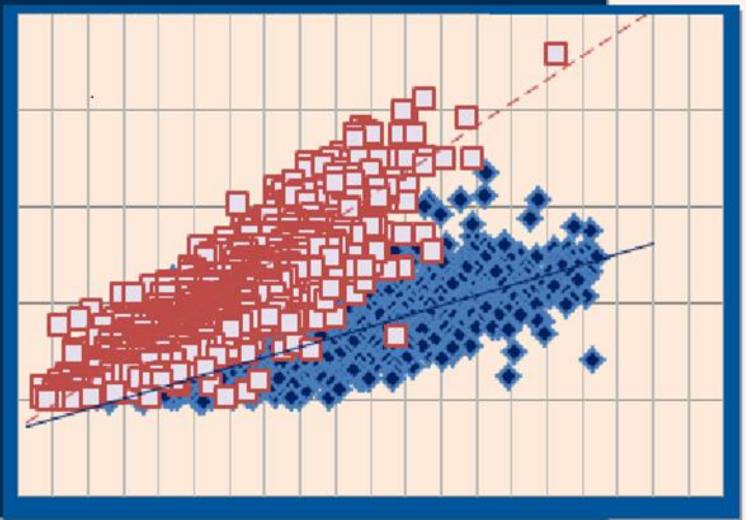

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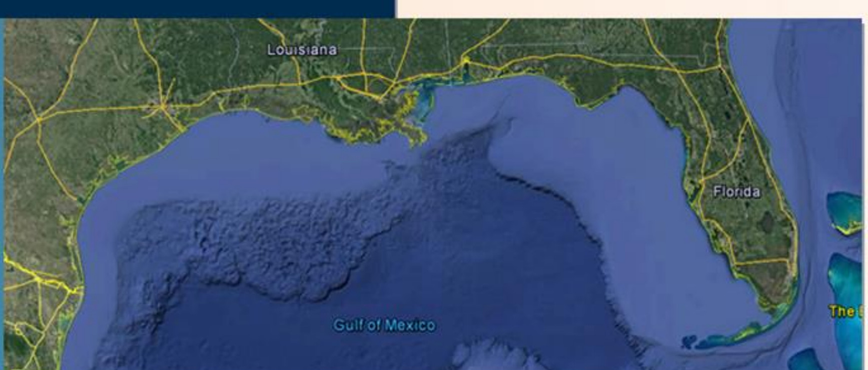
STUDY OF HIGH PRESSURE HIGH TEMPERATURE ZONES IN THE GULF OF MEXICO

Prepared for the

Bureau of Safety and Environmental Enforcement (BSEE)

U.S. Department of Interior

July 2017



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List of Acronyms

BHP	Bottom Hole Pressure
BHT	Bottom Hole Temperature
BSEE	The Bureau of Safety and Environmental Enforcement
CFR	Code of Federal Regulations
DOI	Department of Interior
GOM	Gulf of Mexico
HPHT	High Pressures and High Temperatures
KB	Kelly bushing
MD	Measured depth
MSL	Mean-Sea-Level
MMS	Minerals Management Services
OCS	Outer Continental Shelf
RT	Rotary Table
TVD	True Vertical Depth
TVDss	True Vertical Depth (subsea)

EXECUTIVE SUMMARY

This study was conducted to develop predictive regression models for determining high pressure and high temperature zones in the Outer Continental Shelf (OCS) section of the Gulf of Mexico (GOM). Location of the GOM is shown in Figure ES-1. The study was funded by the Bureau of Safety and Environmental Enforcement (BSEE) of the U.S. Department of Interior (DOI). Data used for the study was provided by the Bureau, collected during the years 2000 to 2016.

Source: National Oceanic and Atmospheric Administration

Figure ES-1 Gulf of Mexico

Pressure data were evaluated for wells drilled at water depths less than 1,000 feet (ft) and greater than or equal to 1,000 ft. Pressure increases with depth, in most cases linearly, except in high-pressure zones. Temperature data were also evaluated for wells drilled in water depths less than 1,000 ft, and greater than or equal to 1,000 ft. Additionally, six different intervals of water depths were also evaluated because the relationship between temperature and water depth in offshore wells is more complex - as water depth increases, temperature decreases while it increases in the rock formations. Additional intervals of water depths used in this study were: 0 – 500; 500 - 1,000; 1,000 - 2,000; 2,000 - 3,000; 3,000 - 4,000; and >4,000 feet.

Predictive models were developed using regression analysis to determine pressure and temperature at various formation depths in the GOM. Based on these models, high pressure and high temperature zones in the GOM can be identified.

Equations of each regression analysis with their R^2 value is presented in Table ES-1. An R^2 is a statistical measure of how close the data was to the regression line. An R^2 of 1 indicates that the regression line perfectly fits the data. Low R^2 values indicate a low correlation between depth and pressure or depth and temperature. It is observed that correlation between Bottom Hole Pressure (BHP) and True Vertical Depth (TVD) (subsea) (TVDss) is strong, as can be expected because pressure increases with depth and is linear unless there is an intervening high-pressure zone. Whereas, the correlation between Bottom Hole Temperature (BHT) and TVDss is not as strong as temperature decreases in water and then begins increasing in the rock formation, producing an inverse effect.

Correlations between high-pressure and high-temperature were also established.

Table ES-1 Regression Equations and R^2

Plot	Water Depth	Regression Equation	R^2 Value
BHP v TVDss	<1,000 ft	$Y=2E\text{-}05x^2+0.5645x-502.31$	0.8970
BHP v TVDss	≥1,000 ft	$Y=5E\text{-}06x^2+05928x$	0.9083
BHT v TVDss	<1,000 ft	Y=0.0121x+70	0.7778
BHT v TVDss	≥1,000 ft	Y=0.0053x+70	0.5282
BHT v TVDss	0 - 500 ft	Y=0.0116x+77.618	0.7984
BHT v TVDss	500 - 1,000 ft	Y=0.0063x+103.08	0.5125
BHT v TVDss	1,000 - 2,000 ft	Y=0.0062x+87.941	0.5237
BHT v TVDss	2,000 - 3,000 ft	Y=0.0063x+65.026	0.7359
BHT v TVDss	3,000 - 4,000 ft	Y=0.0052x+73.286	0.7049
BHT v TVDss	>4,000 ft	Y=0.0058x+50.486	0.6015
BHT v BHP	<1,000 ft	Y=0.0112x+111.95	0.7551
BHT v BHP	≥1,000 ft	Y=0.006x+90.929	0.5847

1.0 INTRODUCTION

The increase in demand for oil and gas, coupled with the depletion in traditional reservoirs is pushing the petroleum industry to explore and produce from frontier regions that are, in many cases, hard to access and very difficult to produce. Some of these regions show abnormally High Pressures and High Temperatures (HPHT) that were not accessible in the past due to technological limitations. Incidents causing considerable economic and environmental damage have occurred while trying to produce from such regions and formations.

According to the US Code of Federal Regulations 30 CFR 250 804 (b) (1), a pressure rating greater than 15,000 psig, or a temperature rating greater than 350^{o}F, is considered HPHT.

Having access to HPHT data can assist in understanding hydrocarbon migration and entrapment, hydrocarbon column integrity and hydrodynamics. In the operational environment, pressure data is invaluable for well planning, casing design, mud program, well control, health, and safety. In appraisal and development, pressure analysis can assist in determining reservoir connectivity, fluid contacts, and lateral or vertical seals.

HPHT zones are generally encountered in deeper producing formations. With drilling depths reaching a TVD of over 30,000 ft in many cases, HPHT zones are quite common. Though pressure and temperature normally increase with depth, this increase may not be linear. HPHT zones can also be encountered at shallower depth if there is an abnormally high pressure/temperature zone resulting from stress in the geological formation. These HPHT zones are more difficult to identify and can cause severe accidents.

This project helped generate necessary information about the pressures and temperatures encountered in the GOM to assist:

(i) The petroleum industry to drill and produce hydrocarbons in a safe and responsible manner.

(ii) The BSEE in ensuring the safe development and conservation of offshore oil and natural gas resources.

2.0 DATA SOURCE AND SUMMARY

2.1 Data Source

All data used for this study were provided by BSEE. Datasets included new and old data:

The new dataset contains records of wells from 2006 to 2016.
The old dataset has records containing wells from 2000 to 2006.

New Data
Records of data in the new dataset = 11,765
Number of wells with pressure and temperature records at final depths = 3,192
Out of 3,192 wells, 65 wells had a BHT less than 100°F. The temperatures for these wells were not included in the study.

Old Data
Records of data in the old dataset = 4,373
Number of wells with pressure and temperature records at final depths = 2,083

2.2 Data Quantification for Pressure Calculations

The study used only the wells with recorded mud weights from which BHP could be calculated. Some wells had missing or inaccurate mud weights. Those wells were not included in the study. The breakdown of wells with mud weight records is shown in Table 2-1 and Figure 2-1, along with the percentage of wells in the datasets that had reliable information regarding mud weight.

Table 2-1 Wells with Mud Weights for Calculating BHP

Mud Weight Records	Count
Old Dataset Wells with mud weight data	2,083
New Dataset Wells with mud weight data	3,192
Total Wells with mud weight data for calculating BHP	5,275

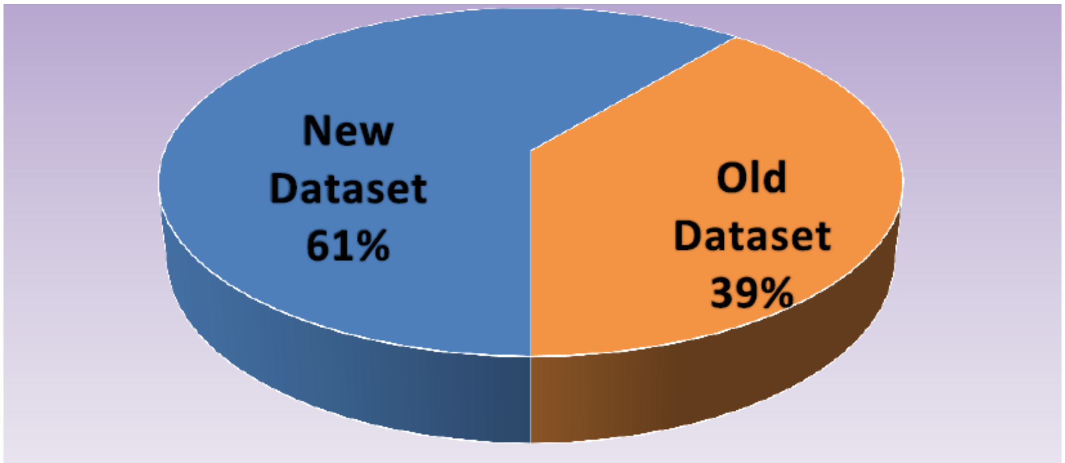


Figure 2-1 Wells with Mud Weights for Calculating BHP

The following equation was used to calculate BHP:
BHP calculated = 0.052 x TVDss x Mud Weight
Where:
Mud Weight = weight of mud in pounds/gallon
0.052 = conversion factor

TVDss is measured from mean-sea-level (MSL) as defined in the diagram (Figure 2-2) below:

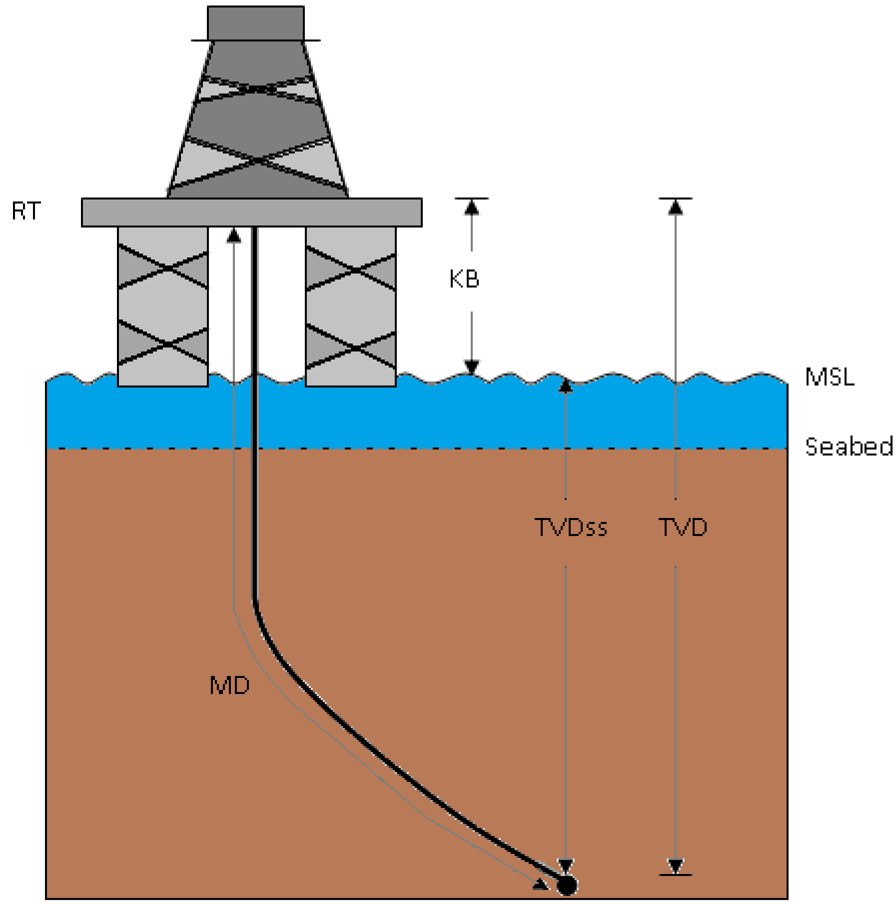


Figure 2-2 Reference Depths

Here TVD = True vertical depth from Rotary Table (RT) to the bottom of the well
MD = Measured depth which is the length of the wellbore measured from the RT to the bottom of the well. For deviated wells, this length is longer than the TVD
KB = Kelly Bushing is the vertical depth from the RT to MSL.

2.3 Data Quantification for Temperature Calculations

Out of 5,275 wells with mud weight data, only 2,897 wells had a BHT data. A breakdown of BHT record is shown in Table 2-2 and Figure 2-3.

Table 2-2 BHT Data Count

BHT*	Count
Wells without BHT	2,378
Wells with BHT	2,897
Total	5,275

*All BHTs were ≥100°F

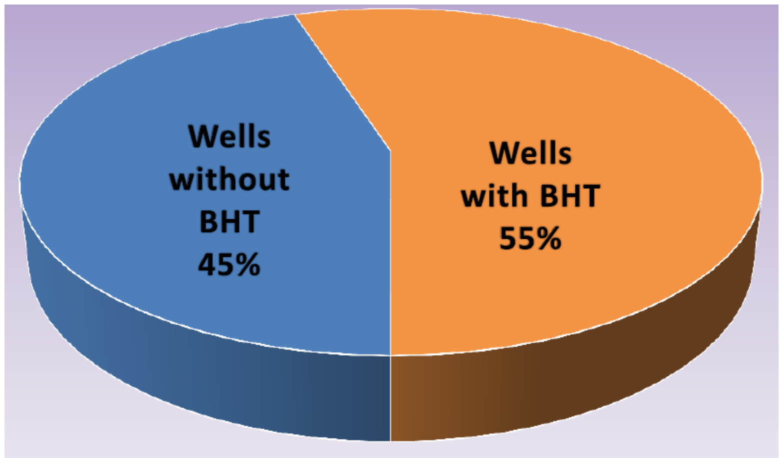


Figure 2-3 BHT Data Count

2.4 Data in Relation to Water Depths

The count of BHP and BHT at Water Depths <1,000 ft and Water Depths ≥1,000 ft are shown in Table 2-3 and Figures 2-4 through 2-5.

Table 2-3 Pressure and Temperature Data Count at Different Depths*

	Water Depth <1000 ft	Water Depth ≥1000 ft
BHP	3,818	1,457
BHT ≥100°F	2,040	857

*BSEE defines deep water as water depth greater than, or equal to 1,000 ft.

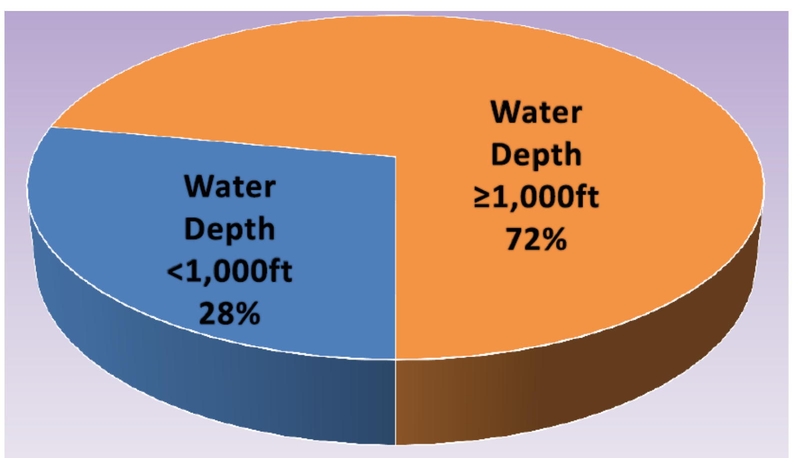


Figure 2-4 BHP Data Count at Different Depths

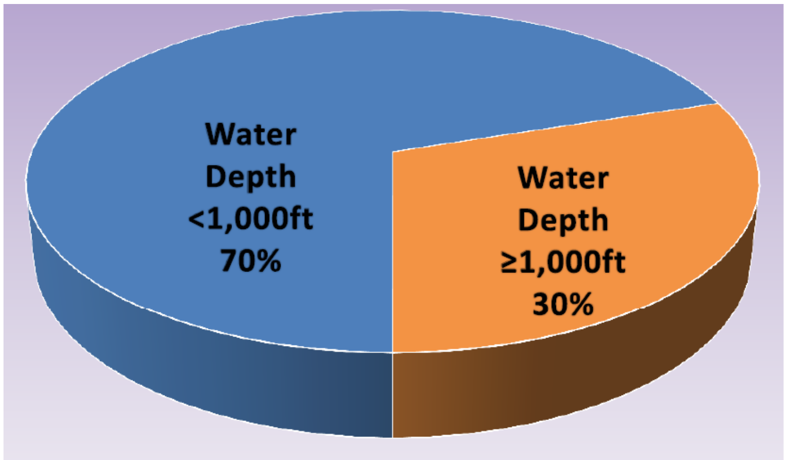


Figure 2-5 BHT (≥100°F) Data Count at Different Depths

2.5 Data within the HPHT Category

As defined earlier, a pressure rating greater than 15,000 psig or a temperature rating greater than 350^{o}F is considered HPHT.

Based on the dataset used for this study, the data counts that fall under high pressure rating, shown in Table 2-4 and Figure 2-6, indicates that for all wells studied 667 were high pressure wells at both shallow and deep water depths. Of those wells, 30% were in shallow water and 70% were in deep water. 4,608 wells were Non-High Pressure wells in both shallow and deep water depths as shown in Figure 2-7. Of those wells, 22% were in shallow water and 78% were in deep water.

Table 2-4 High Pressure and Non-High Pressure Data Count

Data Type	Water Depth <1000 ft	Water Depth ≥1000 ft
High Pressure (≥15,000 psig)	203	464
Non-High Pressure (<15,000 psig)	3,615	993
Total	3,818	1,457

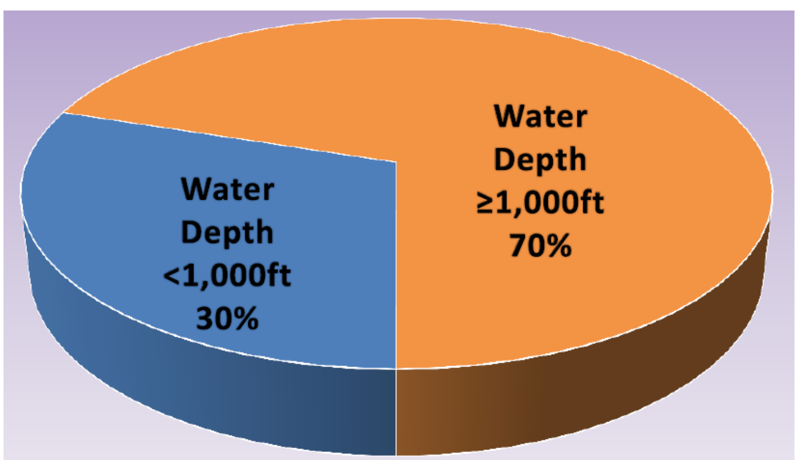


Figure 2-6 High Pressure (≥15,000 psig) Data Count

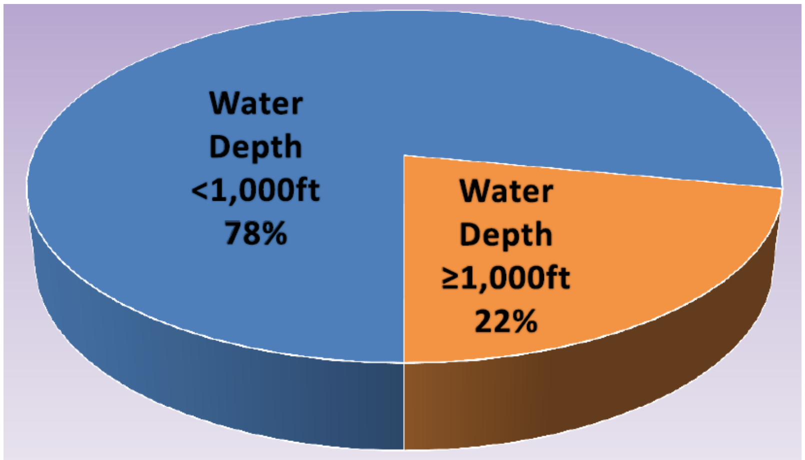


Figure 2-7 Non-High Pressure (<15,000 psig) Data Count

Based on the dataset used for this study, the data count that falls under a high temperature rating is shown in Table 2-5 and Figure 2-8. A total of 25 wells were high temperature wells, and all of them were in shallow water. There were 2,872 Non-High Temperature wells and 70% of them were in the shallow water and 30% were in deep water.

Table 2-5 High Temperature Data Count

Data Type	Water Depth <1000 ft	Water Depth ≥1000 ft
High Temperature (≥350°F)	25	0
Non-High Temperature (<350°F)	2,015	857
Total	2,040	857

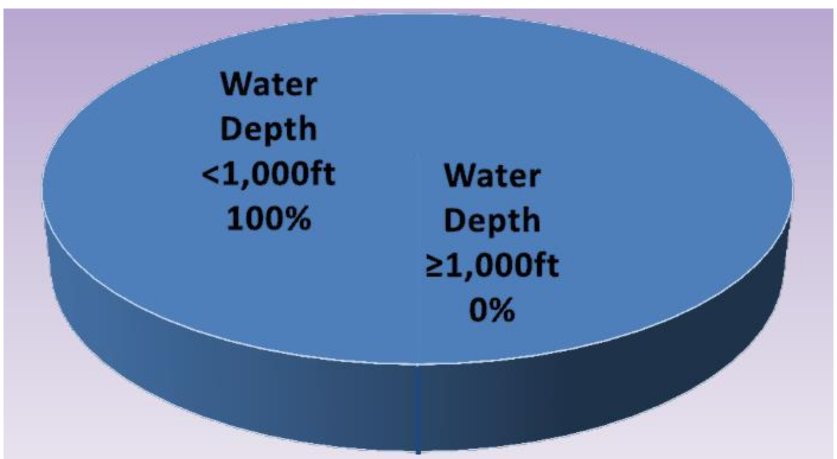


Figure 2-8 High Temperature (≥350°F) Data Count

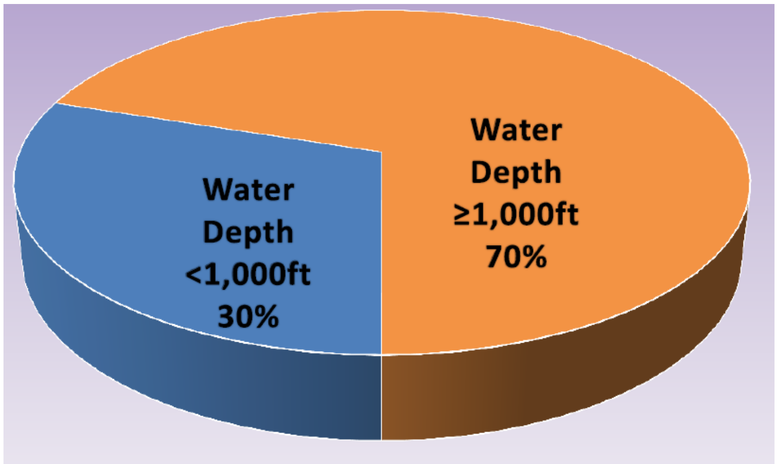
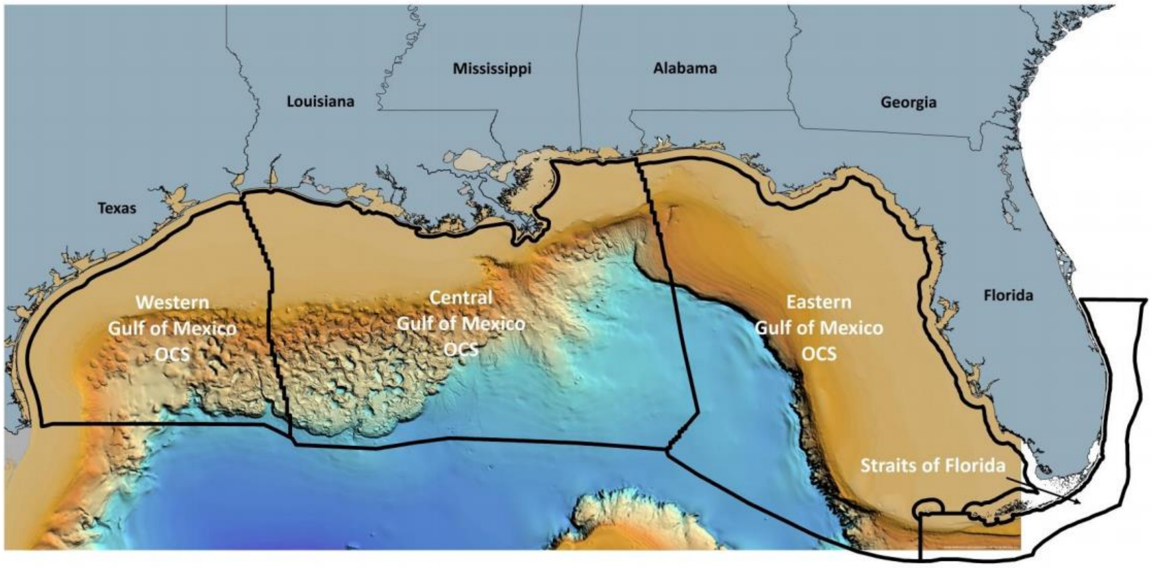


Figure 2-9 Non-High Temperature (<350°F) Data Count

3.0 PRESSURE AND TEMPERATURE PLOTS

Tetrahedron plotted the BHP and BHT well data, provided by the BSEE, from the OCS of the GOM (Figure 3-1). Datasets used for the plots included the old dataset collected between the years 2000 and 2006 and the new dataset collected from 2006 to 2016.



Source: Bureau of Ocean and Energy Management

Figure 3-1 Gulf of Mexico Outer Continental Shelf

Pressure (in psig) and Temperature (in ^{o}F) data were plotted against TVDss for wells drilled between years 2000 to 2016 for:

- Wells in 0 - 500 ft of water depth
- Wells in >500 - 1,000 ft of water depth
- Wells in >1,000 - 2,000 ft of water depth
- Wells in >2,000 - 3,000 ft of water depth
- Wells in >3,000 - 4,000 ft of water depth
- Wells in >4,000 ft of water depth

The rationale behind selecting various bands of water depths is to capture the effect of the water column on pressure and temperature. Pressure increases with water depth and is linear because of the constant water density, albeit at a somewhat lower gradient than in the rock formation. The temperature decreases with depth up to about 4,000 ft in the GOM after which it becomes constant; whereas below in the rock formation, it continuously increases with depth.

Plots include:

BHP versus TVDss   BHT versus TVDss   BHT versus BHP

Equations of the regression plots with their R^2 values are presented in Table 3-1. R^2 is a statistical measure of how close the data is to the regression line.

Table 3-1 Regression Equations and R^2

Plot	Water Depth	Regression Equation	R^2 Value
BHP v TVDss	<1,000 ft	$Y=2E\text{-}05x^2+0.5645x-502.31$	0.8970
BHP v TVDss	≥1,000 ft	$Y=5E\text{-}06x^2+05928x$	0.9083
BHT v TVDss	<1,000 ft	Y=0.0121x+70	0.7778
BHT v TVDss	≥1,000 ft	Y=0.0053x+70	0.5282
BHT v TVDss	0 - 500 ft	Y=0.0116x+77.618	0.7984
BHT v TVDss	500 - 1,000 ft	Y=0.0063x+103.08	0.5125
BHT v TVDss	1,000 - 2,000 ft	Y=0.0062x+87.941	0.5237
BHT v TVDss	2,000 - 3,000 ft	Y=0.0063x+65.026	0.7359
BHT v TVDss	3,000 - 4,000 ft	Y=0.0052x+73.286	0.7049
BHT v TVDss	>4,000 ft	Y=0.0058x+50.486	0.6015
BHT v BHP	<1,000 ft	Y=0.0112x+111.95	0.7551
BHT v BHP	≥1,000 ft	Y=0.006x+90.929	0.5847

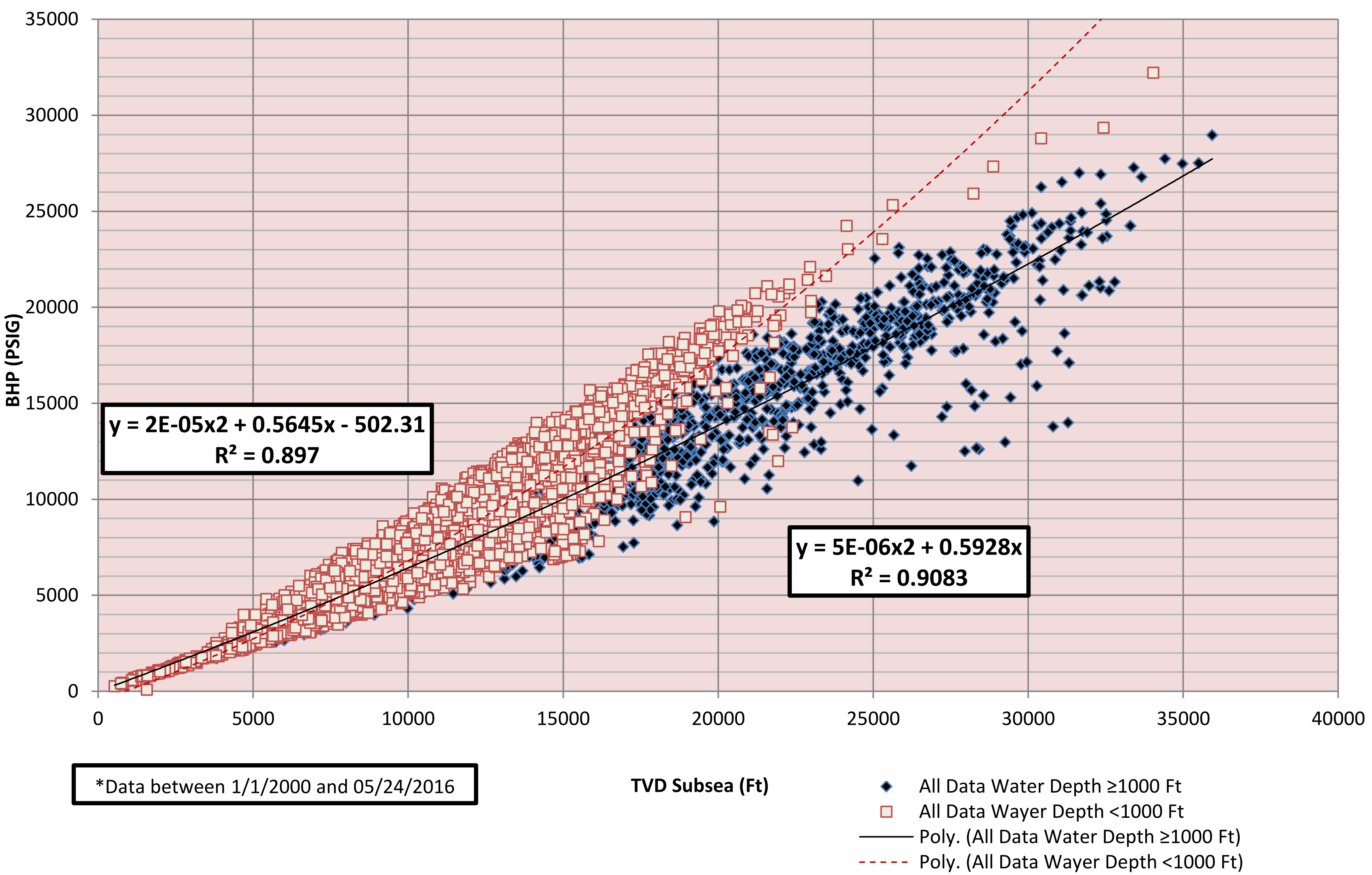


Figure 3-2 BHP vs TVDss (Water Depths ≥1000 ft and <1000 ft)

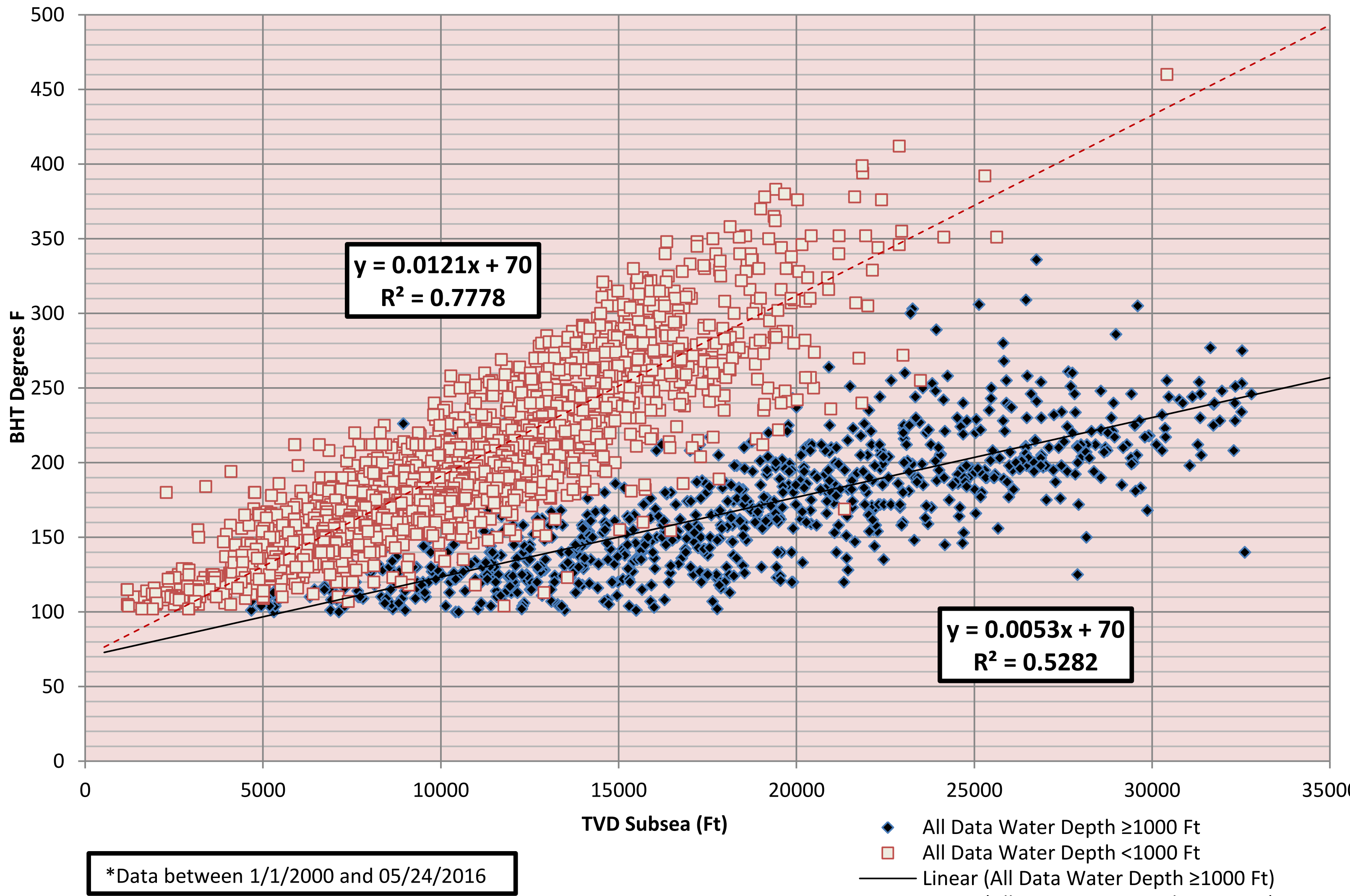


Figure 3-3 BHT vs TVDss (Water Depths ≥1000 ft and <1000 ft)

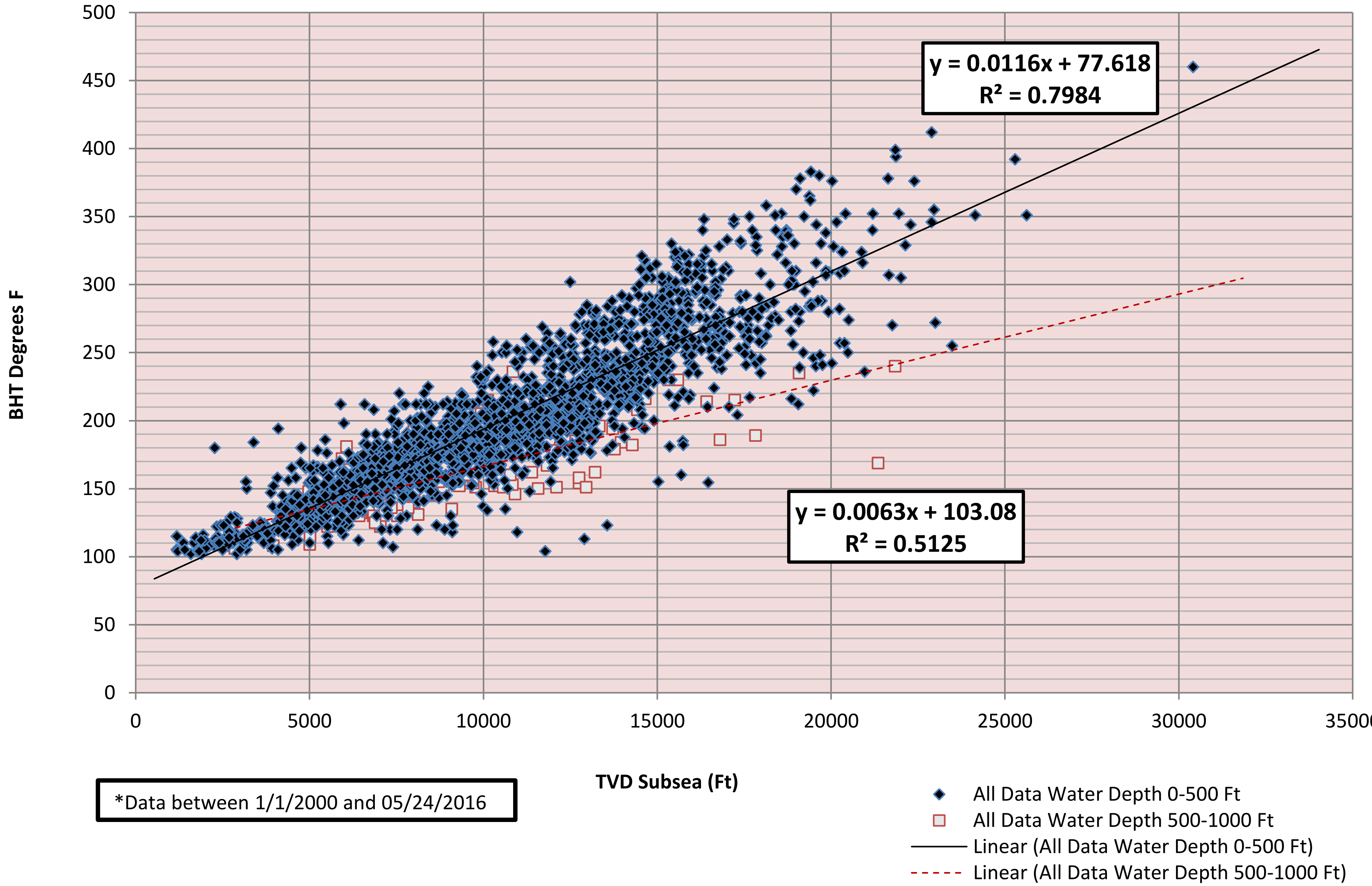


Figure 3-4 BHT vs TVDss (Water Depths 0-500 ft and 500-1000 ft)

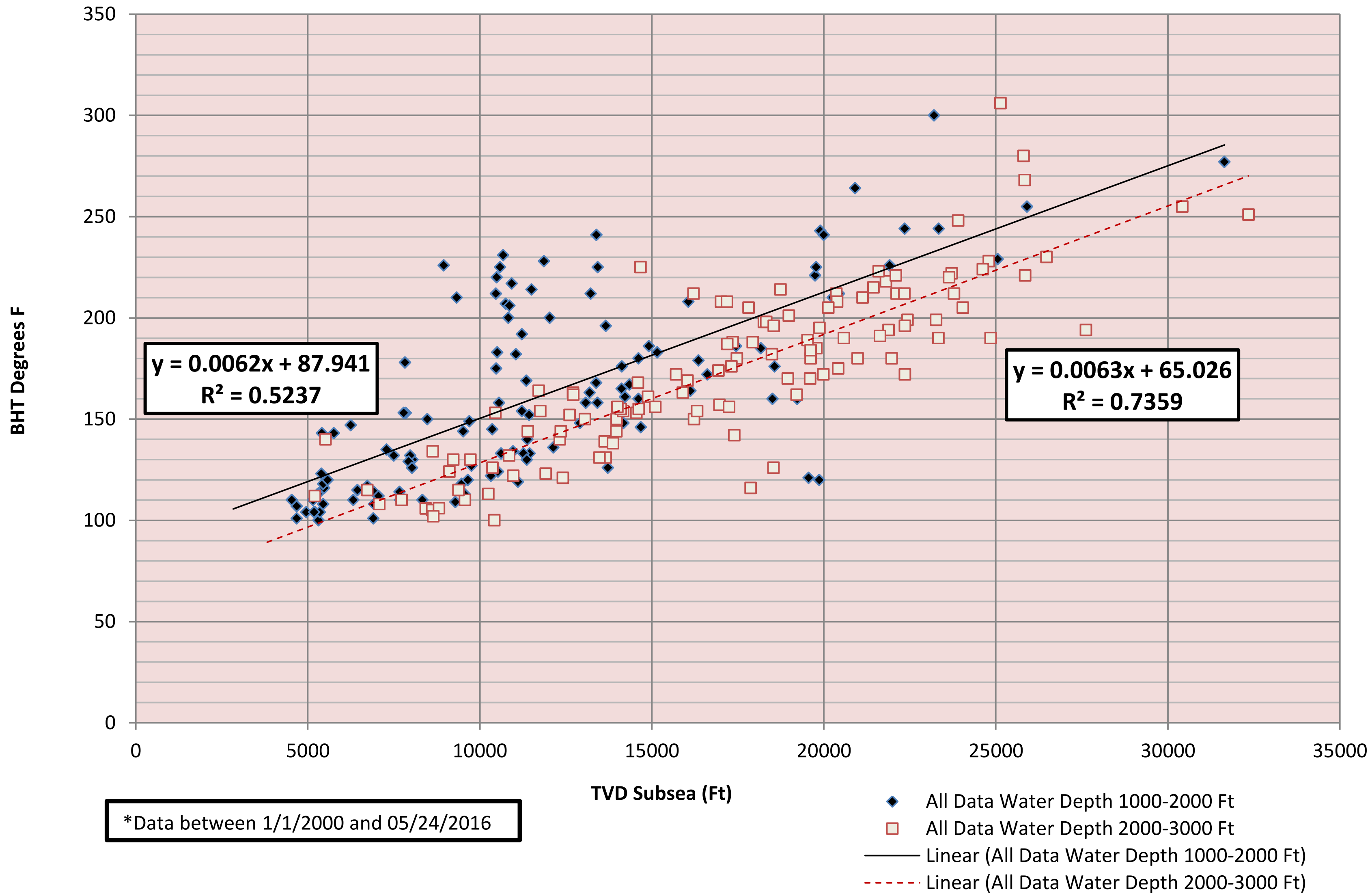


Figure 3-5 BHT vs TVDss (Water Depths 1000-2000 ft and 2000-3000 ft)

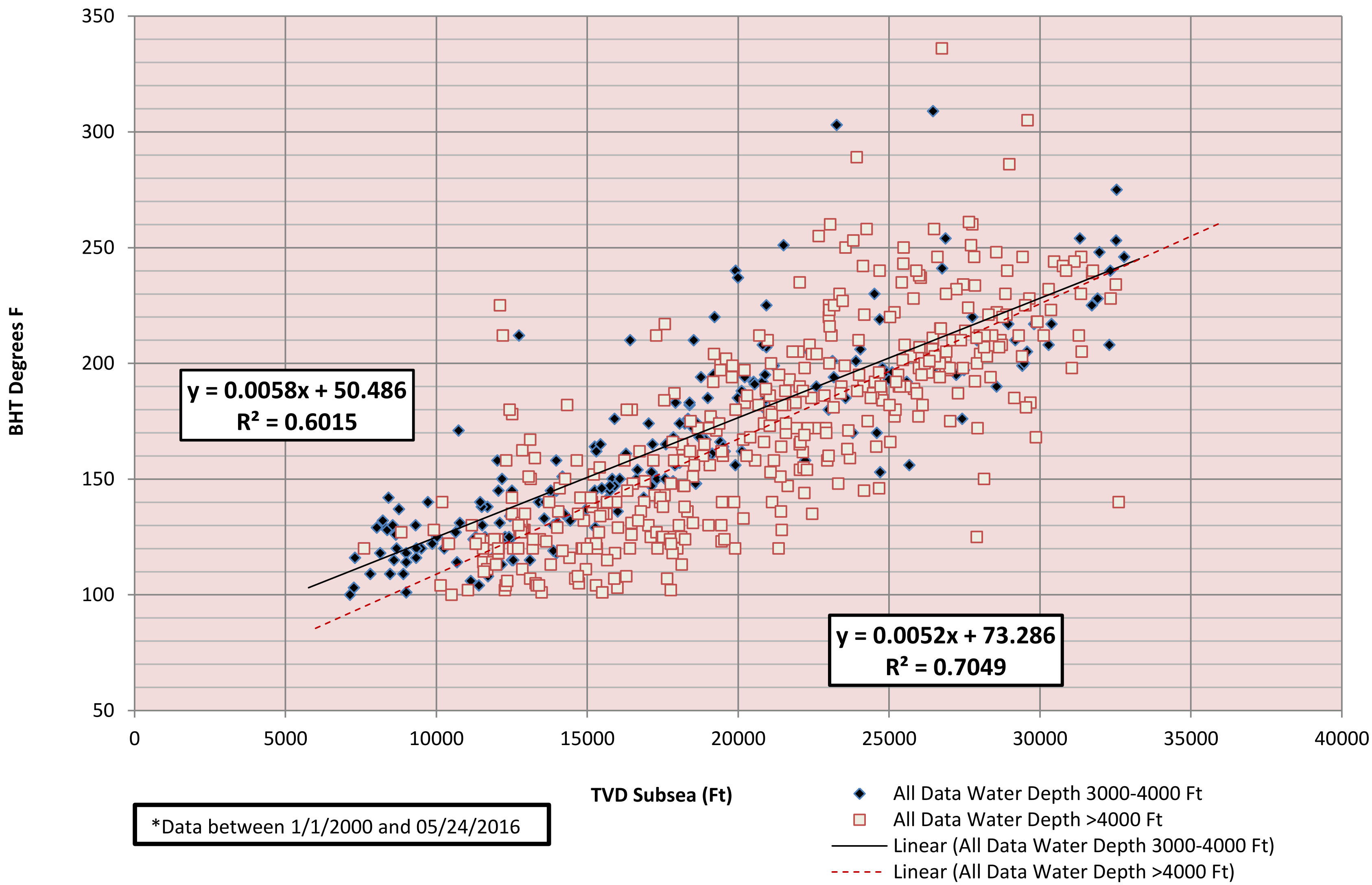


Figure 3-6 BHT vs TVDss (Water Depths 3000-4000 ft and >4000 ft)

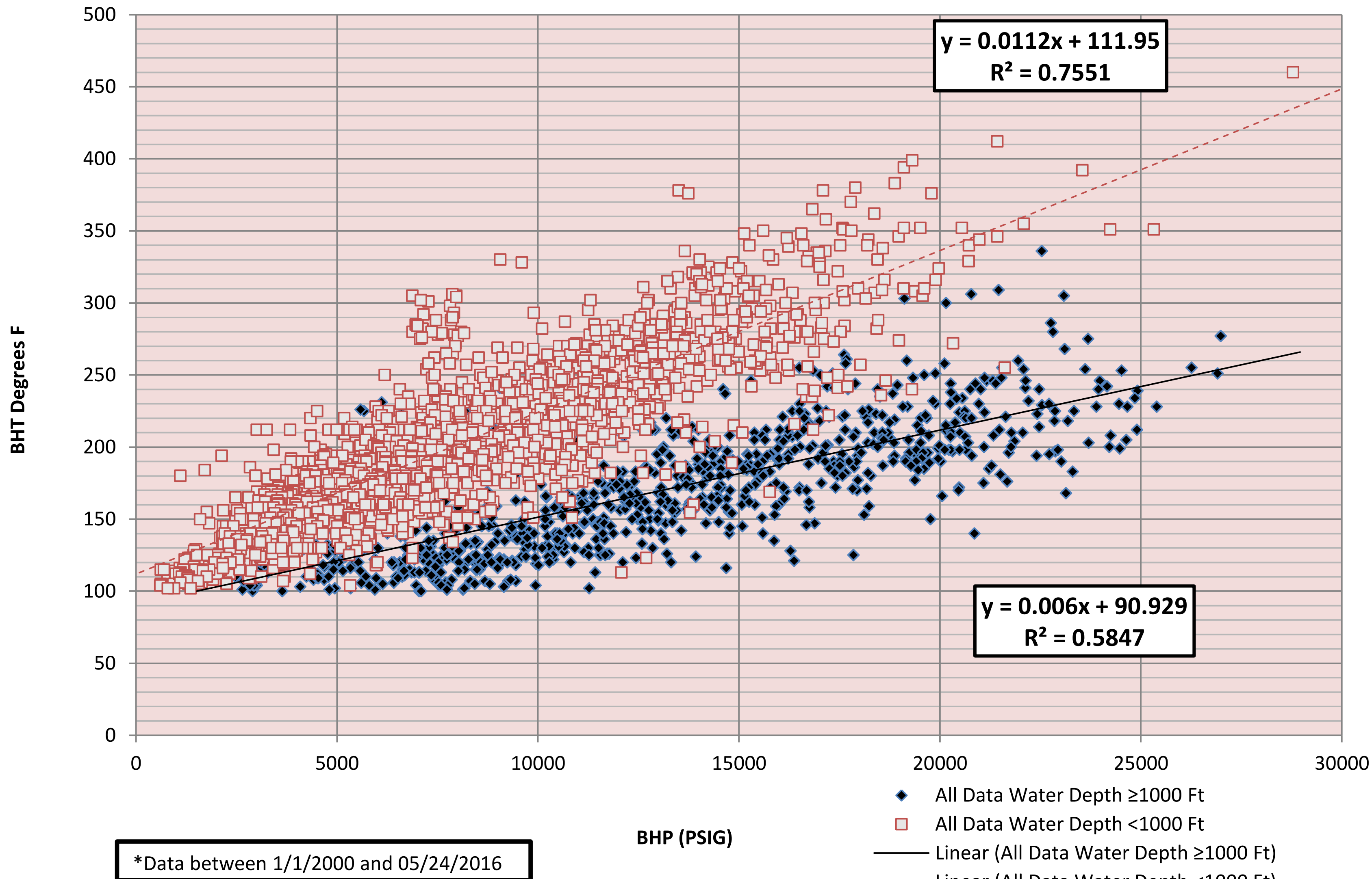


Figure 3-7 BHT vs BHP

4.0 DISCUSSIONS

To be consistent with a previous study conducted in-house by the Minerals Management Services (MMS)[1] of the DOI and instructions from BSEE, the analysis was conducted in a fashion similar to the MMS study.

The plots were generated based on regression analysis of the data and it is apparent that a polynomial model fits the data well. Coefficient of Determination (R^2) statistics were used to test the quality of the fit. In regression analysis, the R^2 is a statistical measure of how well the regression line represents the real data points. An R^2 equal to 1 indicates that the regression line fits the data perfectly. Low values indicate a low correlation between the dependent and independent variables.

The following observations were made from data analyses and regression models:

1. In the geological formation temperature increases with depth - a direct correlation. However, in water, temperature decreases with water depth - an inverse correlation. A regression model to predict temperature based on depth is, therefore, complicated when a system consists of both water and geologic formations. The deeper the water depth, the higher the effect of inverse correlation on the model, resulting in a lower R^2 value.

2. BHT data was more scattered and a large number of BHT data was missing, resulting in lower R^2.

3. A correlation between BHT and TVD below the mudline could be stronger but that correlation would be applicable only to wells with the same datum (mudline depth). A general correlation between BHT and TVD below the mudline for a region cannot be developed or plotted on a single curve since the datum will vary considerably.

4. This study has identified 464 HPHT wells with water depths ≥1,000 ft out of 1,457 wells. There are about 203 HPHT wells with water depths <1,000 ft out of 3,818 wells.

Formation water salinity in the GOM basin is about 100,000 ppm of total dissolved solids according to Gulf Coast Association of Geological Societies. This results in a hydrostatic pressure gradient of 0.465 psi/ft. Overpressure zones are identified with hydrostatic pressure gradients greater than 0.465 psi/ft. Drilling through over-pressured zones can cause a loss of well control if preventive measures are not taken. BSEE data can further be utilized to develop maps showing areas and zones that have high-pressure gradients that are a risk to health and safety, and to the environment.

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[1] Secretary of the Interior Ken Salazar issued a secretarial order on May 19, 2010 splitting MMS into three new federal agencies: the Bureau of Ocean Energy Management, the BSEE, and the Office of Natural Resources Revenue. MMS was temporarily renamed the Bureau of Ocean Energy Management, Regulation and Enforcement during this reorganization before being formally dissolved on October 1, 2011.

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