SPE 25674

A Global Algorithm for Pore Pressure Prediction

David Scott and L.A. Thomsen, Amoco Production Co.

Copyright 1993, Society of Petroleum Engineers, Inc.

This paper was prepared for presentation at the SPE Middle East Oil Technical Conference & Exhibition held in Bahrain, 3–6 April 1993.

This paper was selected for presentation by an SPE Program Committee following review of information contained in an abstract submitted by the author(s). Contents of the paper, as presented, have not been reviewed by the Society of Petroleum Engineers and are subject to correction by the author(s). The material, as presented, does not necessarily reflect any position of the Society of Petroleum Engineers, its officers, or members. Papers presented at SPE meetings are subject to publication review by Editorial Committees of the Society of Petroleum Engineers. Permission to copy is restricted to an abstract of not more than 300 words. Illustrations may not be copied. The abstract should contain conspicuous acknowledgment of where and by whom the paper is presented. Write Librarian, SPE, P.O. Box 833836, Richardson, TX 75083-3836, U.S.A., Telex, 163245 SPEUT.

Abstract

The problem of prediction of in-situ pore pressure (ahead of the bit), on the basis of seismic data, has had a long history of study. It was recognized early that low seismic velocity in a given interval can be caused by high pore pressure in that interval. However, low velocity can also be caused by high porosity, soft lithology, or hydrocarbons, the occurrence of which may be correlated in-situ with high pore pressure. Hence the deduction of pore pressure from seismic information is formally non-unique.

Commonly used prediction techniques empirically fit some equation to a shallow "normally pressured" interval, then extrapolate to greater depths, comparing the observed interval velocity to this reference, independently at each depth point. Such a "point algorithm" reflects a physicist's view of the earth's layers as being independent, like samples in a laboratory.

Instead, we adapt a geophysical view, regarding the various layers as being coupled through geological processes, in ways which we partially understand. Hence our prediction for the pore pressure in a given layer depends upon data from shallower layers as well. As a "global algorithm", it is embodied in a decision tree, rather than an equation. Since it is different in kind from other algorithms, it can offer independent corroboration of, or alternatives to their predictions. Using uphole VSP data acquired during drilling, it can refine its surface-seismic-based predictions below the bit. It can incorporate a priori information of any sort to condition its predictions.

Its predictions lead naturally to the delineation of "subsurface fluid compartments", ie zones several thousand feet thick, each with a local hydrostatic gradient and an elevated hydraulic head, separated by thin seals, with horizontal extents of several km to hundreds of km.

Worldwide applications show that its predictions can be useful for prospect evaluation as well as for drilling safety and efficiency.

References and illustrations at end of paper.

Introduction

The issue of subsurface pore-pressure prediction has a long history, and a long future. Despite a record of some success in prediction (in restricted contexts) via the "classical algorithms", we regard the problem to be unsolved to date. The present work offers a new approach; one that differs in kind from all extant algorithms (Scott and Thomsen, 1992).

The difficulties in predicting in situ pore pressure from remote measurements are three-fold. First, one can never remotely measure pore pressure itself, but must always measure something else, e.g., seismic velocity. The quantity measured is sensitive to pore pressure, which is then inferred indirectly from the measurement. However, the quantity measured is always similarly sensitive to other factors as well, such as porosity or mineralogy.

Hence, the pore pressure may not be inferred from the measurement without an assumption (or conclusion), explicit or implicit, concerning these other factors. The successes of the classical algorithms (cf, e.g., Mouchet and Mitchell, 1989) result usually from the fulfillment of their implicit assumptions concerning these other factors. However, these assumptions are rarely considered with care, and the circumstances which may lead to their fulfillment are not known. Hence, the extension of these methods to new areas is usually problematical, requiring new "calibration", and a new set of assumptions, similarly unstated an unanalysed.

The second set of difficulties in pore pressure prediction arises because the measured quantity, e.g., velocity, is inaccurate and poorly resolved. The inaccuracy involves both random errors, and systematic ones. The systematic errors may arise if the raw data (e.g., arrival times of reflected waves) are interpreted via a theory which makes incorrect assumptions (e.g., that the subsurface rocks are isotropic, or that the moveout is hyperbolic). At best, surface reflection data yield only average velocities over the coarse intervals between major reflectors; this poor velocity resolution affects both the accuracy and the positioning of the consequent pressure predictions.

A third class of difficulties, less fundamental than the previous ones, arises if a prediction method is calibrated using borehole data which do not represent all the rocks present. For example, some methods are calibrated using sonic velocities from shale intervals only, perhaps selected by a gamma ray log criterion. It is then clearly inappropriate to apply this directly to prediction using seismic data, which of course samples all the lithologies present, not just the shales.

A related issue may arise in the calibration process, if data from shale intervals only are utilized for pressure prediction and compared with pressure data (e.g., RFT data) taken from non-shale intervals. If the comparison reveals differences, there may be a temptation to claim that the pore pressure actually differs between sands and the encasing shales, and that this difference persists over geologic time. If commonly true, this assertion would then invalidate calculations which do assume pressures equilibrated between sands and encasing shales. In any case, it is easy to demonstrate that such a difference requires permeability in the nano-darcy range; a condition which probably requires special circumstances, which are not well understood (Dickey, 1993).

Because of these difficulties, it is clear that the problem of pore pressure prediction has no unique solution. (The problem of estimating pore pressure, in the formations surrounding an existing borehole, is better-posed, especially if multiple datasets (e.g., resistivity as well as velocity) are utilized.) Of course, it might remain possible to make predictions which are useful in some sense, especially if appropriate uncertainties are assigned. To this end, it is helpful to have available various prediction algorithms which differ from one another in kind, rather than in degree. Where independent algorithms agree in their predictions, one has added confidence; where they disagree, one concentrates further analysis. The present algorithm does have substantial independence from all algorithms previously in the literature and hence may be useful in this regard.

Most previous algorithms utilize the data of a given point (or a given layer) to estimate, or predict, the pore pressure in that layer, independently for each layer. This may be characterized as the physicist's viewpoint, regarding each layer independently, like different samples in a laboratory.

By contrast, the present algorithm recognizes that the various layers are not independent, but are coupled together via geologic process and history, portions of which we understand. This may be characterized as the geophysicist's viewpoint. We use elementary physical considerations, as well as a priori knowledge if available, to constrain the various contributions of pore-pressure, porosity, and lithology which may yield the observed velocity. In so doing, we consider local gradients of these factors, as well as their local values at any layer, in making the prediction. In this sense, the present algorithm may be termed a "global algorithm," as opposed to the previous "point algorithms."

Most previous algorithms are linear, or weakly nonlinear, in the sense that small perturbations in velocity lead to small perturbations in predicted pressure. This results in predicted pressure profiles which have a vertical structure similar to that of the input. By contrast, the present algorithm is strongly nonlinear, and the resulting predicted pressure profile may have a structure quite different from the velocity profile.

The Algorithm

Two inputs are required for the algorithm. The first is a calibration representing the conditions in the basin when the pore pressure is normal. The second input is a profile of seismic velocity over the depth range of interest, in the locality where the pore pressure prediction is required. The resolution of this profile can be quite coarse, perhaps 500-1000 feet, but it should extend from shallow depths down to the total depth of interest. A good-quality seismic reflection survey should provide adequate data.

To obtain a prediction of the pore pressure profile from the observed velocity profile, certain assumptions must be made. They are listed briefly here; their significance is detailed in the following sections.

(i) The dominant lithology in the sedimentary column has a lower seismic velocity than other lithologies at the same conditions of porosity and effective pressure.

(ii) The present spatial structure of effective pressure is indicative of the temporal evolution of effective pressure during the burial of an element of material to its present depth.

(iii) Sediment compaction is irreversible.

(iv) The gradient of pore pressure with depth is never less than hydrostatic.

These assumptions may be altered, on the basis of a priori information; in the absence of this, these are the default assumptions.

We begin by establishing a reference state for the sedimentary column, representing the expected result of continuous deposition of a uniform reference lithology under conditions of hydrostatic pore pressure. This reference state comprises profiles of density, porosity, total pressure, pore pressure, effective pressure and seismic velocity. The reference state could be established in one of several ways; our preference is to specify the reference state via a calibration process (at a wellsite with known velocity, porosity, and pressure profiles), similarly to the calibration of the classical estimation algorithms. However, here the concept is utilized somewhat differently.

Typically, shale is the most abundant lithology, and shale porosities are used to establish the reference profile. In conjunction with a specified grain density, and a density for the saturating brine, the reference porosity function $\phi_r(z)$ is equivalent to a reference density function $\rho_r(z)$. Through integration of the density from the surface, this is equivalent to a reference confining pressure $P_r^c(z)$. Since the reference fluid pressure condition is hydrostatic, $P_r^f(z) = P_h(z)$, one may define a reference effective pressure

$$P_r^{eff}(z) = P_r^c(z) - P_r^f(z) \tag{1}$$

which is monotonically increasing with depth. Hence, all of the foregoing functions may be parameterized by effective pressure, rather than by depth.

By this procedure, we establish the "compaction function" $\phi_r(P_r^{eff})$, a functional relationship between the reference porosity and effective pressure profiles. Referring to the previous discussion, this compaction function applies to material that has undergone a monotonic increase in effective pressure, as would occur in a normally-pressured sedimentary column. Such a functional relationship indicates a unique connection between porosity and effective pressure, which is misleading, since clastic sediments undergo irreversible compaction as the effective pressure increases. As long as the effective pressure increases monotonically with depth and time, the compaction function $\phi_r(P_r^{eff})$ may be sufficient of itself. If, however, the effective pressure were to decrease at some point in the sedimentary history (perhaps due to an increase in pore fluid pressure) the porosity would not recover in a corresponding way, and the unique connection between porosity and effective pressure would be lost.

The reference lithology is also characterized by a velocity function V_r, which relates its local seismic velocity to the porosity, effective pressure, and mineralogy. Laboratory measurements of seismic velocity in clastic sedimentary rocks suggest that most of the variation in velocity may be attributed to these factors. As an example, Eberhart-Phillips et al. (1989) propose the following functional form based on measurements on a range of sands and shales:

$$V(\phi,\ P^{eff}) = V_0 - A_\phi \phi + A_p P^{eff} - B_p e^{(-P^{eff}/C_p)} \tag{2}$$

The parameters A_ϕ, A_p, B_p, C_p were determined by Eberhart-Phillips et al. to be constants, i.e., to be insensitive to ϕ, P^{eff}, and mineralogy. The grain velocity V_0 was found to be sensitive to mineralogy; specifically (in their dataset) to clay content, through the relationship

$$c = ((V_0^0 - V_0)/V_0^0 A_c)^2, \tag{3}$$

where c is clay content (volume fraction of the solid grains), V_0^0 is the grain velocity of the faster mineralogy (close to that of quartz, in their dataset), and A_c is another laboratory-determined constant. This particular quantification of the effect of mineralogy on velocity may or may not be accurate (cf Marion and Nur, 1991); this issue is not crucial to the determination of the fluid pressure.

The particulars of the functional form, and the constants in Eqs. (2,3) are not important, although it has been used successfully without modification. More important is the sense of the dependences of velocity on porosity, effective pressure, and clay content. Note in Eqs. (2, 3) that the velocity decreases with porosity and with clay content, and increases with effective pressure (hence decreases with fluid pressure). These equations highlight the fundamental problem of non-uniqueness in pore pressure prediction; even if the lithology were known to be uniform, a region of low seismic velocity could be attributed to either high porosity, low effective pressure, soft mineralogy, oe some combination of these.

During the calibration process mentioned earlier, the reference porosity $\phi_r(P^{eff}(z))$ is adjusted, via use of the algorithm described below, so that the observed $\phi(z)$ (or equivalently, the observed $\rho(z)$), is consistent with the observed $P^{eff}(z)$ (and the observed $P^f(z)$). This fitting does not depend on whether the fluid pressure at the calibration well-site is hydrostatic, nor whether its mineralogy is that of the reference lithology. The resulting functional relationship $\phi_r(P_r^{eff})$ may be expressed analytically, or in tabular form. Also, the grain velocity V_0 in Eq. (2) is adjusted so that the velocity $V(\phi(z),\ P^{eff}(z))$, calculated using Eq. (2) (and the other features of the algorithm, described below), fits the observed $V_{obs}(z)$ (whether or not the pressure at the calibration well-site is hydrostatic, and whether or not its mineralogy is that of the reference lithology). With these adjustments made, the application of Eq. (2), using ϕ_r and P_r^{eff}, yields the "reference velocity" V_r. Under favorable circumstances, this calibration process is stable over wide areas, so that frequent local re-calibration is not necessary.

We present first a way to use the foregoing calibration of the compaction function in a simple point algorithm. Combining the velocity and compaction functions produces (for a uniform lithology) a unique relationship between velocity and effective pressure. This relationship can be inverted to give effective pressure as a function of velocity, and hence a prediction of pore pressure. This procedure assumes that the in-situ porosity $\phi(z)$ is coupled to the in-situ effective pressure P^{eff} by the same compaction function $\phi(P^{eff})$ established earlier for the reference curves $\phi_r(P_r^{eff})$ in the context of hydrostatic fluid pressure. This assumption, while plausible, cannot be defended on the basis of physical law. This simple prediction works well, however, for sedimentary columns with little variation in lithology and steadily increasing effective pressure (so that the compaction function is unique). This is in fact a point algorithm, and as such, is similar in principle to previous algorithms for pressure prediction. The above discussion is offered as a clarification of the assumptions underlying such algorithms.

When applied to a more complex observed velocity structure, the point algorithm above produces predictions that are implausible. The additional, global, features of our algorithm are then introduced. Specifically, we change the algorithm in response to "anomalous" increases or decreases in velocity with depth.

The algorithm proceeds downward from the surface, layer by layer. In each layer, the fluid pressure is calculated deterministically, following the flow of logic described below. The logic applies physical reasoning which may usually be relied upon, when applied to averages over coarse intervals, even though it is demonstrably incorrect on a foot-by-foot basis. This necessarily poor resolution is characteristic, in any case, of the surface seismic velocities which form the input dataset. The logical flow may be altered at any layer by a priori knowledge of any sort, if it is available.

Such asserted "knowledge" can have a powerful effect on the predictions, whether it is correct or not; therefore it should be used with care.

At the bottom of the first layer, the reference velocity V_r is calculated, and compared with the observed velocity, V_{obs}. If $V_{obs} > V_r$, the fluid pressure is assumed to be hydrostatic; the fast V_{obs} is attributed to fast mineralogy, and V_0 is adjusted accordingly.

If $V_{obs} < V_r$, then both the pressure and the porosity are assumed to be abnormally high, following the compaction function $\phi(P^{eff})$ established earlier. (It is common that zones of over-pressure are also zones of over-porosity (cf e.g., Hottman and Johnson, 1965); this may be qualitatively understood in terms of the reduction in rates of lithification (loss of porosity), via most of the known mechanisms of lithification, resulting from the high fluid pressure.) With this assumption, the velocity function (2) becomes a function of only one variable, P^{eff}, so that putting $V_{obs}(z)$ on its left-hand side, one can invert for P^{eff}. Assuming a linear variation of $P^{eff}(z)$ throughout the layer, one can compute $\phi(P^{eff}(z))$, and hence $\rho(z)$. This can be integrated to yield confining pressure $P^c(z)$, from which fluid pressure $P^f(z)$ can be found, using Eq. (1).

For subsequent layers, the first step taken is to obtain a tentative prediction using the point algorithm above; apparent "anomalies" are then considered. An anomalous decrease in velocity is defined as a decrease for which the point algorithm predicts a decrease in effective pressure with depth, and an associated increase in porosity. If the lithology is uniform, any decrease in velocity will have this effect (non-uniform lithology is discussed below). In such a case, the point algorithm does not stretch the reference profiles but actually reverses them in depth; we regard this as implausible (albeit not impossible, if a priori information indicates otherwise).

Following assumption (ii) introduced above, we suppose that the material at a given depth has, during burial, passed through the profile of effective pressure which is now found in the material above its present depth. This translation of a spatial pattern into a temporal sequence assumes uniformity in the process of basin development, and is by no means universally justifiable.

Now the significance of a decrease in effective pressure with depth emerges; it means that the sedimentary material has experienced a decrease in effective pressure with time. The irreversibility of sediment compaction means that we should not attribute any of the velocity decrease to an increase in porosity. Instead, the observed velocity is matched by holding the porosity at its value from the preceding depth and further decreasing the effective pressure. This is a deliberately conservative procedure, as it increases the predicted pore pressure relative to the point algorithm.

Alternatively, the velocity decrease could be attributed to the lithology, i.e., the appearance of an unusually clay-rich layer in the sedimentary sequence. This type of attribution is made under certain circumstances, and is discussed at the end of the next section. In general, the algorithm assumes that the most abundant (i.e. reference) lithology in the sedimentary column has the slowest seismic velocity.

An anomalous increase in velocity is defined as an increase for which the point algorithm predicts a local fluid pressure gradient which is less than hydrostatic. The point algorithm responds to a rapid increase in the velocity over a depth interval by rapidly increasing the effective pressure and decreasing the porosity. For each depth interval, the algorithm calculates the pore pressure gradient from the pore pressures at the top and bottom of the interval. A sufficiently rapid increase in effective pressure will produce a pore pressure gradient that is lower than the hydrostatic gradient. This is considered implausible (particularly in an active basin that has experienced continuous subsidence) unless a priori knowledge indicates otherwise.

The algorithm responds to such "anomalous" increases in velocity by requiring the pore pressure gradient to be hydrostatic over the depth interval in question. This provides a prediction of the pore pressure at the bottom of the interval. The porosity is predicted from the pore pressure, using Eq. (2) and the compaction function (this operation involves some iteration, because the total pressure depends on the porosity).

The resulting effective pressure and porosity may predict a velocity for the reference lithology that is lower than that observed. This difference is attributed to a change to a faster lithology, typically with a lower clay content than the reference lithology. If this faster lithology is confined to a limited vertical horizon, the anomalous increase in velocity with depth will be followed by a decrease in velocity as the reference lithology is restored, below. The algorithm attributes the appropriate proportion of such a decrease to lithology before predicting abnormally high pore pressure, as described in the previous section. This "lithology correction" therefore has the effect of filtering out spikes of high velocity in a profile.

The algorithm, as described, frequently produces predictions of "subsurface fluid compartments," as defined by Powley (1990) and Hunt (1990), i.e., zones of significant thickness (perhaps thousands of feet) with a local hydrostatic gradient, and a single hydraulic head. According to these authors, such zones are common, although the data to confirm their existence is sparse, and the classical prediction algorithms rarely show such features.

The present algorithm frequently predicts such compartments, because a velocity decrease is not interpreted as the reverse of a velocity increase (as with a "point" algorithm, expressed as an equation or a nomogram). A velocity decrease is usually (depending on the logical flow) interpreted as a fluid pressure increase. However, a velocity increase is usually not interpreted as a fluid pressure decrease (by the logic above). Instead, the local fluid pressure gradient is assumed to be hydrostatic, and the higher velocity is usually attributed to mineralogy. Since the faster mineralogy (e.g., sandstone) is plausibly more permeable, this conclusion is consistent with the local hydrostatic gradient, and the logic is internally consistent, at least. In any case, it is this feature which naturally leads to predictions of "subsurface fluid compartments," in many instances.

The relationship between the input and the resulting predictions is highly non-linear and incorporates both point and global considerations. This implies that it has a different pattern of sensitivities (compared to a "point" algorithm) to errors in the data. Depending on the structure of the data, it is more sensitive to errors in some layers, and less sensitive to errors in other layers. Comparison of its predictions with those of the classical "point" algorithms is often quite instructive.

However, assessing the errors in a formal way is very difficult. Referring to the discussion of the sources of error in the introduction, we distinguish between systematic algorithmic errors and random errors in the data. We can only offer the general operational success of the algorithm to suggest that systematic errors are not a serious problem. In any case, the foundation of the algorithm is deterministic, and attempts to alter it in the same spirit are acceptable.

We can make an empirical estimate of the error in a predicted pore pressure profile due to errors in the observed velocity profile. An upper and lower bound is assigned to each input velocity point. The algorithm is then repeated multiple times, with one velocity point moved to its upper or lower bound in each run. The envelope of all the predicted profiles from these runs provides a global error bound. This procedure typically highlights certain critical depth intervals in which the pressure prediction is more sensitive to input errors than others. The general structure of the predicted profiles is, however, quite robust.

Applications

The first two examples which follow are taken from the preliminary design study for the algorithm. They both come from the Gulf of Mexico, and both use the same reference profiles for calibration, despite a separation of several hundred miles. In these cases, the pressure structure measured in existing wells (including RFT measurements) was "predicted" using seismic velocity structures obtained from VSP's in the same wells. In the third example, the algorithm is applied in a true prediction (in advance of drilling), using velocities derived from surface seismic data.

The first example illustrates almost every feature of the algorithm. Figure 1 shows the input velocities (left panel), determined from a VSP (ie true vertical velocities, in the seismic band, with coarse resolution. The second panel shows the mudweight program (MW), six RFT measurements, and the predicted fluid pressure profile.

The pressure environment is normal to 7,500', slightly elevated to 14,000', and then highly overpressured to 16,500'. THe VSP-derived velocity profile shows plenty of structure, including two decreases in velocity with depth; a minor decrease at 8,000' and a pronounced decrease at 14,000'.

The algorithm responds to both these decreases by increasing the pore pressure. In both cases, the point above the velocity decrease has a fast lithology due to overlying velocity structure. Hence, the algorithm tempers its estimate of the pore pressure increase by attributing some of the velocity decrease to a return to the slower refrence lithology. As a result, the prediction of required mud weight at 15,500' is again accurate to 0.5 ppg.

An interesting feature of this example is shown between 11,000' and 14,000'. The predicted pore pressure profile suggests that this section was significantly overbalanced during drilling. The isolated RFT pressure measurement at around 13,500' was made through perforated casing after the well was completed, and agrees almost exactly with the predicted pore pressure. The discrepancy between mud-weight estimates, and RFT measurements is a reminder of the fallibility of mudweights as an indicator of formation fluid pressures.

The decision to use heavy mud in this section was based on some nearby wells where heavy mud was required at around 10,000'. Around these wells, the seismic velocity structure does indeed show a pronounced low velocity zone at starting 10,000', instead of at 14,000'.

There is very poor agreement between the predicted density profile (third panel) and the observed values from a compensated formation density log. The observed density shows a marked drop at 14,000', where the pore pressure increases. The densities above that point are remarkably high ($\rho = 2.6 gm/cm^3$), and may not be accurate. In any case, this problem sounds a note of caution in this otherwise successful illustration of the algorithm.

Finally, note the generally good agreement (fourth and fifth panels) between the observed and predicted zones of sandy lithology.

The second example (Figure 2) is from a deep water area where an accurate pore pressure prediction could lead to substantial savings in the cost of drilling. (Note that the reference profiles all originate at the water depth of 2,400'). The pressure environment, at least down to 13,000' is in fact not too severe.

For the most part, the algorithm operates as a point algorithm in this example; the reference profiles are simply stretched in depth in response to the slow increase in velocity with depth. Between 10,000' and 11,500', a significant increase in velocity is interpreted to indicate a faster lithology with a hydrostatic pore pressure gradient. Without this interpretation, the very small velocity increase in the subsequent depth interval (11,500' to 12,500') would be taken to indicate a significant increase in pore pressure. With the lithology correction, the algorithm predicts the required mud weight at 12,500' to within 0.5 ppg.

The predicted density/porosity profile in the sedimentary column also agrees closely with the log-derived density profile, suggesting that the calibration of the compaction function is reliable.

Unfortunately the VSP did not extend to the total depth of 13,500' in this well, so we were not able to see if the apparent increase in pore pressure at the base of the well was observable in the seismic velocity profile. The RFT measurement at the bottom of the well shows a pressure very close to the mud weight and is therefore suspect.

A third example illustrates the use of surface-derived velocities, and of a priori information at a well in another basin. Figure 3 shows the input velocities (left panel), determined from surface seismic reflection data by a migration-before-stack procedure. The second panel shows the mudweight program (MW), three RFT measurements, and the predicted fluid pressure profile. The calibration was performed in a second well, about 30 miles away, using sonic velocities, neutron densities, and RFT pressures.

This prediction was made when the drill-bit was just below the first RFT point. The engineers had anticipated a rise in pressure starting about 11000 ft, had increased the mudweight accordingly and had verified the accuracy of their mud program with an RFT measurement. Shortly afterward, they had gotten stuck and had requested an independent pressure prediction. The present algorithm (applied at that time) predicted that, below the seal, the local pressure gradient was hydrostatic, hence that the pressure-depth ratio was declining, hence that the hole was over-balanced at the sticking point. This provided a plausible explanation of the stuck bit, but other indications convinced the drillers that the pressure was much higher, and the prediction was rejected. Various re-interpretations of the raw seismic data yielded various estimates of the interval seismic velocities, all of which showed the same general character as shown in Figure 6, and which yielded similar pressure predictions.

The stuck bit was abandoned, the hole was side-tracked, and deepened slowly and carefully, with the mud-weight program indicated in the figures (about 19 ppg). Following TD (about 14500 ft), the hole was logged, and the two deeper RFT points revealed that the prediction had been quite accurate after all.

In the aftermath, some shortcomings of the prediction were analyzed; for example, the depth of the seal as predicted is too shallow, by about 500 ft (cf Figure 3). (Alternatively, the error could be taken as an error in fluid pressure, but given the shapes of the curves, and the well-known inaccuracy of time-to-depth conversion from surface seismic data, this alternative was rejected, a priori.) The mis-tie is too great to be attributed to poor seismic resolution (notice that the bottom of the predicted seal lies above, not below, the RFT point). Hence, we conclude that the input velocities are systematically in error, causing depth errors (as well as pressure prediction errors).

It is well-known (cf e.g., Thomsen, 1986) that, if the subsurface rocks are anisotropic, moveout velocities depend upon oblique velocities, rather than the vertical velocities which are required for time-to-depth conversion. (This occurs because the raw data give the variation in arrival time with horizontal offset, rather than with vertical offset.) The derived interval velocities hence differ from the interval vertical velocities, by an anisotropy factor δ which is not determinable without additional information, e.g., true depths determined in the borehole (cf e.g., Tsvankin and Thomsen, 1993).

Therefore, the minimal assumption was made that all velocities above the shallowest RFT point in Figure 3 are in error by the same percentage. This anisotropy was chosen so that the adjusted vertical velocities yielded depths and pressure predictions which tied the RFT point exactly (δ = 5%; a subsequent VSP showed that, on average, this was accurate). The adjusted dataset was then used for prediction of fluid pressures (using the same calibration); this adjustment also improved the accuracy of the pressure prediction above the RFT point, and more importantly, below it as well.

It should be emphasized that the original prediction could have been performed before drilling commenced, and that the adjustment could have been done after the RFT measurement, ie before getting stuck. Since the present algorithm is a global one, information acquired while drilling may be used to refine the prediction ahead of the bit, without re-calibration, as in this case. This is not possible with a "point" algorithm.

Conclusions

The cost and danger of misjudgements when drilling in a hostile environment mean that a novel method for pore pressure prediction should be treated with suspicion. There is a considerable body of expertise amongst drilling engineers that will rightly always be the starting point in formulating strategy for a new well.

However, a reliable remote method for predicting pore pressure brings tremendous advantages, which should be viewed as an aid to the engineers in this task. The algorithm presented here was designed to make the optimum use of field seismic data, laboratory measurements of seismic rock properties, and our understanding of the mechanical processes of operating in a sedimentary basin.

We have presented a "global" algorithm for pore pressure prediction. It uses local gradients and differences (as well as local values of the measured velocity), in conjunction with elementary physical reasoning, to make its predictions. This is useful because pore pressure prediction is intrinsically ambiguous, since the measured quantity (e.g. seismic velocity) is also strongly affected by other variables (e.g. porosity and mineralogy). This feature of the algorithm stabilizes its predictions against some types of error in the input data.

Because of this "global" character, this algorithm is different in kind from others in the literature. The application of different algorithms to the same ill-posed problem is useful; where they agree one has added confidence, and where they disagree one concentrates further analysis. This synergy is not as powerful with the application of similar algorithms, nor with the application of a single algorithm by different individuals with different judgment.

The deterministic basis of the algorithm gives it intrinsic merit, and also lends confidence that successful predictions are not obtained by chance. Because all the primary factors affecting seismic velocity are considered, the predictions of pore pressure are accompanied by predictions of density and lithologic variation. These can be added to the evidence used in the geological appraisal of a play.

The algorithm exploits a data set that is inevitably rather sparse (velocity structure from seismic reflection).

The pore fluid pressure in a basin varies on a broader scale than properties of the solid phase such as porosity or lithology, because it is modified by the diffusive process of percolation. The use of a sparse data set exposes the pore pressure structure and filters out the effects of other variables affecting seismic velocity. A benefit of the small amount of data used by the algorithm is that it requires very little computation. Given a good velocity structure, which is in any case needed for accurate migration, there is no reason not to compute a pore pressure prediction.

The algorithm provides a logical framework that invites adaptation in response to the special conditions in a particular region. Because the non-uniqueness of the prediction is acknowledged explicitly, a priori constraints can be incorporated into the algorithm. Such constraints, on variables that the algorithm sets out to predict, can be used to augment the data set.

The algorithm frequently predicts the existence of "subsurface fluid compartments" (Powley, 1992), with significant intervals of local hydrostatic gradient and elevated head. Because typical drilling practice precludes the accurate delineation of such compartments via mudweight estimates of in-situ fluid pressure, and because RFT measurements are not commonly taken throughout the borehole, these predictions are not fully verified. It is clear that a thorough program of RFT measurements, as opposed to mudweight estimates and ambiguous predictions, is required in order to validate this important conjecture.

References

Eberhart-Phillips, D., D. Han, and M. Zoback, Empirical Relationships among Seismic Velocity, Effective Pressure, Porosity, and Clay Content in Sandstone; Geophysics, 54(1), 82-89, 1989.

Hottman, C. E., and R. K. Johnson, Estimation of Formation Pressures from Log-Derived Shale Properties, J. Pet. Tech., 717-722, 1965.

Hunt, J. M., Generation and Migration of Petroleum from Abnormally Pressured Fluid Compartments, Am. Assoc. Petrol. Geol. Bull., 74(1), 1-12, 1990.

Marion, D. and A. Nur, Pore-filling Material and its Effect on Velocity in Rocks, Geophysics, 56, 225-230, 1991.

Mouchet, J. P., and A. Mitchell, Abnormal Pressures while Drilling, Elf Aquitaine Editions, Boussens (France), 264 pp., 1989.

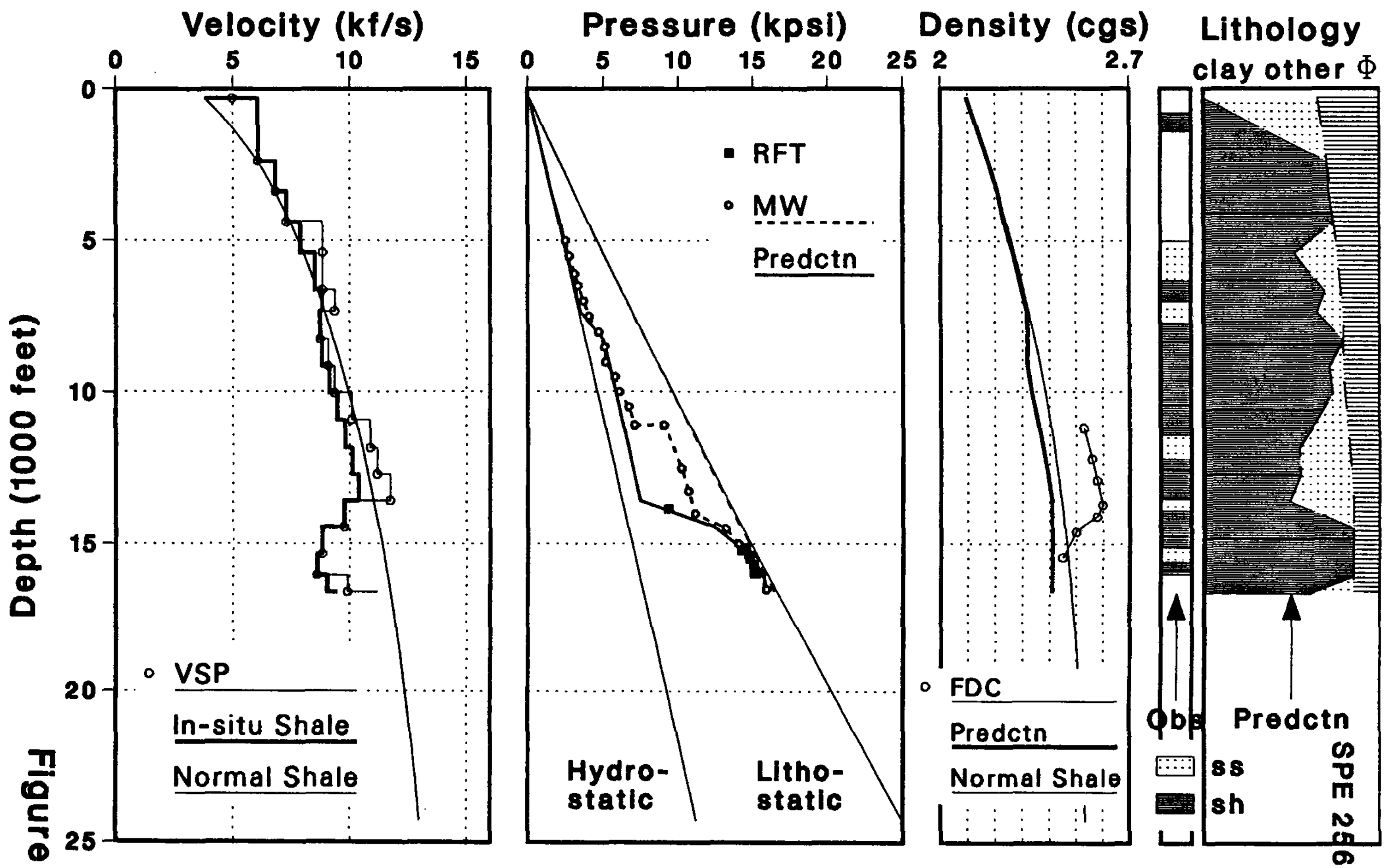
Powley, D., Pressures and Hydrogeology in Petroleum Basins, Earth-Science Reviews, 29, 215-226, 1990.

Scott, D. R. and L. Thomsen, Methods for Estimating the Burial Conditions of Sedimentary Materials, U.S. Pat. 5,081,612, 1992.

Thomsen, L, Weak Elastic Anisotropy, Geophysics, 51, 1954-1966, 1986.

Tsvankin, I. and L.Thomsen, Inversion of Reflection Traveltimes for Transverse Isotropy, to be submitted to Geophysics, 1993.

Example 1: Gulf of Mexico (full-featured)



Calibration: GULFMEX

Figure 1

SPE 25674

SPE25674

Example 2: Gulf of Mexico (Deep water)

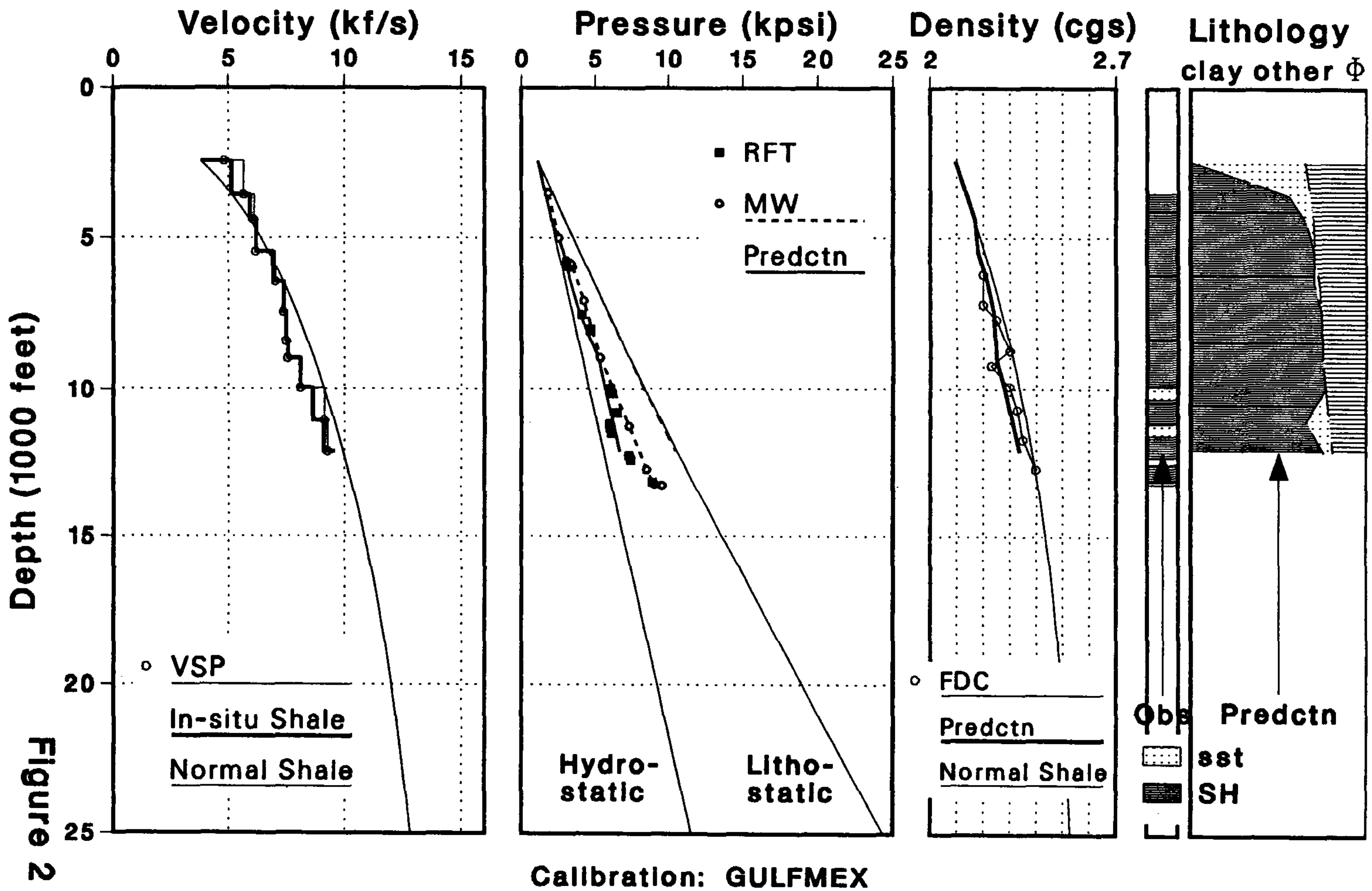


Figure 2

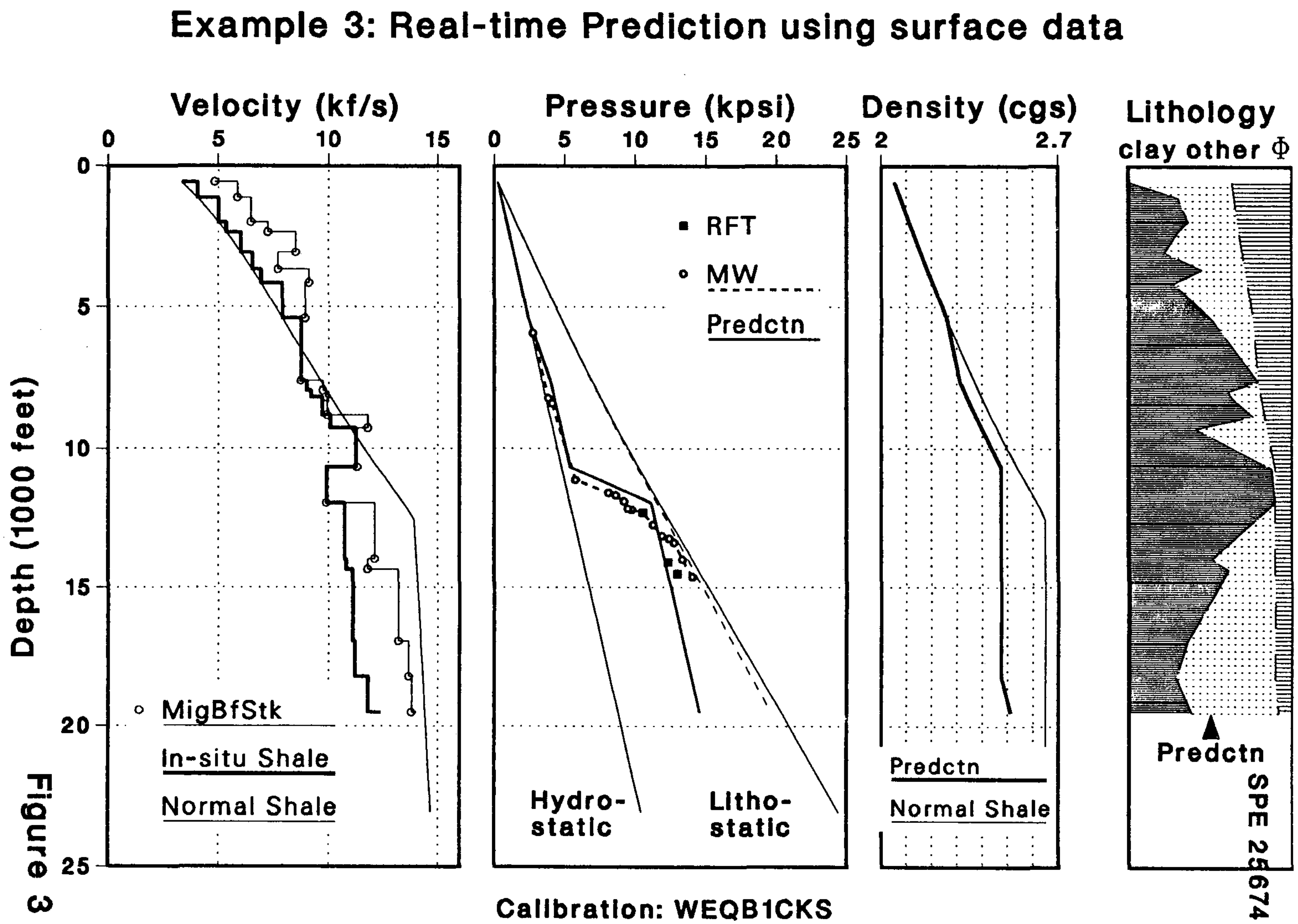

Example 3: Real-time Prediction using surface data
Velocity (kf/s)
Pressure (kpsi)
Density (cgs)
Lithology
clay other Φ
Depth (1000 feet)
MigBfStk
In-situ Shale
Normal Shale
RFT
MW
Predctn
Hydro-
static
Litho-
static
Predctn
Normal Shale
Predctn
Calibration: WEQB1CKS
SPE 25674

Figure 3