GEOTHERMAL CHARACTERISTICS OF THE PISA PLAIN, ITALY

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Abstract

The Pisa plain is mainly made up of neoautochthonous deposits that fill a wide graben striking NW-SE. The NE boundary of this graben is represented by the Pisan Mounts where thermal springs with temperature in the range 20-40 °C are distributed along the contact between these reliefs and the alluvial deposits of the Pisa plain. Thermal springs with temperatures around 35 "C are also located on the SW margin of the graben. Geochemical thermometers applied to S. Giuliano hydrothermal system, sited 5km north of Pisa at the foot of the Pisan Mounts, suggest a possible reservoir temperature of about 70-80 °C, the reservoir being made up of the carbonate-evaporitic complex of the Tuscan Nappe, representing the main regional aquifer and the most important reservoir of the exploited Tuscan geothermal fields. Results obtained from analysis of the temperature data and characteristics of the water produced from wells in the Pisa plain indicate geothermal gradients as high as 60 °C/km. Gravimetric data reveal the existance of a slightly bumpy structure of the denser substratum below the neoautochthonous sediments of the Pisa plain, with local structural highs at depths of about 700m b.g.l.. Thermal gradient wells indicate a temperature of 60-70 °C at the top of the denser substratum. Assuming the presence of a continuous carbonate regional aquifer, large volumes of thermal lluids from the regional circulation could exist at depth.

1. IN'I'HODUCI'ION

This paper presents the data gathered in the Amo river alluvial plain (province of Pisa, Tuscany. Italy), where we hypothesize the presence of a fluid reservoir with temperatures ranging from 60 to 90 °C, at a depth of 1000 - 2000m. Potential end-users of the low enthalpy geothermal resources already exist in the area. The interesting data obtained in this first phase of research should stimulate further exploration, by means of medium-depth drilling (about 1000m).

2. GEOLOGICAL - STRUCTURAL SETTING

The area examined in this survey (Fig. I) is characterised by complex stratigraphic and structural features. This wide, flat area, comprising the alluvial plains of the Arno and Serchio rivers, is bounded by the Pisan Mounts in the north-east, the Livornesi Mounts in the south-west and the gently rounded hills between Guasticce and Ponsacco in the south-east. The Pisa plain, bordered on the Tyrrhenian side by a belt of coastal dunes 5-6km wide, is made up, in its shallow part, by the alluvial silty-clayey deposits of the Anio and Serchio rivers (Upper Pleistocene-Present). Geophysical studies and deep hydrocarbon exploratory wells provide further information on the structural framework and the lithostratigraphic series underlying the shallow deposits (Ghelardoni *et al.*,1968; Mariani and Prato,1988; Mazzanti, 1994; etc.). The correlation between seismic and drilling data allows us to better define the shape of the Neogenic basin that characterises the coastal belt. This basin, which developed in the Upper Miocene-Pleistocene, extends southwards as far as Livorno, and northwards to the Ligurian Sea offshore. The basin trends NNW-SSE, shaped by a series of normal faults of varying throws within the pre-Miocene substratum; the westem, more sunken part of the this subsratum is made up of the Tuscan Series Oligocenic sandstones ("Macigno") (Tombolo I well, Fig. 2), and the eastern part by Mesozoic limestones (Poggio I and Pontedera I wells, Fig. 2) or the "Scaglia" (argillites) of the same series. The Upper Miocene-Pleistocene sequence reaches its maximum thickness on the coastal margin of the basin, and is made up of sandy-clayey formations about 1800m thick, overlain by a Pleistoccnic series of 700m thickness. The structural setting of the Neogenic substratum is shown in Fig. I and in the geological section in Fig. 3 These areas are characterised by widespread extensional tectonics, whose space-time evolution is linked to the fonnation of the Tyrrhenian basin (Boccaletti and Guazzone. 1972; Giglia, 1974). Again there is a normal "master fault" with a vertical throw of about 1500m, located on the eastern margin of the Neogenic coastal basin immediately west of Pisa, and bunches of antithetic faults located on its western margin, west of the coast line, about 10km away (Mariani and Prato, 1988). Another large tension fault, with more than 500m throw, is located at the foot of the western margin of the Pisan Mounts, connecting the villages of S. Giuliano Terme, Uliveto Terme and Cascina. After a series of tectonic events between the Messinian and the Upper Pliocene, which caused the opening of the various basins,with marine transgressions and regressions, a main tectonic subsidence event, at the beginning of the Pleistocene (1.6 Ma ago) is responsible for the present setting. with Pleistocene sediments transgressively overlapping both the coastal basin area and the inland area as far as the Pisan Mounts and the more inland parts of the Anio river basin. These sediments directly overlap the Mesozoic formations of the Tuscan Series in places. or outliers of the Pliocenic series.

3. HYDROGEOLOGICAL SETTING

The hydrogeological model of the area can he summarized as follows, from the bottom up (see Fig. 1):
a) a low permcability complex made up of the phyllitic-quartzitic formations of the Paleozoic-Triassic "Basement" (outcropping in the Pisan Mounts). This complex is the basement horizon of the regional acquifers.
b) above this complex are the carbonate Mesozoic formatioiis belonging to the Metamorphic Units and the Tuscan Nappe. the intense fracturing of these formations assumes preferential trends, with frequent karst cavities in places. These formations act as the main aquifer ofthe area and of a large part ofthe surrounding regions;
c) the carbonate metamorphic formations of the Tuscan Nappe are overlain by a terrigenous complex of medium-to-low permeability. made up of units ofthe Metamorphic Complex and the Tuscan Nappe;
d) an almost impermeable complex, made up of predominantly argillites as well as limestones and marly limestones with Jurassic ophiolites (allochthonous "Ligurids" Flysch of the Cretaceous-Eocene). The flysch outcrop in the Livornesi Mounts has not been encountered in the boreholes on the Pisa Plain;
e) a Neogenic series, made up of conglomerates. organogenic limestones, marls and gypsum (Upper Miocene), with high permeability in the coarse clastic levels and in the gypsum;
fig) a sandy-clayey Plio-Pleistocenic complex, almost impermeable in the clays (f), and with a mediun-to-high permeability in the sand and gravel levels (g).
h) alluvial, mainly silty-clayey, sometimes sandy deposits, which form the shallow cover in this area.

4. GEOCHEMICAL CHARACTERISTICS OF THE LOCAL HYDROTHERMAL SYSTEMS

Three low-temperature hydrothermal systems, S. Giuliano T.. Uliveto T. and Casciana T., are located in the vicinity of the margins of the study area, close to the contacts between the outcrops of the regional aquifer formations and the cover formations (the latter is located immediately southwards of the area shown in Fig. 1). The main regional aquifer formations, which also act as the geothermal reservoir of the exploited high temperature geotherinal fields of Tuscany, are made up of Mesoroic anhydrites and carbonates of the Tuscan Series.
The temperatures of the local hydrothermal systems vary between 23 °C (Uliveto) and 40 °C (S. Giuliano), with salinity in the range 1.2 (Uliveto) - 2.8 g/l (Casciana). The waters of S. Giuliano and Casciana

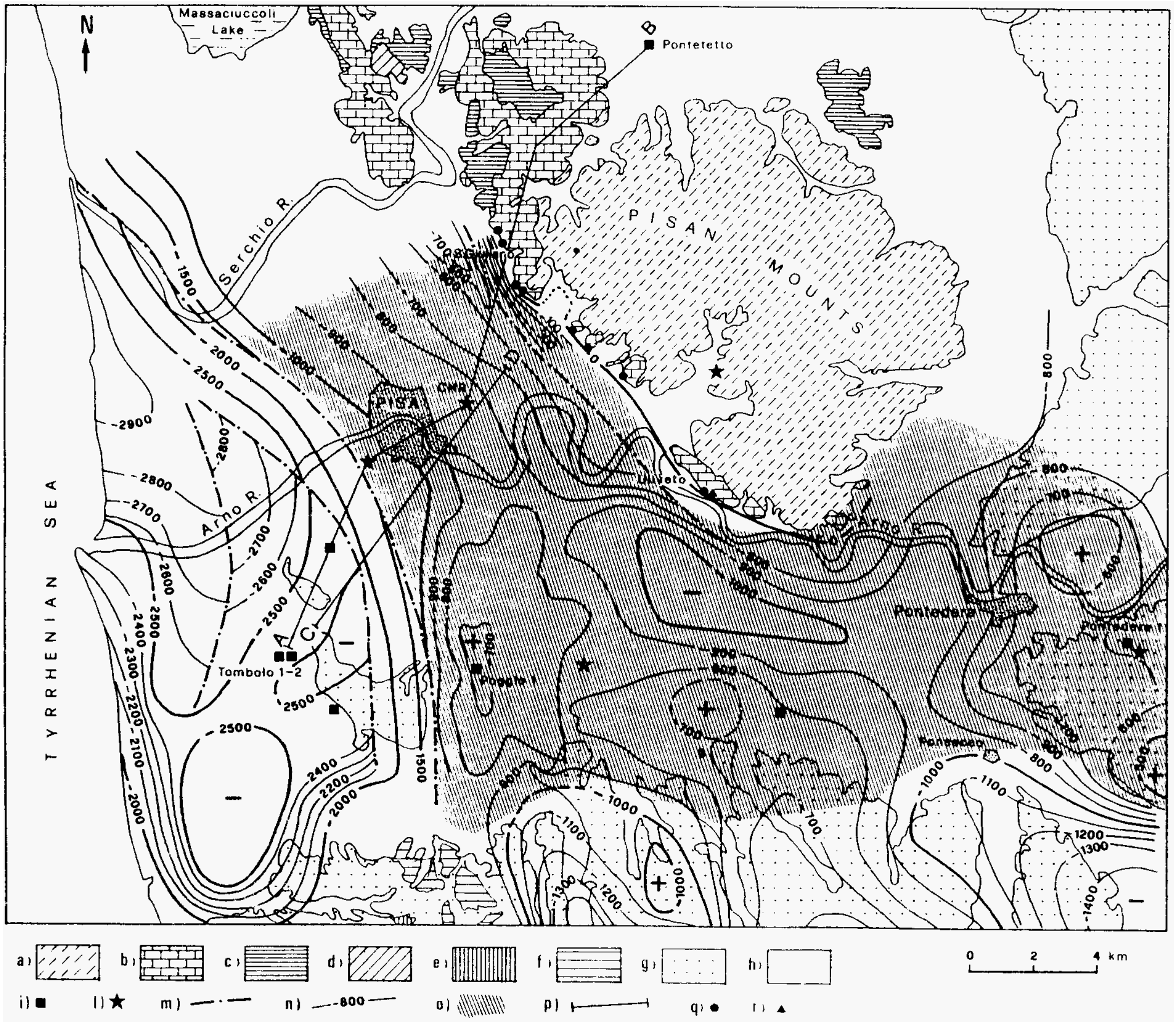

Fig. 1: Geological map; isobaths of the base of the neogenic formations.

a) Phyllites and quartzites (pre-alpine "basement"); metaconglomerates, quartzites and phyllites of the alpine orogenetic cycle (Medium-Upper Trias). - *Medium-low permeability*; b) Metacarbonates of the "Metamorphic Units": limestones and radiolarites of the "Tuscan Nappe". (Mesozoic). - *Medium-high permeability*; c) Terrigenous units of the "Metamorphic Complex" and "Tuscan Nappe" ("Macigno", "Pseudomacigno" and "Scaglia" formations; Upper Cretaceous-Oligocene) - *Medium-low permeability*; d) Argillites, silicic limestones, marly limestones (Flysch allochthonous units: "Ligurids"; Cretaceous - Eocene). - *Low permeability*; e) Conglomerates, detrital biogenic limestones, marls, diatomites and gypsums (Upper Miocene). - *Permeability generally high except marls and diatomites*; f) Clays (Plio-Pleistocene). *Very low permeability*; g) Sands and gravels (Plio-Pleistocene). *Permeability generally high*; h) Alluvial deposits and recent coastal sandy dunes (Holocene). - *Permeability variable from medium-high (terrigenous coarse deposits) to very low (silty-clayey deposits)*; i) Hydrocarbon exploratory deep well; l) Heat-flow measurement shallow well; m) Fault; n) Isobath of the base of the neogenic formations; o) Areas underlain by formations belonging to the carbonatic members of the Tuscan Series; p) Geological cross-section; q) Thermal spring; r) Thermal well.

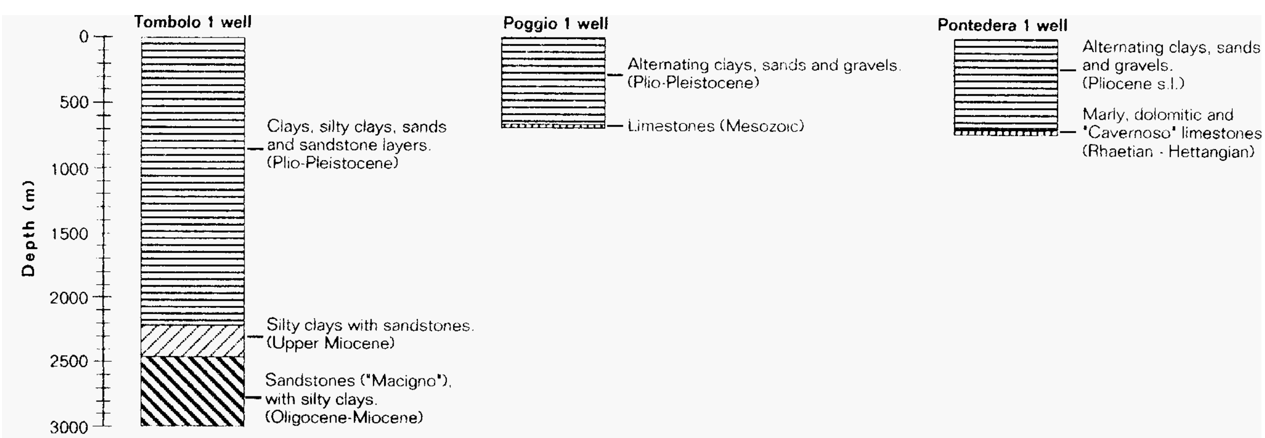

Fig. 2: Stratigraphies of deep hydrocarbon exploratory wells.

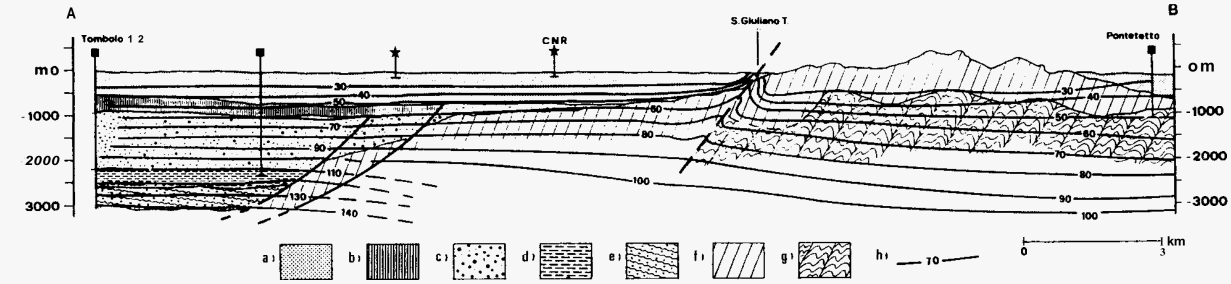

Fig. 3: Geological cross-section through the deep structures of the Pisa plain.

a) Gravels and sands with clays (Upper Pleistocene); b) Clays, silty clays and sands with sandstone layers (Lower Pleistocene); c) Clays, sands and clayey sands (Pliocene); d) Clays with sands (Messinian); e) "Macigno" (sandstone) formation (Upper Oligocene - Lower Miocene); f) Carbonatic formations of the Tuscan Series (Mesozoic); g) "Metamorphic Basement" of the Tuscan Series: phyllites, quartzites (Paleozoic - Trias); h) Isotherm (°C)

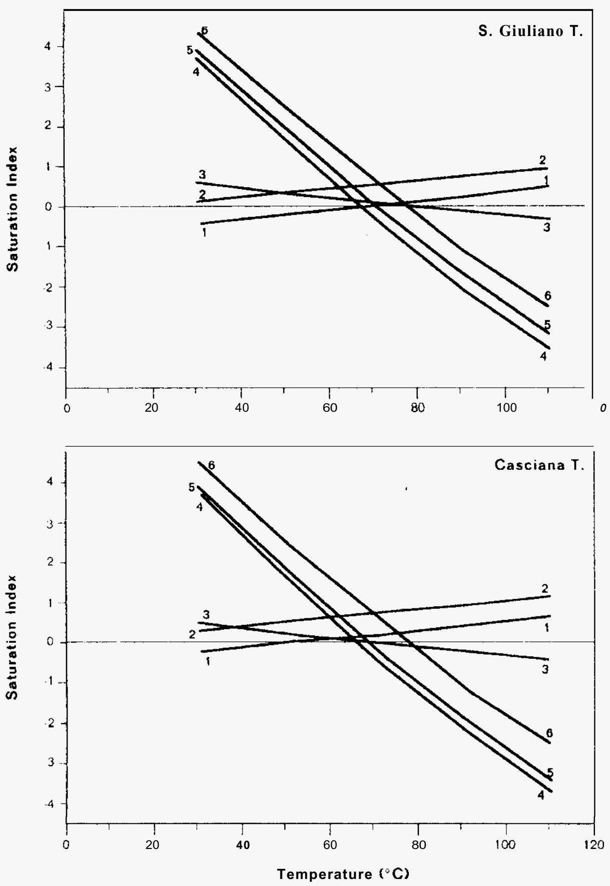

Fig. 4: Saturation index vs temperature for the hydrothermal prospects of S. Giuliano T. and Casciana T. ; 1) Anhidrite; 2) Calcite; 3) Quartz; **4)** K - ; 5) Mg - : 6) Na - Smectites

are of the $Ca\text{-}SO_4$ type and contain practically no tritium, whereas the waters of Uliveto, which are of the Ca-Mg- HCO_3 type, with similar Cl and SO_4 contents, have a tritium content of 13-15 T.U., close to the value measured in the precipitation during the sampling survey in 1989. The waters delivered by the S. Giuliano and Casciana systems are from saturated to slightly oversaturated with respect to typical minerals (calcite, dolomite and anhydrite) of the evaporitic sequence of the Tuscan Series, and derive from a groundwater circulation characterized by a long residence time within the buried part of the Triassic anhydritic formations. The waters of Uliveto that are characterised by a slight degree of water-rock interaction could derive from a rapid circulation within the local carbonate outcrops, or represent the product of a mixing between a small fraction of thermal water, possibly similar to that of the other systems, and shallow cold waters.
Assuming that the hydrothermal systems are fed by a deep reservoir, we can estimate the reservoir temperature by means of the method based on the saturation index (Arnorsson *et al.*, 1982; Michard and Roekens, **1983)** of the most concentrated fluids: in this case, S. Giuliano and Casciana. We used the program Solmin 88 (Kharaka *et al.*, 1989) to compute the saturation index (SI) of these waters in the temperature range 40-110 °C with respect to quartz, anhydrite, calcite and Mg, Na and K sinectites. These minerals were detected in a mud sample collected from a tank fed by a spring in the S. Giuliano prospect. To apply the method we utilised the pH and HCO_3 field data. and Al^{+3} values of 0.0023 and 0.0043 mg/l, measured at S. Giuliano and Casciana respectively. From Fig. 4, which reports the results for both systems, the deep reservoir temperature could plausibly range between 65 and 85 °C.

5. TEMPERATURE DATA

Temperature data were obtained from:
a) Analysis of water temperature from wells drilled in the Pisa plain: temperatures increased with the depth of the water-hearing layers. The geological cross section (Fig. 5) is based on data from wells in which the depth of the water-bearing layers is fairly well known. This figure shows that the data coming from the "CNR" shallow thermal borehole clearly fit in well with the overall temperature distribution of the area. and the temperature values coming from the deepest water-hearing levels are coherent with a "conductive" temperature distribution. to depths of more than 200m. We can therefore estimate, with a reasonable approximation, the temperature distribution at depths of more than the 100m reached by the CNR borehole. The decrease in the isotherms in the S. Piero a Grado and Coltano areas caii be ascribed to the widespread outcrops of dune sands, which act as a recharge area lor the underlying acquifers (Trevisan and Tongiorgi, 1953; Fancelli *et al.*, 1986).
b) Shallow gradient boreholes (100-150m): in some of these wells, recently drilled into highs of the buried carhonate substratum, we have recorded thermal gradients of 50 - 60 °C/km. Temperatures were extrapolated to the top of the carbonate layer (calculated from gravimetric and reflection seismic data to lie at depths ranging between 700 and 850m). Using the Bullard (1939) method and heat flow data from 3 shallow gradient wells (100m deep), we obtained temperatures between 50 and 60 °C. The Bullard method is based on the equation

$$T_z = T_o + q_o \sum_{i=1}^{N} (\Delta_{zi} / \lambda_i)$$

where T_z is the temperature at depth z, To is the mean annual surface temperature in the area, qo is heat flow, assumed constant, Δzi is the thickness of the i-th lithologic formation and **hi** is the thennal conductivity of the formation. This equation is based on the premise that heat flow is conductive and constant along the vertical. The most interesting areas are located in correspondence to culminations of the carbonatic layer: one in the eastern part of Pisa and the other south of it, covering an area of about 30km^2, trending N-S. A borehole drilled to about 800m in this second area encountered intensely fractured limestones at a depth of 700m.
c) Deep hydrocarbon exploratory wells:
These are located on the western side of the basin. where the top of the limestone fonnation (potential geothermal reservoir) is estimated by gravity surveys to lie at depths of more than 2500-3000m; this formation has. in fact, never been encountered by wells inside the basin. **A** few temperature data are available in these wells, and they are useful in order to evaluate temperature at depth, comparing them, contemporarily, with temperatures measured in shallower wells extrapolated downwards.

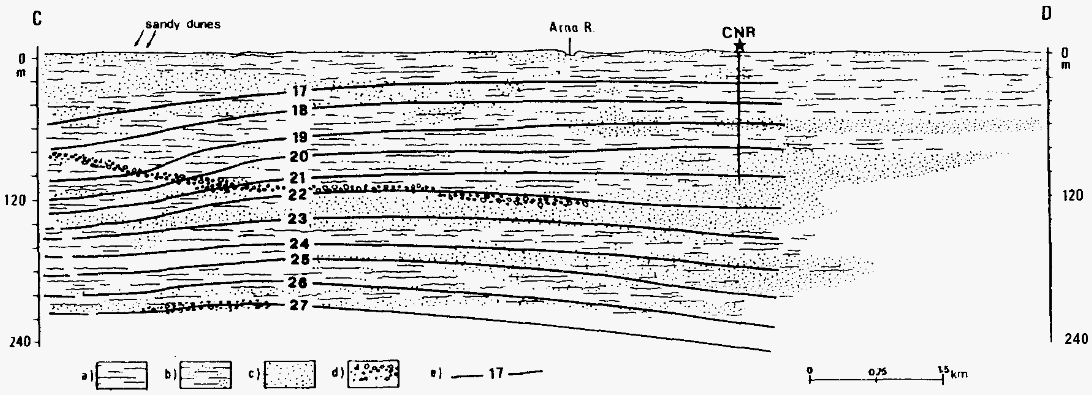

Fig. 5: Geological cross-section through the shallow layers ofthe Pisa plain.

a) Clays and silts. *Almost impermeable*; b) Sandy clays. *Very low* ***permeability;*** c) Sands. *Medium io* ***high*** *permeability*; d) Gravels. *Permeability* ***generally high;*** e) Isotherm (°C).

6) GEOLOGICAL STRUCTURES CONTAINING THERMAL FLUIDS

The carbonate Mesozoic formations outcropping on the westem margin of the Pisan Mounts, in the S. Giuliano Terme zone, are abruptly lowered by the normal fault with a high vertical throw (– 700m) that runs parallel to this margin (Figs 1, 3). In the Pisa plain and a wide area south of the town, as far as the Pisan-Livornesi Mts.. there is a vast cover of Pleistocenic sediments (up to – 1000m thick on its western border) that directly overlies the Mesozoic carbonatic fonnations of the Tuscan Series. The "master fault", with a vertical throw of about 1500m, that runs along the eastern side of the Neogenic coastal basin, rapidly carries the limestones to depths of over 3000m, as was verified in Tombolo 1 well (Fig. **2).** At that depth the well was still crossing the sandstone formations overlying the carbonate formations of the series. Considering that we need a widespread carbonate series at depths of less than 1500-2000m and more than 700-900m to act as a potential reservoir for fluids suitable **for** low-temperature applications, the area between these two main faults, both of which trend NNW-SSE, is an interesting target for further investigations by deep drilling. **A** wide area south of Pisa corresponds to a structural high of the carbonate formation, whose intensely fractured levels have been crossed by a well at less than 700m depth. This zone is *of* particular interest as regards its thennal characteristics. The eastern part of the town itself, where the top of the carbonate fonnation presumably lies at about 850m, also exhibits a fairly good thermal anomaly, as well as being near to the thermal spa of **S.** Giuliano. There are outcrops of the carbonate formation in the latter area, and springs with water temperature of about 40 °C.

7) CONCLUSIONS

Analysis of all the available structural, hydrogeological and thermal data on the Pisa plain allows us to set some targets for future deep exploratory drilling. Fig. 1 summarizes the structural information on this area, based on geophysical data (seismics and gravity) and deep drillings. In the grey-shaded zone. the isolines delineate the top of the Mesozoic carbonate formations, at depths ranging between *500* and 1000m. The permeability of these formations suggests their role as a potential reservoir, with temperatures of 40-60 "C expected in the shallower layers. Inside this area there are two particularly interesting zones: one in the eastern part of the town of Pisa, and the other in a zone south of the town. Fluids of 60-70 °C temperature can be expected from depths of 800-1000m. A study of the hydrothermal systems existing on the margins of these zones ***(S.*** Giuliano T., Uliveto T., Casciana T.) shows that, at least in correspondence to the thermal springs, the fluids have a low TDS (– 3 g/l). Unfortunately, there are few data available on the areas far from the thennal springs. There is no reliable information on whether the Plio-Pleistocene sea water, which certainly saturated the underlying limestones, has been replaced by fresh rainwater from the regional aquifer. Waters with a high NaCl content were sampled in the carbonatic structure encountered by well Pontedera 1 (Agip, 1977). and these brines may still saturate a large part of the structures buried below the cover of Plio-Pleistocene marine sediments. This possibility has to be kept in mind during feasibility studies for utilizing these waters. Direct information on the permeability of the formations underlying the Plio-Pleistocenic cover are available from only two deep wells (Poggio 1 and Pontedera 1), where the Mesozoic limestone formations showed a good permeability. It is difficult to extrapolate these data to other rigid buried structures, and even more difficult to determine the nature of the fonnations beneath the recent sedimentary cover. The uppermost parts of the Tuscan Series ("Macigno" sandstone and/or "Scaglia" argillite), which have a low permeability, may be present in some places. Despite these constraints, a careful evaluation of the data available suggests that it is worthwhile investing in further research. Summarising, we would recommend deep drilling targeted at the recovery of fluids at 60-70 "C in the Pisa plain, which could be profitably exploited in space-heating. greenhouse heating, fish-fanning and other agricultural and industrial applications.

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