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A SURVEY OF POTENTIAL GEOPRESSURED RESOURCE AREAS IN CALIFORNIA

S.K. Sanyal and A. Robertson-Tait
GeothermEx, Inc.
Richmond, California

M. Kraemer and N. Buening
California Energy Commission
Sacramento, California

ABSTRACT

This paper presents the initial results of a survey of the occurrence and characteristics of geopressured fluid resources in California using the publicly-available database involving more than 150,000 oil and gas wells drilled in the State. Of the 975 documented on-shore oil and gas pools studied, about 42% were identified as potentially geopressured. Geothermal gradients in California oil and gas fields lie within the normal range of 1°F to 2°F per 100 feet. Except for the Los Angeles Basin, there was no evidence of higher temperatures or temperature gradients in geopressured pools. The porosity of geopressured pools shows the same normal distribution as for normal pressured pools, with a mode in the range of 20 to 25%. The salinity distribution of both the geopressured and normal pressured pools appear to be bimodal, each with two peak ranges of 0 to 10,000 and 25,000 to 30,000 ppm. Compared to the U.S. Gulf Coast region, geopressured pools in California display much lower water salinities, and therefore, should have a higher solubility for methane. Geopressured pools in California occur in the depth range of less than 1,000 feet to more than 18,000 feet. The modal depth of geopressured pools in California is 2,000 to 4,000 feet, much shallower than that encountered in the Gulf Coast region. The distribution of thickness of geopressured pools is similar to that of normal pressured pools, the majority being less than 250 feet thick. The distributions of the volume of geopressured and normal pressured pools are similar, the modal value being in the range of 1 to 10 billion cubic feet.

INTRODUCTION

Many authors have reported in depth on the potential for commercial recovery of the kinetic energy, thermal energy and dissolved methane from geopressured geothermal reservoirs identified in the U.S. Gulf Coast region. However, the occurrence of geopressured fluids in California has been reported by only a few authors, such as Berry (1973); Berry and Kharaka (1981); Kharaka *et al.* (1981); Lico and Kharaka (1983); Levine and Yerkes (1985); and Price (1988). These studies describe the geologic and tectonic settings of known geopressured zones, and in some cases present data from selected oil and gas wells to characterize the geopressured fluid. The U.S. Department of Energy has recently studied the feasibility of using geopressured fluids for enhanced thermal oil recovery (Negus-De Wys *et al.*, 1991). The present work is part of a systematic survey of the occurrence and characteristics of geopressured fluid resources within on-shore sedimentary basins in the State of California.

THE DATABASE

After reviewing the available literature and consulting with various public agencies and private companies, the primary database chosen for this study was the drilling, well logging and well test data available from oil and gas fields in California. Some of these data are published in California Division of Oil and Gas (1982, 1985 and 1991) but the majority are archived on microfilm at the headquarters of the California Division of Oil and Gas. This database was chosen for several reasons:

- Over 150,000 oil and gas wells have been drilled in California compared to only a few thousand deep geothermal and water wells;
- more extensive logging and testing are conducted in oil and gas wells compared to other types of wells;
- oil and gas well data are more readily retrievable from governmental and private archives;
- the geographical distribution of oil and gas wells is more extensive compared to other types of wells; and
- while numerous oil and gas wells in California have exhibited geopressure, very few occurrences of geopressure from geothermal or water wells have been reported.

For initial screening of data, information on oil or gas pools, rather than on individual wells, were analyzed; an oil or gas field may contain one or more pools. The average initial static pressure, temperature, porosity, salinity, depth, thickness and acreage data available from 975 individual oil and gas pools were gathered from nine different on-shore basins or geographical regions in California (table 1).

Figure 1 is a map of California showing the major regions considered; the subdivisions of the Sacramento Valley and San Joaquin Valley shown in table 1 are not shown in this figure. The only other potentially geopressured areas onshore in California are the Eel River Basin and the Coast Ranges; unfortunately, the publicly available database from these areas proved to be too meager to be useful for this study.

IDENTIFYING GEOPRESSURED POOLS

As the first step in screening the assembled database, plots of the initial static pressure versus datum depth of all pools within a region were prepared. Figure 2 shows a typical plot, representing the oil and gas pools in the Southern

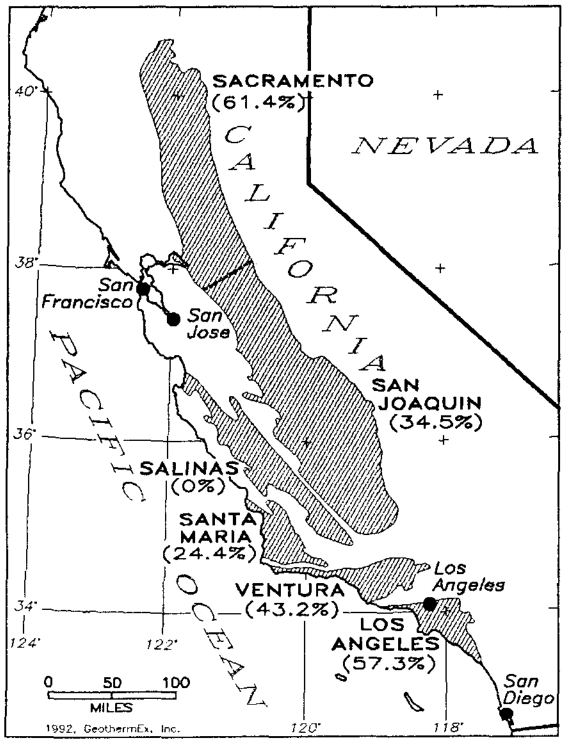

Figure 1. Locations of on-shore oil and gas producing basins, showing the percentage of pools in each basin that are geopressured

Sacramento Valley. On the plot for each region, a visual best fit line was defined; the slope of this line represents the hydrostatic gradient for the region. The estimated hydrostatic gradients fall between 0.40 and 0.45 psi/ft, with the low value being representative of the Salinas Valley, and the highest value being obtained from both the northern Sacramento Valley and the southeast San Joaquin Valley (see table 1).

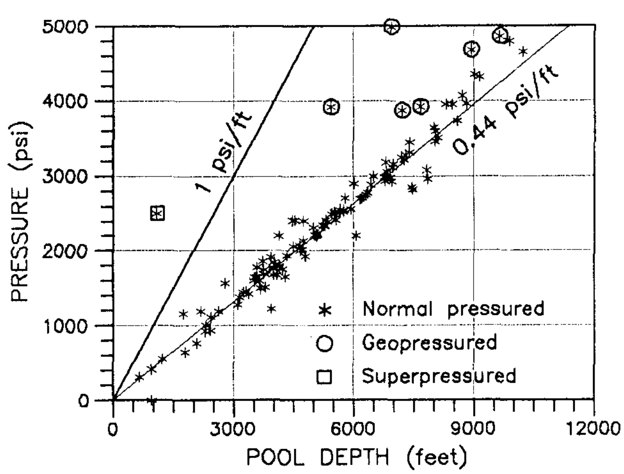

Figure 2. Depth vs. initial pressure for oil and gas pools in the southern Sacramento Valley

On such a plot, any point lying above the hydrostatic line represents an "overpressured" pool. The points lying between the hydrostatic line and the line representing the lithostatic gradient (about 1.0 psi/ft) on each plot represent the "geopressured" pools in the region. Considering the data scatter and the need to prepare a conservative inventory of geopressured pools, only those points falling clearly above the cluster of points along the hydrostatic gradient line were considered to represent distinctly geopressured pools.

These plots display data scatter because of several factors:

- The geothermal gradient and/or water salinity in the various parts of a region can vary significantly, causing variations in the local hydrostatic gradient.
- Unlike the geopressured areas in the well-studied Gulf Coast region, tectonic stresses contribute to the occurrence of geopressure in California; tectonic stresses vary widely even within a given region.
- Static reservoir pressures reported to the State agencies are often imprecise, as these are based on correcting measured pressures from various wells to a common datum, and then volumetrically averaging the datum pressures. Each step in this process is subject to error.
- The assumption of zero pressure at zero depth (used in force-fitting the data) is only an approximation. Some pools may have an artesian condition due to an elevated recharge source or a depressed potential because of depletion due to production.
- Pressures measured in gas pools (and to a lesser extent in oil pools) with high structural relief will be higher than the hydrostatic pressure outside the reservoir; this is clearly not a geopressure phenomenon.

The point falling above the lithostatic line on figure 2 represents a "superpressured" pool. The occurrence of geopressured pools is commonly ascribed to a rapid compaction of shales and consequent entrapment and thermal expansion of excess water in lenticular bodies of sediments enclosed within the shales, with or without any aid from tectonic stresses. The occurrence of superpressured systems, however, requires the presence of a major tectonic stress.

At least 70 distinctly geopressured pools and eight superpressured pools have been identified from such plots. Only the Salinas Valley did not exhibit the occurrence of any overpressured pool. The Ventura Basin had the largest number of distinctly overpressured pools (15 geopressured and two superpressured).

While the above approach identifies distinctly geopressured pools, a more liberal approach can be used to identify potentially geopressured zones by defining a geopressured pool as one with a pressure gradient higher than 0.45 psi/ft, the maximum estimated hydrostatic gradient (based on plots like figure 2) amongst all nine regions. Table 1 shows the number of potentially geopressured pools thus estimated for each region. Table 1 shows that 410 pools, that is, 42% of the on-shore pools in California are potentially geopressured. In terms of the total number of geopressured pools, the San

Joaquin Valley (all three subdivisions combined) has the most (163), nearly 40% of the 410 potentially geopressured pools. In terms of the fraction of pools in a region that are potentially geopressured, the Sacramento Basin (both subdivisions combined) tops the list with 135 geopressured pools out of 220 pools (61.4%); these percentages are also shown on figure 1.

CORRELATION BETWEEN GEOPRESSURE AND TEMPERATURE GRADIENT

Attempts were made to verify the hypothesis that geopressured pools in California display a positive correlation between pressure and temperature gradients. This hypothesis is based on the assumption that the geopressured lenses contain excess water and are, therefore, poorer heat conductors than the surrounding medium, which in turn causes the occurrence of steeper temperature gradients through such lenses. As a first step, a plot of the average reservoir temperature versus datum depth of pools was prepared for each region. Figure 3 is an example of such a plot; it shows the data from the Los Angeles basin.

A visual best fit line through the data points in each plot was defined subject to the constraint that the average ambient surface temperature in central and southern California could not lie outside the range of 60° to 75°F. The geothermal gradients estimated from these plots varied from 1°F/100 ft for the northern Sacramento Valley to 2°F/100 ft for the Los Angeles Basin (see table 1), a perfectly normal range, even though many geopressured reservoirs are known to exist in these regions.

A plot was prepared of the pressure gradient versus temperature gradient for all pools in each region. Figure 4 is an example of a plot of pressure gradient versus temperature gradient representing the Los Angeles basin, and this was the only such plot that indicated a positive correlation between pressure gradient and temperature gradient. A majority of the potentially geopressured pools on this plot indicate an abnormally high temperature gradient (over 2°F/100 ft). In other regions, the above analysis has so far failed to confirm the hypothesis that geopressured pools have a positive correlation between pressure and temperature gradients.

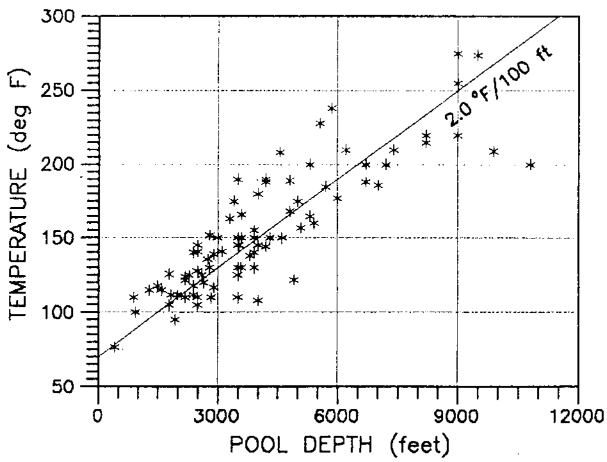

Figure 3. Depth vs. temperature for on-shore oil and gas pools in the Los Angeles Basin

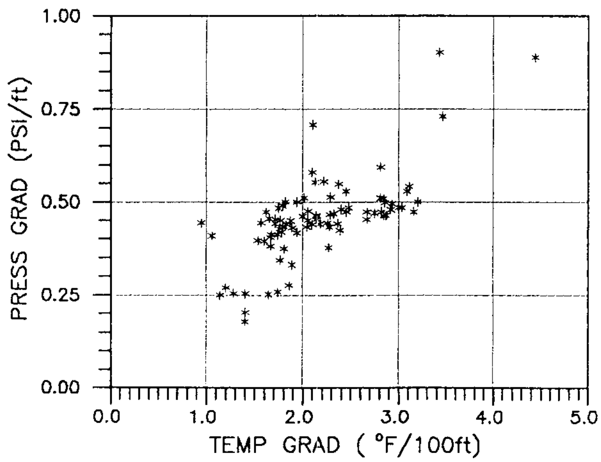

Figure 4. Pressure gradient vs. temperature gradient for on-shore oil and gas pools in the Los Angeles Basin

The data scatter on the plots like figure 3 is caused by the inherently inaccurate nature of this database. There are at least two reasons for this inaccuracy:

- The estimates of the average pool temperature is usually based on the maximum temperature recorded in wells during logging runs. A well may not have recovered from the cooling effect of mud circulation by the time a log is run; therefore, the temperature is often underestimated.
- The maximum recorded temperature is usually associated with the total depth of the well during the logging run, which is not necessarily appropriate; the maximum temperature may have been recorded at a shallower depth than at the well bottom.

The most reliable means of verifying this hypothesis is to review equilibrium temperature profiles in known geopressured wells and to verify if a higher temperature gradient exists through the geopressured sections of the wells. Unfortunately, such profiles were available for very few wells. Therefore, attempts were made to develop temperature profiles of wells from the maximum temperatures recorded during the various logging runs in the same well assuming that the maximum recorded temperature during a run was the equilibrium temperature at the total depth of the well during the run.

Figure 5 shows an example of a maximum recorded temperature profile from a well known to have encountered geopressured pools (from mud records, pressure data and well logs). For the well considered in figure 5 (Well 423, Kettleman North Dome field, central San Joaquin Valley), the geopressured zone occurs from about 11,400 feet to total depth, as indicated by the plot of the mud weight used during drilling as a function of depth (figure 6). Figure 5 does not indicate any obvious steepening of the temperature gradient in the geopressured depth interval.

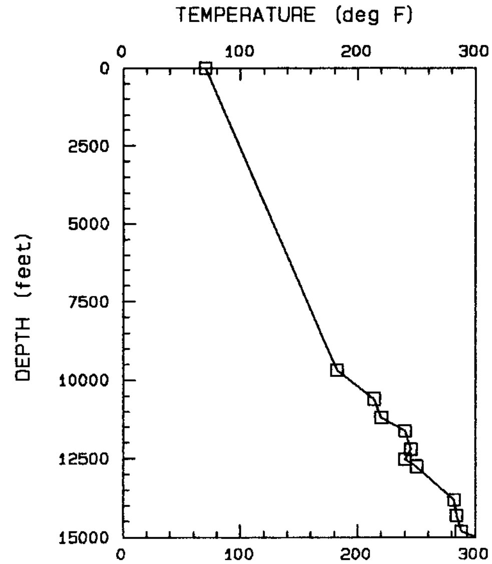

Figure 5. Maximum recorded temperature vs. depth, Kettleman North Dome Field, Well 423

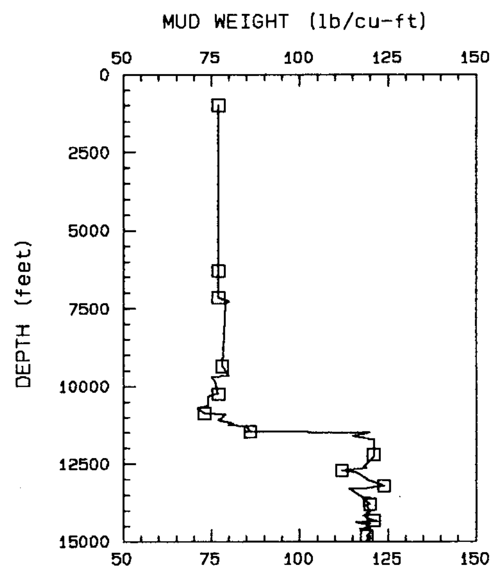

Figure 6. Drilling mud weight vs. depth Kettleman North Dome Field, Well 423

So far we have not been able to confirm the hypothesis that a positive correlation exists between pressure and temperature gradients for geopressured pools in California. If geopressure is caused by tectonic stresses alone, the mechanism postulated above would not be present and, therefore, geopressure need not be associated with a steepening of the temperature gradient.

OTHER CHARACTERISTICS OF GEOPRESSURED POOLS IN CALIFORNIA

Based on the available data on the oil and gas pools, statistical distributions of several characteristics of both geopressured and normal pressured pools were defined and compared. Figure 7 shows a histogram of the porosity values for 878 of 975 pools for which porosity data were available, compared with the porosity histogram for 380 potentially geopressured pools for which porosity data were available. Figure 7 shows that geopressured pools have essentially the same statistical distribution as do all pools, with modal porosity in the range of 20 to 25%.

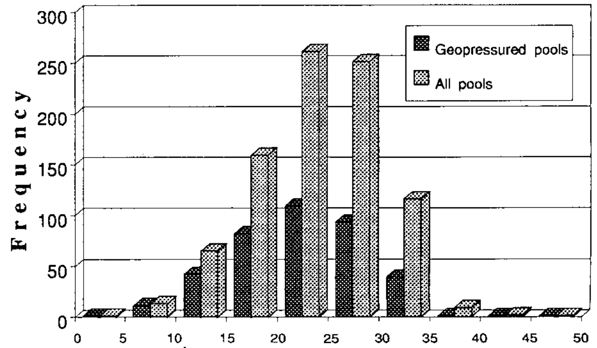

Figure 7. Histogram of porosity (%)

Figure 8 compares the histograms of water salinity based on data from all pools (424 data points) and data from potentially geopressured pools (172 data points). The two histograms are similar, indicating that the water salinity in geopressured pools is statistically the same as in normal pressured pools. The distribution of water salinity appears to be bimodal, the modes being 0 to 10,000 parts per million (ppm) and 25,000 to 30,000 ppm. These ranges of water salinity are much lower than encountered in the geopressured reservoirs of the U.S. Gulf Coast, where it is typically higher than 100,000 ppm. The practical implication of this fact, as pointed out by Kharaka *et al.* (1981), is that higher solubilities for methane can be expected in the geopressured reservoirs in California.

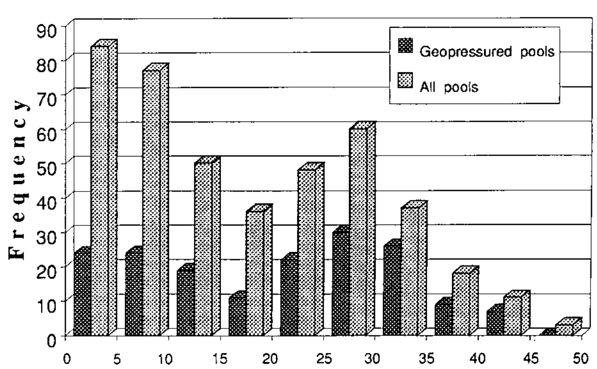

Figure 8. Histogram of salinity (thousands of ppm)

Geopressured pools in California occur in the depth range of 1,000 feet to over 18,000 feet. Figure 9 compares the histograms of the depths of all pools (975 data points) and the depths of the potentially geopressured pools (410 data points). The two histograms are similar, with a mode in the range of 2,000 to 4,000 feet. This depth range is much shallower than that of the geopressured reservoirs in the U.S. Gulf Coast, where geopressure is encountered only below 12,000 feet. Therefore, the drilling cost for any geopressured development should be lower in California than in the Gulf Coast area.

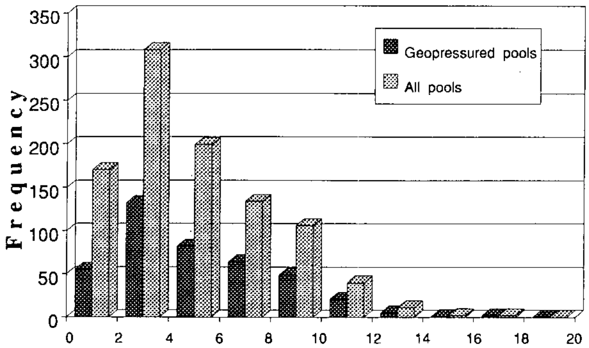

Figure 9. Histogram of pool depth (thousands of feet)

The geopressured pools identified in this study are thin, mostly less than 250 feet in thickness. Figure 10 compares the histograms of all pools (950 data points) and the potentially geopressured pools (400 data points). The highly skewed distributions for both sets of data are similar, with a mode of 0 to 250 feet. It should be noted, however, that the thickness values of oil or gas pools have been used in constructing these histograms; the water aquifer underlying the oil-water or gas-water contact may be much thicker. A statistically significant database on the thicknesses of geopressured aquifers has not yet been developed for California.

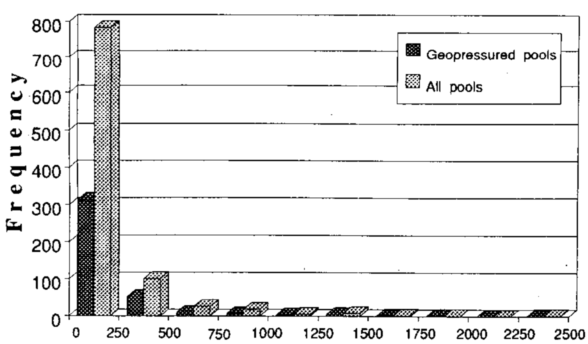

Figure 10. Histogram of thickness (feet)

An attempt was made to define the distribution of the volume of geopressured pools in California. However the effort has not yet been successful because of the scarcity of published data on the areal extent of the pools. Only 264 of the 975 pools provided enough data for estimating the volume; of these 98 were potentially geopressured. Figure 11 shows the two histograms constructed from these data.

Again, the two histograms are similar, with a mode in the 0.1 to 1 billion cubic feet (2,300 to 23,000 acre-feet) range. As mentioned in connection with the thickness data, the volumes of geopressured aquifers must be higher than indicated by the data from the oil and gas pools. Perhaps the volumes of geopressured aquifers would be one or two orders of magnitude higher than they appear from figure 11.

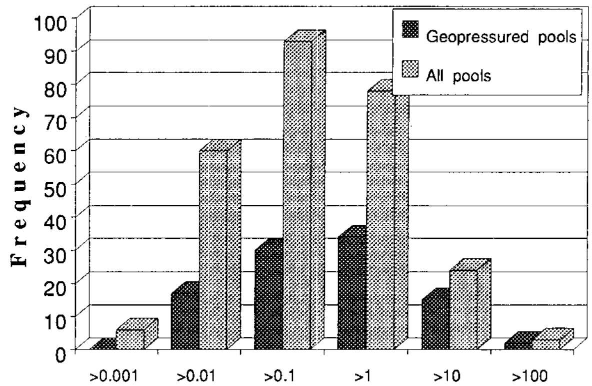

Figure 11. Histogram of volume (billions of cubic feet)

CONCLUSIONS

We have arrived at the following conclusions based on our study to date:

- Of the 975 on-shore oil and gas pools in California, 410 are potentially geopressured with at least 70 distinctly geopressured and eight superpressured. The Sacramento Valley displays the largest relative occurrence of geopressure (61.4%) while the San Joaquin Valley has the largest number of geopressured pools in the State (163). No geopressured pools could be identified in the Salinas Valley.

- Geothermal gradients in the geopressured pools lie within the normal range of 1°F to 2°F per 100 ft, with the pools in the Los Angeles Basin showing the highest gradient. Except for the Los Angeles Basin, the hypothesis of a positive correlation between pressure and temperature gradients could not be validated.

- Both normal pressured and geopressured pools in California show the same distribution of porosity with a mode of 20% to 25%.

- Both geopressured and normal pressured pools in California display a bimodal distribution of water salinity with peaks at 0 to 10,000 and 25,000 to 30,000 ppm; these salinities are much lower than encountered in the U.S. Gulf Coast, and hence, geopressured pools in California should have higher solubilities for methane.

- Both geopressured and normal pressured pools in California occur in the depth range of less than 1,000 feet to over 18,000 feet, the median depth (2,000 to 4,000 feet) for both being much shallower than the depths encountered in the Gulf Coast region; therefore, the drilling cost for any geopressured development would be lower in California.

- The distributions of the thicknesses of the normal-pressure and geopressured pools are the same, with the majority being less than 250 feet thick.

- The distributions of the volume of the normal-pressured and geopressured pools are the same, with the majority being in the range of 1 to 10 billion cubic feet.

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Table 1. Hydrostatic and Temperature Gradients and the Occurrence of Overpressured Pools

Region	Hydrostatic Gradient (psi/ft)	Temperature Gradient (°F/100 ft)	Number of Oil and Gas Pools	Number of Distinctly Overpressured Pools*	Number of Potentially Overpressured Pools**	Percentage of Pools Overpressured
Northern Sacramento Valley	0.45	1.0	98	13	66	67.3%
Southern Sacramento Valley	0.44	1.3	122	6	69	56.6%
Central San Joaquin Valley	0.44	1.6	37	4	20	54.1%
Southwestern San Joaquin Valley	0.43	1.6	212	7	88	41.5%
Southeastern San Joaquin Valley	0.43	1.3	224	10	55	24.6%
Salinas Valley	0.40	1.6	20	0	0	0%
Santa Maria Basin	0.42	1.6	78	9	19	24.4%
Ventura Basin	0.44	1.6	88	15	38	43.2%
Los Angeles Basin	0.44	2.0	96	5	55	57.3%

*Based on plots like figure 2.
**Pressure gradient > 0.45 psi/ft.