Geothermal Resources Council TRANSACTIONS, Vol. 14, Part II, August 1990

RESERVOIR MATRIX POROSITY AT THE GEYSERS FROM CORE MEASUREMENTS

Richard P. Gunderson

Unocal Geothermal Division
3576 Unocal Place
Santa Rosa, CA 95406

ABSTRACT

Matrix porosities of Geysers reservoir rocks are quite low compared to most geothermal reservoir rocks. Porosities measured on nine cores of reservoir graywacke range from 0.6% to 5.8%, with an average of 2.3%. Measured porosities of four graywacke cores from outside the reservoir have a narrower range, from 0.9% to 2.3%. Porosities of three cores of felsite intrusion range from 1.7% to 4.2%, with average background values expected around 2%.

Much of the porosity in the cores is fracture-related, which leads to dependence of measured porosity on sample size. Larger samples include more widely spaced fracture sets and hence yield higher porosity values. Actual bulk reservoir porosities are therefore thought to be somewhat higher than measured core porosities.

The distribution of porosity in the reservoir graywacke appears to be related to two factors: vertical depth and distance above the felsite intrusion. A model has been constructed to describe the distribution of porosity in the Geysers reservoir based on these two parameters. In the model porosities are highest in shallow reservoir that is far above the felsite intrusion. From there porosities decrease downward and toward the edges of the reservoir where the reservoir is deeper.

INTRODUCTION

Previous studies have shown that the majority of initial reserves at The Geysers was stored as liquid water in the matrix of the reservoir rock (Williamson, 1990). During field exploitation the hot water boils in response to the lowering of pressures in nearby fractures, and then flows as steam down pressure gradient through fractures into producing wellbores. In order to realistically simulate past production and predict future field performance, a realistic model of matrix porosity is essential. For this characterization of porosity, the rock matrix is considered as all of the rock outside of the widely spaced fractures that are characterized as "steam entries" during drilling. Matrix porosity thus includes both intergranular pore space and pore space in fractures which do not produce detectable steam. Geysers matrix porosity must be characterized for the two main reservoir rock types: reservoir graywacke and the underlying young intrusion (informally called felsite; Thompson, 1989).

A model for porosity distribution in the Geysers reservoir has been developed, based on direct measurements of porosity on twelve cores of reservoir rock distributed throughout the field. The cores were all taken from below their respective wells' first steam entry and therefore represent rock from within the vapor-dominated section. All but one were taken more than seventy-five feet away from any steam entry in order to acquire background matrix material. The single "non-matrix" core was taken from within a steam entry in felsite (Table 1-J). The cores range from 4 to 32 feet long, with recovery averaging 74%. Typically, one fourth to one half of each core is recovered as segments of full 4 inch diameter, with the remainder ranging from only slightly broken pieces to rubble.

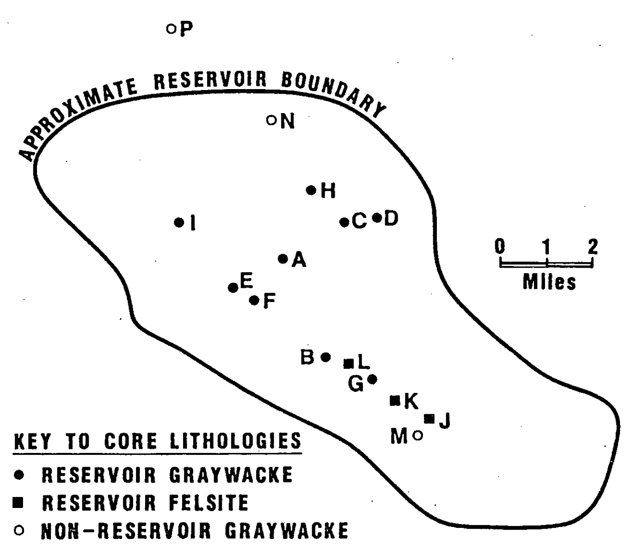

Figure 1: Location of Unocal cores.

TABLE 1

Well	Sample From	Core Interval (Drilled Depth)	Core Elev. (MSL)	Felsite Elev. (MSL)	Rock Type	Porosity (vol %) 4" Core	1" Plug	Range of Values	Grain Density (g/cm^3)
A DX-84	Reservoir	7730-7741'	-4180'	-6200	Graywacke	3.1	3.2	1.5-5.0(12)	2.70
B GDC-30	Reservoir	5012-5022'	-2920'	-4000	Graywacke	1.9	1.4	0.3-3.1(12)	2.71
C GDHS-7	Reservoir	8060-8075'	-4825'	-8000	Graywacke	1.3	1.1	0.2-2.1(12)	2.74
D NEGU-17	Reservoir	8523-8540'	-5245'	-9000	Graywacke	2.9	2.6	1.1-5.6(8)	2.72
E SB-31	Reservoir	3729-3750'	-1565'	-4700	Graywacke	3.1	3.1	1.1-5.7(16)	2.72
F TH-7	Shallow Resv.	~1000'	~+740'	-4500	Graywacke	---	5.8	4.1-8.1(10)	2.69
G GDCF 15D-28	Reservoir	5017-5032'	-2015'	-2500	Graywacke	1.1	0.6	0.1-1.6(8)	2.69
H L'ESP-2	High-T Resv.	11,051-11,067'	-8075'	-9000	Graywacke	0.6	0.7	0.2-1.1(8)	2.74
I OF27A-2 ST1	High-T Resv.	10,366-10,387'	-7225'	-8000	Graywacke	0.9	0.8	0.3-1.5(8)	2.75
J DV-2	Steam Entry	3708-3718'	-665'	-300	Felsite	4.2	4.4	3.1-5.6(4)	2.63
K GDC-21	Reservoir	5864-5868'	-3310'	-1500	Felsite	1.7	0.8	0.8-2.0(4)	2.65
L LF-48	Reservoir	8089-8096'	-4805'	-3000	Felsite	2.1	1.6	1.1-3.0(8)	2.62
M DV-1	Above Resv.	4140-4150'	-1295'	-2200	Graywacke	1.2	0.6	0.4-1.4(5)	2.70
N HVS 94-25	Above Resv.	8234-8248'	-5595'	-10,000	Graywacke	1.9	1.4	0.8-2.1(5)	2.71
P KCS 82-15	Outside Resv.	10,065-10,087'	-7670'	---	Graywacke	0.9	0.3	0.2-1.2(5)	2.78
Q Shallow Cores	Above Resv.	<200'	+3000'	---	Graywacke	---	2.3	1.0-3.2(5)	2.73

The twelve reservoir cores include eight cores of graywacke from the main reservoir, one graywacke core from the shallow Thermal reservoir (Raasch, 1985), and three cores of reservoir felsite. Depths of these cores range from about 1,000 feet to 11,067 feet. For comparison of reservoir porosities with porosities outside the reservoir, four non-reservoir graywacke cores were analyzed. Those include two cores of reservoir cap rocks, one deep core from a well entirely outside the reservoir, and five very shallow cores from within a few hundred feet of the surface. Locations of the deep cores are shown in Figure 1.

ROCK POROSITIES

Matrix porosity was determined for all samples at Terra-Tek Core Services, Inc. of Salt Lake City by comparing grain volume, measured by permeating the rock with helium, with bulk volume, measured by immersion in water or mercury. The resultant values represent effective porosities applicable to a vapor-dominated geothermal reservoir, since they are measurements of that part of the rock which is permeable to a low viscosity gas phase (i.e. steam). Multiple porosity measurements were made on each core to determine an average value of porosity. The measurements were taken wherever possible on both full diameter 4-inch core and 1-inch diameter plugs which were cut from the core. The results are presented in Table 1.

In 10 out of the 14 cores where porosity was measured on both 4-inch and 1-inch diameter samples, the 4-inch samples yielded higher values (Table

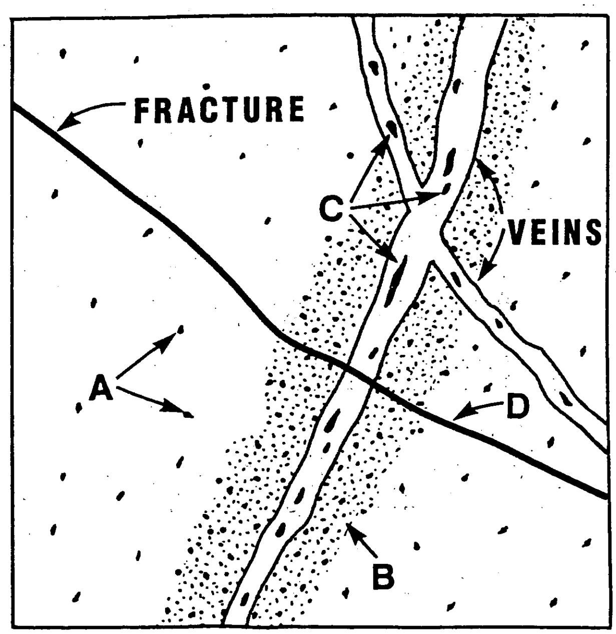

Figure 2: Schematic diagram depicting the four types of matrix porosity recognized in Geysers cores.
A. widely distributed vugs and intergranular voids,
B. concentrations of vugs and intergranular voids associated with vein selvages,
C. vugs within veins,
D. young, unmineralized fractures.

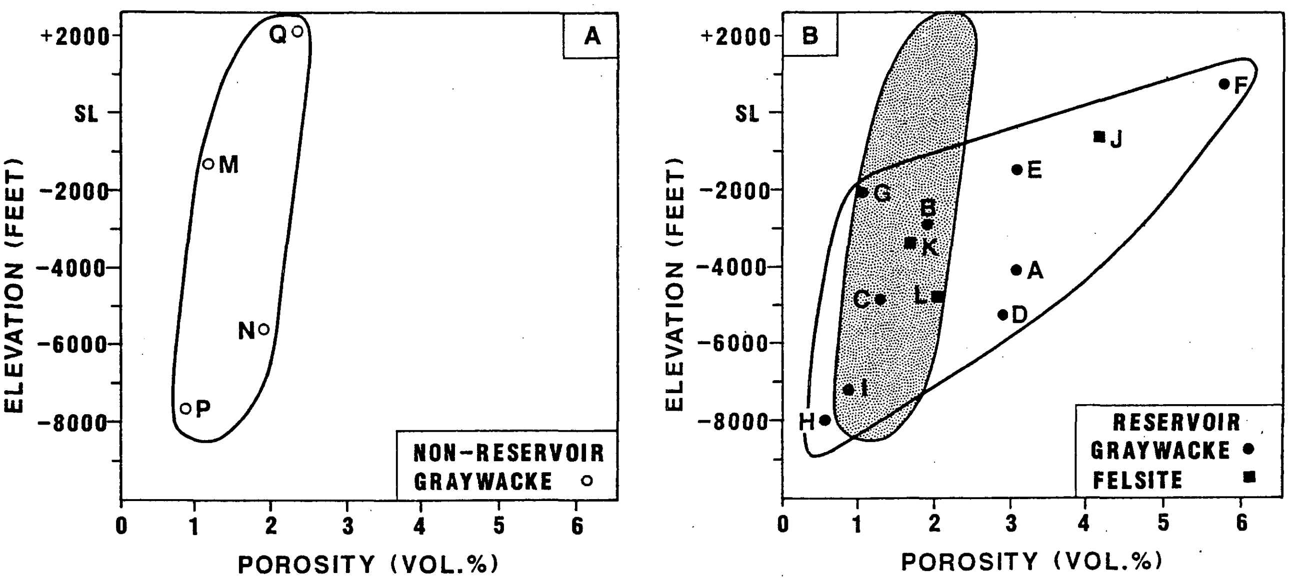

Figure 3: A: Distribution of porosity with depth in Geysers area non-reservoir graywacke cores.
B: Distribution of porosity with depth in Geysers reservoir cores. The shaded area is from 3A. Core names are keyed to Table 1.

1). The average porosity of the 4 inch samples from those 14 cores was 1.9% and the average 1 inch porosity was 1.6%. The disparity between 1-inch and 4-inch samples suggests heterogeneity in the distribution of porosity at the scale of a few centimeters. This heterogeneity is thought to be a result of the fracture-related nature of the porosity, as seen petrographically (Figure 2). The porosity measured on a 1-inch plug represents a uniformly distributed porosity component (Figure 2: Type A) plus a component related to the fractures in that sample (Figure 2: Types B, C, D). Porosities of 4-inch cores are thought to be higher than 1-inch porosities because, by virtue of their larger volumes, they sample additional larger, more widely spaced fractures and hence have a larger fracture-related porosity component. It follows that matrix porosities applicable on a reservoir scale (where all fractures smaller than steam entry-sized fractures contribute to matrix porosity) would be higher still than those measured in the 4-inch core. Lacking a way to sample larger volumes of the reservoir, the 4-inch porosities will be used hereafter in this study (where available). They are probably closer to reservoir values than are the 1-inch porosities.

Geysers rocks have very low porosities when compared to most other geothermal reservoir rocks; however, there appears to be higher porosity and more variation of porosity in reservoir graywacke than in graywacke from outside of the reservoir. Porosities of reservoir graywacke cores vary from a low of 0.6% to a high of 5.8% (Table 1). In contrast, non-reservoir graywacke vary only from 0.9 to 2.3%. The two "matrix" felsite values are very similar at 1.7% and 2.1%.

The difference in porosities between graywackes inside and outside the reservoir is highlighted in Figure 3. In non-reservoir graywackes there appears to be very little variation of porosity with depth (Figure 3A). Reservoir graywackes, while they show considerable overlap with non-reservoir porosities, clearly show much more variation and have a more positive correlation with depth (Figure 3B).

The wider range in porosities of reservoir rocks when compared to non-reservoir rocks suggests that processes which have both enhanced and destroyed porosity have occurred in the reservoir. Processes enhancing porosity probably included fracturing (Figure 2: C,D), mineral solution (Figure 2: A,B,C), and mineral reactions involving a negative net volume change (especially reaction of calcite and clays to form denser silicates; Figure 2: B,C). Such processes are evident in the contrast between core F, the shallowest reservoir core, and Q, a series of even shallower non-reservoir rocks. The shallow reservoir rocks are more intensely fractured, have fractures of wider aperture, and lack the calcite vein-filling which is ubiquitous in graywackes outside the reservoir. These differences are reflected in the measured porosities of the rocks, which are 5.8% and 2.3% inside and outside of the reservoir, respectively. Processes that destroy porosity probably included the sealing or constriction of voids due to mineral deposition and rock recrystallization. Rock recrystallization effects are probably restricted to the contact metamorphic zone enveloping the felsite intrusion. As an example, Core H, a highly recrystallized rock from within this zone, has a porosity of 0.6%, which is lower than any of the samples outside the reservoir.

The net effect of the processes that modified and redistributed porosity in the Geysers reservoir graywacke is the pattern of generally decreasing porosity downward shown in Figure 3B. An even more striking portrayal of this relationship is shown in Figure 4, where porosity is plotted against vertical distance above the underlying felsite intrusion. In this plot two groups of cores can be distinguished. The group marked "over shallow felsite" consists of cores from the central part of the field where felsite is shallower than about 7000 feet below sea level (Table 1, Figure 1). The group marked "over deep felsite" are in areas where felsite is inferred to be deeper than 7000 feet below sea level. The distinct yet parallel arrays of points suggest that porosity-modifying processes have been controlled not by depth alone, but by a combination of depth and the distribution of felsite. If this is true, then it is likely that the distribution of graywacke porosities was largely established during an earlier stage of the hydrothermal system, when the felsite was still very hot and causing recrystallization of graywacke.

The porosity distribution in felsite is less well-constrained than in graywacke. Figure 3 shows that porosities of the three felsite cores appear to follow the same depth correlation as the graywacke cores. However, of the three felsite cores, one (core J) was taken from within a steam zone, so its measured porosity of 4.2% is likely higher than nearby bulk reservoir matrix properties. The other two felsite cores, like all the graywacke cores, were taken in the reservoir but away from steam entries and yielded whole core porosities of 1.7% and 2.1%. These values are higher than the immediately overlying recrystallized graywacke values and are similar to the average graywacke porosities. Without more cores, however, a detailed porosity model of felsite showing vertical and lateral variations remains speculative.

CONCLUSIONS

Based on porosity measurements of twelve cores, the distribution of matrix porosity in the Geysers reservoir is largely related to three factors: rock type, depth and distance above the felsite intrusion. This interpretation permits the construction of a matrix porosity model for the reservoir which is essential in simulating future reservoir performance. Porosity of graywacke is highest in very shallow parts of the reservoir that are far above the underlying felsite. From there, matrix porosity decreases downward as the rocks become closer to felsite, and they decrease toward the margins of the field as the reservoir becomes deeper. A schematic cross section illustrating this concept is shown in Figure 5. Matrix porosity in the upper levels of the felsite intrusion is about 2% and may also decrease with depth.

A significant portion of the matrix porosity in both graywacke and felsite is in or very near fractures. Extrapolation of porosities measured on cores to values representative of large reservoir volumes requires accounting for fracture porosity on scales too large to be sampled by the cores.

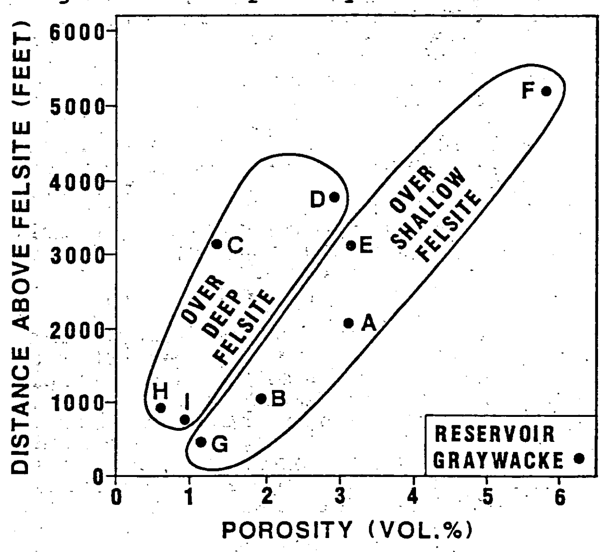

Figure 4: Measured Geysers reservoir graywacke porosities plotted as a function of vertical distance above the underlying felsite intrusion. Cores in group entitled "over shallow felsite" overlie felsite which is shallower than 7000 feet subsea whose depth is known to within about 200 feet. Cores in group entitled "over deep felsite" overlie felsite which is deeper than 7000 feet subsea, and whose depth is known to within about 1000 feet (see Table 1).

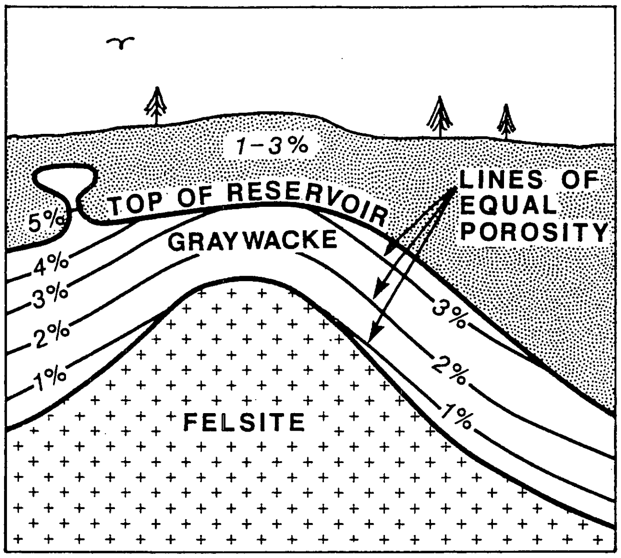

Figure 5: Schematic cross-section illustrating how matrix porosity of Geysers reservoir graywacke is interpreted to vary both with depth and with distance above the felsite intrusion.

ACKNOWLEDGEMENTS

I thank Unocal Geothermal and Thermal Power Company for permission to publish this work. I also thank R. Thompson, H. Crecraft, K. Williamson, and R. Dondanville for their comments on this manuscript.

REFERENCES

Raasch, G.D., 1985, Development of the Thermal Shallow Reservoir, Proceedings: Tenth Workshop on Geothermal Reservoir Engineering, Stanford University, January 22-24, 1985, p.129-131.

Thompson, R.C., 1989, Structural Stratigraphy and Intrusive Rocks at The Geysers Geothermal Field, GRC Transactions, v.13, p.481-485.

Williamson, K.H., 1990, Reservoir Simulation of The Geysers Geothermal Field, Proceedings: Fifteenth Workshop on Geothermal Reservoir Engineering, Stanford University, Jan. 23-25, 1990.