GEOTHERMAL EXPLORATION FROM DEEP-WELL DATA

William F. Tanner[1]

ABSTRACT

Logs from more than 500 deep wells have been studied, covering Florida and adjacent parts of Georgia and Alabama, as part of an effort to assess more accurately the geothermal potential of the area. Within peninsular Florida, two favorable anomalies were confirmed, and other interesting areas were outlined in the Florida panhandle and adjacent states.

Bottom-hole temperatures were used as the basis for several kinds of maps: geothermal gradient, temperature at 1,000 m, temperature at 2,000 m, and depth to 100°C (typically within 4,000 m of the surface, in the anomalous areas). Unlike earlier maps which used county averages, the present work was done on the basis of single-well readings, thereby providing more detail (but more noise).

Groundwater movement at shallow depths distorts the shallow data field, so that measured heat flow values taken from water wells, although confirming the general results from deep wells, provided highly variable numerical values. The deep-well bottom hole temperatures (BHT) are thought not to be equilibrium values, but the errors in BHT measurements appear to be relatively small.

Radioisotope anomalies, from shallow water sources, also confirmed the two anomalies. One of these was explored further by gravity methods, and it may be related to deep structural control.

Two types of information, missing from most geothermal studies based on existing well logs, can be supplied in most instances. One is an estimate of fluid transmissability, which can be developed from ordinary procedures, well known in the oil industry, for obtaining porosity values and permeability indications from logs. This will be important in case of exploitation of relatively low-temperature geothermal sources, such as those in the southeastern states, where circulation of water in large quantities may be necessary.

The other is an estimate of the thermal conductivity of deep rocks. This value can be obtained by direct measurement on cores, or it can be computed from the equation:

$$K_h = kV^a\rho^b$$

where V is sonic velocity (to be read from the Sonic Log or continuous veolcity log) and ρ is mass density (from radioactivity logs). This estimate of thermal conductivity can be used to convert thermal gradient values to heat flow values.

INTRODUCTION

A geothermal study in the southeast was undertaken in 1975-76, under the sponsorship of Florida Power and Light Company. Preliminary work consisted of examination of well logs from Florida, Georgia and the southern half of Alabama, to determine the geothermal gradient at each well location; a regional geothermal gradient map was drawn as the basis for comparison of local target areas. This map was then refined in detail for all of Florida except the Panhandle. More than 500 well logs were studied in this part of the project.

J. K. Osmond, of Florida State University, studied radioactive isotopes in well and spring water in the most attractive areas; Douglas Smith, of the University of Florida, made a number of shallow-well heat flow measurements; and Roman Johns, of the Institute for Geophysical Research and Development, carried out gravity mapping in one target area. The work of Johns, Smith and Osmond is not included in the present paper, but was given in the final report produced for Florida Power and Light (Johns, *et. al.*, 1975). Subsequently, additional work has been done on data from deep wells. (For a current overview of geothermal systems, see Ellis, 1975, and Goguel, 1976.)

WELL LOG DATA

Well logs for the three states were examined for location, date, type of log (such as electrical, or radioactivity), and thermal information. Nearly 600 logs were selected as having apparently good bottom-hole temperature (BHT) readings. In several cases, sequential logs were run in the same hole, providing a detailed gradient (rather than merely an average gradient); one of these wells had 17 separate log runs, thus providing temperature measurements at 18 points.

There had been considerable trepidation, in the oil industry particularly, about using BHT readings as a reliable guide to actual undisturbed temperatures at the same depth. This concern arises, primarily, because the action of the drill bit is thought to elevate the temperature at the bottom of the hole. An elevated BHT is no problem in interpreting electric logs, because the logs are used only for interpreting physical conditions at the time that the sonde was in the drill hole. Important parameters such as porosity, permeability and lithology will not change significantly from week to week. Temperature, however, might.

Jaeger (1961) addressed this problem some years ago, and concluded that temperature departures are relatively small under ordinary conditions of rotary drilling. Eighteen points (including the surface) were available from logs from the Humble No. 2 Williams, in Washington County, Alabama; of the 17 measurements, 11 points plot on a

[1]Geology Department, Florida State Univ., Tallahassee, Fla. 32306. The encouragement and support of Florida Power and Light Co. is gratefully acknowledged.

smooth curve; three measures departed from that curve by 3-6°C; and three measures by 20° C or more. All three of the badly erroneous readings were on the high side.

If a shoulder near the top of the geothermal plot is eliminated, there are four points having small errors (less than 6°C), one point having a medium error (10°C), three having large errors, and 10 points on a single, smooth, almost straight line. The average error (on the high side) is 6.2°C. In this case, a simple plot permits identification of the anomalous points. The result is a line composed of two straight segments; the geothermal gradient down to 10,000 feet is 2.1°C/100 m, and from 12,000 to 15,455 it is 2.64°C/100 m, (1.13°F/100 ft, and 1.43°/100 ft, respectively). One can be reasonably sure that consistent results have been obtained.

Four other wells in the study suite had a total of 22 measure points (plus the surface, in each case). All four of these were plotted on a single diagram, showing only three of the 22 points departing from a straight line by as much as 5°C, and no point more than 7°C. The gradient for the straight line was 2.3°C/100 m (1.25°F/100 ft.). The average error (low) was 1.1° C. For all five wells, the average error (high) was 2.4° C, or 0.11°C/100 m (0.06°F/100 ft.).

It is concluded that consistent results can be obtained, that Jaeger was basically correct, and that BHT values, if taken over an area with fairly dense drilling, are reasonably close to actual temperatures in the undisturbed rocks.

MAPPING PROCEDURE

Griffin *et.al.*(1969) published a geothermal gradient map for the state of Florida and part of Georgia. These authors calculated a "county average" for each county, and contoured the resulting number. Their map shows (in °F/100 feet) three values greater than 2.0, four values higher than 1.5 but not more than 2.0 and four values between 0.50 and 0.75. The remaining numbers (62 map points) were between 0.75 and 1.50. In general, the high values were in Georgia, and the low numbers along the east coast of Florida, but the distribution was close to being uniform. Within Florida, the highest areas were in the Panhandle (gradients up to 1.56°F/100 ft. = 2.9°C/100 m), and in the southwestern part of the penisula (numbers to 1.06°F/100 ft.= 2°C/100 m).

That map had the advantage of smoothed contours due to averaging. Because the averaging was done on a county-by-county basis, it also had the disadvantage of tending to suppress anomalies which did not completely cover one or more counties. For instance, a linear anomaly occupying adjacent parts of three or four counties, but not as much as half of any one county, could be masked entirely by the smoothing procedure.

The AAPG Geothermal Gradient Maps of Florida and Southern Georgia (AAPG, 1975, a, b) were contoured by machine in units of 0.20°F/100 feet, initially at a scale of 1:1,000,000 (the full set of maps at this scale numbers 39, including parts of Alaska and Canada, with latitude and longitude lines, but no culture or political boundaries shown). On this map set, the highest gradient shown in penisular Florida is 2.6°C/100 m (printed as 1.4°F/100 feet). This high value occupies three areas, one in the vicinity of 26°N, 81.8°W, a second one about one degree to the north, and a third one about one degree to the east. The second of the three corresponds to the Charlotte County anomaly discussed in the present paper, but is higher (by about 0.4°C/100 m) than the value obtained here. However,

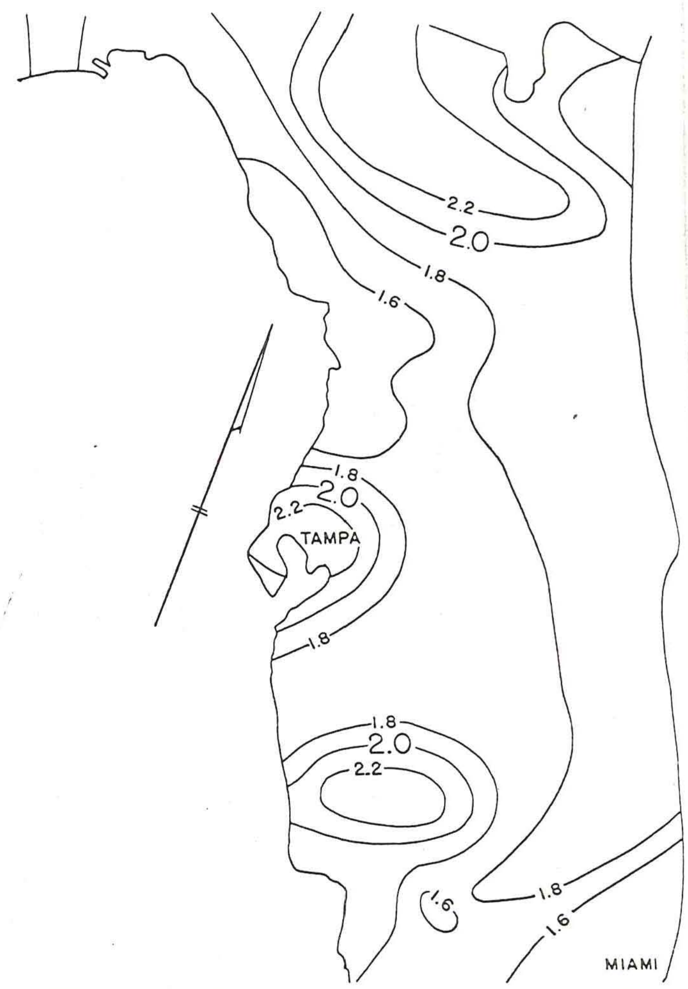

FIGURE 1—Thermal gradient map of part of Florida, showing two peninsular highs (one in the Tampa area, and one farther south), plus an additional high near the Florida-Georgia border, in the northern part of the map. A fourth high, not shown here, occurs in the western panhandle. The figures represent degrees Celsius per 100 meters of depth. In a general way (but not in detail), maximum temperatures at fixed depths (such as 1.0 km, or 2.0 km) tend to match the highest gradient values.

there are three important differences between the AAPG maps, and the maps discussed here. The latter are based on 10 times as many data points, and the former uses a computing method that extrapolates to unreported values in order to maintain more or less even spacing of isopleths, thereby creating high values where in fact no such measures exist. The third difference lies in the correction applied to the geothermal gradient values in order to prepare the AAPG maps; this correction is in the neighborhood of 5 percent.

Kaufman and Dion (1967) studied the hydrology of Charlotte, DeSoto and adjacent counties. Their figure 6 shows Floridan aquifer water temperatures, roughly 200-300 m below mean sea level (MSL). These exceed 85°F (= 29.4°C) in a long, narrow part of the area, covering parts of three or more counties, but in no case occupying as much as half of one county. These values provide a much steeper gradient than found in the present report, but the conclusion drawn here, on the basis of the abundant deep-well data, is that the surface gradient is not representative of greater depths. J. K. Osmond (Johns, *et. al.,* 1975) interpreted these high (shallow) values to be a response to heating from a deeper source.

The decision was therefore made to plot all geothermal gradient values, and then to reject the apparently bad ones in the contouring process. Two maps were drawn initially: one for the entire study area, to provide a regional setting, and a more carefully executed map for the penisula of Florida. Each showed geothermal gradients only. In addition, several other maps (such as: temperatures at 1,000 m, temperatures at 2,000 m) were drawn. These are discussed in other parts of the present paper.

GEOTHERMAL GRADIENT

Work of this kind must be done by using the depth of measurement which appears on the individual well logs; that is, there is no way to obtain measurements at a predetermined, constant depth. Therefore, the gradient values represent, from place to place, different rock thicknesses. The error introduced in this way, however, is small, and the "whole well" gradients are considered to be reasonably reliable.

Figure 1 shows the two most favorable anomalies in peninsular Florida: one located in the vicinity of Tampa Bay, and the other in Charlotte, DeSoto and Sarasota Counties. The maximum observed gradient is 2.2°C/100 m, vertically (1.2°F/100 ft.). There may be steeper gradient values in peninsular Florida, but if so they were not encountered in the present study.

MAXIMUM TEMPERATURES

The highest bottom-hole temperatures noted in peninsular Florida have been in the neighborhood of 100°C (212°F). A partial listing of these results, by counties, is as follows:

Pinellas	3105 m	102°C
Charlotte	3866	128
	3789	92
	4094	98
	3962	97
	4034	96
Hendry	3500	92
	3543	92
	3554	92
	3811	93
	3560	94
	5189	113
Lee	3919	127
	4788	121

In another section, a general extrapolation is made to 100°C. However, the information given here is sufficient to show that high temperatures are available within a few thousand meters of the surface.

The *temperature field* at a depth of 1,000 m shows three clearly defined hot areas, two of them in the Charlotte-Sarasota-DeSoto area. At this relatively shallow position, maximum temperature is 46°C (115°F). The hot spots coincide in a general way, but not in detail, with the maximum anomalies on the geothermal gradient map. This is probably partly due to the averaging effects necessary in constructing the geothermal gradient map, but probably also is due in part to lateral flow of groundwater, at certain depths, which might tend to shift high heat values from one map position to another.

The *temperature field* at a depth of 2,000 m shows a single thermal anomaly: a maximum temperature of 76°C (169°F) in Charlotte Co. This is farther east than the Charlotte Co. anomaly at 1,000 m; perhaps lateral flow of ground water, at higher levels, helps to explain the difference.

Control points are fewer for the 2,000 m surface than for the 1,000 m surface. For this reason, the deeper surface is somewhat less reliable, and more simplistic. Also for these reasons, no map was drawn for the 3,000 m surface. However, projections are made—in a subsequent section—for "depth needed" to reach 100°C.

URANIUM DATA

The water-well uranium data show an anomaly in the Charlotte-DeSoto-Sarasota area, largely in agreement with the geothermal gradient and temperature maps. It is thought that the uranium anomaly is the result of the steeper geothermal gradient (thereby confirming what is shown on figure 1), rather than vice-versa. Osmond treated the topic in detail (Johns *et. al.,* 1975).

DEPTH TO BOILING WATER

The thermal gradient map has been used as the basis for an extrapolation to 100°C (212°F; boiling water). This is not a statement that boiling water occurs at drillable depth; on the contrary, geostatic pressures at very shallow depths are sufficient to prevent boiling. Nevertheless, depth to 100° water is a matter of great interest, especially in view of the fact that each additional foot of hole—at the appropriate depths—may cost (roughly) $100 to drill.

The table below provides estimates of the critical depths:

Geothermal Gradient	Extrapolated depth to 100°C (Meters)	(feet)
2.2°C/100 m	3,636	12,120
2.0 "	4,000	13,333
1.8 "	4,444	14,815
1.6 "	5,000	16,667

The table does not constitute a prediction of the depth at which 100°C will be encountered, for the simple reason that geothermal gradients are not necessarily constant at all depths; instead, it is a simple extrapolation, which may, or may not, turn out to be correct.

HEAT FLOW

Where the rock types are not highly varied, it is possible to estimate the heat flow provided the geothermal gradient is known. In the Florida peninsula, lithologic types are relatively few in number: limestone, dolomite, shale. The average thermal conductivity of such rocks, from published data, is close to 6.5, in units of 10^{-3} cal/cm sec°C.

The heat flow across a unit surface can be expressed as

$$\frac{dQ}{dS} = -K \frac{dT}{dz} \qquad (1)$$

where Q is quantity of heat flow per unit time, K is the thermal conductivity, and dT/dz is the thermal gradient in °C/cm. In centimeter-gram-second units, the unit surface is one square cm. Using the average thermal conductivity given above, the equation is:

$$dQ = -(6.5 \times 10^{-3})\, dT/dz \text{ (cal/sec).} \qquad (2)$$

$$= -6.5\, dT/dz \text{ (millical/sec)} \qquad (3)$$

$$= -(6.5 \times 10^{3})\, dT/dz \text{ (microcal/sec.)} \qquad (4)$$

The table below gives the estimated heat flow, in microcalories per second, across a horizontal surface of 1 square centimeter, for geothermal gradients in Florida, and for "average" limestone:

Geothermal Gradient	Heat flow, across each square centimeter
2.2°C/100 m	1.43 microcal/sec.
2.0 "	1.30 "
1.8 "	1.17 "
1.6 "	1.04 "

The values given in the table are calculated, not observed.

Smith (Johns *et. al.,* 1975) used four core samples from depths of less than 160 m in a single well to obtain actual thermal conductivity values. The mean harmonic conductivity was 4.58. If this is taken to represent deep materials reasonably closely, the table above must be corrected to:

2.2°C/100 m	1.01 microcal/sec.
2.0	0.92
1.8	0.82
1.6	0.73

However, surface limestones of Cenozoic age are not likely to be equivalent in thermal conductivity to Mesozoic limestones buried to a depth of several kilometers, hence the estimates obtained as shown in the first table are preferred for the time being.

FUTURE WORK

The deep temperature, and the geothermal gradient, are two important bits of information in any prospective, or potentially prospective, geothermal area. However, other information is needed before a reasonably reliable assessment of the potential can be made. One additional bit of information is the thermal conductivity of the rocks present at each depth.

Published values for thermal conductivity range widely. Clark (1966), for example, gave the following:

Minimum value: 2.2 (10^{-3} cal/cm sec°C).
Maximum value: 18.9

Even for one rock type, the range is great. Clark reported for limestone (including shaly or argillaceous limestone) values ranging from 2.2 to 8. For a given area, such as the Florida peninsula, it is not possible to say, in advance, either (1) that the local rocks are close to some "average" value, or (2) that the deeper rocks have the same thermal conductivities as the surface rocks (about 4.6, in one shallow well, as determined by Smith).

It should be possible to solve this problem by estimating the thermal conductivity from standard well logs. Bridgman showed, from theoretical considerations (Howell, 1959, p. 55), that the thermal conductivity Kh can be related to the seismic velocity and mass density of certain materials as follows:

$$K_h = kV(\rho^{2/3}) \quad (5)$$

where K is a coefficient not specified, V is the compressional wave velocity, and rho is the mass density. For ordinary sedimentary rocks, the exponents (including the exponent 1.0 on V) may need revision; a closer approximation might be:

$$K_h = k V^a \rho^b \quad (6)$$

where the exponents a and b are not far from 2.0 or 3.0, but need to be specified on the basis of more data than are available at the moment, and where the value of k will depend heavily on the two exponents.

The compressional wave velocity can be read directly from continuous velocity logs (CVL) or sonic logs, and bulk density can be obtained from, for example, the Formation Density Log (a gamma-ray-scattering log). When this relationship is specified in a more rigorous way, sonic velocity, formation density, and BHT—all from logs—will be useful in making direct estimates of heat flow.

If deep rocks are to be evaluated, in relatively low temperature areas, as possible geothermal resources, estimates of permeability will be needed also. These can be made from porosity determinations, which are particularly good when based on cross-plots of two or more log types (such as sonic and radioactivity). And two-well recirculating-pre-heating system will be no more efficient than permitted by transmissability of the selected rock unit at depth.

CONCLUSIONS

The data available indicate the thermal sources are deep, rather than shallow. None of the results are spectacular. However, a good deep source (at depths of 3,000-4,000 m) occurs in southwestern peninsular Florida. This is, in fact, the best source in the peninsula.

A number of wells, drilled in the most prospective area, could supply pre-heated water, by means of a recirculation system, from a reasonable depth. Such pre-heated water could be extremely important at some future date in reducing fuel costs in a thermoelectric power plant. If the wells extended to depths as great as 3,500 m or slightly greater, the reduction in fuel costs might be greater than 50%.

REFERENCES

American Assoc. Petroleum Geologists, 1975a, Geothermal gradient map of Southern Florida (Portfolio Map Area No. 1): AAPG, Tulsa, Okla.

American Assoc. Petroleum Geologists, 1975b, Geothermal gradient map of Northern Florida and Southern Georgia (Portfolio Map Area No. 2): AAPG, Tulsa, Okla.

Clark, Sydney P. (ed.), 1966, Handbook of Physical Constants: Geol. Soc. Amer., Memoir 97, 587 p.

Ellis, A. J., 1975, Geothermal systems and power development: Amer. Scientist, vol. 63, p. 510-521.

Goguel, Jean, 1976, Geothermics: McGraw-Hill, New York, 200 p.

Griffin, G. M., P. A. Tedrick, D. A. Reel and J. P. Manker, 1969, Geothermal gradients in Florida and Southern Georgia: Trans. Gulf Coast Assoc. Geol. Societies, vol. 19, p. 189-193.

Howell, Benjamin F., 1959, Introduction to Geophysics: McGraw-Hill, New York, 399 p.

Jaeger, J. C. 1961, The effect of the drilling fluid on temperatures measured in bore holes: Jour. Geophys. Research, vol. 66, p. 563-569.

Johns, R. K. C., J. K. Osmond, D. L. Smith and W. F. Tanner, 1975, Geothermal energy exploration in Southwest Florida (Sarasota, Charlotte and De Soto Counties): Florida Power and Light Co., Miami, 152 p.

Kaufman, M. I., and N. P. Dion, 1967, Chemical character of water in the Floridan Aquifer in Southern Peace River basin, Florida: Florida Division of Geology, Map Series No. 27.