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INTERPRETATION OF RADON CONCENTRATION IN THE SERRAZZANO ZONE OF THE LARDERELLO GEOTHERMAL FIELD

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ABSTRACT

Wellhead concentrations of radon were made at 22 wells in the south-west region of the Larderello geothermal fields by two analytical methods, a field measurement as reported by D'Amore and laboratory measurement as reported by Semprini and Kruger. Agreement between the two methods was satisfactory.

The radon concentrations were correlated with average specific volume of superheated steam for each well estimated from available thermodynamic parameters of the reservoir. The correlation was improved by adjusting the specific volume of steam by a mass steam saturation value calculated at the boiling front from chemical fluid composition for each well by a method developed by D'Amore and Celati. A compressible flow model for radon transport developed by Sakakura et al. was also tested.

The results confirm that radon behavior in geothermal systems is characterized by thermodynamic conditions in the reservoir. In the Serrazzano zone, abnormally high values of radon concentration with respect to estimated specific volume in four of the 22 wells were observed an area of proposed low permeability. The high values may also result from higher emanating power or lower porosity in this zone. A cross-section normal to the zone of low permeability between the two basins shows a similar radon profile as noted in a Geysers production zone.

A comparison of these data with the set obtained in 1976 by D'Amore shows relatively constant radon concentration despite several wells having large variations in gas/steam ratios.

INTRODUCTION

Radon concentration measurements in the Serrazzano zone of the vapor-dominated field at Larderello, Italy were examined with respect to thermodynamic and geologic conditions in the reservoir. The thermodynamic relationship was evaluated for reservoir pressure and the geologic parameters included porosity and permeability.

Properties of radon and its use in geothermal reservoir engineering have been discussed by Stoker and Kruger (1975), D'Amore, Sabroux, and Zedwoog (1978), Warren and Kruger (1979), and Semprini and Kruger (1981). Wellhead concentrations of 3.83-day ^{222}Rn reflect reservoir conditions during the preceding 30-day residence of the produced geofluid. This time dependent factor makes ^{222}Rn a useful natural tracer for studying spatial and temporal changes in the reservoir. Radon achieves an equilibrium concentration (nCi/kg pore fluid) when the rate of emanation from the rock matrix equals the rate of decay in the fluid,

$$C_f = \frac{E_m \rho_r}{\phi \rho f} \qquad (1)$$

where C_f = mass concentration of radon in the pore fluid (nCi/kg)
E_m = emanation power (nCi/kg rock)
ρ_r, ρ_f = rock, fluid density (kg/m^3)
ϕ = porosity (m^3 fluid/m^3 formation)

The emanation of radon from formation rock is dependent on several parameters, e.g., rock type, intrinsic and fracture porosity and permeability, radium content, moisture saturation, and the local thermodynamic conditions. Radon emanation from graywacke rock has been shown by Macias (1981) and Satomi (1982) to increase with temperature. On the basis that rock in the Serrazzano formation has the same emanation properties as graywacke, the change in emanation over the temperature range of 210 to 270°C (Cappetti et al. 1982) could range from 10 to 15%. On the other hand, for a temperature range of 210 to 270°C, the fluid density in a vapor-dominated reservoir would change by a factor of 2.9. Thus radon concentration should be sensitive to changes in fluid density which is related to changes in formation pressure.

Semprini and Kruger (1981) examined the relationship of radon concentration to specific volume in vapor-dominated and liquid-dominated reservoirs. The specific volume for a static two-phase fluid is

$$\overline{V}_f = \frac{x}{\rho_L} + \frac{(1-x)}{\rho_v} \qquad (2)$$

where x = liquid mass fraction
$(1-x)$ = vapor mass fraction

The equation is valid for a dynamic system if the phases move with equal velocity. Semprini and Kruger (1982) showed a positive linear correlation (with correlation coefficient, $r^2 = 0.80$) between radon concentration and fluid specific volume at the Cerro Prieto geothermal field in Mexico. Specific volumes were calculated from measured wellhead enthalpies and from geothermometer estimates of reservoir temperatures.

In vapor-dominated reservoirs, fluid specific volume is more difficult to estimate because of greater compressibility factors, larger fracture porosity, and immobile liquid saturation. In such reservoirs, specific volume of the steam can change along the flowpath as pressure decreases, while radon can continuously emanate to the fluid with changes in emanation rate as a function of fracture size distribution. Radon concentration can also be affected by liquid saturation in the reservoir, especially if emanation into the vapor phase is small or residence time for buildup is short.

Radon concentration measurements have been evaluated with respect to reservoir thermodynamic conditions in three ways: (1) an equilibrium model with estimated specific volume, (2) the equilibrium model adjusted for estimated steam saturation, and (3) a compressible flow model adapted from Sakakura et al. (1959).

The specific volume model used a reservoir average pressure and temperature to calculate the equilibrium specific volume around each well. Reservoir temperatures and top pressures for the Serrazzano zone were reported by Cappetti et al. (1982). The average pressure was estimated as a root-mean-square pressure from the pressure at saturated reservoir temperature and the lower pressure at the reservoir top.

$$P = \frac{\left(P^2_{(T_{res})} + P^2_{(top)}\right)^{1/2}}{2} \qquad (3)$$

The specific volume of the steam, $\overline{V}_s$, is obtained from superheated steam tables at the estimated reservoir temperature, T_{res}, assuming isothermal flow to the well. On the basis of constant emanation and rock porosity, the volumetric emanation, E_v, is constant, and the radon concentration is given by

$$[Rn]_s = E_v \cdot \overline{V}_s \qquad (4)$$

In model 2 steam saturation is incorporated. It is computed by a method proposed by D'Amore and Celati (1983) using gas composition. In this model, the steam saturation is the average value of the calculted reservoir saturation and the steam saturation near the wellbore, assumed to be 100%. The average steam saturation, $\overline{Y}$, represents the (1-x) term in equation (2). Since liquid density is much greater than vapor density, only the steam term is used for fluids of high vapor mass fraction (as in the Serrazzano zone) to calculate equilibrium radon concentation,

$$[Rn]_s = E_v[\overline{Y} \cdot \overline{V}_s] \qquad (5)$$

The radon transport model proposed by Sakakura et al. (1959) is based on a flow model for a compressible fluid in radial geometry with a uniform emanation source term. The analytical equations of this model were discussed by Stoker and Kruger (1975) and used to interpret radon measurements at The Geysers vapor-dominated field in California. The model parameters include reservoir pressure, flowing wellhead pressure, flowrate, and estimates of porosity thickness and effective reservoir radius. Sensitivity analysis of the Sakakura et al. (1959) model noted that radon concentration was most affected by reservoir static and wellhead flowing pressures. These parameters are estimated as a lumped parameter, K (in units of m^3/kg) such that the radon concentration is given by

$$[Rn]_s = K \cdot E_v \qquad (6)$$

EXPERIMENTAL PROGRAM

The Serrazzano zone of the Larderello geothermal field was selected for evaluation of the three models. The geologic, hydrologic, and geochemical conditions for this reservoir were available from Calore et al. (1980) and D'Amore et al. (1981). The thermodynamic data for the reservoir were obtained from Cappetti et al. (1982). Earlier radon measurements for the Serrazzano zone were reported by D'Amore (1975). The present measurements allow a comparison of the results over a seven-year period of production.

Radon measurements were made by two techniques, one involving field measurements during sampling and the other by laboratory analysis of wellhead samples. The field measurement method was described by D'Amore (1975). The geofluid is condensed at the wellhead sampling port and separated into measured condensate and noncondensable gas fractions. The noncondensable gas, containing more than 95% of the radon, is transferred to ZnS-lined scintillation flasks for radon measurement. The radon concentration at the wellhead is determined from the gas/steam ratio.

The laboratory measurements were made with the method described by Stoker and Kruger (1975). Adsorption-purified radon is transferred to ZnS-lined scintillation counting flasks for measurement in a single-channel pulse-height analyzer.

RADON MEASUREMENT COMPARISON

Twenty-two wells were sampled for radon in the Serrazzano zone using the field technique. Samples of fifteen of these wells were collected for measurement in the Stanford geothermal laboratories. Agreement of the two sets of results was evaluated by linear regression. The regression line of [Rn] (field) = 21.1+1.24 [Rn] (lab) had a correlation coefficient of $r^2 = 0.90$. The slope value significantly greater than 1.0 shows the field measurements with higher concentrations compared to the laboratory measurements. This factor may result from a too low counting efficiency factor for carbon dioxide as the carrying gas in the field technique. Since the two sets of data differ by a constant factor, use of the 22-well data set should not affect the validity of data interpretation.

TEST RESULTS

Table 1 gives the test data and reservoir parameter values used in the set of model evaluations. The values for reservoir temperature (T_{res}) and top pressure (P_{top}) were obtained from Cappetti et al. (1982). The steam mass saturation (Y) was derived from gas composition data from samples obtained by D'Amore during the radon survey. The saturation pressures based on reservoir temperatures of 210 to 270° C ranged from 19 to 55 bar. Reservoir top pressure ranged from 5 to 25 bar. The average pressure calculated from equation (3) ranged from 14.0 to 42.7 bar. The radon concentration ranged from 41 to 302 nCi/kg.

Results of linear regression analysis of radon and specific volume calculated from average reservoir pressure are shown in Figure 1. The resulting regression equation $[\hat{Rn}] = -2.3 + 1500\ (\bar{V}_{s2})$ nCi/kg has a correlation coefficient of $r^2 = 0.65$. A t-test of the regression shows the intercept value of -2.3 cannot be distinguished from zero, which is predicted by equation (4). For estimated values of radium content of 1.0 nCi/kg, porosity of 5%, and rock density of 2.5 g/cm^3, volumetric emanation represents an emanating power of 3 percent.

To check the regression linearity, analysis was also performed for log-log regression. Results showed the regression form could not be distinguished from linear. The correlation coefficient $r^2 = 0.65$ indicates that about two-thirds of the observed radon concentration can be attributed to the fluid specific volume in the reservoir due to the existing pressure distribution for constant porosity and emanation. The linear relationship with specific volume calculated using the p^2-average pressure given in equation (3) indicates that radon concentration reflects thermodynamic conditions closer to true reservoir pressures than pressures near the wellbore.

The effect of steam saturation on specific volume was also examined by regression analysis. Estimates of steam mass saturation ranged from 0.38 to 0.83 kg/kg. Linear regression of radon concentration with steam mass saturation, $\bar{Y}$, shows little correlation ($r^2 = 0.22$). Linear regression with combined saturation-specific volume, $(\bar{Y} \cdot \bar{V}_s)$, in equation (5) resulted in a regression line $[\hat{Rn}] = 13.0 + 1646\ (\bar{Y} \cdot \bar{V}_{s2})$ with an improved correlation coefficient, $r^2 = 0.69$. Log-log regression also showed a regression form that could not be distinguished from linear. The improved correlation suggests that vapor saturation may be an important parameter in reservoirs of low steam saturation.

The Sakakura et al. (1959) model of compressible flow was tested with reservoir pressures ranging from P_{top} to P_{res}. The best fit was achieved with a constant value for the effective reservoir radius, r_e, for all wells and for P_{res} approximately equal to the p^2-average pressure obtained from equation (3). The fit of model to observation was rather insensitive to the value of effective radius with r_e varying from 50 to 1000 m. The correlation of radon concentration to the coefficient K derived by the analytical model is shown in Figure 2. The regression line $[\hat{Rn}] = 36.2 + 1600\ (K)$ nCi/m^3 has a correlation coefficient, $r^2 = 0.63$. The slope value, representing the volumetric emanation factor, E_v, is statistically the same as that obtained for the equilibrium model. However, testing of the linearity by log-log regression showed a regression curve $[\hat{Rn}] = 832(K)^{0.65}$, significantly different from linear. The discrepancy may result from incorrect pressure differentials or nonconstant effective reservoir radius.

SPATIAL VARIATIONS

The observed changes in radon concentration may be due to geologic factors which influence the distribution of emanation, porosity, and permeability throughout the reservoir.

Table 1

RESERVOIR AND RADON DATA FOR THE SERRAZZANO GEOTHERMAL FIELD

Well	T_{res} (°C)	P_{top} (bars)	$\overline{P}$ (bars)	Y (kg/kg)	$\overline{V}_s$ (m^3/kg)	$\overline{Y}\,\overline{V}_s$ (m^3/kg)	K* (m^3/kg)	Rn (nCi/kg)
1	270	20	41	0.39	0.052	0.036	0.020	50
2	250	12	30	0.82	0.072	0.066	0.051	95
3	240	5	24	0.58	0.088	0.070	0.054	148
4	230	5	20	0.43	0.105	0.076	0.070	149
5	230	5	20	0.53	0.105	0.081	0.072	132
6	220	5	17	0.63	0.126	0.103	0.092	145
7	230	5	20	0.66	0.105	0.087	0.071	124
8	220	5	17	0.72	0.122	0.105	0.093	166
9	220	5	17	0.64	0.122	0.100	0.091	157
10	210	5	14	0.82	0.147	0.134	0.114	302
11	270	19	41	0.59	0.052	0.042	0.02	136
12	230	16	23	0.49	0.090	0.072	0.065	153
13	240	17	27	0.38	0.079	0.059	0.052	153
14	220	20	22	0.40	0.092	0.064	0.056	127
15	240	25	30	0.80	0.070	0.063	0.031	95
16	240	22	28	0.74	0.074	0.064	0.048	132
17	270	25	43	0.46	0.049	0.036	0.027	41
18	260	20	36	0.42	0.059	0.042	0.037	108
19	260	25	38	0.38	0.056	0.039	0.042	68
20	220	15	20	0.54	0.105	0.081	0.073	129
21	220	9	18	0.83	0.118	0.109	0.089	183
22	220	8	17	0.65	0.118	0.098	0.084	168

*Based on reservoir radius of 500m and porosity-thickness of 25 m.

Figure 3 shows well locations and contours of radon concentration in the Serrazzano zone. During analysis of radon concentration as a function of specific volume, it was noted that the four wells (Nos. 10, 11, 12, and 13) most deviant from the regression line in Figure 1 were located near areas of low permeability. Linear regression analysis of the 22-well data set without the data for these four wells resulted in an improved correlation coefficient, $r^2 = 0.79$. Although sufficient data are not available for quantitative analysis, the higher radon concentrations in these wells with respect to thermodynamic conditions may be due to lower reservoir porosity and higher surface area for radon emanation associated with zones of low fracture permeability. Laboratory experiments reported by Sammis et al. (1981) showed radon concentration in pore fluids in granite cores was inversely related to permeability. The high radon concentrations for these four wells in this zone may be associated with lower porosity. Using equation (1), a 50% reduction in porosity from the field average of 5% could account for the higher observed concentrations.

Three of the wells (Nos. 1, 17, and 19) showed lower radon concentration from the regression line for specific volume. D'Amore et al. (1981) proposed from the observed high reservoir temperatures and high boron and chloride content of the produced fluid that these wells are located in zones of fluid upflow. Reservoir porosity in an upflow zone may be higher than average field values (Celati, personal communication). A porosity of 7.5% compared to a field average of 5% would account, in equation (1), for these lower observed radon concentrations. It is clear that multi-parameter regression analysis when sufficient data on porosity are available would enhance the interpretation of the radon concentration data with respect to thermodynamic behavior in a geothermal reservoir.

TEMPORAL VARIATIONS

Comparison of results from the 1976 and 1982 surveys shows little change in radon concentration in the 22 wells. These results suggest thermodynamic conditions that influence radon concentrations have remained fairly constant during this period. In several wells, radon concentration remained constant in the fluid while the total noncondensable gas content ratio changed. Decrease in gas/steam ratio occured in wells 12, 13, and 14. These wells are located near a reinjection area that started operation between the two survey periods. Reinjection studies in the Larderello field by Giovannoni et al. (1981) have shown a decrease in gas/steam ratio after start of reinjection. The decrease in gas concentration indicates production of a steam mixture containing original reservoir fluid of high gas/steam ratio and reinjection fluid with negligible gas content. The constant radon concentration, however, indicates the thermodynamic conditions near the producing wells. have not changed, even though the produced steam contains vapor from reinjected fluid.

COMPARISON WITH OTHER GEOTHERMAL FIELDS

The correlation of radon concentrations with estimated values of specific volume for three geothermal reservoirs, Cerro Prieto, Mexico, The Geysers, California, and Serrazzano, Italy are shown in Figure 4. The large increase in specific volume from liquid- to vapor-dominated systems is reflected in the respective increase in radon concentrations. The relationships of radon concentration to specific volume cannot be directly compared among fields due to possible variations in radon emanation and formation porosity for the different reservoirs. Regression analysis of radon in relation to specific volume yields a volumetric emanation factor for each reservoir, from which an estimate of the emanating power can be made. Assuming uniform radium content of 1 nCi/kg, rock density of 2500 kg/m^3, and average porosity values of 15% for Cerro Prieto, 7% for The Geysers, and 5% for Serrazzano, the average emanation power is 1%, 1.5%, and 3% respectively. This small variation in emanation power could result from variations in reservoir rock type for the three fields.

Cross sections normal to zones of low permeability show similar trends at both The Geysers and the Serrazzano reservoirs. Figure 5 shows the transect of radon concentration and estimated values of specific volume in the Serrazzano reservoir along the transect A-B given in Figure 3. Radon concentration increases towards zones of lower permeability to a greater extent than predicted by the specific volume relationship. Figure 6 shows a similar relationship for a transect across The Geysers reservoir. Both data suggest a less porous reservoir and/or a higher amount of emanation in these zones. The similar trends in both the Serrazzano and Geysers reservoirs indicate tht radon concentrations are related not only to thermodynamic conditions, but also changes in physical properties of the reservoir.

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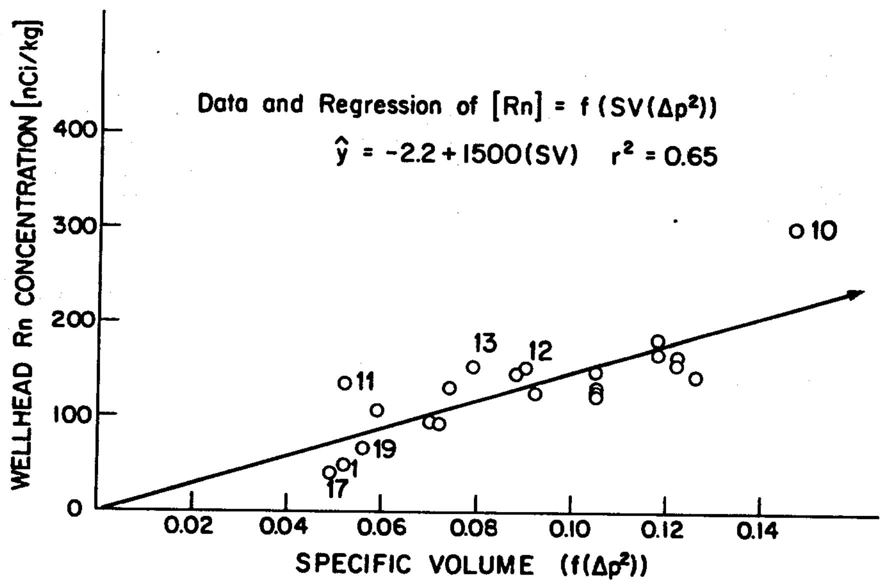

Figure 1. Correlation of radon concentration and specific volume.

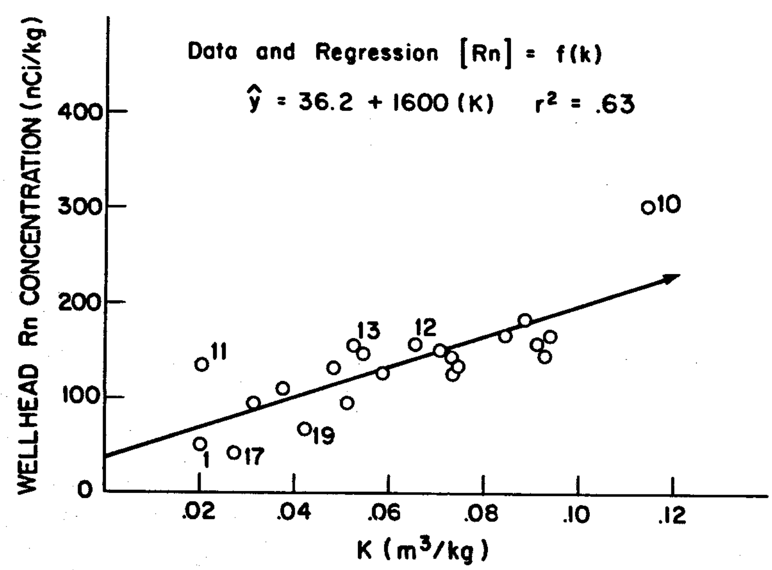

Figure 2. Correlation of radon concenand the K parameter from Sakakura et al. (1959).

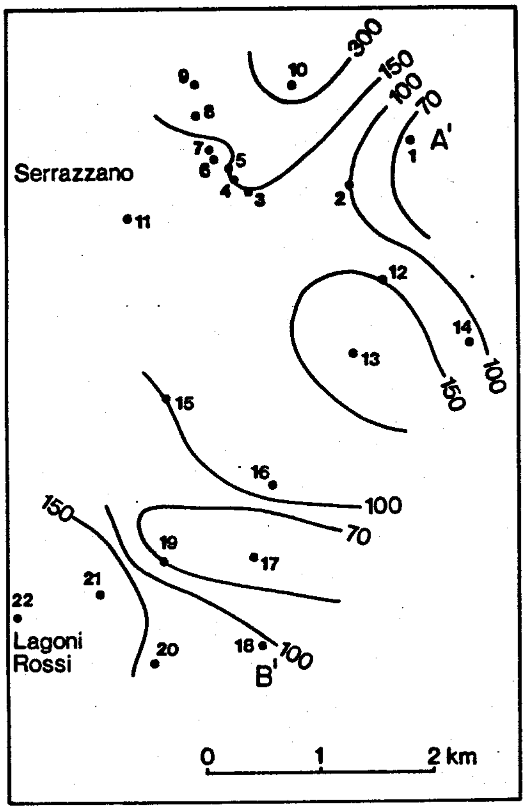

Figure 3. Radon concentration contours in the Serrazzano reservoir.

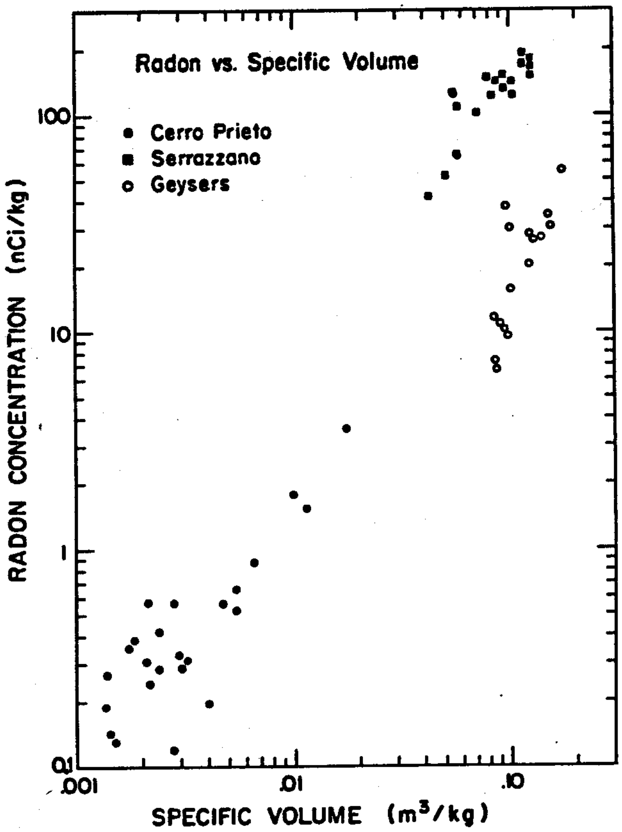

Figure 4. Radon concentration and specific volume for three geothermal reservoirs.

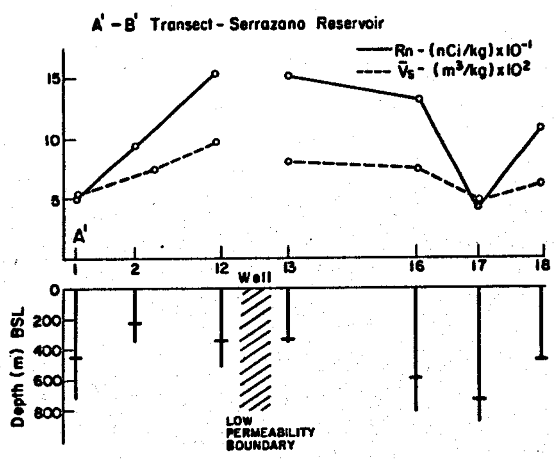

Figure 5. Radon and specific volume across a zone of low permeability in the Serrazzano reservoir.

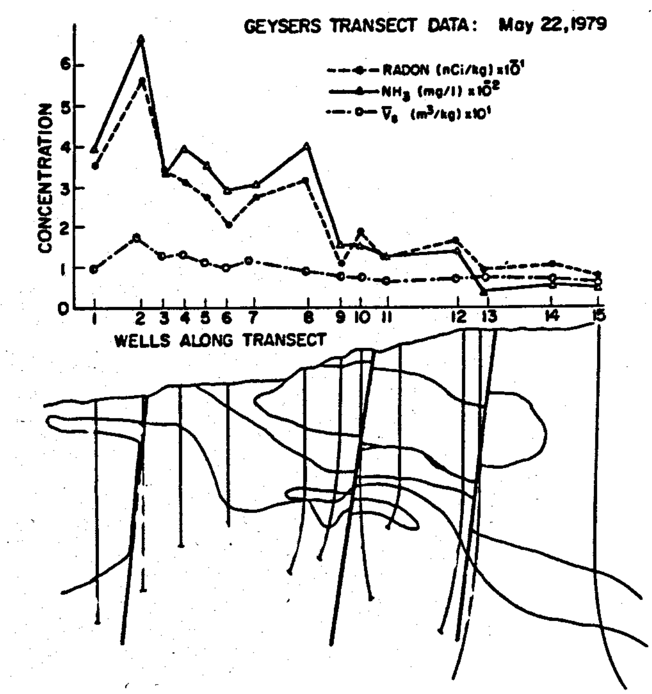

Figure 6. Radon and specific volume transect in The Geysers reservoir.