (Palazzo al Piano) was selected to set up an absolute gravity base, to solve ambiguities on gravity reference data; e.g. Geri et al. (1982). In 1980 the selected site was connected to the topographic network by a line of precise levelling, and the gravity base was measured with an absolute gravity meter in 1981 and 1985: the difference in the gravity values falls in the range of the rms.

The 3 remote bases were tied to 4 bases of the main network to strengthen the grid. Furthermore, in order to avoid that scale factor changes might be interpreted as gravity changes induced by the geothermal exploitation, a calibration line, e.g. Di Filippo et al., (1992), was set up in the Apuane Alps (NW Tuscany), where the reading range was the same of the Travale-Radicondoli area. The scale factor's variations proved to be negligible (maximum 2 parts in 10000, that means 2 μGal every 10000 μGal, with 1 μGal=10^{-8}m s^{-2}), anyway inside the observational error.

During the 24 year period, 1979-2003, the network was measured by 12 annual microgravity campaigns.

The gravity bases were measured simultaneously by two meters, the L&R D-018 and the L&R G-297. The data acquisition followed always the same observation sequence that involved the measurement of at least three gravity differences between two consecutive bases providing also the detection of the instrumental drifts during the field work. To reduce the error propagation the number of stations belonging to each circuit was set in 5 to 7 stations only.

To minimise the effect of irregularities in the dial gear system the L&R D-018 has been reset as accurately as possible so that the identical reading range has been used in the network's resurveying.

The mathematical model and the software used in the network analysis and adjustment are the same used in IGSN71 adjustment, e.g. Morelli et al., (1974), so that each pair of consecutive gravity readings defines a gravity tie that corresponds to a weighted observation equation:

$$g_i - g_j - k_m \Delta g_{ij} - d_m \Delta T_{ij} = \varepsilon_{ij} \qquad (1)$$

where g_i and g_j are the unknown gravity values, k_m is the unknown scale factor for the mth set of observations, Δg_{ij} is the measured gravity difference, d_m is the unknown drift term for the mth set of observations, ΔT_{ij} is the interval time

between the ith and j^{th} measurement, ε_{ij} is the observational error.

The complete system of gravity equations is solved by least squares and the final solution is approached iteratively while holding one station fixed. The average rms of the adjusted gravity values for L&R-D018 was ±3 μGal and ±8 μGal for the L&R-G297: it means that gravity variations of 9 and 24 μGal, respectively, have a confidence level of 99.7 %.

Being interested in changes of mass distribution beneath the surface in terms of gravity residual, the subsidence effect in the gravity observations has been removed by means of a free-air reduction to the November 1979 station elevation. Five sites, in and around the geothermal field, have been selected for the measurement of the local value of the vertical gravity gradient: the average value obtained was 326.2 ±3 μGal/m.

Data on gravity and elevation changes generally allow us to remove the gravity effect of differential subsidence, of regional tectonics unrelated to geothermal activity, or both. The residual gravity variations should be interpreted mainly in terms of fluid mass displacements, compaction of porous rocks, density changes in the fluid content of the reservoir due to temperature or pressure variations, etc.

As already pointed out and discussed in previous papers, e.g. Di Filippo et al., (1985, 1995); Geri et al., (1984), the detected gravity residual changes are very small, just up to the confidence level, and they are also scattered by surface geo-hydrological conditions, largely varying with time, season, etc. during the field works and between different surveys. Notwithstanding, thanks to the accuracy in the measurements, some characteristic residual Δg features can be pointed out. In particular the Figures 2 C and 5 B show, in the area of maximum subsidence, the slight decreasing trend with time of about 15-20 μGal in 20 years, and minor oscillations with period shorter than 10 years.

In Figure 4 one of the most reliable surface distribution of the Δg corrected for the elevation changes, obtained by the data of the L&R D-018, for the 18 year period, 1997-1979, is shown. A rather clear 20-25 μGal negative minimum, crossing the Horst-Graben area, in NS direction, is evident.

5. INTERPRETATION

The main elements dealing with subsidence and microgravity changes are synthesized in Figure 5. The upper part A of Figure 5 shows the three distinct trends versus time of total production flow rates (steam and gas) and reservoir pressure for the Horst, Graben and Deep reservoirs (production from Deep reservoir has been split in N and S). The Deep reservoir pressure curve is represented with a dashed line, because it is not very well defined yet.

In Figure 5-B shows the main results of the altimetric and micro-gravimetric monitoring. In particular, the average trend of elevation and corrected gravity changes (L&R D-18 and L&R G-297 meters) measured in the zone of maximum subsidence (Horst), are plotted vs. time. The individual experimental values of the gravity data are also indicated, showing the noisy scattering effect.

In 30 years a maximum subsidence of 50 cm was measured, with an initial rate of 2.3 cm/year which progressively decreased to the current 1 cm/year. The latter value is very

small specially taking into account that the total production increased from 60 to 240 kg/s in the meanwhile.

Subsidence phenomena prevalently relate to geothermal exploitation according to the following well-known cause-effect relationship: fluid extraction → reservoir pressure decline → reservoir rock contraction → transfer on surface of this contraction. Therefore, the reservoir pressure trend should be correlated with the subsidence rates.
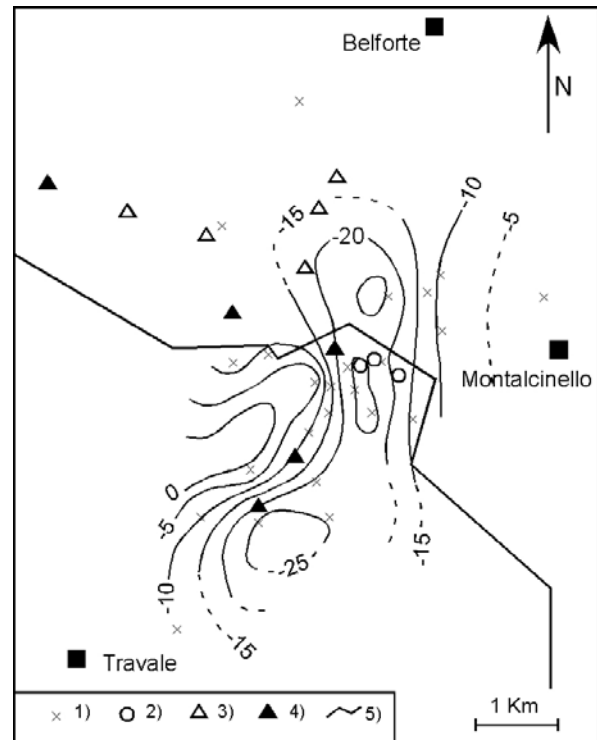

Figure 4: Corrected gravity changes contour lines (μGal), in the 1979-1997 period (L&R D-018 meter) 1) Micro-gravity base; 2) well productive from the Horst reservoir; 3) well productive from the Graben reservoir; 4) well productive from Deep reservoir; 5) main fault system.

This is not so evident by an hasty analysis of Figure 5. In fact, the curve of the Horst reservoir pressure shows a strong initial drop of about 4 MPa in the first 5 years, followed by 25 years of stable trend, while subsidence rates appear more regular in the whole period. The explanation can be found taking into account the complexity of the Travale-Radicondoli geothermal system, made up by adjacent and/or overlapping reservoirs, poorly or not hydraulically connected and with different exploitation histories, e.g. Barelli et al., (1995). The subsidence in a given area would thus result from the cumulative effects induced by pressure declines occurred in different times and zones, within distinct reservoirs. Hence in the first 80's the subsidence in the Horst zone did not show a stabilization, as expected looking at the pressure trend. This did not happen because in the same time the exploitation of the adjacent Graben reservoir began, resulting in a new contribution to the land subsidence. Later on, in the 90's the contribution of the Deep reservoir exploitation was added, first in the northern part of the field, then in the southern one.
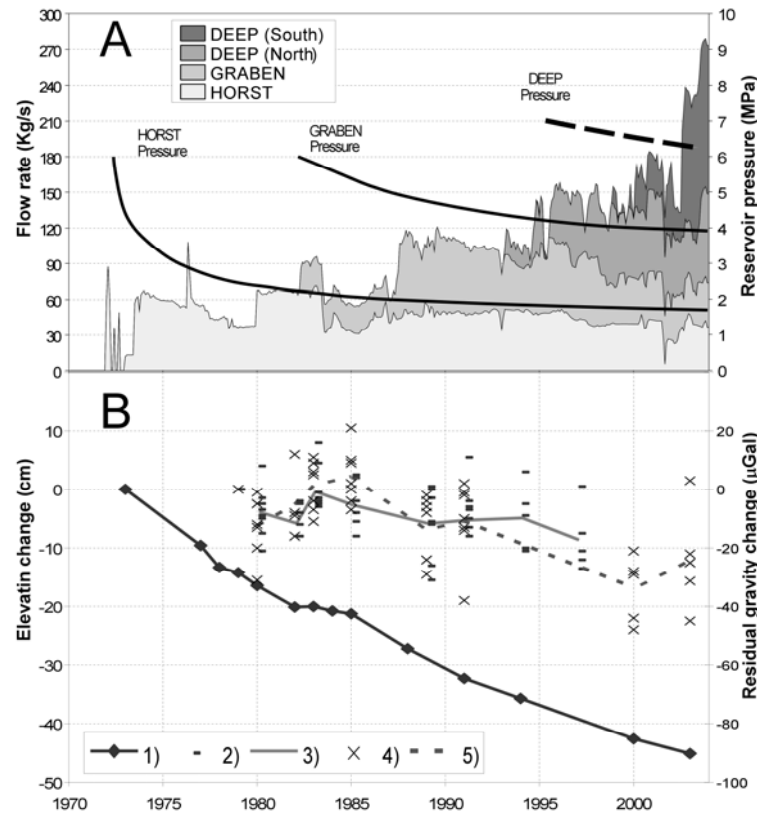
Figure 5: Total discharge flow rate and reservoir pressure history for each reservoir (A); Elevation changes and gravity changes occurred in the area of maximum subsidence, i.e. Horst area (B). 1) Average trend of the elevation changes; 2) micro-gravity changes measured with L&R D18 since 1979; 3) average trend of L&R D18 measurements; 4) micro-gravity changes measured with L&R G297 since 1979; 5) average trend L&R G297 measurements.

Hence the subsidence trend must be considered as a cumulative result of the production that, from 1973 to 2003, increased progressively from 60 to 240 kg/s, supplied from deeper and deeper reservoir levels (< 4000 m).

Precise levelling seems a very effective method of monitoring topographic variations induced by any changes of the exploitation regime. For example, it is worth to compare the subsidence with production during the first half of 80's (see Figure 5). A production decrease from 90 to 60 kg/s in the Horst reservoir (leading to a local pressure recovery) corresponds to an almost zero rate of subsidence measured by the 4 surveys performed from 1982 to 1985. The effect on subsidence seems immediate, without delay between cause and effect. The occurrence is also apparent in Figure 2-B, where, elevation changes of the Horst benchmarks, in the relevant period, are very little.

Moreover, it is interesting to point out that the main fault system determining the hydraulic separation between the Horst and Graben reservoirs (see Figure 2, section A) could probably act also as a mechanical disconnection between the two blocks (the Horst at SW and the Graben at NE), Thus it would minimise the subsidence NE side of the main fault system.

Many of the parameters related to the subsidence, in the Travale-Radicondoli geothermal field, are not easily quantifiable for an accurate mathematical modelling. Anyway, the rock reservoir contraction due to fluid extraction can be roughly estimated in a simple way, assuming a linear relationship between the reservoir pressure decrease and the related volumetric strain. Considering the reservoir as a homogeneous and isotropic medium, and the poro-elastic strains occurring prevalently in the vertical

direction, the decrease in thickness of the reservoir, in accordance with Hooke's law, can be estimated as follow:

$$\varepsilon = \frac{\Delta H}{H} = \frac{\Delta P}{K} \qquad (2)$$

where ε is the vertical strain, H the reservoir thickness, ΔH the decrease in thickness, ΔP the pressure drop and K the Bulk modulus.

Considering the first 10 years of exploitation, which interested only the Horst reservoir, and assuming $H = 1000$ m, $K = 35$ GPa, with a ΔP of 4 MPa, we got a ΔH of about 12 cm. This value is in agreement with the order of magnitude of the experimental data (about 20 cm). However, additional subsidence effects, not easily quantifiable, must be considered. In particular, despite its low permeability, even the cap rock indeed contains a small amount of water that, mainly close to the top reservoir, may be withdrawn because of the pressure drop in the underlying reservoir, thus leading to some cap rock compaction. Reservoir thermo-elastic contraction could also be taken into account, but not quantified because of the uncertainty on thermal decrease.

The small gravity changes measured in the 1979-97 time interval with the L&R D-18 and in 1979-03 with L&R G-297 gravimeter slightly exceed the confidence interval of the method, that is of ± 9 e ± 24 μGal for L&R D-018 e L&R G-297 gravimeters respectively. The data show a slight gravity decrease of about 20-25 μGal during the whole time period. The trend is not regular but is characterised by fluctuations with a period of 5-10 years and within the uncertainty of the confidence interval. As already observed in the Larderello field, e.g. Dini, (1995), these fluctuations could be due to

cyclic climatic effects, like for example a different soaking rate of the shallower soil layers. This is mostly evident in the 1980-1991 period, being confirmed by both gravimeters .

The spatial distribution of the gravity residuals is not clearly defined. However, a NS trend of decreasing gravity is reliable and always recognisable. The most representative example of this feature is shown in Figure 4. Note that location and shape of the central negative anomaly is copying in some way that of the elevation changes, with similar trends, yet with less detail because of the few experimental points available.

The gravity profiles in Figure 2-C, support the overall consistency of the data with time, in spite of the small values: gravity residuals of the 1979-03 are higher than those of the previous 1979-97 period.

The total gravity decrease (20-25 µGal in the 24 year period, 1979-03), must be related to a mass decrease in the underground, due to geothermal exploitation. Some attempts for the evaluation of this mass deficit have been performed with two different approaches. The first one, according to Gauss's theorem, e.g. Hunt, (1970), has been applied to the most representative gravity changes observed (1979-97 with L&R D-018 and 1979-03 with L&R G-297), and has yielded a mass deficit ranging between 4.5 to 7.4 Gkg, that is about 4.7-7.4 % of the total produced fluid (100 Gkg). The second approach, according to a simple gravimetric modelling, and considering a body equivalent in volume to the reservoir (about 4 km^3, in the shape of a cylinder 1000 m thick, with centre of gravity at 2000 m depth), reproduces the observed anomaly (20-25 µGal) with a density contrast of 0.0035 g/cm^3 . This should be consistent with a mass deficit in the reservoir of about 14 Gkg (14 % of the total fluid produced).

6. CONCLUSIONS

Topographic and micro-gravity monitoring of the Travale-Radicondoli geothermal field provided useful information to prevent environmental problems and to better define the development strategies. The main results can be summarized as follows:

– Maximum land subsidence values of 50 cm, just in the small central area, after a 30 year period of industrial exploitation; with almost no help from the reinjection;

– Subsidence rates decreasing from 2.3 cm/year at the beginning, to 1 cm/year at present, while geothermal production has increased from 60 to 240 kg/s. These are among the smaller known subsidence values for such a kind of intensive developed geothermal fields all over the world, e.g. Allis and Hunt, (1986); San Andres and Pedersen, (1993); Mossop and Segall, (1997); Tagomori et al., (1997); Glowacka et al., (1999); Eysteinsson, (2000); Bloomer et al., (2001);

– Subsidence slightness mainly depends on the favourable physical-mechanical properties of the reservoir (e.g. under-pressured, high enthalpy, high elastic moduli of the rocks) beside the watchful management of the field exploitation;

– Rough quantitative analysis of subsidence data support the hypothesis that it may be prevalently due to the reservoir compaction resulting from fluid extraction, but some contribution from the reservoir cap rock must also be considered;

– A very robust, reliable and precise micro-gravity surveying procedure, have been set up, leading to 99.7% of confidence for gravity changes of 9 µGal and 24 µGal for L&R D-018 and L&R G-297 gravimeters respectively;

– Very small corrected gravity changes, in the range of +20, -45 µGal, have been up today detected;

– Quantitative interpretation of the micro-gravity decrease so far measured (20-25 µGal in the 1973-03 period), are consistent with the hypothesis that a conspicuous fraction (95-86%) of the fluids extracted from the reservoir are replaced by other fluids coming from adjacent and deeper areas of recharge. This should finally mean that the geothermal field, under exploitation since some decades, is still far from being depleted.

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