Review of pore-pressure prediction challenges in high-temperature areas

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Pore-pressure prediction relies heavily on interpretation of seismic and well attributes such as velocity, resistivity, and density which capture porosity changes during shale compaction under vertical loading. Relationships such as Eaton (1975) were developed in the Gulf of Mexico using a relatively simple lithological mix of geologically young sandstones and shale mudrocks at relatively low temperatures. An alternative approach using data from the same region was more deterministic—also with vertical stress (e.g., Hottman and Johnson, 1965; Bowers, 1995). Another approach using mean stress, developed by Harrold et al., (2000) used similar sand and shale sequences at relatively low temperatures from data in southeast Asia basins. All the above approaches can be shown to provide acceptable prediction of pore pressure in shale mudrocks in young, rapidly deposited siliciclastic sequences, such as the Baram Delta, Brunei (Tingay et al., 2009) and along the West African margin (Swarbrick et al., 2011). The results can be calibrated, with careful attention to evidence for lateral drainage or lateral transfer, using data from their associated reservoir. However, in higher-temperature environments (e.g., Malay Basin, Hoesni 2004) these methods fail to deliver predictions which may be accurate enough for effective well planning and safe drilling. This paper reviews the above methods and how they can be modified for use at elevated temperatures (e.g., above 100°C). However, the review also draws attention to the wide uncertainty inherent in conventional approaches to prediction in some regions, which may require an entirely different approach to pore-pressure prediction prior to drilling.

Standard pore-pressure prediction technology

Shale mudrocks are highly compressible, and de facto so are the sediments used in pore-pressure prediction. At their site of deposition shales have porosity in the region of 60–80% compared to porosity less than 20% in typical shales at effective stresses appropriate for depths in the region of 3.0 km burial. These shales have a huge volume of water to expel during compaction. Sandstone by contrast has an initial porosity around 40% when first deposited, declining because of mechanical compaction to about 25% porosity at similar stresses and depths of burial. Lower porosity, typical in many deeply buried sandstones, results from additional chemical processes such as mineral cementation which includes diffusive mass transfer during concurrent stylolitisation. Carbonates such as chalk and limestone also experience cementation which can be early in the burial history (low temperature) and even at the site of deposition. The inherent unpredictability of porosity in carbonates, and with no well established relationships between burial and vertical effective stress, makes pore-pressure prediction impossible using standard methods.

Hence pore-pressure prediction in low-temperature sediments is normally accomplished by analysis of shale mudrocks during the progressive burial and compaction, where pore pressure is related to vertical stress and vertical effective stress in the Terzaghi Equation:

\[ P_p = S_v - \sigma v \]

where \( P_p \) is pore pressure; \( S_v \) is vertical stress (also known as overburden); and \( \sigma v \) is the vertical effective stress (the grain to grain contact stress). As vertical stress increases with burial, compaction proceeds when water is expelled from the shale mudrocks, increasing the vertical effective stress and driving the grains closer, thereby reducing pore space. As porosity decreases so does permeability. When the permeability reduces such that water can no longer be effectively expelled, the pore pressure starts to assume some of the load normally borne by the grain contacts, taking the pore pressure above normal pressure and giving the shale mudrock overpressure. Pore-pressure prediction using porosity-vertical effective stress relationships to quantify pore pressure compares the actual porosity (as captured by its proxy: velocity, resistivity, density, etc.) with the expected value of porosity on the “normal compaction curve” for the depth of burial (Eaton method) or uses the normal compaction curve to determine an equivalent depth at which the normal vertical effective stress can be determined (Figure 1).

Velocity plotted against bulk density can be used to demonstrate that shale mudrocks are on their normal compaction curve, and if overpressured remain in balance with the effective stress. The Gardner equation (Gardner, 1974) was a first attempt to demonstrate such a relationship, based on data from the Gulf of Mexico. The pathway during burial with/ without overpressure is shown as trend A on Figure 2. The preferred way to recognise patterns in the data is to plot each

![Figure 1. Pressure versus depth and porosity versus depth profiles illustrate the relationship between vertical effective stress, compaction and porosity change used in predicting pore pressures when the origin of excess pressure is disequilibrium compaction (undrained shale mudrocks).](image-url)
velocity—bulk density point according to a suitable depth interval (e.g., different color each 500 m or 1000 feet for example). Increasing burial in the shallow section is always toward higher velocity and increase in bulk density. Mild development of overpressure has the effect of slowing the rate of velocity increase and bulk density reduction, whereas rapid changes in overpressure may be observed by “reversals” whereby velocity decreases with increasing depth/vertical stress (but decreasing vertical effective stress), and bulk density becomes lower at the same time. Each point remains on or near the “normal compaction curve,” i.e., on trend A (Figure 2).

**Influence of temperature on fluid properties**

Temperature changes fluid properties, in particular reducing density of water and/or hydrocarbons as well as changing the state of hydrocarbons from liquid to gas. Because temperatures increase with depth (at a rate of approximately 30°C/km ± 10°C/km in most basin settings), pore water has a tendency toward density reduction and fluid expansion (the compressibility of water has the effect of increasing water density but the effect rarely outweighs the temperature effect of density reduction). Barker (1972) first described the fluid expansion of buried water and suggested that there would be a significant reduction in vertical effective stress as overpressure was created in the host sediment. In fact, later research (e.g., Luo and Vasseur, 1992; Swarbrick et al., 2002) has shown that the effect is small (< 500 psi even with ultralow-permeability rocks). In terms of volume change, the most significant effect is found in the generation of methane and other light hydrocarbon molecules during kerogen maturation (e.g., Meissner, 1976; Ungerer et al., 1983) and during in-situ oil to gas cracking (Barker, 1990).

Bowers (1994, 1995) extended the use of velocity-bulk density plots to capture the behavior of shale mudrocks during “unloading”—i.e., when effective stress is reduced during uplift/vertical stress reduction and/or during fluid expansion when pore pressures increase from an earlier “maximum” vertical effective stress but without complementary reduction in vertical stress. Because velocity is in part a function of grain-to-grain contact stress, the effect of vertical effective stress reduction during fluid expansion is to decrease the shale mudrock velocity. Bulk density, however, will only reduce according to the poroelastic behavior of the rock, which is a minor change in porosity. Hence the pathway documented during unloading on a velocity-bulk density crossplot is trend B on Figure 2.

**Influence of temperature on rock properties**

Because traditional pore-pressure prediction relies on predictive rock properties, temperature-driven changes in the grain-to-grain contact relationship challenge the original assumption, i.e., that porosity attributes can be related to pore pressure through the Terzaghi effective stress law. Temperature can have a range of effects including:

- Precipitation of cements, making the rock stiffer, and/or filling pore space;
- Dissolution of rock grains, ultimately causing collapse of the rock structure and reducing pore space;
- Weakening of rock grains (more ductile behavior),
- Mineral transformation (e.g., smectite to illite; kaolinite to illite)

The full details of chemical diagenesis in shale mudrocks remain poorly known, but reactions such as smectite to illite transformation (see Lahann, 2001) or kaolinite to illite (Lahann and Swarbrick, 2011a) have been documented in relation to their influence on vertical effective stress. Both of these reactions are kinetically controlled, and occurring over temperatures in the range 80–150°C (Lahann, personal communication) but where recognition is more typically observed around 100–110°C. A consequence of these transformation reactions to illite (and potentially other reactions) is that the rock becomes more compressible and original grain support has been lost—a process referred to as “load transfer” (see Lahann and Swarbrick, 2011b). Many more chemical pathways involving common minerals in shale mudrocks are possible, which together with the transformations mentioned above create highly unpredictable compaction behavior.

Load transfer has the effect of decreasing shale mudrock porosity as minerals (such as illite) are packed more tightly (illite has a preferred orientation of the grains which permit more efficient packing but which collapse easily when escape of water allows compaction). The transfer of load, if not accompanied by expulsion of pore fluid, results in increase in pore pressure and a decrease in vertical effective stress. This behavior is captured on trend C on Figure 2, where a range of possible pathways are illustrated to emphasise the multiple complementary reactions and load transfers associated with different transformations.
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Concurrent escape of displaced fluids through the connect-
ings of pores without development of additional overpressure and simultaneous reduction of vertical effective stress. It is noted that subsequently, and when bulk densities reach values in excess of approximately 2.60–2.65 g/cc, the rate of velocity change increases, likely reflecting ultraslow porosity in the shale mudrock as bulk density approaches rock matrix values (and a minimum porosity). Within this range of densities (i.e., above about 2.60 g/cc) there is no clear discrimination of process (e.g., unloading, load transfer, etc.).

Pore-pressure prediction at high temperatures

The above changes in rock and fluid properties impact vertical effective stress used with porosity attributes such as sonic velocity and resistivity to predict pore pressures. Bowers (1995) offers a solution when there is fluid expansion and reduction in effective stress, when solving for velocity, with the following equation:

\[
Velocity = Vo + a\left(\sigma / \sigma_{max}\right)^{b/u}\]

where \(Vo\) is taken as 5000 ft/s, \(a\) and \(b\) are empirical and locally derived constants, \(\sigma\) is vertical effective stress and \(u\) is the elastoplastic term.

The previous equation can be used with confidence where a clear trend B (Figure 2) can be identified on velocity-bulk density crossplots of well data. From the author’s experience a true “unloading” trend of near-constant density and velocity decrease is rare. Most trends can best be described as one of the trend C type profiles shown in Figure 2. There are no published solutions for pore-pressure prediction for trend C.

Tingay et al., (2009) developed a semiregional correction to the standard Eaton equation, where the modification of the exponent of 3.0 (Eaton, 1975) to a value of 6.5 is required to provide a close predictive result when using sonic velocity in a subset of the wells from Brunei. Velocity-bulk density trends were not included in this study, only velocity-vertical effective stress to capture velocity reduction with decrease in vertical effective stress along a pseudo-unloading trend. This solution is locally calibrated for local use but does not provide a relationship which can be applied universally for pore-pressure prediction at elevated temperatures in shale mudrocks.

The author has experience of sharp transition zones (rapid reduction in vertical effective stress over a narrow depth interval) in shale mudrocks (and intra-formational reservoirs) accompanied by moderate to severe cementation, identified by their ultralow porosity (near matrix bulk density values). Examples include deeply buried, old shale mudrocks such as found in the Triassic of the Central Graben HPHT play, as well as young, Miocene sediments in southeast Asia. Both sequences exhibit no relationship between vertical effective stress (as inferred from direct pressure tests in interbedded reservoirs) and porosity. In the case of the Miocene rocks (at depths in region of 4.0 km and temperatures of 130°C), the porosity is low but vertical effective stress is high, the opposite to a normal relationship for pore-pressure prediction in young, rapidly buried sediments. Yet the shales and reservoirs have high overpressure, created in main by rapid burial. In these undrained shale mudrocks, aggressive cementation is masking any usable prediction relationship with porosity. In cases where there is no usable relationship between porosity attributes (sonic, resistivity, etc.) and effective stress, an alternative geological-model-based solution is required.

Solution using geologic pressure model

Disequilibrium compaction during sediment loading is considered the most common cause of overpressure in shale mudrocks (Swarbrick et al., 2002). At elevated temperatures additional causes of overpressure such as gas generation and mineral transformations/load transfer may contribute, adding to the existing overpressure created by disequilibrium compaction during burial. Under these conditions the relationship between porosity and effective stress is either obscure or nonexistent and an alternative to a Terzaghi-relationship approach is therefore required. One logical starting point for pore-pressure prediction would therefore be an estimate of overpressure in shale mudrocks from disequilibrium compaction alone, using a method independent of vertical

Figure 3. Example of data used to determine relationship between sedimentation rate and fluid retention depth (FRD). In this case, multiple reservoir pressures measurements have revealed a lithostatic gradient-parallel profile of pore pressure, from which the FRD has been determined by intersection with the hydrostatic gradient. Data from a wide variety of global basin settings were used to construct Figure 4. Redrawn and modified from Nile Delta data in Mann and Mackenzie (1990).
Case Study

effective stress and porosity. Swarbrick et al. (2002) demonstrated a broad relationship between the log of sedimentation rate and a “fluid retention depth” (FRD)—a depth below sea floor (when offshore) from which a lithostatic parallel “shale gradient” begins (Figure 3). The original sedimentation rate-FRD relationship from Swarbrick et al. (2002) has now been updated with subsets of lithology added for shales, silty shales, and siltstones from a larger global data set (Figure 4). None of the examples comes from an area in which there are large, known tectonic (horizontal compressive) stresses, but rather are known to be areas where rocks are currently considered at their maximum depth of burial.

Sedimentation rate can be derived from depth-converted seismic data, (where seismic time lines can assigned ages), and calibrated using age-depth data from associated wells. The average sedimentation rate for the rocks in the top 3.0 km (10,000 feet) was used to determine the majority of values on Figure 4. Note that the sedimentation rate values plotted on Figure 4 were estimated using current depths of burial (no uplift was evident in any of the examples used in the data set) and without consideration of back-stripping which would estimate the compaction effects during burial. Hence the same approach should be employed when using the plot for prediction in new areas—i.e., predictions using these data should also adopt a simple sedimentation rate calculation approximating sedimentation rate from depth and age information alone.

As an example of how this prediction method may be shown to work is illustrated using data from a well in the Nile Delta (Mann and Mackenzie, 1990) where an average sedimentation rate is estimated at 810 m/Ma (Figure 3). Applying the sedimentation rate of 810 m/Ma and assuming average “silty shale” lithology in Figure 4 yields a FRD at a depth 0.8 km. Because RFT data are also reported by Mann and Mackenzie (1990) it is possible to verify this estimate. The RFT data in Figure 3 show a lithostatic-parallel gradient when drawing a line through the data over the interval from approximately 2.0 to 4.0 km. When this line is extrapolated to the hydrostatic gradient the intercept occur at approximately 0.8 to 0.9 km below mudline, confirming the suitability of the earlier prediction of FRD at approximately 0.8 km.

Assuming only sedimentation rate is known, then the determination of FRD provides information about the vertical stress at 0.8 km depth. Assuming the well is located at the coast (zero water depth) and the FRD is 0.8 km:

- The hydrostatic stress at 0.8 km is 8 MPa, assuming an hydrostatic gradient of 10.0 MPa/km.
- The total vertical stress is 16.0 MPa, assuming a vertical stress gradient of 20.0 MPa/km as an average from surface to 0.8 km.
- The vertical effective stress (VES) is therefore 16.0 − 8.0 = 8.0 MPa.

Because the assumption is for a lithostatic-parallel profile of pressure for the shales, VES remains constant at depth and represent the pore-pressure prediction for the shale mudrocks. Hence the pore-pressure prediction for undrained shale mudrocks at 4.0 km will be the vertical stress minus the vertical effective stress, which is 86.0 − 8.0 = 78 MPa, where the lithostatic stress averages 21.5 MPa/km down to 4.0 km and the vertical effective stress remains at 8.0 MPa.

The FRD method described above has now captured the vertical effective stress to define a vertical stress/lithostatic stress parallel shale pressure gradient. The method can be used to determine the approximate pressure regime of shale mudrocks independent of any rock property data. In low-temperature regimes the method provides an independent method to compare with porosity attribute driven pore-pressure estimates. In high-temperature regimes, the method may be the only one to offer a useful estimate of overpressures if the porosity-based methods are severely influenced by chemical compaction. A reduction in porosity (e.g., because of the load transfer or chemical compaction) leads to pressure predictions which are underestimates. The shale-pressure-gradient method captures the contribution from burial and disequilibrium compaction...
irrespective of the rock properties. Contributions to overpressure from secondary mechanisms will need to be estimated, with varying degrees of uncertainty, and added to the contribution from compaction disequilibrium.

Case study
Basin “X” is known to have high overpressure in Miocene shales and associated reservoirs beneath a normally pressured, sand-rich delta-top sequence almost 4.0 km thick. The temperature at the base of the sandstone-rich sequence is about 140°C and the shales at this depth and temperature have densities in the region 2.6–2.65 g/cc and velocities in the region of 4200 m/s. The density values indicate low porosities, on the order of < 5.0%, which when using rock properties and global shale normal compaction trends for density predict little to no overpressure. By contrast, the sonic velocities indicate up to 17.0 MPa overpressure in the same zone, estimates using a normal compaction curve developed from analysis of the shale interbeds in the logged interval within the overburden and the associated thick, normally pressured reservoirs. By contrast the actual overpressure encountered was much higher at 51.5 MPa, at the base of a sharp pressure transition zone. Estimates of overpressure using the FRD method described above estimates the overpressure to be on the order of 50.0 to 55.0 MPa at the same depth and a much more useful prediction method than velocity. The reason for the ultralow porosity is not yet known (but expected to be quartz or other diagenetic reaction) and any contribution to overpressure from elevated temperatures is not known either. However, the measured overpressure is close to the estimate from rapid burial based on sedimentation rate from a Miocene age marker at its current depth of burial, and represents a more useful prediction for well planning than the use of rock properties where porosity has been severely impacted by chemical compaction. A schematic representation of the data and results are shown on a pressure-depth plot in Figure 5.

The principal warning of this case study is that velocity, even though it is sensitive to effective stress (unlike density—see review by Bowers, 1994), grossly underestimates the overpressure across this pressure transition zone. In fact, there is a growing global database of deep drilling in high overpressure areas (including the central North Sea and mid-Norway, for example) which illustrates the apparent contradiction of low porosity and high overpressure. In old, deep, and hot shale mudrocks many pathways to create high overpressure may exist and disequilibrium compaction contribution may be uncertain. In the case study above, the young, rapidly deposited sediments will have created enough overpressure from disequilibrium compaction alone to explain the magnitude of overpressure, without recourse to other mechanisms. It is therefore imperative to perform the pore pressure estimate from sedimentation rate to capture the “minimum” magnitude from vertical stress loading, recognizing the pore-pressures will be higher if other, thermally driven mechanisms are present as well.

Conclusions
Traditional methods to accurately predict pore pressures using rock properties are restricted to shale mudrocks at temperatures less than about 100°C. The most likely cause of overpressure will be disequilibrium compaction (undrained shales) alone and vertical effective stress relationships can be developed with confidence to quantify pore pressures. At higher temperatures, chemical compaction, mineral transformations and other processes distort those relationships and make pore-pressure prediction unreliable. Use of velocity-

Figure 6. Workflow suggested for pore-pressure prediction analysis based on lithology, temperature, and overpressure-generating mechanisms. The workflow leads to loose definitions of confidence.
density crossplots facilitates examination of two key rock attributes used in pore-pressure prediction and assists in recognizing mechanisms of overpressure generation and the requirements to adopt more sophisticated prediction methodologies. Figure 6 illustrates a workflow which captures the process described above, including a geologic model to estimate overpressure from compaction disequilibrium compaction as well as any lateral drainage and lateral transfer effects. This geologic model helps to build confidence of prediction in low temperature environments, but is especially important at high temperatures.

References

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