SUBSIDENCE AND GRAVITY CHANGES INDUCED BY EXPLOITATION IN THE TRAVALE - RADICONDOLI GEOTHERMAL FIELD (TUSCANY - ITALY)

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Abstract:

Fifteen precise levelling surveys since 1973 have revealed that Travale-Radicondoli geothermal area is affected by subsidence at a maximum rate of 2.5 cm/year in the first 10 year period and about 2 cm/year since 1983.
Since 1979 eight microgravity surveys have detected in this area very small gravity changes of the order of a few μGal/year. At times these are at the limits of the confidence level of the experimental data (± 15 μGal), or just below the limits of the noise effects introduced by seasonal meteo-climatic conditions.
Maximum gravity changes, corrected for the subsidence effect (Δg), do not exceed a total range of a few tens of μGal, and show a constant trend in time, but different characteristic distributions from zone to zone.
The eastern zone, the most intensely exploited part of the field, has been producing since 1973. Since then subsidence values of more than 40 cm have been observed, associated with the largest negative Δg anomalies, although not exceeding the 30 μGal recorded since 1979.
These negative Δg values could be attributed to a mass deficit in the reservoir rocks of the order of just 3% of the mass of fluids delivered by the local wells during the 1979-91 period.
This hypothesis is consistent with an actual quasi-equilibrium dynamic state of the fluids in the field, where the exploited mass is almost entirely reintegrated by fluid recharge.
The western zone has gradually been exploited over the last few years and has experienced only marginal effects of subsidence so far, mostly due to the exploitation of the eastern basin. In this zone a positive trend of the Δg values is evident, yet they only just exceed the confidence level of the observed data.

1. THE TRAVALE - RADICONDOLI GEOTHERMAL FIELD

The industrial exploitation of fluids for geothermoelectric generation began in this area in 1950 and involved only the small zone known as the "old Travale field", situated at the southern margin of the area, at the boundary of the Mesozoic carbonate outcrops (Fig. 1).

Production of variable quantities of fluids continued over more than 20 years. Steam and water at low temperature and pressure were extracted at depths of a few hundred meters from a shallow reservoir refilled with hot fluids of deeper origin and fresh meteoric water from adjacent permeable outcrops (Cataldi *et al*, 1970).
Intensive exploitation of the geothermal field effectively began in 1972-73 with T22 well. This was the first well to exploit the deep vapor-dominated reservoir with fluids at high temperature and pressure; the T22 well is drilled in a zone north of the old field that is affected by a main direct fault system (Fig. 1); this system separates a structural high on the southern side, with a local horst-type feature, from the downside graben feature with NW-SE regional trend (Burgassi *et al.*, 1975). The previously cited works already showed the important role played by the permeable formations (mainly carbonate) of the upper part of the potential reservoir in the evolution of the Travale field.
These formations directly connect the southern outcrops, which are filled with infiltrated meteoric water, to the northern buried reservoir, which is affected by a fault system through which the circulation of hot rising geothermal fluids develops. All this forms a constraint conditioning the evolution of the thermodynamic characteristics of the fluids during field exploitation, at least for the upper parts of the reservoir.
This constraint results in a possible variable supply of cold water to the parts of the field where exploitation can trigger a decrease of the pressure of the fluids and the inflow of meteoric water.

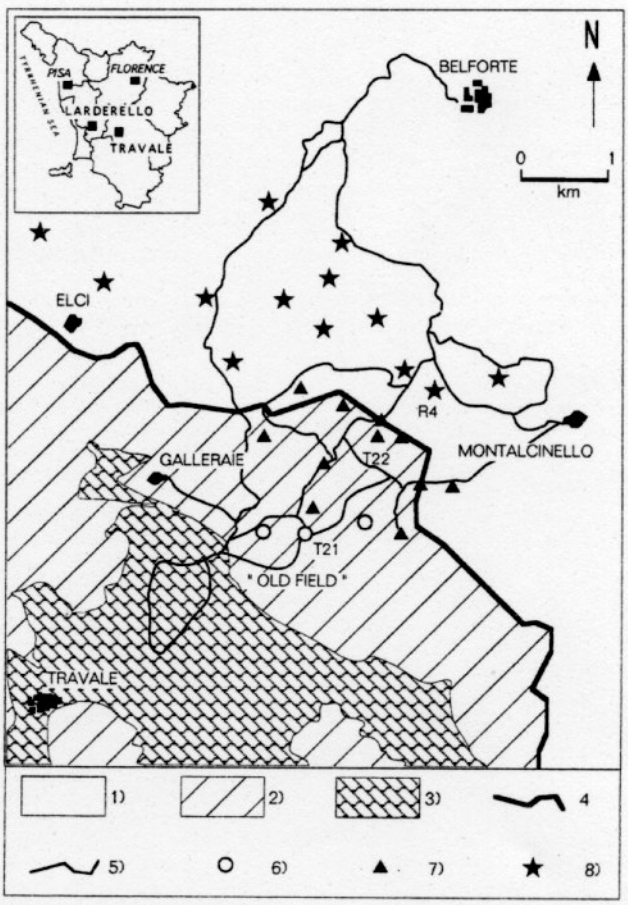


Figure 1: Geological sketch map of the Travale-Radicondoli geothermal area (Tuscany, Italy). 1) Neogenic cover formations; 2) Flysch cover formations; 3) Outcropping reservoir of prevalently carbonate formations; 4) Main fault system; 5)Monitoring network path; 6) Old field well; 7) Well of the horst zone; 8) Well of the graben zone.

The maximum possible contribution has been calculated in 2.5×10^6 m^3/year, based on the geohydrologic balance of the area and on the extent of the adjacent permeable outcrops (Petracco and Squarci, 1975). The actual recharge is variable with time and follows the natural cycle of supply of rains and ground water storage, and also depends on the exploitation parameters of the field. Short and long-period oscillations of meteoric precipitations can vary from 600 to 1200 mm/year, with strong seasonal fluctuations.
Exploitation of the field developed through various episodes of extraction in different areas and at different production depths.
Reinjection was applied to the field for a few years only and with negligible quantities of condensate waters.

2. TOPOGRAPHIC AND MICROGRAVITY MONITORING NETWORKS. MEASUREMENTS AND RESULTS

In 1973 a network for precise topographic leveling was set up and measured for the first time. At present, it consists of 220 permanent

benchmarks, some of which are also utilized as bases for the microgravity network (Fig. 1).
A local reference benchmark has been set up on the SW margin of the area, in the zone of carbonate outcrops that were apparently unaffected by geothermal exploitation; these outcrops were considered more stable and unlikely to be affected by subsidence, because they act as recharge areas of meteoric waters.
This local reference base was tied by periodical microgravity links to 3 remote bases set up, as regional references; on geologically stable sites a few tens of kilometers from the geothermal field.
One of the 3 remote bases (Palazzo al Piano) was measured with an absolute gravity meter in 1981 (Geri et al., 1982) and in 1985.
The absolute gravity base was also connected to the main altimetric network.
So far the local reference benchmark is considered undisturbed, at least within the limits of precision of the measurement methods and for periods of a few years. However, the leveling network did not cover the entire area affected by minor topographic changes for the entire reference period, and some data suggest that land subsidence may have gradually extended to the southwestern carbonate outcrops containing the reference benchmarks (Geri et al., 1984, Beinat et al., 1995, this Congress).
Should future surveys confirm that subsidence is slightly affecting the carbonate outcrops, then we could hypothesize that the values reached throughout the field are higher than those observed so far.
Fifteen precise leveling surveys since 1973 have revealed that the Travale-Radicondoli geothermal area is affected by subsidence at a maximum rate of 2.5 cm/year in the first 10 year period and about 2 cm/year since 1983.
A total land subsidence of more than 40 cm has been recorded in the central part of the area (Fig. 2).

The maximum values occur in the area containing wells that have been producing since monitoring began and where a pressure decrease of about 4 MPa in the upper part of the reservoir has been observed in the same period (Fig. 3).

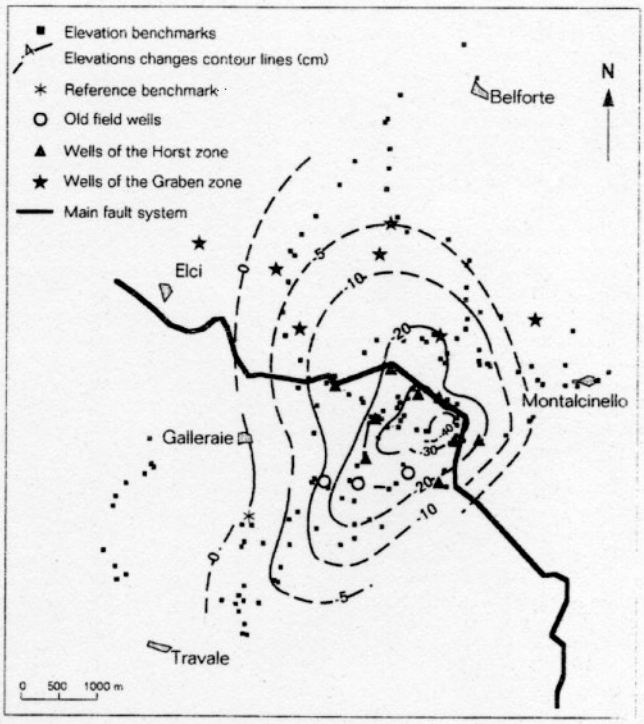


Figure. 2: Total elevation changes in the Travale-Radicondoli area during the 18 year period 1973-1991.

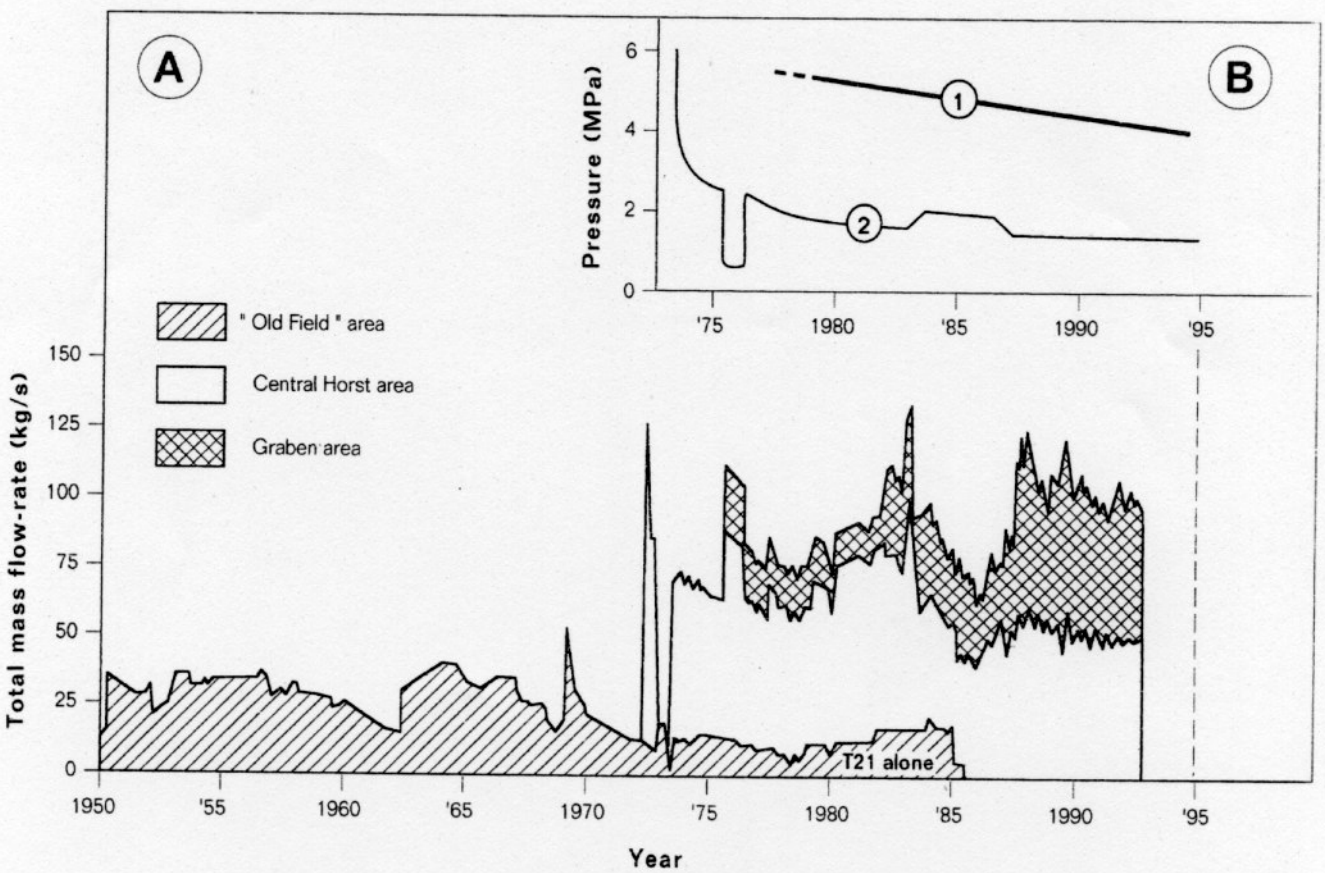


Figure 3 : **A**) Mass discharge rates in kg/s since the beginning of exploitation of the Travale-Radicondoli geothermal area. Individual contribution from the different zones of the field are depicted. **B**) Pressure trend at the top of the reservoir. 1) Data from a non-productive well in the graben zone; 2) Data from the productive wells of the T22 group (horst zone).

During the monitoring period, the negative topographic changes immediately reflected the trend of field exploitation, e.g. matching the activity of new wells entering into production (Geri *et al.*, 1984, Di Filippo *et al.*, 1985) or hot water withdrawal from T21 well in the "old field" during 1980-1985 (Fig. 3A), as pointed out by the small sharp anomaly at the southern boundary of the area (Fig. 4A).
Since 1979 eight microgravity surveys have detected in the area very small relative changes of the order of a few mGal/year. At times these are at the limits of the confidence level of the experimental data, or just below the limits of the noise effects introduced by seasonal meteo-climatic conditions and by surface geohydrological conditions.

Figs. 4 and 5 show the results of several repeated topographic and gravimetric observations. Some comments are necessary.

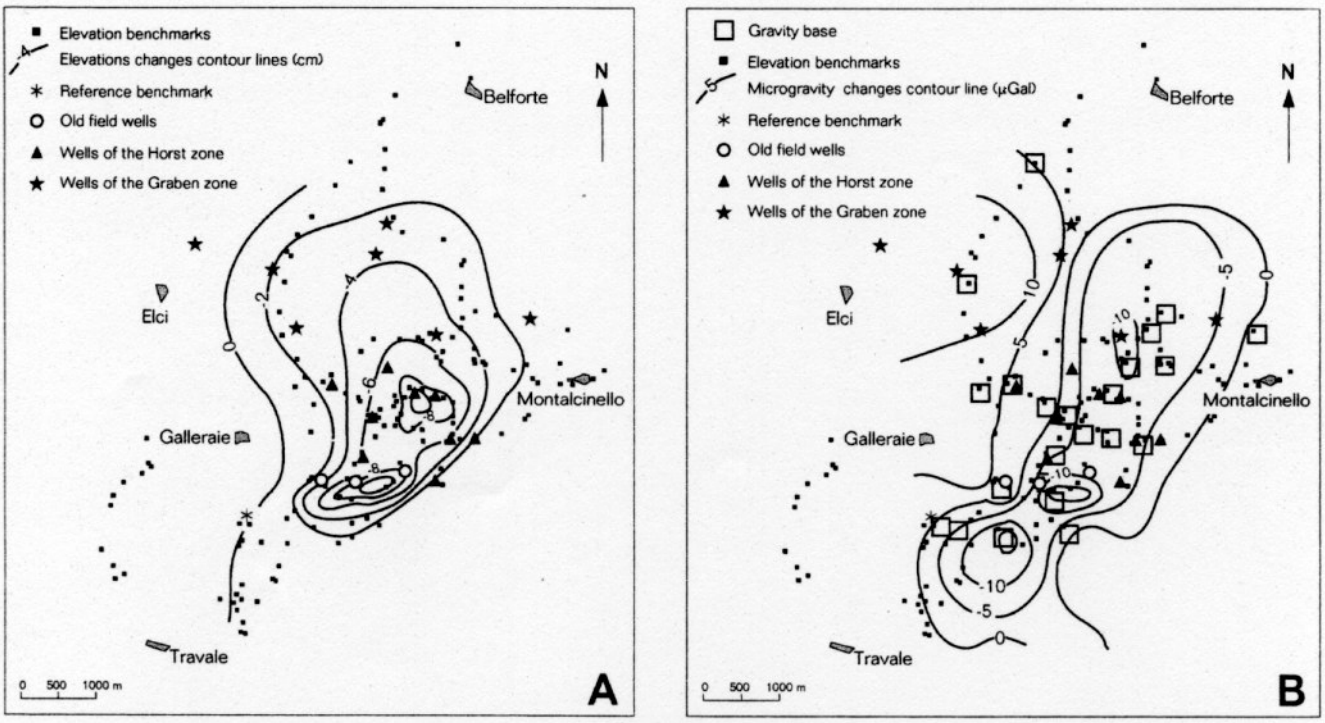


Figure 4 : Land subsidence (**A**) and microgravity changes corrected for subsidence (**B**) during the 6 year period 1979-1985

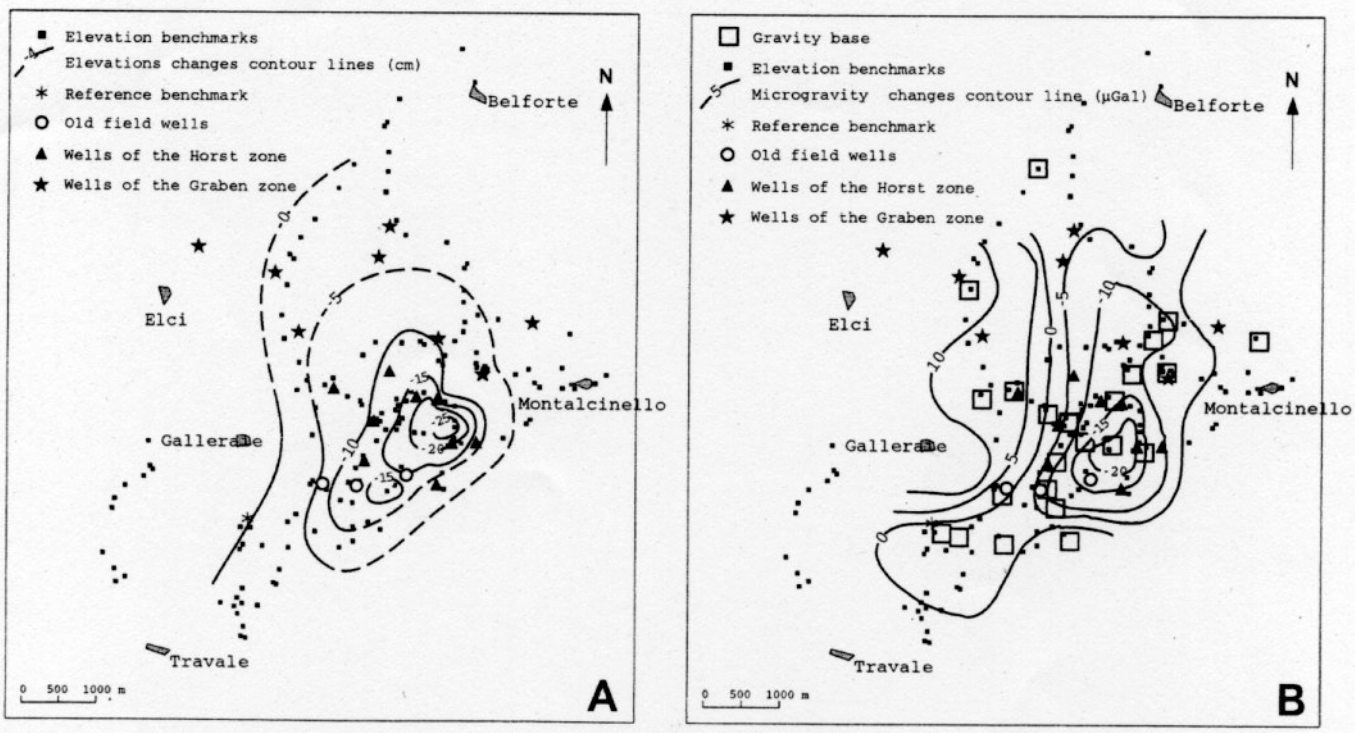


Figure 5: Land subsidence (**A**) and microgravity changes corrected for subsidence (**B**) during the 12 year period 1979-1991

It is evident that the network of experimental points for both sets of measured parameters does not cover the whole area in detail. The small number of gravimetric bases and their relative distribution do not allow us to reach a good definition of the anomalies at the margins of the area, particularly in the southeast where there are very few access roads.
The trend of Δh and Δg has been evident despite their small absolute values, since the early periods of exploitation and since the first measurements (Geri *et al.*, 1985).
The maximum value of land subsidence dramatically coincides with the small structural high of the little horst type feature, cut on 3 sides by the regional fault system (Fig. 1, 2 and 6).
The Δg variations, corrected for subsidence effect, are within a few tens of μGal, and show a coherent trend in time, but different distributions from zone to zone.
During the first years of exploitation of the new field the Δh and Δg contours mainly trended in a NE-SW direction, orthogonal to the main Apennine geological structures (Di Filippo *et al.*, 1985), although a minor N-S component was already evident.
Later on the N-S trend also became important, or even prevailing, when new boreholes entered into production in the northern part of the area.
Both trends reveal a probable predominant permeability distribution within the Mesozoic substratum or the metamorphic basement, which is of fundamental importance to the geothermal field.
These permeability trends, transversal to the main fault system, are complementary structural elements of this area and have already been revealed by other geophysical and geological surveys (Celati *et al.*, 1973).
The N-S trend is typical of the thermal anomalies measured or calculated at the top of the carbonate reservoir and shown in Fig. 6 (Batini *et al.*, 1985).
Fig. 6 also shows the residual Bouguer anomalies from 3D modelling (Toro *et al.*, 1994); once again the Travale-Radicondoli field proved to be a "creation" of the combined main Apennine tectonic feature with structural elements trending N-S and NE-SW.

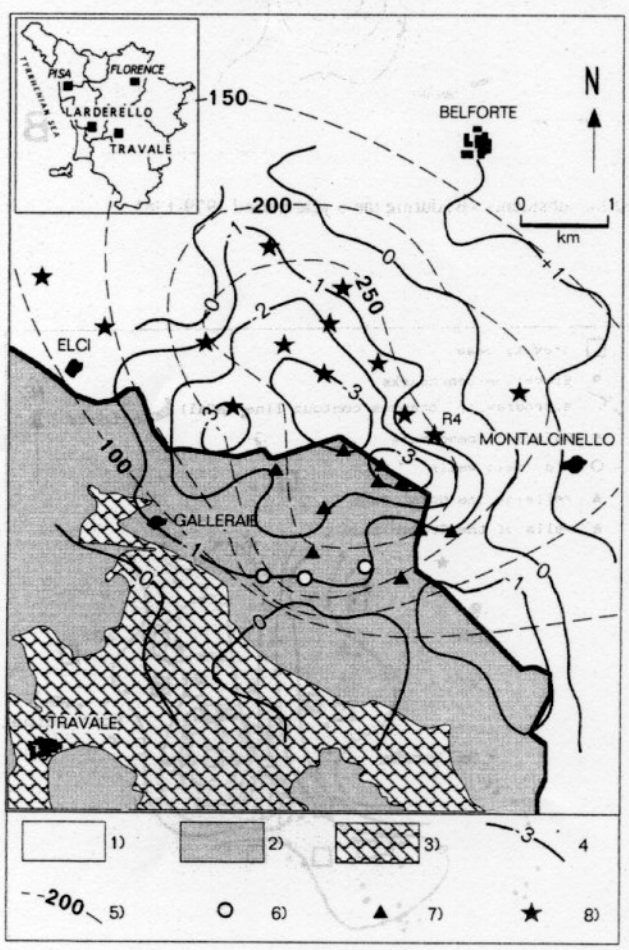


Figure 6: Residual Bouguer anomalies compared to temperature distribution at the top of the reservoir. 1) Neogenic cover formations; 2) Flysch cover formations; 3) Outcropping reservoir of prevalently carbonate formations; 4) Contour lines of residual Bouguer anomaly (μGal); 5) Isotherm contour line (°C); 6) Old field well; 7) Well of the horst zone; 8) Well of the graben zone.

3. CENTRAL AND EASTERN PART OF THE FIELD

This zone has been productive since 1973. Since then subsidence values of more than 40 cm have been observed in the most intensely exploited part of the field, associated with the largest negative Δg variations, although not exceeding the 20 μGal recorded since 1979.
These negative Δg values could be attributed to a mass deficit in the reservoir rocks. Mass deficit was calculated by means of the equation that, according to Gauss's theorem, gives the mass variation as a function of the corrected gravity change (Allis and Hunt, 1986). For the total area of negative anomaly (see Fig. 5B), we obtained a mass deficit of about $1.3 \cdot 10^9$ kg, that is, slightly more than 3% of the mass of fluid delivered by the local wells during the relevant period ($36 \cdot 10^9$ kg from 1979 to 1991).
This hypothesis is consistent with a quasi-equilibrium dynamic state of the fluids in the field, where the exploited mass is almost entirely re-integrated by fluid recharge, without large detectable phase changes in the reservoir. This is also in agreement with the observed almost stabilized or slowly decreasing fluid pressure and temperature trend during the last decade (Fig. 3).
Despite this quasi-steady state dynamic equilibrium, it must be said that not all the fluid extracted from the reservoir can be replaced by other fluids coming from adjacent areas or deeper zones.
Indeed, during the first period of exploitation by wells producing from the upper part of the steam dominated reservoir, a conspicuous mass of uncondensable gas and stagnant or condensed waters was produced together with the steam. The gas was never less than 10% by weight of the total fluid issued (sometimes much more) and was mainly made up of CO_2 that accumulated as a "gas cap". For example for a few years betwen 1975 and 1987 well R4 produced a mixed fluid with a predominant CO_2 percent (from 75% to 65% by weight), with a total production of about $3.4 \cdot 10^9$ kg of CO_2 only. This amount of CO_2 is almost equal to that produced by all the other wells of the field, which has been estimated by Barelli *et al.* (1995) in about $3.7 \cdot 10^9$ kg from 1973 to now. The total mass of CO_2 produced is therefore at least $7 \cdot 10^9$ kg. Most of this mass can be considered as lost by the reservoir; the gas/steam ratios are, in fact, now very low and large parts of the upper reservoir are filled with lighter fluids at low pressure.
It is more difficult to assess the quantity of condensed and "stagnant" water subtracted from the less active parts of the reservoir because of the local rapid drop in pressure.
The condensed water is always a considerable percentage of the total content of the pores and fractures of the reservoir rock that is not affected by active circulation, even in a vapor-dominated domain. However, due to the new low pressure conditions in the reservoir, with two-phase fluid, a liquid water inflow from adjacent areas is possible, at least in quantities comparable to that produced by the wells.
When exploitation began in the central part of the geothermal field, the upper part of the reservoir was depleted and not refilled with heavy fluids and incondensable gases, while hot fluids rose from deeper or nearby zones through preferential pathways characterized by higher permeability and fracture systems. At present part of the almost depleted upper reservoir is bypassed and is no longer involved in production processes.
The non-renewable fractions of the fluids are the heaviest; before and during the first exploitation period, they filled the upper part of the reservoir, which is the most porous part and nearest to the surface. Therefore, the mass variations occurring there can be easily detected by repeated gravity measurements.
This may account for the recorded negative Δg variations, which indicate a modest mass deficit during the early exploitation period, while at later times this negative trend is very slow or is no longer evident.
The small negative Δg changes can be explained by a mass deficit in the exploited upper reservoir of just $1.3 \cdot 10^9$ kg during the monitoring period (12 years). This value is almost negligible if compared with the actual total flow rate of $3 \cdot 10^9$ kg/year, and can be fully justified by the mass of CO_2 issued and lost by the field during the relevant period.
The hypothesis of a local dynamic quasi-equilibrium reached between mass production and recharge is therefore consistent with the microgravity and topographic experimental data.

The above observations have led us to exclude:

- that the meteoric water from local carbonate outcrops is the main source of recharge for the field to replace $3 \cdot 10^9$ kg/year of produced fluids;

- that any appreciable contribution comes from the water contained in the "cover" formations (Flysch and poorly consolidated clastic deposits with a prevalently clayey matrix).

Both these hypotheses would imply subsidence and gravity variations of at least one order of magnitude higher than those observed so far.
The observed data are instead consistent with the hypothesis of a partial

contribution of meteoric water without any significant alteration of the local hydrogeologic equilibrium, and an important recharge from deeper regional aquifers.

4. WESTERN PART OF THE FIELD

The western zone has been exploited over the last few years only by deep wells and has experienced only marginal effects of subsidence so far, mostly due to exploitation of the eastern basin. In the western zone a positive trend of the Δg values is evident over all the eight microgravity surveys, yet the absolute values never exceed the confidence level of the observed data (± 15 μGal).
The unexpected occurrence of a small but intriguing positive Δg variation during exploitation was already recorded in the 1979-1982 period in the "old field" area. This area experienced local positive Δg changes as high as 30 μGal, which have been interpreted as a density increase resulting from water saturation of the upper part of the porous reservoir rocks, as a consequence of well-head shut-in operations in 1979 and 1980. This interpretation was supported by the occurrence of a local unusual positive Δh change, and by a rise of the piezometric level in some wells of the liquid-dominated "old field" during the same period (Geri *et al.* 1984 and 1985; Di Filippo *et al.* 1985).
At present, a similar density increase could be proposed to explain the positive Δg anomaly of the western part of the field.
The geological conditions may be favourable to a local onset of a liquid phase in a shallower part of the reservoir not far from the permeable outcrops and, therefore, directly within reach of the meteoric waters. So few data are available on this newly exploited area, that we are unable to discuss this problem in detail.

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