PORE PRESSURE PREDICTION USING COMBINATION DRILLING EFFICIENCY AND HYDRO-MECHANICAL SPECIFIC ENERGY METHODS

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Thesis Title	PORE PRESSURE PREDICTION USING COMBINATION DRILLING EFFICIENCY AND HYDRO-MECHANICAL SPECIFIC ENERGY METHODS
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Field of Study	Georesources and Petroleum Engineering
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มูนาวีร์ อาจี ปราตามา โอโตโลโม : การพยากรณ์ความดันในรูพรุนโดยใช้วิธีการควบรวมประสิทธิภาพการเจาะและพลังงานจำเพาะไฮโดรแมคคานิค. (PORE PRESSURE PREDICTION USING COMBINATION DRILLING EFFICIENCY AND HYDRO-MECHANICAL SPECIFIC ENERGY METHODS) อ.ที่ปรึกษาหลัก : จิรวัฒน์ ชีวรุ่งโรจน์

การทำนายความดันในชั้นหินทำได้หลายวิธีโดยใช้พารามิเตอร์การเจาะเพื่อตอบสนองการทำนายที่แม่นยำด้วยต้นทุนที่ค่อนข้างต่ำ ความรู้เรื่องแรงดันในชั้นหินเป็นสิ่งจำเป็นสำหรับการวางแผนหลุมอย่างปลอดภัย คุ้มค่า และปฏิบัติได้ วิธีการทั่วไปในการทำนายความดันในชั้นหินโดยใช้พารามิเตอร์การขุดเจาะมีข้อจำกัดในการประยุกต์ใช้ได้เฉพาะในช่วงหินดินดานที่ไม่ปนเปื้อนซึ่งมีการบดอัดแบบปกติเท่านั้น ในการศึกษานี้ได้นำแนวคิดของประสิทธิภาพการเจาะ(DE) และพลังงานเฉพาะทางไฮโดรแมคคานิกสส์ (HMSE)เพื่อการทำนายความดันในชั้นหิน วิธีการนี้ใช้หลักการที่ว่าพลังงานที่ถูกใช้ในการทำลายหินด้วยหัวเจาะเป็นฟังก์ชันของสภาวะของหินในแหล่งกำเนิดระหว่างการขุดเจาะ HMSE คือปริมาณของพลังงานในแนวแกน การบิด และพลังงานไฮดรอลิกที่จำเป็นต่อการทำให้เกิดการแตกหักของหิน ประสิทธิภาพการเจาะ (DE)กำหนดให้เป็นอัตราส่วนของ Confined Compressive Strength (CCS) ของหินต่อ HMSE การทำนายความดันในชั้นหินด้วยวิธี DE-HMSE ใช้ข้อมูลของสองหลุมเจาะในประเทศออสเตรเลียและ 3 หลุมเจาะในประเทศไทย ผลลัพธ์จากการทำนายความดันในชั้นหินด้วยวิธีนี้จะถูกนำไปเปรียบเทียบกับความดันที่วัดได้จริงในภาคสนามและการทำนายความดันในชั้นจากวิธีการอื่นที่มีผู้ศึกษาไปแล้ว เช่น วิธี d-exponent, MSE, HMSE และ DEMSE ผลการศึกษาพบว่าวิธี DE-HMSE ที่นำเสนอสามารถทำนายความดันในชั้นหินได้อย่างใกล้เคียงและเป็นไปในทางเดียวกับความดันในชั้นหินที่ได้เมื่อเทียบกับวิธีทั่วไปอื่นๆ นอกจากนี้วิธีการที่นำเสนอใหม่มีค่าเฉลี่ยความคลาดเคลื่อนกำลังสองของค่าเฉลี่ยรากที่เล็กที่สุด (RMS) ต่ำกว่าวิธีการอื่น อย่างไรก็ตามวิธีการทั้งหมดที่ได้ศึกษาพบว่าการทำนายความดันในชั้นหินมีความคลาดเคลื่อนสูงในบริเวณที่มีความดันในชั้นหินต่ำเนื่องจากการผลิต

สาขาวิชา	วิศวกรรมทรัพยากรธรณีและปิโตรเลียม	ลายมือชื่อนิสิต ....
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Several methods of pore pressure prediction using drilling parameters were introduced and improved to meet the challenges of accurate prediction at a relatively low cost. Knowledge of pore pressure is essential for safe well planning, cost-effective drilling, and operational decision-making. Conventional methods in pore pressure prediction using drilling parameters have limitations on its application of making the normal compaction trendline that is only applicable in clean shale intervals. In this work, the concept of drilling efficiency (DE) and hydro-mechanical specific energy (HMSE) for predicting formation pore pressure is proposed. This method, termed DE-HMSE, is based on the theory that the energy required to break the rock with the bit is a function of in-situ rock's conditions during drilling. HMSE is the amount of axial, torsional, and hydraulic energy required to break and remove a unit volume of rock, and DE is defined as the ratio of the rock's confined compressive strength (CCS) to the HMSE. The pore pressure prediction using DE-HMSE method is performed in two wells in Australia and three wells in Thailand. The results are compared to the actual measured pressure in the field and pore pressure prediction from conventional methods such as d-exponent, MSE, HMSE, and DEMSE methods. The results show that all the methods have inaccurate predictions of pore pressure in the depleted zone. However, the DE-HMSE method has the smallest root mean square (RMS) error and better agreement with the measured formation pore pressure compared to the other conventional methods.

Field of Study:	Georesources and Petroleum Engineering	Student's Signature ....
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CHAPTER 1

INTRODUCTION

Introduction

Formation pore pressure defined as the pressure exerted by the formation fluids on the walls of the rock pores [1]. The pore pressure supports part of the weight of the overburden stress, while the other part is taken by the rock grains [2]. Formation pore pressure is classified into three types, they are normal or termed hydrostatic, subnormal, and overpressure. Normal pore pressure is when the pore pressure can support a continuous column of static formation water from the surface to the formation depth of interest [3]. The gradient of normal pressure generally varies between 0.433 – 0.515 psi/ft depending on the region, the concentration of dissolved salts in the formation water, pore fluid type, and formation temperature. Overpressure is the pressure gradient greater than the normal pore pressure gradient, and subnormal is when the pore pressure gradient is lower than the normal pore pressure gradient. Normal, overpressure, and subnormal conditions can co-exist in the same sedimentary basin and be separated by permeability barriers. The boundaries of such regions are impermeable, preventing the fluid to flow, and making it trapped to take a large proportion of the overburden stress.

Formation pore pressure data is required in all stages of oil and gas exploration and production. Estimating formation pore pressure before and while drilling is an important input for safe well planning and operational decision-making. From a drilling engineering point of view, formation pore pressure data are used for cement design, casing and tubing design, casing depth determination, rig sizing, drilling and completion fluid design, wellhead design, and equipment design. It represents a potential hazard, and this information is used to help to optimize the drilling rate, prevent well control incidents such as kicks/blowouts, minimize formation damage, and reduce the risk of differential sticking of pipes. Facility engineers use this information for surface installation design. Formation pore pressure also provides the necessary energy required to drive liquid and gaseous hydrocarbon to the surface. Production engineers use it for well performance analysis, and reservoir engineers use it in reservoir modelling. Accurate prediction of formation pore pressure is a great importance in oil and gas industry.

Pore pressure can be predicted by using seismic, well logs, or drilling data. Each data has its merits and limitations in pore pressure prediction. Using only one type of data can lead to misinterpretations. For example, in excessive bit wear condition pore pressure prediction using well log data is more accurate than using drilling parameters. But, in poor borehole conditions such as breakouts or washouts pore prediction using drilling parameters is more accurate than using well log data because this condition may have little or no effect on the drilling parameters. Thus, combining all the available data is the best approach for pore pressure prediction.

There are several methods of pore pressure prediction derived from drilling parameters. The methods are d-exponent, mechanic specific energy, Drilling Efficiency and Mechanic Specific Energy, and Hydro-Mechanic Specific Energy. Each method would have the same or different results of pore pressure estimation depend on the condition. The d-exponent method is a common method that only relies on weight on bit (WOB) for estimating pore pressure. Mechanic specific energy (MSE) and hydro-mechanic specific energy (HMSE) methods have limited predictive capability because these methods use normal-compaction trendline (NCT) of clean shale. While the Drilling Efficiency and Mechanic Specific Energy (DEMSE) method combined the concepts of drilling efficiency and energy required to remove a unit volume of rock. But the energy needed to remove a unit volume of rock in this model doesn’t represent the total energy beneath the bit because the hydraulic energy term is omitted. The hydraulic energy term is the key to correctly determining the amount of energy used in the drilling process. In this study, the combination of drilling efficiency and hydro-mechanical specific energy concepts using the drilling parameters and in-situ rock data would be used to predict formation pore pressure and compare it to the field measurement and others methods.

Scope of Work

The objective of this study is to predict formation pore pressure using a combination of drilling efficiency and hydro-mechanical specific energy concepts, termed DE-HMSE method. The main drilling parameters such as rate of penetration (ROP), weight of bit (WOB), torque on bit (TOB), rotary speed (RPM), and bit size, and also rock's confined compressive strength (CCS) data would be used to predict the pore pressure prediction. Two well data sets in Australia and three well data sets in Thailand would be used in this study. The result of formation pore pressure prediction using drilling parameters would be compared to the actual pore pressure measurement taken from the formations of interest and pore pressure estimation from other conventional methods.

Some conventional methods for formation pore pressure prediction such as modified *d-exponent*, Mechanic Specific Energy, Drilling Efficiency and method Mechanic Specific Energy, and Hydro-Mechanical Specific Energy, would be used to compare the result in this study. In addition, the comparison between the results of this work, measurement data in the field, and conventional methods are used to evaluate the model. The root mean square (RMS) error would be calculated to indicate the overall trend of the prediction model.

Outline of Thesis

There are six chapters in this thesis consisting of:

Chapter 1 describes the usefulness of formation pressure data and the methods for predicting formation pore pressure using some concepts with drilling parameters. It also states the objectives, the outline of thesis and the expected usefulness getting from this research study.

Chapter 2 provides brief descriptions of previously published works of literature and methods related to formation pore pressure prediction using drilling parameters.

Chapter 3 includes fundamental theories and concepts related to the study.

Chapter 4 provides the details of the methodology of the thesis methodology.

Chapter 5 highlights the results of formation pore pressure prediction using drilling efficiency and hydro-mechanical specific energy (DEHMSE) and compared it to actual pore pressure and the results from the other conventional methods. Moreover, obtained results are analyzed and discussed in this segment.

Chapter 6 is composed of conclusions of this research and recommendations for further study.

Expected Usefulness

The proposed method, DE-HMSE method, shows better result in formation pore pressure prediction rather than previous method. Moreover, the DE-HMSE method can be used not only in shale formation, but in non-shale formation.

CHAPTER 2

LITERATURE REVIEW

Drilling performance data, such as penetration rate can be used to detect the top of overpressure zone. Jorden & Shirley [4] used 15 selected wells depth intervals, bit weight, rotary speed, mud density, viscosity, water loss, circulating rate and pressure, bit data, and drill string in Texas-Lousiana Gulf Coast. Rate of penetration data can be normalized by using a general drilling equation, d-exponent method, or by maintaining all drilling variables constant in the field. A plot of the normalized rate of penetration versus depth would show a trend that can be identified as a normal pressure or overpressure zone. The trend would be increased with depth in normal pressure formation, and it would be continually decreased in overpressure zone. Rate of penetration is decreased by an increased confining pressure in most formations because of the rock strengthening due to the confining pressure [5]. The predicted depth of the top of the overpressure zone was validated with the shale resistivity and shale transit time. A correlation between normalized penetration and differential pressure was presented in this study. The result showed that a normalized penetration by d-exponent method and differential pressure were recognizable from the available data.

Rehm & McClendon [6] explained that all of the approaches in pore pressure prediction using drilling parameters have their strengths and limitations. There is no method that can be considered to be absolute answer for all conditions. To make the formation pore prediction more accurate, they modified the *d-exponent* equation to include bottomhole pressure. They used drilling data on over 90 wells throughout the world in this method. As the result, the formation pore pressure prediction in all major drilling areas in the world have accuracies approaching 0.2 lb/gal. The ability to correlate the lithology and established a standard for drilling rates are the key of accurate measurements. Another modification of the *d-exponent* method proposed by Bourgoyne et al. [7]. They proposed the *d-exponent* for formation pressure estimation by correcting the bit wear, bit hydraulics, and others. But, the estimation of formation pore pressure using this method is limited in its conventional application because the *d-exponent* Normal-Compaction Trendline (NCT) is determined manually on the basis of drilling data at the start of each hole section.

Further laboratory work by Cunningham & Eenink [8] showed that overburden pressure had practically no effect on rate penetration and confirmed that rate of penetration is dependent on the difference between mud column and formation pressure. They found that the rate of penetration decreased when mud column pressure was greater than formation pressure. They attributed the decreased primarily to the redrilling of a layer of cutting and mud particles held to the bottom hole by the difference in pressure, and secondarily to the strengthening of the rock by the differential pressure.

One of the most common equation used relationships to predict pore pressure were presented by Eaton [9]. This equation estimates formation pore pressure using well logs data and drilling parameters such as resistivity, conductivity, sonic travel-time, and d-exponent. Eaton assumed that the effective stress in a low permeability rock is a fraction of what it would be in high permeability rock. The pore pressure is equal to hydrostatic pressure in very high permeability rock. In contrast, in low permeability rock the pore pressure is larger than hydrostatic pressure and the effective stress is lower. Eaton's equation proposed to consider the ratio of the electrical resistivity of the rock for normal trend that representative hydrostatic pressure to the resistivity at abnormal pore pressure. Eaton's equation would work well in two conditions which are if a hypothetical normal trend of parameter, such as resistivity, in the ratio could be established, and if any deviations of such parameter from the normal trend would be solely due to changes in pore pressure rather than a multiplicity of factors. The most parameters in Eaton's method are the detection of normal compaction trend line, normal compaction trend (NCT), and appropriate exponent constant, which requires modification to be implemented in tight unconventional reservoirs [10].

Eaton's idea is based on the observation of Hottmann & Johnson [11]. They presented a method for predicting geopressured by using resistivity and sonic log data. They were the first to observe that the shale resistivity would decrease in overpressure zone. This is because the electrical resistivity is larger in the rock matrix than in the water formation. A compacted shale formation containing more water is less resistive than a shale containing less water. Moreover, a normal sequence of compacted sediments should have a gradually increasing resistivity trend. The result of this study which they made a plot of resistivity from well log and showed that any resistivity decrease from the normal trend was associated with abnormally overpressure zone.

Mechanical Specific Energy (MSE) was proposed by Teale [12]. MSE is the energy required to remove a unit volume of rock. Two main contributions of input energy in per unit volume of rock. First, the mechanical work done by the rotary movement of the drill bit, and second done on the rock by the vertical thrust of the drill bit. The concept of MSE has been used in the oil and gas industry as a quantifier of common drilling problems [13], as an index to evaluate drilling performance [14], and as an indicator used to maximize the rate of penetration [15]. MSE is not commonly used to predict pore pressure but the use of the rate of penetration (ROP) has been suggested in some investigations to predict pore pressure [16]. Moore presented that a change of pore pressure from a normal trend can be tracked from a change in mud weight when the rate of penetration is maintained in normal trend and keep the rotary speed and bit weight to be constant [17]. MSE can be estimated from the dependability of parameters such as weight of bit, rotary speed, rate of penetration, and torque. MSE can still be estimated from surface data if the downhole data is not available. This study proposed a fundamental parameter such as MSE can take into account the dependable effect of all drilling parameters at once. Furthermore, a relationship between pore pressure and ROP has been established in other investigations [5] [8], and other investigations suggested that there is indeed a relationship between MSE and pore pressure [18] [19].

Cardona [20] was the first to use mechanical specific energy (MSE) concept to estimate formation pore pressure from the field data. A fundamental parameter which is the energy required to break the rock (MSE) instead of electrical resistivity to be used in Eaton’s equation in order to predict pore pressure. MSE may fit as the definition of normal trend since the MSE increases nearly linearly as a function of depth, in the theoretical case where the pore pressure follows a normal trend and no changes in lithology are present. Since the MSE should be a function of the effective stress, the result showed that the changes in effective stress could be tracked by using the MSE. Then, the pore pressure could be estimated from the effective stress concept. This study proposed equation to use for estimating the virgin pore pressure from the overburden stress and the MSE. Estimation formation pore pressure from this method has limited success. The formation pore pressure estimation derived from specific energy concept based on combination of axial and rotary energies, and also exclude the bit hydraulic energy term. This method mostly suitable for hard rock.

The most important factor affecting the rate of penetration (ROP) is the downhole pressure environment [21]. Another investigation by Akbari et al. showed that the pore pressure or bottomhole formation pressure has a similar effect as the confining pressure or bottomhole mud pressure has on the MSE, but in the opposite direction and to a lower degree [22]. These two studies conducted experiments using a single PDC cutter to observe the relation between the rate of penetration (ROP) and equivalent circulation density (ECD). As the result, the ECD and ROP are linked, and the ECD mostly control the drilling response. A correlation was developed based on the data which gives the MSE as a function of the confining pressure and the pore pressure.

Another technique of formation pore pressure prediction is proposed by Oloruntobi et al. [23] using the concept of Hydro-Rotary Specific Energy (HRSE). The HRSE approximates energy required to break and remove a unit volume rock. The principle of this method is less drill energy would be required in overpressure intervals with lower effective stress rather than in normal pressure intervals at the same depth. This method derived from specific energy concept based on the combination of rotary and hydraulic energies. The HRSE method is not like MSE method by Cardona, but this method includes the bit hydraulic energy term and excludes the WOB term. The HRSE would increase with depth as a rock compaction and effective stress increase in normal pressure intervals, and the reversal HRSE trend would occur in overpressure intervals. This method was tested to a deep vertical gas well in Niger Delta in Nigeria. The result of pore prediction using this method was compared to the actual pore pressure measurement in the field, and pore pressure derived from shale compressional velocity. The results showed that pore pressure prediction using HRSE method has an excellent agreement in magnitude and trend with the pore pressure measurement and pore pressure derived from shale compressional velocity. However, the ability of this method to predict the formation pore pressure depends greatly on the quality of the input data. Shock and vibrations should be minimized while drilling in order to improve the quality of the input data.

Majidi et al. [24] proposed a method to estimate formation pore pressure using a combination of in-situ rock data and downhole drilling-mechanics parameters with the concept of mechanical specific energy (MSE) and drilling efficiency (DE). This method, termed DEMSE, based on the theory that the differential pressure in the rock is subjected to during drilling and the energy spent at the bit to remove a volume of rock is a function of in-situ rock strength. This study showed that the DMSE method relies heavily on downhole torque measurements, and also the MSE based approach, as an independent source of information, can give the result that compare favorably with conventional petrophysical pore-pressure estimation methods. The result of the DEMSE method was compared with formation pore pressure estimated through a conventional sonic log, and classical *d-exponent* methods. As a result, the estimation formation pore pressure from DEMSE method generally follows the magnitude and trend with the pore pressure estimated from sonic log data. The normal compaction trend (NCT) used in the DEMSE method is correlated to the normal compaction porosity trendline which is the same trendline used as a basis for conventional log-based pore pressure estimation. It means that when the downhole drilling mechanics data are available and proper to be used, this method can be used as an independent method for formation pore pressure in real-time at the bit, and for post-well analysis for improving pore-pressure forecast. The DEMSE method considers both torque and weight of bit (WOB), not like *d-exponent* method that only consider the WOB. In pore pressure prediction, the DEMSE method has a significant advantage rather than *d-exponent* method.

Specific energy is the energy required to remove a unit volume of rock in a unit of time. It is one of the important parameters to characterize the drilling efficiency. Mechanical specific energy (MSE) has been used to adjust the drilling rates. It amounts the total of energy due to axial and torsional loads. MSE doesn't represent the total energy consumed in removing and breaking the rock fragments beneath the bit because the hydraulic energy term is omitted in the model [25] [26] [27]. Mohan et al. [26] modified the initial MSE correlation to accommodate the new hydraulic term. They introduced the hydraulic energy term in the MSE correlation by defined it as hydro-mechanical specific energy (HMSE). They explained some of drilling occurs due to jet impact impingement caused by the drilling fluid as well. As the result, the new HMSE equation could identify inefficient/efficient drilling condition better that MSE correlation. Drilling efficiency would be increased at a higher ROP, and analyses based on the HMSE equation showed that drilling efficiency should be higher than those forecast by using MSE. They used 2 wells data to calculated the drilling efficiency and the results showed the energy required to break a volume unit of rock increased from 11% up to 28%. Calculated HMSE has a good correlation with the expected requirements for rock removal under existent conditions of stress at the bit face.

A new method of pore pressure prediction derived from specific energy concept based on the combination of axial, rotary, and hydraulic energy was presented by Oloruntobi & Butt [27]. This method based on the concept of Hydro-Mechanical Specific Energy (HMSE). It includes the bit hydraulic energy term, but excludes the torque term. The theory of this concept is that the function of effective stress is total energy of axial, rotary, and hydraulic consumed in breaking and removing a unit of rock beneath the bit. Higher effective stress means the greater amount of energy required to break and remove a unit volume of rocks. The HMSE method for pore pressure prediction was tested to a near-vertical deep high pressure and high temperature in Niger delta basin, Nigeria. Only surface measurements were used in this study. The result from this method compared to the pore pressure measurement from the field. The result showed good agreement between pore pressure from HMSE method and pore pressure measured from the field. HMSE method can provide a good result of formation pore pressure prediction from drilling parameters when there is no reliable downhole measurement data. However, this method applied Eaton's equation that most applicable in clean shale intervals in order to make a normal compaction trend (NCT).

Table 1 summarize the methods of formation pore pressure prediction using drilling parameters. Most of the methods have limitation that only applicable in shale intervals and not consider the effect of hydraulic energy.

Table 1 Comparison of pore pressure prediction methods using drilling parameters

Method	Concept	Limitation
d-exponent (Jorden & Shirley, 1966; Rehm & McClendon, 1971)	• Normalization of ROP for the effects of WOB, N, and bit size. • In normal pressure environments, dX_c would increase with depth.	• Most applicable in shale intervals • Doesn't consider the effect of hydraulic energy • Only rely on WOB
MSE (Cardona, 2011)	• Using Mechanical Specific Energy concept. • Using Eaton's equation.	• Mostly applicable in shale intervals • Exclude the bit hydraulic term
DEMSE (Majidi et al., 2017)	• Combination of downhole drilling parameters and in-situ rock properties using the concept of drilling efficiency and Mechanical Specific Energy (MSE).	• Exclude the bit hydraulic term
HMSE (Oloruntobi & Butt, 2019)	• Using Hydro-Mechanical Specific Energy concept. • Using Eaton's equation.	• Mostly applicable in shale intervals

Regarding the literature review, the study of pore pressure prediction using a combination of the concept of drilling efficiency and hydro-mechanical specific energy has not been done before. Hence, this study is proposed a method, termed DEHMSE, to improve the drilling efficiency and mechanic specific energy (DEMSE) method by including the hydraulic energy term in the pore pressure prediction model.

CHAPTER 3
THEORIES

3.1 Hydro-Mechanical Specific Energy (HMSE)

Specific energy is one of the most important parameters to characterize the drilling efficiency. Teale defined mechanical specific energy (MSE) as the amount of energy required to break and remove a unit volume of rock [12]. MSE is the combined energy of the axial and torsional work performed by the bit. The equation for calculating MSE is given by:

$$MSE = \frac{Axial\ Energy}{Rock\ Volume\ Drilled} + \frac{Torsional\ Energy}{Rock\ Volume\ Drilled} \quad (1)$$

$$MSE = \frac{WOB}{A_b} + \frac{120\,\pi\,N\,T}{A_b\ ROP} \quad (2)$$

Where MSE is the mechanical specific energy (psi); WOB is the downhole weight on bit (lbs); A_b is the bit area (in^2); N is the rotary speed (rpm); T is the torque on bit (lb.ft); ROP is the rate of penetration (ft/hr). However, the MSE does not represent the total energy required to break and remove a unit volume of rock beneath the bit because the hydraulic term is not included in the equation. Mohan et al. modified MSE correlation by introducing the hydraulic energy term as well as the mechanical energy term [26]. The total energy, termed hydro-mechanical specific energy (HMSE), is the combination of axial, torsional, and hydraulic energy. HMSE encompasses both the mechanical energy term and the hydraulic energy term. The equation for calculating HMSE is given by:

$$\text{HMSE} = \frac{\text{Axial Energy}}{\text{Rock Volume Drilled}} + \frac{\text{Torsional Energy}}{\text{Rock Volume Drilled}} + \frac{\text{Hydraulic Energy}}{\text{Rock Volume Drilled}} \quad (3)$$

$$HMSE = \frac{WOB}{A_b} + \frac{120\,\pi\,N\,T}{A_b\ ROP} + \frac{1154\,\Delta P_b\,q}{A_b\ ROP} \quad (4)$$

Where WOB is the downhole weight on bit (lbs); A_b is the bit area (in^2); N is the rotary speed (rpm); T is the torque on bit (lb.ft); ROP is the rate of penetration (ft/hr); ΔP_b is the bit pressure drop (psi); q is the flow rate (gpm).

The pressure drop (ΔP_b) across the bit is given by:

$$\Delta P_b = \frac{MW\ q^2}{10858\ TFA^2} \tag{5}$$

Where the ΔP_b is the bit pressure drop (psi); MW is the mud weight (ppg); q is the flow rate (gpm); TFA is the total flow area (in^2). The fundamental reason for including the hydraulic energy term is that hydraulic energy is required to transport rock drilled using mechanical energy away from the cutting face. In drilling process, mechanical and hydraulic energy can't be decoupled. The impact of hydraulic energy is used to increase the ROP in a very soft formation. In some cases, hydraulic force is sufficient to overcome the strength of the rock, so the rock can be broken and removed without any contribution from the available mechanical energy.

Confinement of rock and cuttings at the bit face would increase in excessive overbalance conditions. This can lead to a reduction in ROP and an increase in the amount of energy required to remove a unit volume of rock. Therefore, equation (4) needs to be corrected for changes in bottomhole pressure and given by:

$$HMSE = \left[\frac{WOB}{A_b} + \frac{120\,\pi\,N\,T}{A_b\ ROP} + \frac{1154\,\Delta P_b\ q}{A_b\ ROP}\right] x \left[\frac{G_{np}}{ECD}\right] \tag{6}$$

Where WOB is the downhole weight on bit (lbs); A_b is the bit area (in^2); N is the rotary speed (rpm); T is the torque on bit (lb.ft); ROP is the rate of penetration (ft/hr); ΔP_b is the bit pressure drop (psi); q is the flow rate (gpm); G_{np} is the normal gradient pore pressure (ppg); ECD is equivalent circulating density (ppg). This correction is similar to d-exponent method by Rehm & McClendon [6]. Another correction needed to be applied in equation (6) due to accelerated fluid entrainment immediately below the jet nozzles of the bit during drilling. Only 25%-40% portion of the available bit hydraulic energy actually reaches the bottom of the hole [28]. The hydraulic energy reduction factor (η) is introduced to convert the jet hydraulic energy into the bottomhole hydraulic energy.

$$HMSE = \left[\frac{WOB}{A_b} + \frac{120\,\pi\,N\,T}{A_b\ \ ROP} + \frac{1154\,\eta\,\Delta P_b\,q}{A_b\ \ ROP}\right]\,x\,\left[\frac{G_{np}}{ECD}\right] \tag{7}$$

Where all parameters are previously defined. For polycrystalline diamond compact (PDC) bits, the hydraulic reduction factor (η_{PDC}) is expressed as a function of junk slot area and total flow area [23] and given by:

$$\eta_{PDC} = 1 - \left[\frac{JSA}{TFA}\right]^{-0.122} \tag{8}$$

Where JSA is the junk slot area (in^2); TFA is the total flow area (in^2). The hydraulic energy reduction for roller-cone bit (η_{RC}) is expressed as a function of bit area and total flow area and is given by:

$$\eta_{RC} = 1 - \left[\frac{0.15\,Bit\ Area}{TFA}\right]^{-0.122} \tag{9}$$

Due to jet impact of the drilling fluid on the formation, an equal opposite (pump-off) force is exerted on the bit. This leads to a reduction in WOB and the effective weight on bit (WOB_e) is given by:

$$WOB_e = WOB - \eta\,F_j \tag{10}$$

Where WOB is weight on bit (lbs); η is hydraulic reduction factor; F_j is the bit jet impact force (lbf), and is given by:

$$F_j = 0.000516\,MW\,q\,V_j \tag{11}$$

Where V_j is the jet velocity (ft/s), and is given by:

$$V_j = \frac{0.32\,q}{TFA} \tag{12}$$

Where q is the flow rate (gpm); TFA is total flow area (in^2). Equation 13 is obtained by combining equation 7 and 10:

$$HMSE = \left[\frac{WOB - \eta\,F_j}{A_b} + \frac{120\,\pi\,N\,T}{A_b\ \ ROP} + \frac{1154\,\eta\,\Delta P_b\,q}{A_b\ \ ROP}\right]\,x\,\left[\frac{G_{np}}{ECD}\right] \tag{13}$$

The hydro-mechanical specific energy (HMSE) that required to break and remove a unit volume of rock would increase with the depth of burial in normally compacted series. In overpressure region with lower vertical effective stress, the HMSE trend would be reversal due to the HMSE required is less than normal pressure region at the same depth.

3.2 Drilling Efficiency

Drilling for petroleum requires many complex factors, such as formation hardness, mud rheology, flow rate, bit size, bit efficiency, torque, weight on bit, and rotary speed. Drilling efficiency is an important cost-saving measure and is known to increase at a higher penetration rate. The hydro-mechanical specific energy helps better to identify efficient drilling conditions. Drilling efficiency is defined as the ratio of the rock's confined strength (CCS) to the HMSE (Equation 14), which is the energy required to break the rock with the bit at in-situ conditions.

$$DE = \frac{CCS}{HMSE} \quad (14)$$

Each type of rock has different rock strengths. Typically, the rock strength would increase with depth as the compacts and the confined compressive strength increase. The Unconfined compressive strength (UCS) and angle of internal friction (θ) are the key parameters needed to address a range of geomechanical problems from limiting during drilling [29]. Internal friction angle (θ) is a measure ability of a unit of rock to withstand a shear stress. It is the angle (θ), measured between the normal force and resultant force, that is attained when failure just occurs in response to a shearing stress [30]. CCS accounts for UCS and the change in rock strength caused by the confining stresses on the rock during drilling. By using Mohr-Coulomb criterion, CCS can be calculated from UCS:

$$CCS = UCS + \Delta P \left(\frac{1 + \sin\theta}{1 - sin\theta}\right) \quad (15)$$

The differential pressure (ΔP) is the difference between the bottomhole pressure which is equivalent circulating density (ECD), and the normal formation pore pressure (Pn). If differential pressure can affect the drill-bit performance, drilling performance should be improved when differential pressure decrease. For example, in underbalanced drilling, the drilling performance generally improves as either the pore pressure increased or ECD is held low relative to pore pressure. Rock strength data can be derived from regional log correlation or seismic data. There are several empirical relations between UCS, internal friction angle (θ), and compressional velocity (Vp) for different type of lithologies [31] [32] [33] [34]. Many studies have been conducted to showed that UCS is related to other physical properties of the rock samples [35] [36] [37] [38] [39].

3.3 Current Pore Pressure Prediction Methods

- d-exponent method

There are several methods of formation pore pressure prediction using drilling parameters. The d-exponent method was the first empirical method using drilling parameters for predicting formation pore pressure [4]. Then, d-exponent equation was modified by including bottomhole pressure in the model [6]. This expression is known as the corrected d-exponent (dX_c), and is given by:

$$dX_c = \frac{\log(\frac{ROP}{60N})}{\log\left(\frac{12\,WOB}{10^6 d_b}\right)} x \frac{G_{np}}{ECD} \tag{16}$$

Where the dX_c is the corrected d-exponent; ROP is the rate of penetration (ft/hr); N is the rotary speed (rpm); WOB is the weight on bit (lbs); d_b is the bit diameter (in); G_{np} is the normal pore pressure gradient (ppg); ECD is the equivalent circulating density (ppg). Then, the pore pressure gradient (G_{pp}) can be calculated by:

$$G_{pp} = \frac{dX_{cn}}{dX_c} G_{np} \tag{17}$$

Where the dX_{cn} is the normal trendline of corrected d-exponent; dX_c is the corrected d-exponent; G_{np} is the normal pore pressure gradient (ppg). When the calculated dX_c is displayed on the semi-log graph with depth as the vertical axis, the

dX_c would show an increasing trend with depth in normal pressure environments. While in abnormal pressure environments, the dX_c would deviate from the normal trend line (NCT). The dX_c would be lower than NCT in overpressure environments, and would be higher than NCT in subnormal pressure environments. The method doesn't consider the effect of hydraulic energy on the ROP. It may cause inaccurate formation pore pressure prediction in soft rock environments or unconsolidated formations and most applicable in shale intervals.

- Eaton's Method

The most widely method for predicting formation pore pressure is Eaton's method. This method mostly suitable for loading condition where the main origin of abnormal pressure caused by compaction disequilibrium. Eaton proposed three sets of formation pore pressure prediction models using measurements of resistivity (R), sonic (Vp), and calculated of corrected d-exponent (dX_c) [9]. These methods based on extended work of Hottmann & Johnson by included the effect of overburden stress [11]. The equation of these models are given by equation 18-20.

$$G_{pp} = G_{ob} - (G_{ob} - G_{np})\left(\frac{R_o}{R_n}\right)^m \tag{18}$$

$$G_{pp} = G_{ob} - (G_{ob} - G_{np})\left(\frac{\mathrm{Vp}_o}{\mathrm{Vp}_n}\right)^m \tag{19}$$

$$G_{pp} = G_{ob} - (G_{ob} - G_{np})\left(\frac{\mathrm{dX}_{cc}}{\mathrm{dX}_{cn}}\right)^m \tag{20}$$

Where G_{pp} is the pore pressure gradient (psi/ft); G_{ob} is the overburden gradient (psi/ft); G_{np} is the normal pore pressure gradient (psi/ft); R_o is the observed shale resistivity (ohm.m); R_n is the normal compaction trend shale resistivity (ohm.m); Vp_o is the observed shale sonic velocity (m/s); Vp_n is the normal trendline shale sonic velocity (m/s); dX_{cc} is the calculated corrected d-exponent; dX_{cn} is the normal trend line from d_c.In unloading condition, Eaton's equation might be suitable by using higher exponent coefficient [40].

- Mechanical Specific Energy (MSE) method

Cardona was the first to use MSE concept to predict the formation pressure [20]. By using Eaton's equation with MSE concept, the pore pressure can be predicted by equation as follows:

$$G_{pp} = G_{ob} - (G_{ob} - G_{np}) \left(\frac{MSE_c}{MSE_n}\right)^m \quad (21)$$

Where G_{pp} is the pore pressure gradient (psi/ft); G_{ob} is the overburden gradient (psi/ft); G_{np} is the normal pore pressure gradient (psi/ft); MSE_c is the calculated MSE (psi) by using equation (4); MSEn is the normal trendline from MSE_c (psi). The formation pore pressure prediction derived from specific energy concept based on combination of axial and rotary energies, and also exclude the bit hydraulic energy term. This method mostly suitable for hard rock.

- Hydro-Mechanical Specific Energy (HMSE)

Pore pressure prediction using hydro-mechanical specific (HMSE) concept was proposed by Oloruntobi & Butt [27]. Similar to MSE method, this method also used Eaton's equation in the model but with HMSE concept. The pore pressure can be predicted by equation as follows:

$$G_{pp} = G_{ob} - (G_{ob} - G_{np}) \left(\frac{HMSE_c}{HMSE_n}\right)^m \quad (22)$$

Where G_{pp} is the pore pressure gradient (psi/ft); G_{ob} is the overburden gradient (psi/ft); G_{np} is the normal pore pressure gradient (psi/ft); $HMSE_c$ is calculated HMSE (psi) by using equation (13); $HMSE_n$ is the normal trendline from $HMSE_c$. This method based on theory that the total energy required in breaking and removing a unit volume of rock, which are the combination of axial, rotary, and hydraulic energy, beneath the bit as a function of effective stress. Higher effective tress means the higher energy required to break and remove a unit of rocks. For instance, in high formation pressure region with lower effective stress would require lower energy to drill if compare to the normally pressure region at the same depth.

- Drilling Efficiency and Mechanical Specific Energy (DEMSE) Method

DEMSE method proposed by Majidi et al. [24]. This method using normal trendline of drilling efficiency and mechanical specific energy. In DEMSE method the pore pressure is calculated as follows:

$$Pp = P_n + (DE_c - DE_n) \ x \ MSE \ x \ \left(\frac{1 - sin\theta}{1 + sin\theta}\right) \tag{23}$$

Where Pp is the pore pressure (psi); P_n is the normal pore pressure (psi); DE_c is the calculated drilling efficiency; DE_n is the normal trendline from DE_c; MSE is the mechanical specific energy (psi); θ is the internal friction angle (degree). Drilling efficiency calculated (DE_c) is from Eq. 14, and MSE from Eq. 2. DEMSE method is most applicable in shale intervals. Therefore, the applying lithology filter to the input is needed. The shale intervals should be picked by using petrophysical lithology discrimination approach such as gamma ray log to distinguish between shale and non-shale intervals.

CHAPTER 4

METHODOLOGY

In this study, the methodology is subdivided into four steps. The first step is calculating the hydro-mechanical specific energy (HMSE) by using drilling parameters, bit data, and well data. The second step is calculating the rock's confined compressive strength (CCS). In the second step, the unconfined compressive strength (UCS) and internal friction angle (IFA) need to be determined first by using subsurface data such as normal pore pressure gradient, sonic data, and equivalent circulating density (ECD). The third step is to determine the drilling efficiency by using the HMSE calculated from the first step and CCS calculated from the second step. The last step is to calculate the pore pressure by using equation (25) and calculate the error to compare it to the other conventional methods. The overall methodology in this study using DE-HMSE method could be illustrated as a flow chart shown in figure 1. The well data that be used in this study is also provided at the end of this chapter.

4.1 Hydro-mechanical specific energy (HMSE) estimation

Hydro-mechanical specific energy (HMSE) calculation at the depth of interest using equations 5-13. HMSE, which has the units of pressure (psi), can be calculated using mud logging data such as weight of bit (WOB), rate of penetration (ROP), torque (T), rotary speed (N), mud weight (MW), flow (q), and also bit data such as bit area (A_b), total flow area (TFA), and junk slot area (JSA). Appendix A displays the plot of the recorded drilling parameters while drilling the well for all wells. Normally in conventional methods of prediction formation pore pressure using drilling parameters, the lithology filter is needed to be applied. Only shale intervals that be used to calculate the HMSE. But in this study, the HMSE were calculated without applying the lithology filter.

4.2 Rock's Confined Compressive Strength (CCS)

To calculate the rock's CCS, the unconfined compressive strength (UCS) and internal friction angle (θ) need to be determined first. In this study, UCS and θ can be determined by using empirical relations between rock strength and rock property. The sonic slowness (Δt) data would be used to calculate the UCS. Table 2 shows the correlation formula for UCS calculation for a different type of rock.

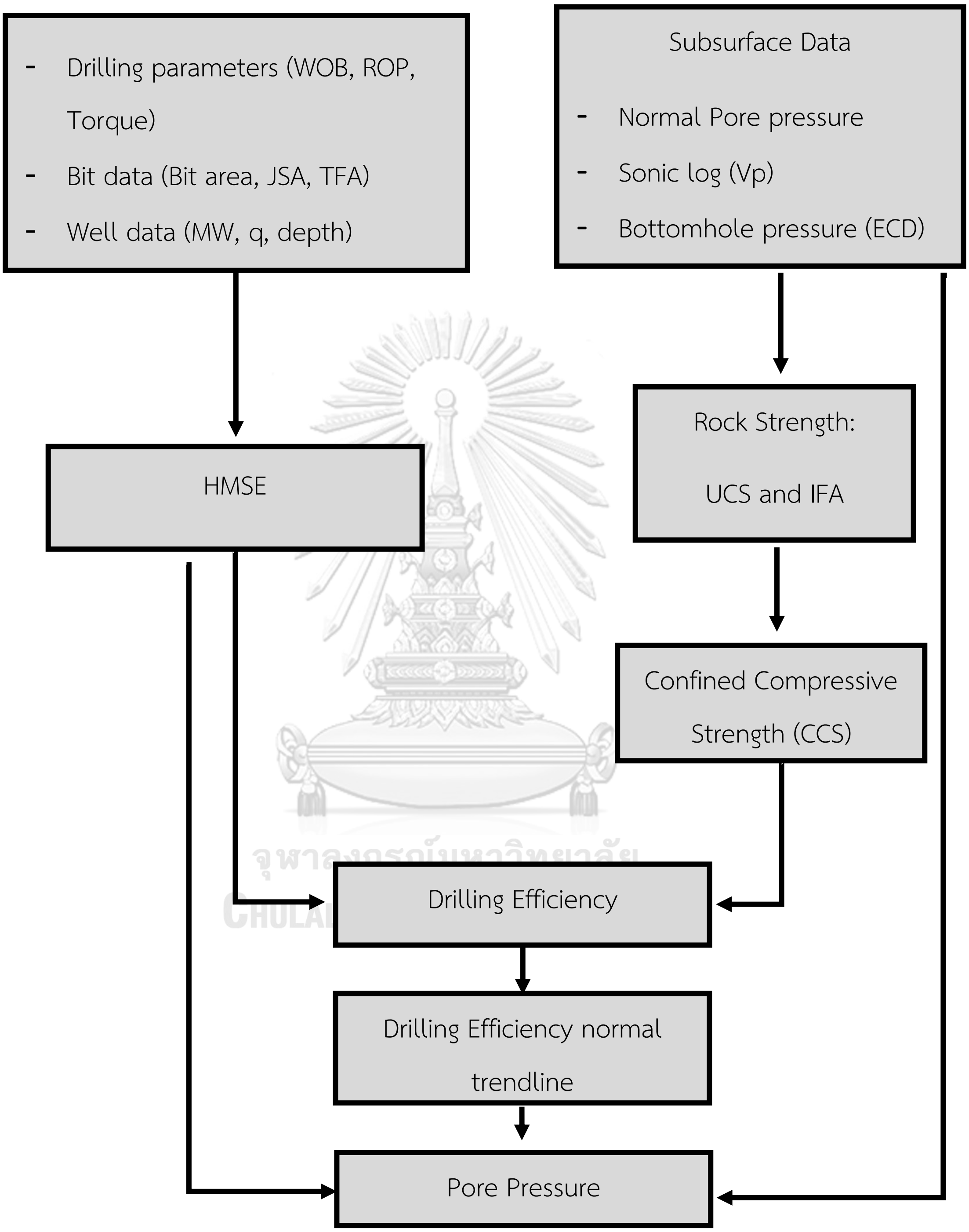

Figure 1 Work flow of pore pressure prediction using Drilling Efficiency and HMSE (DEHMSE) method

Table 2 Correlation formula between UCS and sonic slowness

UCS (MPa)	Comments	Reference
$\frac{10^{\left(2.44+\frac{109.14}{\Delta t}\right)}}{145}$	Limestone formation	[41]
$1200\exp(-0.0036\Delta t)$	Fine-grained, both consolidated and unconsolidated sandstones with a wide porosity range	[42]
$1.35\left(\frac{304.8}{\Delta t}\right)^{2.6}$	Claystone globally	[32]

While the internal friction angle (θ) would be calculated by using sonic velocity (V_p) as follows.

$$\theta = 18.53\, V_p^{0.5148} \tag{24}$$

The unit of sonic slowness (Δt) is in μs/ft, and sonic velocity (V_p) is in km/s. After the UCS and θ are determined, the CCS could be calculated at all depths by using equation 15.

4.3 Drilling Efficiency

Drilling efficiency is the ratio of the Confined Compressive Strength (CCS) to the energy required to break the rock, which is the hydromechanical specific energy (HMSE). Drilling efficiency can be calculated by using equation 14. After drilling efficiency is obtained by calculation (DE_c), normal trendline drilling efficiency (DE_n) can be correlated by using the power function (Figure 2).

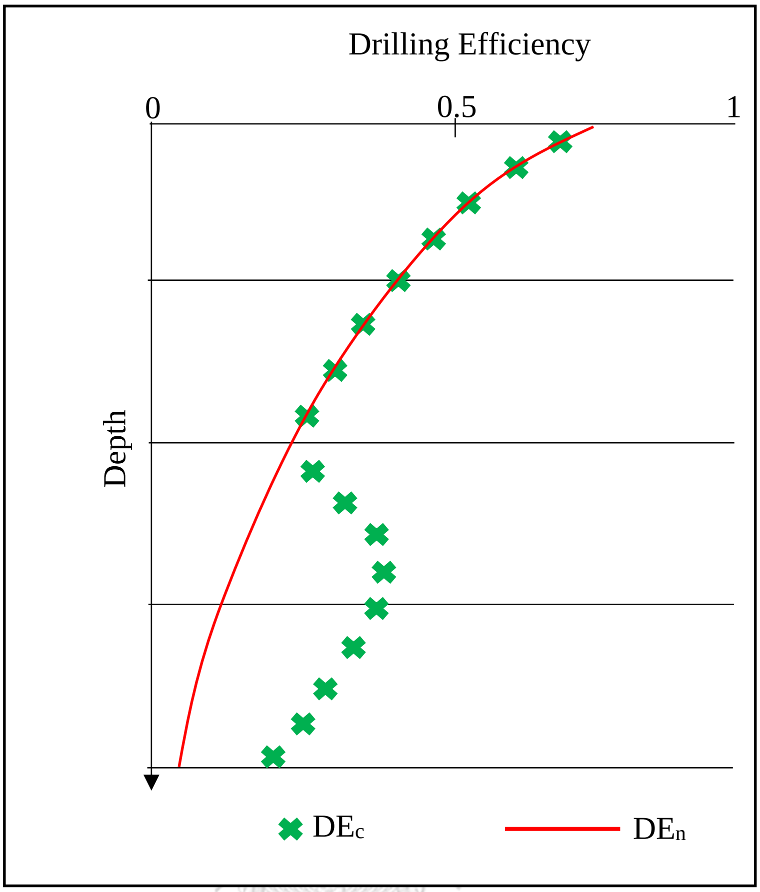

Figure 2 Illustration of the drilling efficiency normal trend estimation

The reason for using power function in making a normal trendline is to follow the trendline of porosity [24]. An advantage of DE normal trendline based on porosity is that the same porosity trendline models that may be used in sonic and resistivity-based pressure-estimation methods can be used in this DEHMSE approach.

4.4 Pore pressure estimation

The pore pressure prediction using DE-HMSE method in this study is calculated as follows:

$$Pp = P_n + (DE_c - DE_n)\ x\ HMSE\ x\ \left(\frac{1 - sin\theta}{1 + sin\theta}\right)^m \quad (25)$$

Where the P_n is the normal pressure (psi), calculated drilling efficiency (DE_c) and normal trendline of drilling efficiency (DE_n) from step 3, HMSE is hydro-mechanical specific energy calculated (psi) from step 1, θ is the internal friction angle from step 2, and m is he exponent coefficient in this method assumed between range 1 to 2. Based on the salinity of the formation waters in the regions, the average normal pore pressure that be used in this study is 8.33 ppg for all wells. The pore pressure prediction using another conventional method was performed to compare the result from the DE-HMSE method. Table 3 provides the formulas that be used to predict pore pressure using conventional methods.

The error from the result of formation pore pressure prediction using these methods would be calculated to evaluate the quality of the prediction. The root mean square (RMS) error would be used in this study. RMS error measures the difference between the prediction value to the actual value. RMS error could be calculated by using the equation as follows.

$$RMSE = \sqrt{\frac{\sum(PP_m - PP_c)^2}{n}} \quad (26)$$

Where the PP_c is the calculated pore pressure (psi), PP_m is the measured pore pressure (psi), and n is the total number of data points. The RMS error would be calculated only at point depth that has measured pore pressure data. RMS error is always non-negative, and a value of 0 would indicate a perfect fit to the actual data. In general, a lower RMS error is better than a higher one.

Table 3 Pore pressure estimation using conventional methods

Method	Formula	Reference
d-exponent	$dX_c = \frac{\log(\frac{ROP}{60N})}{\log\left(\frac{12\,WOB}{10^6 d_b}\right)} x \frac{G_{np}}{ECD}$ $G_{pp} = \frac{dX_{cn}}{dX_c} G_{np}$	[4] [6]
Mechanical Specific Energy (MSE)	$MSE = \frac{WOB}{A_b} + \frac{120\,\pi\,N\,T}{A_b\,ROP}$ $G_{pp} = G_{ob} - (G_{ob} - G_{np})\left(\frac{MSE_c}{MSE_n}\right)^m$	[20]
Drilling Efficiency and Mechanical Specific Energy (DEMSE)	$DE = \frac{CCS}{MSE}$ $Pp = P_n + (DE_c - DE_n)xMSEx\left(\frac{1 - sin\theta}{1 + sin\theta}\right)$	[24]
Hydro-Mechanical Specific Energy (HMSE)	$HMSE = \frac{WOB}{A_b} + \frac{120\,\pi\,N\,T}{A_b\,ROP} + \frac{1154\;\Delta P_b\,q}{A_b\,ROP}$ $G_{pp} = G_{ob} - (G_{ob} - G_{np})\left(\frac{HMSE_c}{HMSE_n}\right)^m$	[27]

4.5 Well Data and Field Example

To demonstrate the applicability of the DE-HMSE method to predict the formation pore pressure, one well data from Gippsland Basin (Well A), one well data from North Carnarvon Basin (Well B), and three well data from Thailand (Well C, Well D, and Well E) are used. The total TVD depth for Well A is 11,033 ft, Well B is 10,392 ft, Well C is 8,766 ft, Well D is 9444 ft, and Well E is 8163 ft. In this study, all depths are with respect to the true vertical depth (TVD) below the rotary table (RT). Table 4 provides summary information about well data and bit data of all wells.

Table 4 Well and bit data

Well A				
Hole Size (inch)	Interval Depth (ft)	Bit Type	TFA (in^2)	JSA (in^2)
17.5	953 – 3,375	PDC Bit	1.12	36.1
12.25	3,375 – 11,033	PDC Bit	1.4	30.5
Well B				
Hole Size (inch)	Interval Depth (ft)	Bit Type	TFA (in^2)	JSA (in^2)
26	848 – 2,609	Roller Cone	1.362	79.6
17.5	2,609 – 6,772	Roller Cone	1.553	36.1
12.25	6,772 – 9,845	PDC Bit	0.994	30.5
8.5	9,845 – 10,494	PDC Bit	0.742	13.2
Well C				
Hole Size (inch)	Interval Depth (ft)	Bit Type	TFA (in^2)	JSA (in^2)
12.25	67 – 832	PDC Bit	1.138	30.5
8.5	832 – 8766	PDC Bit	0.752	13.2

Well D				
Hole Size (inch)	Interval Depth (ft)	Bit Type	TFA (in^2)	JSA (in^2)
12.25	69 - 2854	PDC Bit	1.141	30.5
8.5	2854 – 9444	PDC Bit	0.796	13.2

Well E				
Hole Size (inch)	Interval Depth (ft)	Bit Type	TFA (in^2)	JSA (in^2)
12.25	67 – 2507	PDC Bit	1.138	30.5
8.5	2507 – 8163	PDC Bit	0.818	13.2

The Gippsland Basin (Well A), one of Australia's most prolific hydrocarbon provinces, is situated in southeastern Australia and is located about 200km east of the city of Melbourne. Most of the commercial oil and gas discoveries are reservoirs within the siliciclastic of the Late Cretaceous to Paleogene Latrobe Group. The succession is non-marine clastic to marginal marine clastic, marine clastic and uppermost marine carbonates. The detailed geology of the Gippsland Basin can be obtained from the literature [43] [44].

The Northern Carnarvon Basin (Well B), Triassic to Early Cretaceous deposition is dominantly siliciclastic deltaic to marine, whereas slope and shelf marls and carbonates dominate the Mid-Cretaceous to Cainozoic section. The carbonate-rich sediments were deposited as a series of northwestward prograding wedges as the region continued to cool and subside. This resulted in deep burial of the underlying Mesozoic source and reservoir sequences in the inboard part of the basin. Almost all the hydrocarbon resources are reservoired within the Upper Triassic, Jurassic and Lower Cretaceous sandstones beneath the regional Early Cretaceous seal. The detailed geology of the Northern Carnarvon Basin can be obtained from the literature [45] [46] [47].

In this study, Well A was drilled through the interbedding between shale and sandstone formation to the target reservoir, which is the sandstone reservoir. While in Well B, there is no shale intervals above the reservoir formation. The well was drilled through the limestone formation to the target reservoir, which is sandstone. Well C and D were drilled through the interbedding between claystone and sandstone formation to the sandstone reservoir. Well E was drilled through three reservoirs. The lower reservoir is limestone, and the hydrocarbon is gas, the middle reservoir is sandstone with oil and water in it, and the upper reservoir (shallow depth) is sandstone with gas and water in it. The formation above these reservoirs is interbedding claystone and sandstone, the same with Well C and D. At depth shallower than 2,800 ft in Well C, and Well D, and also at depth shallower than 2,400 ft in Well E, the ROP and torque data have poor quality. Therefore, these interval depths would not be discussed.

CHAPTER 5

RESULT AND DISCUSSION

5.1 Hydro-Mechanical Specific Energy

Hydro-mechanical specific energy (HMSE) was calculated from different interval depths for each well. The interval depth for each well showed in table 4. The HMSE displays on a semi-log graphic against the depth. Figure 3 shows the HMSE profile for all wells.

The lithological effect on the HMSE in Well A is minimum. The minimum lithological effect means the total energy required to break and remove a unit volume of rock beneath the bit, which is HMSE, increased with depth due to the rock porosity decrease and effective stress increase. In other words, the HMSE increase with the normal compaction trendline of the shale lithology. The other wells that have minimum lithology effect are Well C (below depth 3,400 ft), Well D (below depth 3,600 ft), and Well E (below depth 2,700 ft). The normal trendline of HMSE can be established from this depth for each well. In Well C and D at depth less than 3,000 ft, the HMSE value is highly scattered due to fluctuating input data of the ROP. At depth 2,900 ft to 3,600 ft of Well D, the HMSE is a little bit higher due to the well was drilled through the cement. In Well E, at depth of around 2,500 ft the value of HMSE is a little bit higher due to the bit was changed from diameter 12.25 inches to 8.5 inches, and at depth 8,000 ft, the HMSE value is increased which means the energy required to break and remove a unit volume of rock beneath the bit is much higher. This could be due to the existence of the limestone lithology effect.

In Well B, the HMSE increase with depth with different trendline at different interval depth. For example, at depth interval 1,000 ft to 2,700 ft has a different trendline with depth interval 2,700 ft to 4,000 ft. The highest trendline is at interval depth 6,000 ft to 7,500 ft. This difference of trendline is because of the effect of lithology change. So, the normal trendline for this well is hard to establish.

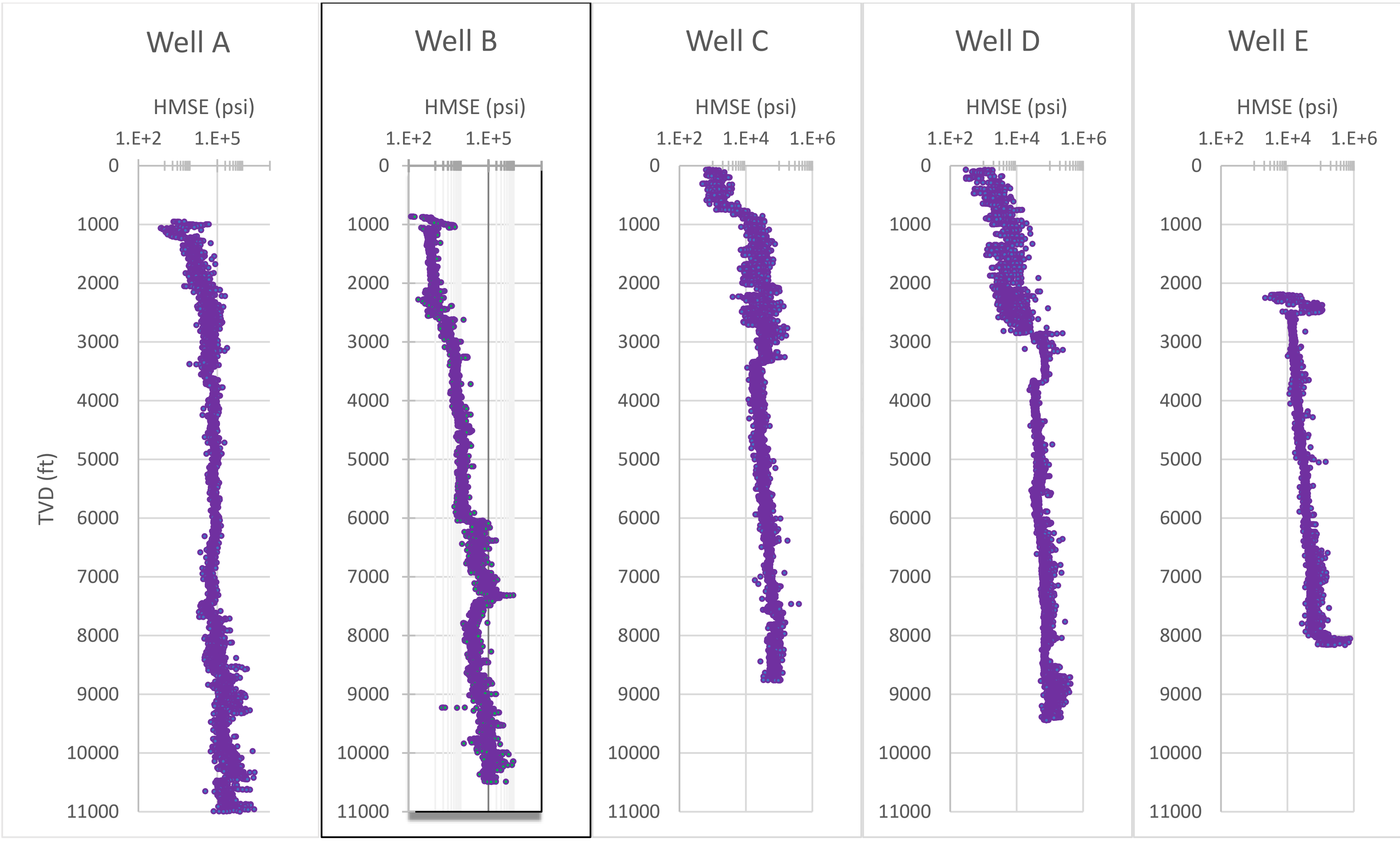

Figure 3 The HMSE profile for all wells

Hydro-mechanical specific energy is the total amount of axial energy, torsional energy, and hydraulic energy. Appendix B displays the plots of calculated axial energy, torsional energy, and hydraulic energy for all wells. The axial energy for all wells has small amount of energy, while the torsional energy has the biggest amount of energy. The energy required to break the unit volume of rock done by torque, which is the product of the applied torsional force and distance, is considerably much larger than axial energy from weight of bit (WOB) over the bit penetration and also higher than hydraulic energy term. For this reason, the pore pressure prediction using DE-HMSE method is highly sensitive to the downhole torque data. However, the amount of hydraulic energy is less than torsional energy, but the difference is not that much. Therefore, the hydraulic energy term has a meaningful effect on this calculation and can’t be neglected. Hydraulic energy estimation only relies on mud weight and flow rate, which is the measurement that could be done easily at the surface. But torsional energy that relies on downhole torque measurement, sometimes the measurements have errors. For instance, the measurements error due to BHA sticking and induced by torsional vibration. These would directly affect the HMSE calculation and also the pore pressure prediction.

5.2 Rock’s Confined Compressive Strength (CCS)

Equation 24 and the formula in table 3 are the common empirical relationship between IFA, UCS, and sonic velocity that be used in this study. In this study, sonic velocity data is only available from depth 1,327 ft to 10,785 ft for Well A, 2,610 ft to 10,392 ft for Well B, 2,653 ft to 6,062 ft for Well C, 2,729 ft to 9,444 ft for Well D, and 2,333 ft to 8,163 ft for Well E. The formulation for estimating UCS is different for each type of rock such as limestone, sandstone, and shale stone.

The display plots of sonic velocity, IFA, UCS, and CCS for all wells showed in Appendix C. The calculated IFA, UCS, and CCS showed the same trend as sonic velocity for all wells. The range IFA is between 26^{o} to 45^{o} for Well A, 28^{o} to 42^{o} for Well B, 25^{o} to 47^{o} for Well C, 20^{o} to 50^{o} for Well D, and 26^{o} to 55^{o} for Well E. While the UCS and CCS range in Well A is from 1,250 psi to 30,000 psi, Well B is from 2,000 psi to 25,000 psi, Well C is from 3,300 psi to 30,000 psi, Well D is 3,000 psi to 30,000 psi, and Well E is from 2,500 psi to 30,000 psi.

5.3 Drilling Efficiency

Drilling efficiency is the ratio between rock's confined compressive strength to the energy required to break the volume of a unit rock. Drilling efficiency can be calculated by using equation 14. Figure 4 displays the plots of drilling efficiency. Figure 4 shows the calculated drilling efficiency (blue dot) at every depth. Well B has higher drilling efficiency than the other wells. It means in Well B, the amount of energy required to break a unit volume of rock is much lower than the energy required in the other wells. The higher drilling efficiency means the lower total amount of energy to break a unit of volume rock. The average of drilling efficiency in Well A is 0.09, Well B is 0.30, Well C is 0.23, Well D is 0.19, and Well D is 0.28.

From the plot, the black line is the normal drilling efficiency trendline (DE_n) that is established from all intervals depth, and the trendline is a power function to correlate to a compaction porosity trend. The normal trendline is decreased with increasing depth, which means that the energy required to break a unit volume of rock (HMSE) is much higher than the rock's CCS. In other words, when the porosity decrease with increasing depth the energy required to break a volume of rock (HMSE) is much higher. As with any other conventional pressure prediction method, refining the trendline model to calibrate the output-pressure estimation is an interpretive process that involves considerable geoscience judgment. When the drilling efficiency is much higher than the normal trendline, this could indicate of overpressure zone. In overpressure zone, the energy required to break a unit volume of rock (HMSE) is lower due to the differential pressure between the bottom-hole pressure (ECD) and the formation pressure is smaller.

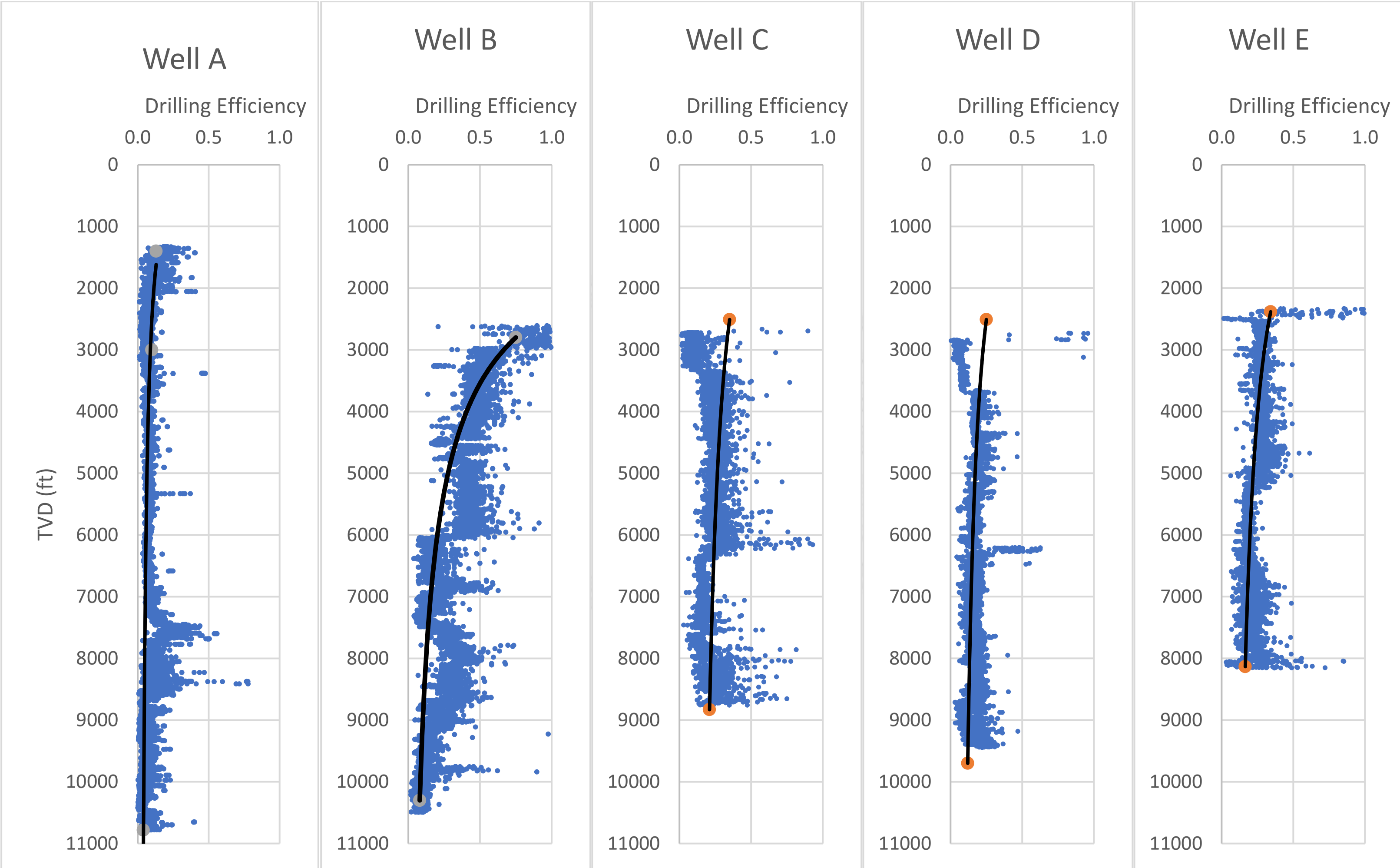

Figure 4 Drilling Efficiency for all wells

5.4 Pore Pressure Estimation

Figures 5 and 6 show the profile of pore pressure calculated using DE-HMSE method at all depths for all wells. In some interval depths, the calculated formation pore pressure is highly scattered. The value of this scattered data tends to be lower than the trendline of the calculated formation pore pressure due to the fluctuation data of drilling parameters used in the calculation (Appendix A). The calculated pore pressure is start to have highly scattered at depth after 7,500 ft in Well A, and at interval depth 6,000-7,500 ft in Well B due to fluctuating data of RPM, ROP, and torque. Other examples are in Well C and D at depth around 3,000 ft, the calculated formation pore pressure is much lower and highly scattered due to the flow rate is much higher. In Well E, there is carbonate reservoir at depth 8,100 ft with gas in it and based on the measured pore pressure this zone is overpressure zone. The DE-HMSE still has a good correlation between calculated and measured formation pore pressure in this zone. But, the DE-HMSE method has large residual between calculated and measured pore pressure in the depleted zone that exists in Well C and Well E. The depleted zone in Well C is at depth 8,142 ft, 8,637 ft, and 8,687 ft. While in Well E, the depleted zone is at depth 7,436 ft and 7,607 ft.

Figure 7 shows the pore pressure estimation derived from DE-HMSE method (Equation 25) compared to the actual pore pressure measured in the field at the same depth point. The actual pore pressure measurements were obtained from the wireline pressure sampling tool at the depths of interest. Pore pressure measurements were conducted in 41 points from depth 9,446 ft to 10,869 ft in Well A, 42 points from depth 9,031 ft to 10,382 ft in Well B, 15 points from depth 4,623 ft to 8,687 ft in Well C, 5 points from depth 7,310 ft to 8,585 ft in Well D, and 20 points in range depth 2,581-3,090 ft and 7,253-8,103 ft in Well E.

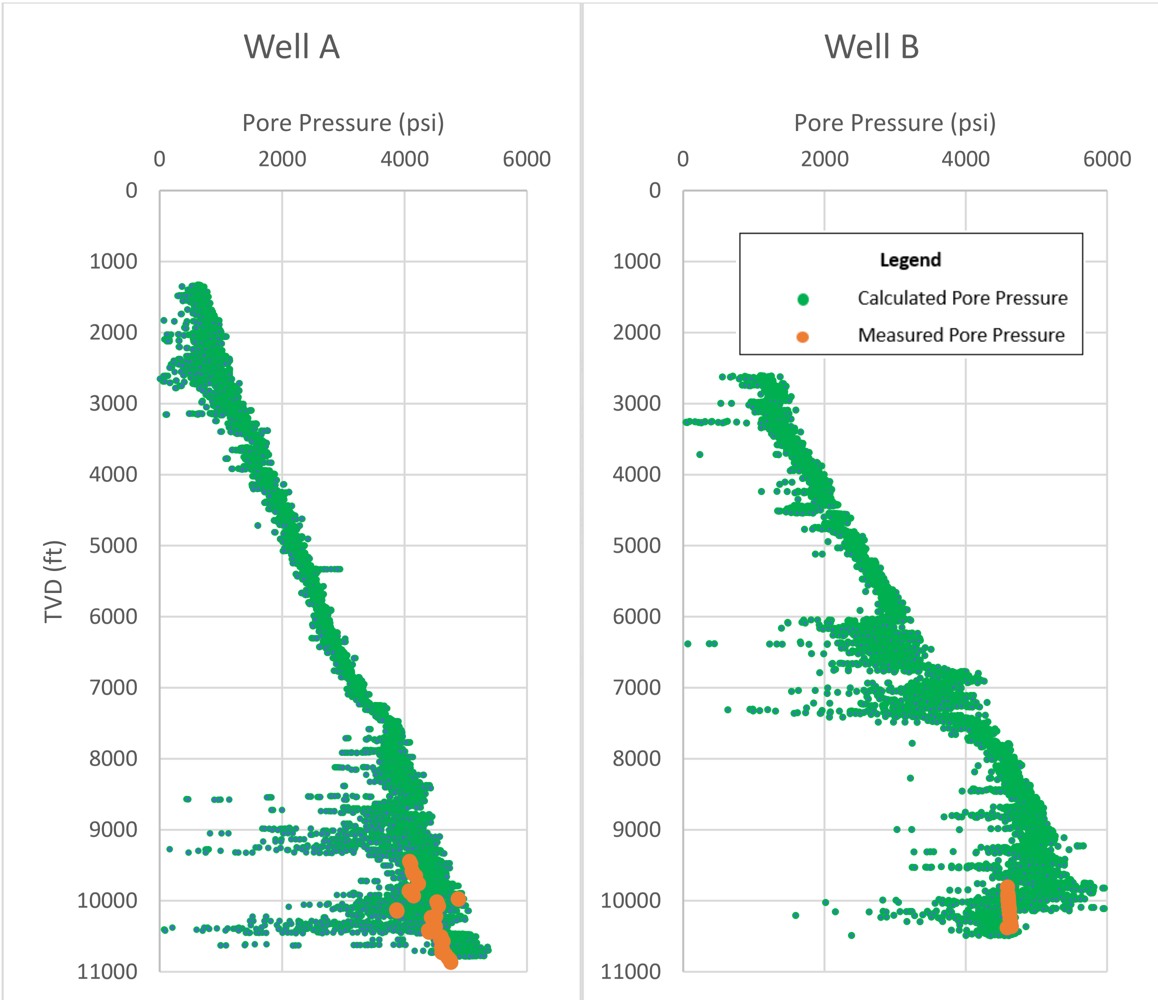

Figure 5 Pore pressure profile using DE-HMSE method for Well A, and Well B

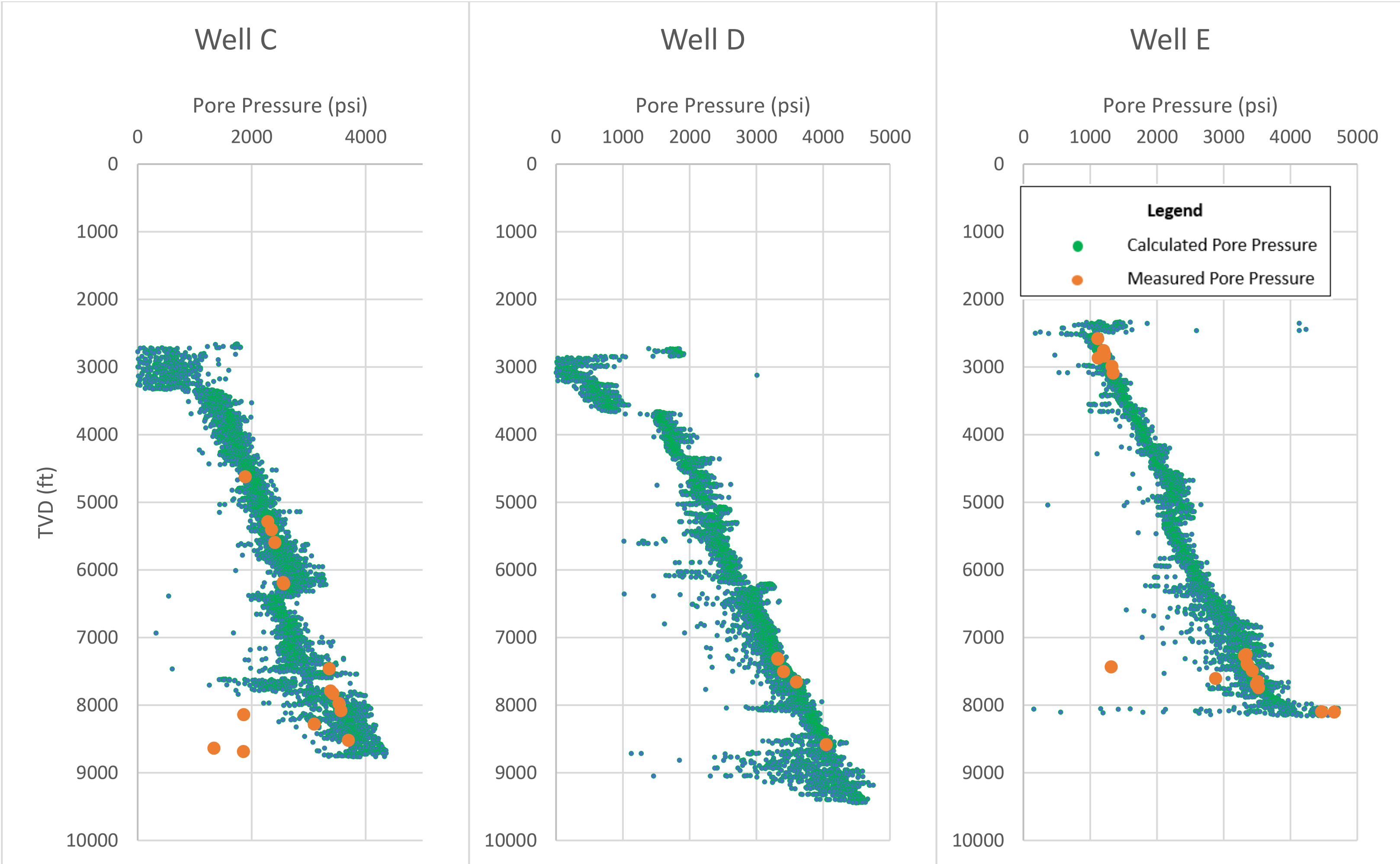

Figure 6 Pore pressure profile using DE-HMSE method for Well C, Well D, and Well E

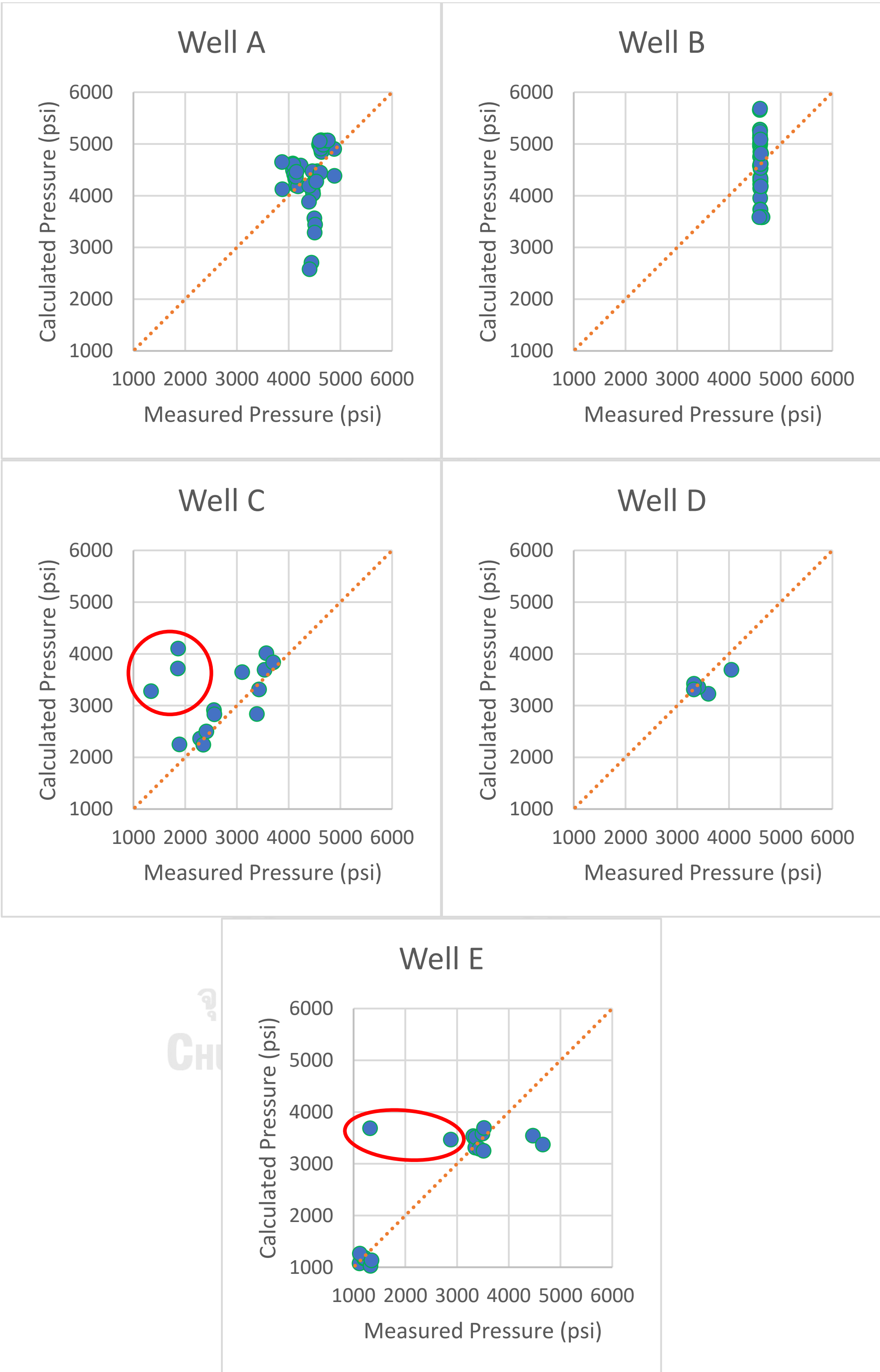

Figure 7 Comparison between calculated pore pressure and measured pore pressure for all wells

In Figure 7, the blue dot is the plot between the calculated pore pressure using the DE-HMSE method on the vertical axis and the measured pore pressure on the horizontal axis. While the orange dash line is the best fit line when the value of the calculated pore pressure equals to measured pore pressure. The closer of the blue dot to the orange dash line means that the error between calculated and measured pore pressure is smaller. The red circle in Well C and Well E is the data in depleted zone. In Well A, most of the points are close to the best-fit line except 5 points that have big residual between calculated and measured pore pressure. In Well B, the measured pore pressure has small range value only between 4,594 psi to 4,609 psi. But the calculated pore pressure has wider range value between 3,730 psi to 5,657 psi. In Well C, 12 points are close to the best-fit line, and 3 points in the depleted zone have significant residual between calculated and measured pore pressure. In Well D, all points are close to the best-fit line. While in Well E, all the points on the lower part are close to best-fit line, 12 points on the upper part are also close to the best-fit line, and 4 points have some residual. All the points in the depleted zone have significant residual between calculated and measured pore pressure. Appendix D shows the table of calculated and measured pore pressure value data for all wells

Based on the result, the pore pressure prediction using DE-HMSE method is inaccurate in the depleted zone. There is a large residual value between calculated and measured pore pressure, around 2,000 psi in depleted zone Well C and Well E. If the pore pressure data in the depleted zone are excluded, the RMS ERROR would be decreased in Well C and Well E. The pore pressure prediction using DE-HMSE method still shows good results in non-shale intervals. For example, in Well B where the formation above the reservoir is carbonate, the calculated pore pressure still shows good match between the calculated and measured pore pressure. The RMS ERROR value is 601 psi.

The other conventional methods which are d-exponent, MSE, HMSE, and DEMSE method have performed on the same well data set to compare the pressure estimation from each method. Figure 8-12 shows the plot of calculated pore pressure using all methods used in this study and the actual pore pressure measured in the field. While appendix E shows the comparison between calculated pore pressure as the vertical axis and measured pore pressure as the horizontal axis for all methods in all wells. Table 5 shows the comparison of the root mean square (RMS) error for these methods using the same data set for pore pressure prediction for all well data sets.

Table 5 Root mean square (RMS) error for all methods of pore pressure prediction

Method	RMS ERROR (psi)				
	Well A	Well B	Well C	Well D	Well E
d_c-exponent	823	602	609 532	423	760 545
Mechanical Specific Energy (MSE)	914	3402	1110 878	530	975 853
Hydro-mechanical Specific Energy (HMSE)	909	756	1154 855	394	968 834
Drilling Efficiency and Mechanical Specific Energy (DEMSE)	714	1407	979 297	242	665 414
Drilling Efficiency and Hydro-Mechanical Specific Energy (DE-HMSE)	588	601	946 288	236	666 401

In table 5, the green color value in Well C and Well D are the RMS error value when the data in the depleted zone are excluded in RMS error calculation. Only d_c-exponent method and DE-HMSE method that have RMS error less than 900 psi for all wells. However, the DE-HMSE method has the smallest RMS error value for all wells when the data in the depleted zone are excluded.

The effect of hydraulic energy term in pore pressure prediction using drilling parameters could be seen in the comparison of MSE method to HMSE method, and DEMSE method to DE-HMSE method. The RMS error value is decreased for all wells when including the hydraulic energy term. For example, Well B has significant decreasing value of RMS error. RMS error decreased 3,326 psi from 3,402 psi for MSE method to 756 psi for HMSE method, and 806 psi decreased from 1,407 psi for DEMSE method to 601 for DE-HMSE method. Therefore, the pore pressure prediction using drilling parameters would have better results when including the hydraulic energy term.

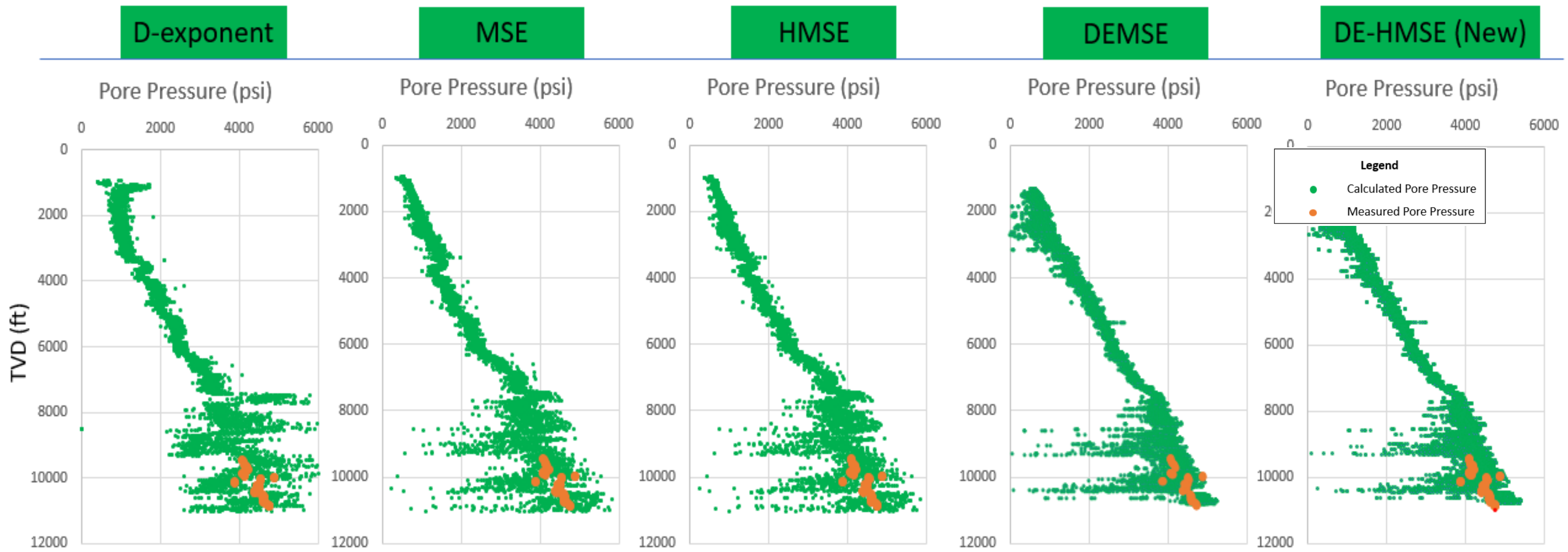

Figure 8 Pore pressure estimation using d-exponent method, MSE method, HMSE method, DEMSE method, and DE-HMSE method for Well A

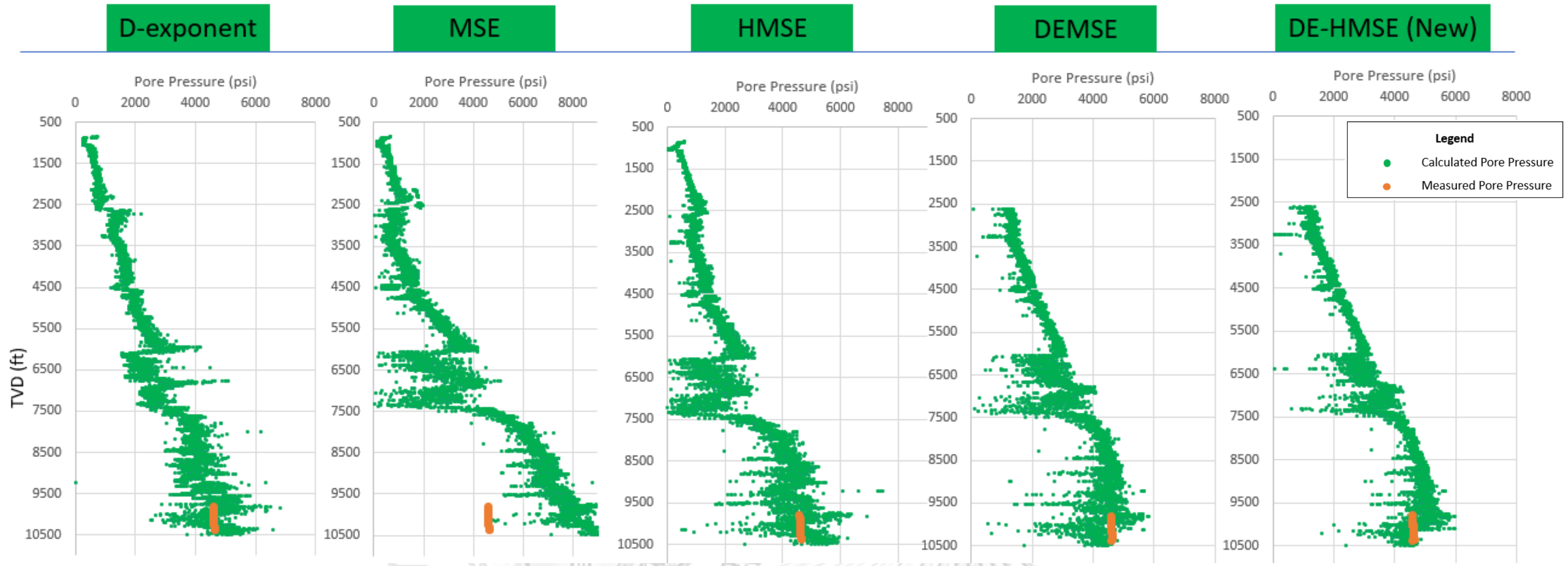

Figure 9 Pore pressure estimation using d-exponent method, MSE method, HMSE method, DEMSE method, and DE-HMSE method for Well B

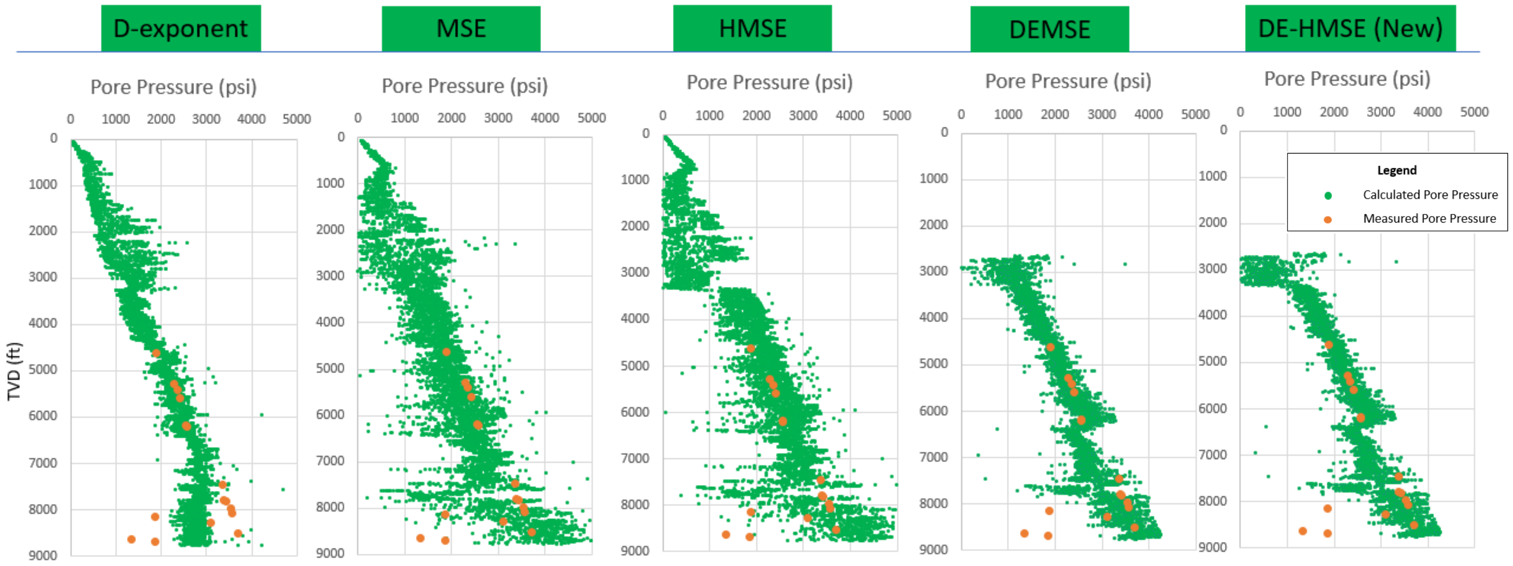

Figure 10 Pore pressure estimation using d-exponent method, MSE method, HMSE method, DEMSE method, and DE-HMSE method for Well C

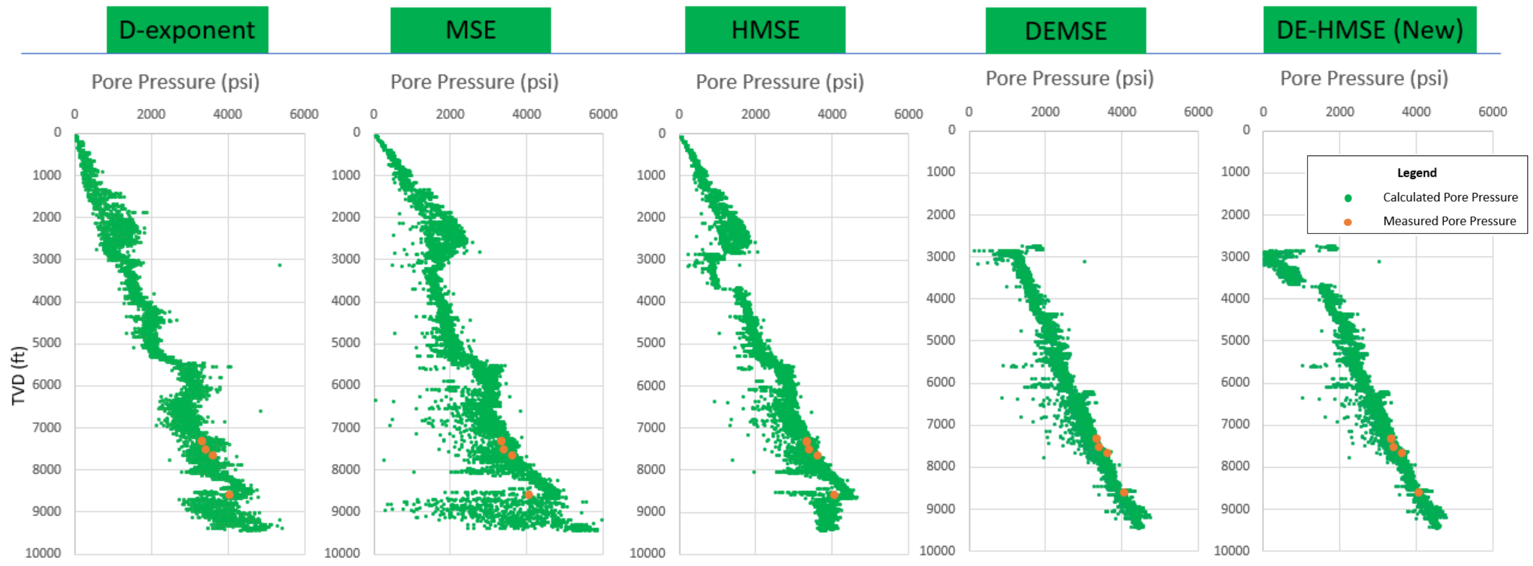

Figure 11 Pore pressure estimation using d-exponent method, MSE method, HMSE method, DEMSE method, and DE-HMSE method for Well D

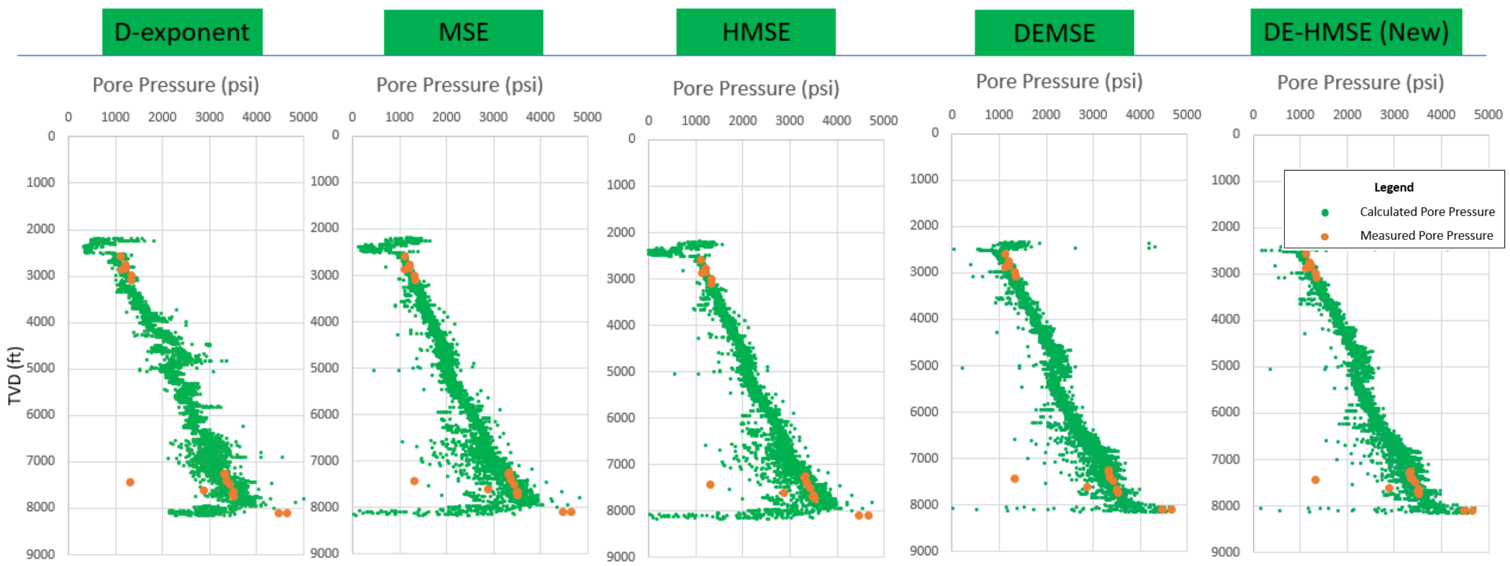

Figure 12 Pore pressure estimation using d-exponent method, MSE method, HMSE method, DEMSE method, and DE-HMSE method for Well E

For Well A (Fig 8), all the pore pressure estimation shows the same trendline. The RMS error are below 1,000 psi. This is because in Well A, the formation above the reservoir is the interbedding between shale and sandstone, which is all the methods are applicable in shale intervals. Depth below 7,800 ft for all wells, the calculated pore pressure values are highly scattered. This is because of the fluctuating data of torque. All of the scattering values of calculated pore pressures for all methods tend to be less than the normal trendline except for the d_c-exponent method. In the dc-exponent method, the calculated pore pressure in some intervals are scattering much higher than the normal trendline.

Pore pressure estimation using data set Well B shows different trends for the first three methods, which are d_c-exponent, MSE, and HMSE method (Fig 9). At the depth shallower than 6,000 ft, the trendline of the calculated pore pressure is not a straight line. The lithology change has a significant effect, especially in MSE and HMSE method. In these three methods, the normal compaction trendline (NCT) couldn't be established because the formation intervals above the reservoir are non-shale. MSE and DEMSE method have large RMS error, 3,402 psi for MSE method and 1,407 psi for DEMSE method. When the hydraulic energy term was included, which are HMSE and DE-HMSE method, the RMS error became much smaller, 756 psi for the HMSE method and 601 psi for the DE-HMSE method. DEMSE and DE-HMSE method show one straight trendline in non-shale intervals. But, the result from DE-HMSE method is much better with smaller RMS error. From the DE-HMSE result, the pore pressure is increased with depth at the non-shale intervals at range depth 2,600-9,500 ft. At depth below 9,500 ft, which is a sandstone reservoir, the pore pressure is less than the pore pressure in the non-shale formation.

For Well C (Fig 10), all interval depths are interbedding between shale and sandstone. The calculated pore pressures at depth shallower than 2,800 ft are highly scattered due to the fluctuating data of the ROP and torque (Appendix A.3). Calculated pore pressure for all methods show the same trendline with the measured pore pressure trendline. But all methods have large differences in pore pressure prediction in the depleted zone. It means that all of these methods are inaccurate in prediction of the pore pressure in the depleted zone. Although the d_c-exponent method has the smallest differences, the trendline of calculated pore pressure after depth 7,500 ft is not the same as the trendline of measured pore pressure in the non-depleted zone.

Figure 11 shows the pore pressure profile for Well D. The lithology of Well D is similar to Well C, interbedding between shale and sandstone. The calculated pore pressure is highly scattered at depth shallower than 2,900 ft due to the ROP and torque fluctuating data. All methods have good correlation with the measured pore pressure. The trendline of calculated pore pressure follows the trendline of measured pore pressure, and the RMS error for all methods are less than 550 psi. However, the DE-HMSE method shows the smallest RMS error, only 236 psi.

Figure 12 shows the pore pressure profile for Well E. The lithology is interbedding between shale and sandstone and below 8,000 ft the lithology change to carbonate. All methods show the same trendline of calculated pore pressure in shale intervals. For example, in the upper reservoir (depth 2,500 ft to 3,200 ft), all methods have small RMS error between calculated and measured pore pressures. While in the middle reservoir (depth 7,200 ft to 7,800 ft), all methods also show small RMS error between calculated and measured pore pressures except at the depleted zone. At the depleted zone, all of these methods have large RMS error, which means all of these methods are inaccurate in prediction of pore pressure in the depleted zone. In the lower reservoir, which is the carbonate interval, there is an overpressured zone based on the measured pore pressure data. But, only DEMSE and DE-HMSE method show higher calculated pore pressure in this interval. However, when the data in the depleted zone are excluded, the DE-HMSE method has the smallest RMS error in the calculated and measured pore pressures.

5.5 Sensitivity Analysis

Sensitivity analysis was performed to identify how much the variation of the input parameters impact the results for a mathematical model. In this study, the input parameters are the drilling parameters and the rock's strength to calculate formation pore pressure using equation 25. The parameters that be used for the sensitivity analysis in this study are rate of penetration (ROP), weight of bit (WOB), rotary speed (RPM), bit area, flow rate, mud weight, slowness (DT), and torque (T).

Figure 13-17 shows the sensitivity of the parameters in all wells. The baseline that be used for sensitivity analysis is when the difference between the calculated pressure and the measured pressure is less than 50 psi. The calculated pore pressure value of well A is 4,115 psi, Well B is 4601 psi, Well C is 3,789 psi, Well D is 3,597 psi, and Well E is 3,364 psi are used as the baseline. The parameter value was changing from the original value (100%) to -50% and +50%. All wells show a similar sensitivity trend for all parameters. The highest sensitivity for all wells is the rate of penetration (ROP). High sensitivity means the changing of the parameter value would change the result significantly. The other parameters that have high sensitivity are torque (T), and rotary speed (RPM). Torque and rotary speed (RPM) sensitivity overlap with each other in all wells, which means these parameters have the same trendline sensitivity. While the parameters that have small sensitivity are sonic (DT), flow rate, mud weight, and bit area. Weight on bit (WOB) doesn't have sensitivity, which means the changing of WOB doesn't have any impact on the result of pore pressure estimation.

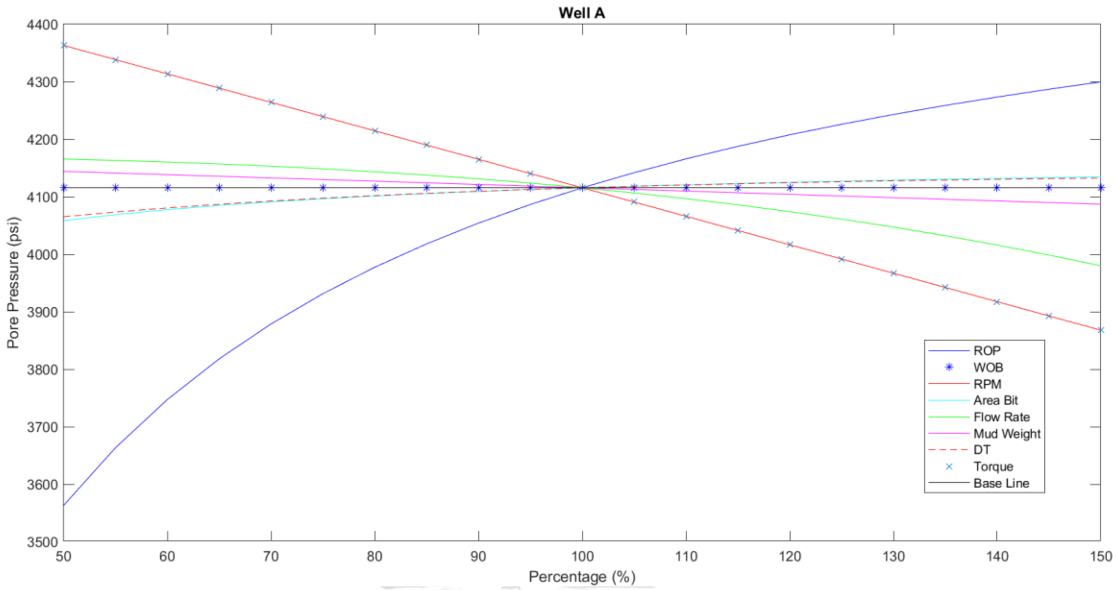

Figure 13 Sensitivity plots of input parameters for Well A

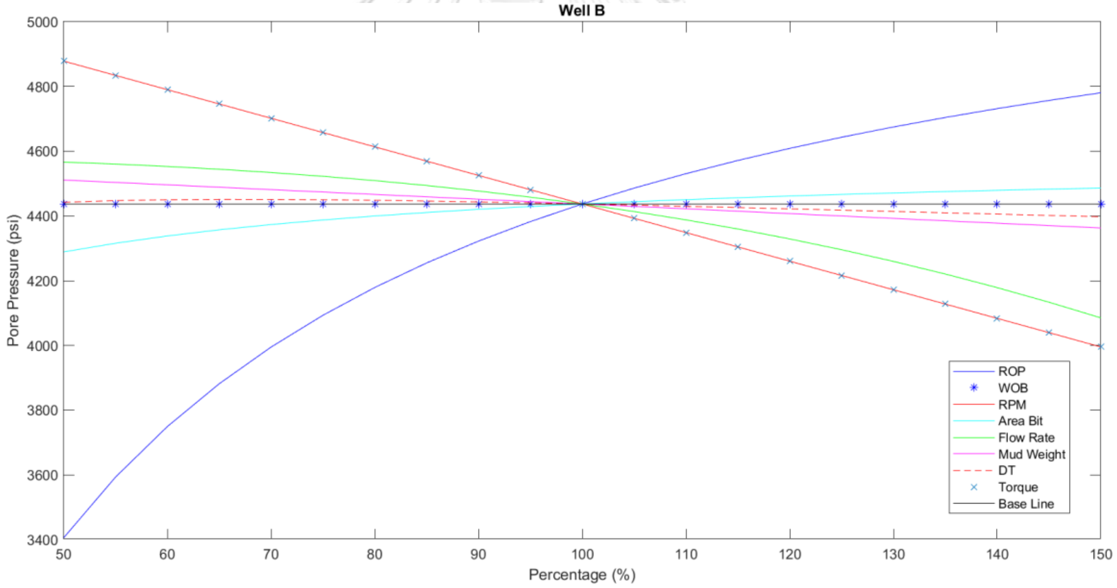

Figure 14 Sensitivity plots of input parameters for Well B

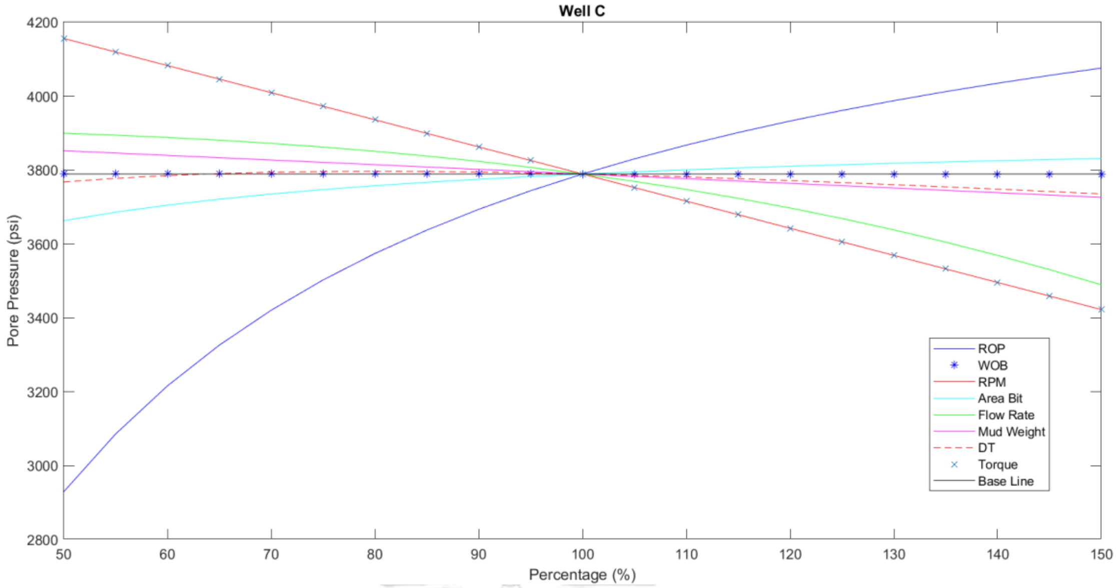

Figure 15 Sensitivity plots of input parameters for Well C

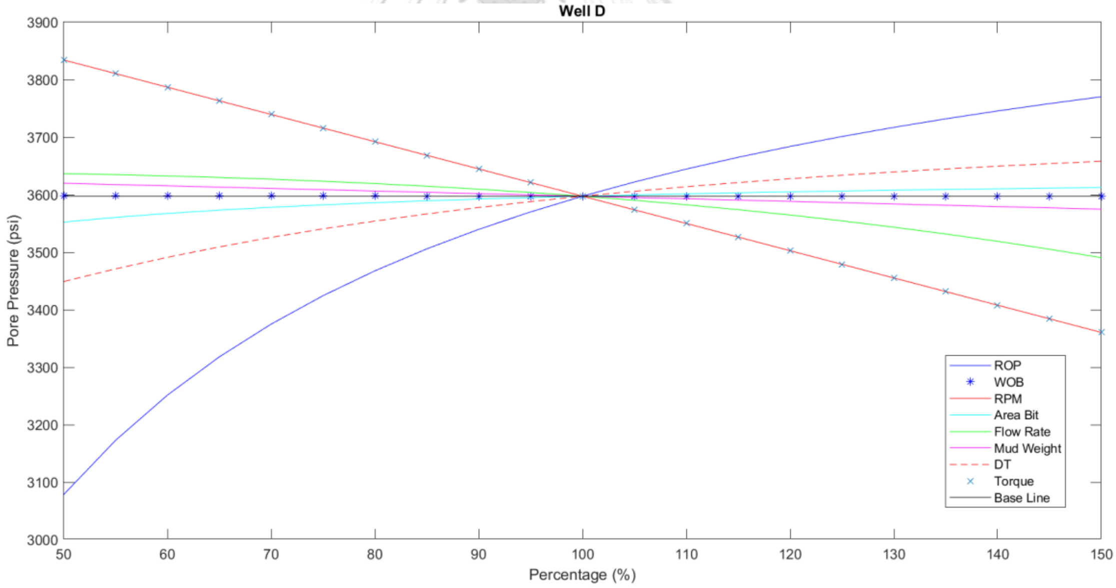

Figure 16 Sensitivity plots of input parameters for Well D

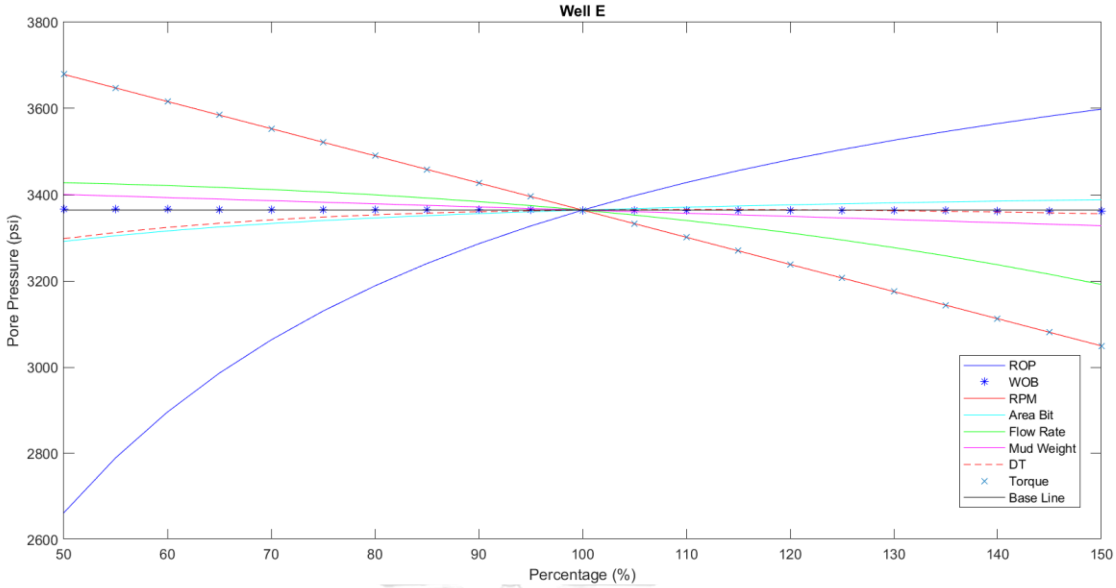

Figure 17 Sensitivity plots of input parameters for Well E

CHAPTER 6

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The DE-HMSE method is proposed to predict formation pore pressure from drilling parameters and subsurface log data. The proposed method is based on the combination concepts of drilling efficiency and hydro-mechanical specific energy which is the total energy (axial, torsional, and hydraulic) required to break a unit volume of rock. The calculated pore pressures from DE-HMSE method have similar trend with measured pore pressures both in shale interval and non-shale interval. From 5 well data in Australia and Thailand, the DE-HMSE method has small root mean square (RMS) error between calculated and measured pore pressure compared to the other methods of pore pressure prediction using drilling parameters, namely d_c-exponent method, mechanical specific energy (MSE) method, hydro-mechanical specific energy (HMSE) method, and drilling efficiency and mechanical specific energy (DEMSE) method.

All the methods used in this study have inaccurate result in pore pressure prediction in the depleted zone. However, when the data from the depleted zone were excluded, the DE-HMSE method showed the smallest RMS error between calculated and measured pore pressure not only in shale intervals but also in non-shale intervals.

The hydraulic energy has meaningful amount of energy in total energy to break a unit volume of rock, which is HMSE, and the result of pore pressure prediction would be more accurate with smaller RMS error value when the hydraulic term is included.

Rate of penetration (ROP), torque, and rotary speed (RPM) have the high sensitivity in DE-HMSE method. It means that the changing of these parameters value would change the result of pore pressure prediction significantly. While weight on bit (WOB) doesn’t have sensitivity, which means the changing of WOB doesn’t have any impact on the result of pore pressure estimation.

6.2 Recommendation

Based on the result in this study, all the methods using only drilling parameters have inaccurate result in pore pressure prediction in depleted zone. Therefore, other methodological approach in pore pressure prediction, such as using seismic data and well logging data, is needed for estimating pore pressure in depleted zone more accurately.

APPENDIX A

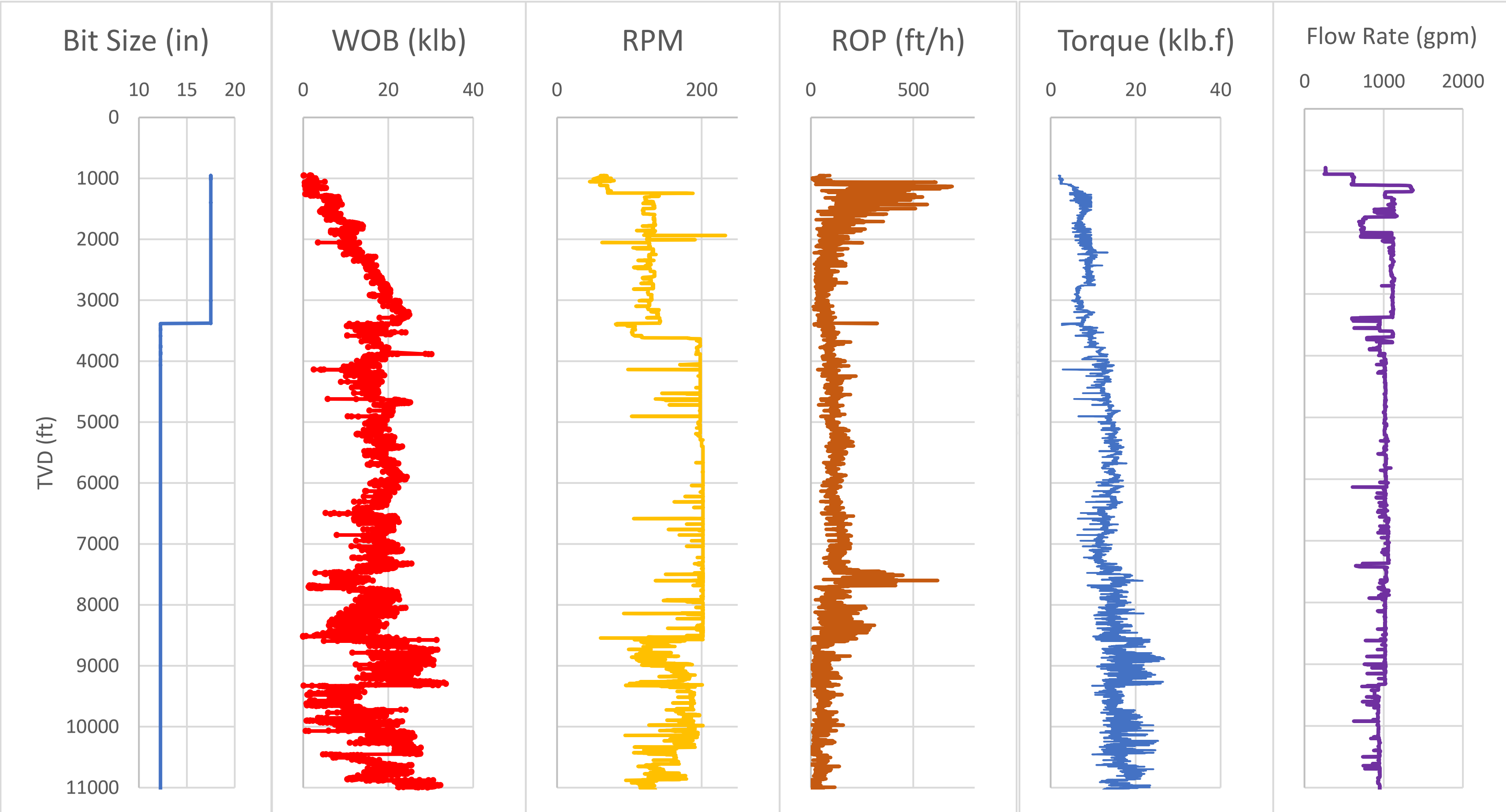

Figure. A.1 The plots of drilling parameters against depth for Well A

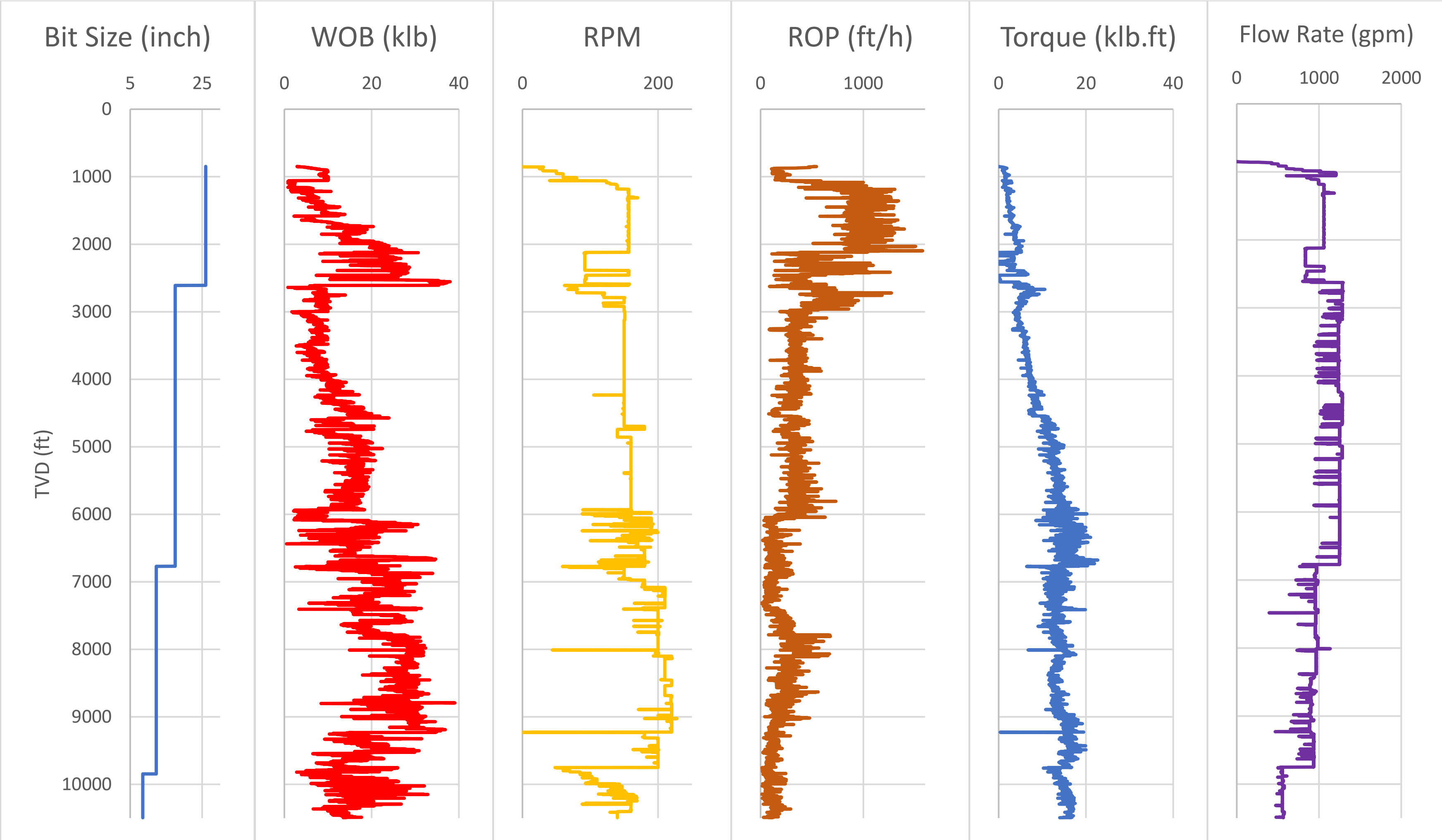

Figure A.2 The plots of drilling parameters against depth for Well B

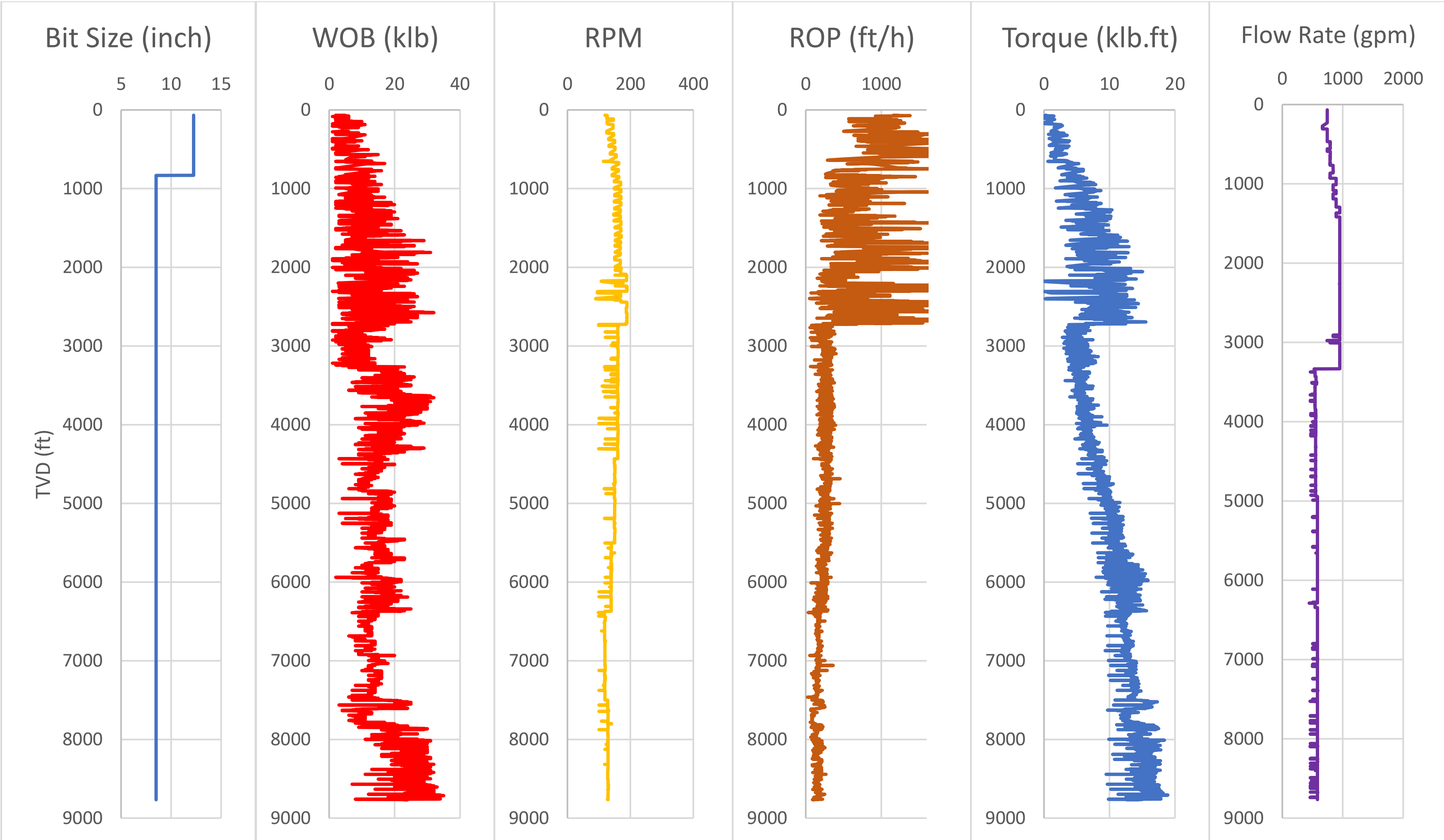

Figure A.3 The plots of drilling parameters against depth for Well C

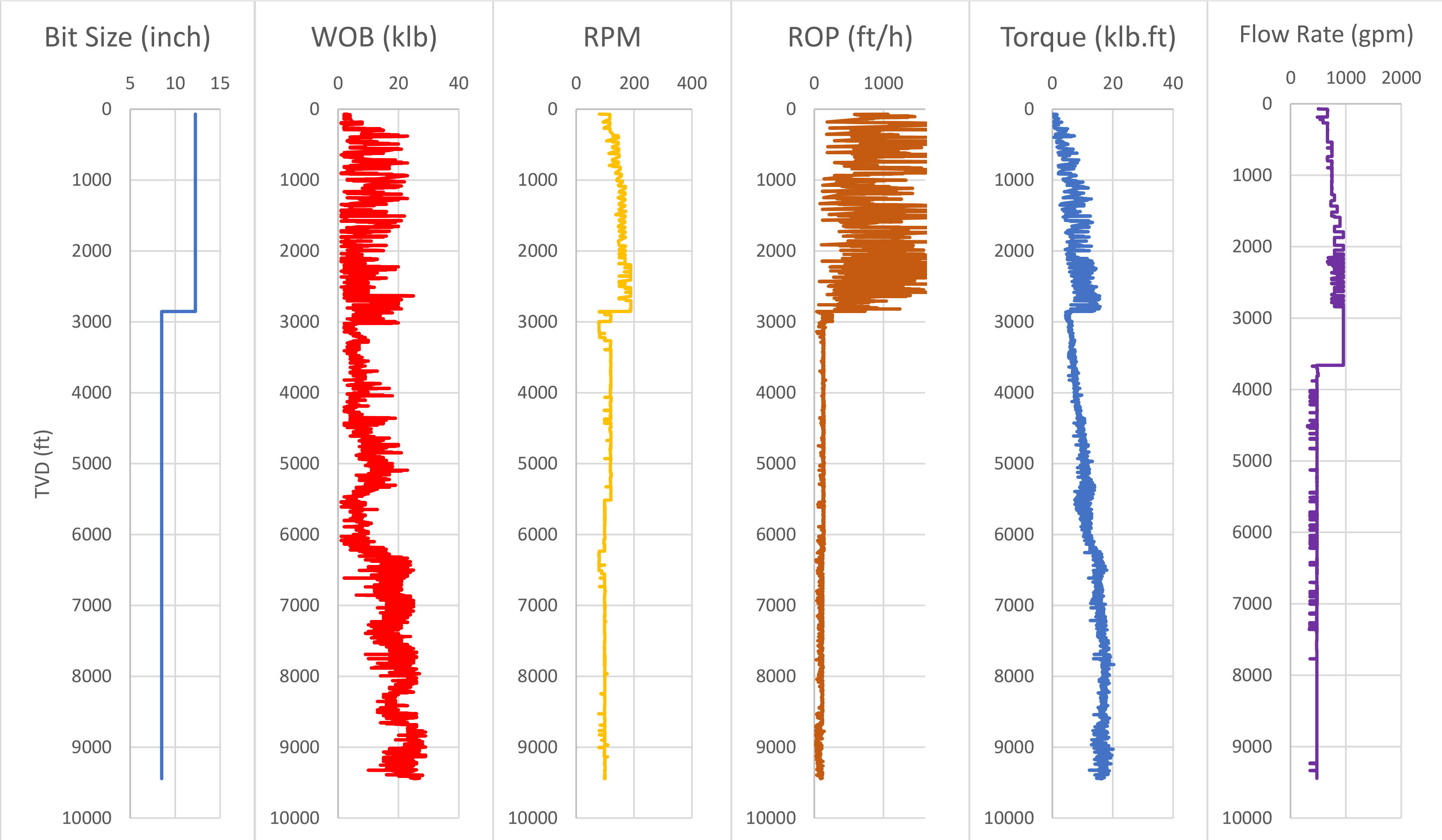

Figure A.4 The plots of drilling parameters against depth for Well D

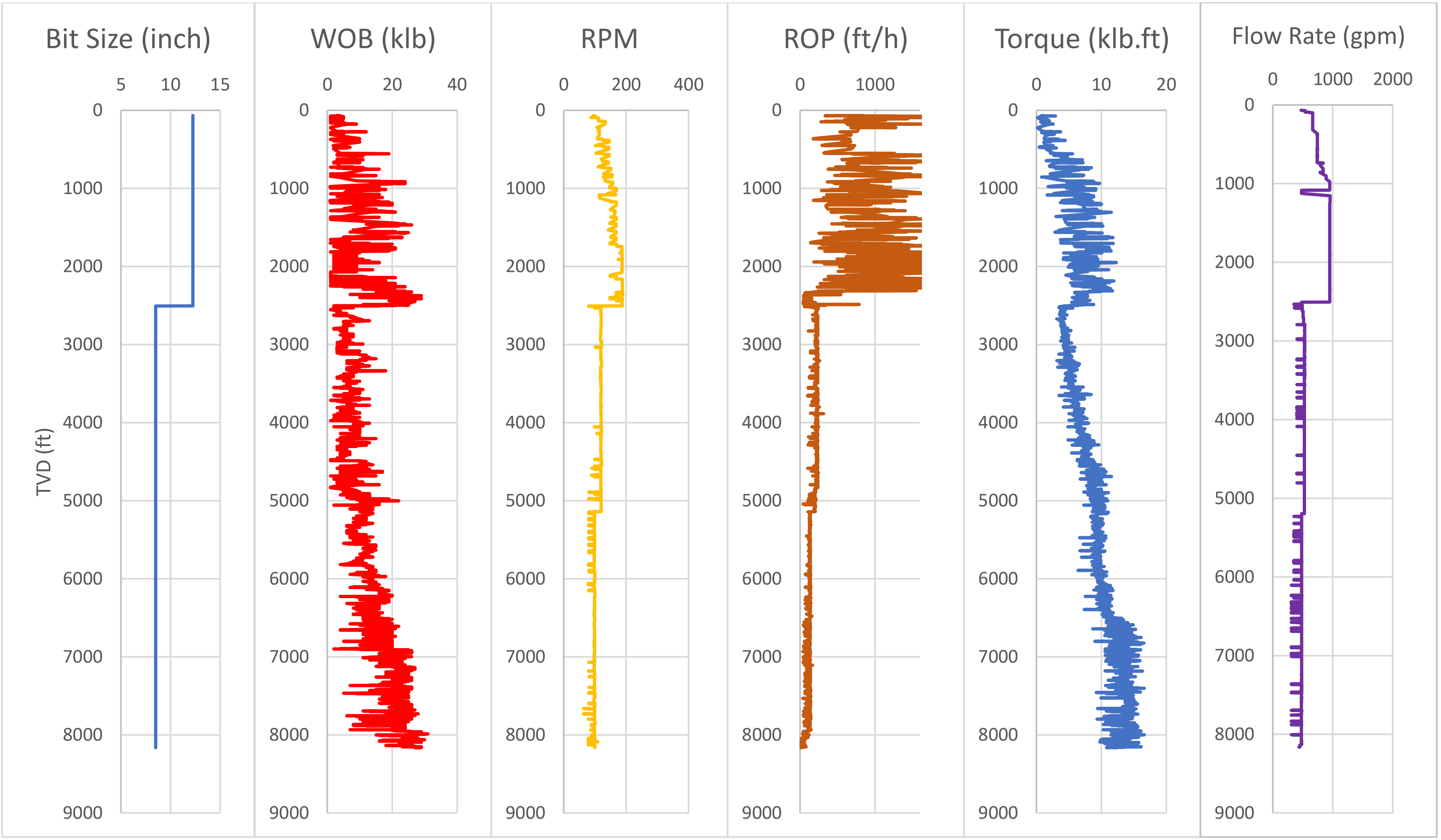

Figure A.5 The plots of drilling parameters against depth for Well E

APPENDIX B

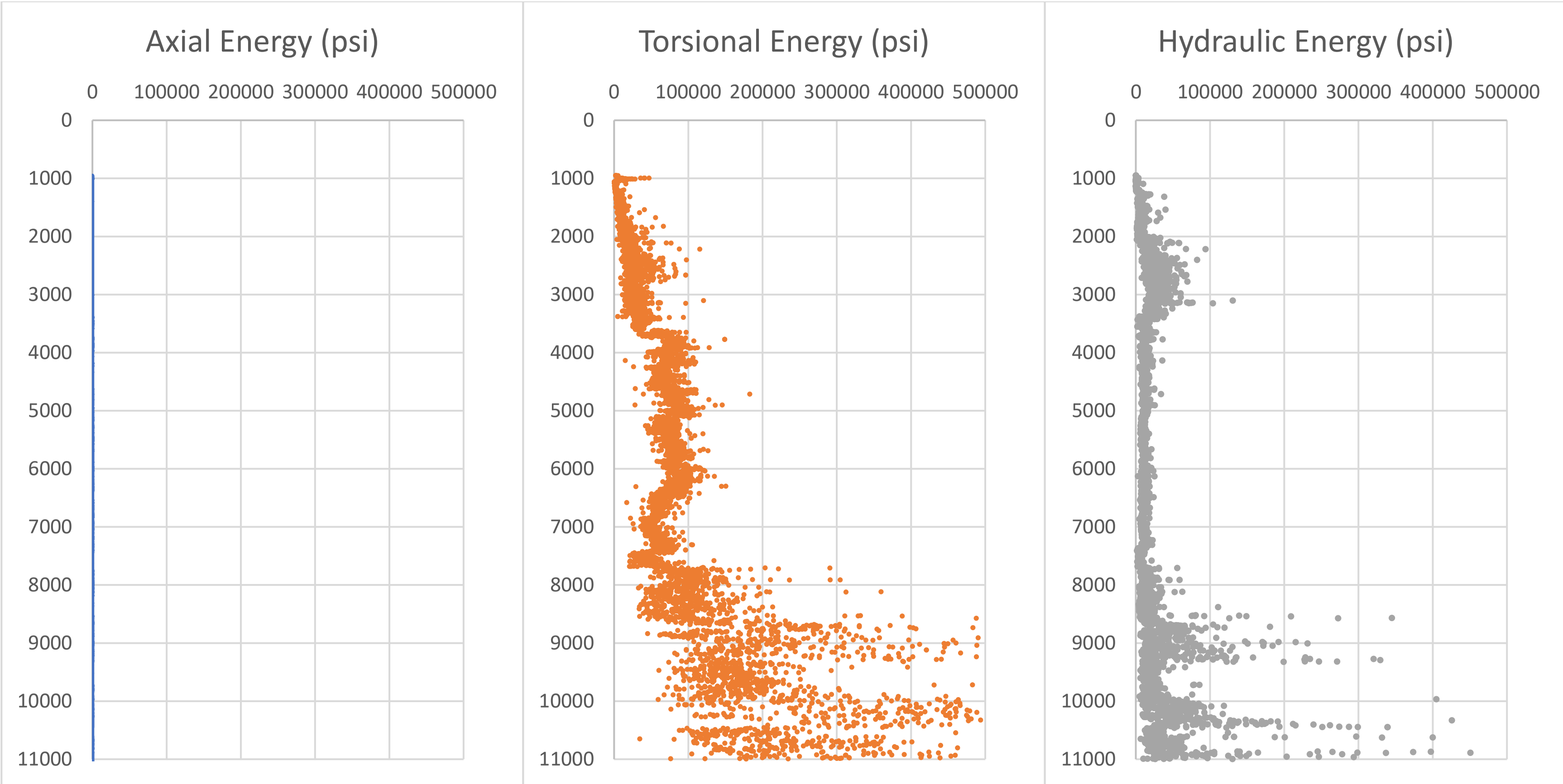

Figure B.1. The plots of axial energy, torsional energy, and hydraulic energy for Well A

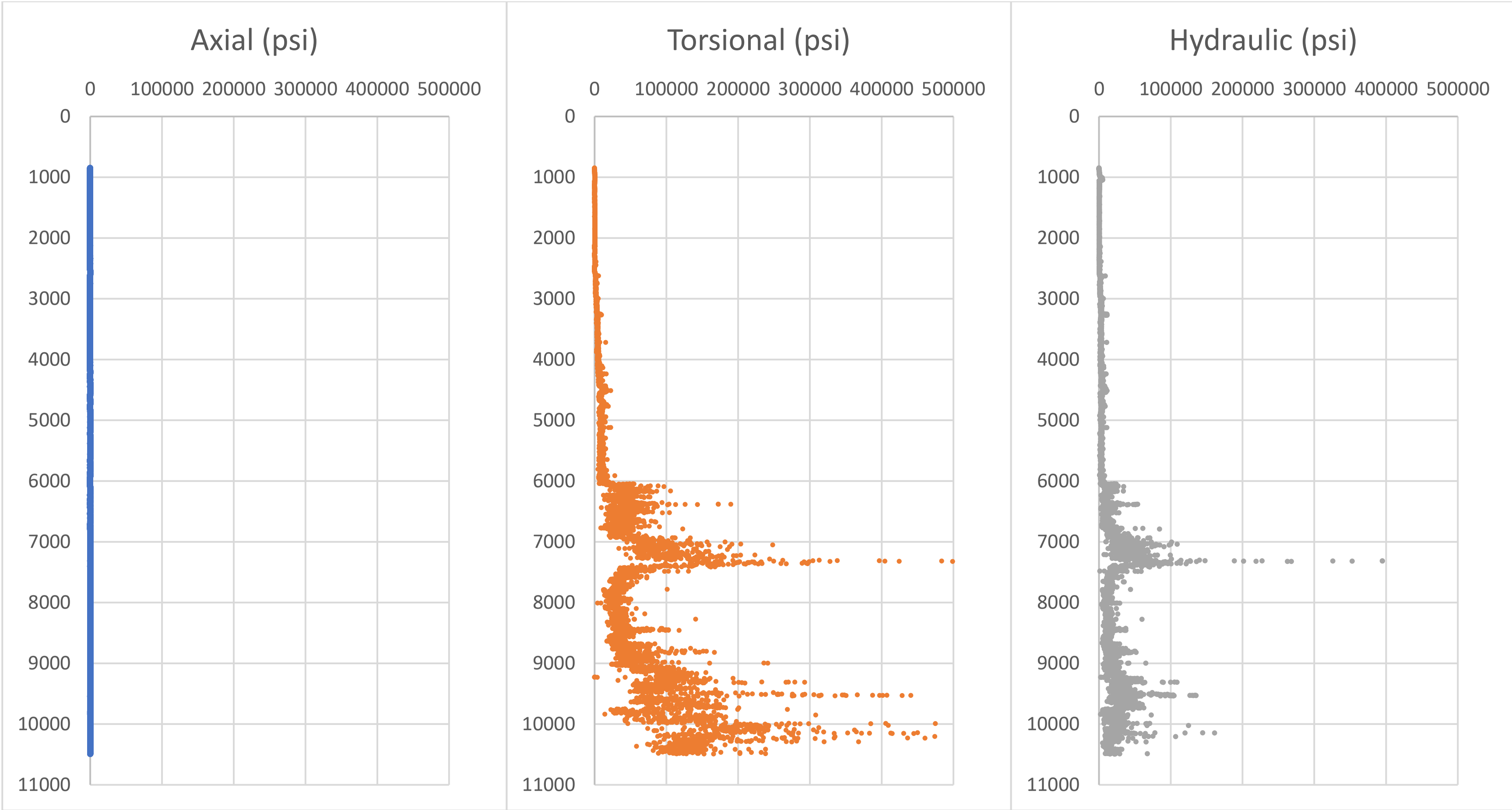

Figure B.2. The plots of axial energy, torsional energy, and hydraulic energy for Well B

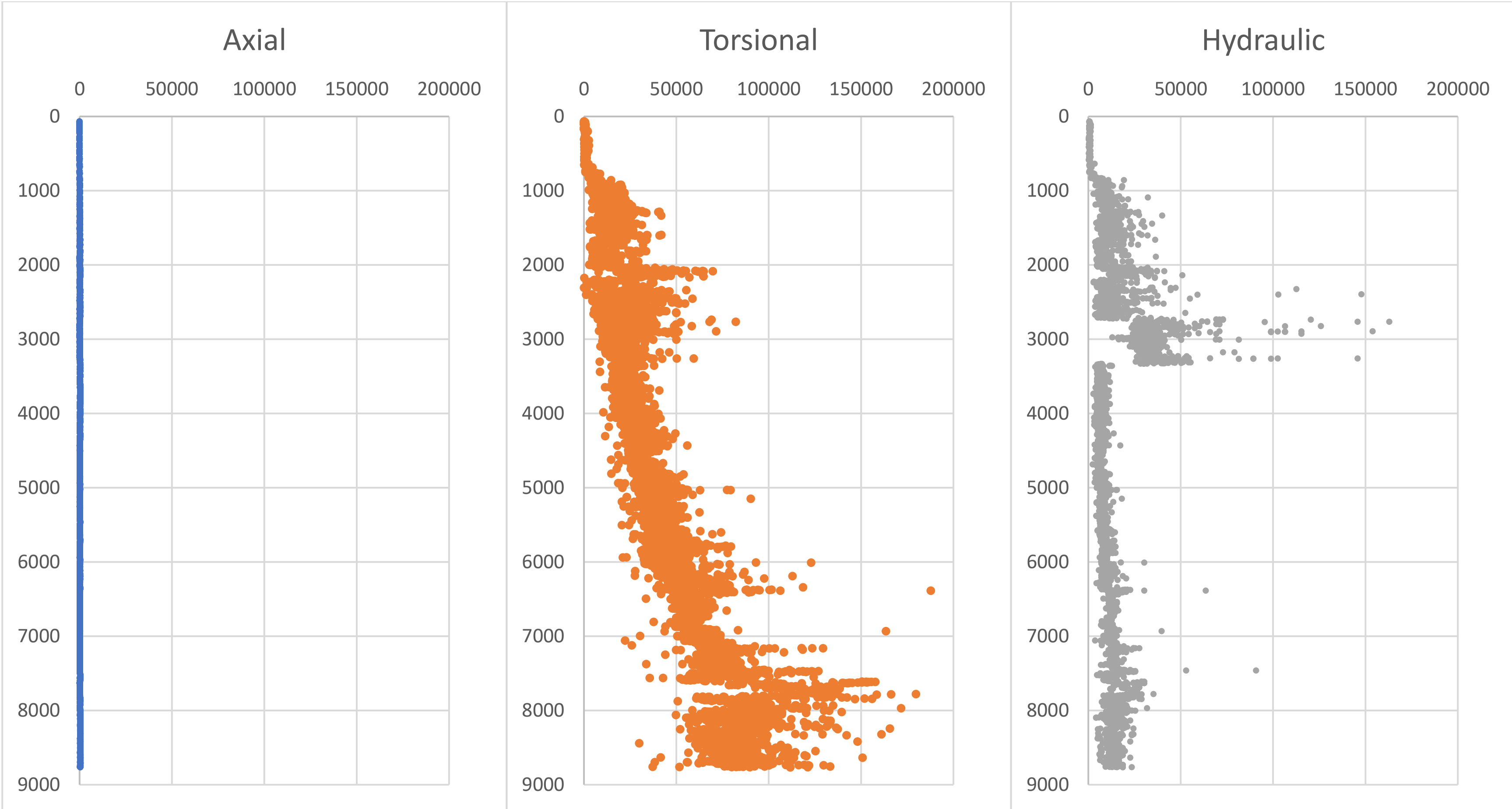

Figure B.3. The plots of axial energy, torsional energy, and hydraulic energy for Well C

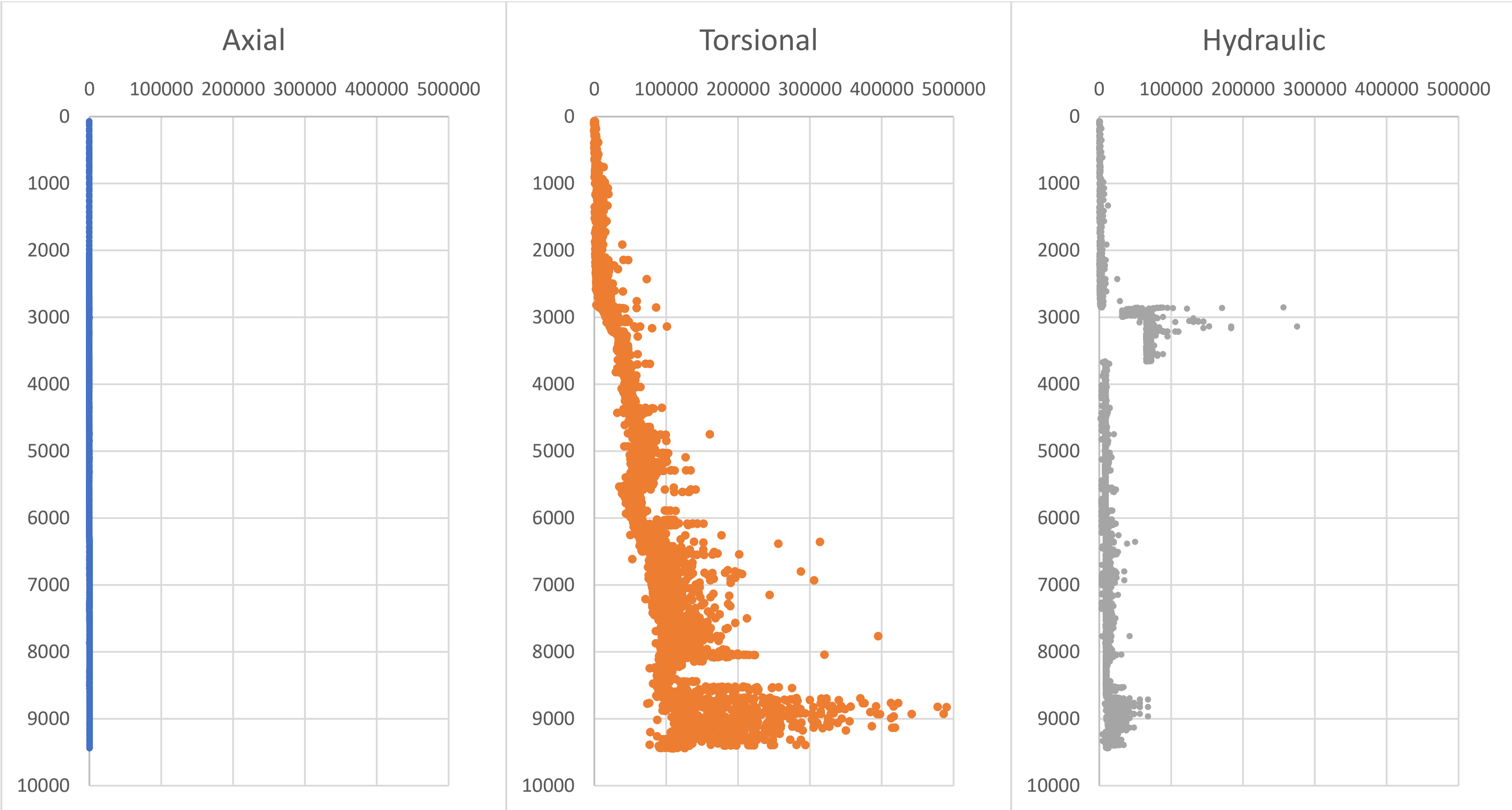

Figure B.4. The plots of axial energy, torsional energy, and hydraulic energy for Well D

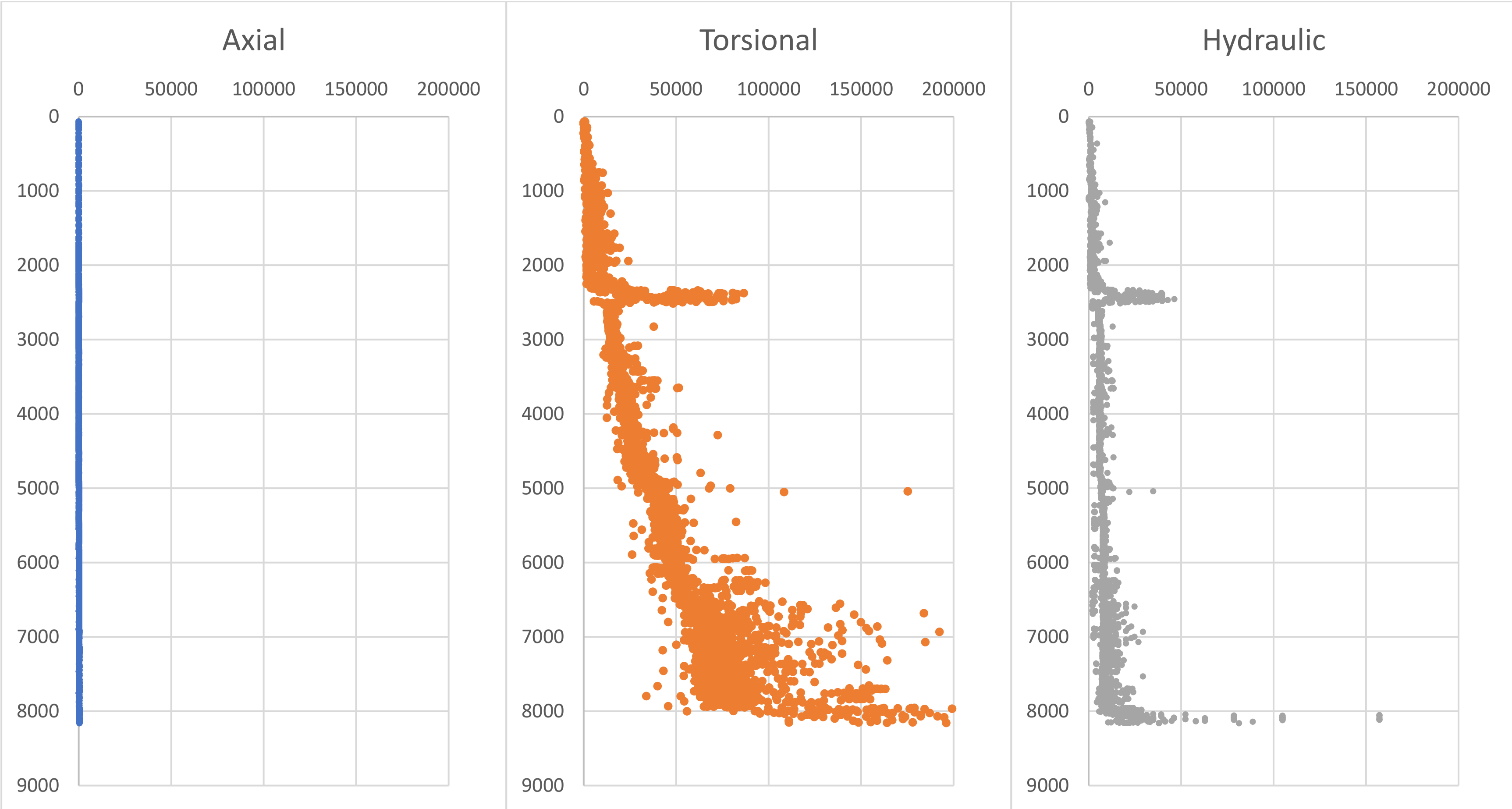

Figure B.5. The plots of axial energy, torsional energy, and hydraulic energy for Well E

APPENDIX C

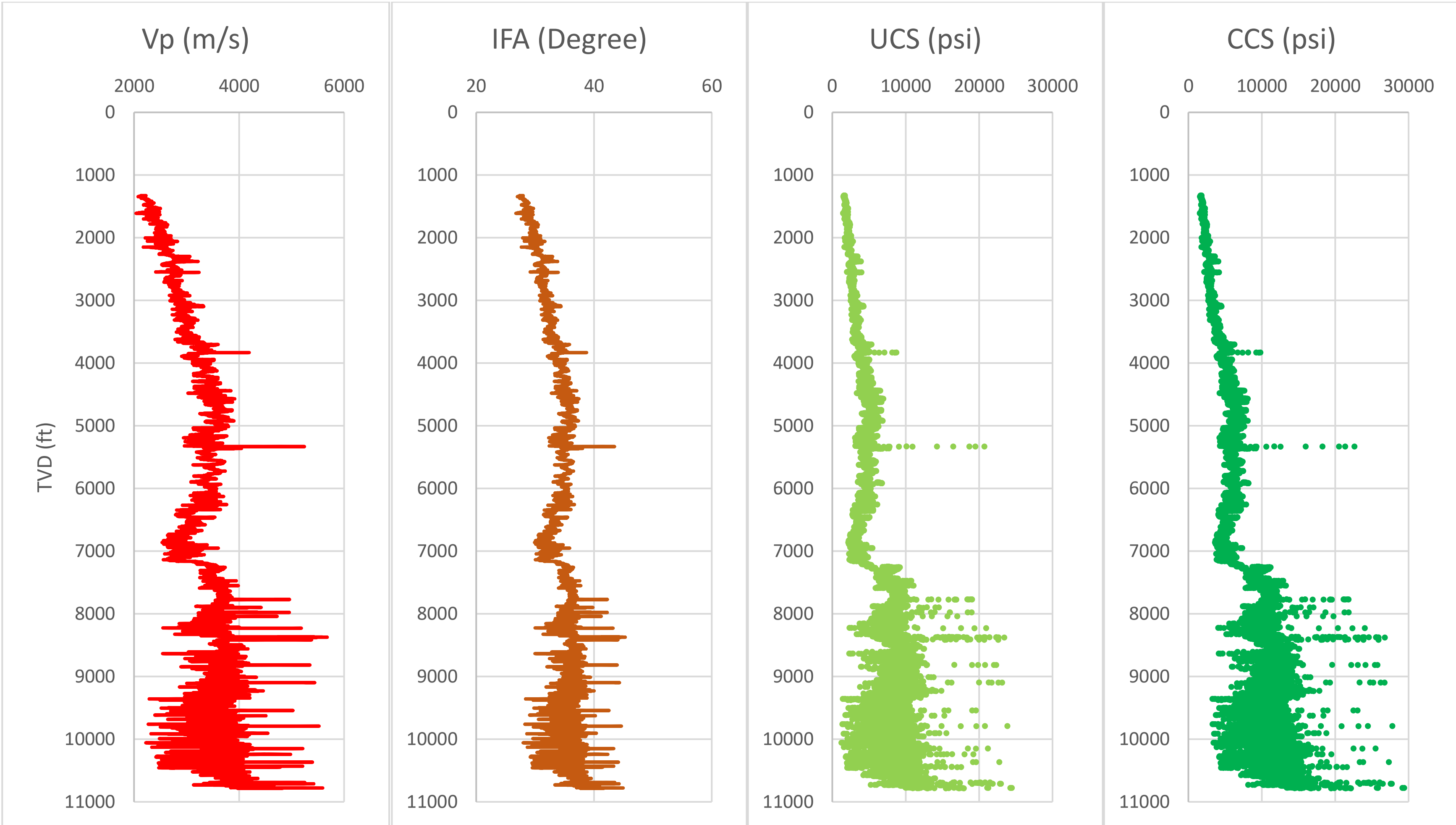

Figure C.1 Display plots of Sonic velocity (Vp), IFA, UCS, and CCS for Well A

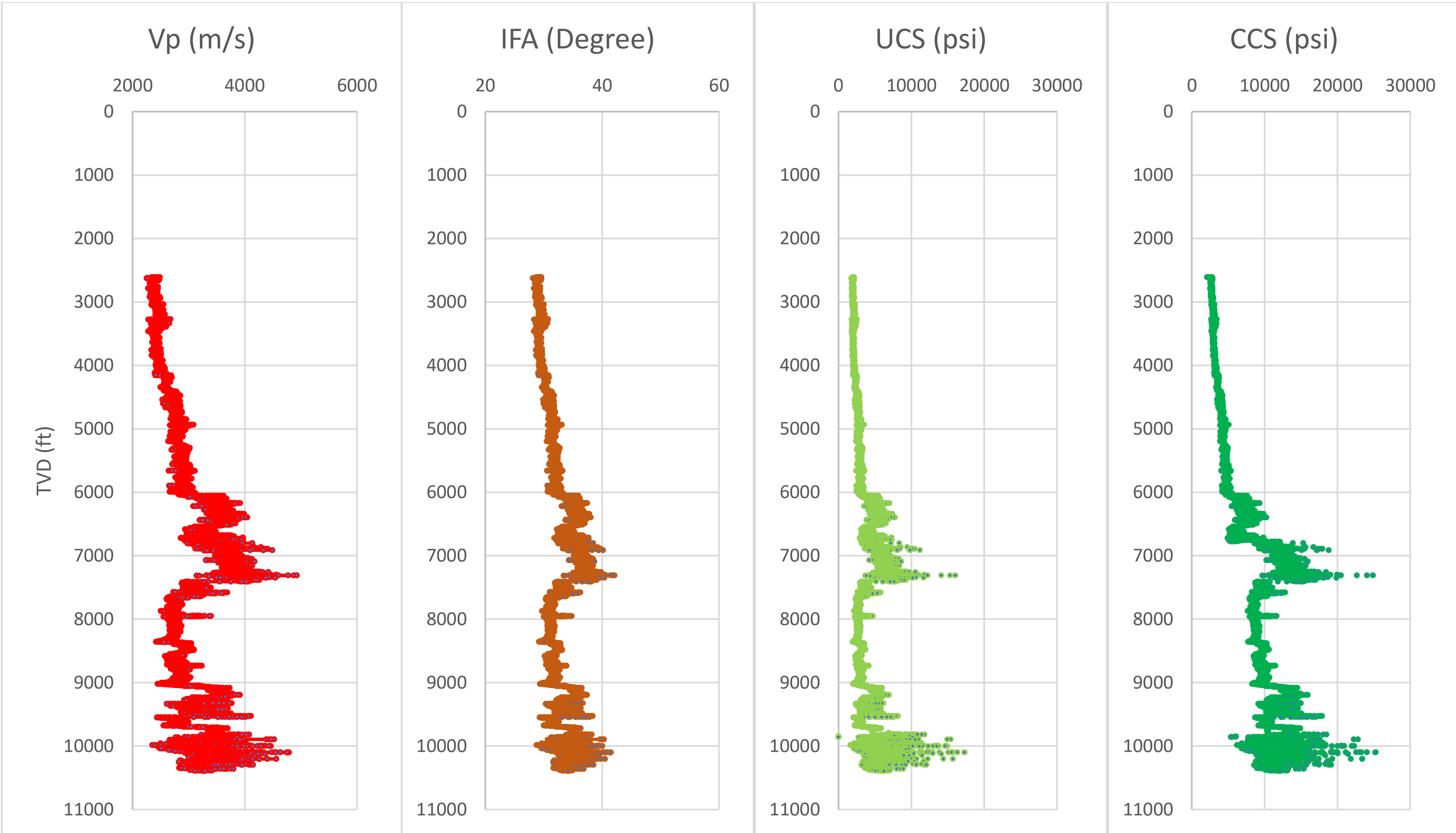

Figure C.2 Display plots of Sonic velocity (Vp), IFA, UCS, and CCS for Well B

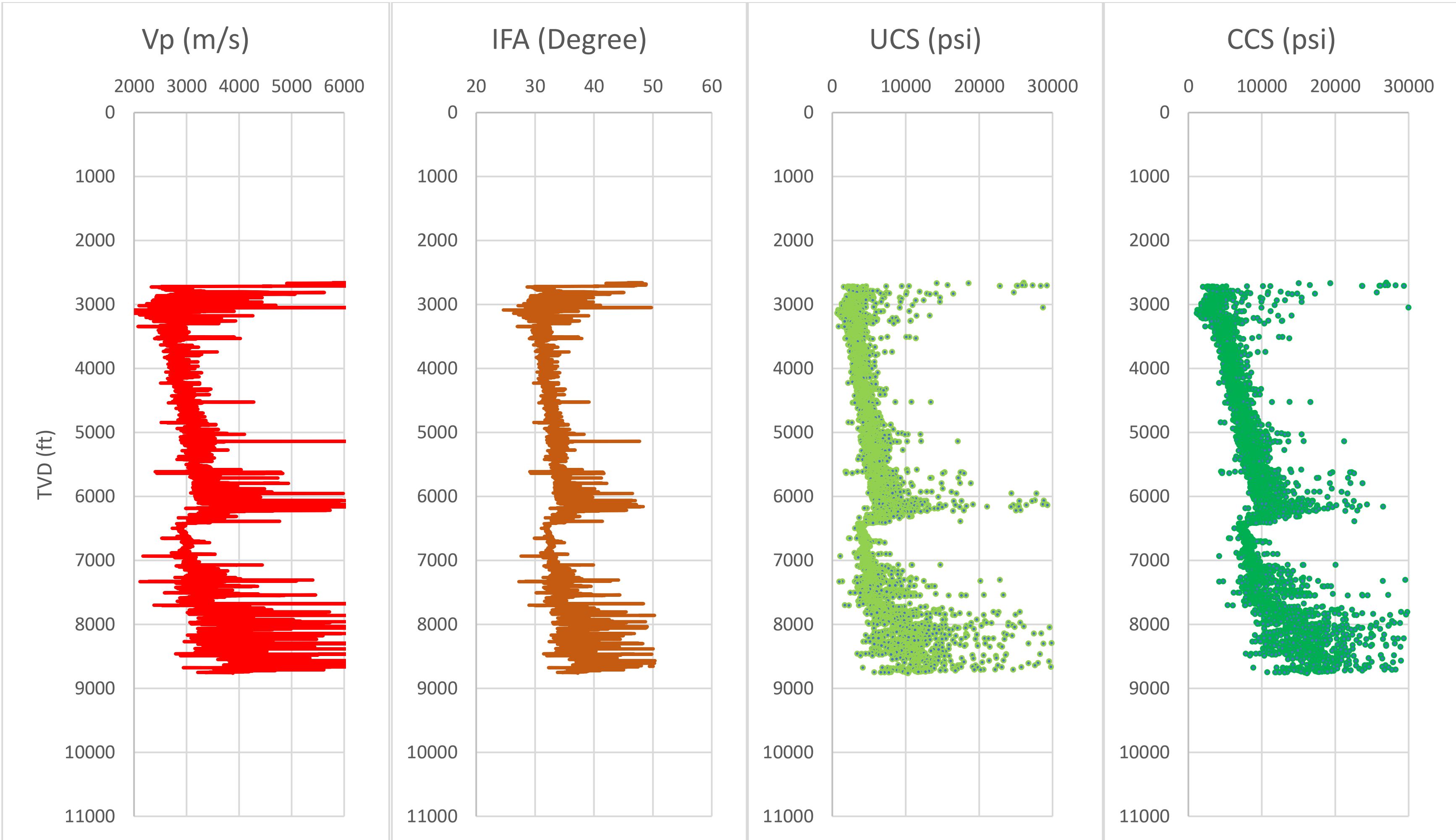

Figure C.3 Display plots of Sonic velocity (Vp), IFA, UCS, and CCS for Well C

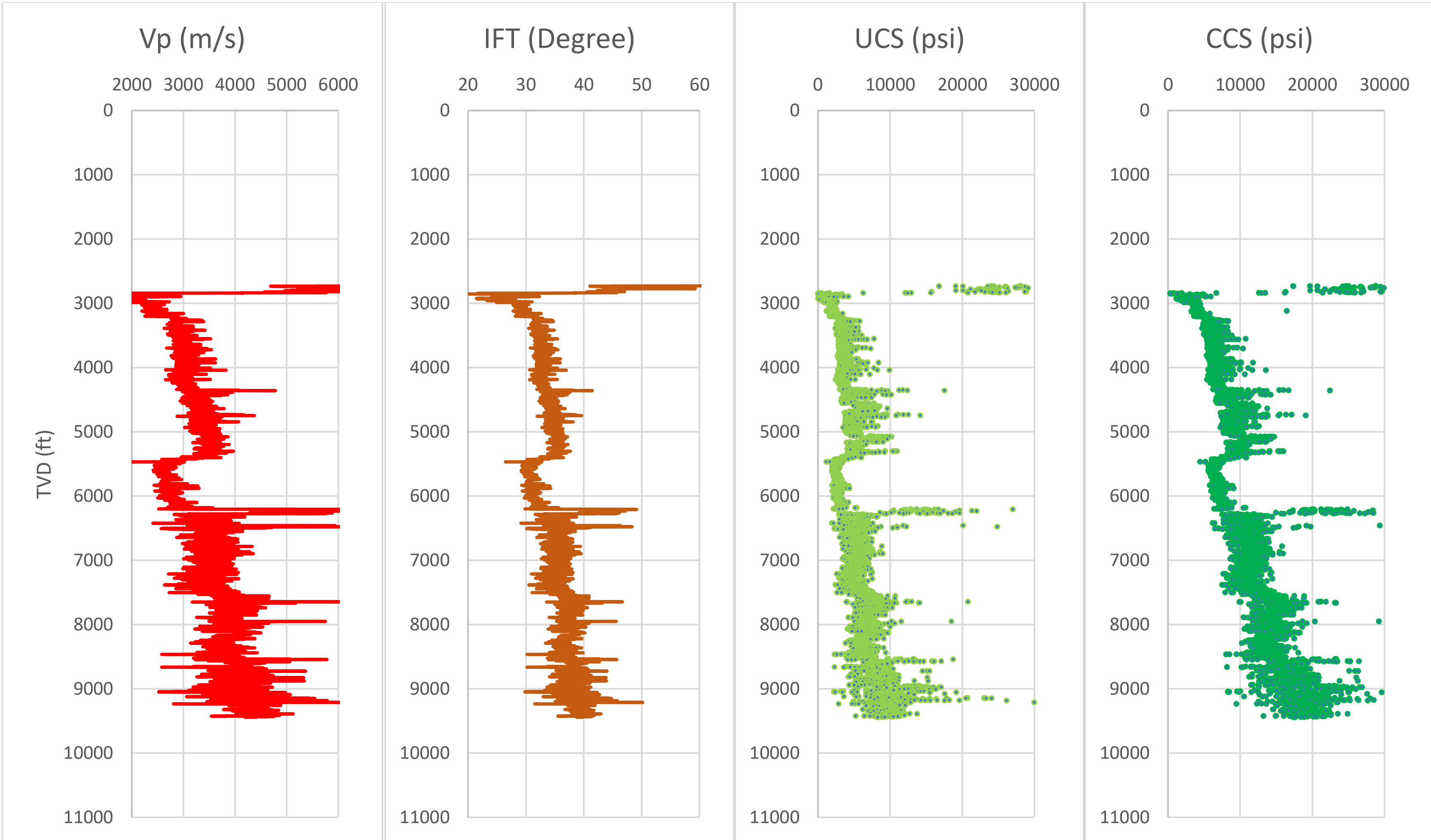

Figure C.4 Display plots of Sonic velocity (Vp), IFA, UCS, and CCS for Well D

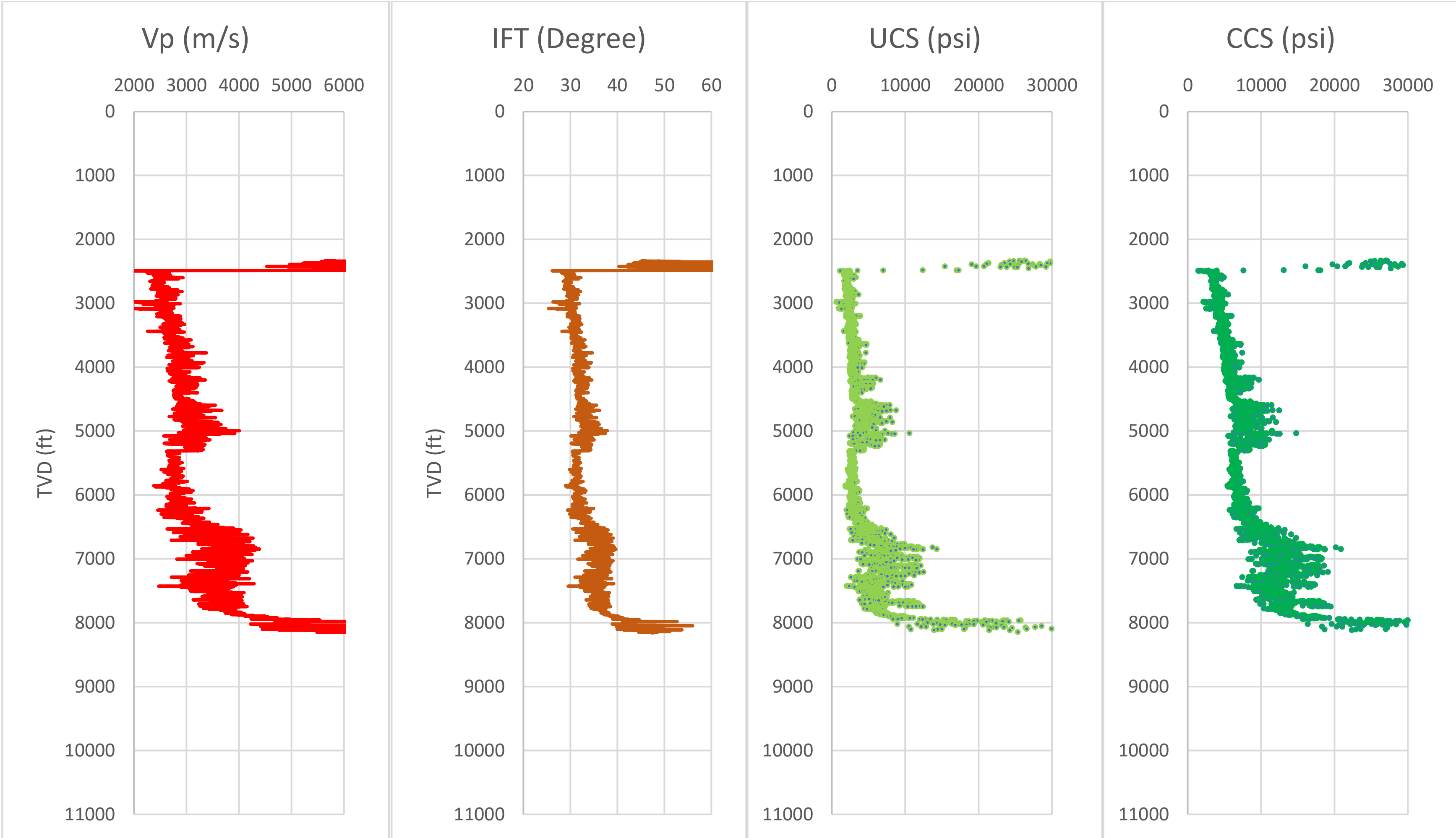

Figure C.5 Display plots of Sonic velocity (Vp), IFA, UCS, and CCS for Well E

APPENDIX D

Table E.1 Comparison data between calculated and measure pore pressure using DE-HMSE method for Well A.

TVD (ft)	Measured Pressure (psi)	Calculated Pressure (psi)	Residual
9446	4083	4494	-411
9484	4104	4413	-309
9583	4124	4331	-207
9624	4143	4198	-55
9653	4182	4182	0
9763	4231	4583	-353
9862	4079	4624	-545
9911	4138	4367	-228
9882	4089	4599	-510
9935	4149	4463	-313
9974	4879	4904	-25
10031	4537	4458	80
10075	4557	4474	83
10130	3871	4652	-781
10147	3879	4125	-247
10236	4439	2705	1734
10260	4461	4473	-12
10269	4465	4087	378
10282	4470	4036	434
10366	4506	4274	232
10388	4495	3563	932
10418	4391	3882	509
10433	4398	4190	207
10445	4403	2579	1824
10542	4588	4988	-401
10571	4634	4845	-211
10658	4608	4963	-356
10667	4612	5000	-388
10679	4620	4910	-290
10703	4626	5073	-447
10732	4612	4446	166
10758	4670	4984	-314
10806	4713	5066	-353
10838	4745	5066	-321
10851	4751	5066	-315
10869	4759	5066	-307
10509	4599	5052	-453
10219	4511	3442	1069
10220	4503	3287	1216
10016	4532	4275	257
9982	4884	4385	499

Table E.2 Comparison data between calculated and measure pore pressure using DE-HMSE method for Well B.

TVD (ft)	Measured Pressure (psi)	Calculated Pressure (psi)	Residual
9807	4594	5657	-1063
9898	4598	4960	-362
9931	4597	5279	-681
9933	4598	5118	-520
9935	4598	5259	-661
9937	4598	4579	19
9939	4605	4607	-2
9962	4600	4979	-379
9965	4600	5166	-566
9966	4600	4753	-152
9969	4601	5000	-399
9971	4601	5009	-408
9973	4601	5273	-672
9976	4601	5232	-631
9977	4601	5684	-1083
10003	4606	4850	-245
10004	4603	5059	-455
10007	4603	4143	460
10009	4604	4351	252
10013	4604	4297	307
10015	4605	4586	18
10017	4605	4221	383

TVD (ft)	Measured Pressure (psi)	Calculated Pressure (psi)	Residual
10020	4604	3953	652
10022	4604	3735	870
10030	4609	3730	880
10070	4608	4276	332
10072	4608	4809	-201
10075	4609	4521	87
10077	4609	5087	-479
10079	4609	4331	278
10081	4609	4536	73
10083	4613	4615	-2
10083	4609	4615	-6
10084	4609	4615	-6
10117	4620	4813	-193
10130	4614	4182	431
10181	4618	3585	1033
10208	4624	3585	1039
10256	4628	3585	1043
10309	4639	3585	1054
10364	4647	3585	1062
10382	4586	3585	1001

Table E.3 Comparison data between calculated and measure pore pressure using DE-HMSE method for Well C.

TVD (ft)	Measured Pressure (psi)	Calculated Pressure (psi)	Residual
4624	1889	2250	-361
5288	2287	2362	-74
5407	2351	2244	107
5596	2409	2501	-92
6187	2556	2914	-358
6207	2564	2831	-267
7791	3386	2838	549
7828	3429	3314	115
7976	3535	3692	-157
8083	3568	4013	-445
8142	1864	4102	-2238
8281	3101	3648	-547
8521	3700	3835	-135
8637	1341	3280	-1940
8687	1859	3718	-1859

Table E.4 Comparison data between calculated and measure pore pressure using DE-HMSE method for Well D.

TVD (ft)	Measured Pressure (psi)	Calculated Pressure (psi)	Residual
8585	4048	3693	354
7659	3601	3228	373
7505	3409	3356	53
7323	3324	3423	-100
7311	3319	3313	7

Table E.5 Comparison data between calculated and measure pore pressure using DE-HMSE method for Well E.

TVD (ft)	Measured Pressure (psi)	Calculated Pressure (psi)	Residual
2582	1116	1074	42
2758	1202	1172	31
2796	1213	1178	35
2822	1208	1184	24
2840	1214	1180	34
2869	1123	1263	-140
2990	1327	1027	299
3090	1346	1135	211
7253	3337	3502	-165
7270	3315	3536	-221
7387	3353	3313	40
7405	3361	3513	-152
7436	1318	3688	-2370
7493	3430	3289	141
7607	2880	3468	-588
7652	3513	3252	262
7691	3492	3583	-91
7743	3523	3691	-168
8098	4468	3544	924
8103	4658	3371	1288

APPENDIX E

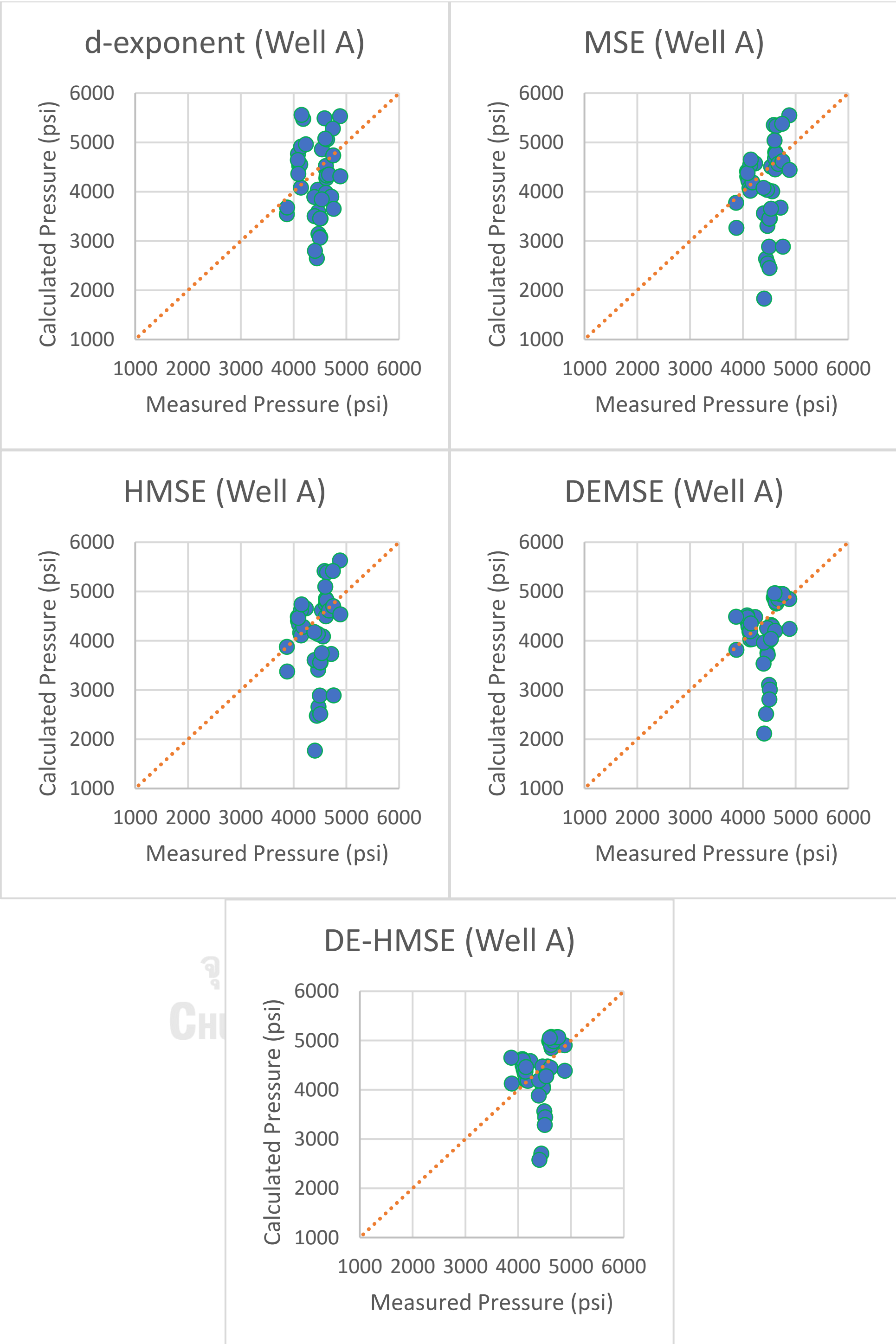

Figure E.1 Comparison between calculated pore pressure, and measured pore pressure for Well A

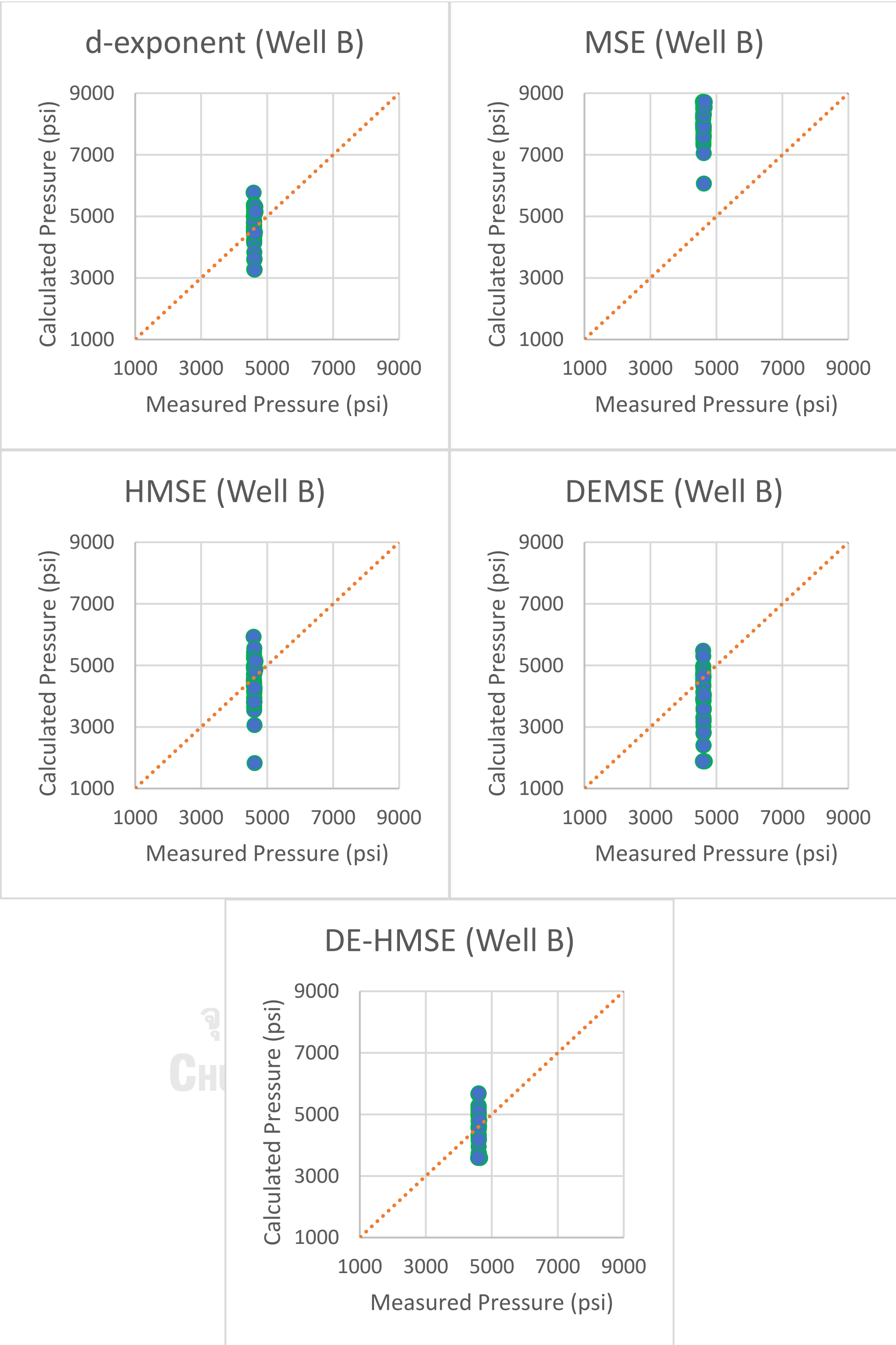

Figure E.2 Comparison between calculated pore pressure, and measured pore pressure for Well B

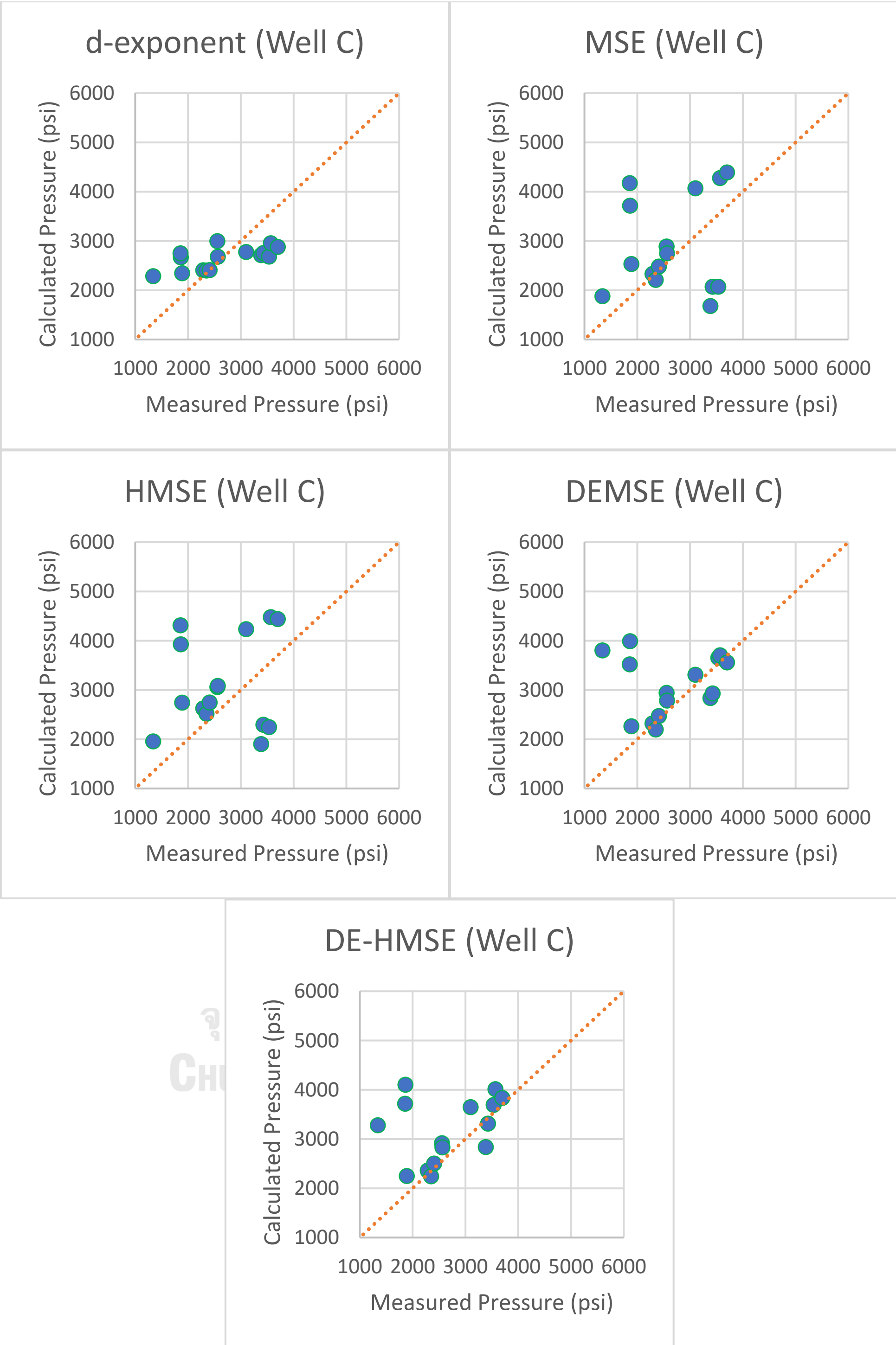

Figure E.3 Comparison between calculated pore pressure, and measured pore pressure for Well C

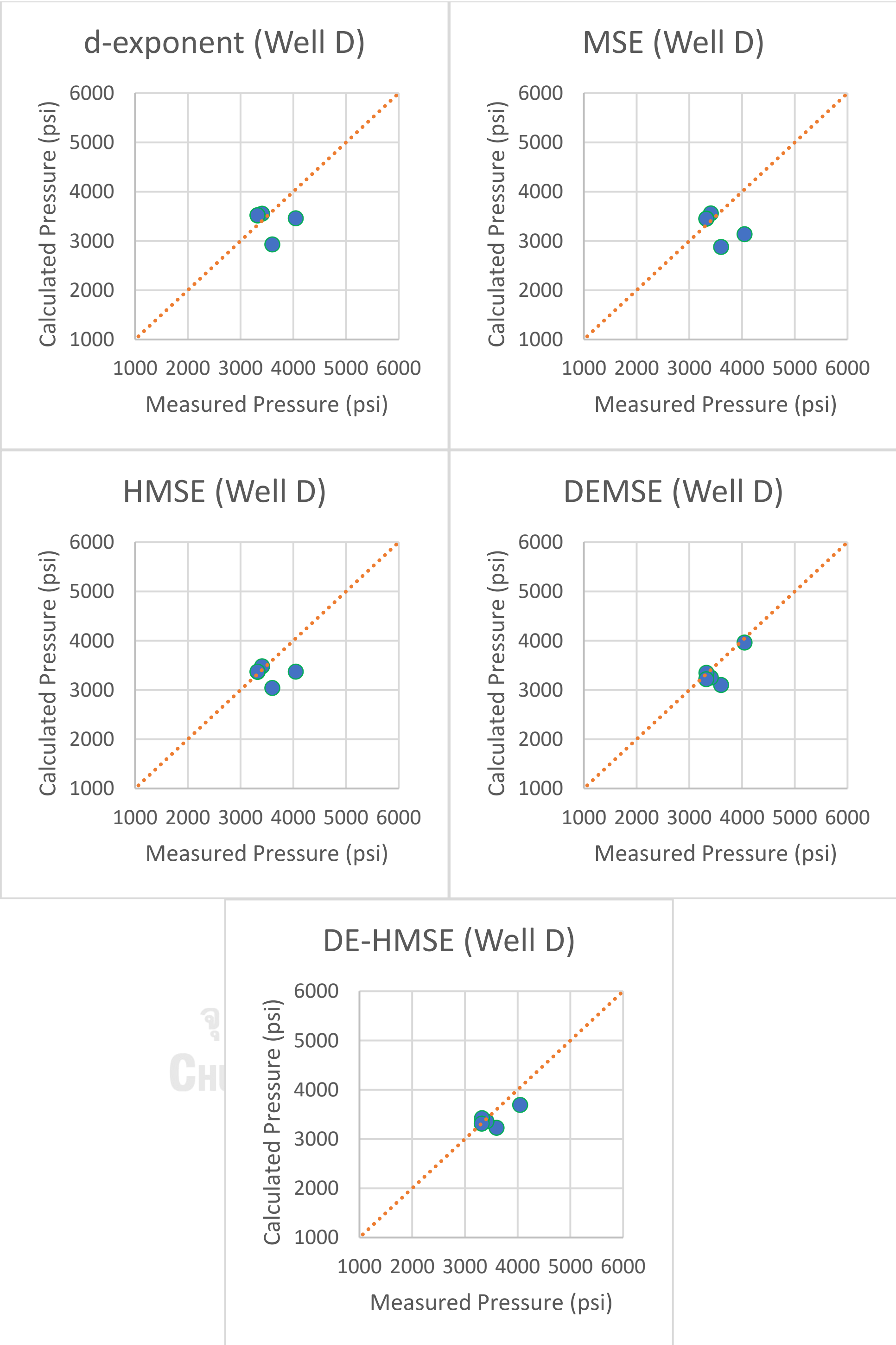

Figure E.4 Comparison between calculated pore pressure, and measured pore pressure for Well D

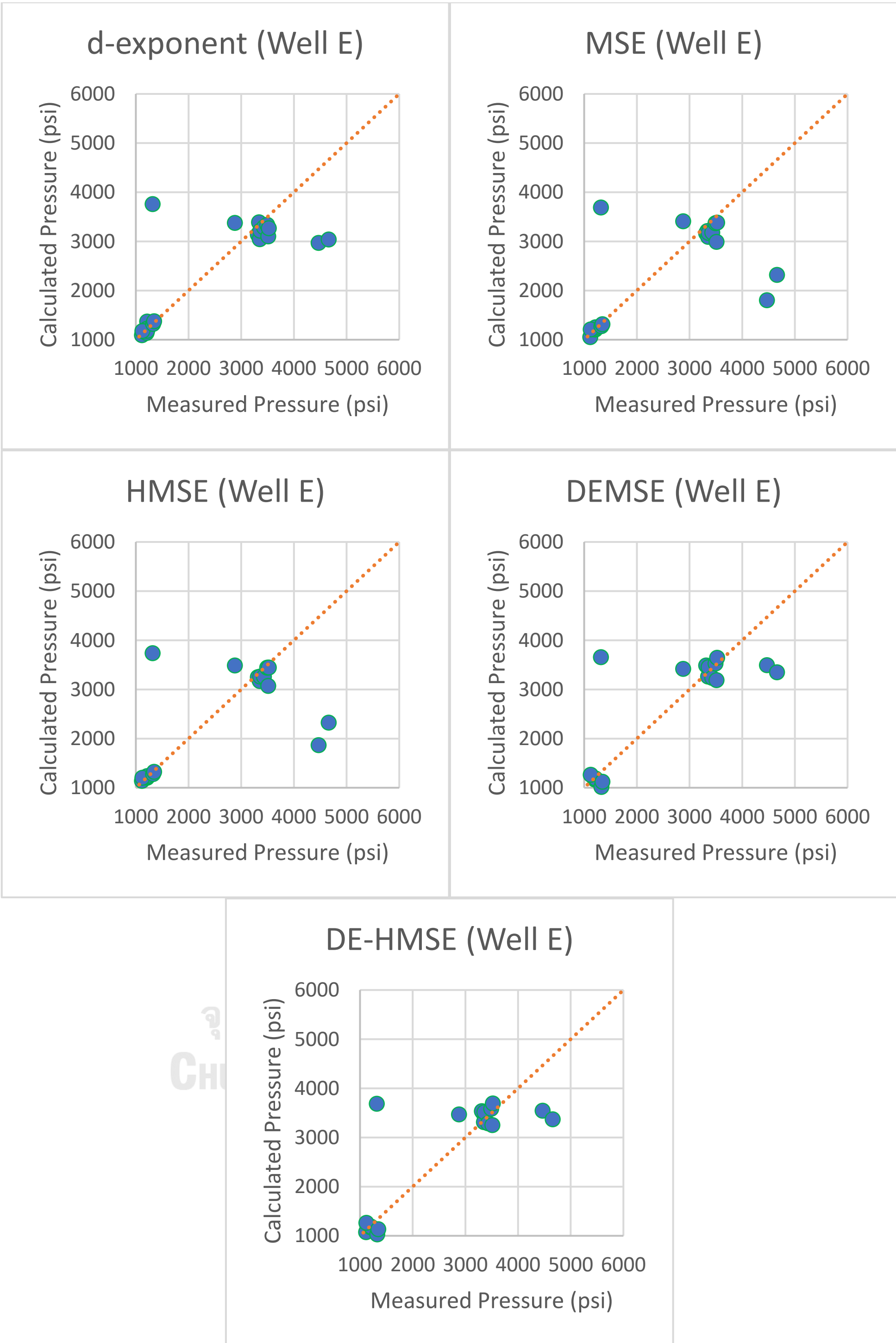

Figure E.5 Comparison between calculated pore pressure, and measured pore pressure for Well E

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