SELECTION OF DRY WELLS IN TUSCANY FOR STIMULATION TESTS

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1. NON-PRODUCING WELLS IN THE LARDERELLO AND TRAVALE FIELDS

Of the 570-odd wells drilled during the last 50 years in the geothermal fields of Larderello and Travale, little more than 220 are now producing.

Excluding a few wells that are not exploited because of the chemical characteristics of the fluid, the productive wells can be classified as follows:

a) Wells that were once productive but are now exhausted (meaning that they are no longer capable of economic production at the working pressure of the power plant).

Apart from a few examples of an unexpected halt in production caused by collapse of the wellbore walls, exhaustion occurred in densely drilled zones in which reservoir pressure decreased to a few tens of atmosphere above the turbine inlet pressure (the reservoir pressure value was measured in shut-in wells during field production). The flow-rate drawdown in these wells (at nearly constant pressure) is generally characterized by a series of sharp decreases that occur with the entry-into-production of new

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Work conducted as part of the Finalized Energy Program of the Italian National Research Council.

wells. Pressure build-up tests, conducted in some wells showing a strong depletion, revealed that transmissivity was still high and skin factors generally negative. The lowering of flow-rate was therefore considered to be attributable neither to an important variation in formation permeability nor to local permeability reduction around the borehole.

These wells are clearly of no interest as far as stimulation is concerned.

Figure 1 shows the location of the non-productive wells in the Larderello field. The exhausted wells are nearly all located in the densely drilled zones.

b) Another group of wells of no interest to stimulation are those lying in peripheral areas, where the temperature in the upper layers of the reservoir is too low, even with a good permeability, to produce fluids exploitable for electricity generation (Figs. 1, 2 and 3).

Note that the low temperature in the top of the reservoir is of no interest to stimulation when dealing with shallow wells only. Temperatures of 250°-300°C have been recorded at depths of about 3 km in various areas that have low temperature values at the top of the reservoir.

c) Dry or low productivity wells, owing to a lack of permeability. Most of these wells are in areas in which the reservoir temperature, at depths between 500 and 1500 m, exceeds 200° and frequently even 250°C, with pressure above 20 atm. The deeper wells are of some interest even though they lie within areas with relatively low pressures in the top of the reservoir. It has, in fact, been noted that reservoir pressure increases with depth[1,2] and values of more than 20 atm were found between 1000 and 1500 m depth in zones with pressures below 5 atm in the uppermost layers of the reservoir.

Our attention was concentrated on hot, low permeability wells in the selection of a few wells with the most favorable characteristics for stimulation. The wells were selected on the basis of their technical characteristics, their state of conservation, the rocks crossed

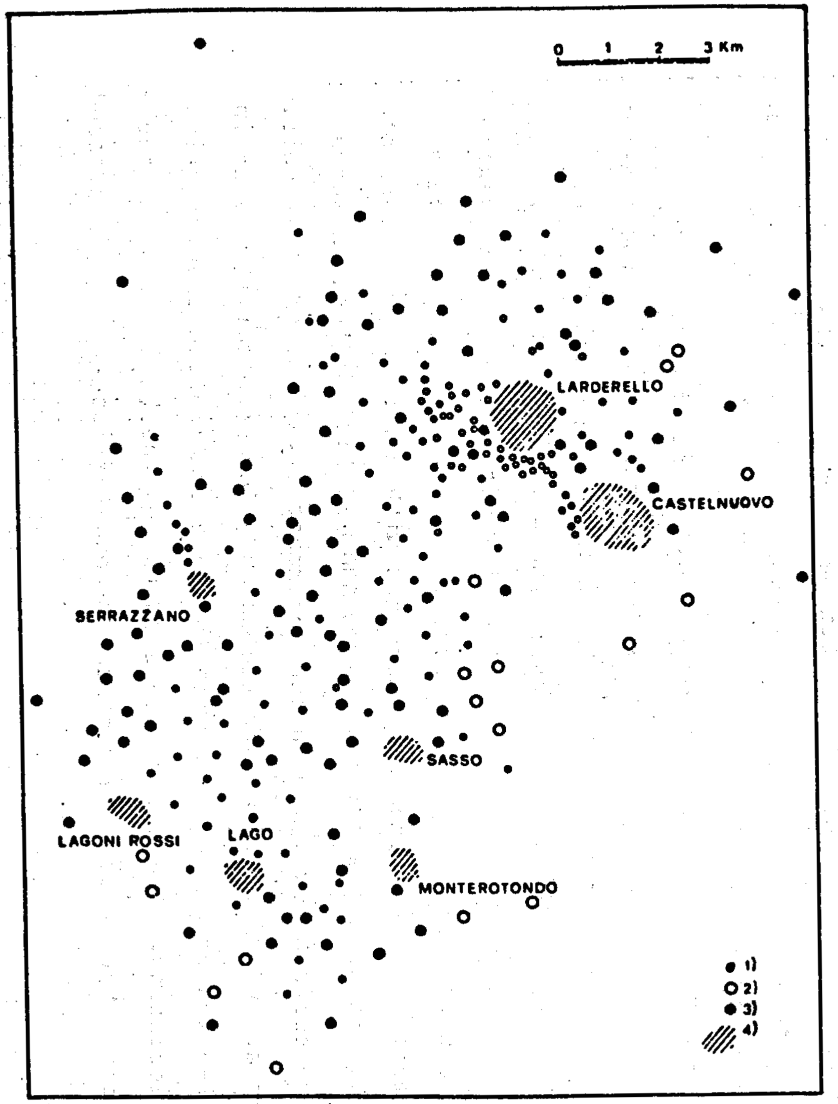

Fig. 1. Location of the wells in the Larderello geothermal field.
1) Productive wells; 2) Non-productive (low temperature) wells; 3) Dry or low productive wells (lack of permeability); 4) Densely drilled areas.

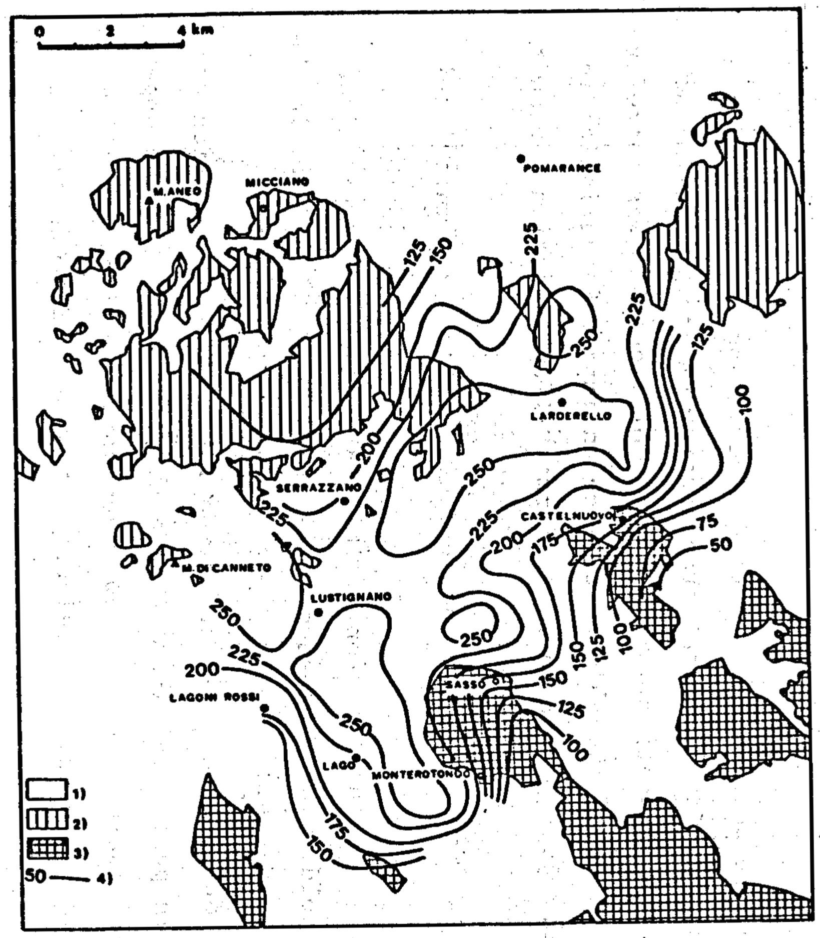

Fig. 2. Temperature distribution at the top of the reservoir in the Larderello geothermal field.
1) Cover formations; 2) Ophiolites and associated sedimentary breccias; 3) Reservoir rocks (including 'Macigno' sandstone); 4) Isotherms (°C).

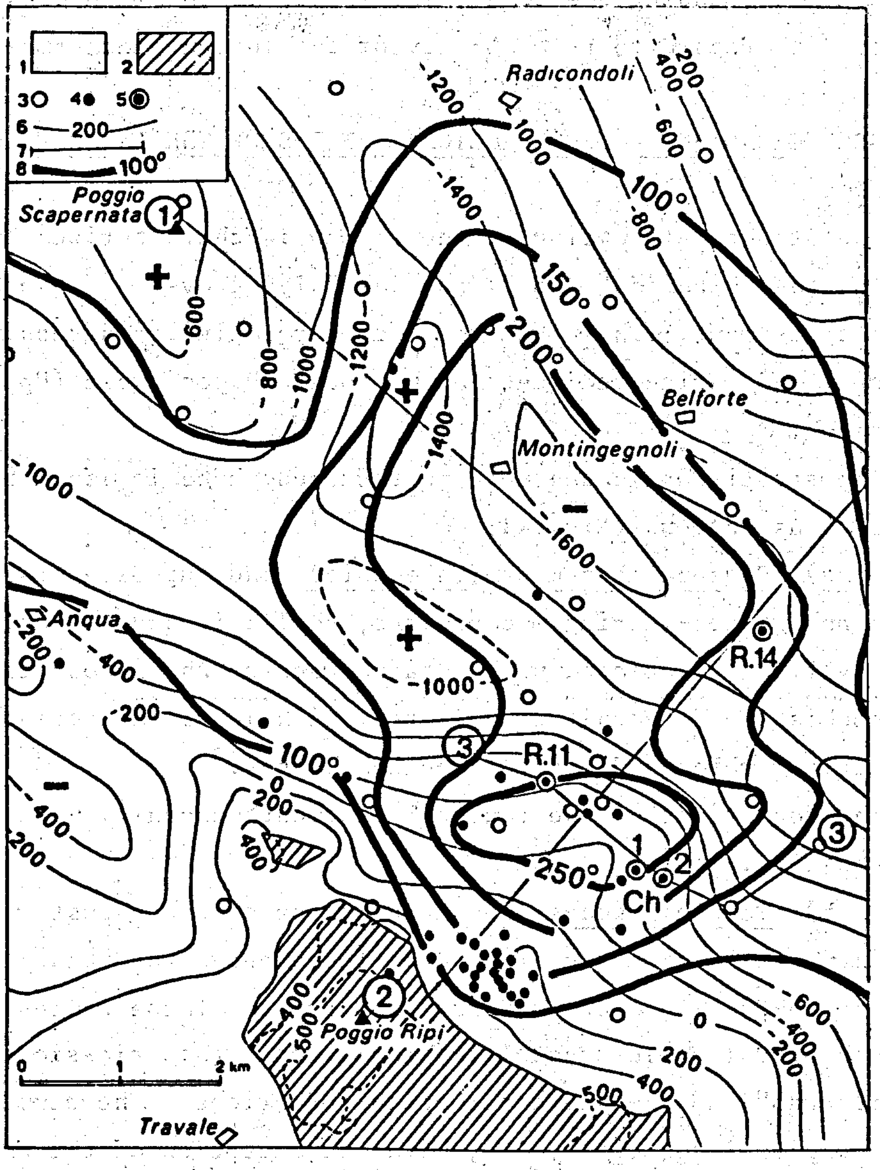

Fig. 3. Structural setting and temperature distribution at the reservoir top in the Travale geothermal field.
1) Cover formations; 2) Outcrops of the mesozoic carbonate formations (reservoir); 3) Geothermal boreholes; 4) Deep wells; 5) Selected wells; 6) Isobaths of reservoir top; 7) Traces of the cross-sections; 8) Isotherms at the reservoir top.

in the open-hole section and, especially, the structural setting in the area surrounding the bore. The latter is the main controlling factor with regard to permeability of the Tuscan geothermal areas.

2. GEOLOGICAL AND HYDROGEOLOGICAL OUTLINE OF THE LARDERELLO-TRAVALE ZONE

The structural setting of the region is characterized by overlying nappes, the "Ligurids" and "Tuscanids," lying over a regional metamorphic basement. These complexes are overlain transgressively by the lagoonal and marine sediments of a neoautochthon cycle (Upper Miocene-Pliocene).

The stratigraphic sequence in the study area is, from bottom upwards, as follows (Fig. 4):

a) Regional basement (Paleozoic), made up of gneiss, plagioclase and garnet-bearing micaschists, phyllitic quartzites, quartzites and phyllites associated with metagreywackes, chloritoschists, calceschists and graphitic phyllites, with local intercalations of dolomitic marbles and crystalline anhydrites.[3]

The formations of the regional basement generally have a low permeability.

b) Tectonic wedge zone, consisting of overthrust wedges (maximum total thickness of 1400 m) found above the "basement" in the Larderello-Castelnuovo and Serrazzano areas. These wedges are made up both of Paleozoic crystalline formations, the Triassic terrigenous ("Verrucano") and mesozoic carbonate formations. The permeability of this complex is generally low, with the exception of the carbonate and quartzitic layers, which may have a good secondary permeability.

c) Tuscan nappe, whose base comprises green phyllite (Verrucano) overlain by evaporitic and carbonate deposits (Burano Formation) of the Upper Trias, followed upwards by a group of mainly carbonate Jurassic formations and, finally, by varicoloured shale ("Scaglia") of the Cretaceous-Eocene and the arenaceous flysch "Macigno" of the Oligocene.

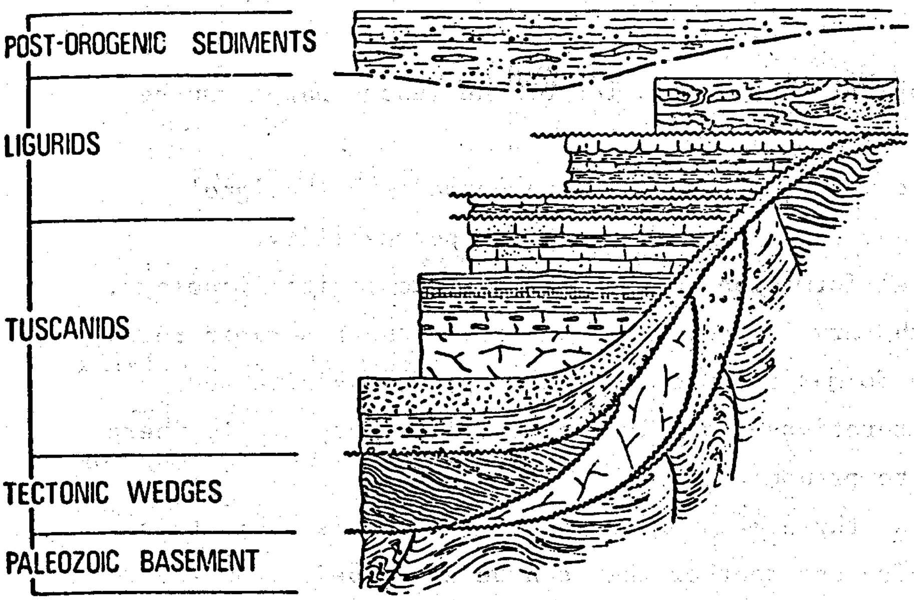

Fig. 4. Relationship between the main stratigraphic units in Larderello-Travale region.

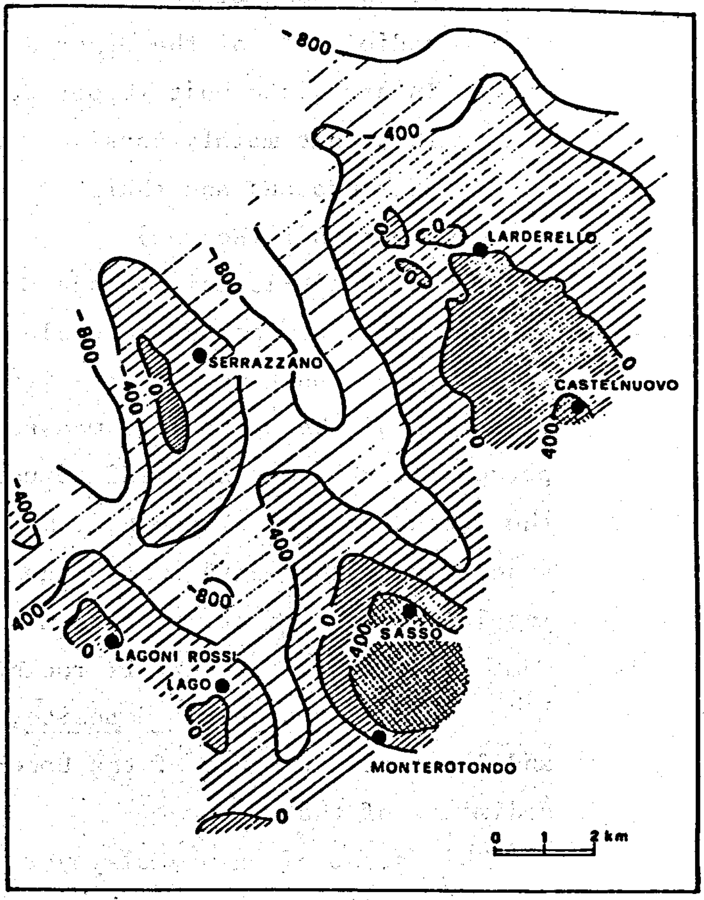

Fig. 5. Isobaths of the top of the geothermal reservoir formations (m.a.s.l.)

The hydrogeological characteristics of the Tuscan nappe can be summarized as follows:

- The Jurassic mainly carbonate sequence and the 'Macigno' formation have a good fracture-derived permeability;
- the 'Scaglia' formation (mainly shale), due to its lithology, a layer with very low permeability within the reservoir rocks;
- the 'Burano formation' which is made up of anhydrite and dolomite alterations has a low permeability, especially where the anhydrite predominates.

d) Ligurids, three main units can be distinguished in this complex. Overlapping one another they can be described, from the top downwards, as:

- Upper unit (Lower Cretaceous)
  This unit consists of shale and siliceous stratified limestone; at the base of the series are masses of ophiolitic rocks and radiolarite of the Upper Jurassic.
- Intermediate unit (Upper Cretaceous)
  This unit mainly consists of marly layers with interbeddings of sandstone and shale.
- Lower unit (Eocene)
  This unit is mainly made up of marly limestone interbedded in marly, sandstone and shaley layers.

The upper unit is characterized by very low permeability, with the exception of the ophiolitic masses that have average fracture-derived permeability. The intermediate unit is similar hydrogeologically to the preceding one, although it has more frequent marly limestone and sandy layers that have an average fracture-dependent permeability. The lower unit has at its base mainly limestone layers that may, in some cases, act as reservoir rocks.

e) Post-orogenic deposits, these consist of lacustrine, marine and lagoonal sediments of the Upper Niocene (Messinian) and marine sediments of the Pliocene.

This group of mainly clayey formations has, on the whole, a very low permeability.

3. INFLUENCE OF GEOLOGICAL-STRUCTURAL FACTORS ON PERMEABILITY

In order to define the main structural parameters that, along with lithostratigraphy, have an effect on permeability and, hence, on well productivity, a systematic analysis was made of the geostructural and hydrogeological conditions of all the wells, productive and non-productive.

This analysis revealed that permeability distribution is greatly influenced by geostructural factors and by related tectonic events. The latter can be attributed to three main phases: the first of these, the Hercynian, affected the Paleozoic metamorphic basement only; the second, Alpine phase of compressional and gravitational tectonics controlled the emplacement and folding of the Tuscan and Ligurid units and led to tectonic shearing within the Tuscan formations, and probably within the regional basement as well, with reduction of the series and creation of the main structural features. A third, tensional phase gave rise to the main horst and graben structures existing in the area. The formation of these structures had the following effects on permeability.

The Alpine compressional tectonics created a series of overthrust planes between the Ligurids and Tuscanids and within the latter. A thin belt of fractures was formed along these planes, especially if the contact involved the carbonate formations, increasing permeability considerably.

The main overthrust planes, from the bottom upwards, are:

- that between the Tuscan nappe and the underlying complexes. In some areas (Serrazzano and Larderello-Castelnuovo) tectonic wedges have formed between the Tuscan nappe and the Paleozoic basement increasing the permeability of the formations involved;
- that between the Ligurid units and the underlying complexes. In some cases strong shearing has carried the Tuscanids off and placed the Ligurids in contact with the Paleozoic basement. Intense fracturation can also occur in correspondence to this plane. In other cases this phenomenon has transformed the

Burano Formation into a breccia of fragments of dolostones, anhydrites and limestones with a very high permeability.

Considering the areal distribution of the dry and noncommercial wells, the structural characteristics of the different areas, drilling data, geophysical logs, in-hole measurements and the production tests from the various geothermal wells, it can be concluded that:

a) the dry wells are generally concentrated in areas (Fig. 1) in which almost all the wells have a low productivity. Consequently, low permeability of the reservoir formations would appear to be a wide spread phenomenon throughout these areas.

b) The reservoir formations show the highest productivity in zones of structural highs.[4,5] Figures 5 and 6 clearly reveal this areal correspondence. Of all the factors responsible for intense fracturation in these zones the most important seems to be the folding undergone by the rocks during the orogenic phases; the fractures are particularly concentrated along the main axes of these structures.

c) The fracturation of the anhydritic carbonate formation (Burano Formation) becomes more intense in its thinner layers. This can be noted in Fig. 7, which shows the thickness distribution of the "Burano Formation" for the wells crossing it and the ratio between productive and unproductive wells* for each thickness interval.

d) The overthrust planes are of great importance in the fracturation of the reservoir rocks. Tied to this overthrusting is the large number of productive fractures found near the contact between the cover and the reservoir formations. Figure 8 shows the frequency distribution of the distance between the fractures crossed by the wells and the tectonic contact. The fractures (or groups of fractures located in small depth intervals) were individualized from drilling data, in-hole measurements and geophysical logs. The data on older wells consist of drilling data only and are therefore less

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* Whenever there are only few elements in a class, this ratio was calculated considering the nearby classes, using a moving average.

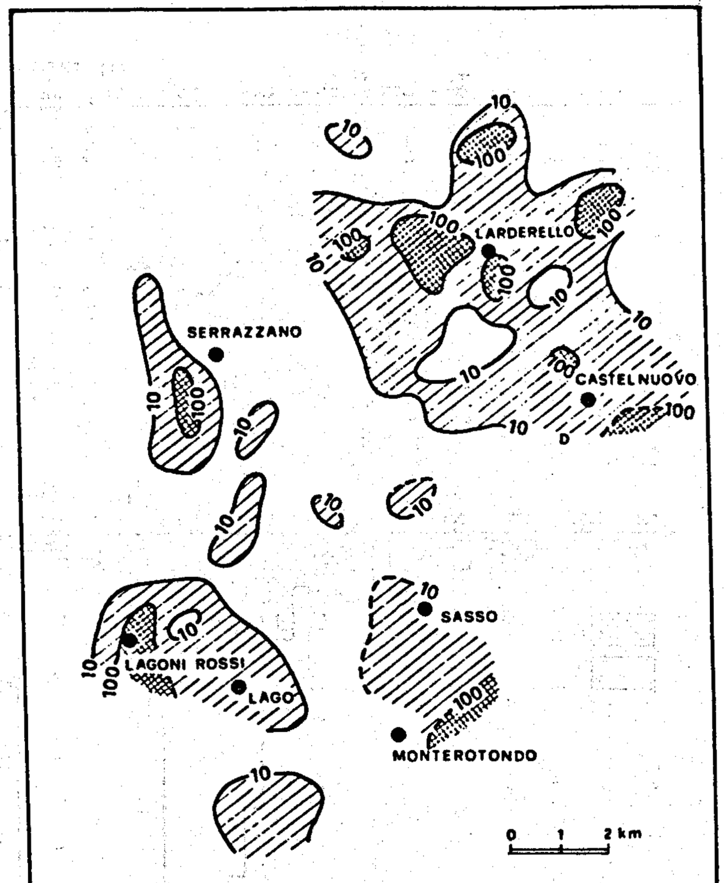

Fig. 6. Distribution of the kh values (Darcy-meters in Larderello geothermal field.

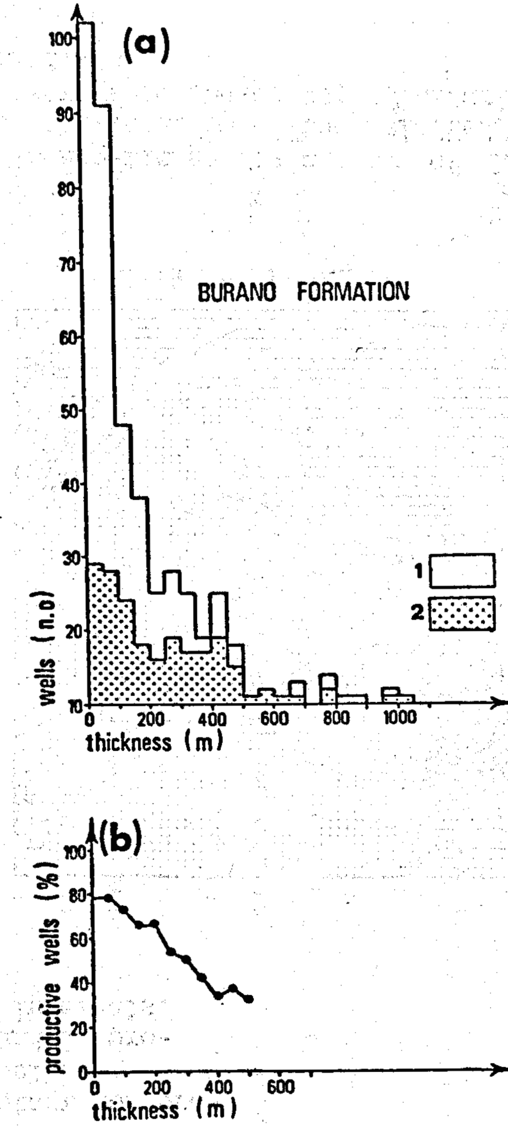

Fig. 7. a) Distribution of the "Burano Formation" thickness for productive (1) and non productive (2) wells.

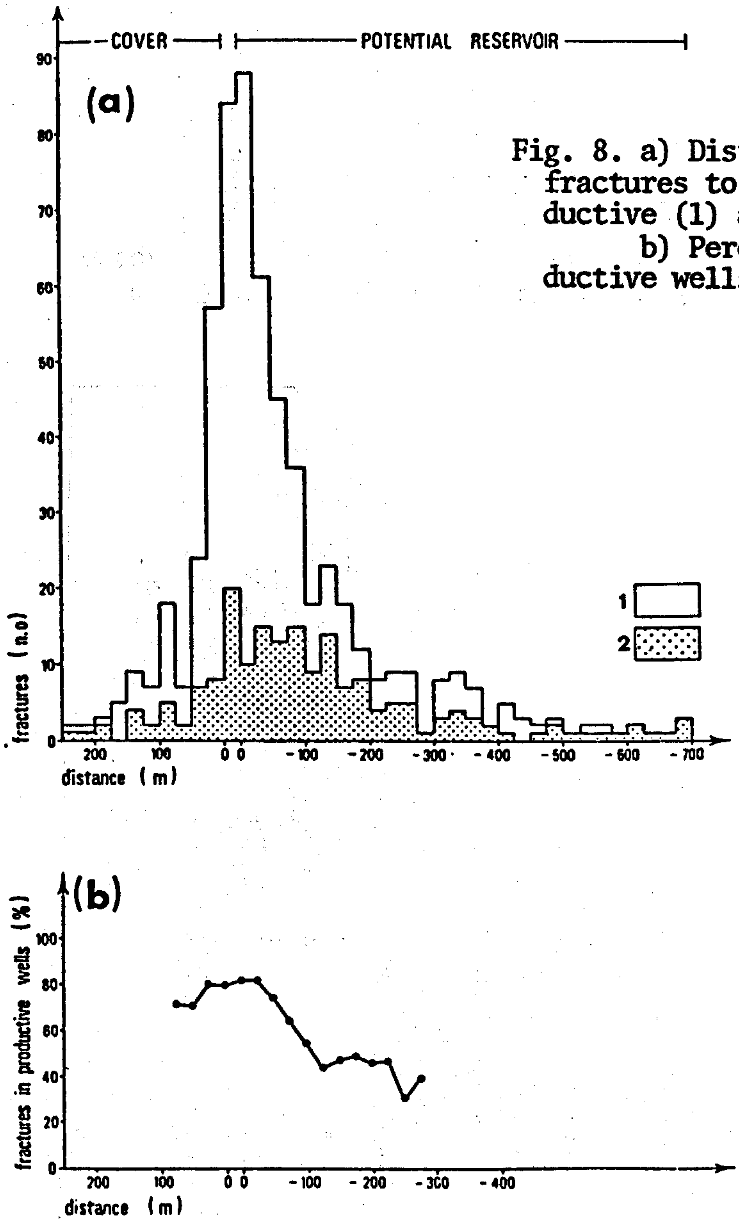

Fig. 8. a) Distribution of the distance from the fractures to the cover-reservoir contact for productive (1) and non productive (2) wells.
b) Percentage of fractures found in productive wells in different distance intervals.

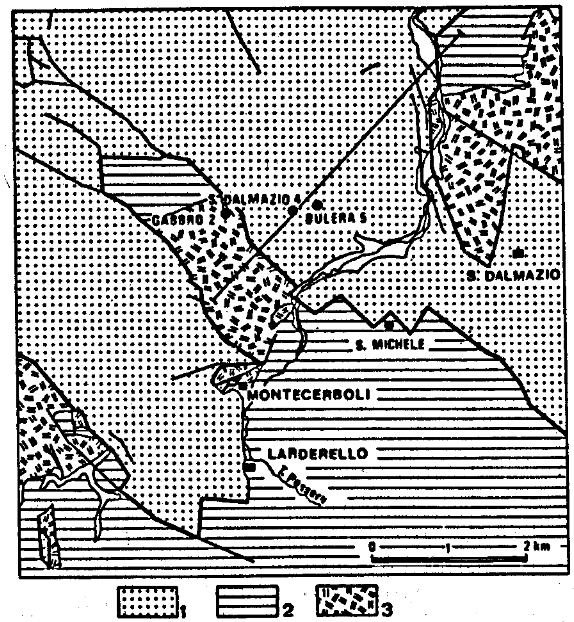

Fig. 9. Schematic geological map of the zone of Gabbro with location of the selected wells. 1) Post-orogenic sediments; 2) Ligurids; and 3) Ophiolites.

reliable than the other data. Class (0,0) of nil width has been added to represent the fractures lying right on the contact.

The distribution shows a clear concentration of fractures near the tectonic contact. The fractures within the cover complex usually lie in correspondence to calcareous or arenaceous layers at the base of the Ligurids. The percentage of productive wells also peaks in correspondence to the contact.

Similar observations could also be made for the contact between the "Burano formation" and the underlying Triassic or Paleozoic terrigenous formations.

e) The influence of the Neogenic tensional tectonics on reservoir permeability is still not clear. The fault systems created during this phase appear to have played an important role in providing connections between permeable horizons at different depths so that the permeable layers of the reservoir can collect fluids from large masses of low permeability rock.

4. SELECTED WELLS

Based on the preceding analysis and on examination of all available data (thermodynamic and technical), 13 dry or low permeability wells were considered suitable for tests and logs, prior to possible stimulation experiments.

Nine of these wells are sited in the Larderello geothermal field and four in the Travale field. Their main geological and thermodynamic characteristics can be summarized as follows.

Part of the wells in the Larderello field lie on the western margin of the Era graben, near the faults bordering this graben with a regional NW-SE trend (Fig. 9). Below the cover formations (Neogene and Liguirids) these wells meet the "Burano Formation" and/or the Triassic-Paleozoic terrigenous complex (Fig. 10).

In addition to reducing the thickness of the Burano formation, this fault may also have created fractures in the Triassic-Paleozoic phyllitic-quartzitic formations. These fractures are probably nearly

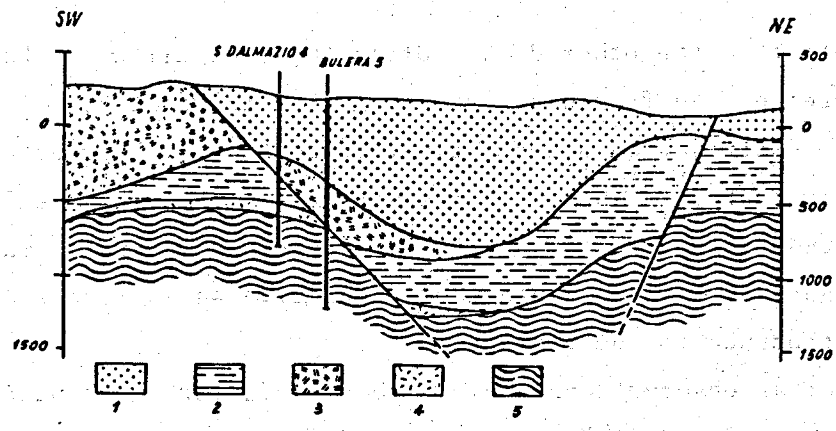

Fig. 10. Schematic geological cross-section of the zone of Gabbro. 1) Post-orogenic sediments; 2) Ligurids; 3) Ophiolites; 4) Burano Formations; 5) Triassic-Paleozoic terrigenous formations.

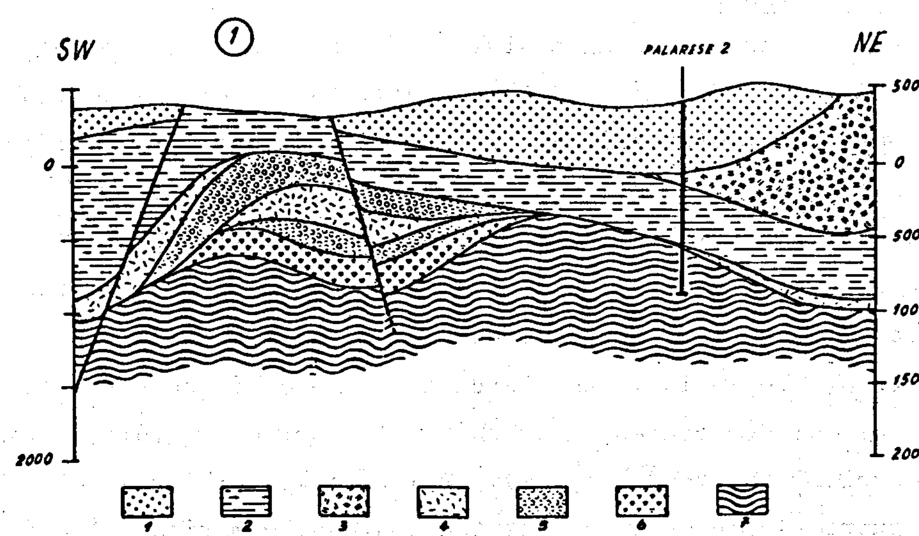

Fig. 11. Schematic geological cross-section of the Serrazzano structure. 1) Post-orogenic sediments; 2) Ligurids; 3) Ophiolites; 4) Burano formation; 5) Quartz conglomerates (Verrucano); 6) Quartzites (Verrucano); 7) Triassic-Paleozoic terrigenous formations.

vertically oriented and irregularly distributed throughout the area, being more concentrated in a belt along the fault. One of the main reasons for selecting these wells was the inferred possibility of connecting them to the fracture system.

A second group of selected wells lies within the northern part of the Cornia River basin, south-west of Larderello.

These bores are sited on the flanks of two main positive structures of the potential reservoir formations: the Serrazzano and Lagoni Rossi structures.

The Serrazzano structure (Fig. 11) extends N-S and is made up of a complex of tectonic wedges of Triassic formations (anhydrites, anagenites, quartzites).[3]

The Lagoni Rossi positive structure trends NW-SE and is formed by Triassic-Paleozoic metamorphic terrigenous formations and Jurassic carbonate formations of the Tuscan Series. Towards the north this structure is separated from that of Serrazzano by a wide NW-SE trending (regional) tectonic depression.

This second group of wells crosses thin layers of the "Burano Formation" and/or the underlying metamorphic terrigenous formations (Figs. 12 and 13). Although some of these wells are dry, they lie in a zone containing other highly productive wells. The low permeability of the reservoir is, therefore, a local phenomenon and there is the possibility of connecting the wells to fractures tied to faults and tectonic laminations.

Other boreholes, on the contrary, are sited in zones with a more general low permeability. In these zones, drastic changes in productivity after stimulation are not expected. However, there are a few wells which could become economically viable with only a relatively small increase in productivity. An even larger number of wells could be used for injection purposes immediately or when stimulation achieves only a limited success. The exploitation of reservoirs which have uniformly low permeability throughout most of their area is a problem. In fact, these characteristics are presented by large areas of the known fields and the majority of deep hot rocks reached by

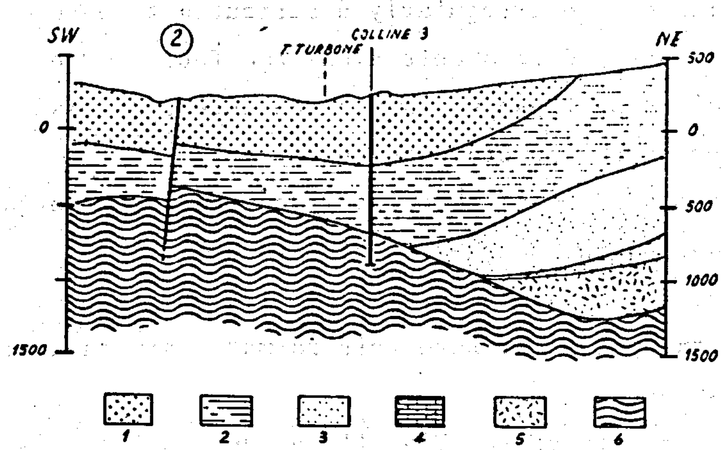

Fig. 12. Schematic geological cross-section of the zone East of the Serrazzano structure. 1) Post-orogenic sediment; 2) Ligurids; 3) "Macigno sandstone"; 4) Mainly carbonate formations of the Tuscan unit; 5) Burano formation; 6) Paleozoic formations.

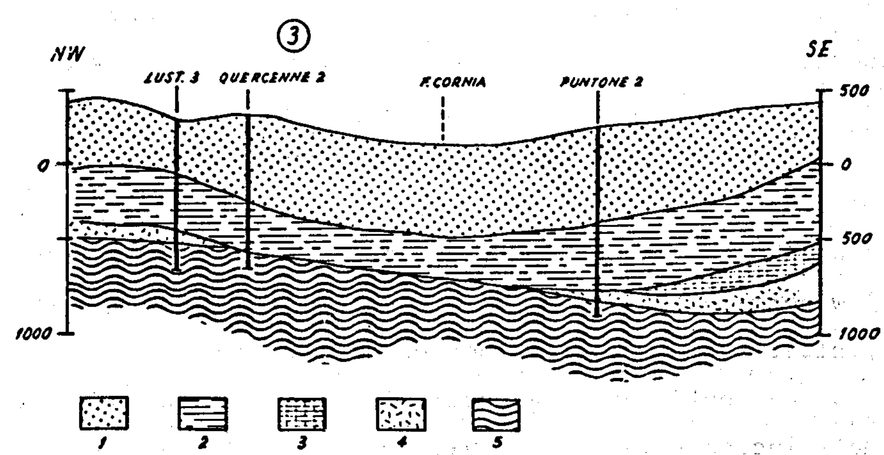

Fig. 13. Schematic geological section of the zone NE of the structure of Lagoni Rossi. 1) Post-orogenic sediments; 2) Ligurids; 3) Mainly carbonate formations of the Tuscan Unit; 4) Burano formation; 5) Triassic-Paleozoic terrigenous formations.

wells. Permeability is too low to permit economic production, too uniformly low to expect positive results from well stimulation attempts, but too high for hot dry rock type exploitation. The injection of large amounts of water into groups of wells in the low permeability area and the production of a flow from the injection zone to the high permeability, depleted areas of the field is now being considered. Feasibility projects based on this idea are now being studied.

Three of the Travale wells are sited over a positive structure of the potential reservoir, on the margin of a graben and near productive or exploited wells (Fig. 14).

This structure is cut by a group of NW-SE trending direct faults in three main steps.

The boreholes have generally crossed rather thick layers of the Burano formation and the metamorphic basement (phyllites and quartzites, followed by alternations of anhydrites and crystalline dolostones).

Again it may be possible to connect these wells to a fracture system tied to the faults bordering the graben.

The fourth well selected in the Travale zone lies in the central part of this graben (Fig. 15). It appears to have been drilled on the E-NE extension of the positive structure characterizing the productive area. The well was chosen because even a small productivity would be of extreme interest for the study of the geothermal reservoir in this zone.

From the thermodynamic point of view, the group of wells in the Larderello geothermal field show temperatures between $\sim$200 and 270^{o}C in the potential reservoir and reservoir pressures between 17 minimum and 36 atm maximum. The Travale group of wells has temperatures of 250-260^{o}C in the potential reservoir and reservoir pressures around 50 atm.

The stimulation methods which can be employed on the 13 selected wells depend on the geostructural situation around the well and on the

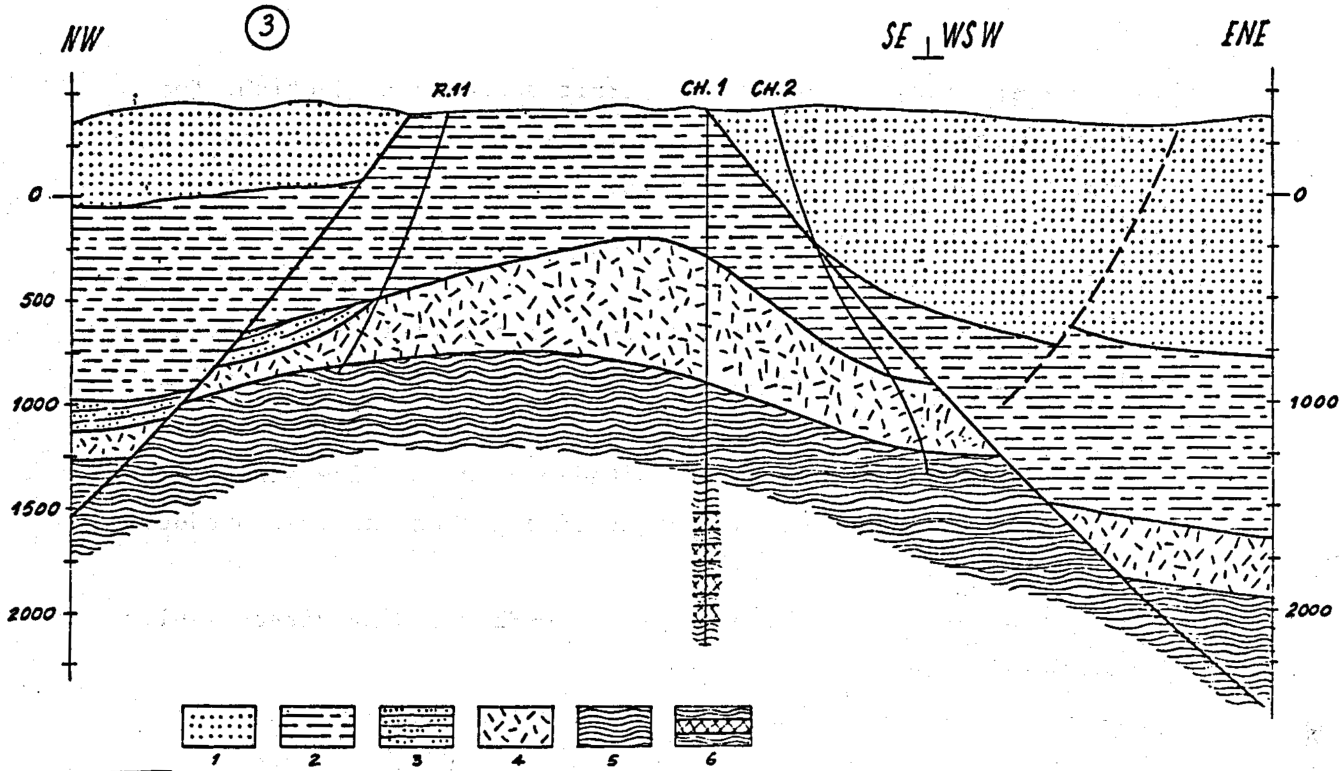

Fig. 14. Schematic geological cross-section of the new field of Travale. 1) Post-orogenic sediment; 2) Ligurids; 3) "Macigno sandstone"; 4) Burano formation; 5) Paleozoic phyllites and quartzites; 6) Paleozoic phyllites, quartzites, anhydrotes, and crystalline dolostones.

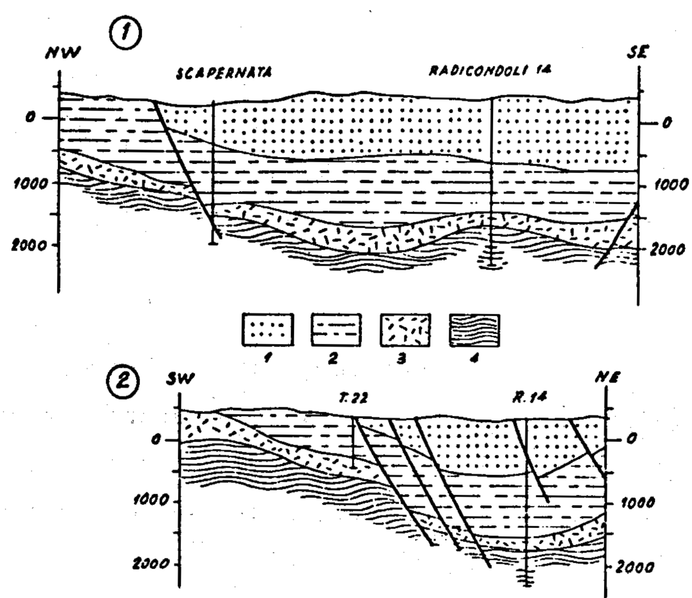

Fig. 15. Schematic geological cross-section of the Travale zone. 1) Post-orogenic sediments; 2) Ligurids; 3) Burano formation; 4) Paleozoic phyllites and quartzites.

type of rock formations involved. In order to define the geomechanical and hydraulic characteristics of the formations, to establish whether stimulation is feasible and to be able to plan the treatment program, permeability tests will be made.

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