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Determining Frac Gradients While Drilling

Determining Frac Gradients While Drilling

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Correctly predicting and evaluating pressures likely to be encountered while drilling is essential for adequate well control.

Because of the recent Sigmalog development,³ a more reliable overpressure prediction and evaluation method, AGIP has devoted its efforts to calculating the overburden gradient starting from the log itself. AGIP's aim is to plot — while drilling — not only the pore pressure gradient development, but also overburden and fracture gradient variations with depth. AGIP will use the resulting gradients to select casing setting depths and mud weight and to evaluate formation characteristics — all based on pressure gradient knowledge.

Pore, overburden, and fracture pressures are determined by applying various methods and techniques at different operation stages:

- Before drilling — from the analysis of seismic data and reference wells.
- While drilling — interpreting recorded drilling parameters.
- From the evaluation of wireline logs at the end of a certain drilling phase.

Analysis of seismic data,¹ available as a printout of interval velocities or interval transit times versus depth, is transformed into overburden, pore pressure, and, finally, fracture gradients.

The same results are reached by correctly interpreting wireline logs;^{2,3} in particular, the Sonic Log and IES. The only limitation is the lithology; in fact, electrical logs can be used for overpressure detection only in clastic series.

Drilling parameters are used mainly for evaluating pore pressures and, only tentatively, for calculating instantaneous porosity in clastics and correlating electrical logs.⁵

At present, determining the overburden gradient with the Sigmalog is limited to only clastic formations (shales, sands, marls, etc.) frequently encountered in Adriatic offshore wells. The possibility of obtaining these values in carbonatic and evaporitic rocks—therefore, covering all the possible lithologies—is being studied.

The method proposed in this article uses the following format: (1) starting from Sigmalog computations, drilling porosities in sand and shale formations are

estimated with proper formulas, (2) these porosities are transformed into bulk densities, and (3) bulk densities are converted into overburden gradients. The pore pressure gradient calculated from the Sigmalog analysis makes evaluation of fracture gradients possible while drilling; hence, drilling personnel are given prompt and adequate analysis of the well bore situation and behavior of the formations penetrated.

Overburden Gradient Calculation

Generally, the overburden pressure at a given depth, H , equals the cumulative weight of the rocks above that depth:

$$P_{ov} = \sum_{i=1}^n P_{ov_i} = \frac{1}{10} \sum_{i=1}^n (\Delta H_i \times d_{b_i}) \quad (1)$$

where

d_b = formation bulk density as a function of depth H , lb/ft³ (g/cc)

ΔH_i = interval of depth considered, ft (m)

Dividing the overburden pressure P_{ov} , obtained from Eq. 1, by the depth $H = \sum \Delta H_i$, the corresponding overburden gradient, G_{ov} , can be calculated:

$$G_{ov} = 10 \left(\frac{P_{ov}}{H_i} \right) \quad (2)$$

The G_{ov} values are plotted versus depth and, therefore, the overburden gradient curve obtained.

To draw the overburden gradient curve, formation bulk densities must be determined first. Bulk densities usually can be derived from density logs (specifically from the FDC log) and from other density measurements (such as the cutting density measurement while drilling). Unfortunately, the FDC log is generally available only for a few wells and limited to the hydrocarbon bearing intervals; the cutting density measurement is time-consuming and is affected by several limitations, such as sample preparation.

To allow accurate calculation of overburden gradients and, consequently, valid pore pressure and fracture gradients — both during the planning phase and at the end of each drilling phase — AGIP developed methods, based on seismic data, Sonic Log readings, and, finally, evaluation of drilling parameters by Sigmalog analysis.

Seismics and Sonic Log

Seismics and Sonic Log are similar — both are based on determination of the interval velocities or interval transit times as a function of depth or both. The only difference is that the Sonic Log, a continuous log, is more reliable and accurate than seismics, even when frequent and good seismic readings are taken.

The following experimental relationships have been found between the formation bulk density, d_b , and the interval transit time, Δt_i :

- For uncemented formations

$$d_b = d_{\max} - 2.11 \frac{\Delta t_i - \Delta t_{\max}}{\Delta t_i + \Delta t_{\eta}} \quad (3)$$

- For cemented and compacted formations

$$d_b = 3.28 - \frac{\Delta t_i}{89} \quad (4)$$

or in terms of interval velocities, V_i , when seismic data are processed

$$d_b = d_{\max} - 2.11 \frac{1 - V_i/V_{\max}}{1 + V_i/V_{\min}} \quad (3a)$$

$$d_b = 3.28 - \frac{3,425}{V_i} \quad (4a)$$

where

Δt_i = interval transit time, $\mu\text{sec}/\text{ft}$

$\Delta t_{\max}$ = matrix material transit time, $\mu\text{sec}/\text{ft}$

Δt_{η} = fluid transit time, $\mu\text{sec}/\text{ft}$ (assumed equal to 200 sec/ft)

V_i = interval velocity, m/sec

$V_{\max}$ = matrix velocity, ft/sec (m/sec); the average value assumed for the Po Valley basin is 22,970 ft/sec (7,000 m/sec)

$V_{\min}$ = minimum soil velocity, ft/sec (m/sec); assumed in most cases equal to 4,920 ft/sec (1,500 m/sec)

$d_{\max}$ = matrix density, lb/ft³ (g/cc); the average value assumed for the Po Valley basin is 172 lb/ft³ (2.75 g/cc)

Eqs. 3 and 3a are applied in uncemented formations such as sands, shales, and marls, which generally show high transit times and, consequently, low interval velocities. Eqs. 4 and 4a are valid in cemented and compacted formations, such as limestones, dolomites, sandstones, etc; these formations show low transit times and, therefore, high interval velocities.

In most cases examined, values of bulk densities and corresponding overburden gradients, obtained with Eqs. 3 and 3a or 4 and 4a, are close to each other when the transit times are in the 40 to 60 sec/ft range. Therefore, Eqs. 3 and 3a can be applied in all situations (although not formally correct), thus avoiding the need to distinguish between cemented and uncemented formations.

Eqs. 3 and 3a calculate the bulk density of each interval, ΔH , in which the well can be subdivided, but neglect the weight of sediments above the interval. To

obtain the corresponding overburden pressures, from which the overburden gradient curve is derived, integrate bulk densities versus depth, using Eq. 1.

By substituting Eq. 3 or 3a into Eq. 1, the following equations are derived:

$$P_{ov} = \sum_{i=1}^n \left[d_{\max} - 2.11 \frac{\Delta t_i - \Delta t_{\max}}{\Delta t_i + 200} \right] \frac{\Delta H_i}{10} \quad (5)$$

or

$$P_{ov} = \sum_{i=1}^n \left[d_{\max} - 2.11 \frac{1 - V_i/V_{\max}}{1 + V_i/V_{\min}} \right] \frac{\Delta H_i}{10} \quad (5a)$$

Dividing P_{ov} by depth, the overburden gradient, G_{ov} , is obtained. Then the G_{ov} values are plotted versus depth.

Signalog

At present, drilling parameters are recorded, interpreted, and processed mainly for detection and evaluation of overpressures at the rig site. To obtain this information, AGIP applies the Signalog method.

The basic equation for Signalog calculations is as follows:

$$\sqrt{\sigma_t} = \frac{WOB^{0.5} \times RPM^{0.25}}{D_h \times ROP^{0.25}} \quad (6)$$

where

$\sqrt{\sigma_t}$ = total rock strength or raw Signalog

WOB = weight on bit, lb

RPM = revolution per minute of rotary table

D_h = hole diameter, in.

ROP = rate of penetration, ft/hr (m/hr)

The term $\sqrt{\sigma_t}$ is related to the true Signalog, $\sqrt{\sigma_o}$, by the following relationships:

$$\sqrt{\sigma_t'} = \sqrt{\sigma_t} + 0.028 (7 - H/1,000) \quad (7)$$

$$\sqrt{\sigma_o} = F^* \sqrt{\sigma_t'} \quad (8)$$

where

$$F^* = 1 + \frac{1 - \sqrt{1 + n^2 \Delta P^2}}{n \Delta P} \quad (9)$$

$$\Delta P = (d_f - G_p) \frac{H}{10} \quad (10)$$

and

$\sqrt{\sigma_o}$ = Signalog

ΔP = differential pressure between mud column and formation pressure, atm

G_p = pore pressure gradient, psi/ft (atm/10 m); when calculating the Signalog values, an initial $G = 0.461$ psi/ft (1.03 atm/10 m) is assumed

d_f = mud density, lb/ft³ (kg/l)

H = depth, ft (m)

n = function of the time required to equalize the differential pressure through the cutting which depends on lithology and, in particular, on porosity:

$$\text{if } \sqrt{\sigma_t'} > 1 \rightarrow n = \frac{1}{640} \left(4 - \frac{0.75}{\sqrt{\sigma_t'}} \right) \quad (11)$$

$$\text{if } \sqrt{\sigma_t'} \leq 1 \rightarrow n = \frac{3.25}{640 \sqrt{\sigma_t'}} \quad (12)$$

The term $\sqrt{\sigma_t'}$ is a correction factor for determining pore pressure gradients at shallow depths.

At the rig site, the drilling parameters are recorded at least every 3 ft (1 m) and immediately processed with a computer to obtain the $\sqrt{\sigma_o}$ values, which are printed and plotted versus depth on a 1/10,000 scale log. On this curve, points on the left indicate porous or fractured formations, and those on the right, impermeable sections—mainly formed by shales and marls. Under normal pressure and, therefore, normal compaction conditions, these points form a straight line called reference trend line, $\sqrt{\sigma_r}$. The equation for determining the reference trend line is

$$\sqrt{\sigma_r} = a \left(\frac{H}{1,000} \right) + b \quad (13)$$

where

a = slope of the straight line; in first approximation it is considered constant and equal to 0.088

b = intercept at the surface ($H = 0$)

H = depth, ft (m)

As a general trend, values of $\sqrt{\sigma_o}$ always increase with depth through shales, indicating the presence of normally pressured and compacted formations. On the contrary, when the curve of the Sigmalog contains points deviating to the left from the reference trend line as depth increases, it indicates the presence of an overpressured zone.

However, the Sigmalog curve abruptly changes value—a common characteristic in all techniques based on the drilling parameters elaboration. Consequently, the reference trend line often is broken into several segments, each segment indicating the presence of a shift. Shifts, represented by the term b in Eq. 13, are due to many causes, the principal ones being:

- Geological causes, such as faults, unconformities, big lithological changes, overthrusts, etc.
- Drilling causes, such as improper bit selection, inadequate drilling parameters, coring, junk in hole, etc.

Pore Pressure

Once the term b is defined for each shift recognizable on the Sigmalog curve, the pore pressure gradient at any particular depth is calculated using the following procedure:

1. Calculate the values assumed by the reference trend line $\sqrt{\sigma_r}$ by solving Eq. 13.
2. Calculate the term F from the equation

$$F = \sqrt{\sigma_r} / \sqrt{\sigma_t'} \quad (14)$$

3. Define ΔP from the formula

$$\Delta P = \frac{2(1-F)}{1-(1-F)^2} \left(\frac{1}{n} \right) \quad (15)$$

4. Calculate the pore pressure gradient G_p :

$$G_p = d_f - \frac{\Delta P (10)}{H} \quad (16)$$

Drilling Porosity

Determination of drilling porosities, from which the G_{ov} subsequently is derived, mainly depends on correctly positioning the reference trend lines $\sqrt{\sigma_r}$, for overpressure evaluation, and $\sqrt{\sigma_\phi}$, for porosity calculation.

To indicate overpressures the Sigmalog curve usually is plotted. An initial $G_p = 0.461 \text{ lb/ft}^3$ (1.03 atm/10 m) is entered into Eq. 10. This assumption is valid if drilling occurs in normal pressure zones; however, the Sigmalog deviates to the left when overpressures are entered. The ΔP , used for calculating pore pressure gradients in overpressures, is clearly higher than what really exists between the mud column and the formation. While this assumption allows evaluation of subsequent pore pressure gradients, it makes calculating porosities in overpressured intervals more difficult. Therefore, to obtain drilling porosities in overpressures, it is necessary to correct the standard Sigmalog curve—represented by the $\sqrt{\sigma_o}$ values—for the effect of differential pressure. The new curve's values are indicated with the $\sqrt{\sigma_o^*}$ symbol and can be traced, once the actual pore pressure gradients and the real ΔP acting on the formations are known.

Obviously, in normal pressure zones, $\sqrt{\sigma_o}$ and $\sqrt{\sigma_o^*}$, as well as $\sqrt{\sigma_r}$ and $\sqrt{\sigma_\phi}$, will coincide, while they differ in overpressure zones.

In normal pressure formations (Fig. 1, Zone A), the two reference trend lines coincide—that is, $\sqrt{\sigma_r} = \sqrt{\sigma_\phi}$. At this point two alternatives are possible:

1. Formations show values of $\sqrt{\sigma_o} \geq \sqrt{\sigma_r} = \sqrt{\sigma_\phi}$. In this case the points lying on the reference trend line, or having higher values, are considered shales and their drilling porosities are calculated by means of the following equation:

$$\alpha_{sh} = 1 / [1.4 + 9 (\sqrt{\sigma_r} + K - b)] \quad (17)$$

where

α_{sh} = shale drilling porosity, percentage fraction

K = intercept value at the surface of the first reference trend line

b = intercept values at the surface of subsequent trend lines

2. Formations showing a lefthand departure of the $\sqrt{\sigma_o}$ values from the reference trend line ($\sqrt{\sigma_o} < \sqrt{\sigma_r} = \sigma_\phi$) are considered sands. Drilling porosity of these points is determined as follows:

$$\alpha_{sa} = 1 / [1.4 + 9 (\sqrt{\sigma_o} + K - b)] \quad (18)$$

where

α_{sa} = sand drilling porosity, percentage fraction

In overpressured intervals (Fig. 1, Zone B), the reference trend line $\sqrt{\sigma_r}$ always is used to compute pore pressure gradients, while porosities are calculated once the $\sqrt{\sigma_o}$ curve and the $\sqrt{\sigma_\phi}$ reference trend line for the overpressure effect are corrected for shifts and differential pressures. The resulting $\sqrt{\sigma_o^*}$ line—which

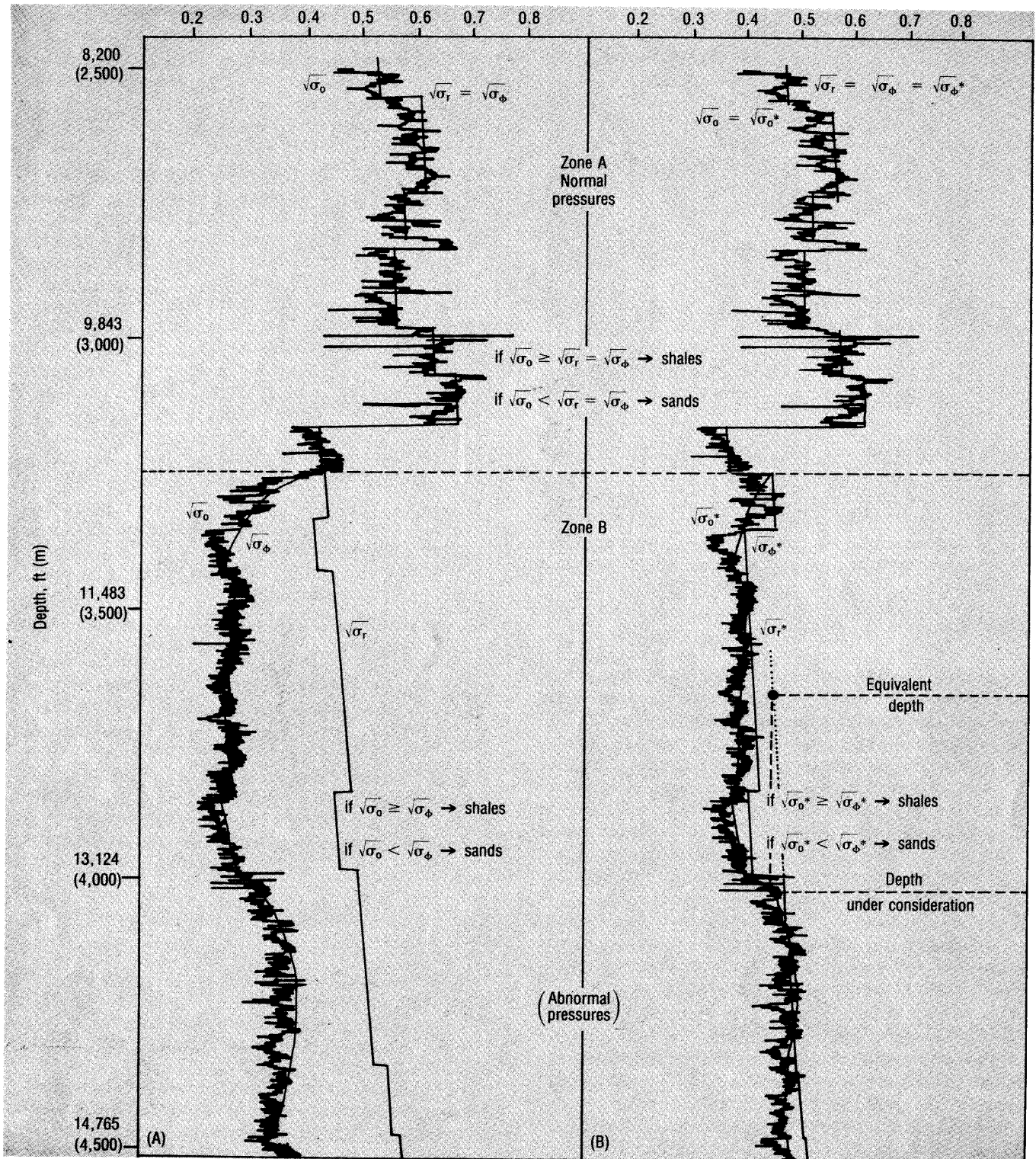


Fig. 1. The standard Signallog curve is used for overpressures detection and evaluation while drilling. The Signallog, corrected for the actual differential pressures, allows the calculation of drilling porosities and overburden gradients. (A) Standard Signallog, used for overpressures detection and evaluation. (B) Signallog, corrected for ΔP , used for drilling porosities calculation.

passes through shale points indicated on the $\sqrt{\sigma_o^*}$ curve — does not coincide with $\sqrt{\sigma_r}$ in this case. Here, two alternatives are possible:

1. Points $\sqrt{\sigma_o^*}$ lying on the porosity reference trend line $\sqrt{\sigma_\phi^*}$ or having higher values still are considered shales, and their drilling porosity is calculated by

applying the equivalent depth principle, as shown in Fig. 1B. Therefore, two points, characterized by the same $\sqrt{\sigma_\phi^*}$ value, also have the same drilling porosity. This porosity is calculated by using Eq. 17, valid in case of normal pressures, at the equivalent depth and then referred to the depth under consider-

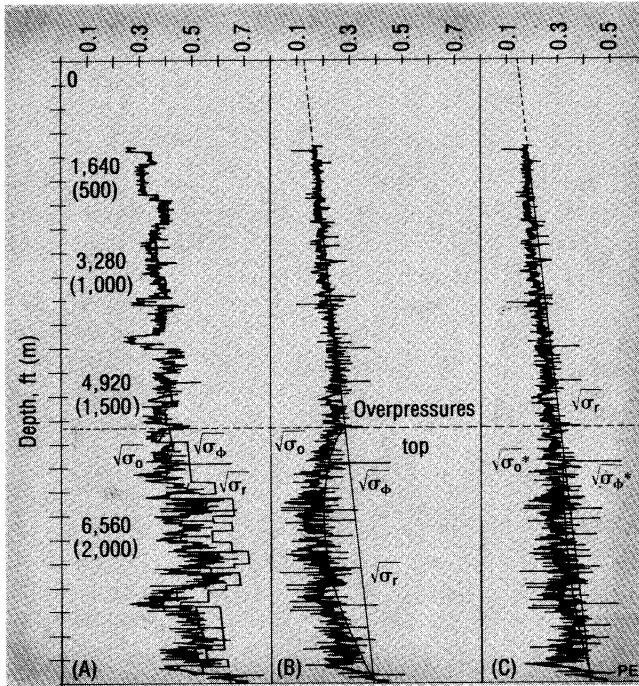


Fig. 2. Drilling porosities can be obtained from normalized Sigmalog curves (C) by directly entering the $\sqrt{\sigma_o^*}$ and $\sqrt{\sigma_\phi^*}$ values into Eqs. 17 and 18. (A) Standard Sigmalog. (B) Normalized Sigmalog (corrected for shifts). (C) Normalized Sigmalog (corrected also for ΔP).

ation. Calculation of the drilling porosities is simplified, once the standard Sigmalog curve is corrected for shifts, thus transforming the Sigmalog obtained at the rig site into a new curve, indicated as the normalized Sigmalog in Fig. 2C. In this case, the shale drilling porosities are calculated directly by entering the $\sqrt{\sigma_\phi^*}$ values into Eq. 17. For calculations in overpressured intervals, the $\sqrt{\sigma_\phi^*}$ curve is computed with a polynomial regression, once the significant points on the normalized Sigmalog curve corresponding to shale points are selected.

2. Points showing $\sqrt{\sigma_o^*}$ values lower than $\sqrt{\sigma_\phi^*}$ are considered sands, and their porosities are calculated with Eq. 18 by following the same procedure indicated in the previous paragraph.

Bulk Density

Once drilling porosities are defined for each point as a function of depth, corresponding bulk densities and overburden gradients are easily obtained.

Equations which relate porosity and bulk density are as follows:

- In sands

$$\alpha_{sa} = 1.228 \frac{\Delta t_{sa} - \Delta t_{max}}{\Delta t_{sa} + \Delta t_n} \quad (19)$$

where

- α_{sa} = drilling porosity in sand as obtained from Sigmalog, percentage fraction
- Δt_{sa} = transit time in sands, $\mu\text{sec/ft}$
- Δt_{max} = matrix transit time, $\mu\text{sec/ft}$ (for the sand assumed equal to 50 $\mu\text{sec/ft}$)

Δt_n = fluid transit time, $\mu\text{sec/ft}$ (assumed equal to 200 $\mu\text{sec/ft}$)

If Eq. 19 is defined in terms of Δt_{sa}

$$\Delta t_{sa} = \frac{\alpha_{sa} (200) + 61.4}{1.228 - \alpha_{sa}} \quad (20)$$

The transit times Δt_{sa} then are transformed into the corresponding bulk densities by means of the following equation:

$$d_{b,sa} = 2.75 - 2.11 \frac{\Delta t_{sa} - 50}{\Delta t_{sa} + 200} \quad (21)$$

- In shales

$$\alpha_{sh} = 1.568 \frac{\Delta t_{sh} - \Delta t_{max}}{\Delta t_{sh} + \Delta t_n} \quad (22)$$

$$\Delta t_{sh} = \frac{\alpha_{sh} (200) + 73.70}{1.568 - \alpha_{sh}} \quad (23)$$

$$d_{b,sh} = 2.75 - 2.11 \frac{\Delta t_{sh} - 47}{\Delta t_{sh} + 200} \quad (24)$$

where

α_{sh} = drilling porosity in shale as obtained from Sigmalog, percentage fraction

Δt_{sh} = transit time in shales, $\mu\text{sec/ft}$

Δt_{max} = matrix transit time, $\mu\text{sec/ft}$ (for the shale assumed equal to 47 $\mu\text{sec/ft}$)

Δt_n = fluid transit time, $\mu\text{sec/ft}$ (assumed equal to 200 $\mu\text{sec/ft}$)

Once bulk densities of the formation are determined and the depth interval defined, the densities are integrated versus depth and transformed into overburden pressures and gradients with Eqs. 1 and 2:

$$P_{ov} = \frac{1}{10} \sum (\Delta H_i \times d_{b,i}) \quad (1)$$

$$G_{ov} = 10 \frac{P_{ov}}{H_i} \quad (2)$$

The G_{ov} values obtained according to this procedure are plotted versus depth.

For offshore wells, to obtain correct values of overburden gradients, it is necessary to consider the effect of water depth and the air gap between the rotary table and sea level. Assuming seawater density to be $d_{H_2O} = 62.43 \text{ lb/ft}^3$ (1.03 g/cc), the pressure corresponding to the seabed is

$$P_{seabed} = \frac{1.03 \times H_m}{10} \quad (25)$$

and the overburden gradient at the seabed is

$$G_{ov} = \frac{P_{seabed} \times 10}{H_m + H_{ag}} \quad (26)$$

where

H_m = sea depth, ft (m)

H_{ag} = air gap, rotary table-sea level distance, ft (m)

The main problem with this method is selection of the first reference trend line — that is, the term K in Eqs. 17 and 18. Generally, recording and processing of drilling parameters starts at a certain depth, usually after setting the surface casing string. Consequently, because no data are available in the interval between surface and this casing shoe, there is an uncertainty in positioning the first reference trend line. Extrapolation to the surface of the first $\sqrt{\sigma_r}$ available is not recommended, because, in this interval, some shifts could be present, which could affect subsequent $\sqrt{\sigma_r}$ values.

This limitation is easily overcome by deducing the first reference trend line with one of the following methods:

- Analysis of seismic data. Interval velocities or the corresponding interval transit times are transformed into bulk densities with Eqs. 3 and 3a.
- Sonic Logs of reference wells in the area. Also, the transit times are transformed into bulk densities with Eqs. 3 and 3a.
- Test measurements of soil densities.
- For complete lack of data, an initial density, ranging around 125 lb/ft³ (2 g/cc), can be assumed in most cases.

Fracture Gradient

Starting with the pore pressure and overburden gradients calculated from recorded drilling parameters, the corresponding fracture gradients can be easily obtained.

AGIP uses the following formula for fracture pressures in formations with elastic behavior (sands, sandstones, etc.) and when the differential pressure between the mud and the formation is totally withstood by the well bore walls, because of the mud cake action or the low permeability of the formation exposed:

$$P_{fr} = P_p + \frac{2\nu}{1-\nu} (P_{ov} - P_p) \quad (27)$$

In elastic rocks, when the drilling fluid deeply invades the formation crossed, the fracture pressure is better expressed by the equation

$$P_{fr} = P_p + 2\nu (P_{ov} - P_p) \quad (28)$$

In formations showing a plastic behavior (shale, marls, salt, etc.), fracture pressures coincide with overburden pressures:

$$P_{fr} = P_{ov} \quad (29)$$

where

P_{fr} = fracture pressure, atm

P_{ov} = overburden pressure, atm

P_p = pore pressure, atm

ν = Poisson's modulus

Values for the Poisson's modulus can be either:

$\nu = 0.25$ for clean sands, sandstones, and unfractured carbonates at shallow depth

$\nu = 0.28$ for shaly sands, carbonates, and sandstones at great depth

Fracture gradients, G_{fr} , can be calculated by dividing the fracture pressures by the depth, H :

$$G_{fr} = 10 \frac{P_{fr}}{H} \quad (30)$$

Practical calculations of fracture gradients at the wellsite are done according to the following procedure:

- In normal pressure zones, when $\sqrt{\sigma_r} = \sqrt{\sigma_\phi}$, a normal pore pressure gradient [$G_p = 0.461$ lb/ft (1.03 atm/10 m)] is assumed and the G_{ov} values are obtained from processing the Sigmalog curve. These gradients values are entered into Eqs. 27, 28, and 29, making G_{fr} calculations a function of lithology.
- In overpressured zones ($\sqrt{\sigma_r} \neq \sqrt{\sigma_\phi}$), the G_{ov} values are always calculated from the Sigmalog and put into the computer's memory. Because the pore pressure gradients are calculated independently — every 3 ft — a certain discrepancy in the values is observed on the G_p curve. To avoid a similar distribution of the fracture gradient values, select the significant points on the pore pressure gradient curve passing through shale points and, by using a polynomial regression, define and record the curve representing the true G_p development. By knowing the corresponding G_p and G_{ov} of each foot drilled, it is possible to determine and automatically plot the G_{fr} curve in overpressured zones.

For simplification, fracture gradients can be calculated alongside the whole well profile by using Eq. 27, theoretically valid only in elastic formations. Obviously, if very thick plastic levels or very coarse sands are encountered, fracture gradients are better calculated with Eqs. 29 and 28, respectively.

Computer Processing

At the rig site a computer (generally a HP-9825A for off-line systems) is used to process the drilling data recorded and monitor data on an XY plotter and printer.

To obtain an automatic overburden gradient computation while drilling, in addition to the calculated pore pressure and drilling porosity, the conventional Sigmalog program must be modified.

A computer code is capable of processing and plotting the normalized Sigmalog according to the various, successive shifts of the reference trend line $\sqrt{\sigma_r}$ kept in the computer's memory.

Porosities are directly computed from the normalized Sigmalog by using Eqs. 17 and 18, and the corresponding, equivalent transit times are calculated to give the formation bulk densities. By integrating these densities, the overburden gradient is calculated continuously from the Sigmalog and ready to use for subsequent fracture gradient calculations together with the pore pressure gradients, either obtained from Sigmalog or any other method.

The results are plotted as a function of depth on a 1/10,000 scale, reporting any or all of the following:

- Standard Sigmalog.
- Normalized Sigmalog.

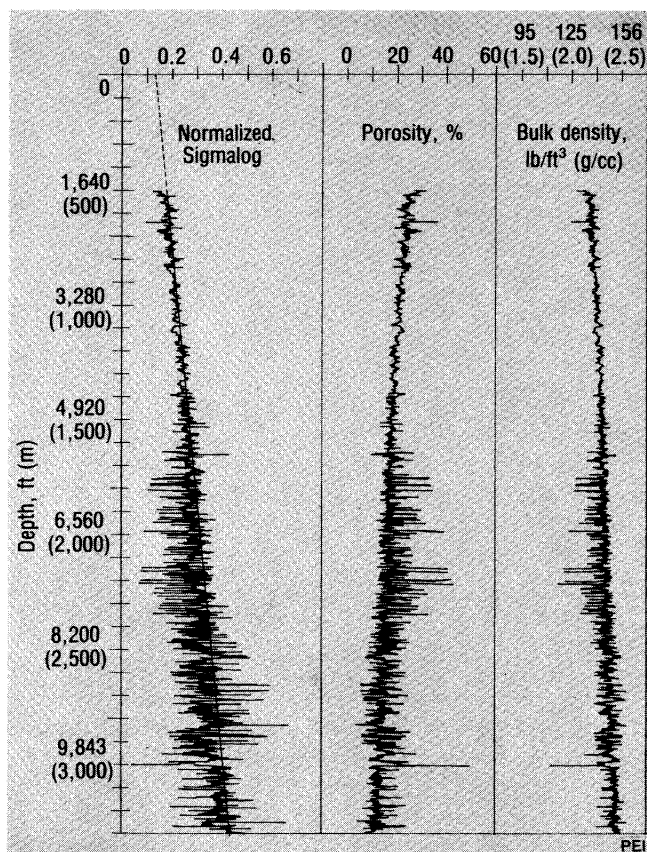


Fig. 3. The normalized Sigmalog allows the calculation of drilling porosities and bulk densities (Adriatic offshore well).

- Standard and normalized reference trend lines.
- Drilling porosity.
- Bulk density.
- Overburden gradient.
- Pore pressure gradient.
- Fracture gradient.

These programs are designed for use with computers usually installed in logging units at the rig site. Programs are still being developed by AGIP's Drilling Technology Department for operations carried out in lithologies other than shales and sands — in particular, limestones and dolomites.

Field Examples

To verify practical applications of the method discussed here, examples of gradient calculations in some Adriatic offshore wells, characterized by predominantly clastic series, are presented.

The drilling parameters of the well, shown in Fig. 3, were analyzed to a depth of 10,827 ft (3,300 m); normal pressure sands and shales from Pleistocene to Lower Pliocene were crossed. Water depth was 69 ft (21 m). Correction of the standard Sigmalog curve led to the normalized Sigmalog curve (Fig. 3A), which clearly points out the normal development of the pore pressure gradient. For the first reference trend line, $K = 0.13$ is assumed, corresponding to an initial bulk density, $d_b = 128 \text{ lb/ft}^3$ (2.05 g/cc).

Once the position of the reference trend line $\sqrt{\sigma_r}$ is determined, the drilling porosities in shales and sands (Fig. 3B) are calculated by using a program prepared

for a HP-9825A desk computer with the equations previously discussed. Drilling porosities regularly decrease with depth — at least as a general trend — starting from an initial value of $\alpha = 40\%$ to $\alpha = 20\%$ at 10,827 ft (3,300 m); this behavior denotes normal compaction conditions. Drilling porosities then are transformed into bulk densities (Fig. 3C), which, on the contrary, show a continuous, general increase of the values versus depth; this increase also indicates normal compaction and pore pressure gradients.

Drilling porosities and bulk densities sometimes show unusual corresponding values at particular points. Because the Sigmalog is processed and plotted every 3 ft drilled, the shifts cannot be increased excessively if the method is to remain practical and usable at the rig site. An automatic selection of the shifts could help in interpreting the curve and minimize erroneous values. However, these abnormal values are limited to only short intervals and do not absolutely affect the resultant overburden gradient curve.

Fig. 4 shows a well with a pore pressure gradient increase at about 4,920 ft (1,500 m). The formations crossed are shales and sands from Pleistocene to Pliocene. Water depth and air gap total 330 ft (70 m). Starting with the Sigmalog curve at only 1,150 ft (350 m), an initial K value of 0.14 is assumed. The normalized Sigmalog, corrected for the shifts (Fig. 4A) and also for the differential pressure (Fig. 4B), allows the calculation of reliable drilling porosities and bulk densities in the overpressured interval. The Sigmalog's reliability and accuracy, compared to average porosities obtained from a Sonic Log on 164 ft (50 m) intervals, shows good correlation between the values.

Fig. 5 summarizes the proper processing of the drilling parameters at the rig site into the three basic pressures. The overburden gradient curve, obtained from the normalized Sigmalog, is compared with the overburden gradients derived from the Sonic Log analysis; the comparison between the two curves is significant — the maximum difference in the range is 1.25 lb/ft^3 (0.02 g/cc). The fracture gradient curve, considering the effect of water depth and air gap, is calculated with Eq. 27.

The same three curves illustrated in Fig. 6 show the abnormal pressure well of Fig. 4. Also, this example demonstrates the close correlation between overburden gradients derived from drilling parameters processing and Sonic Log elaboration; a maximum difference of about 2.5 lb/ft^3 (0.04 g/cc) is observed at bottomhole. The fracture gradient curve is obtained by applying Eq. 27.

Future Prospects

The method proposed in this article allows the calculation of overburden and fracture gradients by using on site programs for off-line and on-line computer systems. The method is based on a more detailed and accurate interpretation of Sigmalog curves, previously used essentially for overpressures detection and evaluation while drilling.

Important points of the method to consider are:

- Calculation of pore pressure gradients with the standard Sigmalog.

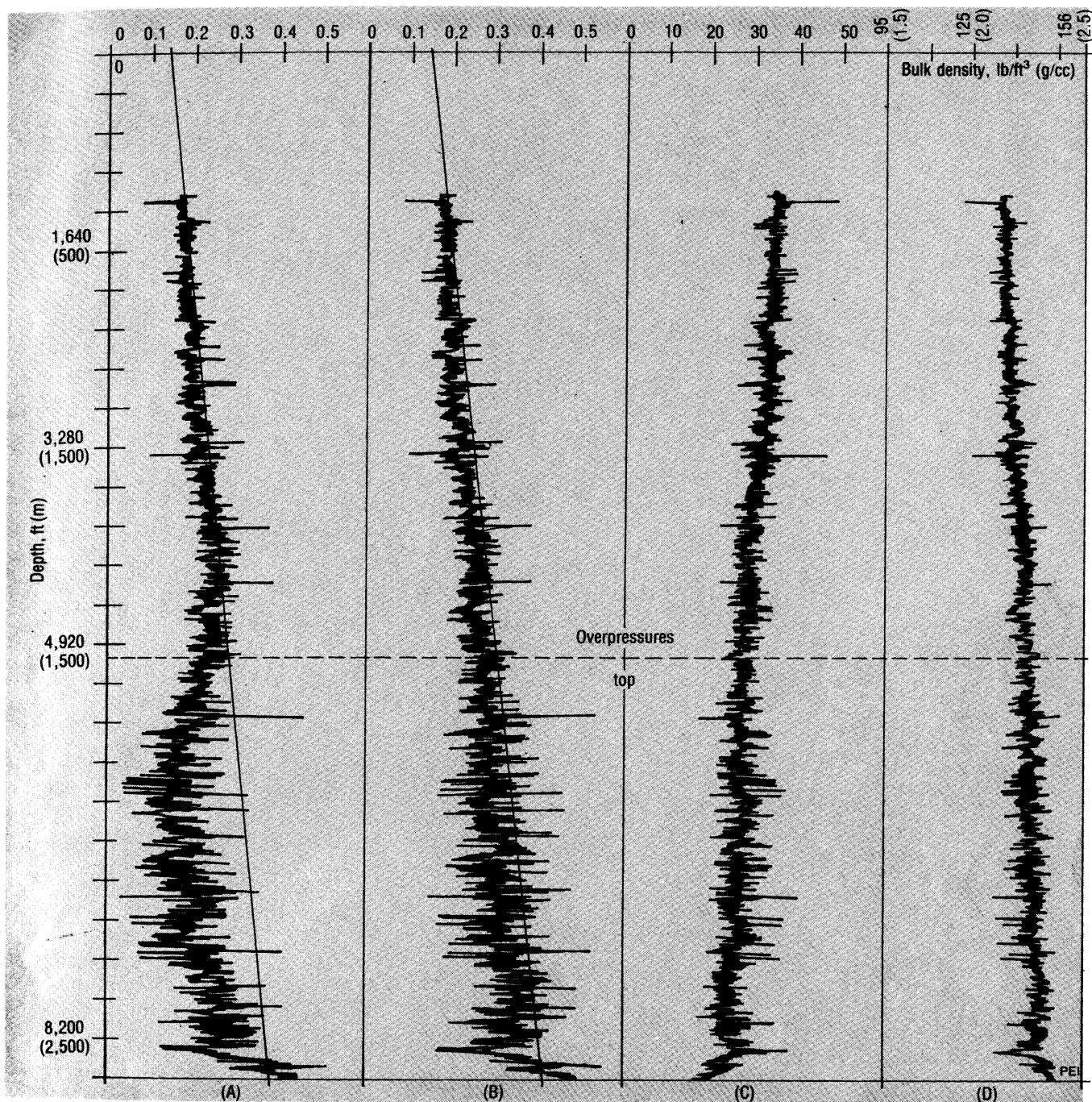


Fig. 4. The normalized Sigmalog, corrected for shifts and ΔP (B) allows the calculation of drilling porosities and bulk densities in overpressured intervals. Drilling porosities are compared with porosities (+) obtained from Sonic Log analysis (Adriatic offshore well). (A) Normalized Sigmalog (corrected for shifts). (B) Normalized Sigmalog (corrected also for ΔP). (C) Drilling porosities compared with Sonic Log porosities (+), %. (D) Bulk density, lb/ft^3 (g/cc).

- Correction of the standard Sigmalog curve for the shifts in normal pressure zones and, also, for the actual differential pressure in overpressured intervals.
- Selection of the first reference trend line, K.
- Calculation of drilling porosities in shales and sands according to Eqs. 17 and 18.
- Calculation of the corresponding bulk densities with Eqs. 21 through 24.
- Integration of the bulk densities versus depth to obtain the overburden gradient curve with Eqs. 1 and 2.

- Calculation of fracture gradients from overburden and pore pressure gradients with Eqs. 27, 28, and 29. Determining pore pressure, overburden, and fracture gradients while drilling provides drilling personnel with valuable information from which rapid and efficient decisions can be made on the rig site.

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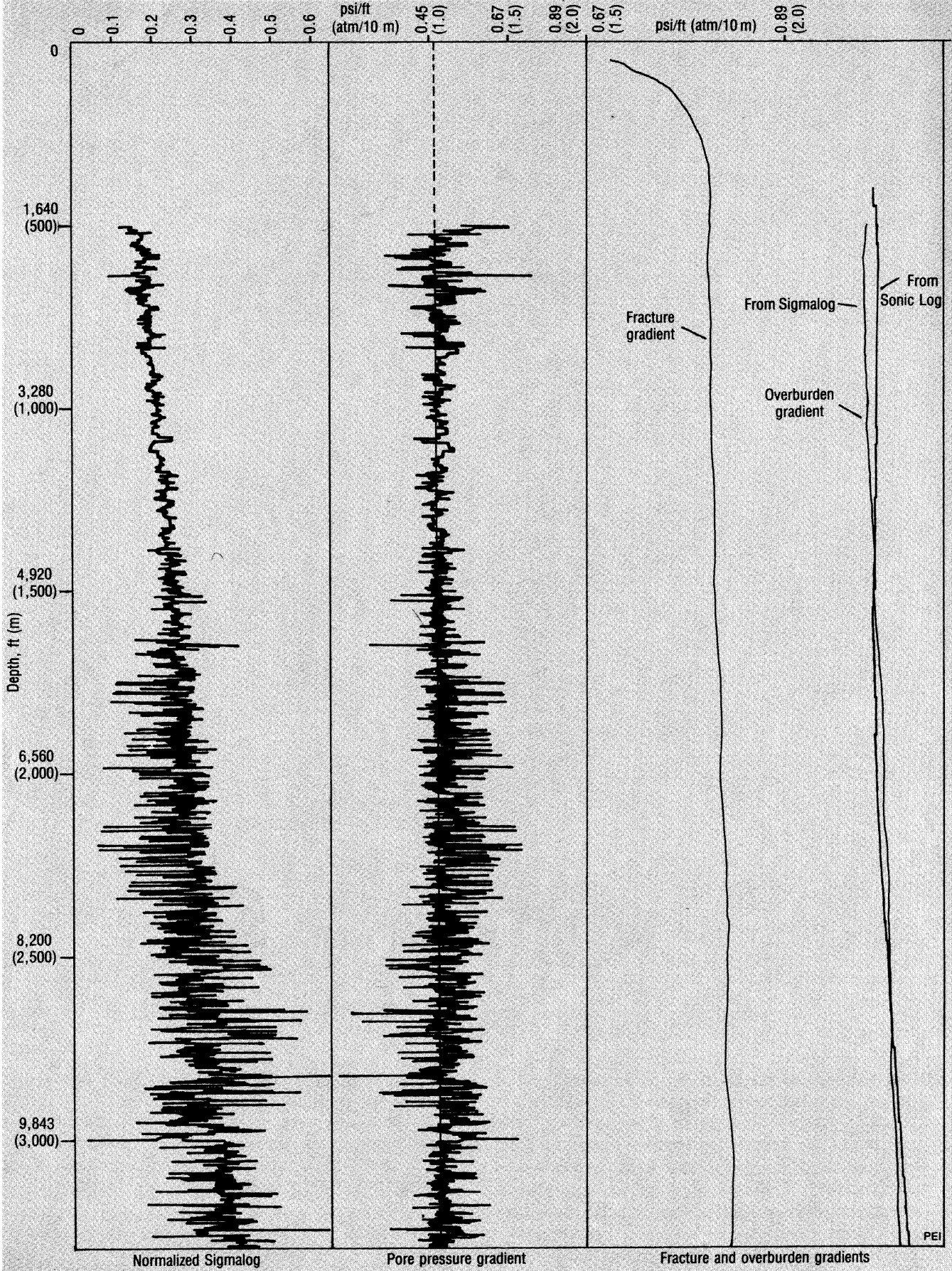


Fig. 5. The analysis and processing of drilling parameters from Sigmalog allow the calculation of pore pressure, fracture, and overburden gradients at rig site.

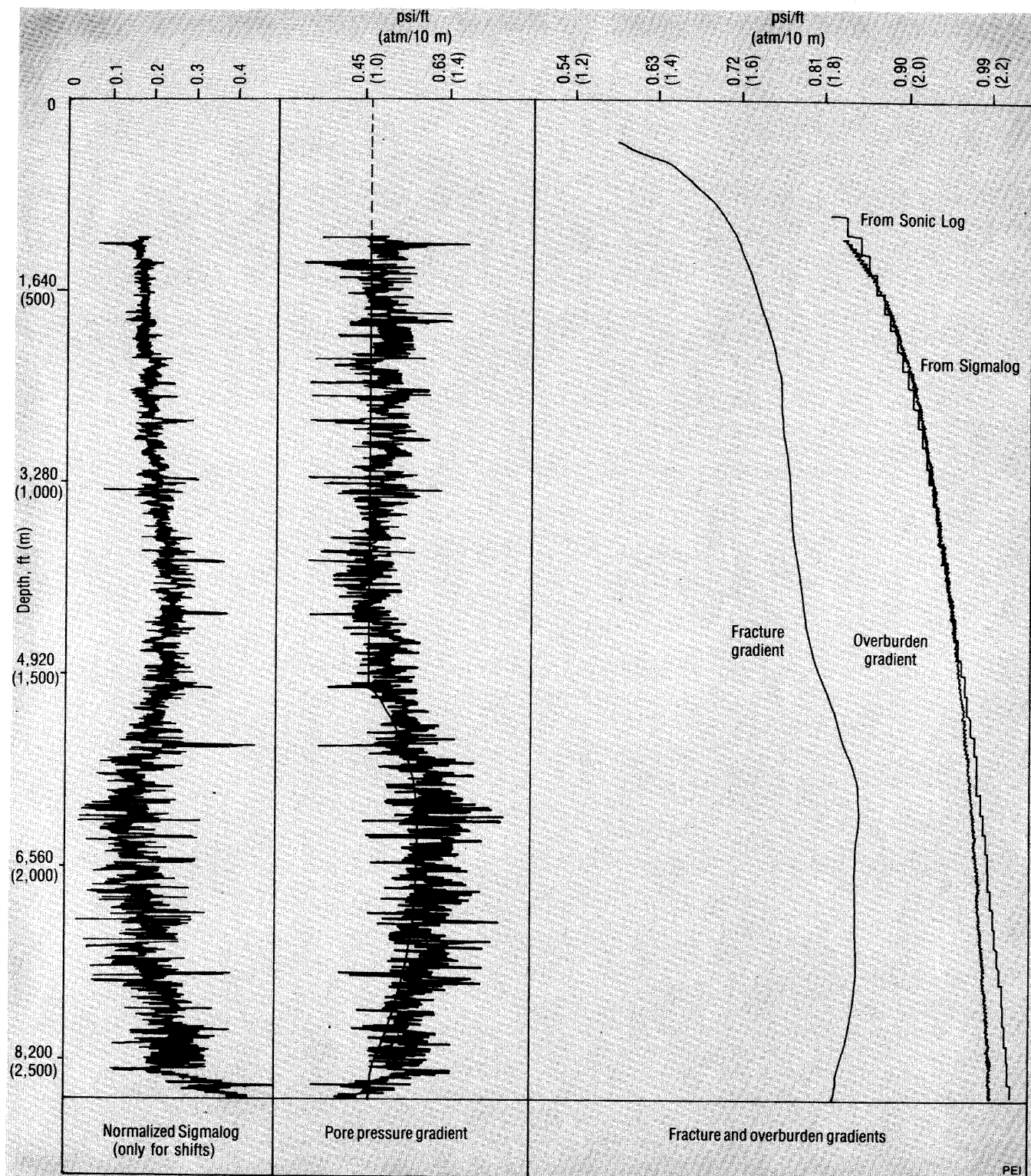


Fig. 6. The correction of Signalog for shifts and differential pressure (normalized Signalog) leads to reliable overburden and fracture gradients calculation also in overpressured intervals (Adriatic offshore well).

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