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SOME ASPECTS OF GEOPRESSURED RESOURCES IN CALIFORNIA

by

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ABSTRACT

This paper presents the results of a continuing study of geopressured resources in California. Three aspects of geopressured resources were examined in this study: the identification of geopressured zones in wells; quantification of the excess pressure from well logs; and the quantity of dissolved methane in California geopressured fluids.

Except for well logs, particularly the electrical resistivity log, no other consistently available database could be found for identifying and quantifying geopressured zones in a well. Shale resistivity versus depth plotting, as used in the Gulf Coast, can be used in California to identify and quantify geopressure. The utility of other well logs in identifying and quantifying geopressure in California needs to be investigated further.

For quantifying geopressure from shale resistivity data, the well known Gulf Coast correlations cannot be used, without major modification, in California. We have tentatively derived a correlation similar to those used in the Gulf Coast region for a linear correlation between the pressure gradient and the ratio of the observed shale resistivity to the resistivity expected from the normal trend defined on the shale resistivity versus depth plot. We believe that a single correlation as above for entire California will prove to be inadequate. Similar correlations should be developed for each sedimentary basin in California and/or for various ranges of overburden pressure.

Dissolved methane content in the geopressured aquifers in California is estimated to range from 10 to 100 standard cubic feet per barrel. The gas content is dependent mainly on the depth of the aquifer; the deeper the aquifer, the higher is the gas content.

INTRODUCTION

A systematic survey of the occurrence and characteristics of geopressured fluid resources within on-shore sedimentary basins in the State of California was presented in Sanyal *et al.* (1993). Using data from individual oil and gas pools collected by the California Division of Oil and Gas (1982, 1985 and 1991), potentially geopressured pools were identified and data on temperature gradient, porosity, salinity, depth, thickness and volume of these pools were evaluated. Figure 1 shows the locations of the pools and the percentage of potentially geopressured pools in each on-shore basin.

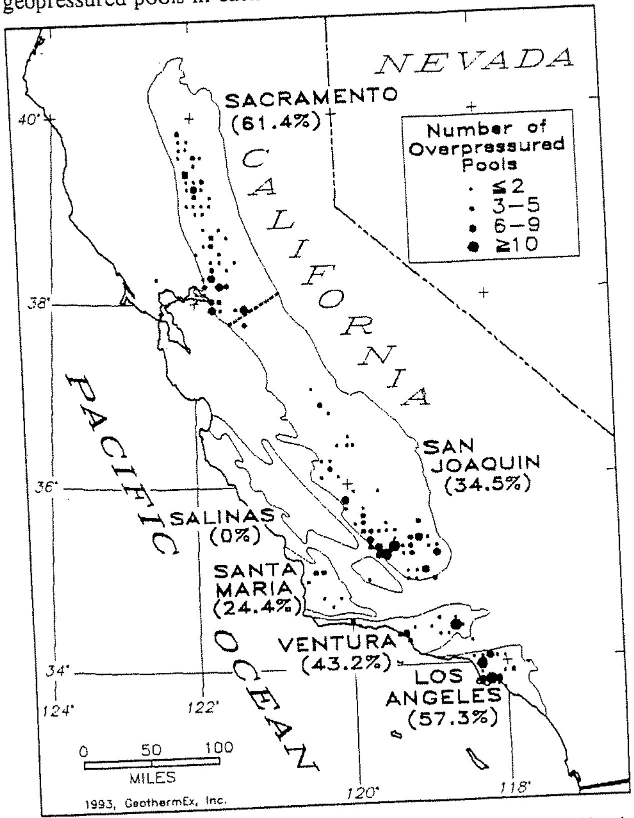

Figure 1: Geographical distribution of geopressured pools in California

While the earlier work concentrated on the characteristics of potentially geopressured oil and gas pools, this paper discusses the approach to identifying and quantifying geopressure in individual wells in California. In addition, the range of dissolved methane content expected in geopressured reservoirs in California will be estimated.

IDENTIFYING GEOPRESSURED ZONES IN WELLS

There are three basic means of identifying geopressured zones in a well: from drillstem test data; from mud weight records; and from well logs. While drillstem data provide a direct means of verifying the presence of geopressure in a well, such data are not available from most wells, and those that are available represent measurements at only a few discrete depths. Therefore, drillstem test data are not ideal for the vertical definition of geopressure in a well.

Mud weight records reveal the presence of geopressure in a well simply by the fact that the driller had to use a heavier mud than would be used in a normal well. Figure 2 is a typical example of the use of mud weight records for identifying geopressure; this figure shows the mud weight (in lbs/ft^3) plotted against drilled depth. In this figure, the top of the geopressured zone is easily identified by the sharp increase in mud weight just below 7,000 feet depth.

Mud weight records are publicly available from many oil and gas wells in California and the mud weight data clearly reveal the top of the geopressured zone. However, there are two drawbacks in using mud weight records to determine the location and amount of excess pressure of geopressured zones:

- Out of concern for safety, drillers tend to drill geopressured zones with an "overbalanced" mud; that is, the mud weight exceeds the fluid pressure in the formation by an unknown amount.
- Once the mud weight is increased before drilling into a geopressured zone in a well, it is not reduced again, even though the well may have passed through the geopressured lens into a normal pressure zone. Therefore, the data allow the identification of only the top of the first geopressured zone. The bottom of the first geopressured zone or any deeper geopressured sections in a well cannot be identified unless the shallower geopressured zone is cased off and drilling's resumed with a normal mud.

In the Gulf Coast region of the United States, overpressured zones are identified by plotting the electrical resistivity of individual shale beds as a function of depth. Normal-pressured shale beds on such a plot define an increasing trend with depth; the geopressured shales fall off the trend with significantly lower resistivities. Typically, the shale bed just above the geopressured zone falls off the trend with a higher resistivity, indicating the presence of a well-compacted shale layer acting as a cap rock over the geopressured lens.

This departure in shale resistivity from the normal trend increases with depth through a transition zone until the geopressured lens itself is reached. Following this maximum departure, sometimes the shale resistivity increases again with depth until normal shale resistivities are encountered again below the geopressured lens. Thus it may be possible to identify the top and bottom of a geopressured zone, and therefore, estimate its thickness. Multiple geopressured zones in a well may be detected this way.

The applicability of the above approach in California has not been demonstrated to date in the literature. There may be two possible reasons for not expecting satisfactory application of the Gulf Coast approach in California:

- While the geopressured basins in the Gulf Coast region contain alternating layers of sand and shale, the basins in California often have highly disturbed and mixed sediments, such as turbidities. In fact, in California basins, pure shale layers are far less common than in the Gulf Coast region; productive sands often alternate with nonproductive silty layers rather than pure shale layers.
- The widespread occurrence of tectonic stresses in California may cause overpressuring without causing selective compaction in shales.

With the above limitations in mind, we have conducted the Gulf Coast type analysis based on resistivity logs. Figures 3 and 4 are examples of such analysis based on short-normal resistivity. Figure 3 (well Section 4 Unit 1, Arbuckle gas field, Sacramento Valley) clearly identifies the top of a geopressured formation at 7,000 feet; this is also verified from the mud weight records from this well (figure 2). The normal shale resistivity trend with depth is also identified on this plot.

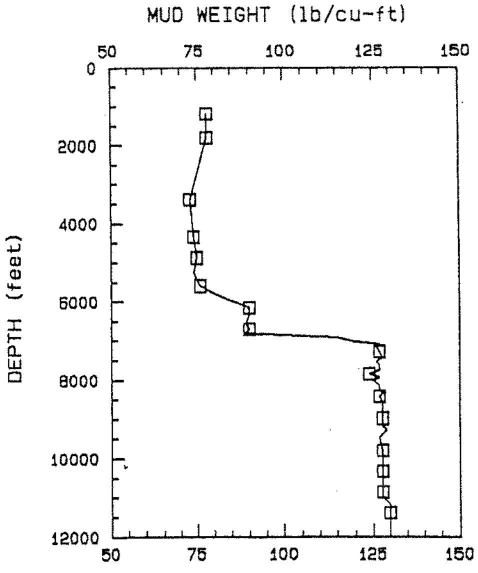

Figure 2: Mud weight vs. depth, Arbuckle well Section 4 Unit 1

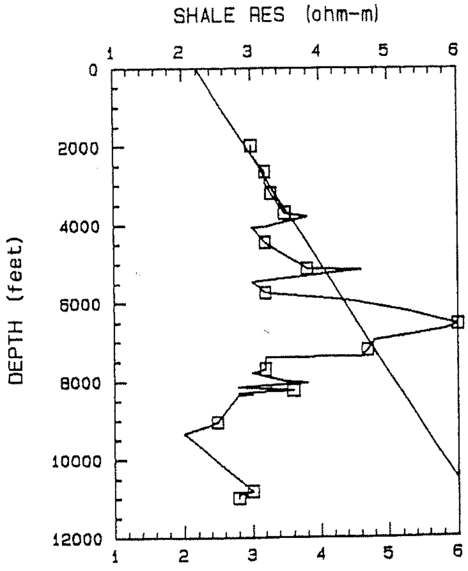

Figure 3: Shale resistivity vs. depth, Arbuckle well Section 4 Unit 1

Figure 4 shows a similar plot (well 423, Kettleman North Dome oil field, San Joaquin Valley) indicating the top of a geopressured zone between 10,600 and 10,800 feet; the mud weight records from the same well (figure 5) indicate that the geopressured zone starts about 600 to 800 feet deeper in the well than indicated by the log data. The reason for this discrepancy is unclear; it is possible that the mud weight was not increased until after the well had actually encountered the transition zone and started to take in fluid.

Several problems have hampered our efforts to date to identify geopressured zones by interpreting resistivity logs:

- Sand-shale discrimination based on Self Potential and Gamma Ray logs was difficult, as the shale baseline proved elusive in many wells.
- Shifts in shale resistivity trend can be caused by sudden and major changes in water salinity or depositional environment, rather than by geopressure.
- The limited budget did not allow detailed computer analysis of digitized well logs which would resolve the above two problems to a large extent.
- The legibility and quality of well logs retrieved from microfilms, particularly old ones, were often poor.

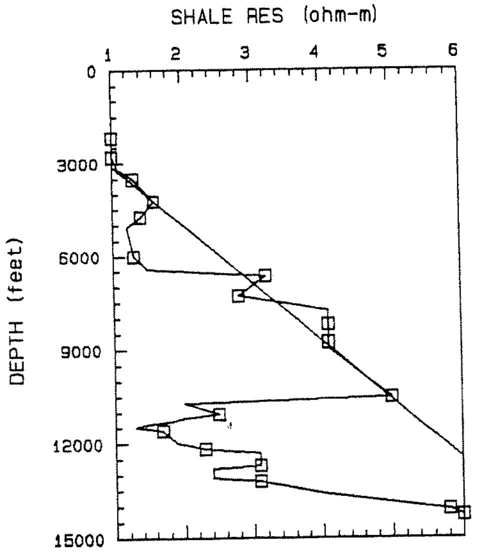

Figure 4: Shale resistivity vs. depth, Kettleman North Dome well 423

In spite of the above limitations and the continuing nature of our study to date, we believe that shale resistivity versus depth plotting can be used in California to identify geopressured zones. Our conclusion is preliminary, and it would be prudent to confirm this approach with more case histories.

It is possible to use some other logs, such as density, neutron, pulsed neutron and sonic, to identify geopressured zones by making similar types of plots. Unfortunately, logs other than electrical resistivity logs are not routinely available from public archives; therefore, our study has concentrated mainly on resistivity logs to date.

QUANTIFYING GEOPRESSURE FROM WELL LOGS

In the Gulf Coast region, methods and correlations have been developed for estimating the amount of geopressure from well logs, particularly from the electrical resistivity log. In the petroleum industry, there are several practical reasons for quantifying geopressure from well logs:

- to ensure safe and efficient drilling using proper mud weights;
- to design safe and efficient casing programs; and
- to design a safe and efficient well completion that would allow killing the well, when necessary, without undue formation damage.

While drilling in an area known to have geopressure, the well is often logged frequently, after drilling every few hundred feet, to determine if the transition zone above a geopressured zone has been reached, in which case the mud weight would be increased. "Measurement while drilling" (MWD) or drill pipe logs are often used in such cases to monitor pore pressure. The presence of several hundred feet of the transition zone gives an early warning to the driller about the need for increasing the mud weight before entering a permeable geopressured lens.

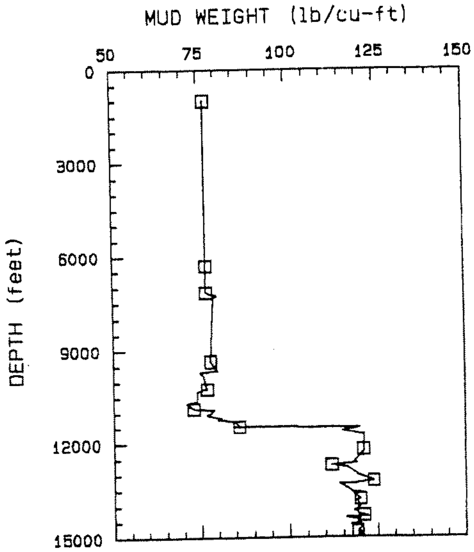

Figure 5: Mud weight vs. depth, Kettleman North Dome well 423

The transition zone can be detected as discussed before. However, the methods discussed before do not allow quantification of the amount of overpressure, and therefore, cannot aid the driller in determining the mud weight required to balance formation pore pressure. Once a transition zone is detected, often associated with a "gas-cut" mud, the driller often plays safe by unduly "weighting up" the mud. This often leads to serious formation damage and consequent poor well productivity. If the overpressure can be quantified at the time it is detected, the driller can choose the correct mud weight and avoid formation damage. In fact, repeated quantitative estimation of pore pressure from well logs taken during drilling is a common practice in well-engineered drilling programs in geopressured areas.

For this study, quantification of geopressure is considered an important step towards an assessment of the geopressured resources in California. Therefore, quantitative methods for estimating pore pressure from well logs are being reviewed.

Hottman and Johnson (1965) were the first to show that in the Gulf Coast region, the pore pressure gradient (p/D) can be correlated to the ratio of the observed shale resistivity (R_{sh}) at any depth in a well to the normal shale resistivity (R_{shn}) that is expected at that depth from the trend on the R_{sh} versus depth plots. The Hottman-Johnson correlation is:

$$p/D = 0.465 + 0.592 \left(1 - \frac{R_{sh}}{R_{shn}}\right) \tag{1}$$

For a normal (that is, non-geopressured) shale, $R_{sh}/R_{shn} = 1$; therefore $p/D = 0.465$ psi/ft, the normal hydrostatic gradient in the Gulf Coast region.

Lane and MacPherson (1976) developed a similar correlation based on newer data. The Lane-MacPherson correlation is:

$$p/D = 0.465 + 0.519 \left(1 - \frac{R_{sh}}{R_{shn}}\right) \tag{2}$$

Lane and MacPherson (1976) also pointed out that correlations (1) and (2) could be improved if one also took into account the overburden stress. Based on estimated overburden gradients (g_o) from density log and gravimeter data, they proposed that:

$$p/D = 0.465 + m \left(1 - \frac{R_{sh}}{R_{shn}}\right) \tag{3}$$

$$\begin{aligned} \text{where } m &= 0.590 \text{ when } 0.95 < g_o \leq 1.00 \\ &= 0.550 \text{ when } 0.90 < g_o \leq 0.95 \\ &= 0.509 \text{ when } 0.85 < g_o \leq 0.80. \end{aligned}$$

Eaton (1972) suggested incorporating the overburden gradient into the correlation and proposed the following correlation:

$$p/D = g_o - 0.535 \left(\frac{R_{sh}}{R_{shn}}\right)^{1.5} \tag{4}$$

Equation (4) fits the data base of Hottman and Johnson (1965) fairly well. It should be noted that for a normal Gulf Coast formation, $g_o = 1$ psi/ft and $R_{sh}/R_{shn} = 1$, giving $p/D = 0.465$ psi/ft, the normal hydrostatic gradient in the Gulf Coast region.

The methodologies, let alone the correlations, discussed above are not directly applicable to the California reservoirs for at least two reasons:

- All of the correlations imply a p/D of 0.465 psi/ft., whereas the range of hydrostatic gradients for all the California regions studied is 0.40 to 0.45 psi/ft (Sanyal *et al.*, 1993). This is so because the formation waters in California have much lower salinity than those in the Gulf Coast area.
- The correlations discussed above do not take into account the effect of tectonic stress, which is present in many parts of California.

Therefore, as a part of this study we are attempting to develop new correlations for California, if feasible. The results presented here are preliminary.

At first we attempted to develop a correlation of the type (1) and (2). Ideally, separate correlations should be developed for each of the different sedimentary basins shown on figure 1. Because of the limited budget available for this study, we have attempted to develop, from the limited number of well logs studies so far, a single correlation covering all the regions studied, keeping in mind that such a universal correlation based on a very limited number of logs is not expected to be very accurate.

Figure 6 is a plot of the R_{sh}/R_{shn} ratio versus p/D for a few geopressured wells from California. The R_{sh}/R_{shn} ratios were estimated from the plots such as figures 3 and 4. The p/D values were obtained from actual pressure measurements (such as drillstem test data) or estimated from mud weight records. Figure 6 also includes a normal pressure point represented by $R_{sh}/R_{shn} = 1$ and an average hydrostatic gradient of 0.44 psi/ft.

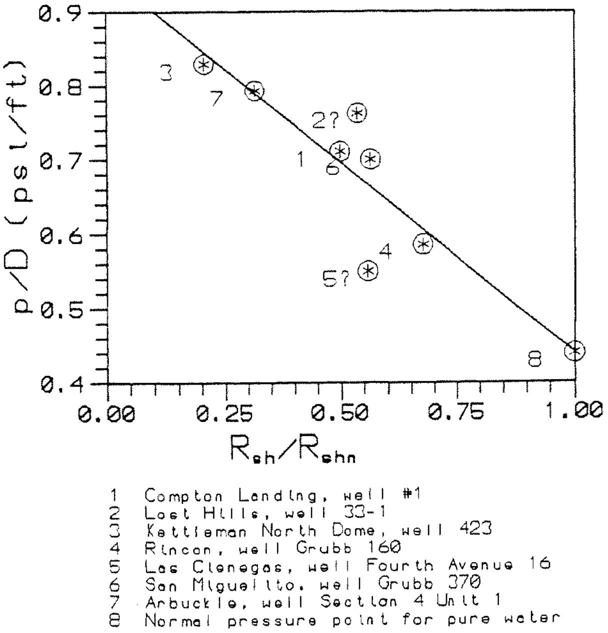

Figure 6: Pressure gradient vs. shale resistivity ratio

The data points in figure 6 have been force-fitted to a straight line passing through the normal pressure point. The data points 2 and 5 on the plot are known to represent questionable log data. The remaining data points seem to define a linear trend, from which one can derive the following correlation for California in the manner of (1) and (2):

$$p/D = 0.440 + 0.511\left(1 - \frac{R_{sh}}{R_{shn}}\right) \qquad (5)$$

It should be noted that the above correlation is tentative and should be refined by further log analysis. It may be useful to develop separate correlations like (5) for each major region in California, and separate correlations for several ranges of overburden pressure, similar to (3).

It may also be useful to try the approach of Eaton (1972) referred to before. The density log could be used to estimate g_o in (4) as follows:

$$g_o = \int_0^D \frac{\rho g dz}{D} \qquad (6)$$

Where g is the acceleration due to gravity (cm/sec^2), ρ is the bulk density (gms/cc) from the log at a depth z (cm).

Using depth in feet, (6) can be expressed as:

$$p/D = \frac{0.433\int_0^D \rho dz}{D} - \alpha\left(\frac{R_{sh}}{R_{shn}}\right)^{\beta} \qquad (7)$$

In equation (7), the unknown parameters α and β can be obtained by statistical correlation using resistivity and density logs, and pressure records (or mud weight records). It should be noted that an approximate value of α can be estimated as follows. The first term in (7) should be about 1.0 psi/ft except in high tectonic stress areas, and when $R_{sh}/R_{shn} = 1$, p/D should be about 0.44 psi/ft.

$$\therefore \alpha = 1 - 0.44 = 0.56 \ psi/ft.$$

So (7) can be written approximately as:

$$P/D = \frac{0.433\int_0^D \rho dz}{D} - 0.56\left(\frac{R_{sh}}{R_{shn}}\right)^{\beta} \qquad (8)$$

This indicates that the first priority in defining an accurate correlation is to investigate the nature of parameter β. We are continuing this effort.

DISSOLVED METHANE CONTENT

Figure 7 (from Culberson and McKetta, 1951), presents a family of curves showing the solubility of methane gas in pure water at various temperature and pressure levels. Figure 8 (from Brill and Beggs, 1975) presents a family of curves showing the solubility of methane in a brine relative to the solubility in pure water as a function of temperature and water salinity. One can use these figures to estimate the ranges of dissolved methane to be expected in geopressured pools in California.

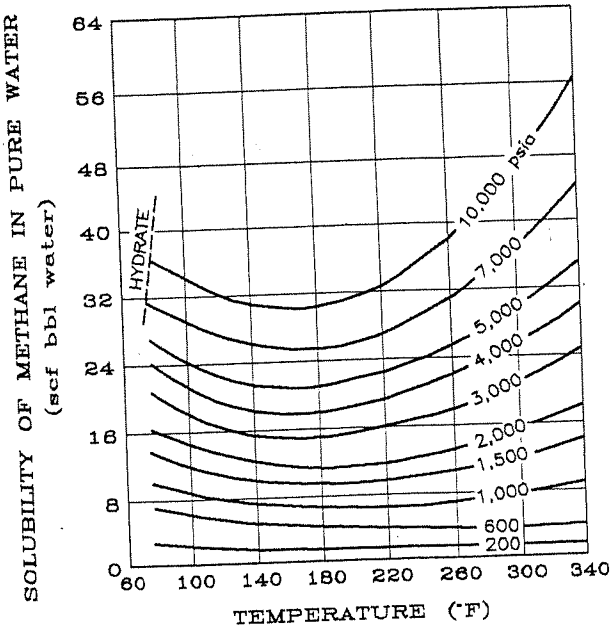

Figure 7: Solubility of methane in water (from Culberson and McKetta, 1951)

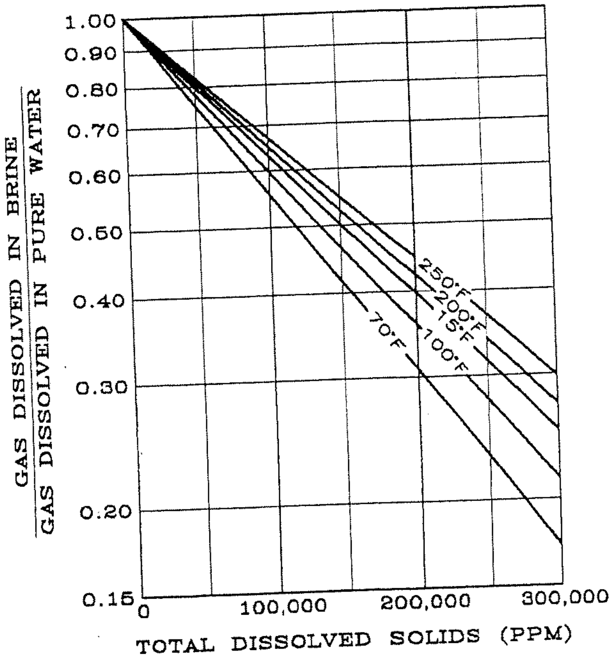

Figure 8: Effect of salinity on the amount of gas in solution when fully saturated with gas (from Brill and Beggs, 1975)

Based on the results presented in Sanyal *et al.* (1993), the ranges of temperature gradients, pressure gradients and depths of the known geopressured pools in California are as follows:

Temperature gradient:	1 to 2°F/100 feet
Pressure gradient:	0.45 to 1.0 psi/foot
Depth:	1,000 to 18,000 feet

From the above ranges, we estimate the following temperature and pressure ranges for geopressured pools in California:

Temperature range: 70°F to 420°F (assuming an ambient temperature of 60°F)
Pressure range: 1,000 to 18,000 psi

Therefore, from figure 7, we estimate a dissolved methane content range of 10 to 100 standard cubic feet per barrel (scf/bbl) for pure water corresponding to the temperature and pressure ranges in geopressured pools in California. Figure 8 shows than for the salinity range of 0 to 50,000 ppm encountered in geopressured pools in California, methane solubility will be in the range of 75% to 100% of the solubility in pure water. Therefore, the methane content in geopressured pools in California should lie in the 10 to 100 scf/bbl range. It should be noted from the nature of the graphics in figures 7 and 8 and the characteristics of the geopressured pools as revealed in this study, the most important variable controlling the amount of dissolved methane in geopressured pools in California is depth; the methane content is, in general, higher for deeper pools.

CONCLUSIONS

We have arrived at the following conclusions in addition to those reported in Sanyal *et al.* (1993) as a result of this study to date:

- Except for well logs, particularly the electrical resistivity log, no other consistently available database could be found for identifying and quantifying geopressured zones in a well.
- Shale resistivity versus depth plotting, as used in the Gulf Coast, can be used in California to identify and quantify geopressure.
- The utility of other well logs in identifying and quantifying geopressure in California needs to be investigated further.
- For quantifying geopressure from shale resistivity data, the well known Gulf Coast correlations cannot be used, without major modification, in California.
- We have tentatively derived the following correlation similar to those used in the Gulf Coast region for a linear correlation between the pressure gradient (p/D) and the ratio of the observed shale resistivity to the resistivity expected from the normal trend defined on the shale resistivity versus depth plot:

$$p/D = 0.440 + 0.511\left(1 - \frac{R_{sh}}{R_{shn}}\right)$$

- We believe that a single correlation as above for the entire state of California will prove to be inadequate. Similar correlations should be developed for each sedimentary basin in California and/or for various ranges of overburden pressure.
- Dissolved methane content in the geopressured aquifers in California is estimated to range from 10 to 100 standard cubic feet per barrel. The gas content is dependent mainly on the depth of the aquifer; the deeper the aquifer the higher is the gas content.

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