GEOTHERMAL RESEARCH IN THE MONTEVERDI ZONE (WESTERN BORDER OF THE LARDERELLO GEOTHERMAL FIELD)

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ABSTRACT

The Monteverdi zone, which extends acrosss approximately 25 km^2, is sited on the western border of the Larderello geothermal field From a geological point of view, this zone **is** a structural high of the metamorphic substratum. showing **a** tectonic denudation of the carbonatic-evaporitic sequence which usually constitutes the shallow geothermal reservoir in the Larderello field, the cap-rock lies directly on the metamorphic formations. No fractured level occurs just below the cover. The producing levels cannot be attributed to any specific lithotype or formation; they are found at elevations of -1500 to -3300 m s.l. and correspond to different metamorphic rocks. Formation-temperature versus depth shows a conductive gradient in the cover. decreasing between -1500 and -3300 m because of the presence of producing levels, in this reservoir the temperature ranges from 270 to 370°C and the pressure is roughly uniform, close to 7 MPa From the values of the conductive thermal gradient, observed in the impermeable parts of the metamorphic substratum, a deep heat flow of about 260 mWm^{-2} is estimated

ENEL **S** p.A. has begun a project for drilling a total of 30 wells and installing two units of 20 MW each

1. INTRODUCTION

The Monteverdi zone is located in the western border of the Larderello geothermal field, a well defined boundary, constituted by dry or non commercial wells, has not yet been found The explored area is included approximately between the H F contours 200 and 600 mWm^{-2} (Baldi *et al*, 1994); it extends for about 25 km^2 in a hilly area with elevations ranging from 200 and 400 m a s l (Figure1)

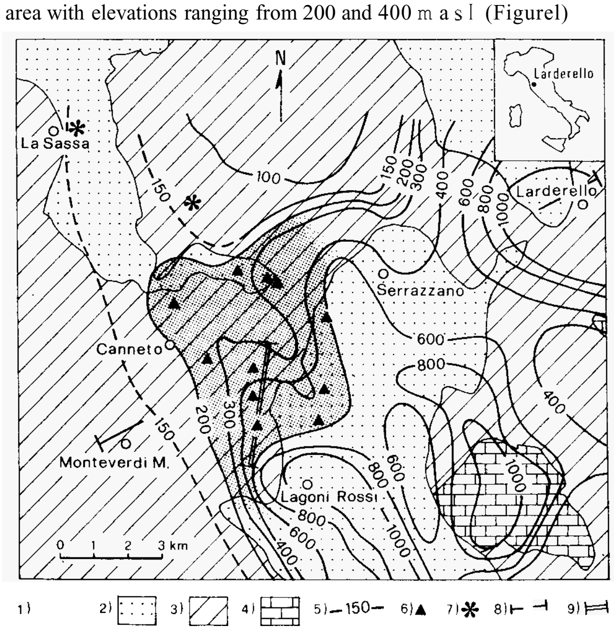

Figure 1. Geological sketch map **of** Monteverdi geothermal zone 1)Study area 2)Neogenic Formations (U Miocene-L Pliocene) 3)Flysch Facies Formations 'Ligurids s l (L Cretaceous-U Eocene) 4)Tuscan Nappe (Triassic - L Miocene) 5) Heat **flow** (mWm^{-2}) 6)Geothermal wells **7)** Surface mineralizations 8) Geological cross section **9)** 3D **Seismic** line

The shallow gradient boreholes showed a thermal picture (gradients 1 - 1.5°C/10m) that, once extrapolated at the bottom of the cover, was not encouraging in order to find high temperature fluids as in Larderello zone In fact, the rare drilling attempts that investigated only the high part of the potential reservoir gave negative results

The success of the deep geothermal exploration (2500-3500 m) in Larderello and in the Amiata fields, which began in the early 1980's, suggested a consideration also of the Monteverdi zone, where 23 wells, mostly directional and with a maximum depth of 3658 m, have been drilled up to now (Figure 1) They found about 300 t/h of fluid Seven more wells will be drilled in the next future

On the basis of the results obtained from the wells so far drilled and from an estimate of the fluid stored in the reservoir, within a short time two power plants of 20 MW each will be put into service

2. GEOLOGIC-GEOPHYSIC CHARACTERIZATION

The Monteverdi zone is crossed by a relative structural high of the 'Tectonic Wedges Complex" (Pandeli *et al.*, 1991). mainly of phyllitic and quartzose lithotypes and of the metamorphic substratum, with a NW-SE trend (Figure 2)

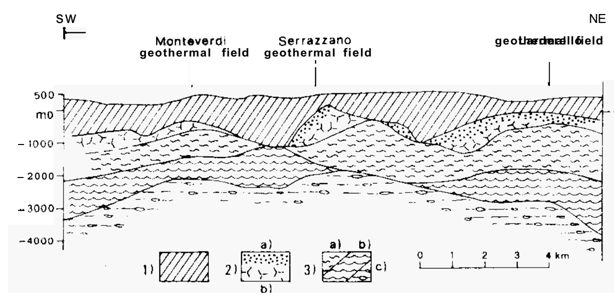

Figure 2. Geological cross section 1) Neogenic and Flysch Units (cap-rock) **2)** Tectonic Wedges Complex a) mostly **carbonatic-anhydritic rocks** (upper **reservoir)** b) mostly quartzites and phyllites 3) Metamorphic Basement (lower basement) a) phyllites b) micaschists c) gneiss

The stratigraphic sequence from top to bottom **is** comprised of:

1- Mainly argillaceous neogenic formations (Upper Miocene-Lower Pliocene Age), when present; Flysch facies formations (Ligurid Units) (Lower Cretaceous - Eocene Age), total thickness **is** of 800-1000 m;

2- 'Tectonic Wedges Complex", made up of an irregular phyllites, quaitzites and quartzose conglomerate assemblage, the thickness is variable, on the average of 200-300 m, the carbonatic-anhydritic level constituting the shallow reservoirs of the Serrazzano, Lagoni Rossi, Larderello fields. is absent here,

3- 'Polymetamorphic Complex" constituted by. phyllites (mean thickness 500 m); micaschists (mean thickness 600 m), separated from the underlying formation by mylonitic horizons (Bertini *et al.*, 1994); gneiss, representing the deepest lithotype and whose thickness **is** unknown. In the deepest part of this complex there are strong thermometamorphic effects, according to Barberi and Franceschini (1993), at least a part of the gneiss would be paragneiss deriving from thermometamorphism of micaschists Aplitic and microgranitic veins, dated 3.8 Ma by the K/Ar method (Villa *et al.*, 1987), were also found.

Since the 'Tectonic Wedge Complex" is not very permeable, together with Neogenic and Flysch formations, they form the cap-rock; the

potential reservoir is represented by the 'Polymetamorphic Complex".
According to Franceschini (1993) a pliocenic granitic body, belonging to the Tuscan anatectic magmatism and to which thermometamorphism would be linked, is inferred. Such an intrusion does not seem responsible for the actual thermal anomaly which is probably linked to a Quaternary rejuvenation of magmatic activity.
In the study area, active thermal manifestations do not exist, however, a few more kilometers north we find traces of fossil hydrothermal activity (Figure 1) witnessed by calcite, quartz and magnesite, sphalerite, Ag-galena and chalcopyrite mineralizations, filling high-angle NW-SE faults.
This "Apennine" tectonic trend is confirmed at depth by mesostructural analysis on oriented cores and by FMS logs interpretations, showing NW-SE extensional fractures dipping 70°-80" towards NE (Figure 3). Further evidence of the NW-SE tectonic trend could also be given by the preferential trend of directional wells towards the NE

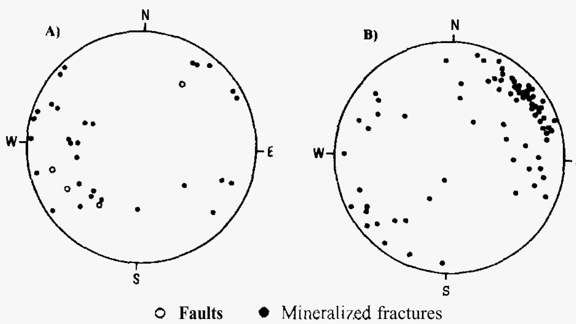

Figure 3. Schmidt stereografic projection (loweremisfere) A) Onented cores B) Formation MicroScanner log

Besides this regional tectonic style, locally there is the evidence of natural hydraulic fracturing (Gianelli and Bertini, 1993) The above mentioned fractures are, in most cases, sealed by hydrothermal mineralization

The main geophysical characteristics are summarized in Figure 4.
Monteverdi zone is marginally sited in the wide gravimetric minimum of Larderello-Travale region The seismic tomography, effected on data of local and remote earthquakes, shows a wide low seismic velocity body whose top is located at about 7 km depth; it seems to extend to depths greater than 20 km and it can be interpreted as a still partially melted acidic intrusion (Foley *et al.*, 1990)
Two important seismic horizons were detected by reflection seismic profiles (Figure *5):* the deepest and more energetic one (called K), is present in the entire Southern Tuscany at notable depths (7-9 km), it is here located between 4 and *6* km
The second horizon (called **H)** is less energetic and occurs at a depth of about 3500 m, sometimes it seems to correspond to reservoir fractured levels (Batini *et al.*, 1990)
The hydrothermal mineral distribution with depth shows that the equilibrium temperature of the main minerals **is** in conformity with the current temperatures (calcite, quartz, chlorite etc. up to 250°C and epidote, K-feldspar, etc over 250°C). This, together with the dating of 60-10 ka, obtained by $^{230}Th/^{234}U$ method on some secondary mineralizations, would indicate that Monteverdi hydrothermal system is very recent
Fluid inclusions inside secondary mineralizations has permitted to reconstruct the evolution of the system: from an early magmatic stage, with high TDS and LiCl-rich, subsequently the fluid evolved towards a mixing with a meteoric component (Cathelineau *et al.*, 1994, Petrucci *et al.*, 1993)

3. OUTLJNE OF PHYSICAL AND CHEMICAL FEATURES OF THE RESERVOIR

The western side of the Monteverdi zone is characterized by thermal gradients and heat flows in the cover which are relatively low (gradients of 1°C/10 m or slightly higher, heat flow between 200 and 400 mWm^{-2}); the eastern side, which borders on the operative fields of Serrazzano and Lagoni Rossi, is instead characterized by a rapid increase in the above mentioned parameters (see Figure 1)

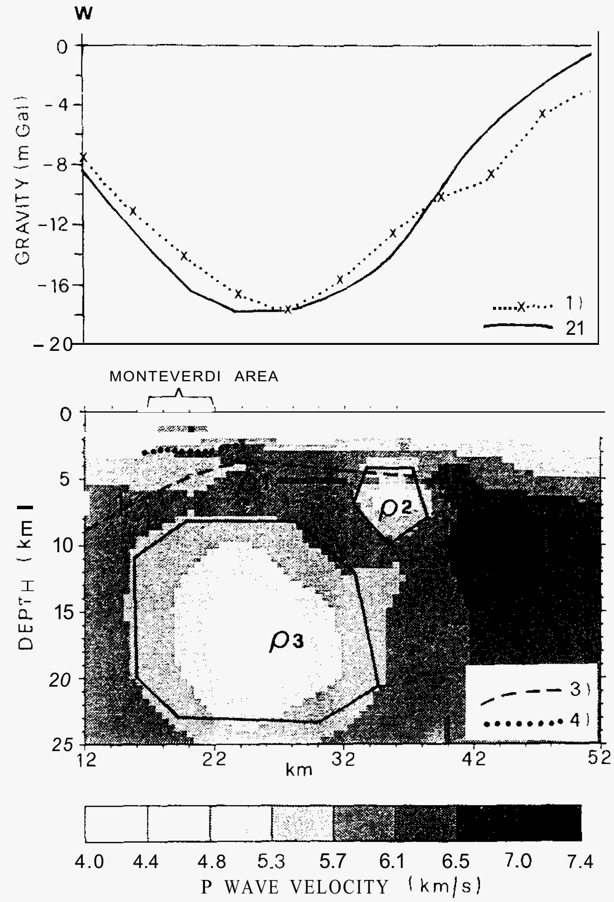

Figure 4. Two-dimensional modeling of the remaining gravity anomaly after stripping of the geological formations crossed by **wells** The model is created according to the main seismic tomographic features The densities are. ρ_1=2.7g/cm^3 (background). ρ_2= 2 6g/cm^3, ρ_3= 2 58g/cm^3. (1)observed gravity **values** (after stripping). (2)computed gravity values. (3)K-seismic horiron. (4)H-seismic horizon

The temperature trend along with the depth and distribution of the main productive fractures (Figure *6)* provides the following indications
Almost all the formation temperatures fall between curves **A** and B, the reservoir is represented by convective flows between the two curves curve **A** outlines the conductive thermal gradient (1 4°C/10 m) in the cover, curve B (0.84°C/10 m). underlined by a series of measurements taken in dry wells, can be interpreted as a conductive gradient at the reservoir base
Very few points, concerning the northern side of the Monteverdi zone, fall below curve B; they belong to the wider thermal context of Larderello field Here infact a similar aligment of thermometric measures, taken in marginal and purely conductive dry wells, show a deep thermal gradient with the same trend as Monteverdi's curve "B", but with a downward shifting
In Figure *6* is also shown the cover thermal gradient of Serrazzano and Lagoni Rossi fields (C) Comparing this gradient with that measured in the cover of Monteverdi field, the effect of the different reservoir depths becomes evident Here the first fractured level is sited at about -1500 m s l (or 1800-1900 meters from the country plain) whereas in the Serrazzano and Lagoni Rossi fields the reservoir top, which is very permeable, is located at heights near sea level
The formation-temperatures corresponding to the top of Monteverdi reservoir (between elevations of -1500 and -2000) is about 270°C The deepest part of the reservoir (up to about -3300m) is instead characterized by temperatures of 340-350°C (Figure 7)

The reservoir pressures, ranges between 6 and 7 5 MPa, independently from the fracture elevations.
As, up to now, prolonged production tests have not been carried out, a reliable reconstruction of the chemical composition of the formation fluid was not possible More trustworthy, instead, are the data up to now obtained relative to the gases

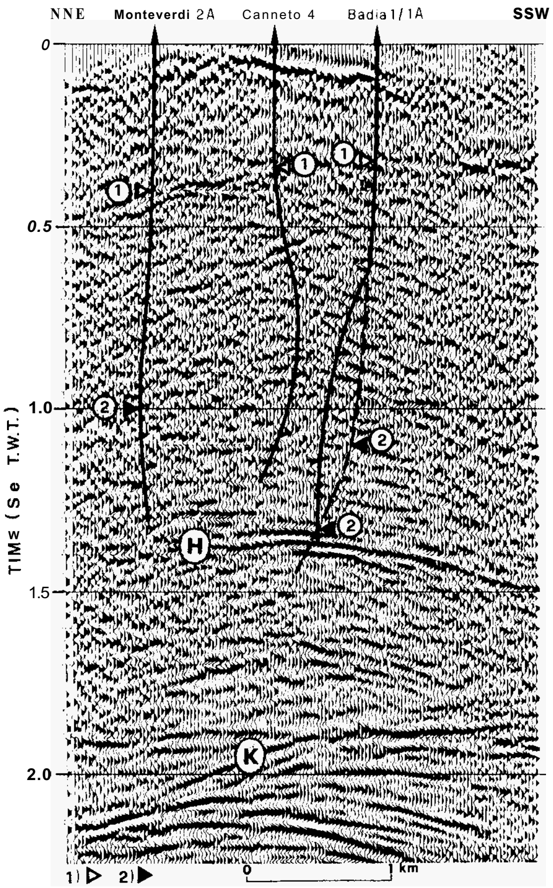

Figure 5. Section of the 3D seismic profile uith NNE-SSW trend and crossing Monteverdi 2A Canneto 4, Badia 1 (solid **line)** and Badia 1A (dashed **line)** well sites (see Fig 1) Reference time from 200 m a s l Depth/time conversion of the projection of the ucll paths **is** done by VSP Velocity-function
(1) Flysch-Polymetamorphic Complex boundary
(2) Productive laver not exploitable in Badia 1A **well**
(H) H seismic horizon (K) K **seismic** horizon

In table 1 these gases are compared to those of Serrazzano field The more noticeable difference is the higher content of H_2 in the gas of Monteverdi, the high H_2 content can be considered coherent to the measured reservoir temperatures

Table 1. Mean gas composition of Monteverdi and **Serrazzano** field

	CO_2	H_2	H_2S	CH_4	N_2
Monteverdi	83%	8%	3.5%	3.5%	2%
Serrazzano	93%	2.5%	2.5%	1.5%	0.5%

From the composition of Monteverdi gases and considering a homogenous steam phase, one can obtain equilibrium temperatures in the reservoir ranging between 330 and 370°C with the corresponding CO_2 pressures between 0 023 and 0.066 Mpa.

4. CONCEPTUAL MODEL

The main geological-geophysical characteristics of the Monteverdi zone (Figure 7) can be summarized as follows.
The wide gravimetric minimum, which covers the entire Larderello-Travale region, encloses, even if marginally, the study area.

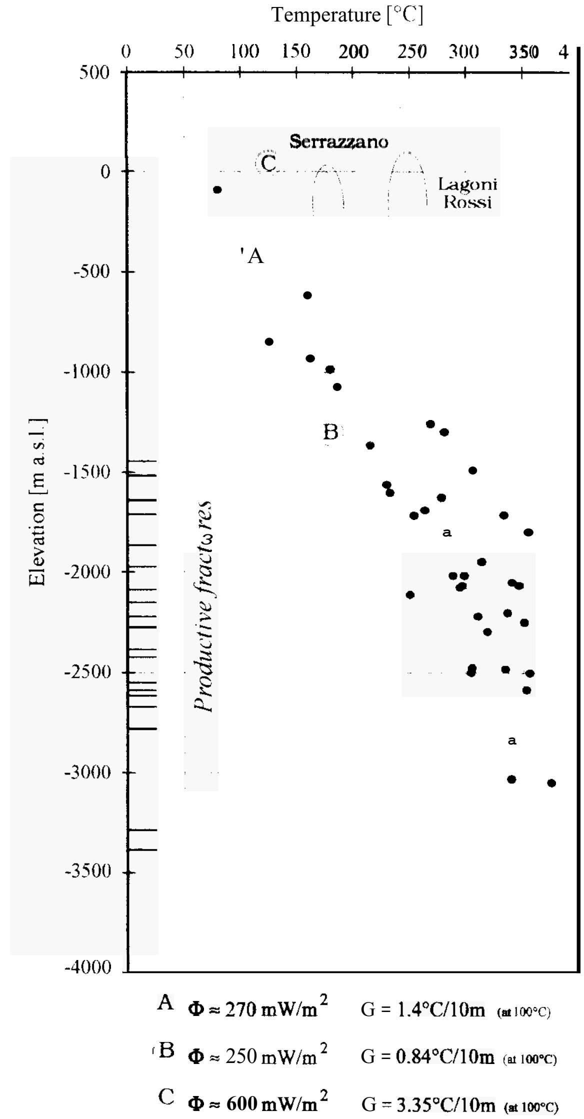

Figure 6. Formation-temperature versus elevation and fractures distribution in Monteverdi field.
A. B. *C* conductive gradients (conductivity decreasing with temperature according to Somerton . 1992)

The presence of a Quaternary low seismic velocity body starting from a depth of 7 km is inferred from seismic and petrologic evidences, the presence, at shallow depths (4-6 km) of the seismic horizon **K is** shown by reflection seismic profiles
Deep conductive gradient (curve "B" in Figure 6), assuming an average thermal conductivity of metamorphic rocks of 3.7 $mWm^{-1}°C$ (at room temperature), allows to estimate the basal heat flow of the Monteverdi zone in the order of 250-260 mWm^{-2}. This value is essentially in agreement with that obtained by similar extrapolations for the Larderello-Travale region Therefore, in terms of deep heat flows, the Monteverdi zone, in spite of bordering the western side of the so far productive Larderello field, can be considered an integral pan of it.
In reality, it's necessary to observe that the temperatures of the deepest levels in Larderello s.l are, at equal elevation, a little lower than those of Monteverdi. This could be caused either by a lower depth of the heat source or by a greater efficiency of fluid transfer in Larderello This would imply an upward transfer of heat with a consequent heat removal from the deeper levels.
The different slopes between the conductive thermal gradient measured in the cover and the gradient measured in the deepest conductive levels of the reservoir can be related to the amplitude and intensity of convective phenomena In Figure 6 it can be seen that in the Monteverdi field a rather small angle between the two curves "**A**" and "B" should indicate the lack of a proper reservoir.

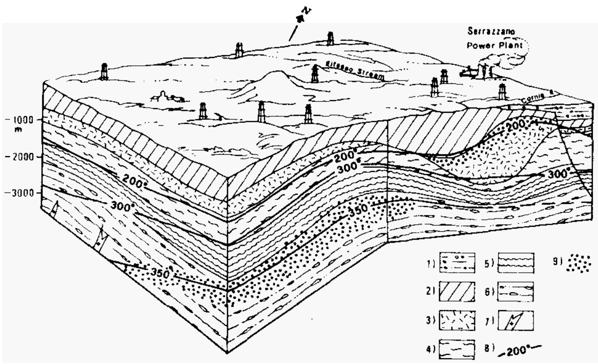

Figure 7 Geological and thermic block diagram of the Monteverdi field 1) Neogenic sediments 2) Ligund Units *3)* Tectonic Wedge Complex 4) phyllites *5)* micaschists 6) gneiss 7) granitic dykes 8) Isotherms (°C) 9) Productive levels

The different development of the convective circulation of fluids in the reservoir distinguishes the Monteverdi zone from that of Larderello

Even if well-testing effected up to now didn't last long enough to be completely trustworthy, they show that the entities of the fractures and therefore the average reservoir permeability connected with them, could be relatively poor

The fracturing extends, even if discontinuously, over a wide interval of metamorphic rocks (from -1500 to -3300); inside each well it's concentrated in specific levels, independently from lithology

The presence of hydraulic fracturing breccias, steeply dipping fractures and microfaults (70° - 85°), with a NW-SE direction as the main regional. structures, together with what we have above mentioned about fractures distribution, can be explained by the fracturing model described by Norton (1984); two main mechanisms could have acted in time. the first one connected with a stress field controlled by magmatic intrusions, with hydraulic fracturing phenomena, and, subsequently, the other characterized by a regional stress field of tensional type, trending NE-SW.

The model explains also the geochemical evolution suffered by fluids, in fact, through the study of fluid inclusions, it has been reconstructed a gradual evolution from magmatic Li-rich fluids to a recent hydrothermal system, represented by a liquid phase, with a low salinity and a high component of surface water, in thermal equilibrium with the surrounding rocks. Most of these fractures are generally sealed by secondary mineralizations and they seem not to give important contribution to permeability. Actually, productive fracture distribution, reconstructed by means of geological cross section and reflecting seismic horizons (such as **H** horizon) (Batini *et al.*, 1990) shows the existence of preferential subhorizontal fractured belts, whose origin is not yet well known.

The reservoir is characterized by a pressure ranging from 6 to 7.5 MPa and temperatures that vary from 270" to 350°C (Figure 6); such thermodynamic conditions are responsible for the presence of a saturated level in the top of the reservoir, passing to a superheated zone towards the bottom.

The relatively high pressure values indicate a poor lateral connection with fields under exploitation in the nearby (Serrazzano and Lagoni Rossi), where pressures, due to exploitation, don't exceed 10-30 bar

The Monteverdi zone has. likely, conditions similar to the initial ones of Larderello geothermal region The study of its evolution in response to exploitation will be very interesting

On the base of the experience acquired during the exploitation of the bordering fields, geothermal resource for electric production is estimated such as to supply two 20 MW units for at least 20 years This evaluation is based on the availability of superheated steam as well as adsorbed water vaporization and a probable recharge from external aquifers, once field exploitation has started

5. CONCLUSIONS

The study of Monteverdi zone represents an attempt **of** reconstructing a conceptual model of a geothermal system not yet expolited on the western margin of the Larderello geothermal field This study revealed that, as far as the deep geothermal anomaly is concerned, the Monteverdi zone belongs to the greater Larderello system.

However, as opposed to the situation of Larderello, the shallow reservoir has low permeability while the deep reservoir is represented by local fractured levels within the polymetamorphic complex The wells drilled so far have tapped fluids ranging from 270° to 350°C with pressures of about 7 MPa, which can be referred to a scarcely depleted reservoir compared to the nearby, intensely exploited geothermal fields of Larderello.

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