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Formation Damage Caused by Excessive Borehole Fluid Pressures During Environmental Drilling in Unconsolidated Coastal Plain Sediments: A Petroleum Engineering Analog

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Introduction

Shallow drilling activities in the unconsolidated sediments of the Atlantic Coastal Plain often report zones of lost circulation and rod drop. During the initial characterization and engineering studies of the USDOE Savannah River Site (SRS, Figure 1), South Carolina, performed by the Corps of Engineers, numerous zones of lost circulation, ''grout take'' and rod drop were noted. Large foundation grouting programs discovered that intervals of ''micro-channeling'' and fracturing occurred during pumped grout programs. Ongoing drilling activities over the last 50 years have also reported zones of lost circulation and rod drop, generally thought to be ''soft zones''. In many cases rod drops and lost circulation are due to soft zones, however an abundance of cone penetrometer (CPT) data, combined with drilling and geophysical data, suggests that many unconsolidated coastal plain sediments may be subject to hydraulic fracturing during drilling operations. Hydraulic fracturing may be the cause of some of the lost circulation problems and may cause problems if key aquitards are damaged. A typical sediment profile and geophysical log is shown in Figure 2.

Few, if any, studies have been completed on the potential formation damage effects caused by hydraulic fracturing during casing and cementing activities within these sediments. Intuitive experience from the petroleum industry suggests that formation damage is likely when the hydraulic pressure gradient from the drilling or grouting exceeds the fracture gradient of the formation.

Data from SRS were utilized for a comparison study between borehole fluid property measurements, geophysical log and CPT data. The pore pressure of the formation fluids at a given depth was determined from FMT data. The fracture stress gradient of the sediments was determined from CPT data.

Using standard equations, a table or graph can be generated to show pressure relationships. A review of these data demonstrate that: 1) overburden pressures from the CPT and the minimum fracture pressure from the equations generally agree, 2) the FMT pressures are equivalent to the extrapolated minimum Fracture Pressure and CPT Effective Overburden pressures, 3) it is likely these type sediments are hydraulically fractured, and 4) it may be possible to predict the potential for fracturing in shallow unconsolidated sediments.

An Example of the Problem

State regulations and SRS drilling procedures require that surface casing be set in monitoring wells penetrating deeper aquifers in 1) areas where known contamination exists in overlying aquifers, and 2) areas downgradient from facilities or areas with known contamination. Typical casing set points are within the ''Green Clay'' interval (Gordon Confining Unit) of the Warley Hill Formation and occasionally within the ''Tan Clay'' interval of the Dry Branch Formation (Tan Clay Confining Zone of the Upper Three Runs Aquifer). These two units are clayey aquitards that are generally less than ten feet thick for the ''Tan Clay'' and less than six feet thick for the ''Green Clay''. Neither of these units are massively bedded clays but generally consist of thin to thick (<1'' to <2') lamina interspersed within clayey silts and fine grained sands. However, few studies have been completed on the potential formation damage effects caused by hydraulic fracturing during casing and cementing activities within these sediments. Exploration conducted to investigate the effects of foundation grouting programs showed that large volumes of injected grout traveled radially, in thin layers, considerable distances from the borehole. Intuitive experience from the petroleum industry suggests that formation damage is likely when the hydraulic pressure gradient from the drilling or grouting exceeds the fracture gradient of the formation. Formation damage may lead to ''leaking'' of downward moving contaminants or upward moving groundwater through

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fractures and micro-fractures adjacent to the borehole. Hydraulic over-pressuring may be caused by excessive mud weight, grout weight or pump over-pressuring.

Approach

Since few measurements of formation damage have been made at the SRS, a theoretical approach is made based on data collected at the Hydrogeological Field Test Site in well MWD-12. This well is centrally located at the SRS and is representative of the majority of monitoring wells in the area. MWD-12 was completed to provide core information for a comparison study between core property measurements and data obtained from geophysical tools, principally the magnetic resonance and formation fluid/pressure tester (the MRIL and Formation Multi-Tester (FMT) tools). In addition to core and geophysical measurements, Cone Penetrometer Test (CPT) information was also obtained immediately adjacent to the boring location. CPT data are available to a depth of 153' and geophysical data to a depth of 342'.

Formation damage is probable once the fluid pressures in a borehole exceed the fracture stress pressure of the formation. When this happens, borehole fluids will tend to flow under gravity and/or pumped pressure into the formation along preferentially oriented planes of weakness. In most sediments, these planes of weakness are lateral or horizontal (along the shear plane) rather than vertical (along the compressive plane) (Adams and Charrier, 1985). However, vertical fractures are known in soft sediments in outcrop Formation damage is caused by flowing borehole fluids displacing formation fluids and sediments.

Two key values are required to estimate whether formation damage is likely, the pressure of the borehole fluids at a given depth, and the fracture stress gradient of the sediments. For this study, it is assumed that sediments at the SRS are not over-pressured (for example, due to hydraulic charging from oil or gas) and are in iso-static equilibrium. If the density or composition of the borehole fluids is known, or the weight of the fluids per unit volume, then the hydrostatic pressure of the fluid per depth may be calculated, or read from prepared tables. The formation fracture gradient, by rule of thumb in Gulf Coastal Plain type sediments is approximately 1.0 psi/ft (Adams and Charrier, 1985). However, in the shallow sediments of the SRS, which are relatively less consolidated than deeper Gulf Coastal Plain sediments, (although they are of the same relative type and age) it is possible to calculate and extrapolate a stress gradient based on data from the CPT and FMT information.

Figure 3 is a graph showing the calculated pressure at depth for typical drilling mud and grout as defined in the Halliburton Cementing Tables. Overburden pressures, from the CPT tool from MWD-12 and hydrostatic pressures from the FMT tool are also shown. The FMT is a direct measure of total formation fluid pressure. CPT overburden pressure are calculated as ''total'' which is a function of depth, while ''effective'' overburden pressures consider the effects of saturated sediments below the water table. The CPT data (measured to a depth of 153') are extrapolated to approximately 300'.

If the pore pressure is known, then it is possible to calculate the formation fracture stress gradient using the equation of Hubbert and Willis (in Adams and Charrier, 1985) as follows:

$$P/Z(\min, \max) = (1/3 \text{ min}, {}^{1}/_{2} \max)(S_z/Z + 2p/Z)$$

Where:
P = fracture pressure, psi
Z = depth, feet
S_z = overburden at depth Z, psi
p = pore pressure, psi

Example:

$$\text{for } p = 43 \text{ psi}, S_z = 68 \text{ psi}, Z = 100 \text{ ft.}, \text{ then } P = 78 \text{ psi minimum and } 118 \text{ psi maximum}$$

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The maximum and minimum calculated fracture pressures from this equation are also shown on Figure 3. It should be understood that this equation is generally used for much deeper strata, however, the match between the CPT derived Effective Overburden pressure and the minimum fracture pressure, is interesting (the pore pressure, p, used in the Hubbert and Willis equation is utilized from the CPT data).

The FMT tool measures formation fluid pressure directly at discrete depths. These data are also shown on Figure 3. Compared to the normal hydrostatic curve (assuming freshwater) demonstrates that the measured FMT pressures are higher and tend to parallel the normal hydrostatic curve.

An assumption that the CPT Effective Overburden pressure, measured FMT MWD-12 hydrostatic pressure and the minimum Formation Fracture pressures are equivalent is valid because the curves are similar on Figure 3 (the CPT Effective Overburden pressure and the minimum Fracture Pressure curves are measured to 153' and extrapolated to approximately 300'). This assumption is intuitive for saturated sediments if the total pressure at a given depth is a sum of the lithologic and hydrostatic pressure at that depth. Since the sediments are not over-pressured, the measured formation pressure from the FMT and measured Effective Overburden Pressure from the CPT will be equivalent to the hydrostatic pressure of the formation at a given depth.

Results and Conclusions
A review of the graph demonstrates that:

◆ calculated overburden pressures from the CPT and the minimum fracture pressures from the Hubbert and Willis equation generally agree, and are equivalent with the FMT derived pressures,
◆ the CPT Total Overburden and Effective Overburden curves diverge at the water table,
◆ the hydrostatic pressure from the 13.2 lb./gal. grout exceeds the Total Effective Overburden curve at approximately 90 feet (Area A) suggesting the possibility of hydraulic fracturing in sediments at this depth,
◆ the 10 lb./gal. mud weight exceeds the CPT Effective Overburden and minimum Fracture Pressure at approximately 240 feet, suggesting the possibility of hydraulic fracturing at this depth (Area B),
◆ the FMT pressures are essentially equivalent to the extrapolated minimum Fracture Pressure and CPT Effective Overburden, but demonstrate a divergence in Area C suggesting that measured formation pressures and calculated formation pressures also diverge at these depths.
◆ the maximum Formation and Total Overburden Pressures are generally greater than pressures anticipated in the depth ranges evaluated,
◆ any pumping pressures from the surface must be added to the hydraulic pressures to estimate subsurface pressure effects.

Based on these observation, it is possible for drilling operation to hydraulically fracture typical unconsolidated sediments when grout and mud weights exceed the CPT measured Effective Overburden Pressure or the calculated Minimum Formation Fracture Pressure. It may be worthwhile, in areas to be evaluated using monitoring wells requiring casing, to obtain CPT derived data formation pressure data, and perform a hydraulic fracture potential analysis. Key formations, such as those mentioned earlier, may be damaged by excessive mud and/or grout weight induced hydraulic fracturing.

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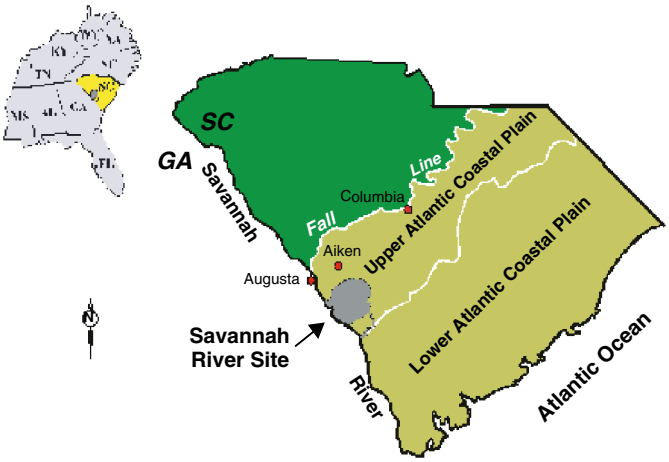

Figure 1. SRS is located within the Upper Atlantic Coast Plain.

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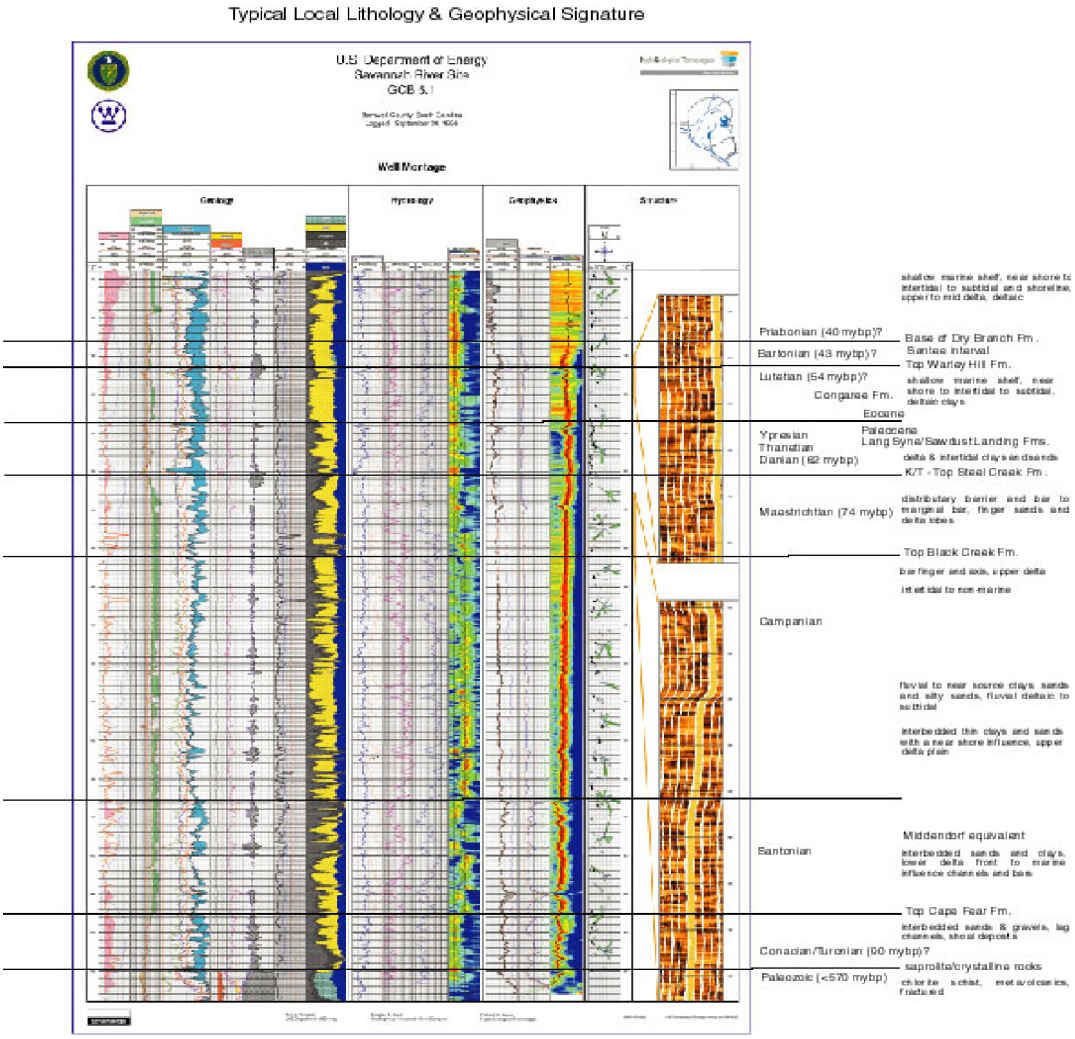

Figure 2. Typical unconsolidated sediment column in the Upper Atlantic Coastal Plain as derived from geophysical data. The ''Tan Clay'' is the first clay above the Priabonian contact. The ''Green Clay'' is found at the Bartonian/Lutetian contact.

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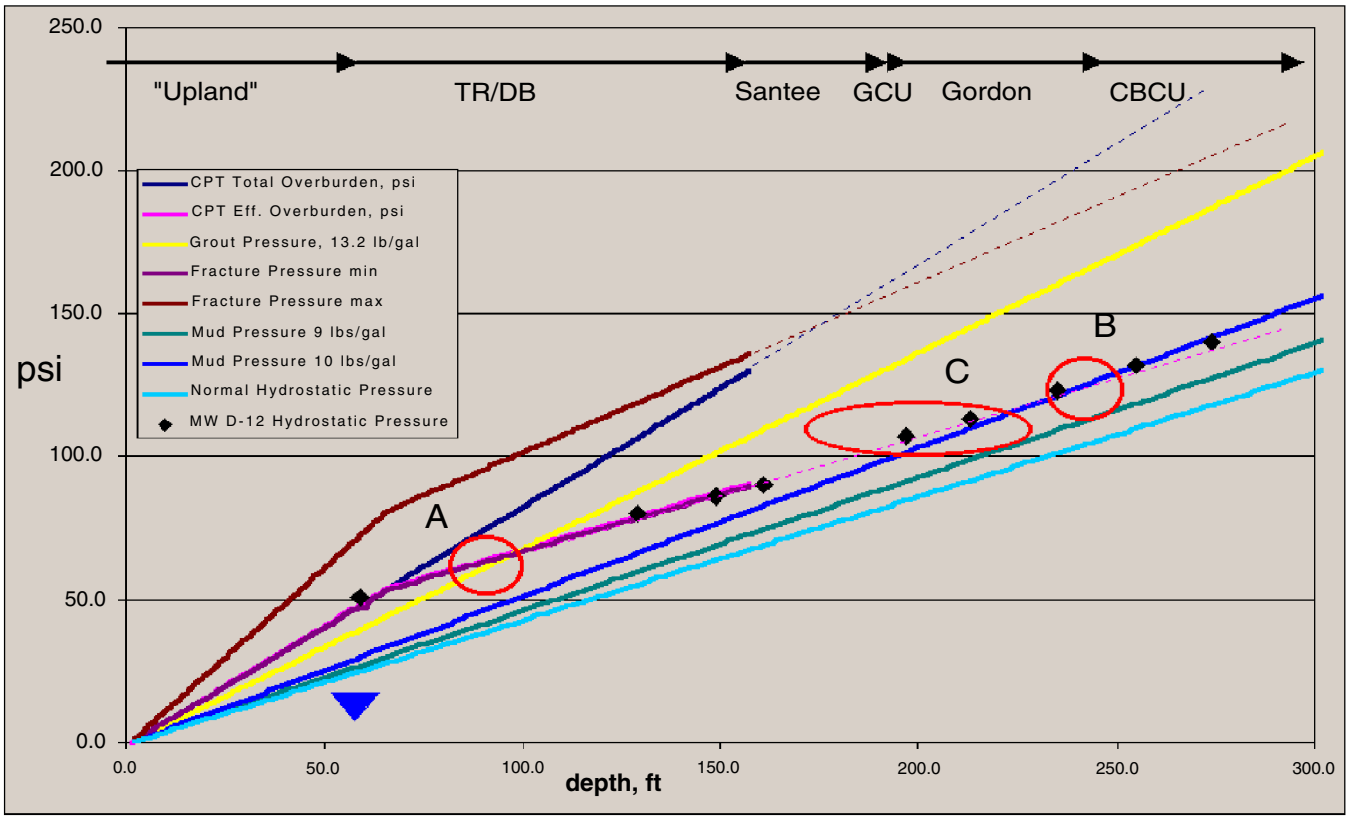

Figure 3. This graph presents the calculated maximum and minimum fracture pressures, measured hydrostatic pressures from the FMT tool, total and effective overburden pressures measured from the CPT tool, pressure weights of typical grout and drilling mud versus depth, from well MWD-12. A normal freshwater hydrostatic curve is also shown for comparison. The interpreted formation horizons are shown across the top of the graph associated with the depth. "Upland" is the Upland Unit, "TR/DB" is the Tobacco Road Fm. – Dry Branch Fm. contact, "Santee" is the Tinker/Santee Fms. interval, "GC" is the Green Clay or Gordon Confining unit of the Warley Hill Fm., ""Gordon"" is the Gordon Aquifer Unit and "CBCU" is the Crouch Branch Confining Unit. Several lines are extrapolated (dashed lines) to depths beyond the available CPT data. The water table depth is shown as a blue triangle. These data do not include surface pump pressures the inclusion of which would shift the intersection areas "A" and "B" to shallower depths.

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