Regional trends in undercompaction and overpressure in the Gulf of Mexico

Summary
Shallow water flow and overpressure, arising primarily from rapid sedimentation rates generated by the Mississippi River depocenter, represent major drilling hazards in the deepwater Gulf of Mexico. In this paper, checkshots released by the Minerals Management Service (MMS) for the Gulf of Mexico are inverted for velocity versus depth below mudline, then kriged to populate a 3D Mechanical Earth Model (MEM) with both velocity and expected uncertainty. The 3D velocity cube thus obtained is used to infer regional variations in overpressure and undercompaction of shallow sediments.

Introduction
Overpressure and shallow water flow represent significant drilling hazards for deepwater drilling. For shallow sediments in the deepwater Gulf of Mexico, compaction disequilibrium is the most important cause of overpressure. For sediment to compact, pore water must be expelled. However, if sedimentation is rapid compared to the time required for fluid to be expelled from the pore space, or if a seal is formed that prevents dewatering and compaction during burial, the pore fluid becomes overpressured and supports part of the overburden load. Shallow water flows originating from overpressured sands are generally encountered within the shallowest 1000 ft of overburden. These sands can flow into the open wellbore and up to the seabed. Shallow water flows often cannot be controlled by mud weight alone because shallow sediments are usually too weak to contain a mud column circulating up to the rig. The erosion caused by shallow water flows can also lead to loss of structural support in adjacent wells, creating an increased risk for casing buckling and failure.

As part of an effort to understand the problem of shallow water flow, Ostermeier et al. (2001) examined data from several geotechnical wells drilled in the central Gulf of Mexico, where shallow water flow problems have occurred. It was found that significant overpressures begin at or close to the mudline and increase almost linearly with depth. Moreover, measured overpressures exhibit regional trends that are generally consistent with sedimentation rate and that correlate with the incidence and severity of shallow water flow.

In this paper, all presently available checkshots released by the MMS for the Gulf of Mexico are inverted to obtain compressional velocity versus depth below mudline. These velocity functions are then kriged to populate a 3D MEM with both velocity and expected uncertainty. The 3D velocity cube thus obtained is used to infer the regional variation in overpressure and undercompaction of shallow sediments. By applying a threshold to the predicted kriging error, maps of undercompaction and overpressure can be restricted to areas of greater reliability. The results of this analysis are expected to find application in the drilling of safe and economic wells.

Sensitivity of seismic velocities to undercompaction
Elastic wave velocities in rocks normally increase during loading due to porosity reduction and increased grain contact. However, if the rate of sedimentation exceeds that of fluid expulsion from the pore space, or if dewatering is inhibited by the formation of seals during burial, the pore fluid becomes overpressured and thus supports part of the overburden load. As a result, the porosity is higher and the elastic wave velocity is lower than in normally pressured sediments. This situation is illustrated in Figure 1, where the increase in velocity with depth below the mudline is approximated by a linear depth gradient $k$:

$$v = v_0 + kz \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots$$

Figure 1. Schematic variation of elastic wave velocity with depth below mudline for normally compacted and undercompacted sediments.

In areas undergoing rapid sedimentation, the compaction coefficient $k$ is thus smaller than in areas of slower sedimentation, where pore pressures induced by loading have sufficient time to dissipate. Overpressures resulting from compaction disequilibrium can therefore be predicted,
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given sufficiently accurate seismic velocities (Sayers et al., 2002). Velocities employed for this study were obtained by inversion of checkshot data released by the MMS for the Gulf of Mexico, as described below.

Checkshot inversion

Figure 2 shows the locations of checkshots included in the study, corresponding to all the surveys available from the MMS archive at the end of 2004.

Figure 2. Locations of checkshots currently released by the MMS (red dots) in the Gulf of Mexico relative to the coastline (blue).

Figure 3 shows time-depth pairs from a typical checkshot survey, together with interval velocity calculated from the relation:

\[ v_{ij} = \frac{z_i - z_{i-1}}{t_i - t_{i-1}} \]  \hspace{1cm} \text{(2)}

where \( v_{ij} \) is the interval velocity between receiver positions, \( z_i \) and \( z_{i-1} \) are the depths at adjacent positions, and \( t_i \) and \( t_{i-1} \) are the first-arrival times at each receiver depth.

From Figure 3, it is evident that the velocity versus depth profile is adversely affected by picking errors in the measured travel time. Accordingly, a weighted damped least-squares inversion of the measured travel times was employed to compute velocity-depth profiles consistent with the errors in the travel time data.

Following Lizarralde and Swift (1999), the interval velocities between receivers may be determined from measured first arrival times by solving the linear equation:

\[
\begin{bmatrix}
    t_1 \\
    t_2 \\
    \vdots \\
    t_N
\end{bmatrix} =
\begin{bmatrix}
    \Delta z_1 & 0 & \cdots & 0 \\
    \Delta z_1 & \Delta z_2 & \cdots & 0 \\
    \vdots & \vdots & \ddots & \vdots \\
    \Delta z_1 & \Delta z_2 & \cdots & \Delta z_N
\end{bmatrix}
\begin{bmatrix}
    s_1 \\
    s_2 \\
    \vdots \\
    s_N
\end{bmatrix}
\]  \hspace{1cm} \text{(3)}

where \( t_i \) are the first-arrival times at each receiver depth (\( i = 1 \ldots N \)), \( \Delta z_i \) are difference in depths between receivers, and \( s_i = 1/v_i \) are the interval slownesses, \( v_i \) being the interval velocities. It is convenient to write equation (3) as

\[ T = ZS. \]  \hspace{1cm} \text{(4)}

A damped least-squares inversion was performed (Lizarralde and Swift, 1999), employing a penalty function based on the second derivative of estimated slowness as a smoothing criterion. A least-squares solution was obtained by minimizing:

\[ L = \| T - ZS \| + \epsilon^2 \| DS \| \]  \hspace{1cm} \text{(5)}

where \( \| \cdot \| \) denotes the \( L_2 \) norm, \( D \) is the second-derivative matrix, \( DS \) is the penalty function, and \( \epsilon \) is the damping parameter, governing the trade-off between minimization of the data misfit and the penalty function. Figure 4 shows the inverted interval velocity as a function of depth for several values of \( \epsilon \). An appropriate choice of \( \epsilon \) was made by examining the associated travel time residuals.

Figure 4. Damped least-squares inversion of a checkshot (Figure 3) for various values of \( \epsilon \) in equation 5.
Construction of the 3D velocity model

Following inversion of the checkshots, the derived interval velocity versus depth profiles were loaded into a 3D geostatistical modeling application, together with sonic and density logs from several deepwater wells released by the MMS. A detailed sea-bottom surface for the entire western Gulf of Mexico (15-sec resolution) was derived from bathymetry and elevation data (NGDC) for the geographical region between –83° and –97° longitude and 26° and 30° latitude, as shown in Figure 5.

A 3D curvilinear stratigraphic grid was constructed conformable to this mudline surface by spline interpolation, to a maximum depth of 30,000 ft subsea. Each cell in the stratigraphic grid measures 0.05° × 0.05° in area (approximately 3.5 × 3.5 sq. miles, or one block), by 60 ft thick. A 3D estimate of bulk density was derived using a relation of the form given by Traugott (1997), calibrated to available deepwater density logs. Density was then integrated to obtain overburden stress. A corresponding 3D velocity trend was obtained from density via Gardner’s relation, calibrated to available sonic logs. After upscaling to the stratigraphic grid, the combined checkshot and sonic velocities were kriged, using the 3D velocity trend as an estimate of the local mean in each cell, assuming an exponential model of spatial correlation with a laterally isotropic effective range of order 1° and vertical range of order 600 ft. The resulting trend-kriged velocity model is shown in Figure 6, with the 3D distribution limited to a region where the average predicted kriging error (Figure 7) is less than ±1200 ft/sec. Figure 8 shows a map of the compaction coefficient $k$ draped on the water-bottom surface, also limited to the area where velocity error is less than 1200 ft/sec. This map was obtained by minimizing the rms difference between kriged velocity and equation 1 for the first 5000 ft below mudline. The compaction coefficient thus obtained is seen to be minimum in the deepwater areas near the shelf edge, indicating that the undercompaction is greatest in this region.
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Pore pressure prediction

Since any increase in pore pressure above the normal hydrostatic gradient reduces the amount of compaction that can occur, elastic wave velocities can be used to predict pore pressure. This was first demonstrated by Hottman and Johnson (1965) using sonic velocities, and again by Pennebaker (1970) using seismic velocities. In the following discussion, it is assumed that elastic wave velocity is a function only of the vertical effective stress $\sigma$, defined by:

$$\sigma = S - p$$

where $p$ is pore pressure and $S$ is total vertical stress.

The vertical effective stress, $\sigma$, was obtained from trend-kriged velocity assuming a Bowers-type relation between seismic interval velocity and effective stress of the form:

$$v = v_0 + A\sigma^B$$

where $v_0$ is the velocity of the sediment at low stress, and $A$ and $B$ describe the variation in velocity with increasing effective stress. Parameters $v_0$, $A$, and $B$ were obtained as described by Sayers et al. (2002).

Figure 9 shows the 3D pore-pressure estimate, in pounds per gallon (ppg) mud weight equivalent, obtained using the trend-kriged velocity and computed overburden stress as input to equation 7. Note that a mud weight of 1 ppg is equivalent to a density of 0.1198 g/cm$^3$, and a pressure gradient of 1.17496 kPa/m.

Figure 9. Pore pressure [ppg] predicted from trend-kriged inverted checkshots and sonic logs for deepwater wells released by MMS, for all locations where pore pressure exceeds 10 ppg and predicted velocity error (Figure 7) is less than $\pm1200$ ft/sec. (Scale for land elevation above sea level is not shown.)

Conclusion

Shallow water flow and overpressure are major drilling hazards in the deepwater Gulf of Mexico, mainly due to rapid sedimentation from the Mississippi River depocenter. Data from several central deepwater Gulf of Mexico prospects indicate that significant overpressures begin at or near the mudline and increase linearly with depth. Moreover, regional overpressure trends correlate with both the incidence and severity of shallow water flow.

In this study, checkshots released by the MMS for the Gulf of Mexico were used to estimate the 3D distribution of elastic wave velocity. The map of compaction coefficient, $k$, derived from this velocity model suggests that undercompaction, and hence associated risk from overpressure and/or shallow water flow, is likely to be largest in the vicinity of the continental shelf edge, particularly near the present mouth of the Mississippi. These results were obtained by assuming that velocity is a function only of vertical effective stress, defined as the difference between total vertical stress and pore pressure. It may be anticipated that such regional knowledge of undercompaction trends will aid in the planning and safe drilling of future economic deepwater wells.

References

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EDITED REFERENCES

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