REGIONAL MAP OF THE 0.70 PSI/FT PRESSURE GRADIENT AND DEVELOPMENT OF THE REGIONAL GEOPRESSURE-GRADIENT MODEL FOR THE ONSHORE AND OFFSHORE GULF OF MEXICO BASIN, U.S.A.

Lauri A. Burke, Scott A. Kinney, Russell F. Dubiel, and Janet K. Pitman

U.S. Geological Survey, Denver Federal Center, Box 25046, MS 939, Denver, Colorado 80225–0046, U.S.A.

ABSTRACT

The U.S. Geological Survey has created a comprehensive geopressure-gradient model of the regional pressure system spanning the onshore and offshore portions of the U.S. Gulf of Mexico basin. Over 300,000 mud-weight measurements from more than 860,000 wells were examined, of which over 200,000 mud-weight measurements from approximately 70,000 wells were used to create the geopressure-gradient model. The model was used to generate contour maps that characterize the depth and distribution of isopressure-gradient surfaces from 0.60 psi/ft to 1.00 psi/ft, in 0.10 psi/ft increments, as well as supporting maps that display the spatial density of the data used to construct the isopressure-gradient maps. In this paper, we focus on the details of the geopressure-gradient model and the creation of the 0.70 psi/ft pressure-gradient map. The depth at which the 0.70 psi/ft pressure gradient occurs is significant as it is generally considered to represent the "top of overpressure" or the "top of the overpressure transition zone."

Characterization of the regional pressure system is critical for assessing the occurrence of undiscovered petroleum resources, evaluating areas with potential pressure-related production, identifying potential pressure-related geohazard issues, evaluating hydrocarbon reservoir-seal integrity, and determining the feasibility of geological sequestration and long-term containment of fluids.

INTRODUCTION

A depth-contour map representing the 0.50 psi/ft pressure-gradient surface in the Gulf of Mexico basin was first published by Wallace et al. (1981). The map was constructed from approximately 6,000 pressure measurements across the Gulf Coast onshore and offshore region (Wallace et al., 1979, their Table 17, p. 143). Documentation accompanying this map, and earlier pressure-gradient studies (Wallace et al., 1977; 1979; 1981; Wesselman, 1977; Wesselman and Heath, 1977), in conjunction with pressure-gradient evaluations in this investigation indicate that the map published by Wallace et al. (1981) corresponds to a 0.70 psi/ft pressure-gradient surface that extends across the Gulf Coast region, including the onshore, State waters, and offshore areas.

The availability of 30 additional years of drilling and production data results in a substantial 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 (Fig. 1). 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, as well as identifying potential pressure-related geohazard challenges in order to minimize possible environmental consequences of petroleum production. Knowledge of the depth and magnitude of various pressure-gradients is essential for identifying the geographic and stratigraphic distribution of 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 evaluating reservoir-seal integrity and for estimating potential undiscovered hydrocarbon accumulations. Additionally, identification of overpressured and

Figure 1. Map showing the extent of this regional pressure-gradient investigation. The western, northern, and eastern extent of the study area (solid red line) is approximated by the Upper Jurassic–Cretaceous–Tertiary Total Petroleum System boundary (Dubiel et al., 2010), and the southern extent (dotted red line) coincides with limit of the deepwater data available for this study.

underpressured regions is a critical parameter for assessing the viability of geological sequestration and long-term containment of supercritical fluids (Brennan et al., 2010; Burke, 2011), such as carbon dioxide.

For this regional study, more than 300,000 mud-weight measurements from over 860,000 wells were examined; of these, over 200,000 mud weights from approximately 70,000 wells were incorporated into the geopressure-gradient model. The mud-weight data are from multiple sources: (1) the proprietary industry IHS database (IHS Energy Group, 2011), and (2) several folios (Bebout and Gutiérrez, 1982; 1983; Dodge and Posey, 1981; Eversull, 1984; Foote et al., 1990) that are comprised of regional cross-sections based on well log curves. Subsurface pressure and wellbore temperature data from the folios were compiled and digitally archived (Burke et al., 2011).

Although the geopressure-gradient model characterizes the regional subsurface distribution of the 0.60, 0.70, 0.80, 0.90, and 1.00 psi/ft pressure gradients, this paper focuses on the 0.70 psi/ft pressure-gradient surface across the Gulf of Mexico basin. This paper includes a description of the source and distribution of the pressure data incorporated into the model, as well as the equations used for calculating pressure gradients and their conversions into different industry-standard unit systems. Equations

were developed using linear interpolation principles to take advantage of intermediate pressure gradients within a single wellbore. Interpolation methods increased the data quantity while maintaining data accuracy.

The geopressure-gradient modeling resulted in a series of regional subsurface geopressure-gradient maps that characterize surfaces of equal pressure in the onshore, State waters, and offshore portions of the Gulf of Mexico basin. In order to accurately evaluate the pressure system in the onshore and State waters, which are the principal areas in the Gulf Coast region that the U.S. Geological Survey (USGS) assesses for undiscovered petroleum resources, the offshore pressure distribution was taken into account. Although this geopressure-gradient model characterized subsurface isopressure gradients spanning the Gulf of Mexico basin, the results from this regional investigation are not applicable for small-scale, detailed pressure examinations of specific locations.

STUDY AREA

The geographic extent of our regional pressure-gradient investigation (Fig. 1) is defined in the west, north, and east by the Upper Upper Jurassic–Cretaceous–Tertiary Total Petroleum Sys-

tem boundary, which was defined for the assessment of undiscovered hydrocarbon resources in the Gulf Coast region (Dubiel et al., 2010). The study area extends for some distance along the United States–Mexico international border and continues northward and eastward through Texas, Louisiana, Mississippi, Alabama, and Florida. The study area also includes small 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 coincides with the regional extent of the data available from the IHS database (IHS Energy Group, 2011) used for this investigation. The geopressure-gradient model encompasses an area that represents the maximum extent of the calculated pressure-gradient data.

PRESSURE GRADIENTS

In the shallow subsurface of the Gulf Coast, pressure gradients generally follow a hydrostatic pressure-gradient trend (Fig. 2). A normal or hydrostatic gradient represents the theoretical pressure gradient exerted by a column of fresh water. The typical formation water salinities in the Gulf of Mexico basin are approximately 100,000 parts per million of total dissolved solids (Schlumberger, 2012), which results in a hydrostatic pressure gradient of 0.465 psi/ft. As pressure builds in the subsurface strata with increasing depth, the pressure gradient departs from the hydrostatic gradient line (Fig. 2). Pressure gradients in the region below the hydrostatic gradient represent underpressured regimes; whereas, overpressured regimes refer to regions that exhibit pressure gradients above the hydrostatic gradient. Overpressured regimes are further subdivided: (1) a pressure gradient of 0.70 psi/ft marks the top of the transition zone from moderate to extreme increases in pore pressure, and the depth at which this change in pressure occurs is referred to as the top of overpressure; and (2) hard overpressure describes pressure regimes varying from approximately 0.70 psi/ft to as high as the lithostatic pressure gradient, which occurs at 1.00 psi/ft. Pressure gradients that significantly exceed 1.00 psi/ft are not typically encountered in nature because the lithostatic pressure gradient represents the theoretical gradient exerted by a column of solid rock with no pore space.

In this investigation, mud-weight measurements were the primary data source used to compile an internally consistent database. These in-situ pressure gradient measurements provide geographically extensive coverage, and mud-weight measurements are routinely recorded during all phases of wellbore drilling and completion operations. Additionally, multiple mud-weight measurements are commonly available within a single wellbore, which enables the reconstruction of a pressure-gradient curve for that well.

Drilling mud weights can be used as a proxy for subsurface pressure as a function of depth. Wells are commonly drilled with a balanced or slightly over-balanced drilling scheme to increase the margin of safety with respect to unforeseen pressure hazards in the subsurface. With this technique, drilling mud weights are generally increased by approximately 0.03 psi/ft, or 0.5 lbs/gal (ppg) above the expected in-situ pressure gradients. Because this technique is conducted throughout the entire depth range of a well, and for the majority of wells in the Gulf of Mexico basin, the magnitude of the mud-weight measurements and their relative increases are reasonably representative of subsurface pressures. Thus, drilling mud-weight data were not corrected for this study.

Conversion between pressure gradients, *P*, in units of pounds force per square inch per foot (psi/ft), and drilling mud
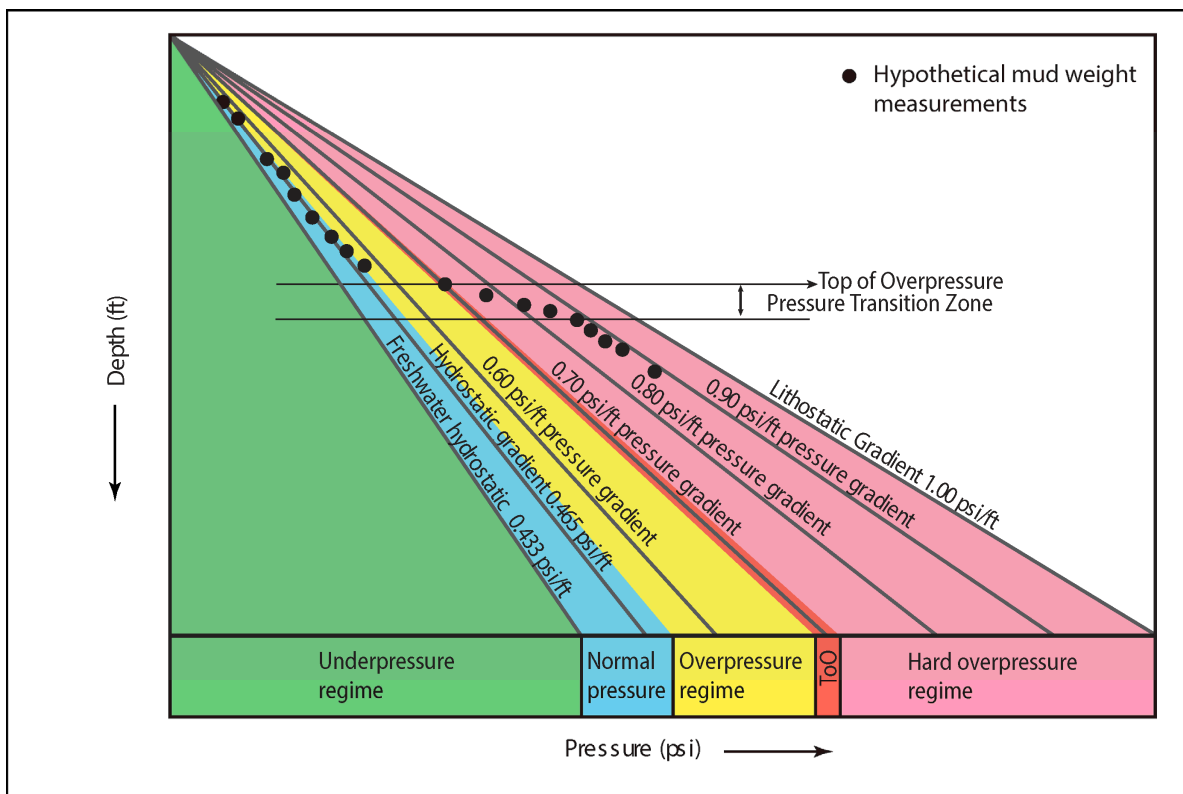

Figure 2. Schematic diagram of generalized pressure gradients and associated pressure regimes. The top of overpressure is denoted by ToO.

weights, *MW*, in units of pounds force per gallon (ppg), can be calculated by the relations:

$$MW \cdot c_1 = P, \tag{1}$$

or conversely,

$$MW = c_2 \cdot P, \tag{2}$$

where the conversion constants c_1 = 0.0519405 psi/ft/ppg and c_1 = 9.252803 ppg/psi/ft, respectively. Table 1 provides the magnitude of select pressure gradients in industry standard units. Note that pounds per square inch per foot is a weight divided by a volume; hence it is a pressure gradient. Mud weight, in units of pounds per gallon, is also a weight divided by a volume; hence, it too represents a pressure gradient.

Table 1. The magnitude of selected pressure gradients given in pounds force per square inch per foot (psi/ft) and pounds force per gallon (ppg). Note that 0.465 psi/ft, or 8.9 ppg, is the normal, hydrostatic pressure gradient for the formation salinities typically found in the Gulf of Mexico basin (Schlumberger, 2012). The 1.00 psi/ft, or 19.2 ppg, is the lithostatic pressure gradient.

Pressure Gradient (psi/ft)	Pressure Gradient (ppg)
0.465	8.9
0.50	9.6
0.60	11.5
0.70	13.5
0.80	15.4
0.90	17.3
1.00	19.2

METHODOLOGY AND LINEAR INTERPOLATION CALCULATIONS

The dataset available to the USGS for this Gulf Coast regional investigation consists of 336,681 mud-weight measurements from 863,340 wells; of these, over 202,060 pressure measurements from 69,381 wells were incorporated into the geopressure-gradient model. The data are from the proprietary industry IHS database (IHS Energy Group, 2011), as well as measurements from several folios (Burke et al., 2011). Only vertical wells were used for this investigation. Data were systematically removed from the pressure-gradient model based on the following criteria: (1) mud-weight measurement was null; (2) depth measurement was null; (3) mud-weight measurement equaled depth measurement, which is likely a data transcription error but would ultimately result in an erroneous pressure gradient approaching the lithostatic pressure; (4) pressure gradient was less than 35% of the hydrostatic pressure gradient, i.e., 5.8 ppg (0.30 psi/ft); and (5) pressure gradient was greater than 35% of the lithostatic pressure gradient, i.e., 30.0 ppg (1.56 psi/ft).

Pressure gradients were calculated from mud-weight measurements using the relations described in equations 1 and 2. Pressure gradients were determined on a well-by-well basis and included only vertical wells. As a result, several pressure gradi-

ents were obtained at successive depths within a single well. Ideally, only mud weights yielding exact 0.70 psi/ft pressure gradients would be used for generating the corresponding depth surface. Because this would greatly decrease the number of well-control points, 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 multiple depth and corresponding pressure-gradient pairs within a given wellbore. The algorithm searches for the nearest pressure-gradient value above and below the value closest to 0.70 psi/ft.

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, is given by the relation:

$$z_P = \frac{P - P_1 + z_1 A}{A}, \tag{3}$$

where

$$A = \frac{P_2 - P_1}{z_2 - z_1}, \tag{4}$$

for a value of P = 0.70 in units of psi/ft.

To maintain the accuracy of the linear interpolation results, lower and upper bounds were established for the input pressure gradients such that the search range was limited to ±0.09 psi/ft above and below the contoured pressure-gradient horizon. For the 0.70 psi/ft pressure-gradient map, the lower bound included gradients as low as 0.61 psi/ft and the upper bound included gradients as high as 0.79 psi/ft. These range restrictions were applied on a well-by-well basis. This method limits the search to the nearest neighboring values within a single wellbore so that only localized gradients are calculated. In addition, this method avoids creating over-generalized gradients; for example, in the case of a gradient calculated based on a near-surface data point and an ultra-deep data point. The linear interpolation method maintains the accuracy as well as the finer details offered by multiple mud weights that track the subsurface pressure as a function of depth.

In order to maintain the accuracy of the pressure-gradient surface, no extrapolations of pressure measurements were conducted to supplement the existing dataset; linear interpolation was the only method employed. In the case of a pressure reversal in a well, the depth corresponding to the first occurrence of the pressure gradient, which is the shallowest depth, was used in the calculations.

MAP CONTOURING ALGORITHM

The pressure-gradient surface was contoured using the local polynomial interpolation (LPI) algorithm in ArcGIS (ArcGIS, 2011a; 2011b). This interpolation method is deterministic, as opposed to geostatistical, and is used for spatial interpolation. The LPI is classified as an inexact interpolator, which allows for calculating values between known data points. The calculated values are weighted by proximity using a moving ellipse, whereby the semi-major and the semi-minor axes constitute the neighborhood proximities. Several parameters are available for customization within the LPI algorithm. To generate the 0.70 psi/ft pressure-gradient surface, the LPI algorithm was parameterized with an exponential kernel function to allow for proportional growth and decay, as expected in the natural sciences, and
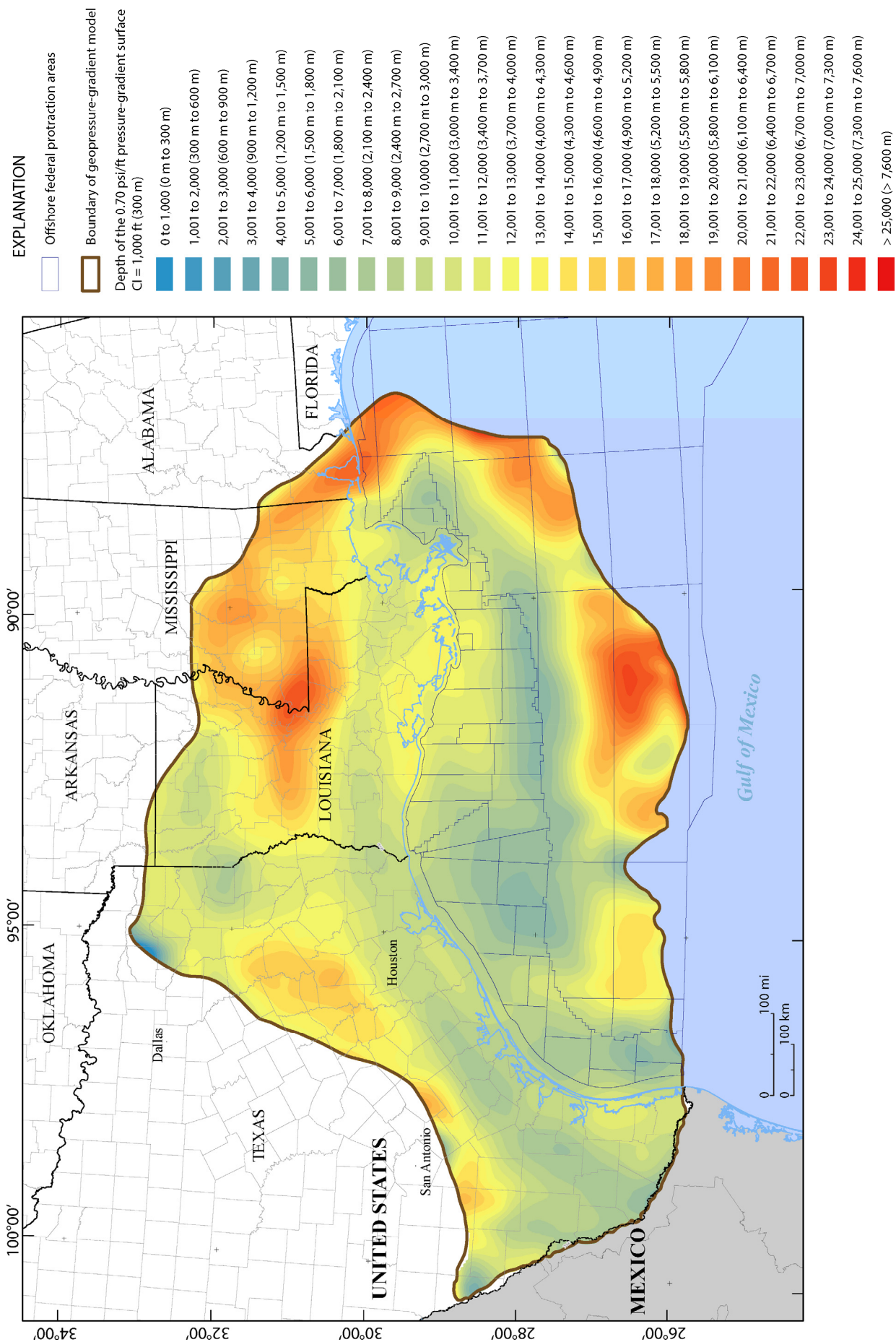
Figure 3. Map showing the regional distribution of depth contours of the 0.70 psi/ft pressure-gradient surface spanning the onshore and offshore Gulf of Mexico basin.

EXPLANATION

Offshore federal protraction areas

Boundary of geopressure-gradient model

Depth of the 0.70 psi/ft pressure-gradient surface
CI = 1,000 ft (300 m)

	0 to 1,000 (0 m to 300 m)
	1,001 to 2,000 (300 m to 600 m)
	2,001 to 3,000 (600 m to 900 m)
	3,001 to 4,000 (900 m to 1,200 m)
	4,001 to 5,000 (1,200 m to 1,500 m)
	5,001 to 6,000 (1,500 m to 1,800 m)
	6,001 to 7,000 (1,800 m to 2,100 m)
	7,001 to 8,000 (2,100 m to 2,400 m)
	8,001 to 9,000 (2,400 m to 2,700 m)
	9,001 to 10,000 (2,700 m to 3,000 m)
	10,001 to 11,000 (3,000 m to 3,400 m)
	11,001 to 12,000 (3,400 m to 3,700 m)
	12,001 to 13,000 (3,700 m to 4,000 m)
	13,001 to 14,000 (4,000 m to 4,300 m)
	14,001 to 15,000 (4,300 m to 4,600 m)
	15,001 to 16,000 (4,600 m to 4,900 m)
	16,001 to 17,000 (4,900 m to 5,200 m)
	17,001 to 18,000 (5,200 m to 5,500 m)
	18,001 to 19,000 (5,500 m to 5,800 m)
	19,001 to 20,000 (5,800 m to 6,100 m)
	20,001 to 21,000 (6,100 m to 6,400 m)
	21,001 to 22,000 (6,400 m to 6,700 m)
	22,001 to 23,000 (6,700 m to 7,000 m)
	23,001 to 24,000 (7,000 m to 7,300 m)
	24,001 to 25,000 (7,300 m to 7,600 m)
	> 25,000 (> 7,600 m)

used elliptical search neighborhoods with smoothing. The algorithm was augmented by geologic interpretation to rectify aberrant contours as necessary.

MAP OF 0.70 PSI/FT
PRESSURE-GRADIENT SURFACE

The 0.70 psi/ft pressure-gradient map (Fig. 3) characterizes the occurrence and distribution of this pressure gradient in subsurface strata of the onshore and offshore Gulf of Mexico basin. The contours represent the depth to the top of the pressure-gradient surface and are shown in 1,000-ft (300-m) increments. Cooler colors represent shallower occurrences of the 0.70 psi/ft pressure-gradient surface and warmer colors represent deeper occurrences of the surface. The depth datum is with respect to land surface or sea floor, as appropriate.

Figure 4 depicts the spatial density of the data used in contouring the 0.70 psi/ft pressure-gradient surface. Warmer colors represent areas with greater well control; cooler colors represent locations with less well control. The regional distribution of the data was subdivided, based on the surface locations of the (vertical) wells, using a 6.0-mi^2 grid. The number of wells located within a 6.0-mi^2 grid block yields the data density by surface area.

COMPARISON OF
PRESSURE-GRADIENT MAPS

The legend on the map published by Wallace et al. (1981) (Fig. 5A) stated that the depth contours represent the 0.50 psi/ft pressure-gradient surface; however, references in the documentation accompanying the map (Wallace et al., 1979; 1977; Wesselman, 1977; Wesselman and Heath, 1977) indicate that these contours actually correspond to the 0.70 psi/ft pressure-gradient surface. To resolve this discrepancy, we compiled a database of mud-weight measurements (IHS Energy Group, 2011) from wells drilled during or before 1981, and then created a series of maps at various pressure-gradient magnitudes, ranging from 0.50 to 1.00 psi/ft, in 0.10-psi/ft increments. These maps were contoured using the ArcGIS Nearest Neighbor algorithm (ArcGIS, 2012a; 2012b), which most closely approximates the computer-based contouring algorithms that were used in the 1981 map construction (Wesselman and Heath, 1977). Comparison of the 0.70 psi/ft pressure-gradient surface (Fig. 5B) and the 0.50 psi/ft surface (modified from Wallace et al., 1981) (Fig. 5A) shows they are in close agreement. It thus appears that the caption on the map published by Wallace et al. (1981) was mislabeled.

A portion of the 0.70 psi/ft pressure-gradient surface in a region off the coast of southeast Louisiana is shown in Figure 6 (see box in Figure 5A for location). The depth surface for this locale is contoured in grey, at a 100-ft (30-m) contour interval, which enables a more detailed characterization of this pressure-gradient surface. The areas in red depict where the pressure-gradient surface of Wallace et al., (1981) (Fig. 5A) is deeper than 13,000 ft (4000 m). Overall, the depths of the 100-ft (30-m) contours correspond to those characterizing the red areas, except in the southwest part where they are at shallower depths (~11,000 ft or 3,300 m). Two main factors might account for the differences in these depths. First, the map by Wallace et al. (1981), was constructed using only one mud weight to determine an overall pressure gradient in a well. In contrast, our linear interpolation algorithm utilizes all successive pressure measurements in a wellbore to determine multiple, localized pressure gradients, which results

in enhanced depth accuracy. Second, the contouring algorithm used in this study (LPI) was not available in 1981. LPI uses a two-dimensional elliptical smoother to capture north-south as well as east-west spatial variability in the contours.

The vintage of pressure data also might account for some of the variability in the depth contours. The map of Wallace et al. (1981) (Fig. 5A), the map we created using pre-1981 data (Fig. 5B), and the 0.70 psi/ft pressure-gradient map (Fig. 3) each display slightly different depths associated with the overpressured areas. The exact pressure dataset used in the map of Wallace et al. (1981) is unknown. Data (IHS Energy Group, 2011), with no consideration of data quality (see factors 1–5 in methodology section), were used to generate our pre-1981 map. The most complete, current, and quality-checked dataset, which was derived from IHS data (IHS Energy Group, 2011) and folios complied by Burke et al. (2011), was used to construct the current 0.70 psi/ft pressure-gradient map.

SUMMARY

A comprehensive geopressure-gradient model was developed to characterize the regional pressure system in the Gulf of Mexico basin, which is one of the most important petroleum producing provinces in the United States. This geopressure-gradient model is detailed in this paper and was used to generate a series of isopressure-gradient surfaces spanning the Gulf of Mexico basin. The 0.70 psi/ft pressure-gradient map, which is presented in this paper, reveals the location and depth of overpressured zones in onshore and offshore areas. Isopressure-gradient maps, in general, enable the identification and quantification of the overpressured and underpressured regions, as well as zones of normal pressure. This map provides insight into potential pressure-related challenges associated with oil and gas production, which are critical for the safety and mitigation of pressure induced geohazards related to new and ongoing exploration as well as to the development of the Nation's petroleum energy endowments. In addition, this map broadly defines overpressured areas, which are critical to recognize when exploring for deep oil and gas resources with distinct pressure signatures. This is essential for the evaluation of reservoir-seal integrity and for assessing potential undiscovered hydrocarbon accumulations. The identification of overpressured or underpressured regions is also a critical parameter for evaluating the feasibility of geological sequestration and containment of supercritical fluids (Burke, 2011), such as carbon dioxide for alternative disposal methods of waste greenhouse gases. Regional subsurface pressure characterization needs to be updated on a regular basis as more drilling data become available.

NON-ENDORSEMENT

Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.
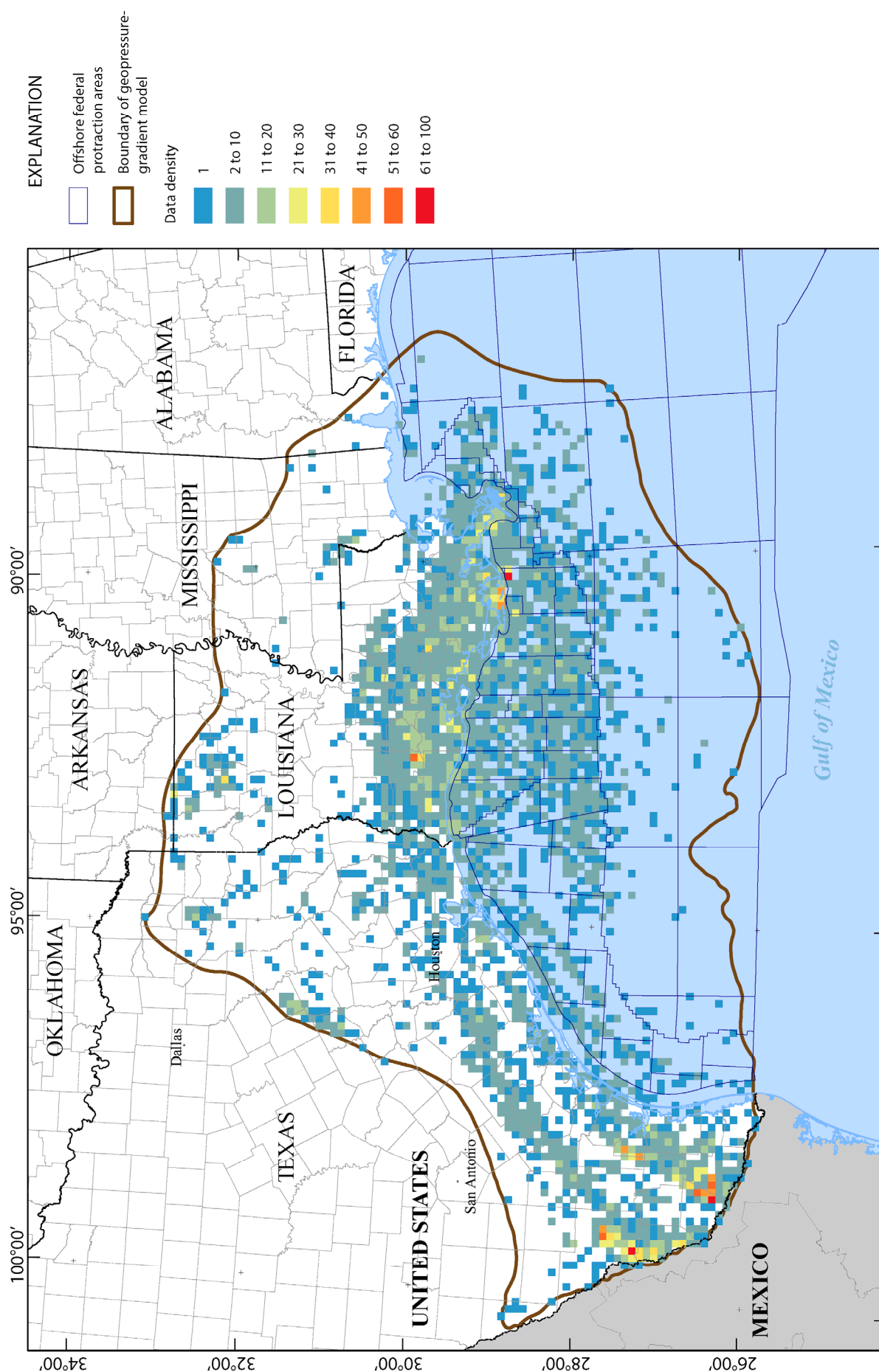
Figure 4. Map showing the spatial density of the data used for contouring the 0.70 psi/ft pressure-gradient surface. The data density for a given surface location is determined by the number of wells within a six square mile grid block.
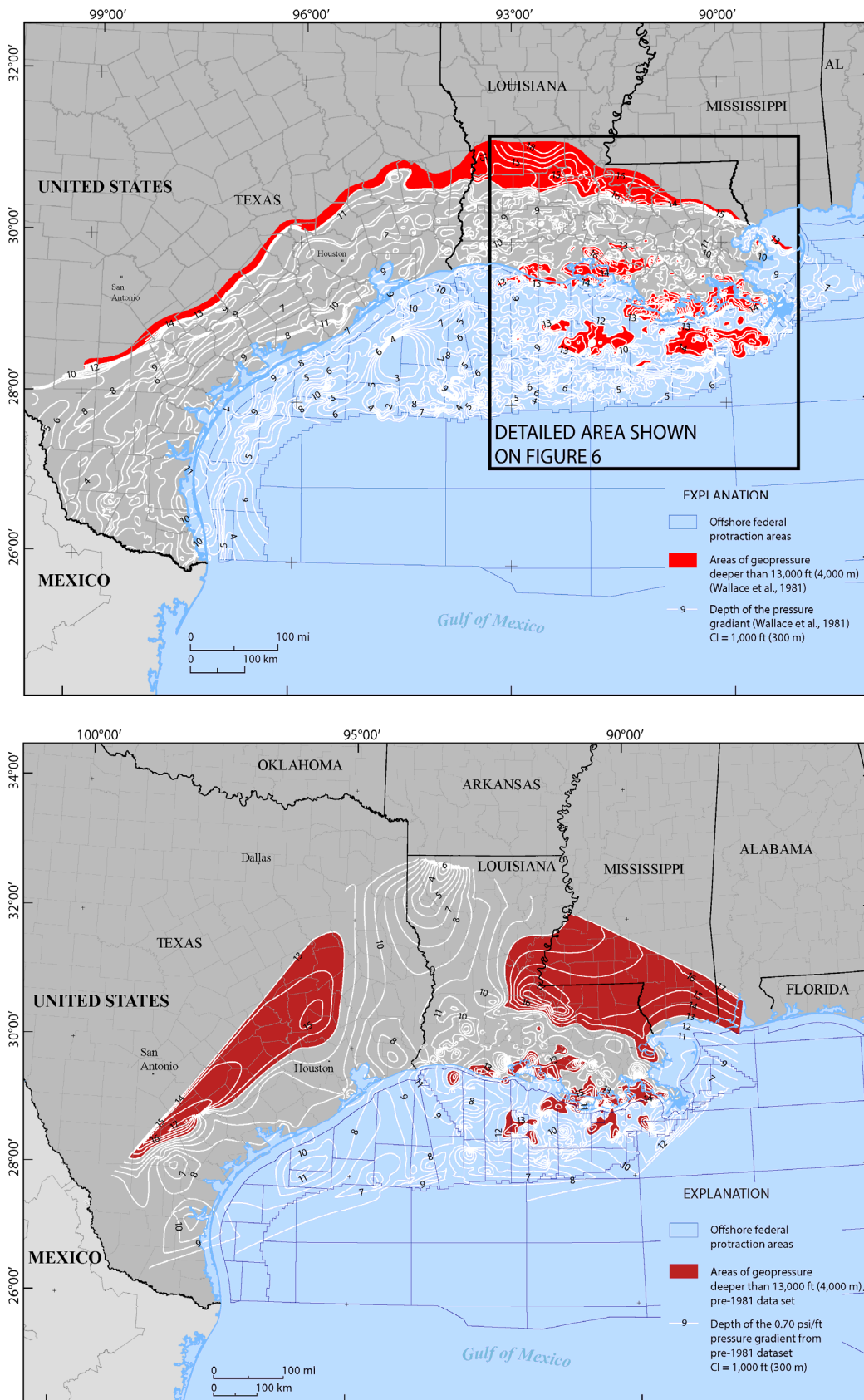
Figure 5. (A) Map showing the depth of the 0.70 psi/ft pressure-gradient surface in the northern Gulf of Mexico basin (modified after Wallace et al., 1981). Red identifies areas in which the 0.70 psi/ft pressure-gradient surface is located 13,000 ft (4,000 m) or deeper. Note that contour depths refer to thousands of feet. (B) Map showing the depth of the 0.70 psi/ft pressure-gradient surface, which was constructed using mud-weight measurements (IHS, 2011) from wells drilled during or before 1981. Red identifies areas in which the 0.70 psi/ft pressure-gradient surface is located 13,000 ft (4,000 m) or deeper. Note that contour depths refer to thousands of feet. Compare with Figure 5A, and refer to text for further explanation.
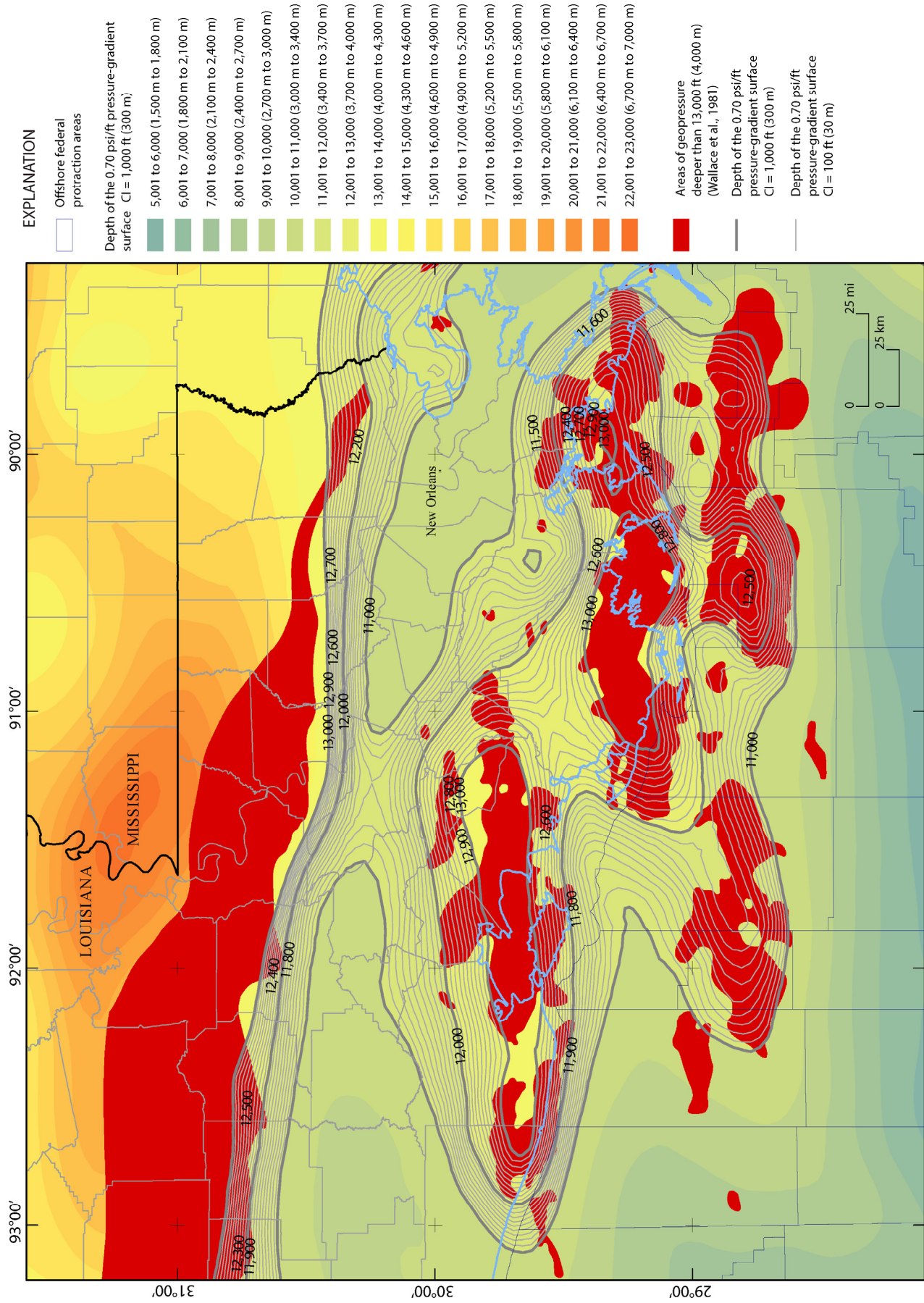
Figure 6. **Map showing detail of the location depicted in the black box in Figure 5A. Grey contours represent the depth of the 0.70 psi/ft pressure-gradient surface in 100-ft (30-m) increments, for depths ranging from 11,000 to 13,000 ft (3,400 to 4,000 m). Red identifies areas in which the pressure-gradient surface of Wallace et al., (1981) (Fig. 5A) is located 13,000 ft (4,000 m) or deeper. Compare and contrast the agreement of the grey contours with the contours published by Wallace et al. (1981), as discussed in the text.**

EXPLANATION

Offshore federal
protraction areas

Depth of the 0.70 psi/ft pressure-gradient
surface   CI = 1,000 ft (300 m)

5,001 to 6,000 (1,500 m to 1,800 m)
6,001 to 7,000 (1,800 m to 2,100 m)
7,001 to 8,000 (2,100 m to 2,400 m)
8,001 to 9,000 (2,400 m to 2,700 m)
9,001 to 10,000 (2,700 m to 3,000 m)
10,001 to 11,000 (3,000 m to 3,400 m)
11,001 to 12,000 (3,400 m to 3,700 m)
12,001 to 13,000 (3,700 m to 4,000 m)
13,001 to 14,000 (4,000 m to 4,300 m)
14,001 to 15,000 (4,300 m to 4,600 m)
15,001 to 16,000 (4,600 m to 4,900 m)
16,001 to 17,000 (4,900 m to 5,200 m)
17,001 to 18,000 (5,200 m to 5,500 m)
18,001 to 19,000 (5,500 m to 5,800 m)
19,001 to 20,000 (5,800 m to 6,100 m)
20,001 to 21,000 (6,100 m to 6,400 m)
21,001 to 22,000 (6,400 m to 6,700 m)
22,001 to 23,000 (6,700 m to 7,000 m)

Areas of geopressure
deeper than 13,000 ft (4,000 m)
(Wallace et al., 1981)

Depth of the 0.70 psi/ft
pressure-gradient surface
CI = 1,000 ft (300 m)

Depth of the 0.70 psi/ft
pressure-gradient surface
CI = 100 ft (30 m)

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