CRUSTAL DEFORMATIONS DETECTED BY GEODETIC CONTROL NETWORK IN THE TRAVALE GEOTHERMAL AREA - TUSCANY - ITALY

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Abstract: A geodetic network, installed in 1988 to integrate an existing precise levelling control network in the Radicondoli-Travale geothermal area (Tuscany, Italy), has also monitored horizontal ground displacements, as part of a study of the geodynamic effects of natural neo-tectonic activity and of the intensive industrial exploitation of the Travale geothermal field.
The network consists of 7 benchmarks distributed along the main distensive fault system on the SW margin of a regional graben-shaped tectonic feature that trends in an Apenninic direction. Measurements on the network were conducted both by conventional geodetic instrumentation (EDMs, theodolites and levels) and by GPS satellite techniques.
Both the expected and observed ground displacements have been very small so far, so that very precise techniques are required to achieve the highest possible accuracy. Various measurement techniques and procedures have been tested, in order to compare the experimental results. The difference between the values measured permits us to evaluate the deformation field. Horizontal ground displacements of about 1 cm per year have been detected.
The analysis and the comparison between methodologies and results are the aims of this paper.

1. INTRODUCTION

The Travale area is located a few kilometres E-SE of the Larderello geothermal basin (Figure 1). The first drilling in this area, to exploit the H_3BO_3 present in the thermal manifestations, dates back to 1860.
Until 1940 interest was concentrated on the production of boric acid, but in the post-war period the Travale area was included in the development programmes for the production of geothermal power (Cataldi *et al.*, 1970).
The first period of industrial exploitation for electric power generation began in 1951, with an average fluid mass extraction of the order of 100 ton/h of water and steam.
Extraction continued with varying results, even after the closure of the old power plant in 1960.
Until 1973, the total extraction of water and steam from the small area of less than 1 km^2 of the old Travale field can be evaluated in no more than $20 \cdot 10^6$ tons over a period of 22 years.
After 1973 a new exploitation program began in a more productive area, a few kilometres north-east of the old field, with a new power plant and an initial extraction of about 200 tons/h of steam (Burgassi *et al.*, 1975).
During recent years, exploration of the new Travale-Radicondoli area intensified, with the drilling and utilization of several other wells. At present 4 geothermal power plants are operating in the area, with a total installed capacity of 80 MW. The production of fluids from the wells is at present about 400 tons/h.
Further details on this geothermal field are described in other papers presented at this Congress.

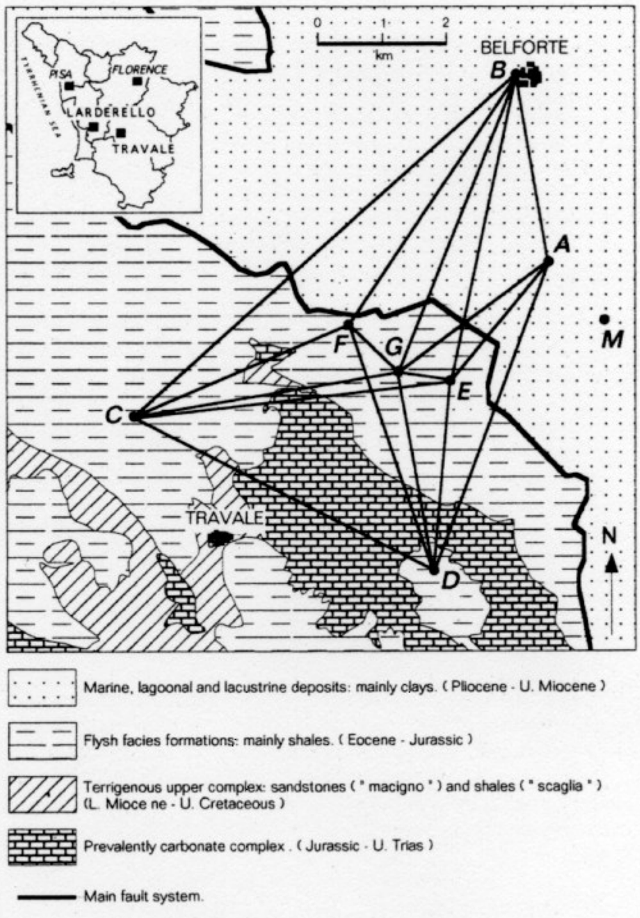

Figure 1: Travale - Radicondoli area (Tuscany, Italy). Schematic geological map and geodetic network.

2. THE TRAVALE NETWORK

2.1. SPIRIT LEVELLING

From 1973 on, the study of some geodetic parameters on the Travale-Radicondoli area has provided a useful tool for monitoring the exploitation-induced field evolution.
A network of elevation benchmarks was set up in the Travale geothermal area and the first measurements made in June 1973 using precise spirit levelling. The local geothermal power plant began operations one month later (Burgassi *et al.*, 1975).

Vertical changes in the area throughout the various phases of development and exploitation of this field were monitored by 15 different surveys on the network over a period of 15 years. At present the levelling network of 220 benchmarks covers an area of more than 50 km^2, including the geothermal field with producing wells.

The results of the observations reveal a maximum subsidence effect in the central part of the most productive area, at an average rate of 20-25 mm/yr (Geri *et al.*, 1984; Di Filippo *et al.*, 1985). Figure 2 shows the topographic elevation changes measured in the period 1988-1991.

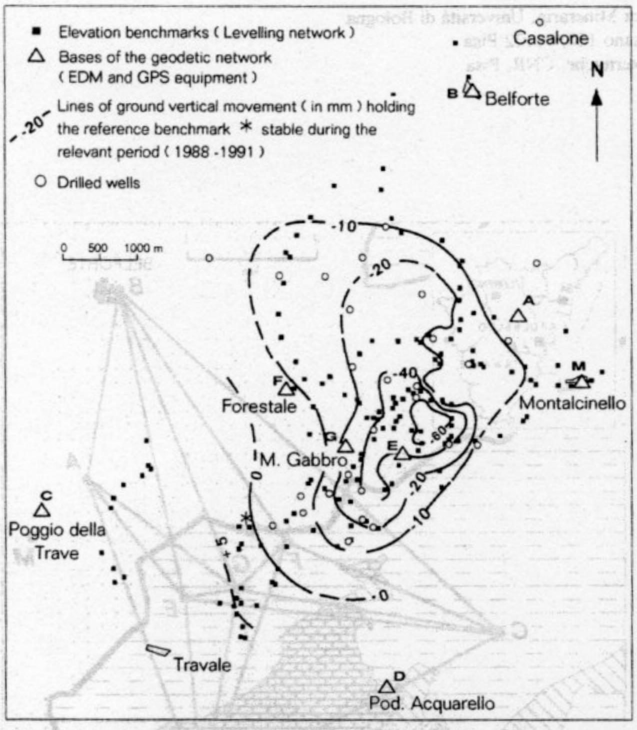

Fig.2: Elevation changes in the Travale - Radicondoli area during the 3 year period (1988 - 1991)

2.2. Micro gravity Variations (Δg)

A precision gravity network was set up in 1979 to acquire information on any density variations or fluid mass movements within the reservoir. Gravity measurements were repeated several times. The Δg residuals reached values of only a few tens of μGal, suggesting a quasi-equilibrium condition of fluid mass in the reservoir, the latter being still far from depletion (di Filippo *et al.*, this Congress).

2.3. Horizontal Network

A geodetic network was then set up and the first measurements made in 1988, mainly to monitor the horizontal ground displacements occurring as natural neotectonic activity unrelated to fluid withdrawal, or induced by the exploitation of the geothermal field. This network consists of 7 benchmarks located across the main distensive fault system at the SW boundary of a regional graben-shaped tectonic feature that trends in the Apenninic direction (Figure 1) (Beinat at al., in press). This important fault system, with a local total throw of the order of 1000 m, is considered to be a preferential pathway for hot geothermal fluids rising from depth (Celati *et al.*, 1973).

The 7 points are located as follows (Figure 1):

- C and D are on the uplifted side of the main tectonic feature, where the Mesozoic carbonatic formation outcrops;
- F, G and E are located in the zone where very high-to-maximum subsidence values and geothermal fluid production occur;
- A, M and B are in the area corresponding to the main tectonic depression. A was destroyed in 1992.

As regards the terrain in which they are embedded:

- C and D are buried pillars in Cretaceous flysch terrain on the top of the hills;
- E and F are benchmarks installed on outcropping rocks;
- G is on a specially constructed monument on the top of a wooded hill made up of Gabbro rocks;
- B is on the top of a medieval tower built on a bedrock of cemented conglomerates;
- M is on the top of the bell-tower of a church several centuries old. This benchmark was set up and measured for the first time in 1994, in place of the one destroyed in 1992 (A).

The five points B, E, F, G and M are directly connected to the main topographic network by precise spirit levelling.

2.4. EDM Measurements

Since 1988, all the slope distance measurements have been performed using a Kern Mekometer ME5000, the most precise distance meter currently available. Due to its high intrinsic precision (0.1 mm ± 0.1 mm/km) the fluctuations of the air refraction index along the path of the laser beam constitute most of the measurement error. Special care was taken in the determination of temperature, pressure and humidity profiles along the sides of the network during the measurement operations. For this purpose the records from the portable meteorological instrumentation at the two sides of the measurement line were compared and integrated, from time to time, with the data coming from the fixed meteorological stations owned by ENEL and operating inside the area.

2.5. Network Adjustment

For all the measurement campaigns (1988, 1990, 1991 and 1994) carried out so far, 2-dimensional and 3-dimensional network adjustments were executed using the least squares method, with the further condition of minimal norm of the vector of the unknowns (Crosilla and Marchesini, 1983). Operating a completely free network adjustment in the same arbitrary local reference system (with the Y axis towards North and the X towards East, approximately) for all the campaigns, permits us an easy comparison of the relative position of the nodes of the network and their pseudo-displacements at the various epochs. To increase the redundancy of the design matrix of the network, azimuth angles and their m.s.e. were also considered in the computation. Trigonometric height determinations, with contemporaneous reciprocal zenith angle measurements to minimize the effects of the refraction coefficient, were carried out to connect C and D, located on top of hills, to the levelling line so as to reduce the distance measurements to ground-level. Limited to this application only, the lower precision of the trigonometric method does not significantly affect the precision of the adjustment.

Distances, levelling height differences and azimuth angles were processed at the same time using scientific software that also corrects the distance measurements for the atmospheric effect. The a priori mean standard errors (σ_D) used in the adjustment were computed with the non-linear formula of Marchesini (1990). The a posteriori sigma zero (σ_0) were 1.22, 1.56, 0.72 and 0.75 respectively.

Figure 3 represents the pseudo-displacements computed from the differences between the adjusted horizontal co-ordinates of the four campaigns, along with the error ellipses at 95% of the last epoch adjustment. Table 1 gives the numerical data: *a* and *b* are 2.43 times the major and minor semiaxis of the error ellipses of the 1994 campaign, γ is the angle between the major semiaxis and the X axis.

Table 1: Pseudo-displacements at different epochs and 1994 error ellipses of the EDM measurements.

	Displ. 1990-1988		Displ. 1991-1988		Displ. 1994-1988		Error ellipses 1994		
Point	X	Y	X	Y	X	Y	*a*	*b*	γ
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(gon)
A	-14.02	-10.53	-6.25	-4.47	- -	- -	13.51*	6.54*	-27.19*
B	-18.78	-15.27	-12.28	-19.36	-12.07	-26.88	23.97	9.73	-14.99
C	5.97	10.87	-7.44	1.67	-1.73	-1.62	12.97	8.01	94.56
D	-9.49	-0.08	-13.49	5.41	-12.16	4.32	16.78	7.73	23.24
E	-0.97	16.08	11.62	30.23	-7.18	35.58	13.36	7.28	148.4
F	13.33	-10.14	6.88	-14.71	9.31	-3.92	14.33	8.89	6.35
G	9.93	-1.45	14.71	3.23	23.83	-7.48	11.34	9.14	-28.63

* Error ellipse 1991

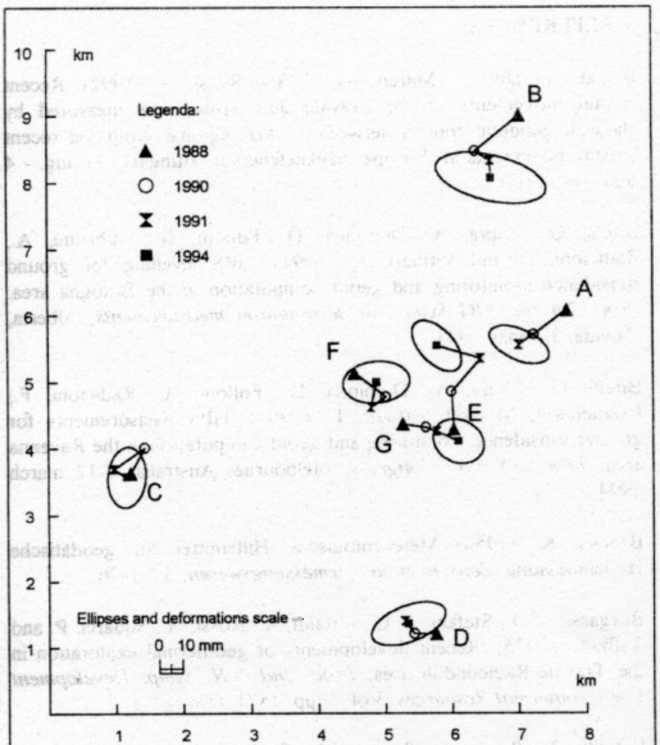

FIGURE 3: Error ellipses and pseudo-displacements of the benchmarks in the Travale network (EDM measurements).

2.6. GPS MEASUREMENTS

In order to test another complementary technique suitable for detecting crustal deformations, the GPS technique was also applied.

The advantages of GPS measurements with respect to traditional surveying methods are project simplicity, because it is not necessary to maintain visibility between the points of measurements, and operating simplicity.

The GPS technique has also been utilized with success in the control of crustal deformations during the last few years, for instance by Bitelli *et al.*, (1993) and Bitelli *et al.* (1994). A GPS campaign was therefore planned and carried out contemporaneously with the Mekometer survey, and the measurements on the geodetic network were conducted both by conventional geodetic instrumentation and by GPS satellite techniques. In this way a double check was made on ground displacements and the two methods compared.

Unfortunately only two GPS campaigns have been carried out, one in April 1990 and a second in May 1994, during the EDM-Mekometer measurements.

In the first campaign, April 1990, two Trimble 4000 SL single frequency and three Trimble 4000 SST double frequency receivers were used. The survey was carried out in two days and all the sessions were measured using an observation time of 90 minutes.

In the last campaign, May 1994, four Trimble 4000 SSE double frequency with 6th observable receivers were used. The survey was carried out in two days using from 30 to 90 minutes of observation.

The periods of observation were shorter in 1994 because of the development of GPS data elaboration software. During the first campaign the static method was used for measurements, while in 1994 it was possible to apply the "Fast Static" survey that permits shorter sessions (up to 20-40 minutes length) for baselines as short as the sides of the Travale geodetic network, maintaining the same accuracy.

Unfortunately the double frequency receivers in the 1990 campaign did not work properly, so only the L1 frequency was utilized for the data elaboration. The data were elaborated with the program Trimvec of Trimble Ltd. All the quality control parameters (RMS and Ratio) were always within the significativity range.

The data of the 1994 campaign were elaborated with the Topas Turbo program (by TerraSat).

In order to compare the coordinates of the two campaigns the data of the 1990 measurements were also elaborated with Topas Turbo software to homogenize the results.

All the baselines were elaborated using the same emanating coordinates of point B as the fixed point of the network.

The baseline solutions were good and passed the internal quality tests of the software. All the cycle slips were solved and the ambiguities computed: all the solutions are fixed.

Using only single frequency observable for the 1990 campaign did not create any problems, because the L1 solution is probably the best in a network like that of Travale-Radicondoli, where the baselines range from only 0.6 to 8 km.

After elaboration of the baselines, the program made a network adjustment and provided the values of the coordinates shown in Table 2 and 3.

TABLE 2: Adjusted ellipsoidal WGS-84 coordinates in the 1990 campaign.

Point	Latitude N (° ' ")	Longitude E (° ' ")	Height h (m)	σ_N (mm)	σ_E (mm)	σ_h (mm)
B	43 13 58.0599	11 3 41.7346	629.137	0.0	0.0	0.0
A	43 12 23.0283	11 4 12.2793	485.278	7.6	4.9	17.2
C	43 11 3.8028	10 59 24.6054	913.980	7.5	4.8	17.0
D	43 9 45.3647	11 2 45.4396	709.608	7.0	4.6	16.1
E	43 11 25.2629	11 2 57.5677	540.095	5.9	3.9	14.7
F	43 11 52.5324	11 1 51.8053	530.969	6.8	4.5	15.1
G	43 11 27.7341	11 2 23.6353	624.277	5.9	4.1	14.6

TABLE 3: Adjusted ellipsoidal WGS-84 coordinates in the 1994 campaign.

Point	Latitude N (° ' ")	Longitude E (° ' ")	Height h (m)	σ_N (mm)	σ_E (mm)	σ_h (mm)
B	43 13 58.0599	11 3 41.7346	629.137	0.0	0.0	0.0
M	43 11 53.6655	11 4 48.2840	456.361	4.4	3.3	7.7
C	43 11 3.8031	10 59 24.6052	913.925	5.2	3.4	8.8
D	43 9 45.3648	11 2 45.4392	709.544	4.3	3.4	8.4
E	43 11 25.2636	11 2 57.5682	540.071	4.2	3.3	7.0
F	43 11 52.5327	11 1 51.8036	531.010	4.7	3.5	7.8
G	43 11 27.7342	11 2 23.6363	624.320	4.3	3.2	7.6

TABLE 4: Differences in ellipsoidal WGS-84 coordinates between 1990 and 1994 measurements.

Point	Δ Latitude 1994-1990 (m)	Δ Longitude 1994-1990 (m)	Δ Height 1994-1990 (m)	$\sigma_{\Delta lat.}$ (mm)	$\sigma_{\Delta lon.}$ (mm)	$\sigma_{\Delta h}$ (mm)
B	Fix	Fix	Fix			
C	0.009	-0.005	-0.055	9.1	5.9	19.1
D	0.003	-0.009	-0.064	8.2	5.7	18.1
E	0.021	0.014	-0.024	7.2	5.1	16.3
F	0.009	0.002	0.041	8.3	5.7	17.0
G	0.003	0.023	0.043	7.3	5.2	16.4

The standard deviation of the 1994 campaign is slightly better than in 1990, moreover the receivers used in 1994 had a better signal acquisition capacity.

In Table 4 the differences between the adjusted coordinates of the two campaigns are shown. The values of latitude and longitude variation were utilized to compute the coordinate differences in metric system for an average latitude of the area.

The planimetric coordinate differences of the points are not significant. The values of point E, although higher than the others, are still within the limit of the 3σ confidence region.

It is remarkable that both the GPS and EDM methods highlighted the same trend in planimetric coordinate variation.

The altimetric differences also appear to be not significant, being within the limit of the 3σ confidence region, except for point D, which exceeds the limit but only by 1 cm.

The trend of the vertical displacements, showing a relative positive vertical movement of the central area, contradicts the spirit levelling results, which show a relative negative vertical displacement of that same area (Geri *et al.*, 1984).

This result confirms the doubts that have already emerged in other GPS measurements on the reliability of the GPS technique for control of ground vertical displacements, where the latter have a magnitude of the order of a few centimetres.

Errors on repeated measurements have a significant effect on all the height determinations and their values often exceed the internal error parameters of the measurements obtained from data elaboration and network adjustments.

Such errors are principally due to satellite orbit indeterminations, to the tropospheric model parameters and to the lack of invariability of the reference system.

3. CONCLUSIONS

Monitoring of both the horizontal and vertical displacements in the area with combined EDM and GPS techniques has led us to make some observations.

On a time scale of a few years, the small values detected for the horizontal displacements emphasize the substantial stability of the area under examination, in spite of the intense fluidodynamic effects on the rocks of the reservoir during the geothermal exploitation.

Other parameters of the geothermal field corroborate this conjecture, revealing a very slow and regular evolution of the induced effects, which merely consist of depressurisation of the reservoir and subsidence of the central part of the area (di Filippo *et al.*, this Congress).

Regarding the vertical displacements occurring on the vertical plane (height variations), it should be noted that the plano-altimetric network extends to the main morphological structures and is connected to the levelling line by 5 bases over 7.

We were thus able to monitor a wider and almost inaccessible area compared to that of the levelling network. However, this introduces a casual variability in the experimental data that leads to a consequent worsening of the level of confidence of the data themselves.

We must emphasize that most of the casual variability is determined by "real" variations of the physical experimental environment of the large mountain masses constituting the frame of the geodetic network. This is subjected to natural and irregular deformations induced by daily and seasonal thermal oscillations, terrestrial tides, swelling in phase with the periods of great meteorological rainfall, etc.

The results are shown in Tables 1 and 4 and in Figure 3. The data of the vertical displacements show little coherence with those obtained by the precise levelling monitoring: this is not a drawback, particularly considering the small number of GPS measurements and the small values of the measured variations, practically at the limits of the confidence level.

As far as horizontal changes are concerned, and those obtained with EDM measurements in particular, the displacement vectors of benchmarks A, B, E, F and G trend towards the part of the area with the highest values of subsidence. The vector of benchmark D, quite far from the exploited area, is less affected by induced stress: its trend, although less direct, runs towards the nearest peripheral part of the subsiding area.

Benchmark C, sited in a relatively remote position, seems practically unaffected by the stress induced by the subsiding area, both as regards its displacement trend and its absolute value.

On the whole, the impact of the geothermal area is evident, producing a stress field that runs roughly towards the subsiding area of the exploited geothermal field.

It is worth noting that the sum of the absolute values of the displacements over the entire period, reaches an appreciable total value, with an average rate per year that is comparable with the subsidence rate, up to 1 cm/year.

It is not possible to recognize any particular behaviour connected with the local geological features, although the hypothesis of a component ascribable to a preexisting stress field of tectonic origin cannot be excluded.

4. REFERENCES

Beinat, A., Dini, I., Marchesini, C. and Rossi, A. (1992). Recent crustal movements of the Travale geothermal area measured by classical geodetic control network. IAG regional symp. on recent crustal movements in Europe, Székesfehérvár, Hungary, 31 aug. - 4 sept. *[in press]*.

Bitelli, G., Capra, A., Dominici, D., Folloni, G., Gubellini, A., Radicioni, F. and Vittuari, L. (1993). GPS levelling for ground subsidence monitoring and geoid computation in the Bologna area. *Proc. 7th Int. FIG Symp. on deformation measurements*, Alberta, Canada, 3-5 may 1993.

Bitelli, G., Capra, A., Dominici, D., Folloni, A., Radicioni, F., Unguendoli, M. and Vittuari, L. (1993). GPS measurements for ground subsidence monitoring and geoid computation in the Ravenna area. *Proc. XX FIG Congress*, Melbourne, Australia, 5-12 march 1994.

Brocks, K. (1950) Meteorologische Hilfsmittel für geodätische Höhenmessung. *Zeitschrift für Vermessungswesen*, S. 71-76.

Burgassi, P. D., Stefani, G. C., Cataldi, R., Rossi, A., Squarci, P. and Taffi, L. (1975). Recent developments of geothermal exploration in the Travale-Radicondoli area. *Proc. 2nd U.N. Symp. Development Use Geothermal Resources*, Vol. 3, pp. 1571-1581.

Cataldi, R., Rossi, A., Squarci, P., Stefani, G. C., and Taffi, L. (1970). Contribution to the knowledge of the Larderello geothermal region, remarks on the Travale field. *Geothermics* special issue 2, pp. 587-602.

Celati, R., Musé, L., Rossi, A., Squarci, P., Taffi, L. and Toro, B. (1973) Geothermal prospecting with magnetotelluric method (M.T.-5-E.X.) in the Travale area (Tuscany, Italy). *Geothermics*, 2, pp. 186-190.

Crosilla, F. and Marchesini, C. (1983). Geodetic network optimization for the detection of crustal movements using a Mekometer. *Bollettino di Geodesia e Scienze Affini*, vol. XLII, pp. 301-315.

Di Filippo, M., Geri, G., Marson, I., Palmieri, F., Perusini, P., Rossi, A. and Toro, B. (1985). Exploitation, subsidence and gravity changes in the Travale-Radicondoli geothermal field. Int. symp. on geothermal energy, august 1985, Kailua Kona, Hawaii. *Geothermal Resources Council Transaction*, vol. 9-I, pp. 273-278.

Di Filippo, M., Dini, I., Marson, I., Palmieri, F., Rossi, A. and Toro, B. (1995). Subsidence and gravity changes induced by exploitation in the Travale-Radicondoli geothermal field (Tuscany, Italy). *[This congress]*.

Geri, G., Perusini, P. and Rossi, A. (1984). Topographic changes in the Travale-Radicondoli geothermal field during the first ten years of exploitation. 3rd Int. Symp. on Land Subsidence, Venice, Italy, 19-25 march 1984.

Marchesini, C. (1990). Zum Fehlermodell bei Streckenmessungen. *Zeitschrift für Vermessungswesen*, vol. 115, pp. 481-488.