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Regional Maps of Subsurface Geopressure Gradients of the Onshore and Offshore Gulf of Mexico Basin

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1. INTRODUCTION

A published map (**fig. 1**) of the geographical distribution of a regional geopressure gradient in the Gulf of Mexico basin was first released by Wallace and others (1981). Their map was constructed from approximately 6,000 pressure measurements across the Gulf Coast onshore and offshore region (table 17, page 143, Wallace and others, 1979). These mapping efforts (Wallace and others, 1977, 1979, 1981; Wesselman, 1977; Wesselman and Heath, 1977) resulted in the first, publicly available, regional-scale map of the 0.70 pounds force per square inch per foot (psi/ft) pressure-gradient surface across the Gulf Coast region, including the onshore, State waters, and offshore areas.

The availability of 30 additional years of drilling and production data affords an order of magnitude increase in data coverage, both stratigraphically and geographically, which allows for a more detailed and accurate characterization of the subsurface pressure system in the Gulf of Mexico basin. A modern understanding of the regional distribution, depth of occurrence, and magnitude of subsurface pressure gradients, depressurization zones, and overpressured regions is critical for assessing undiscovered hydrocarbon resources, evaluating areas with potential pressure-related production, and identifying potential pressure-related geohazard issues in order to minimize possible environmental consequences of petroleum production. These pressure-gradient maps help identify the possible geographic and stratigraphic distribution of anomalously overpressured and underpressured regions, which is necessary for the evaluation of deep hydrocarbon resources based on their distinct pressure signatures. Regional subsurface pressure characterization is also essential for the evaluation of reservoir-seal integrity and the determination of potential undiscovered hydrocarbon accumulations. Additionally, the identification of overpressured or underpressured regions is a critical parameter for evaluating the viability of geological sequestration and long-term containment of fluids (Brennan and others, 2010; Burke, 2011), such as supercritical carbon dioxide.

For this regional study, more than 300,000 mud-weight measurements from over 860,000 wells were examined, of which 200,000 mud weights from 70,000 wells were incorporated. The data used in this pressure-gradient investigation are from multiple sources: (1) the proprietary industry IHS database (IHS, 2011), and (2) measurements from several historical folios (Dodge and Posey, 1981; Bebout and Gutiérrez, 1982, 1983; Eversull, 1984; Foote and others, 1990) that show regional cross-sections based on well log curves. Mud weight measurements and wellbore temperature data from the historical folios were compiled and digitally archived (Burke and others, 2011).

The geographical extent of the regional pressure-gradient investigation (**fig. 2**) is defined in the west, north, and east by the Upper Jurassic-Cretaceous-Tertiary Total Petroleum System boundary, which was defined for the assessment of undiscovered hydrocarbon resources in the Gulf Coast region (Dubiel and others, 2010). The study area extends from the United States-Mexico international border along southwestern Texas and continues eastward into Texas, Louisiana, Mississippi, Alabama, and Florida. The study area also includes parts of Oklahoma, Arkansas, Missouri, Illinois, Kentucky, Tennessee, and Georgia. State waters of Florida and Georgia represent the eastern extent of this study area. The southern boundary of the study area is approximated by the 10,000-ft (3,048-m) deep bathymetric contour (National Oceanic and Atmospheric Administration, 2012) along the modern shelf margin in the Gulf of Mexico, which coincides with the regional extent of the data available from the IHS database used for this investigation (IHS, 2011).

The U.S. Geological Survey (USGS) created a comprehensive geopressure-gradient model of the regional pressure system spanning the onshore and offshore Gulf of Mexico basin, USA. This model (Burke and others, 2012a), was used to generate ten maps (Burke and others, 2012b) that included (1) five contour maps characterizing the depth to the surface defined by the first occurrence of isopressure gradients ranging from 0.60 psi/ft to 1.00 psi/ft, in 0.10-psi/ft increments; and (2) five supporting maps illustrating the spatial density of the data used to construct the contour maps. Equations were developed using linear interpolation methods to take advantage of intermediate pressure gradients within a single wellbore. This approach increases the data quantity while the accuracy of the data.

The regional pressure system extends from the onshore, through the State waters, and into the offshore waters in the Gulf of Mexico basin. In order for accurate evaluation of the pressure system in the onshore and State waters, which are the principal areas in the Gulf Coast region that the USGS assesses for undiscovered petroleum resources, knowledge of the offshore pressure distribution is necessary. Because this study examines subsurface geopressure gradients across the entire Gulf of Mexico basin, the results from this regional investigation are not applicable for small-scale, detailed examinations of specific locations.

Figure 2. Map showing the extent of the regional pressure-gradient investigation in the Gulf of Mexico basin. The western, northern, and eastern extent of the study area (solid red line) is defined by the Upper Jurassic-Cretaceous-Tertiary Total Petroleum System boundary (Dubiel and others, 2010), and includes all or parts of the states of Texas, Louisiana, Mississippi, Alabama, Florida, Oklahoma, Arkansas, Missouri, Illinois, Kentucky, Tennessee, and Georgia, as well as the associated State waters. The southern extent (red dashed line) of this investigation extends into offshore waters and is approximated by the 10,000-ft (3,048-m) deep bathymetric contour (National Oceanic and Atmospheric Administration, 2012), which coincides with the deepwater data availability for this investigation. The dotted red line connects the two boundaries.

2. PRESSURE GRADIENTS

2.1 Generalized pressure gradients and associated pressure regimes (fig. 3)

- 0.465 psi/ft is the generalized hydrostatic pressure gradient for the Gulf of Mexico basin (Schlumberger, 2012)
- 0.70 psi/ft is associated with top of overpressure (Bourgoyne, 2003)
- 1.00 psi/ft is the lithostatic pressure gradient (Bourgoyne, 2003)
- Pressure regimes are subdivided into underpressure, normal pressure, overpressure, and hard overpressure regimes (Bourgoyne, 2003)

2.2 Mud-weight measurements were the primary data source for this investigation because of the following features

- Internally consistent database
- In-situ measurements
- Geographically extensive coverage
- Routinely recorded during all phases of wellbore drilling and completion operations
- Multiple mud-weight measurements are commonly available within a single wellbore
- Enable the reconstruction of a pressure-gradient curve for individual well locations

2.3 Drilling mud weights approximate the subsurface pressure as a function of depth because

- Wells are commonly drilled with balanced or slightly over-balanced drilling scheme
  - Increases the margin of safety with respect to unforeseen pressure hazards in the subsurface
  - Mud weights increased by ~0.03 psi/ft, or 0.5 pounds per gallon mud weight equivalent (ppg mwe), above expected gradients
  - Technique conducted throughout the depth range of well
  - Conducted for the majority of wells in the Gulf of Mexico basin
- Mud-weight measurements, and their relative increases, are reasonably representative of subsurface pressure gradients

2.4 Conversion between pressure gradients, *P*, in units of psi/ft, and drilling mud weights, *MW*, in units of ppg or ppg mwe as appropriate, can be calculated by the relations

$$P = c_1 \cdot MW \qquad (1)$$

or conversely,

$$MW = c_2 \cdot P \qquad (2)$$

where $c_1 = 0.052$ and $c_2 = 19.231$, respectively (McCray and Cole, 1959).

3. METHODOLOGY AND LINEAR INTERPOLATION CALCULATIONS

3.1 Data available to the USGS for this regional Gulf Coast investigation

- 863,340 wells and 336,681 mud-weight measurements
- Data are from various sources:
  - Proprietary industry IHS database (IHS, 2011)
  - Measurements from several historical folios (Dodge and Posey, 1981; Bebout and Gutiérrez, 1982, 1983; Eversull, 1984; Foote and others, 1990)
  - Data from historical folios were compiled by Burke and others (2011)
- Only boreholes with vertical orientations were used for this investigation
- The final dataset used for this study had a total of 69,391 wells and 202,060 mud-weight measurements
- **Table 1** provides data metrics for each pressure-gradient map

3.2 Data were removed from this 863,340-well database based on the following criteria

- Mud-weight measurements were null
- Depth measurements were null
- Mud-weight measurements were exactly equal to depth measurements, which is likely a data transcription error but would ultimately result in an erroneous pressure gradient approaching the lithostatic pressure gradient of 1.00 psi/ft
- Pressure gradients below 35 percent of the hydrostatic pressure, that is 0.30 psi/ft (5.8 ppg mwe) and below
- Pressure gradients above 35 percent of the lithostatic gradient, that is 1.56 psi/ft (30.0 ppg mwe) and above

3.3 Pressure gradient calculations

Pressure gradients were calculated from mud-weight measurements using relations described by equations 1 and 2. Individual pressure gradients were determined at successive depths within a single vertical wellbore. Ideally, only the 0.70 psi/ft pressure gradients, for instance, would be used in the creation of the mapped horizon. This would, however, limit the number of well control points that compose the final map. In the absence of an exact 0.70 psi/ft value, a linear interpolation algorithm was derived to calculate the depth, z_P, at which a specific pressure gradient, P, occurs in the subsurface. This calculation takes advantage of the occurrence of multiple depth and corresponding pressure-gradient data pairs within a given wellbore. This algorithm searches for the nearest pressure-gradient value above as well as below the value closest to $P = 0.70$ psi/ft, for example.

In this formulation, z_1 and P_1 are, respectively, the depth and corresponding pressure gradient above the interpolated depth; z_2 and P_2 are, respectively, the depth and corresponding pressure gradient below the interpolated depth. The interpolated depth, z_P, for a value of P in units of psi/ft, is given by the relation:

$$z_P = \frac{P - P_1 + z_1 A}{A} \qquad (3)$$

where

$$A = \frac{P_2 - P_1}{z_2 - z_1} \qquad (4)$$

For a pressure reversal in a well (**fig. 4**), the depth corresponding to the first occurrence of the pressure gradient, which is the shallowest depth, was used for the calculations.

3.4 Accuracy of linear interpolation results

- Lower and upper bounds were established to limit the search range to the nearest neighboring values within a single wellbore
- Search range was restricted to ±0.09 psi/ft above and below the contoured horizon, with the exception of the 0.60 and 1.00 psi/ft pressure-gradient surfaces
- **Table 2** summarizes range restrictions for each pressure-gradient map
- Restrictions were applied on a well-by-well basis, which honors the finer details offered by multiple mud weights in a wellbore
- Localized gradients were calculated within each well to reconstruct subsurface pressure gradients as a function of depth
- This method avoids creating over-generalized gradients from, for example, a gradient calculated using a near-surface data point and an ultra-deep data point
- No extrapolations were conducted to supplement the existing dataset

4. PRESSURE-GRADIENT MAPS

4.1 Map contouring algorithm

- Local polynomial interpolation (LPI) algorithm available in ArcGIS (ArcGIS, 2011a; 2011b)
- Interpolation method categorized as a deterministic method, as opposed to a geostatistical method, for spatial interpolation
- LPI classified as an inexact interpolator, which allows for calculating values between known data points
- Calculated values weighted by proximity using a moving ellipse, whereby semi-major and semi-minor axes constitute the neighborhood proximities
- LPI algorithm parameterized with exponential kernel function to allow for proportional growth and decay, as expected in the natural sciences

4.2 Pressure-gradient maps (figs. 5A – 9A)

- Characterize occurrence and distribution of isopressure gradients of the onshore and offshore Gulf of Mexico basin
- Isopressure-gradient surfaces were mapped at 0.60, 0.70, 0.80, 0.90, and 1.00 psi/ft magnitudes
- Contours represent the depth to the top of the first occurrence of the isopressure-gradient surface
- Cooler colors represent shallower occurrences of the isopressure-gradient surface; warmer colors represent deeper occurrences of the isopressure-gradient surface

4.3 Data density maps (figs. 5B – 9B)

- Each data density map uniquely corresponds to one of the five pressure-gradient maps
- Number of wells within a six-square-mile grid block yields the data density by surface area
- Depict spatial density of data distribution, in which warmer colors represent higher well control, cooler colors represent lower well control

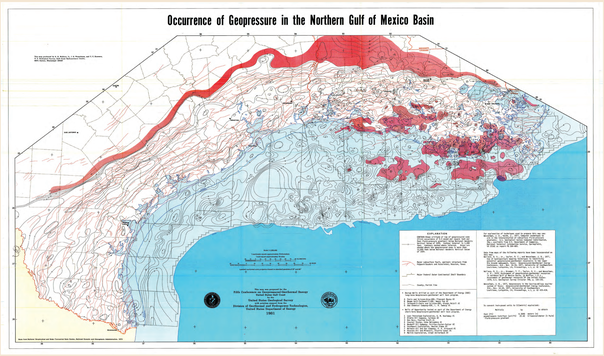

Figure 1. Previously published map of the geographical distribution of a regional geopressure gradient in the Gulf of Mexico basin (Wallace and others, 1981).

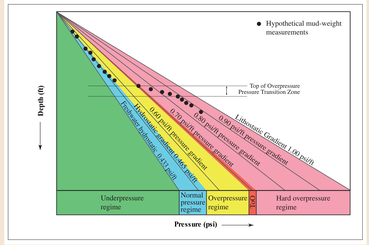

Figure 3. Schematic diagram of generalized pressure gradients and associated pressure regimes. The hydrostatic pressure gradient, for the formation water salinities typically encountered in the Gulf of Mexico, is 0.465 psi/ft (Schlumberger, 2012). The range of normal pressure bounds the hydrostatic pressure gradient. Overpressure describes the pressure regime above normal pressure. The top of overpressure generally coincides with the 0.70 psi/ft pressure gradient. Hard overpressure occurs beyond this regime. Subsurface pressure gradients above the lithostatic gradient, which occurs at 1.00 psi/ft, are not frequently encountered in nature. ToO (red) denotes top of overpressure.

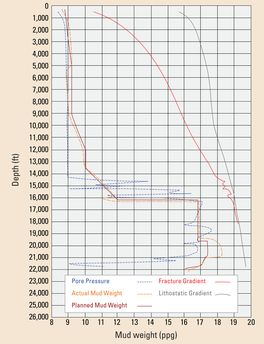

Figure 4. Example of a pressure gradient reversal in a well (modified from Cox and others, 2007).

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