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Overpressure Sources in the Western and Central Deepwater Gulf of Mexico

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ABSTRACT

Previous results from the central Gulf of Mexico (CGOM) protraction areas of Garden Banks, Green Canyon, Keathley Canyon, and Walker Ridge included calculation of both geopressure and geothermal gradients from 150 wells and produced a new understanding of the overpressure distribution within the deepwater CGOM. Disequilibrium compaction is a major component of the overall GOM overpressure; but it is more easily discernible in the interval from the seafloor down to where formation temperatures were <65°C, at which point temperature-based chemical reactions commenced sequentially with rising temperature. These reactions, which generally produce more quantitative overpressure than disequilibrium compaction, include hydrocarbon generation, smectite to illite transformation, and sandstone diagenesis. Recent work has included the western Gulf of Mexico (WGOM) protraction areas of Port Isabel, Corpus Christi, East Breaks, and Alaminos Canyon, where 249 wells were similarly analyzed to verify the CGOM results. The result of this work indicates that the WGOM is very different from the CGOM in that it is geothermally warmer and considerably underpressured. Measured and calculated temperature-pressure pair data points at varying depths within the boreholes were plotted separately for both regions. The distribution of the data on each plot is regionally unique. In the CGOM, most overpressure encountered was likely created in situ or proximal. In the WGOM, due to increased geothermal heat, the implication is that formations fractured at some point in geological time and overpressure escaped. Therefore, in the WGOM, the majority of the overpressure observed today likely is either a diminished remnant pressure or geologically recent disequilibrium compaction pressure. Compressional velocities versus density crossplots were created for four wells, each well in a different protraction area to indicate the source of local overpressure.

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INTRODUCTION

Sediment pore pressure studies have changed over the past 20 years from theoretical modelling to data-driven analyses (Zhao et al., 2018; Li et al., 2019). In basins having high sedimentation rates, the presumed cause of overpressure has always been disequilibrium compaction pressure. However, as data from deeper wells in deeper water depth settings became available, it soon became apparent that other pressure mechanisms were also involved and this is also true for the GOM. Data shows evidence for overpressure due to temperature-dependent chemical reactions such as hydrocarbon generation, shale diagenesis, and sandstone diagenesis in addition to the shallower disequilibrium compaction. All pressures are additive, so more than one source could be present in the borehole as a function of the temperature, as some of these reactions could overlap at the same depth.

Geothermal gradients were calculated for 357 wells and geopressure gradients were calculated for 382 wells in the combined regions. The western Gulf of Mexico (CWGOM) and the central Gulf of Mexico (CGOM) are very different in terms of both temperature and pressure regimes, but we also consider the similarities (lithology, allochthonous salt, and high sedimentation rates). Analyses of >500 wells show that geologic environments change quickly within short distances, making it unlikely that overpressure determinations in a single well are valid over distances >5 mi away from the well, especially if changing fault blocks. For this study, we will use the top of overpressure (ToO) to mean sedimentary pore pressure = 0.70 psi/ft, or its equivalent mud weight of 13.5 ppg. This is also referred to as the top of "hard" overpressure by some GOM workers (Burke et al., 2012). The study area is shown in Figure 1.

METHODS USED

For calculation of geothermal gradients: In the WGOM, multiple values of temperature were common since the wells are older and shallower, so it was possible to use Horner plots to determine the bottom-hole formation temperature (BHFT). The more recent, deeper, and more expensive wells in the CGOM rarely have anything more than the well log bottom-hole temperature (BHT) measurement. Based upon the few wells that had multiple measurements and were able to yield Horner plots, we estimated an increase of 15% in the BHT to determine the BHFT for wells in Garden Banks and Green Canyon; and an increase of 10% for the generally deeper wells in Keathley Canyon and Walker Ridge.

To determine the geothermal gradient, we used Equation 1:

Geothermal gradient of sediment = (BHFT in °F – seafloor temperature in °F) / total depth in ft (depth between the seafloor and true vertical depth of the well). (1)

Then we converted the geothermal gradient to the depth below the seafloor (mudline) where the temperature reaches 300°F for that well location by using Equation 2:

X = (TVD depth below mudline * 300)/temperature in °F at TD due to sediment only, (2)

where X is the depth in ft below the mudline where the temperature reaches 300°F. This hypothetical isothermal surface is useful for comparing temperature differences over large distances.

For calculation of geopressure gradients: Bottom-hole formation pressures, drill-stem tests, and repeat formation test results were not publicly available for these deepwater wells. Hence, in order to have relative comparisons between different protraction areas, the geopressure (sediment pore-pressure) gradients must all be determined by the same methodology, and that means using bottom-hole mud weights (BMWs). In using BMWs, we use the standard con-

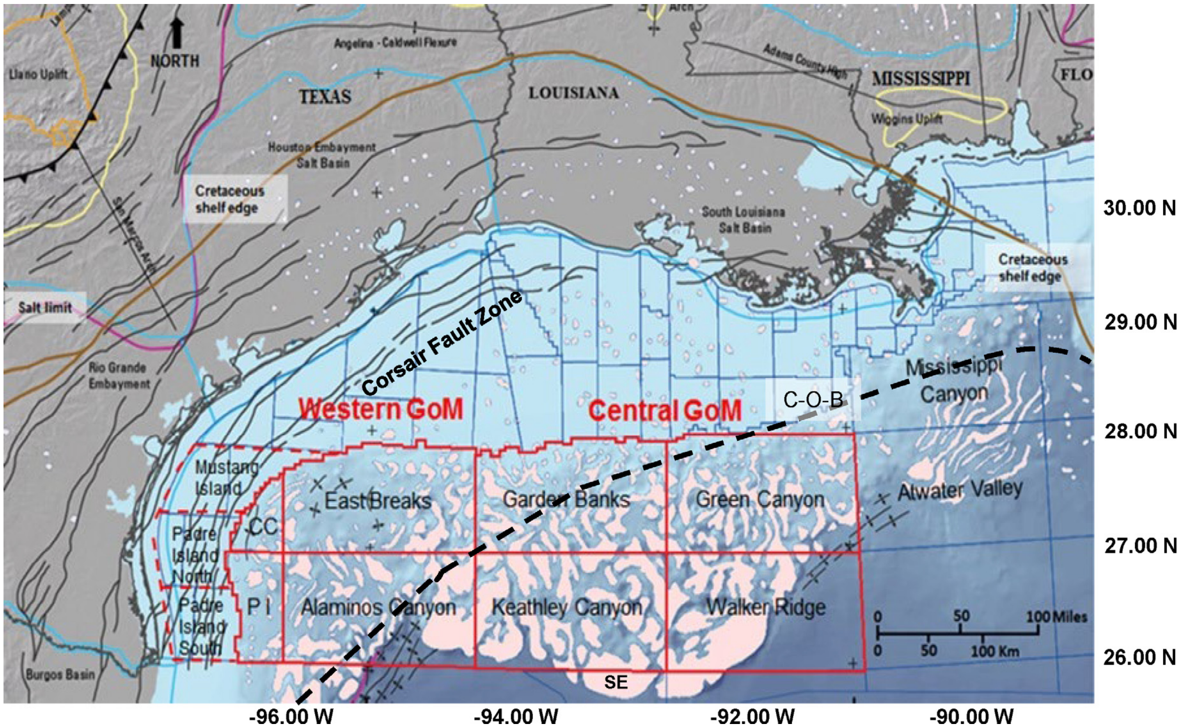

Figure 1. Study area showing both the Western and Central Gulf of Mexico continental slope protraction areas. The allochthonous Louann Salt is shown in pink. The approximate location of the C-O-B (continent to ocean boundary) is shown by the dashed black line. The small protraction area of Sigsbee Escarpment (SE) is south of Keathley Canyon.

version factor of 0.052 when changing pounds per gallon (ppg) to pounds per square inch (psi) (Shaker, 2003); the procedure is as follows:

First, a BMW recorded in ppg is converted to the equivalent psi value by Equation 3.

BMW in psi = BMW in ppg * 0.052 * (TVD minus the KB) in feet. (3)

Next, the pressure gradient for sediment only is calculated by subtracting the pressure due to the water column above the sediment column in the borehole (Eq. 4):

Bottom-hole pressure due to sediment only = BMW in psi – 0.465 * water depth in ft. (4)

Finally, the sediment pressure gradient (SPG), also called the pore pressure gradient in psi/ft is given by Equation 5:

SPG = BH pressure due to sediments only / sediment thickness (ft). (5)

Another way to display the variability in pressure gradients is to create an isobaric surface (similar to the isothermal surface) representing the depth at which the ToO is reached, which was discussed earlier in this study to be operationally defined as 0.70 psi/ft or an equivalent mud weight of 13.5 ppg. In most wells this depth can be read directly or if it occurs beneath the well, it can be calculated by Equation 6:

Depth to top of overpressure (ft) = ((TVD depth – KB) * 13.5) / BMW in ppg. (6)

For exploring the CGOM and WGOM relationships between subsurface temperature and overpressure: Borehole measurements of temperature and pressure at specific depths within the borehole (mostly available in the WGOM) and calculations for the temperature and pressure also at specific depths, using the geothermal and geopressure gradients in all other wells, were used to make regional temperature vs. pressure plots separately for the WGOM and CGOM regions.

RESULTS

The regional depth to 300°F map is shown in Figure 2. The difference between the CGOM and the WGOM becomes visually apparent. What is not apparent is why they are different since both areas have similar sediment thicknesses above the magnetic basement. Two of the possible reasons why the WGOM is so much hotter is the presence of diapiric salt and extremely thinned continental crust on the WGOM side.

The regional depth to the top of 0.70 psi/ft overpressure (ToO) map is shown in Figure 3. There are two surprising elements here: (1) the WGOM is under pressured in spite of its increased temperatures, and (2) the regional tilt of this hypothetical surface from northwest to southeast is similar to the tilt of the seafloor.

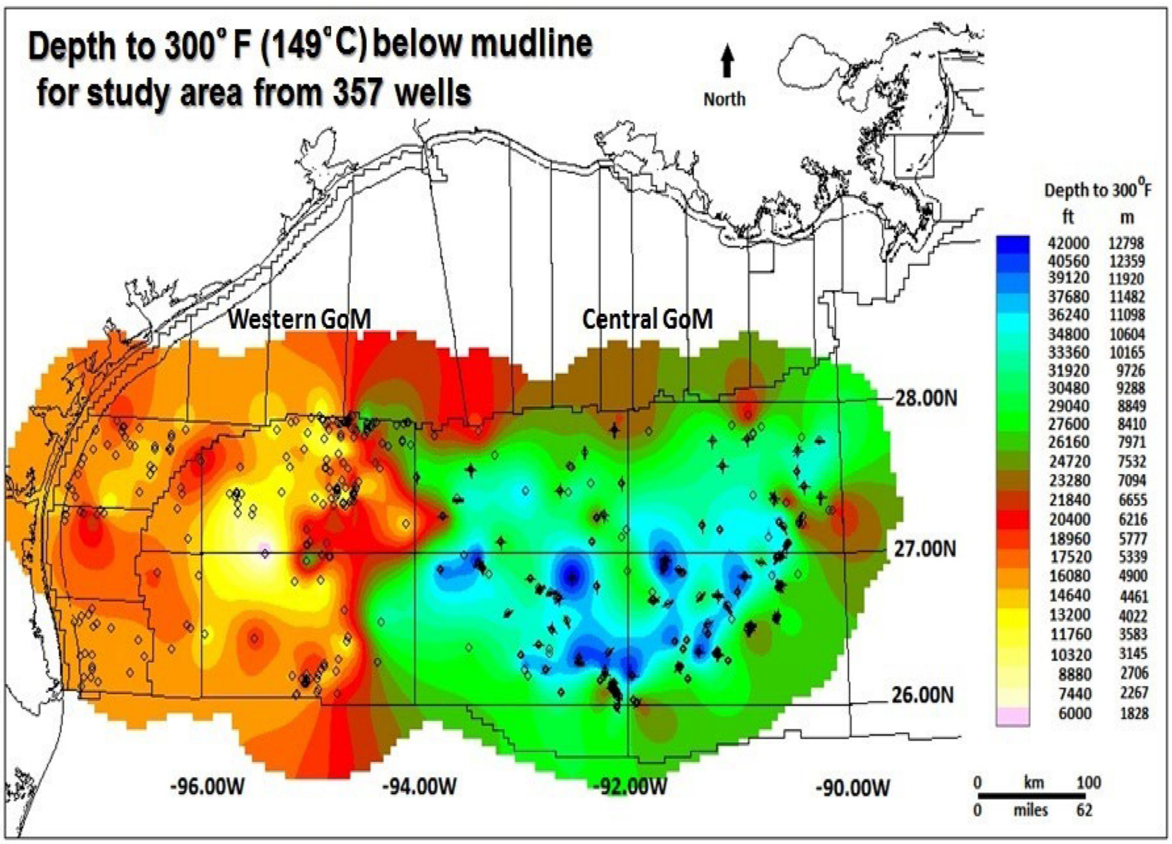

Figure 2. Study area map showing depth to an isothermal surface of 300°F. The relative shallowness of this surface in the WGOM emphasizes the difference in geothermal heat flow between the WGOM and CGOM.

The temperature vs. pressure plot for 355 data points from 130 wells in the CGOM is displayed in Figure 4. This is more or less a statistical scatter plot since the data are from many wells. Nonetheless, distinct pressure jumps are noticeable as the temperature reaches the threshold for specific pressure-producing chemical reactions. Zone 1 shows most all pressures to be ≤ 8702 psi in the temperature range 66° to 138°F with this pressure predominantly caused by disequilibrium compaction. It is possible that some minor portion of this pressure is due to biogenic gas. In zone 2, the presence of pressure due to hydrocarbon generation is at a maximum pressure of 17,404 psi in the temperature range of 138° to 212°F. Noticeable also are all the data points below 8702 psi, which could be from continued temperature-independent disequilibrium compaction. Smectite to illite transformation pressure is evident in the pressure jump to 26,100 psi) in the zone 3 temperature range of 212° to 302°F. Complicating zone 3 is the possibility of sandstone diagenesis that could begin at 248°F. Zone 4 is the high-temperature, high-pressure (HTHP) zone; only 9 data points are in the temperature range 302° to 400°F. This is the environment of gas condensate and thermal dry gas generation.

The temperature vs. pressure plot for 513 data points from 249 wells in the WGOM is displayed in Figure 5. For the sake of comparison, the temperature zonation in Figure 4 has been superimposed on Figure 5; however, the stair-step increases in pressure at increasing temperatures are missing. The overall plot appears as a continuous spectrum of values on the temperature scale with more scatter at the lower end than at the higher end. The inference is that most of these pressures, with the exception of disequilibrium compaction, were not formed locally; but rather have been transferred from elsewhere as deeper formations cracked due to the high-

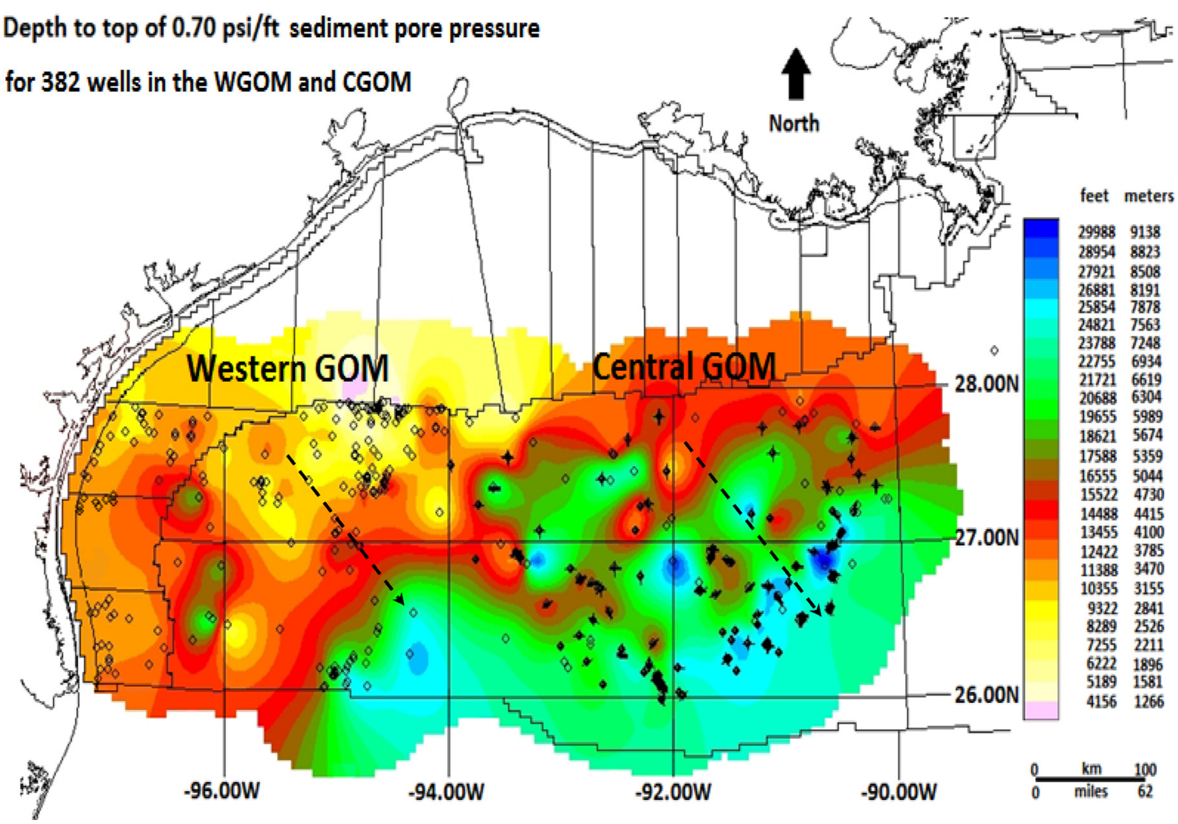

Figure 3. Depth to the top of overpressure at 0.70 psi/ft (or 13.5 ppg) in the WGOM and CGOM continental slope areas. Note that this theoretical surface tilts from northwest to southeast.

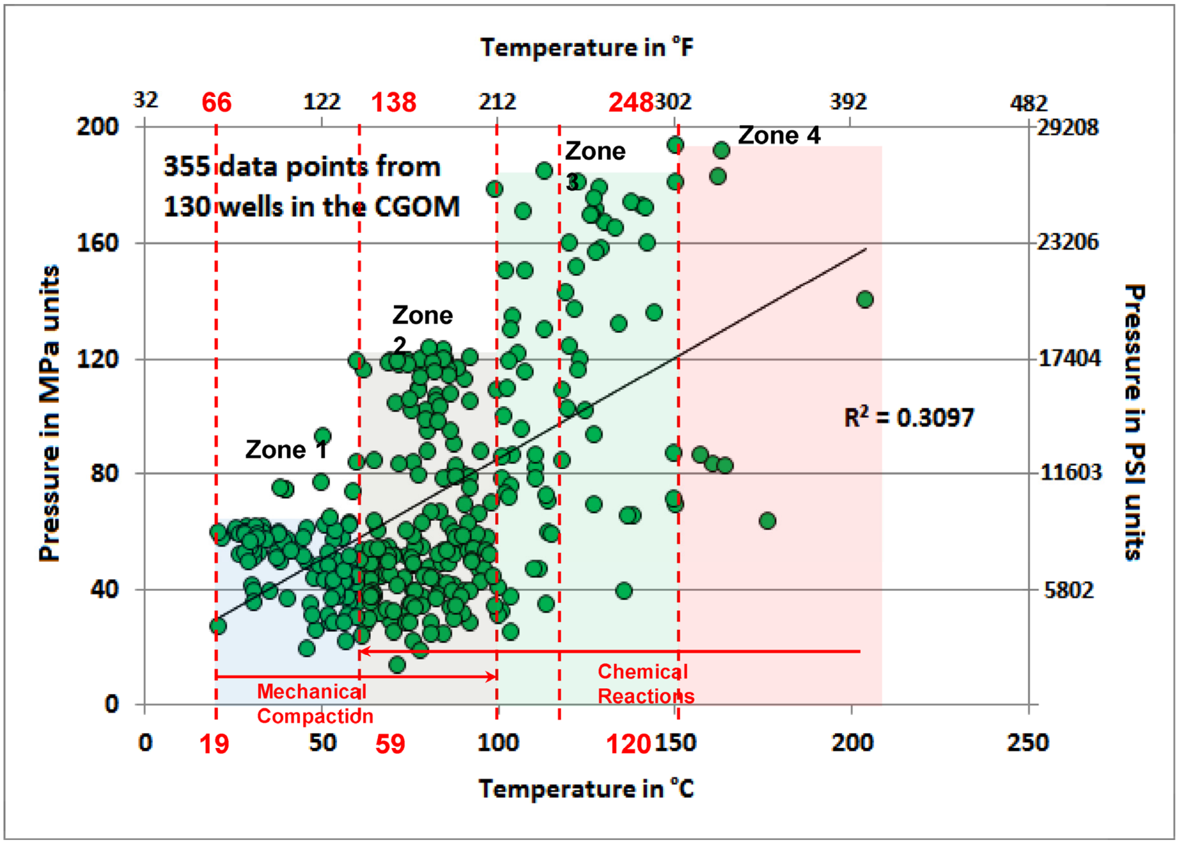

Figure 4. Temperature vs. pressure for 130 wells in the CGOM, interpreted.

er temperatures below. Even the data points above 302°F are significantly under-pressured compared to those same temperatures in the CGOM.

One of the better methods to determine the source of overpressure is to plot compressional velocity vs. density from continuous well log data through overpressure zones. This is not an easy task using publicly accessible data, as it is rare to have both a density and a sonic log through the relevant part of the borehole in deepwater GOM wells. We have plotted data from four wells, each well in a different protraction area to test this method in Figure 6. Figure 6A shows the schematic concept of how to determine the probable source of overpressure in a velocity vs. density crossplot (Li et al., 2019). Figures 6B–6D all show varying evidence for the presence of illitization overpressure in wells from Alaminos Canyon, Keathley Canyon, and the Sigsbee Escarpment, respectively. Figures 6B and 6D also show the presence of pressure generated by hydrocarbon synthesis. Figure 6E is from the shallow well WR–313–001 in Walker Ridge where the log data are from sediments too geothermally cool to produce either hydrocarbons or illitization. Consequently, the only overpressure present is due to disequilibrium compaction. Other examples of velocity vs. density crossplots are found in Zhao et al. (2018) and Souza et al. (2020).

SUMMARY AND CONCLUSIONS

The process of calculating both the geothermal and geopressure gradients for all these well locations on the continental slope in both the WGOM and the CGOM has allowed confirmation

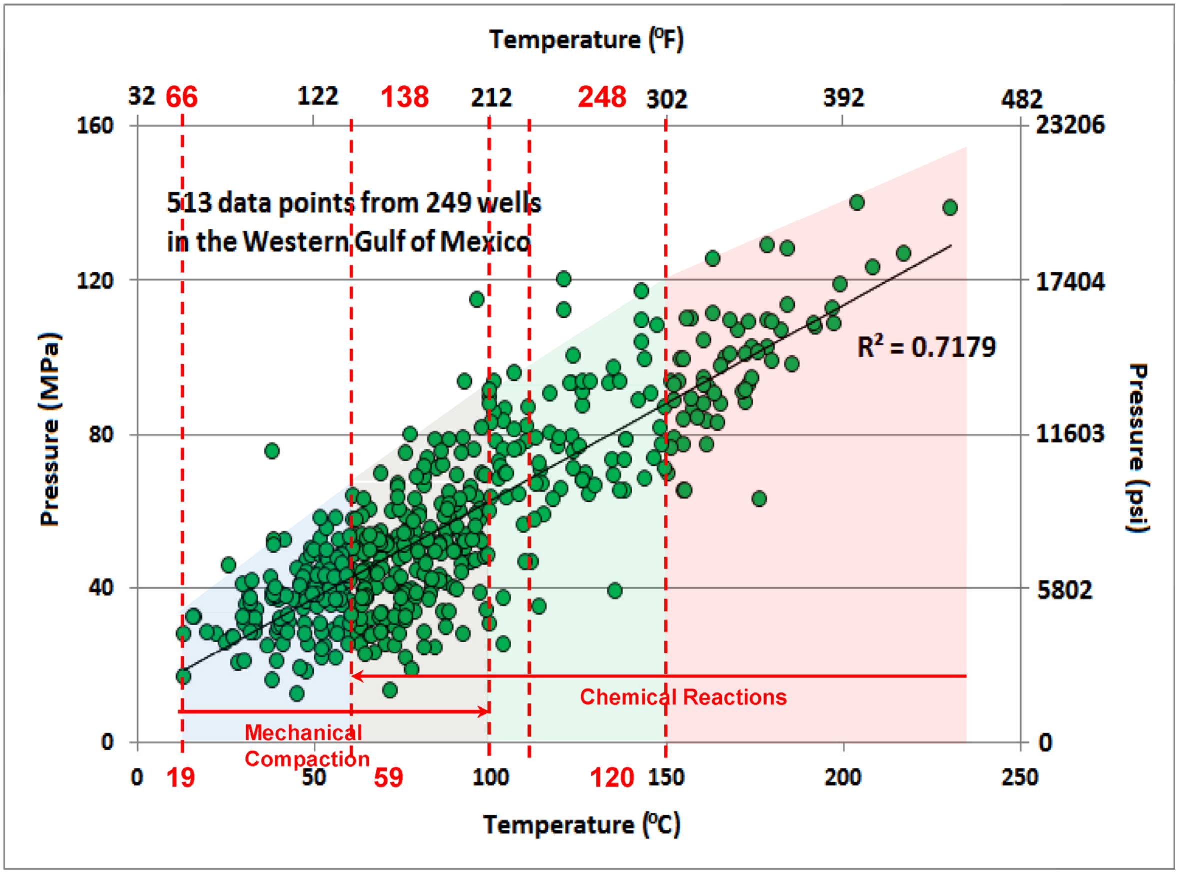

Figure 5. Temperature vs. pressure for 249 wells in the WGOM, interpreted.

as to how different one is from the other. Possible explanations as to why the WGOM is geothermally warmer include the presence of diapiric salt and hyper-thinned continental crust, whereas the CGOM mostly overlies thicker oceanic crust. This heat disparity has had a significant effect on hydrocarbon and reservoir pressure preservation over geologic time.

REFERENCES CITED

Li, J., J. Zhao, X. Wei, M. Chen, P. Song, and Z. Han, 2019, Origin of abnormal pressure in the Upper Paleozoic shale of the Ordos Basin, China: Marine and Petroleum Geology, v. 110, p. 162–177.

Shaker, S. S., 2003, The controversial pore pressure conversion factor: PSI to PPG MWE: The Leading Edge, v. 2, p. 1223–1225.

Souza, J. M. G., N. Cubas, C. Rabe, J. Letouzey, R. Divies, D. B. Praeg, D. Granjeon, A. M Cruz, C. G. Silva, A. T. dos Reis, and C. Gorini, 2020, Controls on overpressure evolution during the gravitational collapse of the Amazon deep-sea fan: Marine and Petroleum Geology, v. 121, p. 1–24.

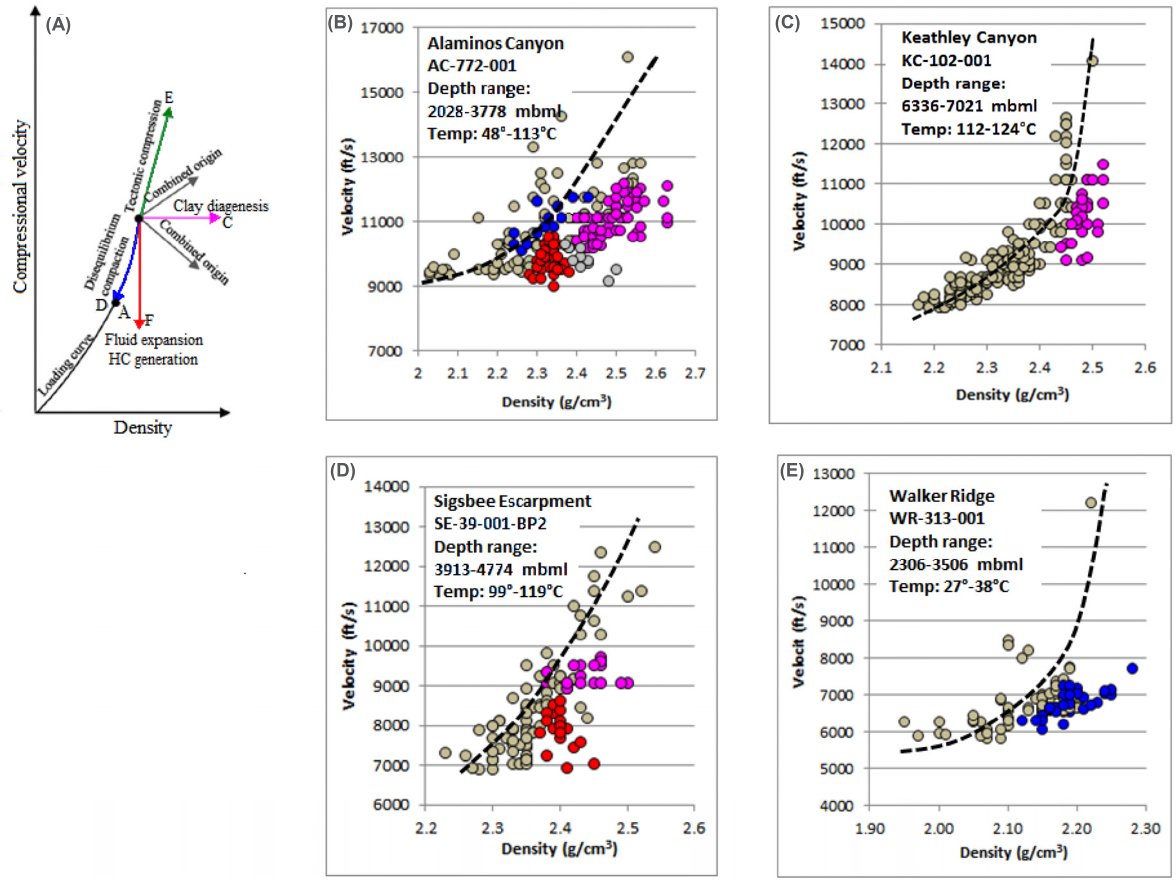

Figure 6. (A) Crossplot of Vp vs. density as a means of indicating the likely source of overpressure. These four plots are from different parts of the study area. Note the differences in velocity and density scales; (B) AC–772–001 well has SPG = 0.596 psi/ft; (C) KC–102–001 well has SPG = 0.840 psi/ft; (D) SE–39–001--BP2 well has SPG = 0.841 psi/ft; and (E) well WR–313–001 has SPG = 0.843 psi/ft. Note: mbml = meters below mudline.

Zhao, J., J. Li, and Z. Xu, 2018, Advances in the origin of overpressures in sedimentary basins: Petroleum Research, v. 3, p. 1–18.