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DISCLAIMER

A MODEL OF THE SERRAZZANO ZONE

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Lithology

For hydrogeological purposes, the rocks of the Lardarello Basin may be divided into three main complexes:[1]

i) A weakly metamorphic basement complex of quartzites, phyllites, and schists. Although deep exploratory drilling has found occasional fractures and isolated pockets of permeable rock, it is believed that the basement complex is largely impermeable and contributes little to steam production.

ii) A so-called "evaporite" complex of anhydrite, limestones, dolostones, and radiolarites. These rocks are absent in some areas and up to a kilometer thick in others. The limestones and dolostones are known to be highly porous and permeable. The lower-lying anhydrite is believed to be highly porous and permeable where it has been tectonically sheared and brecciated. Because a major regional thrust fault passes through this complex, the tectonically sheared and brecciated zones are believed to be extensive. Overall, this complex is believed to be the main reservoir of liquid water and source of steam in the geothermal system.

iii) A largely sedimentary caprock sequence consisting of unmetamorphosed and weakly metamorphosed shales, marls, feldspathic sandstones, and ophiolitic rocks. Although there are significant volumes of permeable and porous limestones and sandstones in this complex, the preponderance of argillaceous rock types makes it effectively impermeable as a whole. It serves as a caprock for the geothermal system.

Structure

Most wells in the Lardarello Basin produce from an interval at or near the bottom margin of the caprock. Where the evaporites are absent, the producing interval is the thrust fault zone at the contact of basement and caprock. This fault zone is not the ultimate source of steam, but only a conduit which conducts it from permeable complex rocks elsewhere to the wellbores.

The elevation of first commercial steam throughout the Basin is shown in Figure 1. It is apparent that the Castelnuovo-Lardarello, Serrazzano, Lago, and Lagoni Rossi productive areas are centered near distinct highs in the reservoir top. (They account for nine tenths of the Basin's steam production). At Castelnuovo-Lardarello and Serrazzano the permeable complex rocks are thin or absent and the highs are simply highs in the basement.

Reservoir Statics and Dynamics

There is a clear analogy to the well-known structural trap reservoirs of petroleum geology. Steam can be trapped under an anticlinal caprock like petroleum.

There appears to be reasonably continuous permeability and flow at the reservoir top throughout the Basin. Isotopically demonstrated flow of water from surrounding aquifers into the reservoir [3] indicates hydraulic continuity with them as well. This suggests that prior to exploitation there must have been hydrostatic equilibrium between reservoir and aquifers. The (simplified) condition for such equilibrium is that

$$h_{aq} - h_{res} = 10 \times [P_{sat}(T_{res}) - 1]$$

where h_{aq} is the isopiestic level of the surrounding aquifers (in meters), h_{res} is the elevation of the steam-water interface under the trap, and $P_{sat}(T_{res})$ is the steam saturation pressure at reservoir temperature. Analysis of water level and temperature survey data from the few "wet" wells in the Serrazzano zone should provide a good test for this equation.

A detailed analysis of various published data has led to an estimate of 275°C for the initial reservoir temperature. As h_{aq} averages about 100 meters around the periphery of the Basin, an initial h_{res} of about -500 meters is indicated.[4] This is deep enough to allow for fair-sized initial steam zones in the major areas.

Early wells never reached 500 meters subsea and never encountered water. The fact that most modern deep wells have also not encountered water is probably due to a lowering of the water table by steam production.

Hydrogen and oxygen isotope studies[3] show clear evidence of massive incursions of recently meteoric groundwaters from the southeast at Castelnuovo and Sasso. Smaller incursions are suggested from the southwest between Lagoni Rossi and Lago, and from the west at Serrazzano.

It is likely that the incursion of surrounding cooler groundwaters is due to the lowering of reservoir pressure caused by steam production. A hydrological balance calculated for the entire basin suggests that the rate of recharge is about one-third that of steam production[5].

Toward a Numerical Model of the Serrazzano Zone

LBL's part in the U. S. DOE/ENEL cooperative program is to numerically model the reservoir dynamics of the Serrazzano and Castelnuovo zones. The author is presently well along in the development of a geologically accurate computer-generated mesh for use in modelling Serrazzano.

Figure 2 shows a recent version of this mesh. The input data for the mesh generator is essentially a set of digitized geological cross-sections. The two cross-sections labeled in Figure 2 are shown as such in Figure 3.

The three lithological layers distinguished in the cross-sections are the three complexes defined and discussed above. Where there is a significant thickness of "the evaporites," the mesh elements all lie completely within this complex. Where the basement and caprock are in direct contact, the mesh elements are taken to lie along the contact surface and to be about 120 meters thick. 120 meters was chosen because it is about twice the root mean square distance for heat diffusion through rock over 25 years. (This roughly corresponds to the history of full-scale steam production at Serrazzano.) The underlying physical model is that of steam flowing through a thin fault zone and extracting heat from the surrounding impermeable rock by conduction.

The points plotted within the evaporite stratum and at the caprock-basement contact correspond to the individual elements of the mesh. The points within the basement or caprock and not on the contact do not correspond to mesh elements. Their function is to define the bounding planes of the adjacent mesh elements. In all cases, the bounding and interface planes are the plane bisectors of the line segments between the corresponding pairs of points. This prescription for choosing interface planes is believed to be optimal for our purposes. The only input data required are the coordinates of the various points. The mesh shown has 227 elements and 448 bounding points. The calculation found 2404 boundary and interface planes between them.

Water Reserves and Boundary Conditions

The mesh in Figure 2 is geologically accurate in its depiction of the reservoir, and the volume and elevation of each element is known. This allows us to estimate initial heat and water reserves within the region modelled.

Figure 4 shows just those elements whose content is about one-half or more "evaporitic" rock. The total volume of these elements is about 4.2 km^3 Of this, about 3.1 km^3 is below about-450 to-500 meters and was probably initially water saturated. How much water this represents depends on the average porosity which is unknown. If we make a moderately optimistic estimate of 10%, this is 0.31 km^3. Assuming an initial temperature of 275°C gives an estimated initial mass of about 2.3×10^8 metric tons. This amount of steam would suffice to run the 32MW Serrazzano power plant for about one hundred years. The magnitude is completely consistent with cumulative steam production of about 0.9×10^8 tonnes to date.

Clearly, the extent of mass flow in and out of the region studied will also effect the validity of such estimates. It appears that the Serrazzano zone is the most isolated subarea within the Basin in this regard. (This is one reason why Serrazzano was chosen for study. The other is that relatively complete historical production data is available.) However, as is evident from the concentration of the "evaporites" at the very edges of the mesh, it cannot be perfectly isolated. The very thick evaporite stratum in the southeast corner of the mesh (also see Section C) is continuous with the diapiric evaporite outcrop between Monterotondo and Sosso. This is known to be a major recharge area.[3] Although the recharge water does not appear to have reached the Serrazzano zone yet, it is possible that it has already displaced significant volumes of "old" water toward Serrazzano. There may also be some influx of water and/or steam from west-southwest where the mesh is truncated due to lack of stratigraphic data. The large volume of evaporites in the south-southwest octant is about midway between Serrazzano on one side and Lagoni Rossi and Lago on the other. It is very likely that some of the steam generated here flows south toward the latter two zones.

Heat Reserves

We will assume a volumetric heat capacity of 2460 kJ/m^3 °C for the reservoir rock and an initial temperature of 275°C. 8 bar seems to be a reasonable estimate for ultimate abandonment pressure, and this corresponds to an abandonment temperature of 170°C. We again take $\phi = 0.1$ for the "evaporites" and $\phi \approx 0$ for the other rock types.

This leads us to estimate the total quantity of useful heat within just the "evaporite" elements of the mesh to be about 9.8×10^{14} kj. This quantity of heat is enough to convert 3.6×10^8 metric tonnes of water initially at 25°C to steam of 2800 kj/kg enthalpy. Water initially at 275°C would require less heat. If we assume an initial "preheated" water supply of 2.3×10^8 tonnes, we find that an equal volume of cold recharge water is needed to cool the evaporites down to 170°C. Another 2.0×10^8 tonnes would be required to cool the nonevaporite portions of the mesh down to 170°C, for a grand total steam production of 6.6×10^8 tonnes. This is enough for 9,400 MW-years of electrical generation.

It seems clear that water reserves will prove to be the limiting factor at Serrazzano. A long term program of water injection appears to be called for if anything like the above figure is to be reached.

Acknowledgements

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Mr. Chris Weaver generated the excellent graphics which make my mesh output comprehensible. Ms. Chris Doughty assisted me with the tedious work of digitizing the geological input data.

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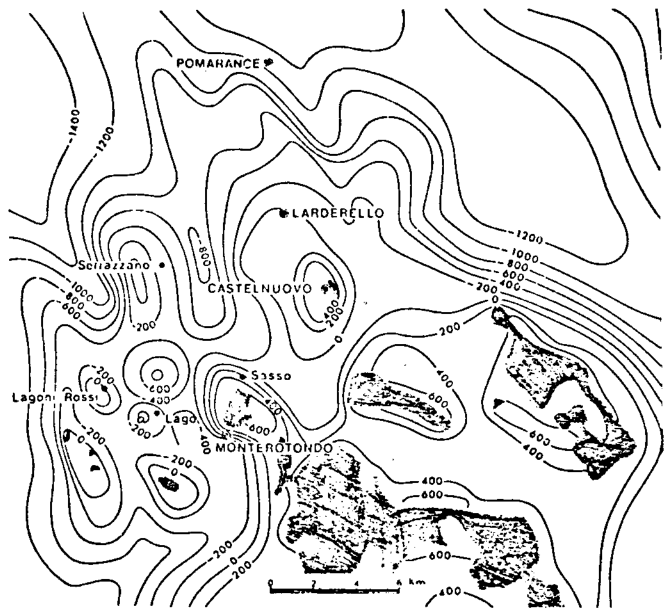

Figure 1. Elevation of reservoir top throughout Lardarello Basin in meters. Shaded areas indicate "evaporite" outcrops. From Reference 2.

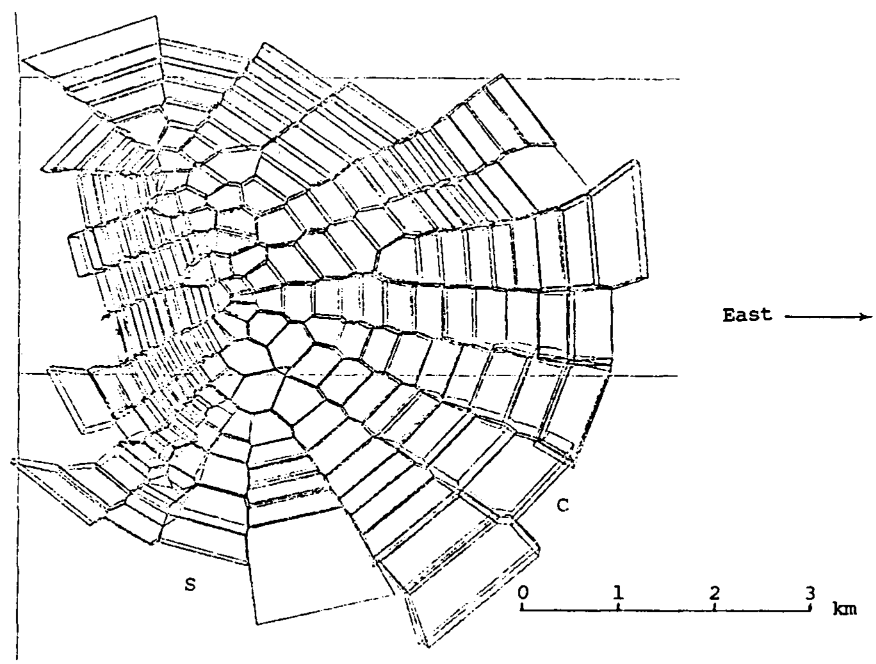

Figure 2. A computer-generated mesh for modelling the Serrazzano zone reservoir.

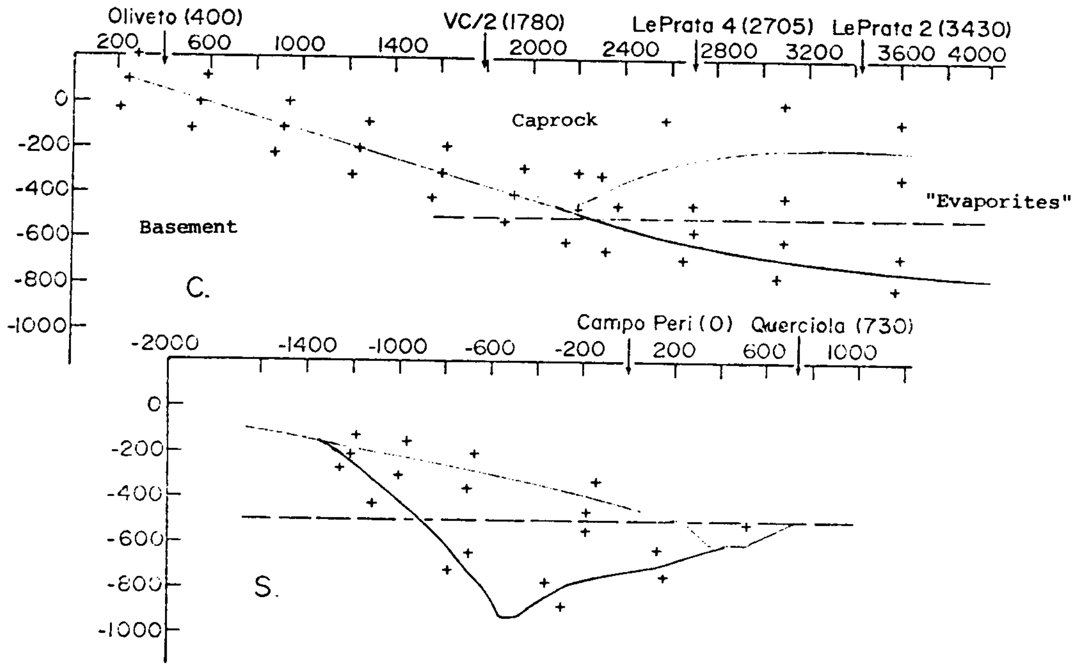

Figure 3. Typical geological cross-sections of Serrazzano zone. The points are input for the mesh generator code.

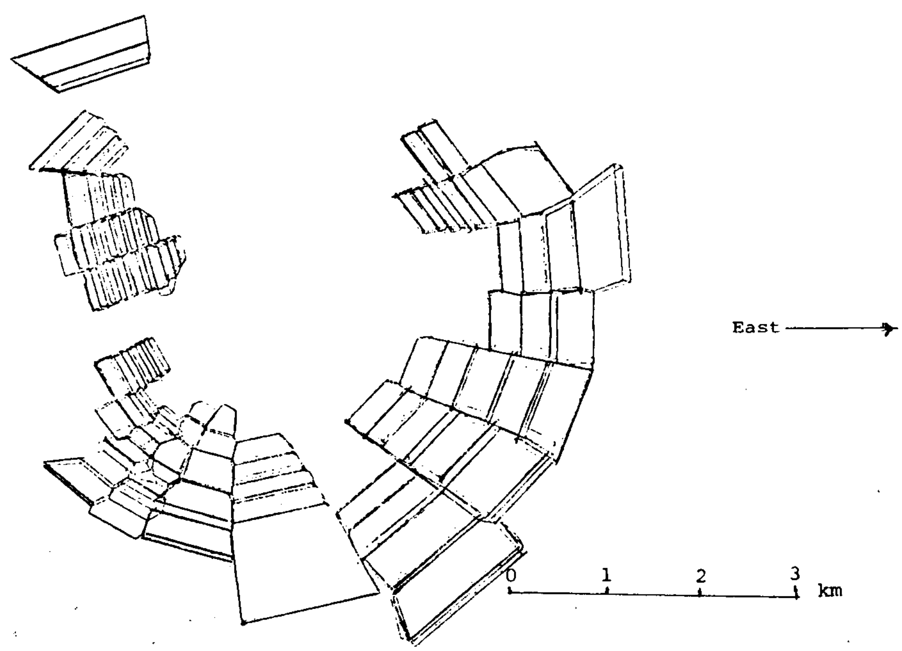

Figure 4. Same as Figure 2, but showing "evaporite" mesh elements only.