REINJECTION MONITORING IN THE LARDERELLO GEOTHERMAL FIELD USING MICROGRAVITY AND TOPOGRAPHIC MEASUREMENTS

Ivano Dini [1], Iginio Marson[2], Francesco Palmieri[2], Aristide Rossi[3]

[1] ENEL S.p.A./DPT/VDT-G, via Andrea Pisano 120,56122 Pisa (Italy)
[2] Universita di Trieste, Dip. di Ingegneria Navale, del Mare e per l'Ambiente, via A. Valerio 10, 34127 Trieste (Italy)
[3] CNR, Istituto Intemazionale per le Ricerche Geotermiche, piazza Solferino 2,56126 Pisa (Italy)

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ABSTRACT

In 1986 a geodetic network was set up to monitor the ground vertical movements and gravity changes of the Larderello geothermal field.

Elevation measurements carried out in 1986 on benchmarks belonging to a precise leveling line of 1923 showed that the zone of Larderello that had been exploited for the longest time had experienced a maximum subsidence of approximately 170 cm in 63 years (an average of 2.7 cdyear). Systematic measurements performed after 1986 show that the subsidence is now less than 1 cm/year and that only the zones exploited most recently are subsiding, while the longest exploited zone appears to be relatively stable.

Gravity variations in the time span 1986-1993 have been very **small;** practically with the same order of magnitude, or slightly higher, than the estimated "environmental noise" (± 15 μGal). This is in agreement with a quasi-equilibrium dynamic state of the fluid mass involved in geothermal exploitation.

The gravity changes, although very small, have a good coherence in time and space. Therefore a rough evaluation of the masses that cause the most reliable gravity change features is possible. Two positive gravity change anomalies observed at the end of the 1986-91 and 1986-93 periods, in the zone of maximum reinjection (west Valle Secolo zone), seem to indicate an accumulation of mass equal to approximately 14% of the water reinjected in the first period and 3% in the second period.

1. INTRODUCTION

A geodetic network was set up in the Larderello geothermal area in 1986 to monitor any ground vertical movements and gravity changes, that could be ascribed to exploitation of the geothermal field and, in particular, to reinjection.

The network covers the historical area of Larderello and Castelnuovo V.C. geothermal fields with a total surface extension of about 35 km^2. The location of the benchmarks, together with the main production and reinjection wells, is shown in Fig. 1.

To date six complete surveys have been performed in the months **of** June and July of the years 1986, 1987,1988, 1989, 1991 and 1993.

The elevation changes have been detected by means of precise geometric leveling measurements with an accuracy of 1 cm.

The gravity changes have been observed by means of microgravity measurements, all of which have been performed with the same gravimeter (L. & R. mod. D), by the same operator, in the same seasonal condition, and at the same time as the elevation measurements. The standard deviation for microgravity measurements has always been smaller than ±5 μGal.

Both the elevation and the microgravity measurements have a reference benchmark located more than 4 km away from the well field ("Pomarance" benchmark in Fig. 1). The microgravity measurements also have an absolute reference, located far from the **limits** of the geothermal field (Palazzo al Piano near Siena), on a stable geological structure used as an absolute gravity site (Geri et al.; 1982, Dini and Rossi, 1990).

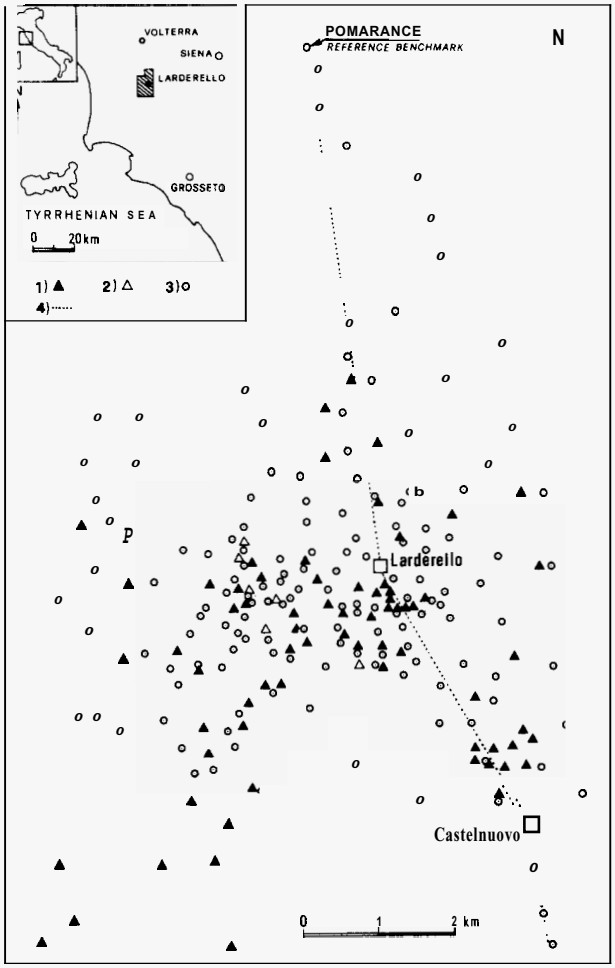


Figure *1.* Location map of the benchmark network. 1) main production well; 2) main reinjection well; 3) benchmark, **4)** profile shown in Fig. 3.

2. GROUND VERTICAL MOVEMENTS

The ground vertical movements (Ah) observed on the network at the end of the 7-year period (1986-1993) were only of negative sign, that is, of the subsidence type (Fig. 2).

Values ranging from 0 to -2 cm occurred in the central area of the historical Larderello field and from -6 to -8.5 cm in the surrounding zones.

These data further confirm and quantify the conclusions of Dini and Rossi (1990), i.e., that the longest exploited central Larderello zone is substantially stable, while subsidence with maximum rates of 1.2 cm/year is present in the peripheral zones of the field where exploitation developed in more recent times ('60s and **'70s).**

Evolution of subsidence along the profile Pomarance-Larderello-Castelnuovo V.C. is shown in Fig. 3, where Ah values for the 1986-89, 1986-91 and 1986-93 periods are drawn in mm, whereas those for the 1923-86 period are shown in cm.

Figure 2. Total elevation change during the 7-year period 1986-93. 1) main production well: ***2)*** main reinjection well; 3) elevation change contour line (cm).

The data for this last period refer to some old benchmarks belonging to a precise leveling line established in 1923 (I.G.M., 1924). The graph of Fig 3 again points out that the longest exploited zone of Larderello, with maximum subsidence of 170 *cm* in 63 years (Dini and Rossi, 1990; Arca et **al.,** 1988), is now almost stable.

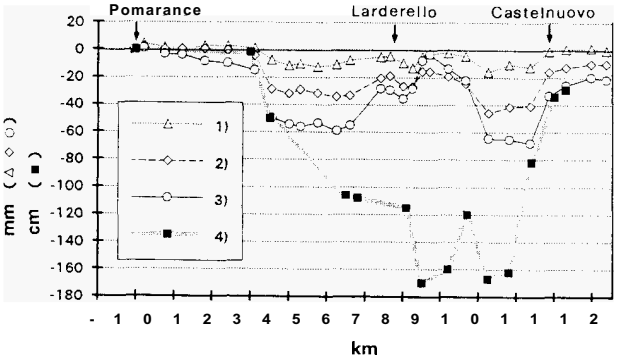


Figure 3. Elevation changes along the profile Pomarance-Larderello-Castelnuovo V.C.. 1) 1989-86 period; ***2)*** 1991-86 period: 3) 1993-86 period; 4) 1986-23 period.

Subsidence of the historical zone of the Castelnuovo V.C. well field represents a special case: despite the fact that it has been subjected to a geothermal exploitation regime similar to that of the historical Larderello zone, it still shows rather high subsidence rates (about 1 cdyear). This behaviour is probably due to the shallow hydrogeologycal condition of the area (see *sect. 5).*

3. GRAVITY CHANGES

Measurements of the gravity changes (Ag) are available starting from 1986, that is, about 65 years after the beginning of industrial exploitation of the geothermal field.

The Ag corrected for the relevant elevation changes (Δgc) for the last two periods, 1986-1991 and 1986-1993, are mapped in Fig. 4.

From analysis of all the available Δgc data, it has been possible to evaluate an "environmental noise", caused by natural phenomena such as meteorology, etc. , of the order of ±15 μGal. Keeping this in mind, the smallness of the observed Δgc appears evident, since altogether they never exceed the value of 20-25 μGal. This means that the mass balance inside the geothermal reservoir averages to zero or, at least, that the variations are negligible compared to the total mass involved by exploitation (an average of 1000 t/h as mass extracted and 120 t/h as mass reinjected).

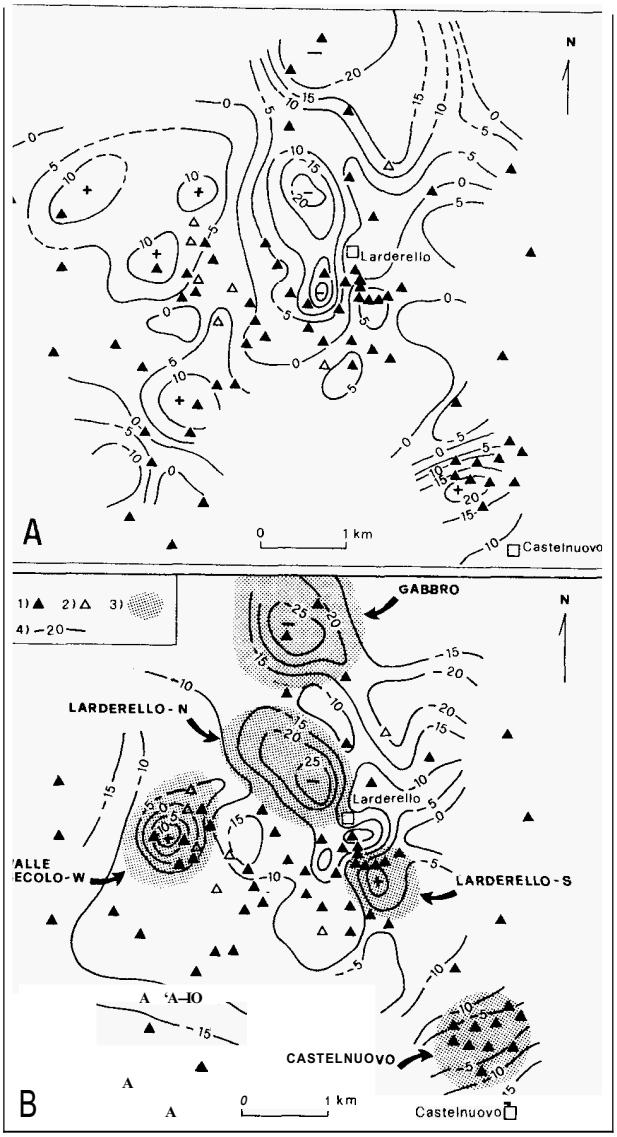


Figure 4. Gravity change contour maps of 1986-91 period **(A)** and 1986-93 period (B). 1) main production well; ***2)*** main reinjcction well: 3) main gravity change anomalies; 4) gravity contour line (μGal)

However, some local Δgc anomalies, although very small, evolve in time with constant and coherent trends. This leads us to believe that they are related to local reservoir exploitation. The most meaningful anomalies appear in Fig. 4B (Gabbro, Larderello N, Castelnuovo, Larderello *S* and Valle Secolo **W).**

The mass discharge rates associated with these anomalies, and the mass reinjection rate associated with the Valle Secolo anomaly, are shown in Fig. 5 and Fig. 6, respectively.

4. DATA ANALYSIS

For more detailed data analysis, the gravity and elevation changes observed since 1986 in each survey are shown in Fig. **7.**

The evolution with time of the dispersion of Ah toward more and more negative values demonstrates that subsidence is in progress. The corresponding dispersion of Δgc, however remains roughly the same, within a range slightly larger than the "environmental noise" of ±15 μGal.

Observing Fig. 7B it is also possible to notice that such a dispersion is not centered on the 0 μGal value as one would expect, but shows a trend apparently sinusoidal with a period of about 7 year (dotted curve).

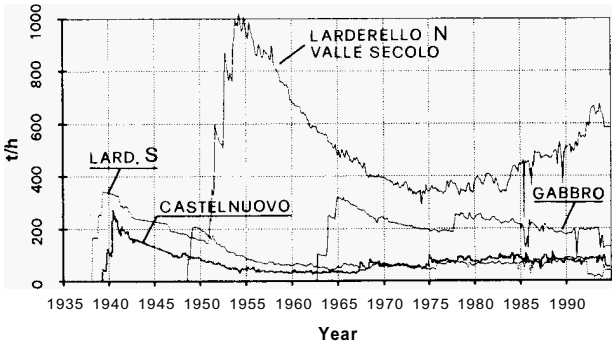


Figure 5. Mass discharge rates of the geothermal zones associated with the main microgravity change anomalies.

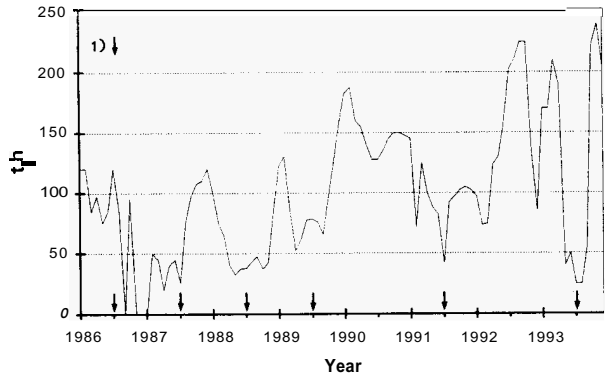
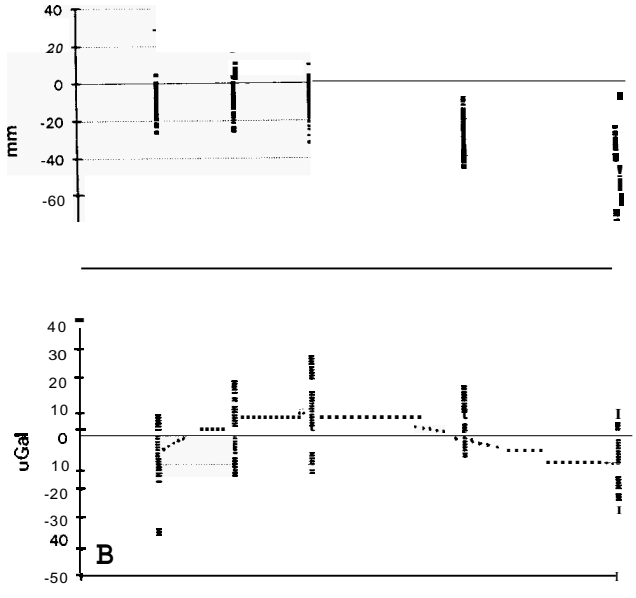
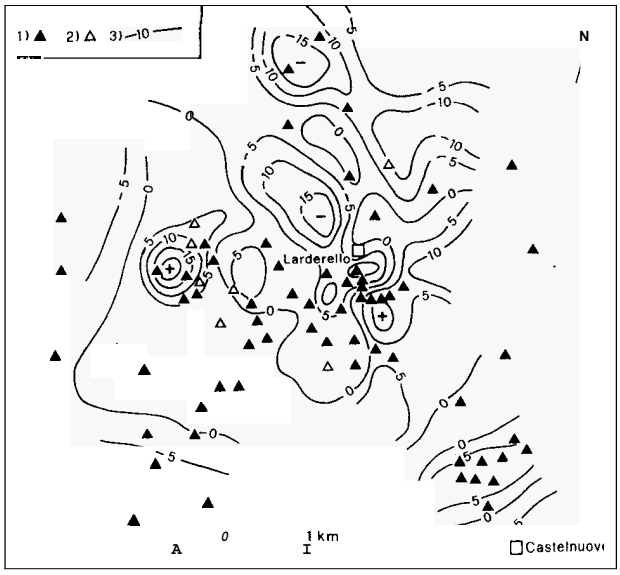


Figure 6. Mass reinjection rates of the main reinjection zone (Valle Secolo W) 1) leveling and microgravity surveys.





'igure8. Contour map of the gravity changes of the 1986-93 period corrected for the "long period noise". 1) main production well, **2)** main reinjection well; 3) gravity changes contour line (μGal).

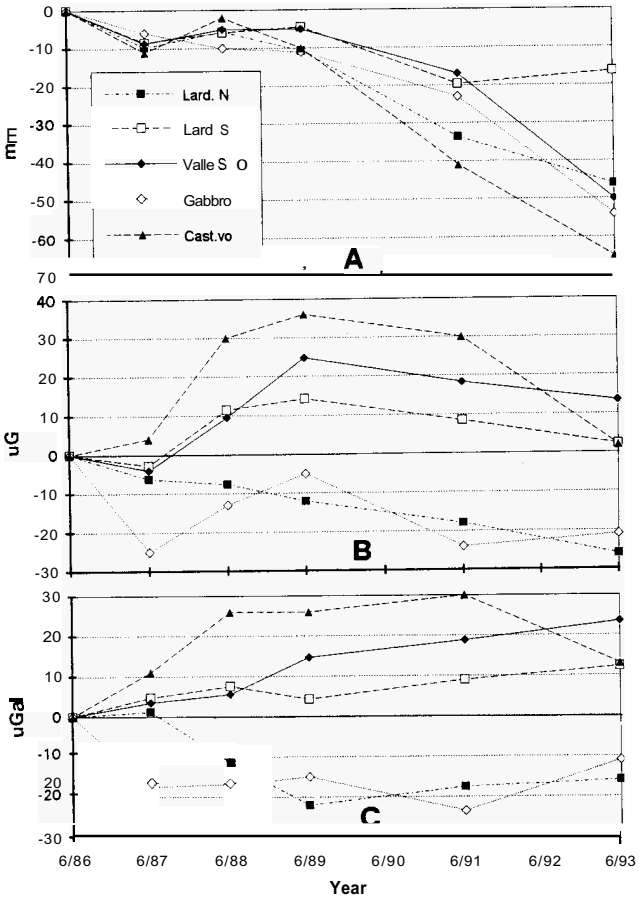


Figure 9. Distribution for the meaningful selected zone (see Fig. 4B) of the average elevation changes **(A),** average gravity changes (B) and average filtered gravity changes (C).

In Fig. 9 the mean trends in time of Ah **(A),** Δgc (B) and Δgc filtered for the above-mentioned "long period noise" **(C)** are shown for the most meaningful selected zones.

5.INTERPRETATION

The above described data indicate first of all that in the longest exploited Larderello zone, fluid extraction and total recharge (natural recharge + reinjection) reached a substantial balance. The physical conditions in the reservoir are therefore almost stable and the observed elevation and gravity changes almost negligible.

Since all the Δgc are generally small, this condition of substantial balance can therefore be extended to the whole area under examination. Although this can be considered the most important result the data on the most meaningful zones previously selected deserve a closer examination (Figs. 9A, 9C, 4A and 8):

- **Larderello N:** a small decrease in Δgc (20 μGal maximum) can be observed immediately north of the intensively exploited zone of Larderello-Valle Secolo. This indicates a mass deficit that is negligible if compared to the mass extracted ($32 \cdot 10^9$ Kg in 7 years). A subsidence rate of about 0.5 cm/year has been detected.

- **Gabbro:** a decrease in Δgc, of the same order of magnitude as the previous zone, can be observed here too. It is localized in the productive well field of Gabbro. Again the deficit in mass balance can still be considered negligible compared to the extracted mass ($12 \cdot 10^9$ kg in 7 years). The subsidence rate is similar to that at Larderello N (see above).

- **Castelnuovo:** the largest positive gravity changes have been detected in this zone, despite the fact that, together with the Larderello S field, this is the longest exploited area. This indicates a certain excess in mass balance. The most likely explanation at the moment is that of a progressive steam displacement inside the geothermal reservoir due to water. This phenomenon might be the result of the presence in thie zone of an important shallow aquifer, connected locally with the geothermal reservoir and with a very close natural recharge area. This aquifer extends northward so as to cover also the Larderello S zone.
This interpretation is in agreement with the geochemical data, which seem to indicate the same phenomenon (Scandiffio et al., 1995).
A subsidence rate of slightly less than 1 cdyear has been measured.

- **Larderello S:** this zone is included within the longest exploited Larderello field.
The Δgc are stable around zero or weakly positive (a maximum of 10 μGal in 7 years). This may indicate an equilibrium or perhaps a small excess in the mass balance inside the geothermal reservoir. The explanation may be the same as given above for the Castelnuovo zone. The phenomenon may be less evident here, because the aquifer - which might be interacting with the geothermal reservoir - is less thick and its recharge area (the same as for the Castelnuovo zone) is further away.
As expected, the subsidence is negligible or absent.

- **Valle Secolo W:** the Δgc tend to increase or at least they remain positive (slightly over 20 μGal in 7 years). The relevant anomaly develops in the westem part of the Valle Secolo area, where the most important reinjection wells are located.
Unlike the Castelnuovo and Larderello S zones, here there is no shallow aquifer, so that the weak increase of Δgc could be due to a partial accumulation of the water reinjected. The subsidence is smaller than 1 cm/year.

Gravimetric monitoring of the Valle Secolo W zone becomes particularly important if we consider that reinjection is mainly concentrated here and that recently it has been augmented to increase steam production. For this reason we attempted a quantitative analysis of the masses involved, by means of the relation that, according to Gauss's theorem, gives the mass variation Am as a function of the corrected gravity changes Δgc (Allis and Hunt, 1986):

$$\Delta m = 1/2\pi G \sum_{A} \Delta gc \cdot \Delta a$$

where G is the Universal Gravitational Constant ($6.67 \cdot 10^{-11}$ Nm^2/kg^2) and Ad is an element of the total area A to which a variation Δgc is associated.
Analysis was performed for the gravity change anomalies that were observed in the "Valle Secolo W" zone at the end of the 1986-91 and 1986-93 periods (Fig. 4A and 8).

The integrated sum Σ Δgc·Δa was computed over the total area of the above-mentioned anomalies, which extend 5.8 and 1.4 km^2 respectively.
The results show mass increases of about $0.5 \cdot 10^9$ kg for the 1986-91 period and of about $0.14 \cdot 10^9$ kg for the 1986-93 period.
Considering that the total amount of the nearby water reinjected is about $3.6 \cdot 10^9$ kg and $6 \cdot 10^9$ kg for the same periods, we might assume that about 14% of the water reinjected in the fust period remains accumulated in the reservoir, while at the end of the second period the water accumulated would be very much reduced (2-3%). From the reinjection rates given in Fig. 6, we could infer that reduction of the water accumulated during the second period depends upon the strong reduction of reinjection rate just before the 1993 survey. This would allow us to deduce that, in the actual physical conditions of the reservoir involved, the amount of accumulated-water changes rapidly (of the order of days) according to variations in reinjection rate.

6. CONCLUSIONS

The method used has proved adequate for measuring small elevation and gravity changes, of the order of ±1 cm and ±15 μGal respectively, induced by exploitation of the geothermal field.
The elevation change in the 1986-93 period shows maximum subsidence rates of 1.2 cdyear in the peripheral zones of the geothermal field where exploitation started more recently, while the longest exploited Larderello zone appears to be stable or weakly subsident.
In the same period the gravity changes assume values of the same order of magnitude as the ±15 μGal "environmental noise" or slightly larger.
All this is in agreement with a quasi-equilibrium dynamic state of the fluid mass involved in geothermal exploitation.
The gravity changes, though very small, have a statistical coherence over time and space, such as to allow a tentative interpretation of the most reliable Δgc features.
In particular, the positive Δgc values measured in the main reinjection zone (Valle Secolo W), may indicate that, at almost constant reinjection rates, up to 14% of the total reinjected water can be accumulated. Such accumulations, however, may be characterized by a highly dynamic state, so that, as reinjection rate is rapidly reduced, they are reduced as rapidly. In this sense, more precise and detailed evaluations would be possible if data were available from much more frequent measurements than those performed up to now.

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