Detection of Overpressured Formations During Drilling Operations in World-Wide Environments

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INTRODUCTION

The purpose of this paper is to show that abnormal pressure can be detected during drilling operations in world-wide environments. It can also be evaluated quantitatively in certain instances.

Formation pressure is defined as that pressure exerted by the fluid in the pore spaces of a given formation. The formation pressure may be normal, abnormal or subnormal.

Normal pressure is defined as the hydrostatic pressure exerted by all fluids in the formations above the depth of interest. The average normal pressure gradient in the Mid-Continent area is 0.433 psi/ft, and the average normal pressure gradient is 0.465 psi/ft in the Gulf Coast Area. Generally speaking, gradients of the magnitudes mentioned are experienced in most world-wide drilling areas. However, the normal gradient for any area is affected by the salinity of formation waters.

Abnormal or overpressure is that pressure greater than normal, and can exist for several reasons. The four most common causes are as follows: (1) a formation may outcrop below the normal water table for a given area; (2) a formation may be charged with pressure from fluid injected during secondary recovery operations or from another higher-pressured formation; (3) abnormal pressure can result from rapid burial of sediments; and (4) another possibility is the result of faulting or uplifting, which is in evidence around salt domes. The uplifted formations maintain approximately original pressures, but due to the uplift, the formation pressure gradient has increased.

Subnormal pressures are those pressures less than normal. This type of pressure is often encountered in a tectonic environment where a formation outcrops at some elevation lower than the drilled formation. Subnormal pressures are also in evidence in depleted formations.

OVERPRESSURE DETECTION METHODS

There are many methods available for detecting overpressured zones. Some of these methods require specialized equipment and people and, therefore, are seldom used.

There are five practical tools available that have been used throughout world-wide operations to detect abnormal pressures while drilling. Each of these techniques was primarily developed in the U.S. Gulf Coast area.

One of the first techniques developed was that of monitoring the rate of penetration through shale sections. It was noted that the penetration rate through shale sections decreased with depth. However, in some instances, penetration rate would increase in these shale sections. After analyzing this change, it was concluded that the differential between the mud column pressure and formation pressure caused the anomaly.[1] Therefore, by monitoring penetration rate, an increase in formation pressure gradient can be detected (Fig. 1).

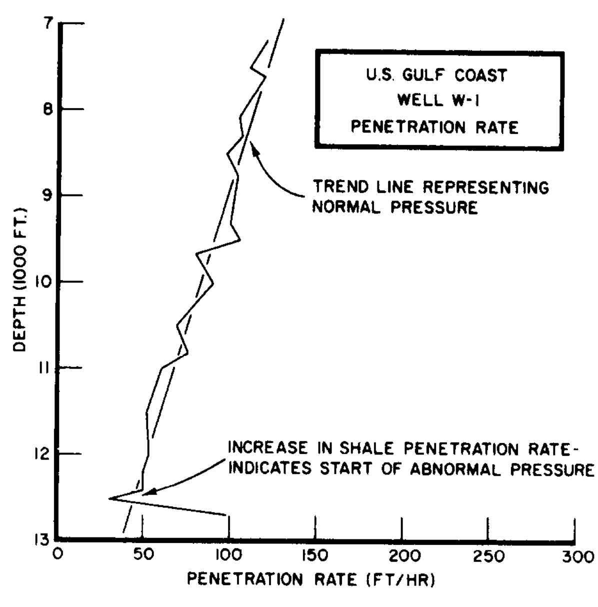

FIGURE 1

A second method is that of measuring the bulk density of drilled shale.[2] Since the bulk density of shale reflects the porosity within the shale, then as bulk density decreases porosity increases. Porosity decreases with depth due to the increase in compaction of formation rocks. However, in abnormal pressure situations, shale porosity increases; i.e., the amount of formation fluid present is greater for that depth than is normally encountered.

A plot of shale bulk density will yield a formation pressure profile from which an estimation of formation pressures can be obtained. Figure 2 illustrates a Gulf Coast well shale density profile.

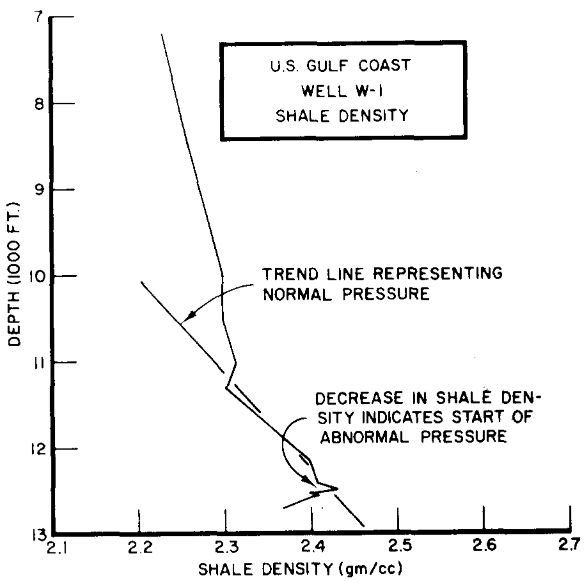

FIGURE 2

A third technique was developed by Shirley and Jorden in 1966.[3] This method utilizes an equation to normalize penetration rate through shale. The "d" exponent is expressed as:

$$\text{"d"} = \frac{\log (R/60N)}{\log (12W/10^6D)}$$

where:

R = Rate of penetration, ft/hr
N = Rotary speed, RPM
W = Weight on bit, lb
D = Hole diameter, in.

A plot of "d" exponent versus depth reflects changes in penetration rate due to a change in differential between the hydrostatic pressure of the mud column and formation pressure. By observing the "d" exponent plot in Fig. 3, the areas of abnormality can be readily seen.

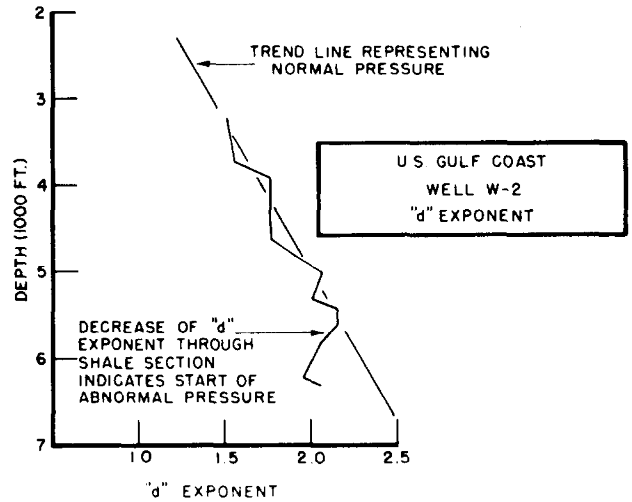

FIGURE 3

The fourth technique concerns flowline temperature which is a reflection of formation temperatures. Formation temperatures increase with depth for normally compacted sediments. However, it has been noted that a temperature phenomenon occurs when a pressure transition zone is encountered.[4] The phenomenon exists in the form of a temperature gradient increase in the transition zone and a temperature gradient decrease as porosity and permeability are incurred. In some instances the increase is not observed.

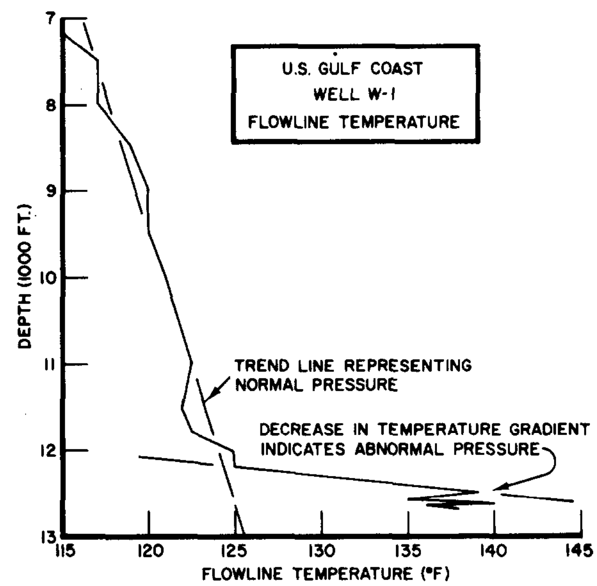

FIGURE 4

In either case a radical change in flowline temperature can be the result of abnormal pressure. By monitoring flowline temperature, areas of abnormal pressure can be observed (Fig. 4).

The last method predicts actual formation porosity.[5] The general equation is stated as:

$$R = k\, f_1(W/D)\, f_2(N)\, f_3(H)\, f_4(\Delta P)$$

where: R = Penetration rate.
k = Drillability constant or normalized rate of penetration.
$f_1(W/D)$ = Function defining the effect of bit weight, W, per inch of bit diameter, D, on penetration rate.
$f_2(N)$ = Function defining the effect of rotary speed, N, on penetration rate.
$f_3(H)$ = Function defining the effect of tooth dullness, H, on penetration rate.
$f_4(\Delta P)$ = Function defining the effect of the differential pressure across the hole, ΔP, on penetration rate.

The normalized rate of penetration, k, is then related to bulk density by:

$$\rho_b = 2.65 - 1.65\ \frac{Sg + \mathrm{Log}_{10}k^{-6}}{Sg}$$

where: ρ_b = Bulk density, gm/cc
Sg = Rock strength parameter

Bulk density is then converted to formation pseudo-porosity. The pseudo-porosity will closely agree with the calculated porosity as determined from the density log.

The five tools mentioned will detect abnormal pressure. In some cases all of the methods will complement each other as to general areas of abnormality. However, in some cases two or three techniques may show an abnormally pressured interval and the remaining methods may not show anything.

APPLICATION OF PRESSURE DETECTION TOOLS

The five practical tools available for detecting pressure have been used successfully on both the North American continent and in other world-wide areas. Notably, the tools were used in the African area, Southeast Asia and the North Sea. In most cases the wells were drilled in areas where little, if any, formation pressure information was available. Therefore, some or all of the practical pressure detection tools were utilized while drilling.

A well was drilled in the African area with little formation pressure information available. During the drilling operation penetration rate, "d" exponent, shale density and flowline temteratuer were monitored.

The rate of penetration plot is shown in Fig. 5. The graph illustrates curves A and B. Curve A is a series of individual curves of rate of penetration. The break between curves defines bit changes. To compensate for the difference between the final penetration rate of a dull bit and the rate for a new bit, a new composite curve was constructed. The new smooth curve B was composed by shifting the initial point for a new bit to coincide with the last point of the previous bit run. The other points for the bit run were shifted accordingly. By doing this, a correction for bit wear is introduced. Since the actual rate of penetration is not important, the curve provides a means to look at penetration rate trends for consecutive bit runs.

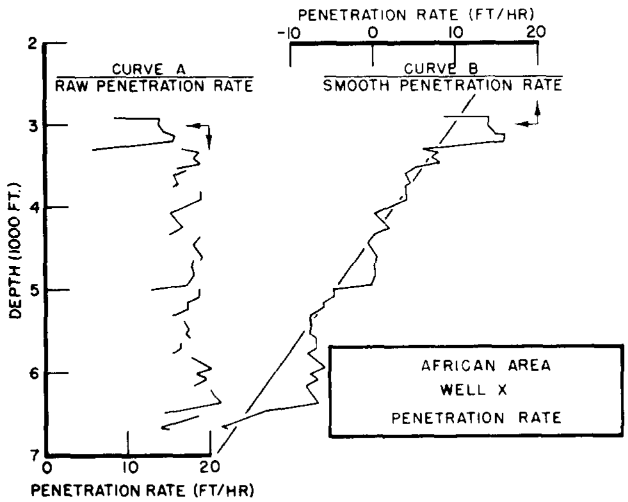

FIGURE 5

Curve B indicates that abnormal pressure was encountered at the intervals, 4410-4900 ft and 5400-6650 ft. The smooth "d" exponent curve in Fig. 6 illustrates one major area of abnormality from 5650-6670 ft. This closely agrees with the second interval shown on the rate of penetration curve. The initial zone indicated by the penetration rate curve was discounted due to the changes in bit weight and rotary speed at this point.

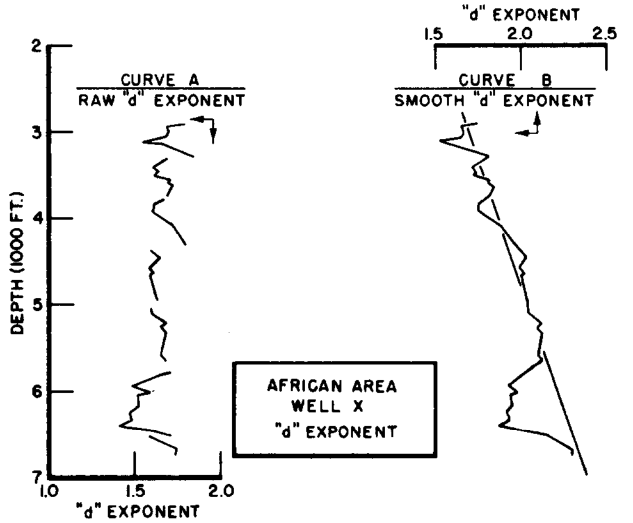

FIGURE 6

The shale density profile (Fig. 7) suggested that two areas of abnormal pressure existed. The first area at 4630 ft was questioned as to the possibility of being a fault. The second interval from 5600-6650 ft was suggestive of abnormal pressure.

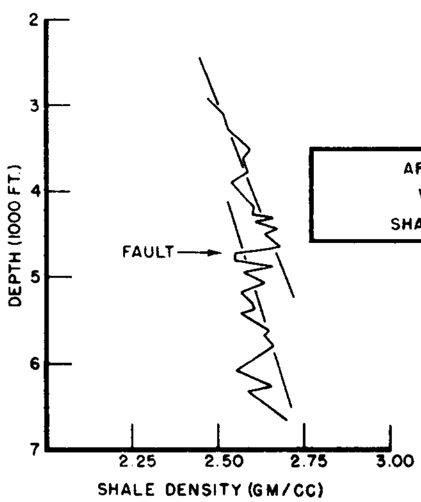

FIGURE 7

The smooth flowline temperature curve (Fig. 8) appeared to be normal throughout the entire drilling operation. However, there is a definite break at 6000 ft. The flowline temperature curve in many cases is highly interpretive. This comes about due to the many factors affecting the profile, such as trips and circulating mud. Either of these items changes the profile almost instantaneously.

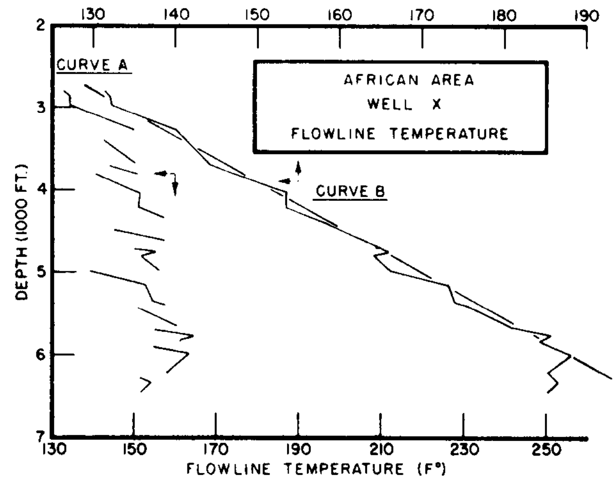

FIGURE 8

Throughout the drilling of the well, mud weights were adjusted as the pressure information was obtained from the detection tools. In some instances, logs were run to verify the abnormal pressure horizons. The log data suggested that only one pressure transition zone was encountered and that was at 5600 ft and continued to 6500 ft. Hence, the major pressure horizon was detected by three tools and the fourth tool was off considerably. However, enough indicators were suggestive of abnormal pressure; corrective action was taken.

The Southeast Asia area is known for the high occurrence of abnormal pressure. Because of this fact, during the drilling of Well Y-1, the "d" exponent, bulk shale density and flowline temperature were monitored.

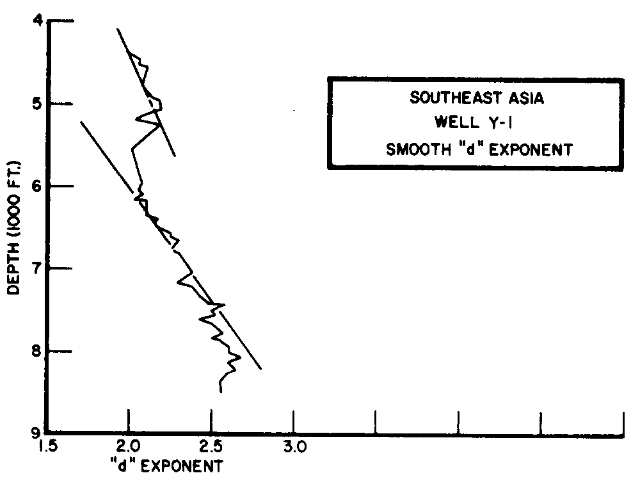

FIGURE 9

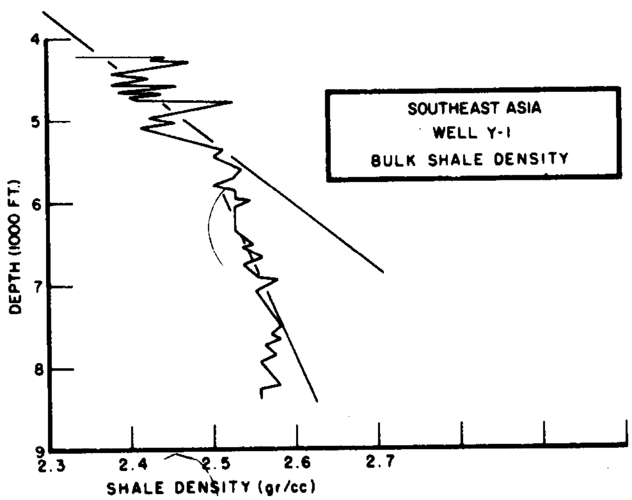

FIGURE 10

The smooth "d" exponent curve (Fig. 9) indicated two pressure transition zones, the first at 5250 ft and the second at 7490 ft. The shale density curve (Fig. 10) showed anomalies at 5350 ft and 7500 ft. These two transition zones are almost identical to those suggested by the smooth "d" exponent plot.

Smooth flowline temperature (Fig. 11) suggested that abnormal pressure existed at 6500 ft and 7540 ft. The zone indicated at 6500 ft differs from the depths found by the first two tools, but there is complementary agreement on the second abnormal pressure horizon depth.

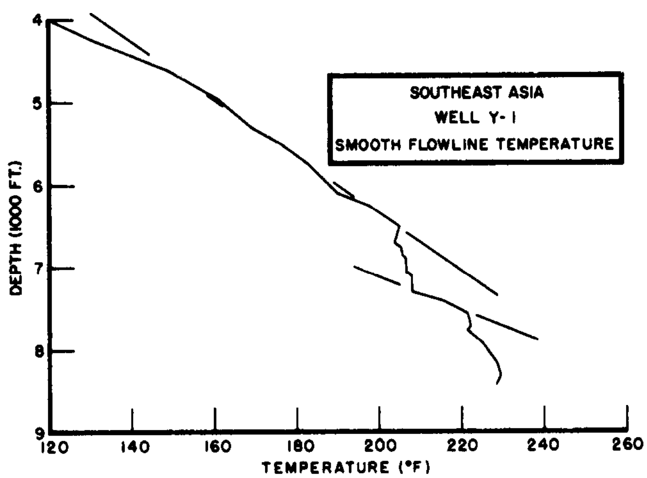

FIGURE 11

Again, as in the African area, corrective action was taken as the abnormally pressured zones appeared. Either the mud weight was raised or logs were run to confirm the pressure. Sonic log data confirmed the abnormal pressure zones as being very near the 5300 ft and 7500 ft levels.

A second well, Y-2, was drilled at some distance from Well Y-1 in Southeast Asia. The smooth "d" exponent curve (Fig. 12) indicated that an abnormal pressure transition zone started at 6400 ft with high pressure continuing to total depth. The bulk shale density (Fig. 13) verified the "d" exponent. The smooth flowline temperature curve (Fig. 14) complemented both the bulk density and "d" exponent trend.

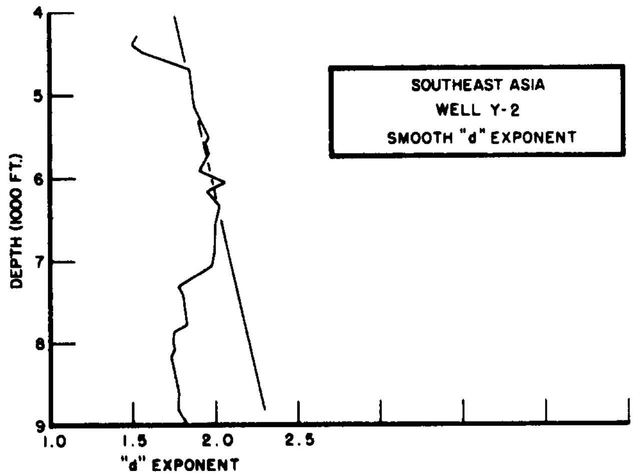

FIGURE 12

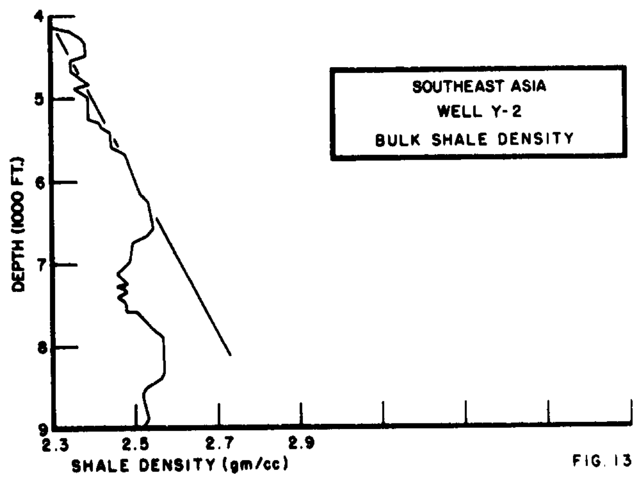

FIGURE 13

On this well a variation of the porosity detection tool was used. Instead of using the two equations as presented previously, only the first generalized equation was used. The equation was solved for ΔP, or the difference between the formation pressure and hydrostatic pressure. The difference was then utilized to predict actual formation pressure while drilling.

Figure 15 shows the formation pressure com-

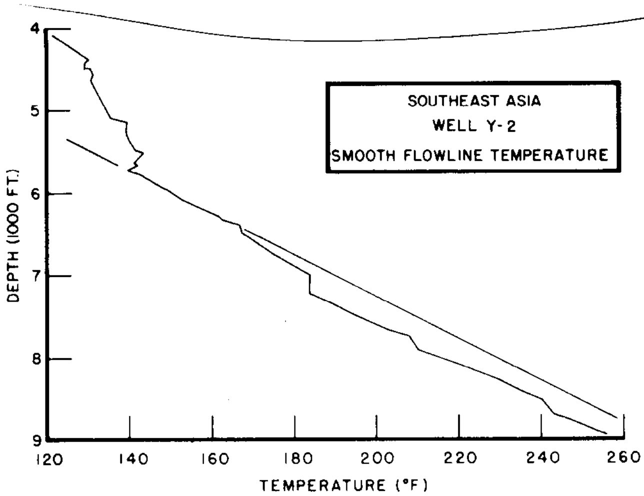

FIGURE 14

parison between the method discussed and the pressures as derived from sonic log data. An actual test pressure is shown at 8150 ft and lies between log pressure and drilling-calculated pressure.

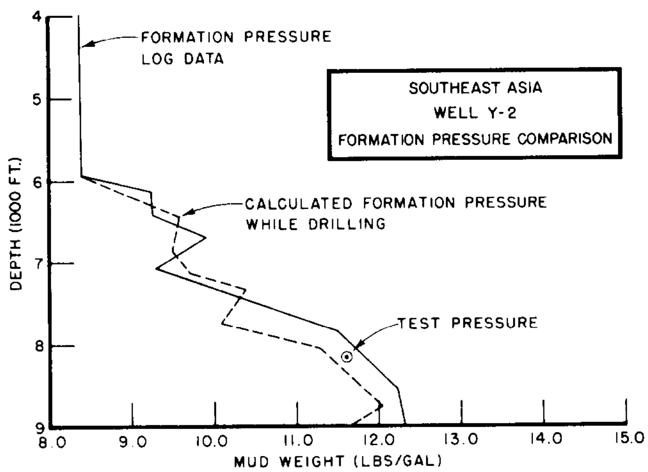

FIGURE 15

In this particular instance not only was the major abnormal pressure horizon detected, but formation pressures were calculated during the drilling operation.

In the North Sea, Well Z-1 was drilled to a depth of 9350 ft. Two abnormal pressure detection tools were used. The smooth "d" exponent (Fig. 16) pointed out abnormal pressure transition zones at 2600 ft, 4600 ft and 7400 ft. An attempt was made to determine actual formation pressures while drilling by utilizing "d" exponent data.

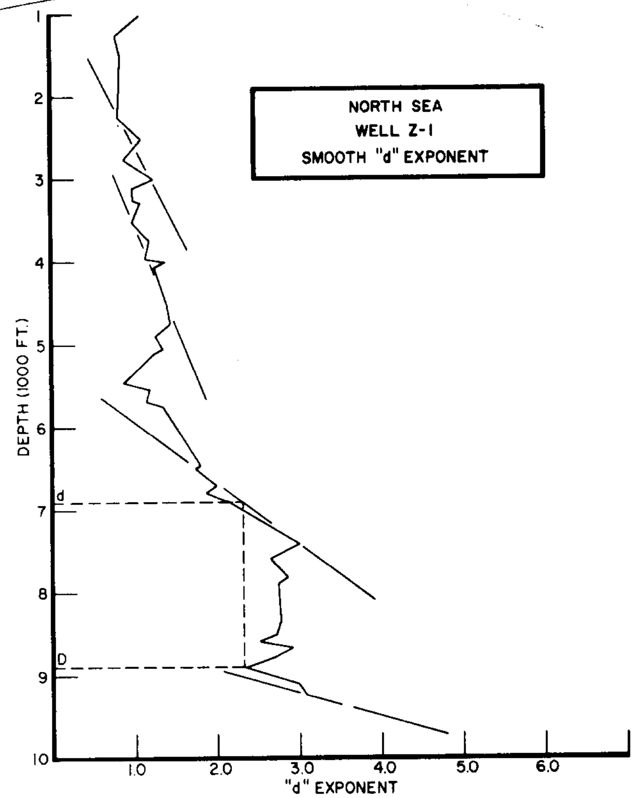

FIGURE 16

The following equation was used:

$$P = (G)(D) - (G-g)(d)$$

where:

- P = Formation pressure, psi.
- G = Overburden gradient, psi/ft
- D = Depth of interest, ft
- g = Normal formation pressure gradient, psi/ft
- d = Equivalent depth, ft

Example: What is the formation pressure at 8900 ft?

G = 1.0 psi/ft, D = 8900 ft, g = 0.465 psi/ft

d = 6910 ft

$P = (1)(8900) - (1.0 - 0.465)(6910)$

P = 5200 psi or 11.2 lb/gal equivalent

Formation pressures were calculated during the drilling operation. A comparison of pressures calculated while drilling and those pressures calculated from log data is shown in Table 1.

TABLE 1

WELL Z-1
FORMATION PRESSURE COMPARISON
"d" EXPONENT VERSUS LOG DATA

DEPTH, FT	LOG VALUE, LB/GAL.	"d" EXPONENT, LB/GAL.
2750	10.4-11.2	10.2
3600	12.7*	11.8
5450-5750	13.4 MAXIMUM	13.1 MAXIMUM
8748	10.3	10.6
8900	10.2	11.2

*MUD WEIGHT USED TO BALANCE KICK.

The smooth flowline temperature curve (Fig. 17) indicated pressure transition zones at 4000 ft and 8110 ft, which did not completely agree with the "d" exponent.

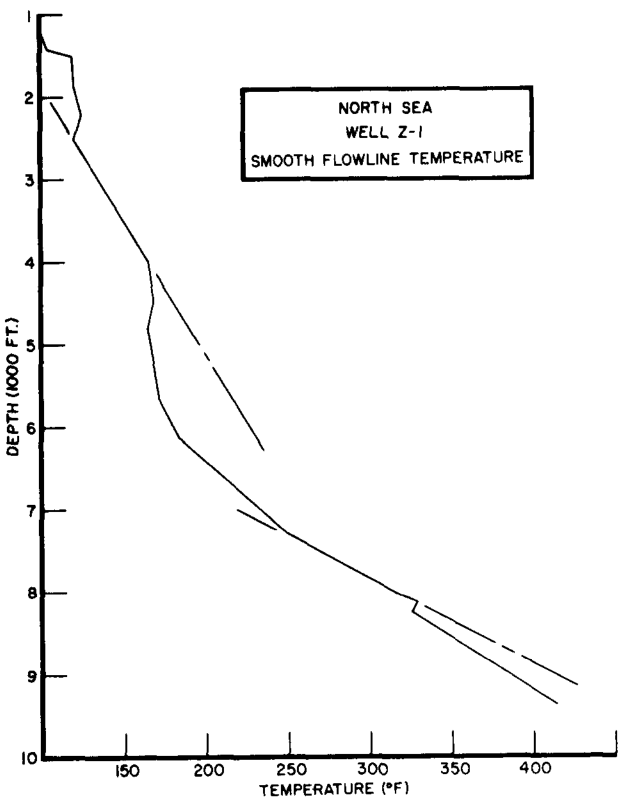

FIGURE 17

A second well, Z-2, was drilled in the North Sea at some distance from Well Z-1. Again "d" exponent data (Fig. 18) yielded good formation pressure while drilling. Table 2 illustrates the comparison of log values versus those calculated while drilling. As shown by this table and Table 1, there is some disagreement between the two methods. However, it is the author's opinion that in these cases the values calculated while drilling may be closer to true values than those values obtained from log data.

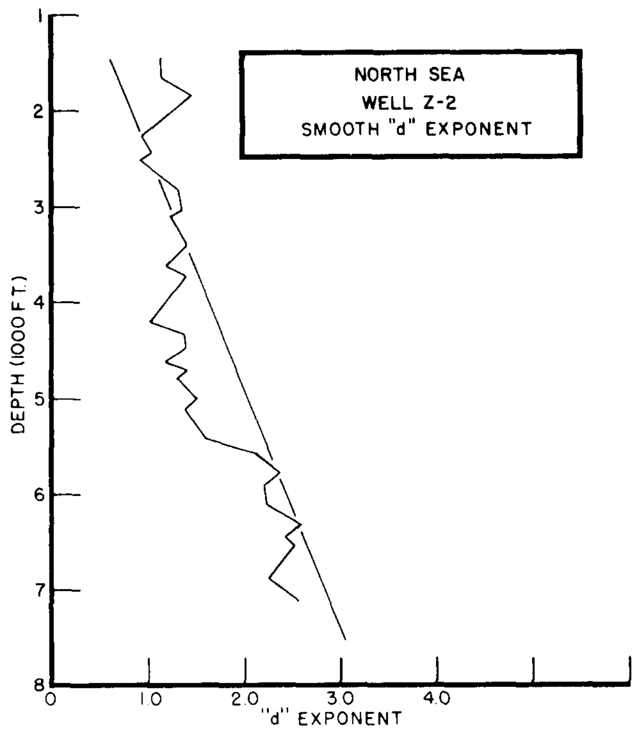

FIGURE 18

TABLE 2

WELL Z-2
FORMATION PRESSURE COMPARISON
"d" EXPONENT VERSUS LOG DATA

DEPTH, FT.	LOG VALUE, LB/GAL.	"d" EXPONENT, LB/GAL.
4000	11.6	11.8
4500	11.2	11.7
5000	12.4	11.7
6000	11.7	10.0
6800	9.6	10.9

The bulk shale density curve (Fig. 19) yielded pressure transition zones at 3150 ft, 5300 ft and 6900 ft and agrees somewhat with "d" exponent data. It should be stated that the low shale densities obtained were the result of the method used in measuring densities in the "gumbo" type formation. However, the absolute shale values were not important, only the general shape of the curve was required.

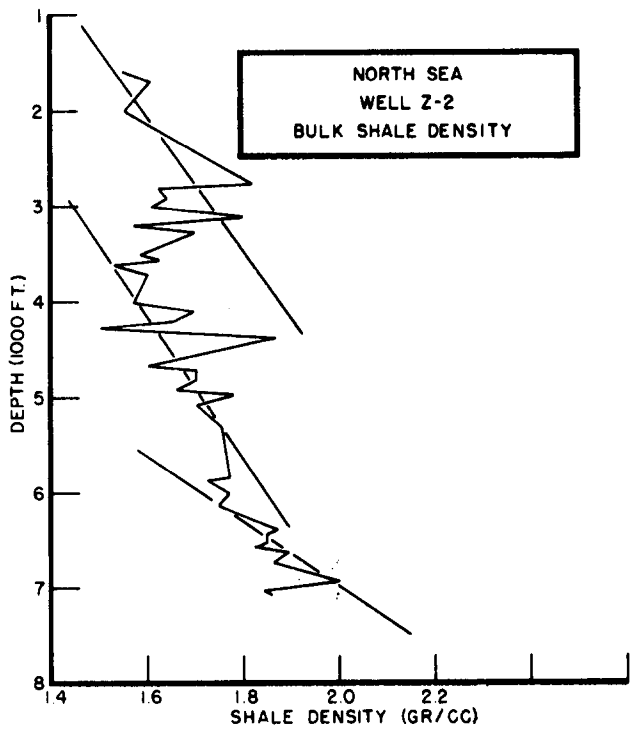

FIGURE 19

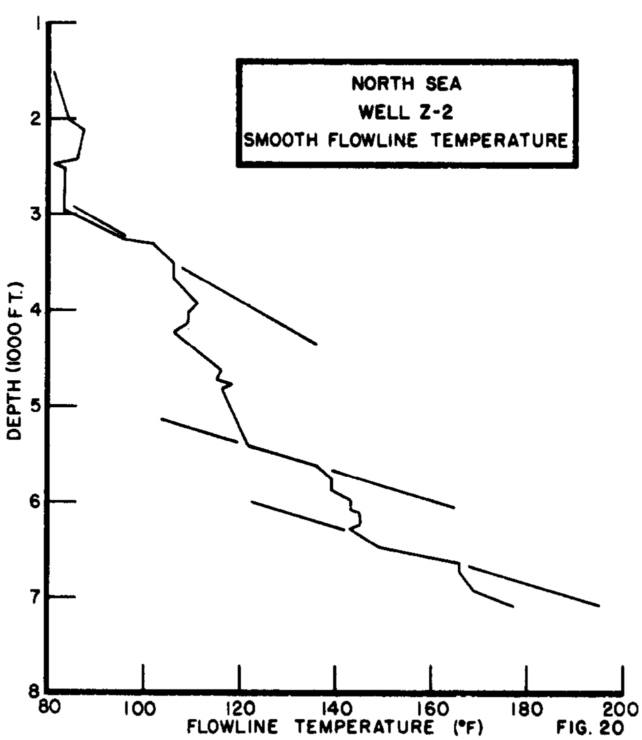

FIGURE 20

For this well, the transition zones indicated by the flowline temperature profile in Fig. 20 closely agreed with those detected by the other two tools used.

CONCLUSION

There are five practical tools that can be used to detect abnormal pressure in world-wide areas while drilling, namely:

1. Rate of penetration change in shale sections
2. Bulk density change in shale sections
3. "d" exponent change in shale sections
4. Flowline temperature change
5. Shale porosity change.

Two of the above techniques can be used to predict actual formation pressures while drilling. By utilizing these five tools, most of the abnormal pressure transition zones will be detected during the drilling operation.

REFERENCES

1. Combs, George D.: Prediction of Pore Pressure from Penetration Rate, Paper SPE 2162, AIME, 43rd Annual Fall Meeting, Houston, Texas, 1968.
2. Boatman, W. A.: Shale Densities Key to Safer, Faster Drilling, ***World Oil,*** 69-74, Aug. 1967.
3. Jorden, J. R. and Shirley, O. J.: Application of Drilling Performance Data to Overpressure Detection, ***Jour. Petr. Tech.,*** 1387-1394, Nov. 1966.
4. Lewis, C. R. and Rose, S. C.: A Theory Relating High Temperatures and Overpressures, ***Jour. Petr. Tech.,*** 11-16, Jan. 1970.
5. Bourgoyne, A. T.: A Graphic Approach to Over-Pressure Detection While Drilling, ***Petr. Engr.,*** 76-88, Sept. 1971.

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