İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

RESERVOIR QUALITY CONTROLLING FACTORS, DELIVERABILITY AND RESERVE ESTIMATES IN DELTAIC DANİŞMEN AND OSMANCIK FORMATIONS AT İKİHÖYÜK GAS FIELD, THRACE BASIN, TURKEY

M.Sc. Thesis by
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Programme : **Petroleum and Natural Gas Engineering**

Thesis Supervisor : **Asst. Prof. Dr. İ. Metin MIHÇAKAN**

JUNE 2011

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JUNE 2011

<u>İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ</u>

TRAKYA BASENİ İKİHÖYÜK GAZ SAHASININ DELTA TİPİ DANİŞMEN VE OSMANCIK FORMASYONLARI REZERVUARLARINDA NİTELİĞİ DENETLEYEN UNSURLAR, GAZ VEREBİLME VE REZERV KESTİRİMİ

YÜKSEK LİSANS TEZİ

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FOREWORD

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This thesis, though meticulously studied and completed by myself, is the integrated product of the accumulated knowledge and experience on the subject, that were contributed by the acknowledged experts below and were gained by myself in time.

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Finally, no words can express my gratitude to my parents for their endless love, never ending patience, and constant and continuous support of my efforts to reach my scientific achievements.

May 2011

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ABBREVIATIONS

AOF	:	absolute open flow
BHP	:	bottom hole pressure
BVSXO	:	bulk volume Sxo
BVW	:	bulk volume water
C	:	Rawlins and Schellhardt deliverability coefficient, or wellbore storage coefficient
DT	:	delta time
GR	:	gamma ray
GRV	:	gross rock volume
$\mathbf{h_{net}}$	:	net pay thickness of the formation
KB	:	kelly bushing
k	:	permeability
kh	:	transmissivity
LD_SAND1	:	Lower Danişmen Sand 1
m	:	slope of the Horner plot
n	:	Rawlins and Schellhardt deliverability exponent
OGIP	:	original gas in place
O_SAND1	:	Osmancık Sand 1
O_SAND2	:	Osmancık Sand 1
$\mathbf{P_D}$	:	dimensionless pressure
$\mathbf{P_e}$	:	stabilized reservoir pressure
$\mathbf{P_{wf}}$	:	bottom hole (sand face) flowing pressure
PİGM	:	Petrol İşleri Genel Müdürlüğü (General Management of Petroleum Works)
$\mathbf{q_{sc}}$	:	flow rate at standard conditions
Rmf	:	mud filtrate resistivity
Rw	:	formation water resistivity
SP	:	spontaneous potential
$\mathbf{S_w}$	:	reservoir connate water saturation
TD	:	total depth
$\mathbf{t_D/C_D}$	:	ratio of dimensionless time to dimensionless wellbore storage
TOC	:	total organic carbon
TPAO	:	Türkiye Petrolleri Anonim Ortaklığı (Turkish Petroleum Corporation, Inc.)
$\mathbf{t_p}$	:	production time prior to the flow test
UR	:	ultimate recovery

Greek Letters

ϕ	:	porosity
Δ**t**	:	time difference in well testing

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SUMMARY

RESERVOIR QUALITY CONTROLLING FACTORS, DELIVERABILITY AND RESERVE ESTIMATES IN DELTAIC DANİŞMEN AND OSMANCIK FORMATIONS AT İKİHÖYÜK GAS FIELD, THRACE BASIN, TURKEY

The Tertiary-age Thrace basin is located to cover most of the area in the Thrace region of Turkey and is known to include relatively small-size reserves of natural gas and some oil. İkihöyük field is discovered with productive shallow gas reservoirs in the deltaic Danişmen and Osmancık formations within the Concession 3839, of which the exploration and production licence is held by TransAtlantic Petroleum Ltd. Co., in the northern Thrace basin. Until 2008, 2D seismic surveys were the main data set for oil and gas exploration activities in Concession 3839 of northern Thrace basin.

It is widely known fact that the reservoir quality in deltaic sedimentary environments changes rapidly in short distances. Such changes directly affect the success of the activities for hydrocarbon exploration and production. This study is conducted to identify the architecture of reservoirs, the spatial distribution of factors that control the quality and production capability of reservoirs in İkihöyük field. In order to achieve this purpose all the data, obtained from the geologic and geophysical surveys as well as the data acquired during the drilling of two wells, are utilized so that the sequential framework is established and the potential gas reserves in İkihöyük field are estimated.

In the present study, 3D seismic survey data was used to identify the areal extension of reservoirs in Danişmen and Osmancık formations. Based on the regional geology and the 3D seismic interpretation results a sequence stratigraphy study is performed to identify the depositional characteristics of each sedimentary cycle within and without İkihöyük field. The acquired data from the well logs and the transient and deliverability tests in wells are interpreted to estimate the physical reservoir properties as well as the deliverability capacity of gas bearing zones. Eventually the data of gas production along with the gas properties are utilized to estimate the existing reserves in the reservoirs under İkihöyük field.

3D seismic data has also revealed that syn-sedimentary faults were the major controlling factor for reservoir distributions in both formations within the study area. The production analysis data is found to be in very good agreement with an area that were controlled by these syn-sedimentary faults. The well test analyses has confirmed the initially detected pressure difference between two wells in İkihöyük field that indicate the existence of two separate reservoirs.

ÖZET

TRAKYA BASENİ İKİHÖYÜK GAZ SAHASININ DELTA TİPİ DANİŞMEN VE OSMANCIK FORMASYONLARI REZERVUARLARINDA NİTELİĞİ DENETLEYEN UNSURLAR, GAZ VEREBİLME VE REZERV KESTİRİMİ

Tersiyer yaşındaki Trakya baseni Türkiye'nin Trakya Bölgesi'nin büyük bölümünü kapsayacak biçimde konuşlanmış olup, görece küçük boyutta gaz ve bazı petrol rezervuarlarını içerdiği bilinmektedir. İkihöyük sahası, Trakya baseninin kuzeyinde bulunan ve lisansını TransAtlantic Petroleum Ltd. Şirketi'nin elinde tuttuğu 3839 Ruhsatı içinde, delta tipi Danişmen ve Osmancık formasyonlarında sığ ve üretken gaz rezervuarlarının keşfi ile bulunmuştur. Trakya baseni kuzeyinde bulunan 3839 Ruhsat alanında sürdürülen petrol ve gaz arama faaliyetlerinde 2B sismikler 2008 yılına kadar başlıca veriler olmuştur.

Delta tipi çökel ortamlarda rezervuar niteliğinin (kalitesinin) kısa uzanımlar içinde hızlı bir değişim gösterdiği yaygın olarak bilinen bir gerçektir. Böylesi değişimler hidrokarbon arama ve üretim faaliyetlerini doğrudan etkilemektedirler. Bu çalışma İkihöyük sahasındaki rezervuarların mimarî yapısı ile, nitelik ve üretim yetkinliğini denetleyen unsurların uzamsal dağılımlarını tanımlamak ve ortaya koymak üzere yapılmıştır. Bu amaca ulaşmak üzere, jeolojik ve jeofizik araştırmalarla elde edilen ve iki kuyunun delinmesi sürecinde toplanan tüm veriler kullanılarak, formasyonların dizinsel iskelet yapısı oluşturulmuş ve İkihöyük sahasındaki erke (potansiyel) gaz rezervlerinin kestirimi yapılmıştır.

Eldeki bu çalışmada, Danişmen ve Osmancık formasyonlarının Trakya baseni kuzeyi içindeki rezervuarları belirlemek ve tanımlamak üzere, 3B sismik veriler yorumlanmıştır. Bölgedeki jeoloji ve 3B sismik yorumlama sonuçlarına dayalı olarak, İkihöyük sahası içinde ve dışında kalan alandaki her bir çökel çevriminin depolanma karakterisitiklerini belirlemek için bir dizinsel stratigrafi çalışması gerçekleştirilmiştir. Kuyu logları ile birlikte kuyularda yapılan geçici ve gaz sağlama testlerinden elde edilen veriler yorumlanarak, gaz içeren kayaç bölümlerinin fiziksel rezervuar özelikleri ile gaz sağlama yetkinlikleri kestirilmiştir. Son olarak gaz üretim verilerinin yanısıra gaz özelikleri, İkihöyük sahası altındaki rezervuarların var olan gaz rezervlerinin kestirimi için kullanılmıştır.

3B sismik veri analizi sin-sedimenter fayların çalışma alanındaki formasyonların rezervuar dağılımlarını başlıca kontrol eden faktörler olduğunu ortaya koymuştur. Üretim analizi verileri de bu sin-sedimenter fayların kontrol ettiği alanla oldukça iyi bir uyumluluk göstermiştir. Buna ek olarak, saptanan gazlı bölümleri çevreleyen faylar, büyük ölçekli sismik veri analizi ve dizinsel stratigrafi çalışmasının tümlevi ile belirlenmiştir. Böylece tahmin edilen hacimsel rezervlerin, üretim verileri analizi ile kestirilen rezervler ile çok iyi bir uyum içinde olduğu görülmüştür. Kuyu testleri analizleri, başlangıçta İkihöyük sahasının iki kuyusunda saptanan basınç farkını onaylamış ve saha altında iki ayrı gaz rezervuarı bulunduğunu onaylamıştır.

1. INTRODUCTION

Thrace basin is a sedimentary basin of Tertiary age and, as shown in the box with dashed lines in **Figure 1.1**, is located to cover most of the area in Thrace region, the European part of Turkey. Thrace basin, extending close to the straight of Bosporus in East, is bounded clockwise by the Sea of Marmara in Southeast and South, Aegean Sea in Southwest and West, the borders of Turkey with Greece and Bulgaria in Northwest, Istranca (Strandja) mountains in North, and the Black Sea on Northeast.

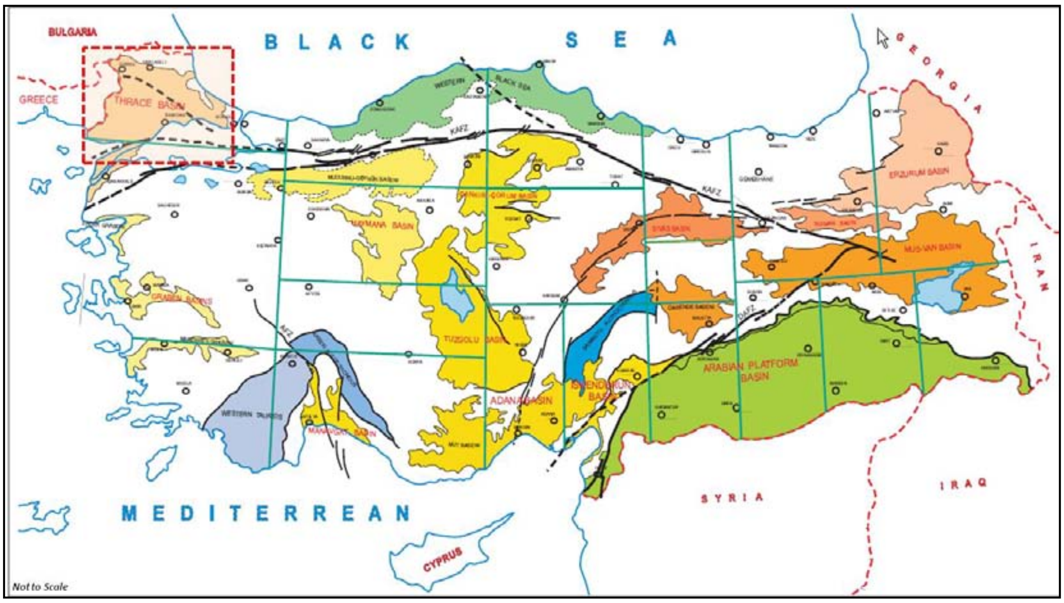

Figure 1.1 : Sedimentary basins in Turkey (anonymous origin).

The major geological features and structural elements in the region are illustrated in the geological map in **Figure 1.2**. In terms of hydrocarbon reserves, Thrace basin is known to include relatively small-size reserves of natural gas and some crude oil. It should be noted that some of the reservoirs in the basin contain hydrocarbons that are remarkably rich in carbon dioxide (CO_2) gas.

Thrace basin has evolved as an extensional basin during the majority of its geological history. Early extensional phase caused a Southwest-Northeast marine transgression, resulting in a rapid subsidence and subsequent deposition of thick interbedded sandstone, conglomerate, and shale sequences, starting from Eocene until the end of early Miocene. By the late Miocene, uplifting of the southern flank of the basin caused a northward tilting of the basin, which, in turn, led to the creation of several low-angle thrusts, possibly of a gravity-sliding nature.

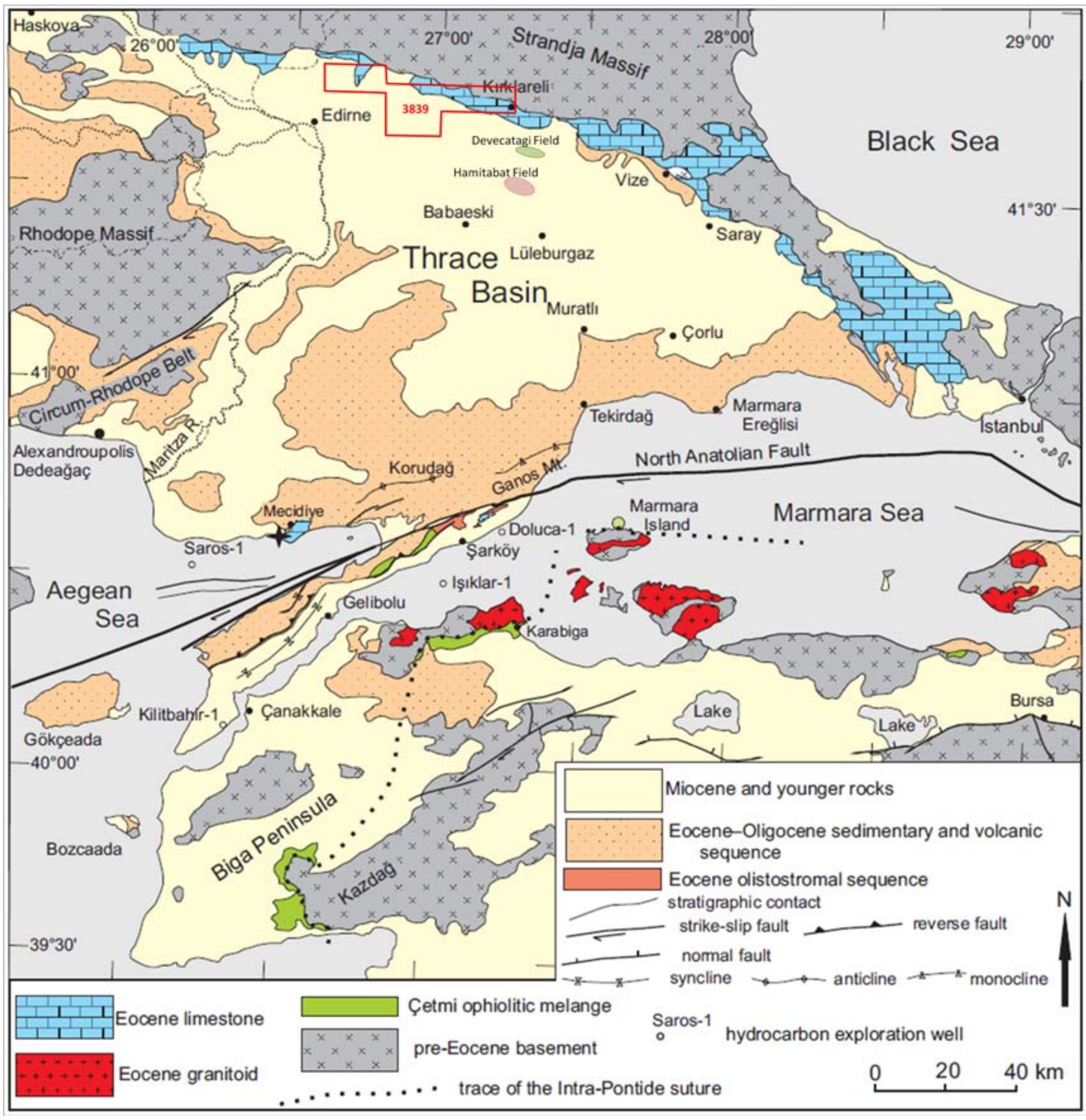

Figure 1.2: The geological map of Thrace Basin (after Aral et al., 2010,) and the location of study area, (License 3839,) marked as a polygone with solid red line.

As of today, with more than 700 drilled wells the petroleum exploration activity in Thrace Basin has reached a major stage. Following the first hydrocarbon gas discovery at N°1 well in Hamitabat field in 1970, other oil and gas fields have been discovered in the basin. Kuzey Marmara gas field, Değirmenköy gas field, Osmancık oil field, and Deveçatağı oil field are the other significant discoveries besides the Hamitabat gas field. During the early stage of exploration activites the principal targets were Hamitabat sandstones of Eocene age and Soğucak limestones of Lower Oligocene age. Since then, however, the discovery of shallow gas potential in the deltaic Danişmen and Osmancık formations of Tertiary age has led many companies focus their exploration efforts on the shallow gas reservoirs in these formations.

For instance, TransAtlantic Petroleum Ltd. Company discovered hydrocarbon gas in both Danişmen and Osmancık formations within the concession 3839, marked with a polygon in **Figure 1.2**. In the same concession the prospectivity of stratigraphic and combination traps are also considered high, and in this respect, İkihöyük field was discovered with a potential gas producing reservoirs, in the year of 2008.

1.1 The Statement of Purpose

The essential objective of this study consists of establishing the geologic model, assessing the production controlling factors, estimating the reserves, and determining the deliverability potential of the hydrocarbon gas reservoirs under İkihöyük field. The data utilized to achieve the objectives are gathered from the geological studies, 3D seismic surveys, well records on drilling, testing, and production. The present study addresses both the geological and reservoir factors controlling the production from the target reservoirs in Danişmen and Osmancık formations. Identification of reservoir quality and architecture, areal distribution and timing of tectonic activity, compartmentalization and filling of the structure, which are believed to be the main controlling factors on production in İkihöyük field, are focused in this research.

The tasks that have been performed in the course of the study are,

i) interpretation of 3D-seismic surveys to identify the areal extent of reservoir rocks associated with structuring;

ii) application of sequence stratigraphy to define the subdisions of Danişmen and Osmancık sedimentary successions, through the identification of depositional characteristics of parasequences, i.e., the sedimentary cycles;

iii) interpretation of well logs to determine the reservoir properties of gas bearing reservoir rocks;

iv) analysis of formation and production tests;

v) estimating the gas reserves.

1.2 Study Area and İkihöyük Field

The area of study is marked by a box with solid black lines in **Figure 1.3** and covers an area of approximately 6.4 km^2 within the area of concession 3839, of which the licence boundaries are indicated with a polygon of solid red lines in **Figure 1.2**. The main focus in the study area is İkihöyük field with the approximate area of 1.7 km^2 and is located within the central-north portion of the licence (concession 3839) area. Of two wells, drilled in the field at about 25 kilometers East of the city of Edirne, İkihöyük-2 well is located at 618 meters (or 2028 ft) on the West of İkihöyük-1 well. The area, marked by solid purple lines in **Figure 1.3**, indicates the coverage of 3D-seismic survey conducted.

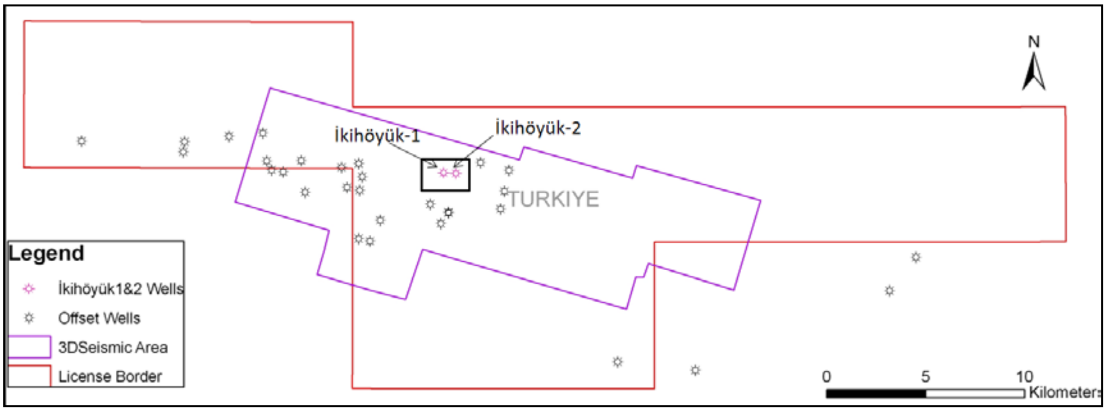

Figure 1.3: The distribution of dry and discovery wells in addition to the locations of İkihöyük field, the study area, and 3D-seismic survey area with respect to the coverage of Concession 3839 (licence) area.

The deltaic deposits of Danişmen and Osmancık sandstones of Tertiary age are known to be important gas-bearing sedimentary successions, within and without the Concession 3839 in Thrace Basin. Therefore, a program for the exploration along İkihöyük structure was launched to evaluate the shallow natural-gas potential in both Lower Danişmen and Osmancık formations. The structural closure, trending almost in E-W direction, was mapped on 3D seismic-data comprised of two culminations.

The first well, İkihöyük-1, was drilled to the total depth (TD) of 500 meters (1640 ft) on eastern sub-closure, in late March and early April of 2008. The wildcat was successful with the discovery of dry natural gas that flowed with initial rates up to 3.8 MMscf/d (108 Mscm/d) from the reservoirs in Lower Danişmen and mainly in Osmancık formations. About a year later, in January 2009, İkihöyük-2 was drilled down to the TD of 540 meters (1772 ft) to confirm the western extention of the gas reservoirs within the second culmination of the same structure in Lower Danişmen and Osmancık formations,. The well İkihöyük-2 intersected natural-gas saturated reservoir only in Osmancık formation and flowed at a rate of 4.7 MMscf/d (134 Mscm/d.) The well had no show of gas accumulation in the Lower Danişmen sandstone, which was gas saturated in İkihöyük-1.

During the initial and limited production period, it was detected that the reservoir pressures were different in both wells at the same depths of the gas producing zones in Osmancık formation. The gas production from İkihöyük-1 and İkihöyük-2 started to decrease significantly in a time frame of six and four months, respectively, and has never reached to a level of pre-drill expectation. Therefore, it should be clear to one that not only the conditions of deposition, but also the characteristics, diagenesis, and the lateral variations of facies, in relation with the timing of structuring, determine the overall reservoir properties in such depositional environments of Danişmen and Osmancık formations.

1.3 Exploration History

The tectonics, sedimentation and the potential of economic hydrocarbon reserves of Thrace Basin were first investigated in early 1930s. During the initial period of exploration efforts, very useful information for comprehending the structure and stratigraphy in the basin was gathered through geological field studies, geophysical surveys, and drilled wells.

According to a report by the General Directorate of Petroleum Affairs of Turkey (PİGM, 2009) more than 700 wells drilled in Thrace Basin, since the first surveys and investigations performed in the region. Some of the major fields with economic hydrocarbon reserves in the basin are Hamitabat gas field, Kuzey Marmara gas field, Değirmenköy gas field, Kuzey Osmancık oil field, and Deveçatağı oil field. Except Hamitabat gas field, producing from a pay zone in Hamitabat formation, rest of the aforementioned fields produce from the pay zones in Soğucak formation. The first commercial hydrocarbon-gas discovery in Thrace Basin was realized in 1970 by TPAO at Hamitabat-1 well, produced at a rate of 5 MMscf/d (142 Mscm/d) from the depth of 3000 meters (9843 ft) in Hamitabat formation. Three years later, in 1973, the first commercial oil discovery in the basin was also realized by TPAO at the well of Deveçatağı-1, produced 37°API gravity oil from the depth of 1450 meters (4757 ft) in Soğucak formation.

Hamitabat sandstones of Eocene age and Soğucak limestones of Lower Oligocene age were considered to be the primary objectives for oil and gas drilling during early stage. Many shallow and uneconomic gas accumulations at about 400 to 500 meters (1312 to 1640 ft) of depth were encountered during the drilling of deep wells. Since 1987, as the shallow gas potential in the region was discerned, the oil and gas E&P (exploration and production) companies have targeted the clastic reservoirs in Upper Oligocene–Lower Miocene Danişmen and Osmancık formations at shallow depth. Between 1987 to 1990, commercial gas reserves have been discovered in the deltaic Osmancık sandstones of Oligocene age. For instance, Umurca gas field of TPAO (18 MMscf/d or 510 Mscm/d), Hayrabolu gas field of Thrace Basin Natural Gas Corporation (1 MMscf/d or 28 Mscm/d), and Kandamış gas field of Polmak (1 MMscf/d or 28 Mscm/d) are few of the fields producing from Osmancık sandstones at shallow depths (Aksoy, 1987; Coskun, 1991.)

In 2005, when the well Batı Umur-1 was drilled as the first exploration well (wildcat) in Concession 3839 the commercial gas accumulations were intersected in the fluvial deltaic sandstone deposits of both Danişmen and Osmancık formations. Note that the hydrocarbon exploration until the last quarter of 2008 was conducted mainly based on 2D seismic surveys and prior drilling results. By the end of 2008, however, the area surveyed by 3D seismic in **Figure 1.3** reached a total of 149 km^2 (about 47 thousand acres) to develop and further explore the structural and stratigraphic plays both at shallow and deep horizons.

2. REGIONAL GEOLOGY AND STRATIGRAPHY OF THRACE BASIN

Thrace Basin is of Tertiary age and has a shape resembling a triangle that occupies the most of the area of Thrace Region, as seen in **Figure 1.2**. The basin is surrounded by the Paleozoic-Mesozoic magmatic and metamorphic basement of Istranca (Strandja) Mountains in north, the basement of Rhodope massive in West, and the North Anatolian Fault Zone in South (Huvaz et al., 2005.) The geologic and tectonic setting of the basin has previously been studied and documented by many researchers and investigators (Holmes, 1961; Doust and Arıkan, 1974; Saner, 1980; Perinçek, 1991; and Coşkun, 2000.). It is rather common to appraise Thrace Basin in three sections, namely the northern part, the central part, and the southern shelf (Doust and Arıkan, 1974; Turgut, et al. 1991.).

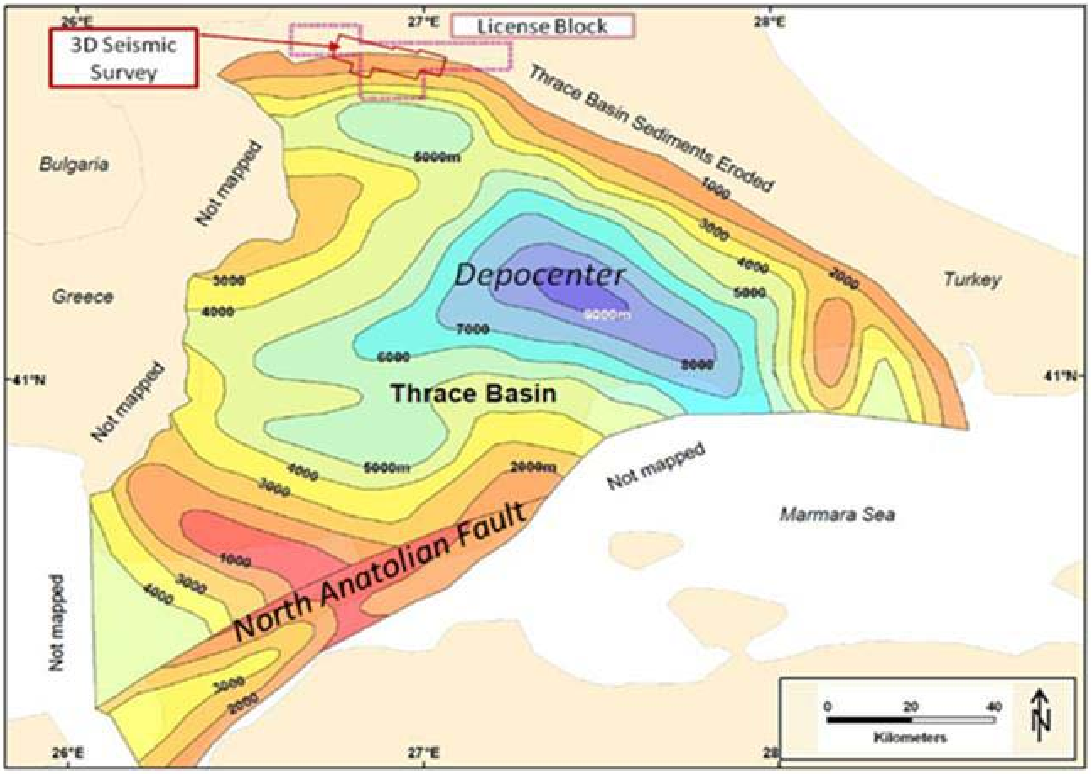

Figure 2.1 : The map of total sedimentary thickness in Thrace Basin (after Burkan, et al., 1992).

In the northern part the deposits of shallow-marine limestones of Eocene age extend along the Istranca (Strandja) massif. In laterally parallel fashion to this extension, these deposits change into deeper marine deposits of limestones, marls and turbidites towards south.

The central part encompasses the deepening part of the basin, located in the SE–NW direction from Marmara Ereğlisi to Babaeski. As seen in **Figure 2.1**, the sedimentary thickness in the central part of the basin reaches up to 9000 meters and is composed of mostly turbidites and clastic sediments that are alternating with volcanic interbeds of Eocene-Pliocene age (Sonel, 1981; Turgut, et al., 1983; Turgut, et al. 1991; Siyako and Huvaz 2007.)

The southern shelf of the basin is characterized by the deposition of shallow marine limestones of Eocene age (Şengör 1979; Okay, et al., 1999; Janssen, et al., 2009; Okay, et al., 2010.)

2.1. Basin Evolution and Stratigraphy

Görür and Okay (1996) interpreted the Thrace basin as a fore arc basin, initiated during a plate convergence in the Late Cretaceous (Maastrichtian), whereas Keskin (1974) and Perinçek (1991) proposed an intermontane origin. Huvaz, et al., (2005) claimed that the initial sedimentation and the development of basin had begun with an extension of the Pontid plate in early Eocene.

The early extensional phase, starting from Eocene until the end of early Miocene, had caused a Southwest-Northeast marine transgression that resulted in a rapid subsidence and the deposition of thick inter-bedded sandstone, conglomerate, and shale sequences of Keşan and Yenimuhacir groups. From the Upper Eocene to Miocene, structural activities resulted in the rapid deepening of the basin and, thus, the central part of the basin was over-pressured by the late Miocene. The uplifting of the south side of the basin (in response to transform fault activities) appears to have caused the northward tilting of the basin and, therefore, led to the creation of several low-angle thrusts, possibly of a gravity-sliding nature.

A conceptual SW-NE cross-section in **Figure 2.2** illustrates the shape and history of Thrace basin with the basement topography, location of License 3839, and the lateral and vertical extensions of overlying sedimentary successions.

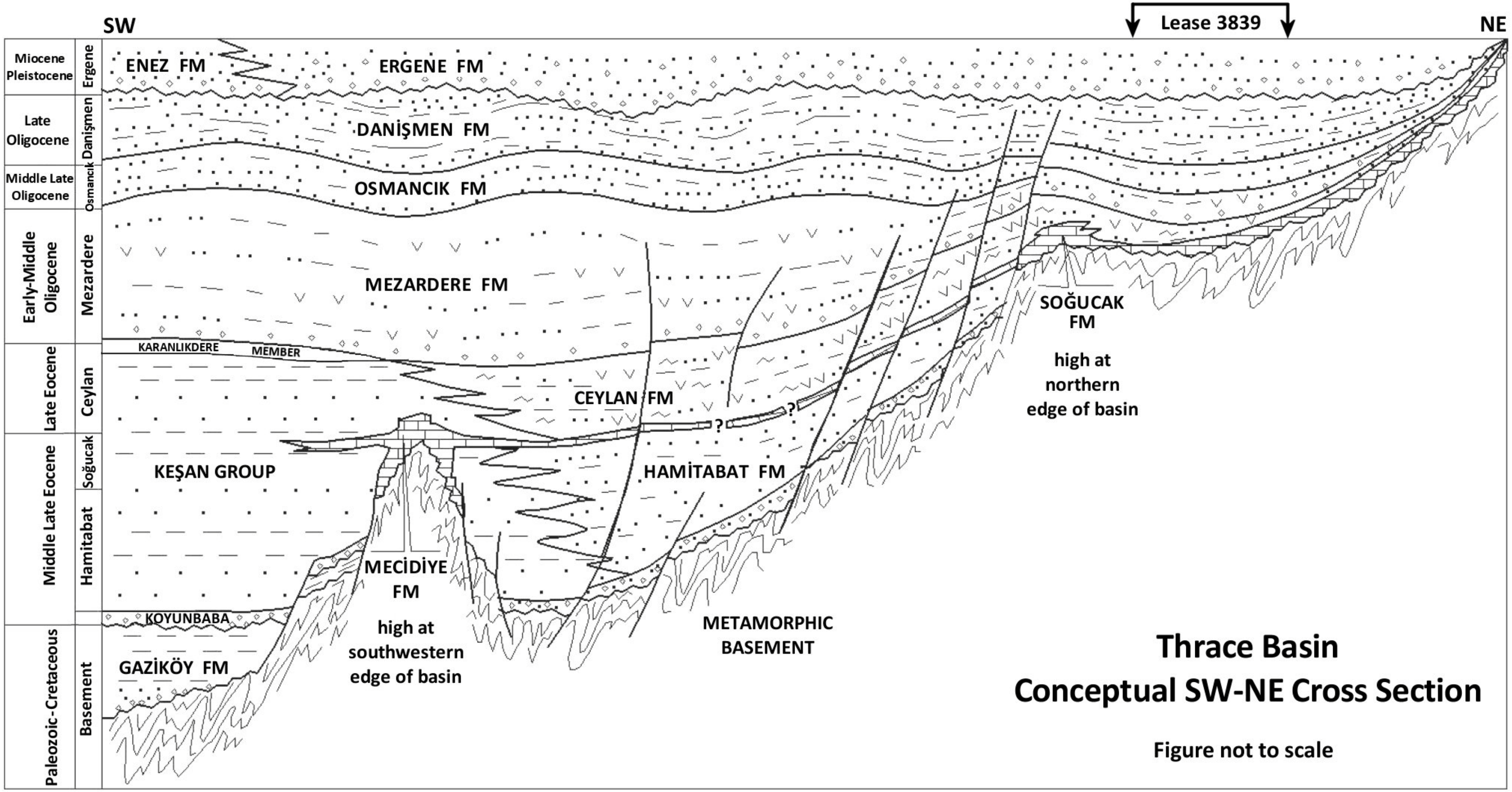

Figure 2.2 : A conceptual illustration of the basement topography, lateral and vertical extension of basin successions, and the approximate location of License 3839 in the SW NE cross section of Thrace Basin (anonymous origin).

At an early stage in the evolution of the basin development, initial filling period, major sedimentary successions were deposited within deeper marine environment whilst carbonate deposits have taken place over basement highs at shallower depth along the basin margins. As the sedimentary filling continued, basin had been peneplained and younger sedimentary successions were deposited over a smooth topography to result in the deposition of very uniform thicknesses across the basin, such as in Osmancık formation.

The detailed stratigraphy, petroleum system and structural history of the Thrace Basin is illustrated in **Figure 2.3**.

Huvaz, et al., (2005) subdivided the Tertiary sedimentary successions into three groups of 1) Keşan, 2) Yenimuhacir, and 3) Ergene, as shown in **Figure 2.3**.

2.1.1. Keşan Group - Eocene

The Eocene formations of Keşan group are Hamitabat formation, Koyunbaba formation, Soğucak formation, and Ceylan formation.

2.1.1.1. Hamitabat Formation

During the first regional transgression period, the structural lows in the basin were infilled by Hamitabat formation, which deposited over Istranca metamorphics and its upper contact is unconformable with either Soğucak or Ceylan formations. The deposition of the formation is limited to the central portion of the basin and consists of sedimentary successions that are as thick as 2000 meters and represent the wide range of depositional environments from shallow marine to the proximal turbiditic deposits of deeper marine settings. The presence of major reservoir and source interval within Hamitabat Formation makes the central portion of the basin very attractive area for hydrocarbon exploration.

2.1.1.2. Koyunbaba Fm

Koyunbaba formation is interpreted as the lateral facies equivalent of Hamitabat formation and has been intersected at the northern edge of Thrace Basin.

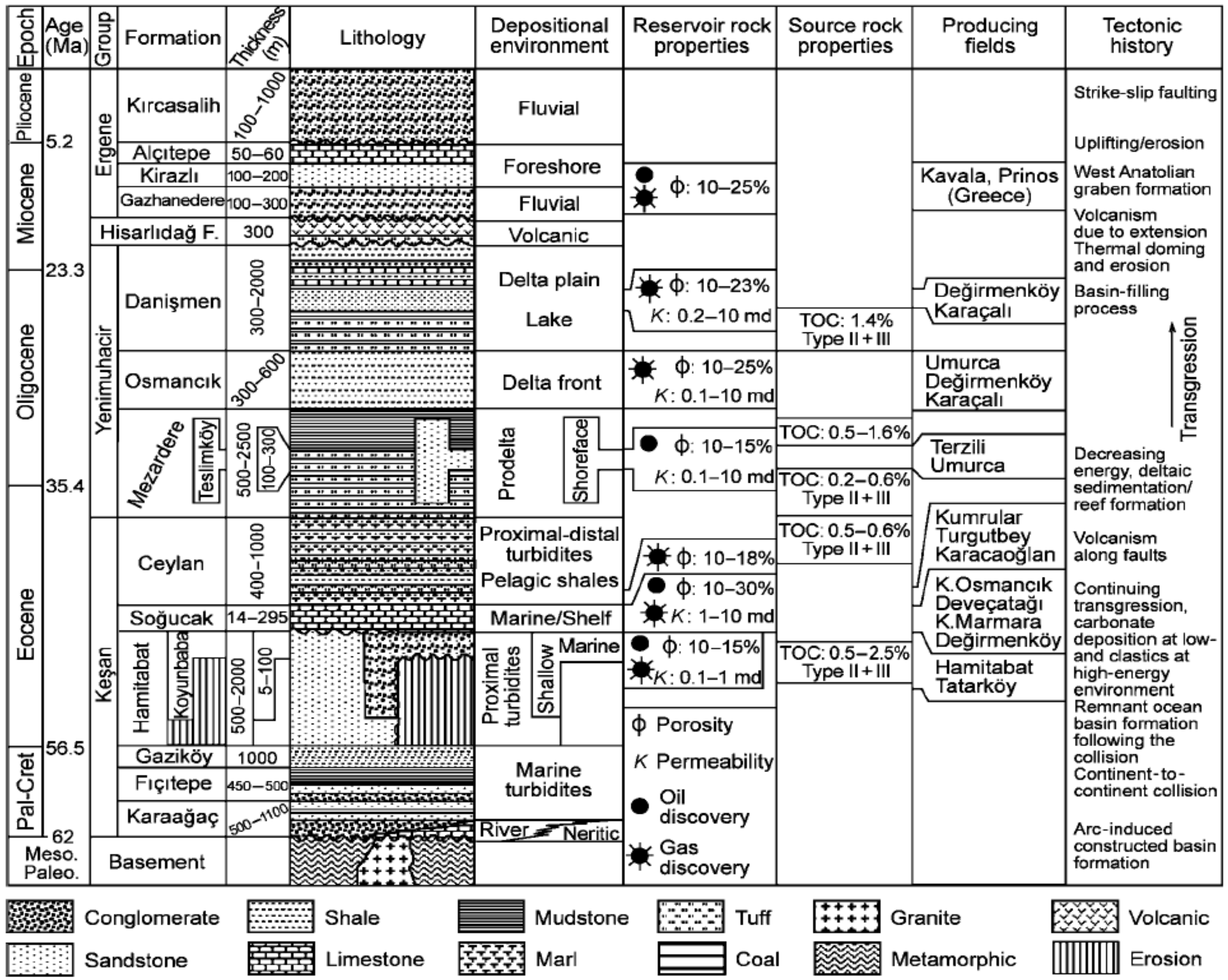

Figure 2.3 : A generalized stratigraphy of Thrace Basin including the formations, structural and tectonic history, elements of petroleum systems, and producing fields (after Huvaz et al., 2005.)

The formation consists of conglomerate at basal part and mainly siltstone and sandstone that were deposited in a shallow marine environment. Koyunbaba formation sits unconformably on the older units and is conformably overlain by Soğucak formation. The Koyunbaba clastics, which exhibit a varying thickness from 5 to 100 meters, are generally flushed and, thus, are considered as non-productive unit in the basin.

2.1.1.3. Soğucak Formation

Soğucak formation is partly reefoidal and dolomitic and, in part, interbedded with marl and sandstone layers. Soğucak limestone, with a varying thickness of 14 to 295 meters, is the only oil producing formation in the basin. One of the best example for Sogucak reefoidal limestone outcrop occurs near Kirklareli village at the northern shelf of the basin, as seen in **Figure 1.2**. Based on the information obtained from drilled wells, the formation becomes argillaceous and grades into marls towards the basinal area. Soğucak formation was deposited within a wide range of depositional environments, from open marine and shelf to lagoon, and unconformably overlies the older units, while its upper contact is conformable with the Ceylan and Mezardere formations.

2.1.1.4. Ceylan Formation

Ceylan formation, with the thickness of 400 to 1000 meters, is mainly consisted of black shales, marls, tuffs, and turbiditic shale-sandstone alterations deposited in deep marine environment. While Ceylan formation is conformably overlain by Mezardere formation, a gradual facies change exists between the marls of Ceylan formation and the underlying Soğucak formation towards the deeper part of the basin. The pelagic shales are considered to be one of the important source rocks. Gas producing tuffs, with the thickness of 2 to 100 meters, are widespread in the entire basin and accepted as a marker horizon on gamma ray logs.

2.1.2. Yenimuhacir Group – Upper Eocene to Lower Miocene

The Upper Eocene to Lower Miocene age formations of Yenimuhacir group are Mezardere formation, Osmancık formation, and Danişmen formation. Note that both Danişmen and Osmancık formations include major producing reservoirs within the area of License 3839 and, therefore, are discussed in detail later in the Sequence Stratigraphy and Log Analysis sections of this document.

2.1.2.1. Mezardere Formation

Mezardere formation mainly comprises of interbedded dark grey and black shales, siltstones, and sandstones, all of which are pro-delta facies deposited in shallow to open marine environments. According to Kasar, et al, (1983) the formation is 1540-meter thick at the type section and, yet, based on seismic surveys the thickness may reach to 2500 meters in deeper portion of the basin. As indicated in **Figure 2.3**, the black shales with TOC up to 1.6 % are considered to be good source rocks in the basin. Mezardere Formation transitionally grades upwards into the deltaic Osmancik formation (Siyako, 2006.)

2.1.2.2. Osmancık Formation

Osmancık formation consists of fine to medium grained, grey to white, sometimes friable and 100- to 150-meter thick sandstones, with a carbonate matrix in general. Osmancık formation, intercalated with thin shales and lignite layers, was deposited mainly in a pro-delta environment, as resembled in **Figure 2.4**. The formation thickness at the type section is 810 meters (Temel and Çiftçi, 2002). Osmancık sandstones are gas producers in Umurca, Hayrabolu and Kandamış fields as well as in license 3839. Osmancık formation does not exhibit any outcrop but is intersected by drilling only in the study area of this present work. To establish its upper contact Osmancık formation transitionally grades into the overlying Danişmen formation. The lower portions of Osmancık formation consist of turbiditic pro-delta sedimentary deposits, which exhibit mainly the upward-coarsening of sedimentary depositional cycles, as illustrated in **Figure 2.4**.

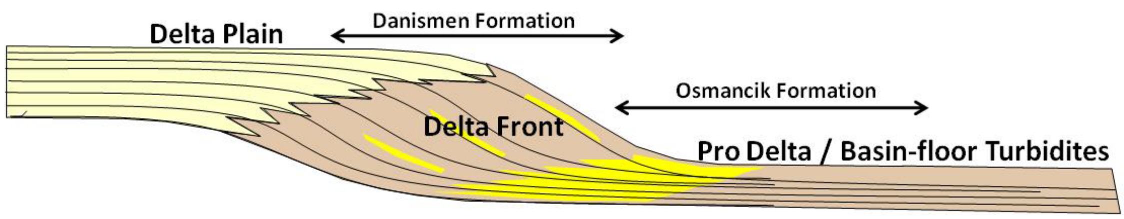

Figure 2.4 : An interpretation for the depositional environments of the Lower Danişmen and Osmancık formations in the license area.

2.1.2.3. Danişmen Formation

Danişmen formation is composed of an alternation of gray, yellowish gray, brownish gray sandstones that include mica fragments, mudstones, and claystones within the study area. The formation, of which the thickness may reach up to 2000 meters, contains lignite bands in patches through the upper levels of its section. Medium to thick bedded and occasionally well cemented sandstones with plant remnants were deposited mainly in a delta plain environment, as schematically shown in **Figure 2.4**. The sandstone units range from thick bedded (from 0.5 to several meters) to bundled thin bedded (from centimeter to decimeter scale). The sandstones are generally very fine to fine grained, well sorted, and friable. The upper portion of the formation consists of interbedded dark-grey shales, light-grey marly clay beds and, in part, patchy lignite bands. Danişmen formation is unconformably overlain by the younger units. A photograph showing the contact of Lower Danişmen and Osmancık formations at an outcrop by the highway about Barbaros Çeşmesi, Tekirdağ, is presented in **Figure 2.5**.

Figure 2.5 : The outcrop of Lower Danişmen and Osmancık contact by the highway at Barbaros Ceşmesi,Tekirdağ.

As mentioned previously, both Danişmen and Osmancık formations are discussed in detail in the Sequence Stratigraphy and Log Analysis sections of this thesis.

2.1.3. Ergene Group – Miocene

The Miocene age formations of Ergene Group fill the existing young depressions and unconformably overlie the older formations. The group consists of unconsolidated conglomerates, mudstones, limestones, and sandstones.

2.2. Petroleum Systems of Thrace Basin

First oil discovery in the well of Kuzey Osmancık-1 in 1970 was an indication of the existence of petroleum systems in Thrace Basin. Since then, the intensive exploration activities of both international and domestic companies resulted in the discovery of umpteen oil and gas fields in the basin. Continuing activities for the oil-and-gas field exploration and development have provided significant information that improved the understanding of hydrocarbon potential of the basin. Currently, Thrace Basin has become another significant hydrocarbon province besides the SE region of Turkey.

The documentation and discussion of petroleum systems as well as the structural and depositional history of Thrace basin, by many researchers and investigators, has led to the recognition of the presence of reservoirs rocks in the formations of various ages in the basin. Major discoveries have been in reefal carbonates and siliciclastic rocks, which were deposited in a wide range of depositional environments from fluvial, deltaic to the turbidites of deeper marine successions. For example, the turbiditic sandstone of Hamitabat formation and the deltaic sandstone of Osmancık and Danişmen formations can be named as the key formations that bear producing reservoirs.

In Thrace Basin the potential good-sealing formations do exist within a number of stratigraphic units. The shaly intervals of the Mezardere, Ceylan, Osmancık and Danişmen formations, in particular, exhibit excellent seal potential.

Regarding the source rock development in the basin, the organic-rich shaley intervals of Hamitabat, Ceylan and Mezardere formations, which were deposited in the deeper part of the basin, are considered to have sufficient content of organic matters. These shales are identified as the three major source rocks that are associated with types II-III, III and II and III respectively (Huvaz, et al., 2006).

3. SEQUENCE STRATIGRAPHY

Sequence stratigraphy is an alternative but powerful method to the interpretation of sedimentary packages. It provides the understanding of depositional process and the factors, i.e., basin geometry, sea-level changes, subsidence rates, climatic conditions, and sediment supplies, which have direct influence on the description and prediction of the occurence, extent, and geometry of sedimentary facies. Van Wagoner, et al., (1988) pointed out that sequence startigraphy is the study of genetically related strata that were deposited within same chronostartigraphic framework which were bounded by erosional surfaces or non depositional surface or correlative unconformities.

Consequently, sequence stratigraphy assists to recognize and reservoir, seal and source-rock facies, and improves correlation of reservoir units within successions.

The sequence is genetically related strata , which is bounded by regional uncorfomities or transgressive surfaces (Mitchum et al., 1977). Internally, these sequences consist of key intervals (such as systems tracts and parasequences) and surfaces (transgressive surface and maximum flooding surface.).

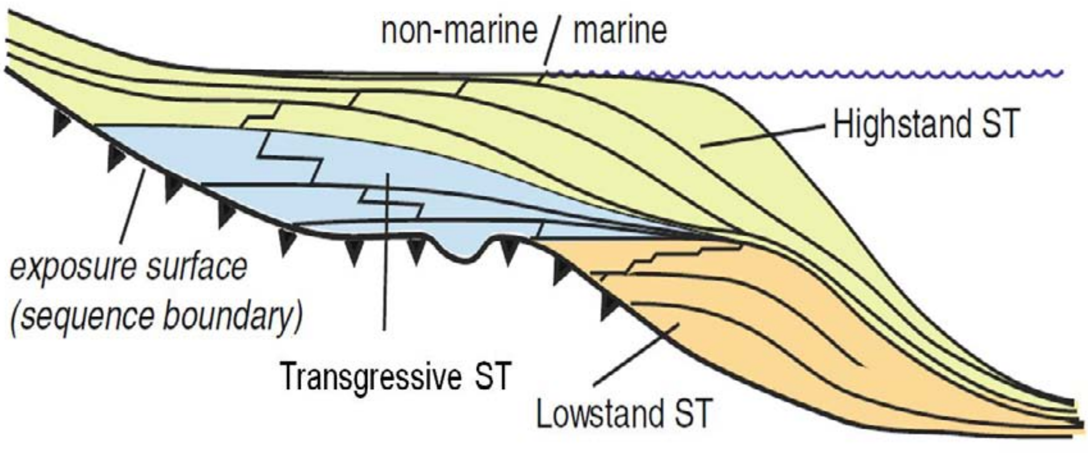

Figure 3.1: Standard model of stratigraphic sequences (Schlager, 2009)

These intervals and surfaces form in response to cyclical changes in relative sea-level, creating repetitive and predictable sequences and they are called System Tract

(Van Wagoner et al., 1988). There are three types system tracts a) Lowstand (LST), b) Transgressive (TST) and c) Highstand system tracts (HST) as shown in Figure 3.1.

Based on these principles, following steps have been applied in the study.

- First, the transgressive surfaces were identified on well logs.
- Second, these surfaces were correlated within the field.
- Third, the secondary correlative transgresive surfaces and parasequences were identified.
- Fourth, An areal extension of reservoir sand bodies (both lateral and vertical) within specific depositional cycles (parasequences) were defined. This technique is also applied to the other fields in the Thrace Basin (e.g. Alpullu Field).

3.1. Sequence Stratigraphic Correlation

Chronostratigraphic correlation of selected wells, based on an integration of sequence stratigraphic principles, electric well logs and 3D seismic data in license 3839 is shown in Figure 3.3 and Figure 3.4. Figure 3.2 shows the relationship between sequence stratigraphic and lithostratigraphic correlation. The major transgressive surface at the top of gas-bearing reservoir sands which show an upward coarsening characters is interpreted as the top of Osmancik Formation (İkihöyük-1 : 382m ; İkihöyük-2: 396m). (Figure 3.4) Utilising of the secondary transgressive surfaces, recognized on electrical logs and confirmed on 3D seismic data, further parasequences were identified within the Osmancık and Lower Danişmen formations (Figures 3.4 and 3.5).

Detailed chronostratigraphic subdivision and depositional cycles of the İkihöyük-1 and 2 are shown in Figure 3.4. As described above subdivison is based on mainly transgressive surfaces within the both formations. The contact between the lower and upper parsequences in Lower Danişmen is identified at 311m in İkihöyük-1 and and 323m at İkihöyük-2 (Figure 3.5).

In İkihöyük-1, Lower Danişmen LD_SAND1 (314-321m) has an upward coarsening characteristics, gas saturated within 314-316m and contains very high shale content.

In İkihöyük-2, LD_SAND1 intersected within 327 and 336m and has more shale content than İkihöyük-1 and it is not gas saturated.

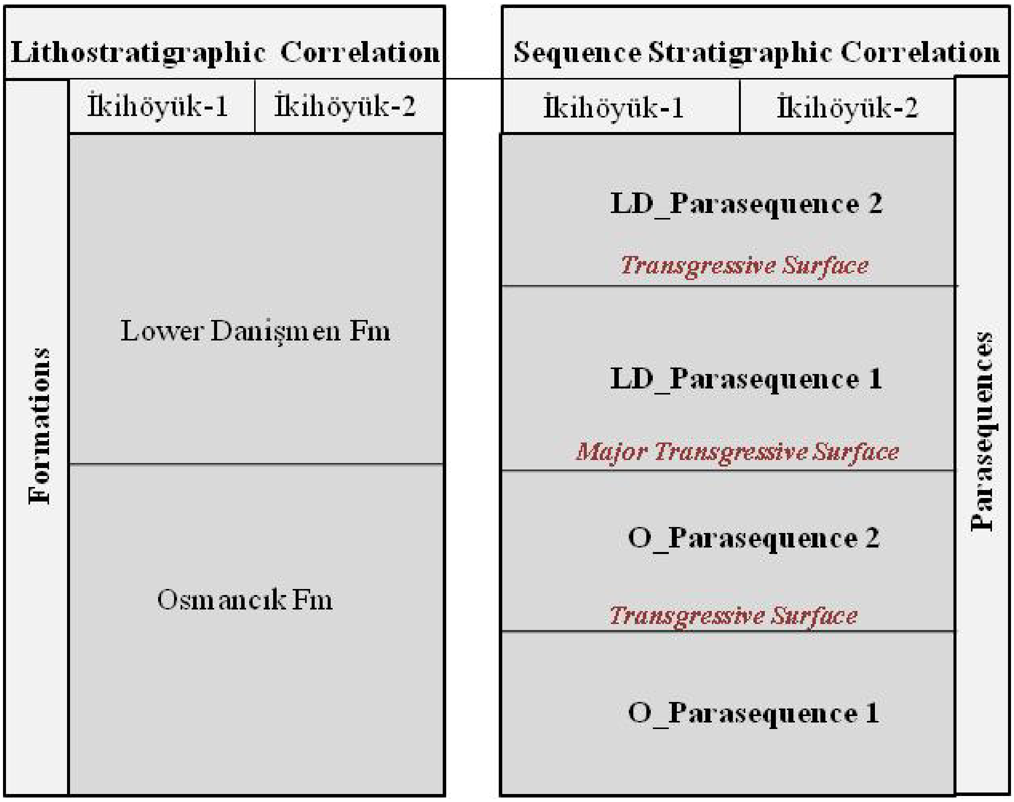

Figure 3.2: Lithostratigraphic and sequence stratigraphic correlation of İkihöyük wells.

The upper parasequence of Osmancık formation, Top Osmancık level, is identified at 382m in İkihöyük-1 and 396m in İkihöyük-2.

The thickness of the O_SAND2 on top of this unit, is 14 m from 382 to 396m in İkihöyük-1, and 13 m thick from 396-409m in İkihöyük-2. O_SAND2 is gas saturated in both wells. Shale contents in both wells is approximately 70%.

The second parasequence of Osmancık is at 440m in İkihöyük-1, 453m in İkihöyük-2. The sand zone, O_SAND1, has upward coarsening. The sand facies in this level is better in İkihöyük-1. Both sands are gas saturated.

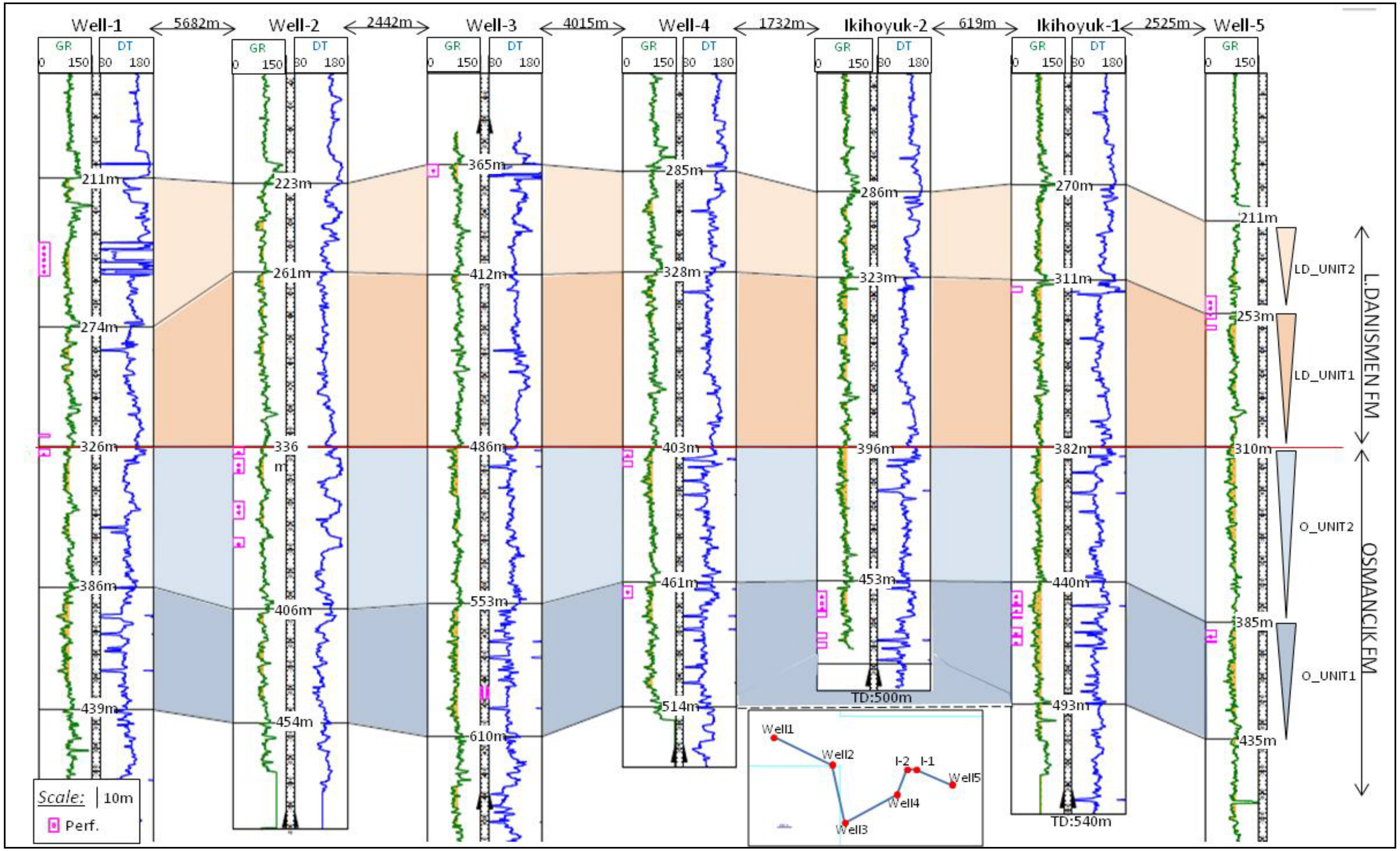

Figure 3.3: General sequence stratigraphic correlation of selected wells in Concession 3839.

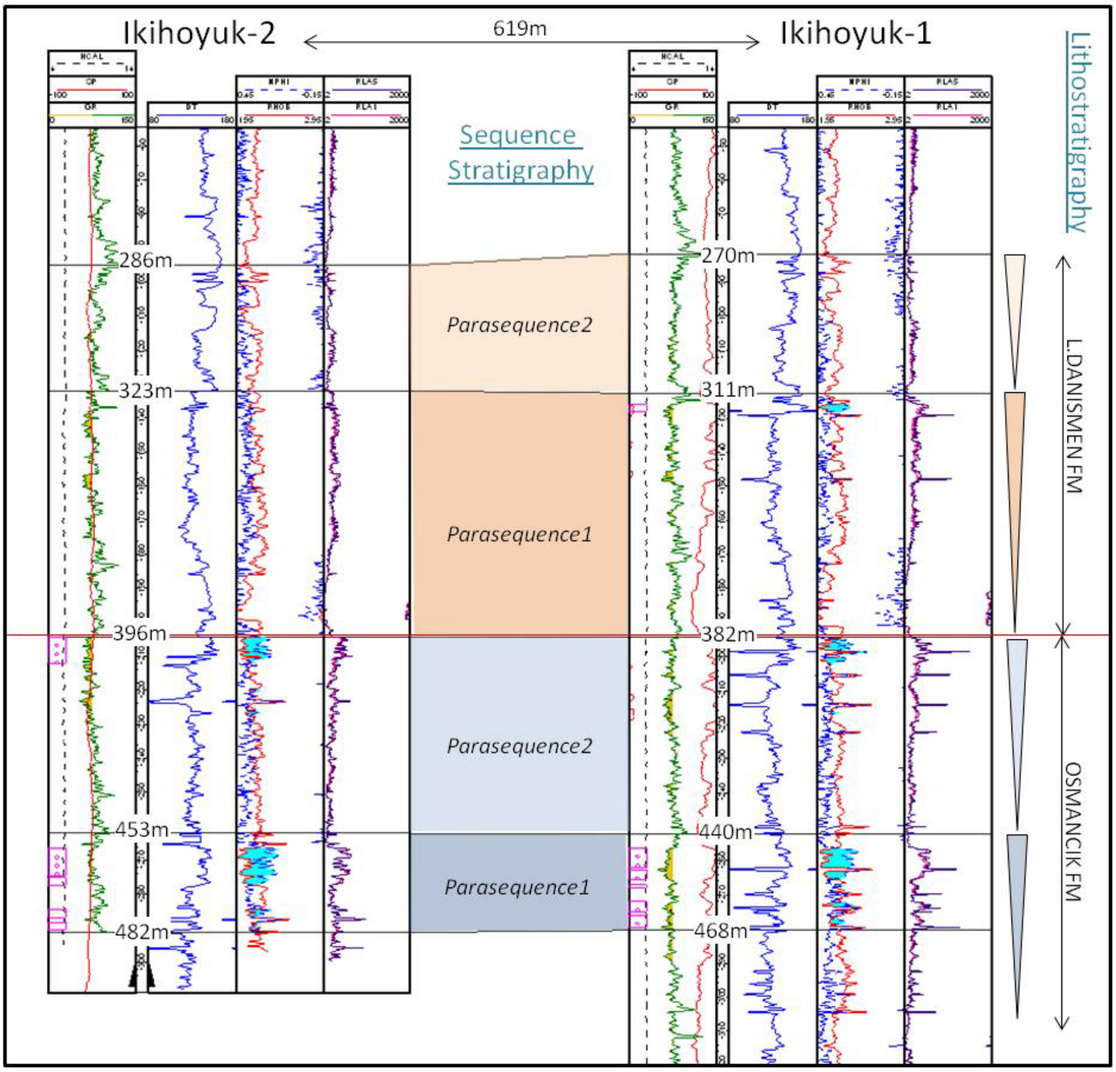

Figure 3.4: Sequence stratigraphic correlation of İkihöyük wells.

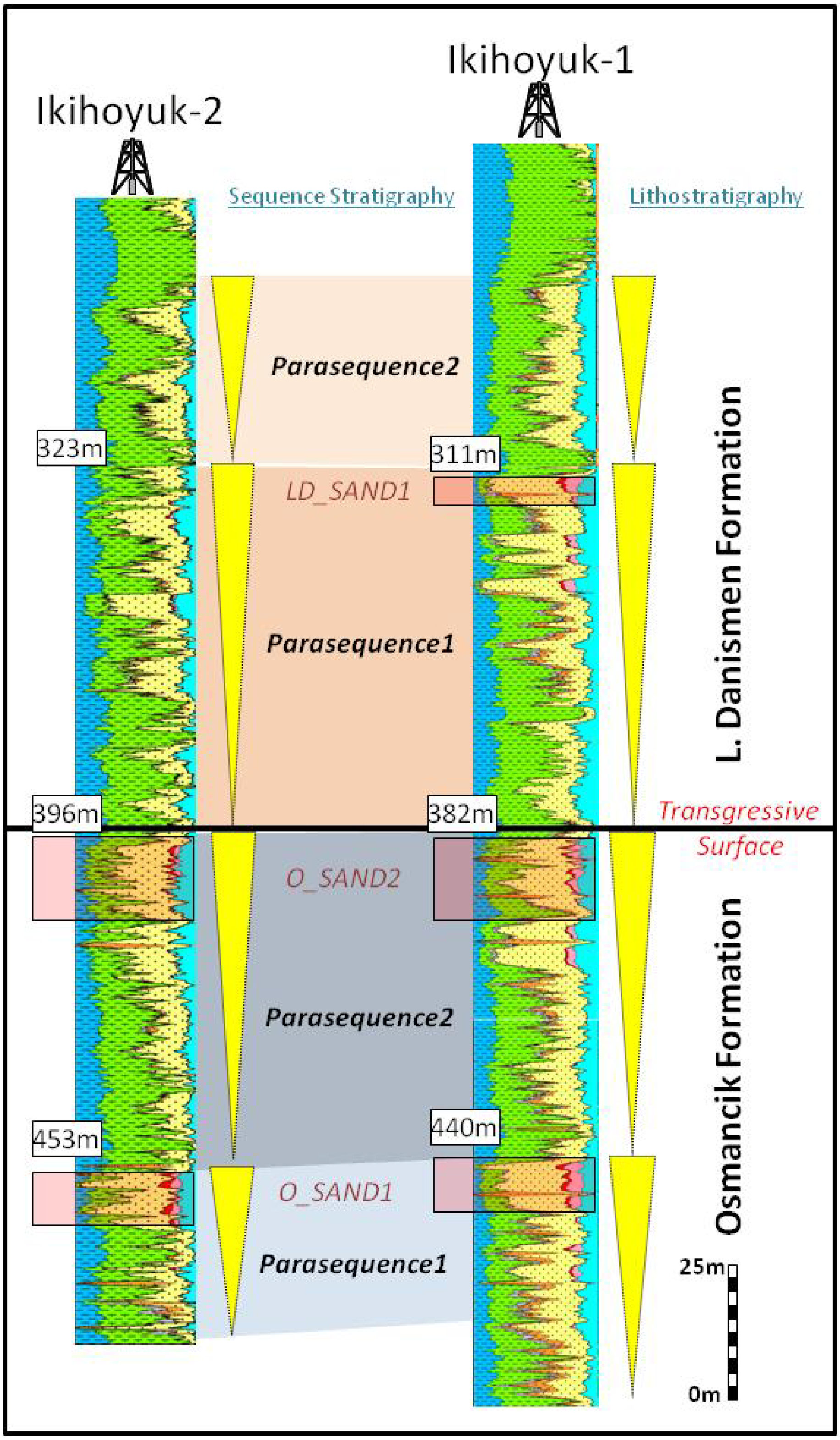

Figure 3.5: Parasequence correlation of İkihöyük wells. Note that each parasequence shows upward coarsening cyle.

4. 3D SEISMIC INTERPRETATION

Exploration activities in Concession 3839 were mainly based on 2D seismic data until 149 km^2 of 3D seismic data was conducted in late 2008 by PEMI (Figure 4.1).

Acquired new 3D seismic data have assisted further to identify both structural and stratigraphic plays at shallow and deep horizons.

Even though, this is not the case always, previously drilled more than 10 wells in concession area have proved that strong amplitude anomalies at Lower Danişmen and Osmancık sand reservoirs are associated with gas accumulations in this part of the basin. İkihöyük-1 and 2 wells were drilled mainly based on this concept to evaluate gas potential at Lower Danişmen and Osmancık reservoirs (Figures 4.1 and 4.2).

4.1. Pre-Drill Seismic Interpretation

Re-mapping of the area on new 3D seismic data, Ikihoyuk structure is defined as a hanging wall inversion anticline with a three way dip closure and two structural culminations, which is bounded to the North by a South-dipping normal fault.

Depth structural maps of the Near Top Lower Danişmen and Osmancık formations are shown in the Figure 4.1 and 4.2. The depth structure map to the near Lower Danişmen level shows that amplitude anomalies are weaker at western structural culminations where İkihöyük-2 was drilled.

The Depth Structure Map to the Near Top Osmancık Formation (Figure 4.2) shows that strong amplitude anomalies are extended over greater area that covers both structural culminations and east of İkihöyük-1 high.

Seismic mapping revealed a maximum total vertical relief of 40 meters at the top of the Osmancık reservoir, while the Lower Danişmen sand is characterized by a 35 m relief for İkihöyük-1.

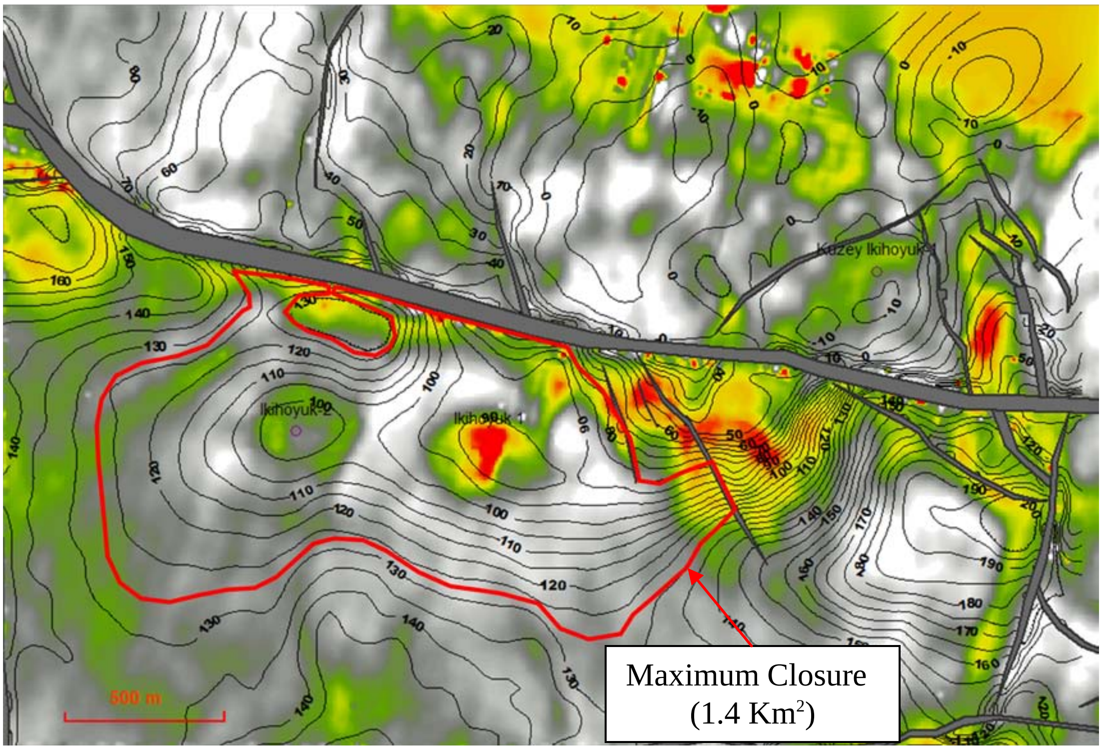

Figure 4.1: Depth Structure Map to Near Top Lower Danişmen Level Showing Amplitude Anomalies (mSS). C.I. 5 meters.

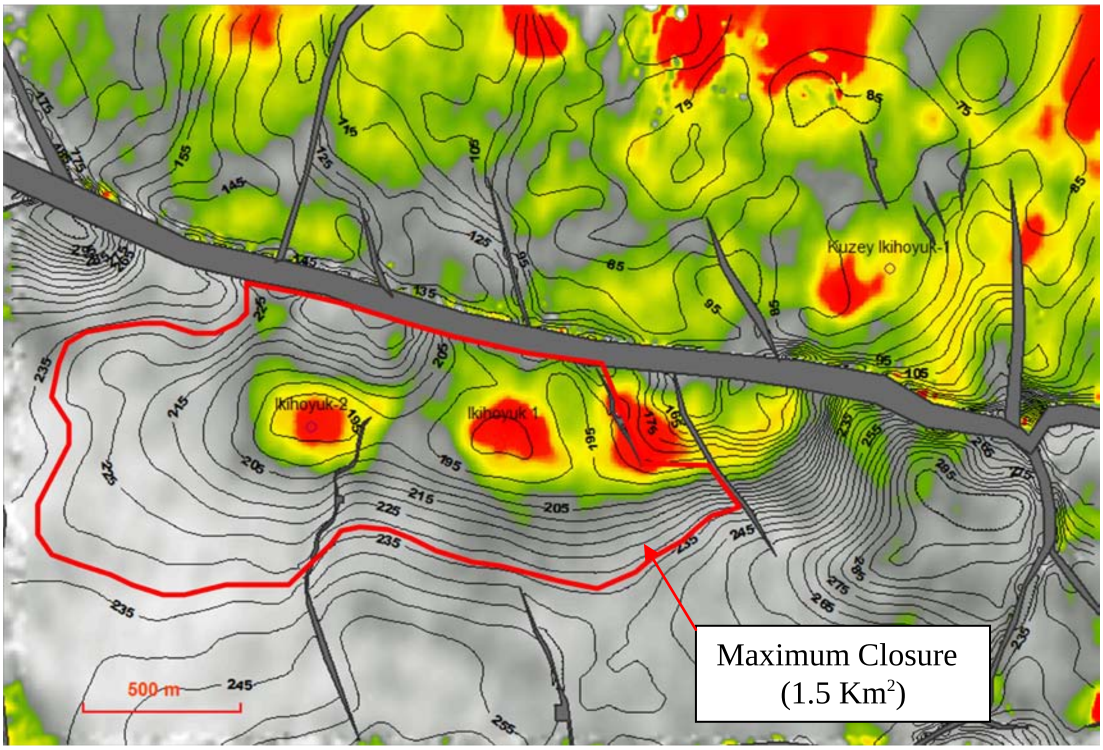

Figure 4.2: Depth Structure Map to Near Top Osmancik Level Showing Amplitude Anomalies (mSS). C.I. 5 meters.

As an expected outcome, İkihöyük-1 intersected gas filled reservoirs in both Lower Danismen and Osmancik formations. Log and test data from İkihöyük -1 indicates that estimated the net thickness of the Osmancik reservoir sandstones are within the range of 18 m, whereas the Lower Danişmen Sandstone net reservoir thickness is only 2-3 m. Based on net pay thicknesses, petrophysical data from İkihöyük-1, and the seismic mapping of the structure, it is estimated that the Ikihoyuk structure contains a total of 2.12 Bscf recoverable gas reserve. (Well Proposal Company Report)

Second well, İkihöyük-2, was drilled to confirm gas accumulation at western area of structure and to evaluate the overall reservoir heterogeneity, and specifically the connectivity of individual gas bearing sandstones between Ikihoyuk-1 and 2.

However, Osmancik sandstone reservoirs were gas saturated only in this well and there was no evidence for gas accumulation in the Lower Danişmen sandstone reservoir. In fact it was an expected outcome because amplitude anomalies were almost absent in İkihöyük-2 structure as illustrated in Depth Structure Map to Near Lower Danişmen (Figure 4.1) Absence of gas in the Lower Danişmen sandstone reservoir was further confirmation of significance of amplitude anomalies in relating to gas accumulation in concession 3839.

Based on log and petrophysical data the net thickness of the Osmancık reservoir sandstones is calculated 16 m in İkihöyük-2. Therefore, it can be pointed ot that quality and net thickness of producing reservoirs in Osmancık Formation are very similar within both wells.

4.2. Post-Drill Seismic Interpretation

East-West oriented seismic section illustrate strong amplitude anomalies in reservoir sandstones of both Lower Danişmen and Osmancık Formations. However, amplitude anomalies are stronger at Osmancık Formation indicating of possibly better reservoir development within this sedimantary succession.

New 3D seismic data has better resolution therefore it provides an opportunity to generate very detailed mapping at reservoir levels in Concession 3839.

Although so many factors controll reservoir facies or reservoir distribution in many places (basins), it is widely accepted that tectonism is probably the first and most significant controlling factor particularly in a fluvio-deltaic depositional environment where active tectonism (synsedimentary faulting) is constantly present.

In such areas where fluvial depositional systems were controlled by synsedimentary faulting, subsidence occur realitively faster compared to adjacent areas. Therefore paleocurrent pattern mainly developed and or limited within these areas where stacked sandstone deposition or upward coarsening cycles were commonly occurred.

In the study area, synsedimentary faults were identified and interpreted as shown in **Figure 4.3**.

Relatively rapid subsidence occur within synsedimentary fault controlled area therefore main channel area is limited within this zone. Based on total production and other petrophysical data indicates that gas production has been made only from the area where syndepositional faults controlled area. This is further confirmation that even minor scale active faulting has significant impact on reservoir distribution.

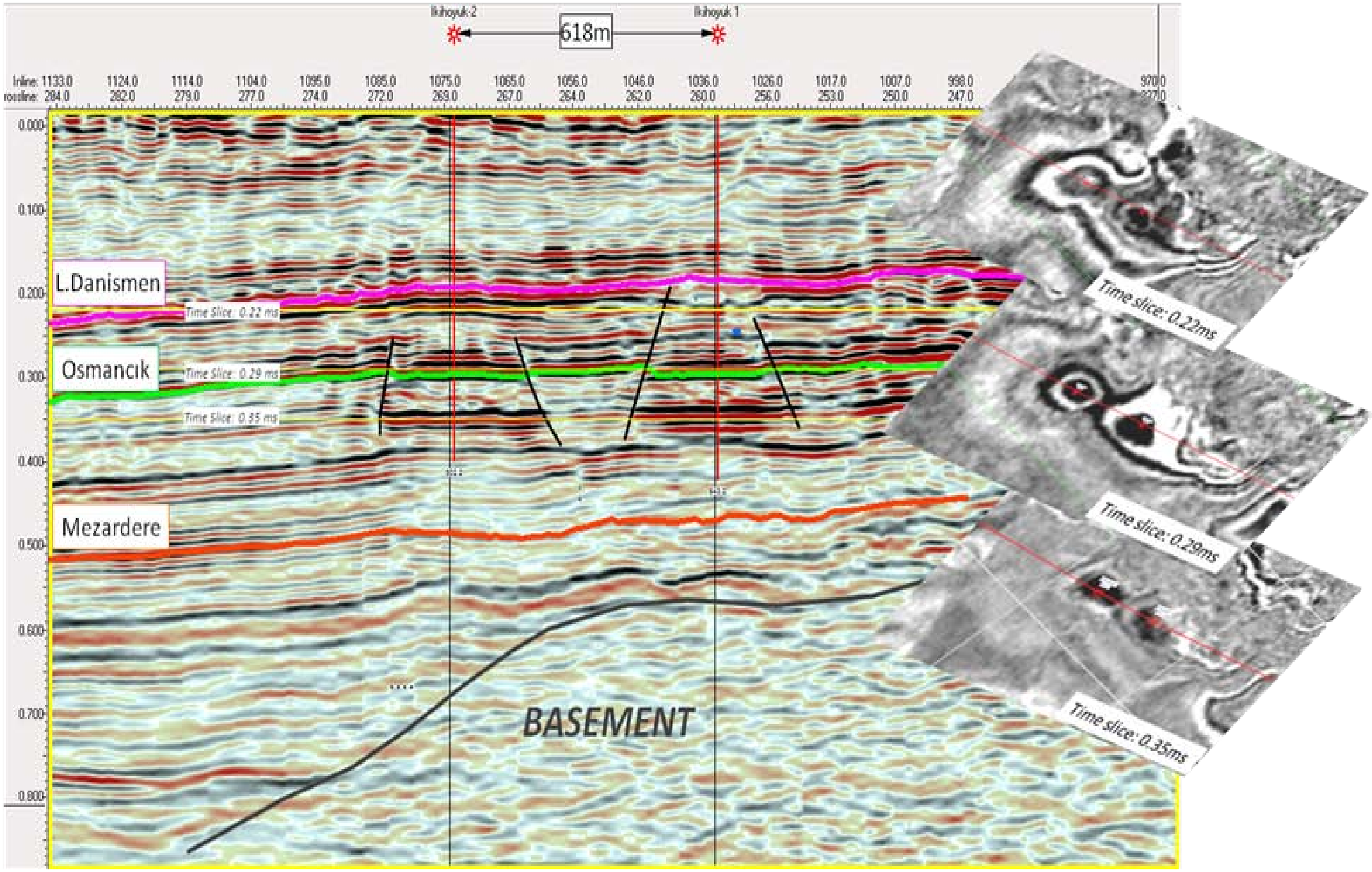

Figure 4.3 : Arbitrary seismic line showing the amplitude anomalies and time slices that indicate the gas zone.

5. WELL DRILLING AND COMPLETION SUMMARY

The two wells in İkihöyük field were drilled sequentially with seven and half month apart. First, İkihöyük-1 well was spudded on 26th of March 2008 and completed as a gas producer on 25th of May 2008. Later, İkihöyük-2 well was spudded on 7th of January 2009 and was completed as a gas producer on 15th of January 2009. The latitude and longitude of İkihöyük-1 well are 41.7479889° North and 26.879525° East, respectively. Similarly, the latitude and longitude of İkihöyük-2 well are 41.748225° North and 26.8720941° East, respectively. Since the distance between two wells was 619 meters and both wells were drilled in two neighboring relief structures, the question of whether or not the pay sections of both wells were in hydrodynamic communication was arisen. Therefore, the search for the answer to this question became one of the issues investigated in this study.

5.1. Drilling and Completion Summary for İkihöyük -1 Well

As seen in the drilling and completion configuration of İkihöyük-1 well in **Figure 5.1**, the well was drilled to a total depth of 540m. The ground level (GL) elevation was 186.83 meters and the rotary table elevation (RTE) was 190.58 meters from the MSL (mean sea level.) Initially, a three-cone bit with 8 ½” diameter was used to drill the first 73-meter section of the bore hole, which was cased with the J-55 STC casing with nominal diameter of 7” and the unit weight of 26 lbs/ft down to the depth of 71 meters. After installing the blowout preventer (BOP) stack the bore hole with 6” in diameter was drilled down to the depth of 540 meters and cased with the L-80 STC production casing with nominal diameter of 5” and the unit weight of 15 lbs/ft down to the depth of 537 meters, and the well was suspended.

The 6” bore hole was logged with BHC, TLD, NPHI, HRLA, SP, and CAL from 70.5 to 528 meters; with HNGS and FMI from 81 to 532 meters; and with XPT and GR from 101 to 476 meters of depth.

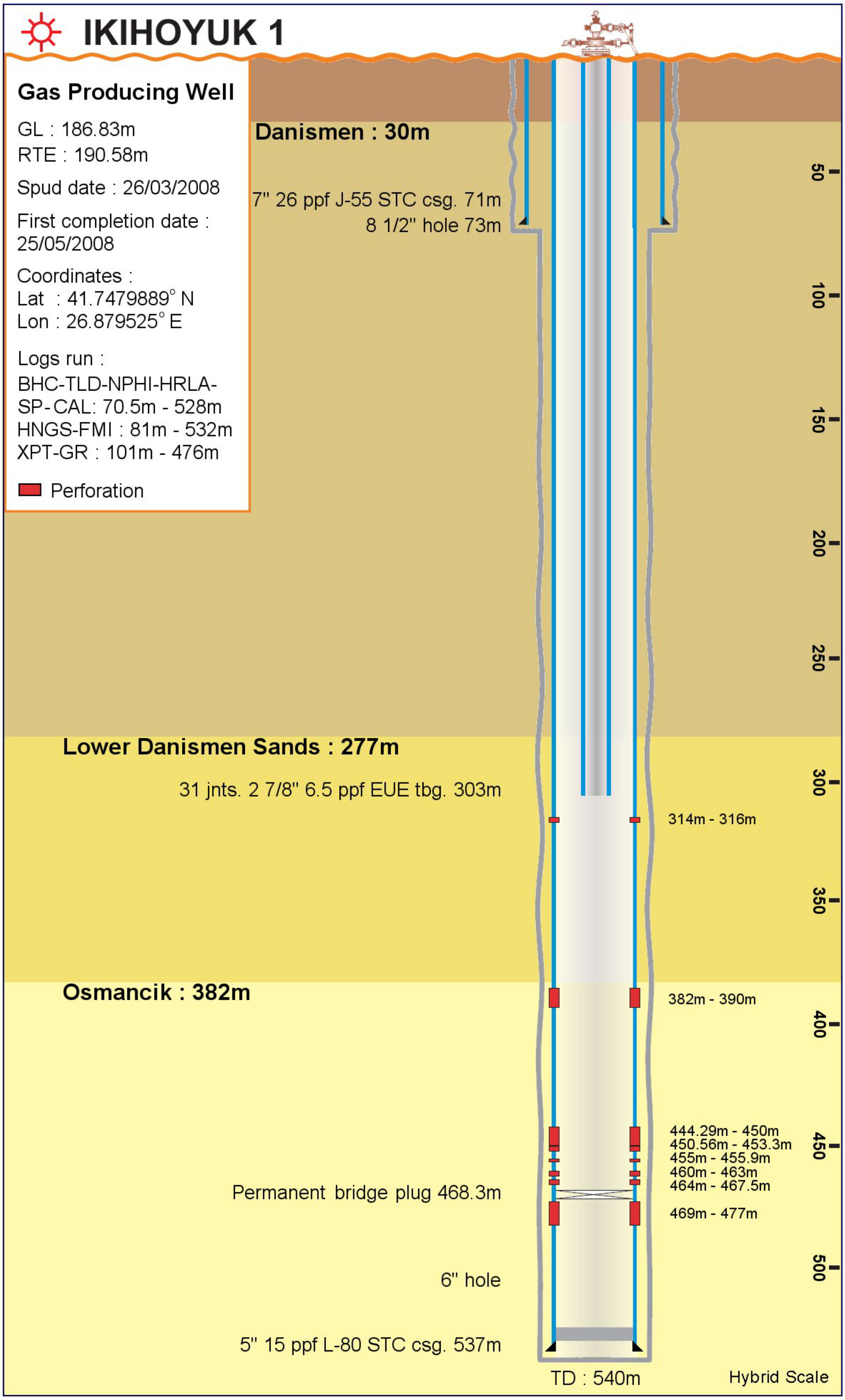

Figure 5.1 : İkihöyük-1 Well Drilling and Completion Configuration.

According to the drilling records and the well logs the Lower Danişmen sand and Osmancık formation were penetrated at the depths of 277 and 382 meters, respectively. During the drilling of İkihöyük-1 well gas shows were recorded and, later, confirmed with the results of wire-line logs. Based on the log analysis results the depth intervals of 314 to 316 meters in the Lower Danişmen formation and of 382 to 390 meters, 444.29 to 450 meters, 450.56 to 453.3 meters, 455 to 455.9 meters, 460 to 463 meters, 464 to 467.5 meters, and 469 to 477 meters in the Osmancık formation were selected as the gas productive zones and perforated. These perforated intervals within the LD-SAND1, O-SAND2, and O-SAND1 are also indicated in the parasequence correlation given in **Figure 3.5**.

At the beginning of perforation operations the brine completion fluid level was at the depth of 400 meters. First, an interval of 469 to 477 meters in Osmancık formation was perforated with underbalanced condition. A clean flow of water was observed and practically no gas flow was measured immediately after the perforation, due to the formation water entry and lack of gas rate into the wellbore. After a short time frame, the liquid (water) level raised to the depth of 292.29 meters, indicating the water entry into the wellbore, as detected by the static pressure survey in **Figure 5.2**.

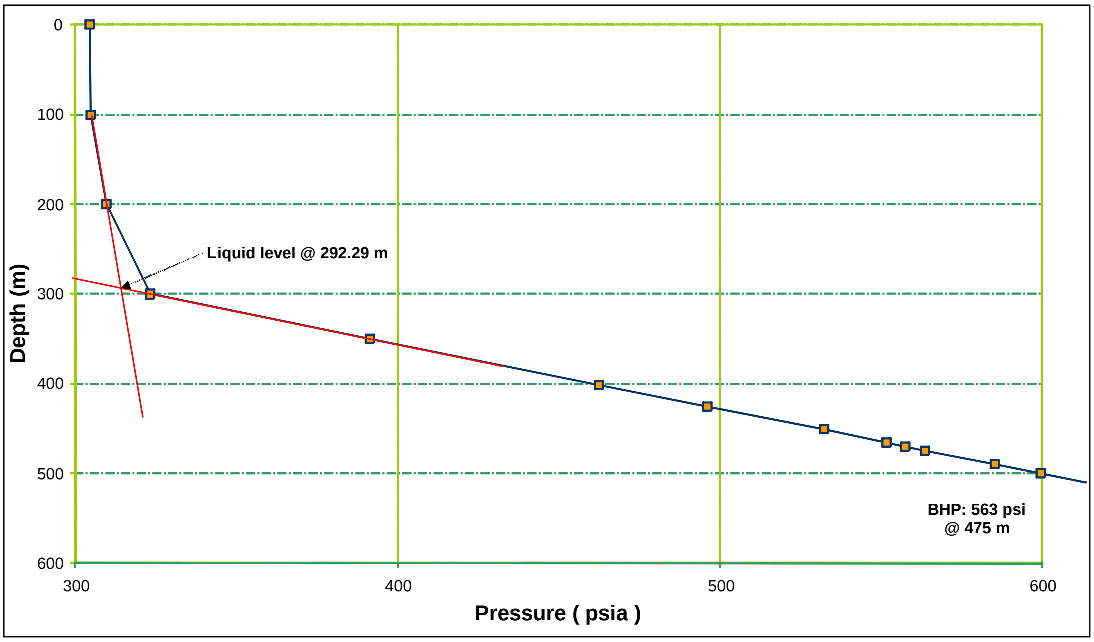

Figure 5.2 : The Graphical Presentation of the Results of Static Pressure Gradient Survey, Conducted After the First Perforation in İkihöyük-1 Well.

In order to selectively test the gas potential of the upper zones, a permenant bridge plug was set at the depth of 468.3 meters in the 5” wellbore, as seen in **Figure 5.1**, before proceeding with the perforation of the upper intervals.

Then, the intervals of 464 to 467.5 meters, 460 to 463 meters, 455 to 455.9 meters, 450.56 to 453.3 meters, and 444.29 to 450 meters in Osmancık formation were perforated, sequentially from the deepest to the shallowest and one interval at a time, all at underbalanced conditions. After each perforation job, the well was flowed for a short time to confirm clean gas flow. At the end, all of the perforated intervals were tested together and 1 MMscf/d initial gas rate at 20/64” choke was measured with 521 psia tubing head pressure, under untabilized flow condition. The perforated intervals in Osmancık formation are shown along with the open hole log records in **Figure 5.3**.

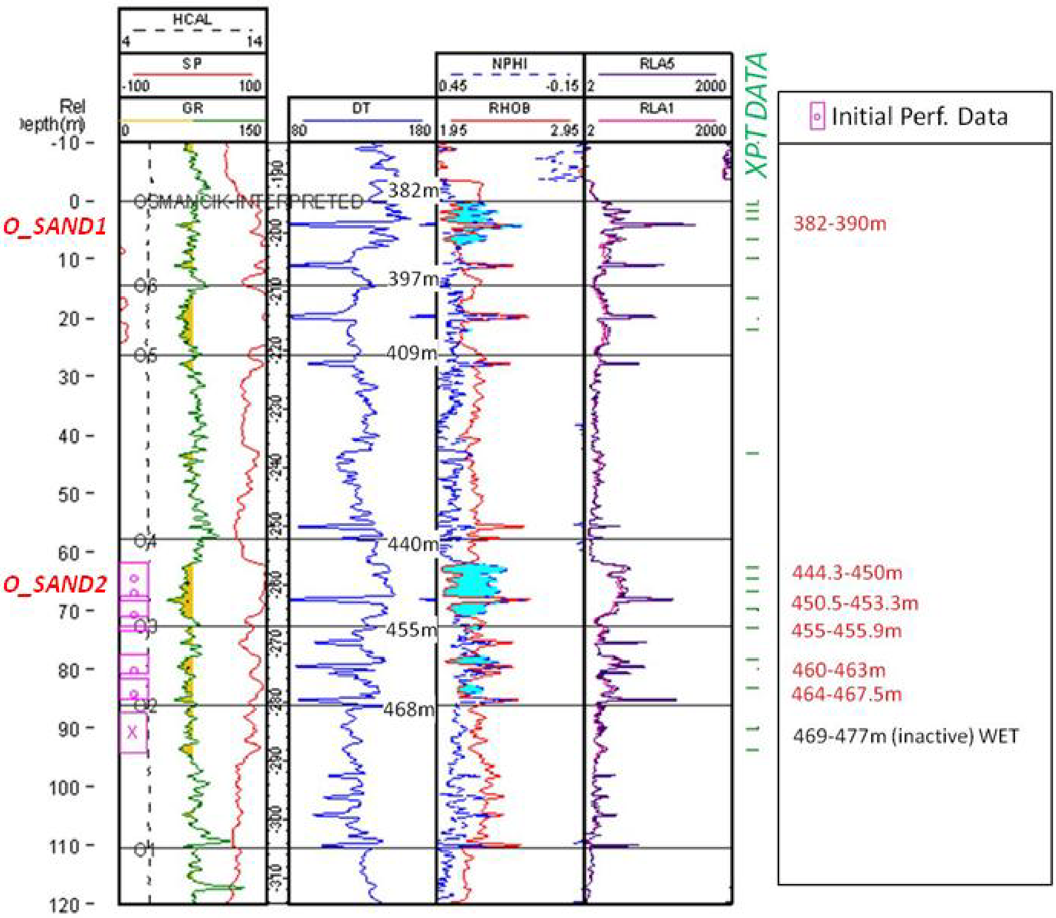

Figure 5.3 : The Perforation Intervals and Open Hole Log Records in Osmancık Formation in İkihöyuk-1 Well.

Note that during the course of this thesis work, the perforation of 314 to 316 meter interval in the Lower Danişmen formation was planned but not realized yet. Thus, no detailed information regarding that perforation is given here. Finally, it was decided to perform a flow-after-flow and a pressure build up test upon completing the perforation job. For this purpose the well was kept shut-in for 3 hours for the pressure equilibration in the reservoir. Eventually, the well was completed by installing a string of EUE (external-upset-end) production tubing with the nominal diameter of 2 7/8” and the unit weight of 6.5 lbs/ft down to the depth of 303 meters.

5.2. Drilling and Completion Summary for İkihöyük -2 Well

As seen in the drilling and completion configuration of İkihöyük-1 well in **Figure 5.4**, the well was drilled to a total depth of 500m. The ground level (GL) elevation was 187.7 meters and the rotary table elevation (RTE) was 191.45 meters from the MSL (mean sea level.) Initially, a three-cone bit with 8 ½” diameter was used to drill the first 116-meter section of the bore hole, which was cased with the J-55 STC casing with nominal diameter of 7” and the unit weight of 26 lbs/ft down to the depth of 114 meters. After installing the blowout preventer (BOP) stack the bore hole with 6 1/8” in diameter was drilled down to the depth of 500 meters and cased with L-80 STC production casing with nominal diameter of 5” and the unit weight of 15 lbs/ft down to the depth of 498 meters, and the well was suspended. The top of cement (TOC) was left at the depth of 484.3 meters and, then, it was drilled through and the float collar was milled out until the top of float shoe (TOF) at the depth of 499.5 m.

The 6 1/8” bore hole was logged with GR, CAL, BHC, HRLT, TLD, NPHI, HGNS, and SP from 114 to 500 meters; with GR and FMI also from 114 to 500 meters; and with XPT and GR from 396.4 to 475.5 meters of depth.

The drilling records and the well logs indicated that the Lower Danişmen sand and Osmancık formation were penetrated at 287 and 396 meters of depths, respectively. During the drilling of İkihöyük-2 well gas shows were recorded and, later, confirmed with the results of wire-line logs. Based on the log analysis results the depth intervals of 395.3 to 400.5 meters, 400.5 to 403 meters, 457.5 to 465.45 meters, 466 to 468.44 meters, 475.36 to 477.8 meters, and 479.3 to 481.43 meters in the Osmancık formation were selected as the gas productive zones and perforated. These perforated intervals within O-sand2 and O-sand1 are indicated in the parasequence correlation given in **Figure 3.5**.

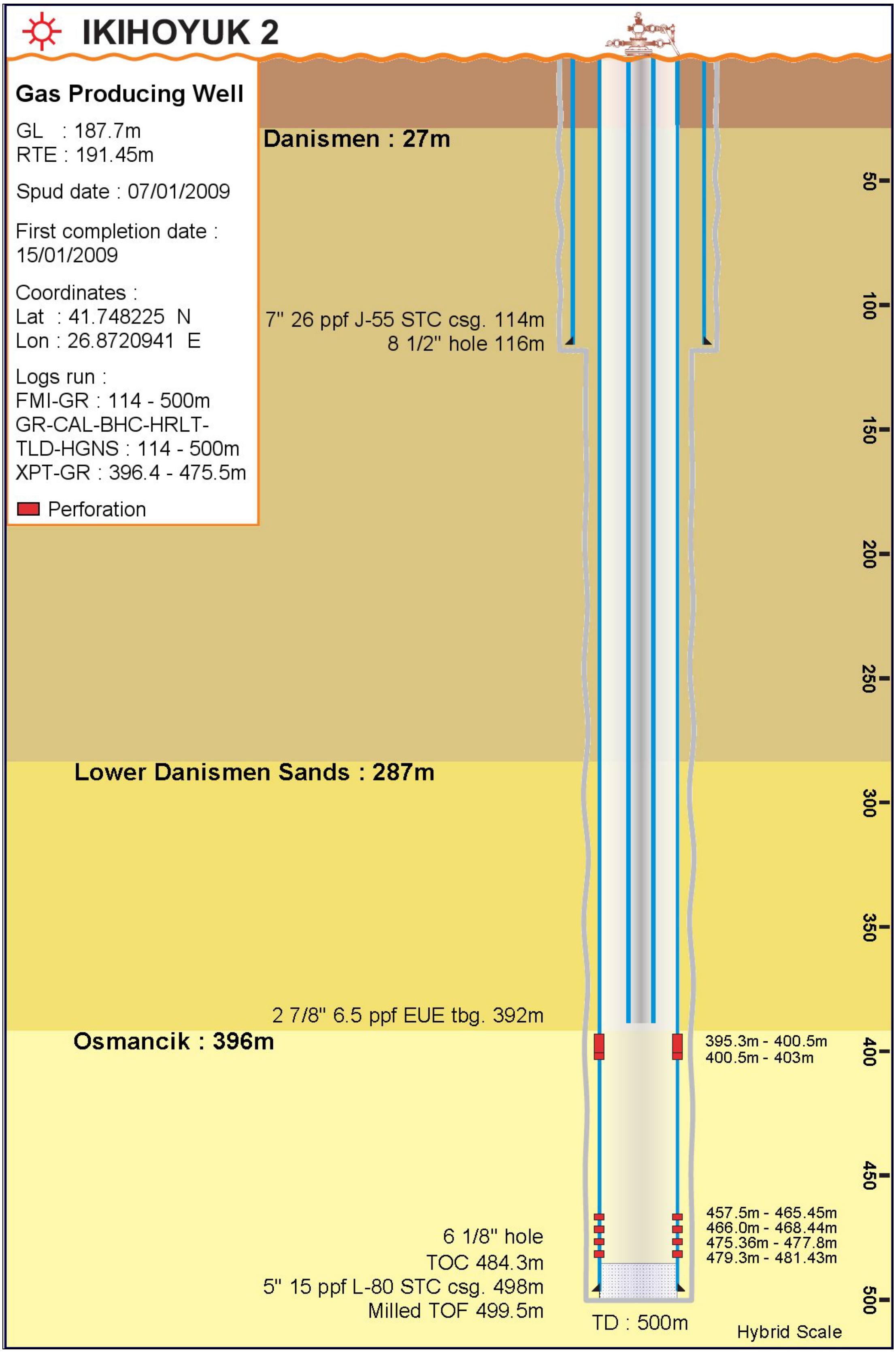

Figure 5.4 : İkihöyük-2 Well Drilling and Completion Configuration.

In İkihöyük-2 well, first, the interval of 479.3 to 481.43 meters in the Osmancık formation was perforated with underbalanced condition and tested water with some gas. The maximum pressure reached was 345 psia, after 443 minutes shut-in time. Next the intervals of 475.37 to 477.8 meters, 466 to 468.43 meters, and 457.5 to 465.45 meters in Osmancık formation were perforated, sequentially from the deepest to the shallowest and one interval at a time, all at underbalanced conditions. After the perforation of 475.37 to 477.8 meter and 457.5 to 465.45 meter intervals, the well was flowed for a short time to confirm the clean gas flow. In the mean time, it was decided to perforate the interval of 475.36 to 477.8 meters, also at underbalanced conditions with 21 psi wellhead pressure. After the clean-up flows all intervals were tested together on 48/64” choke and through the separator for 2 hours at the gas rate of 2.21 MM scf/d and the wellhead pressure of 207 psia. In 2 hours, 2.3 bbls of water was produced, corresponding to 12.49 bbls/MMscf water-gas ratio. The produced water had a chloride (Cl^{-}) content of 14,400 ppm, density of 8.4 ppg, and pH of 7.8.

As the brine completion fluid level was at the depth of 330 meters, a static pressure gradient survey was conducted, just before initiating the flow-after-flow test. As seen in **Figure 5.5**, no any additional liquid accumulation in the wellbore was observed.

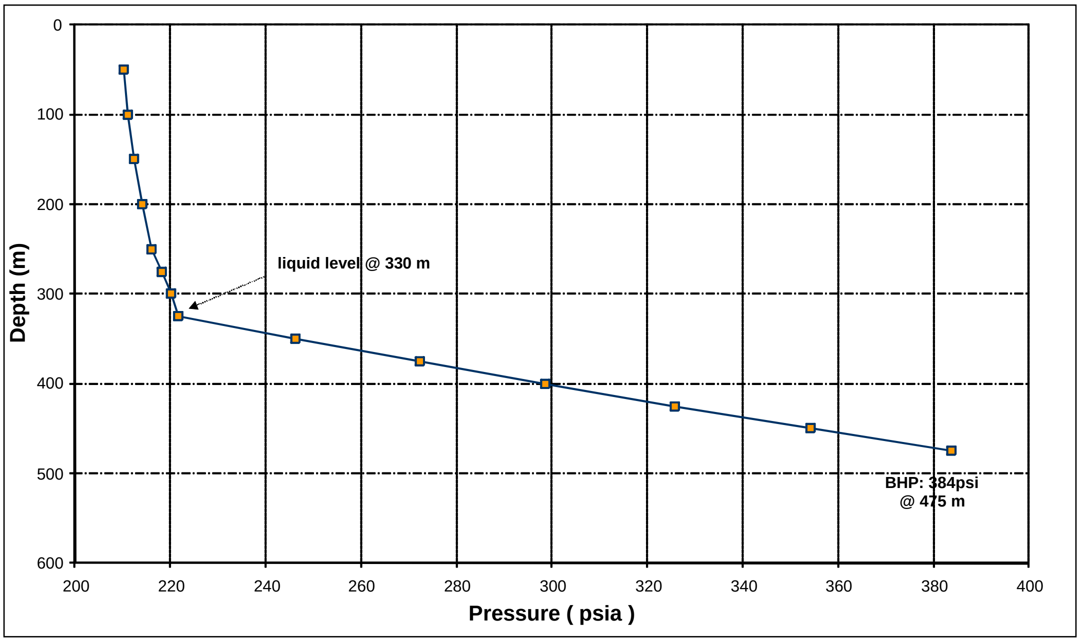

Figure 5.5 : The Graphical Presentation of the Results of Static Pressure Gradient Survey, Conducted After the First Perforation in İkihöyük-2 Well.

Eventually, the actual well tests were performed on all four intervals open together. The perforated intervals in Osmancık formation in İkihöyük-2 well are shown along with the open hole log records in **Figure 5.6**.

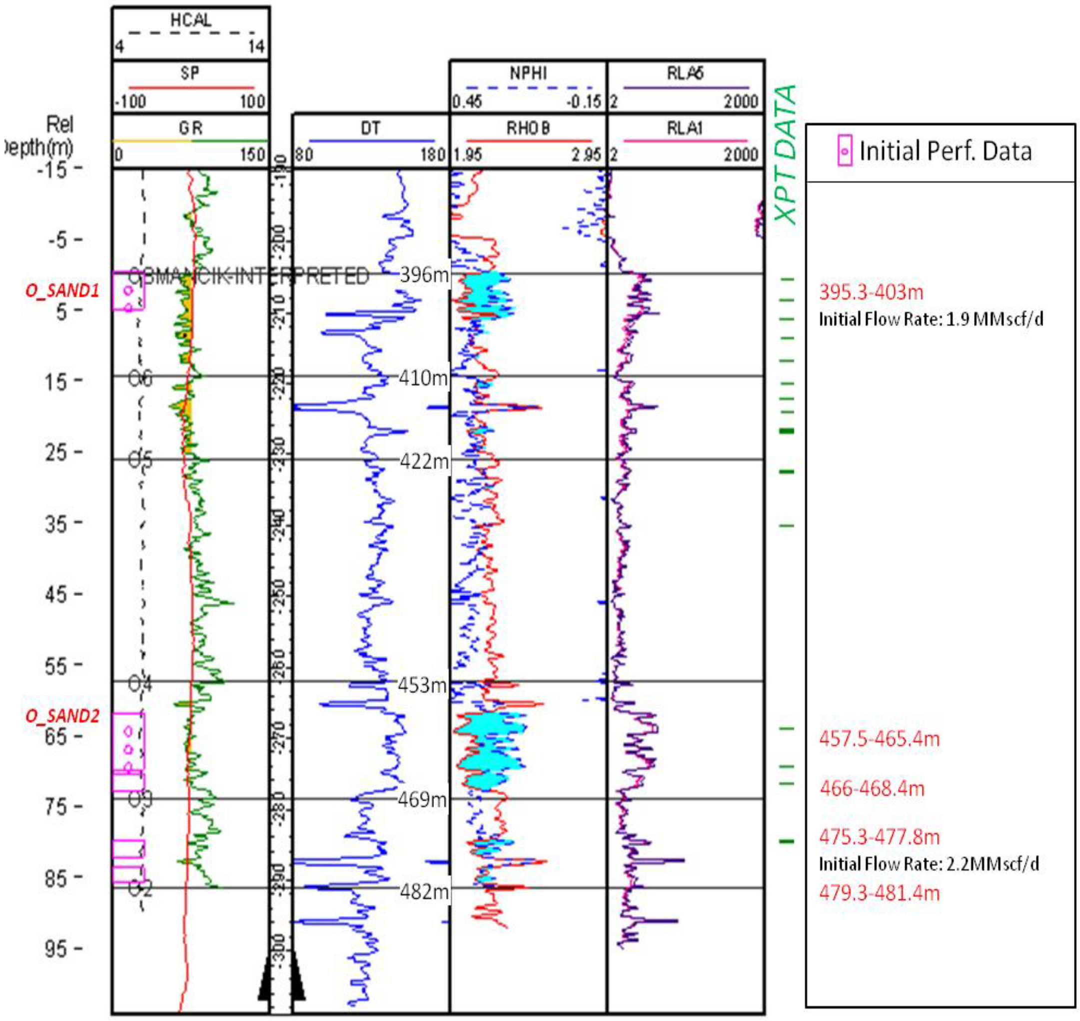

Figure 5.6 : The Perforation Intervals and Open Hole Log Records in Osmancık Formation in İkihöyuk-2 Well.

Note that during the course of this thesis work, the perforations at 400.5 to 403 meter and 395.3 to 400.5 meter intervals in the Osmancık formation were planned but not realized yet. Thus, no detailed information regarding that perforation is given here.

Eventually, the well was completed by installing a string of EUE (external-upset-end) production tubing with the nominal diameter of 2 7/8” and the unit weight of 6.5 lbs/ft down to the depth of 392 meters.

6. WIRELINE LOG INTERPRETATION

All open hole logs in İkihöyük-1 and İkihöyük-2 wells were recorded by wireline logging tools and were analyzed using Interactive Petrophysics Software (IP) package. As mentioned previously in the 5^{th} Section, entitled "Well Drilling and Completion Summary," of this study, the open hole logs recorded in İkihöyük-1 well were BHC, TLD, NPHI, HRLA, SP, and CAL from 70.5 to 528 meters; with HNGS and FMI from 81 to 532 meters; and with XPT and GR from 101 to 476 meters of depth. In the same section of this study it is reported that the open hole logs recorded in İkihöyük-2 well were GR, CAL, BHC, HRLT, TLD, NPHI, HGNS, and SP from 114 to 500 meters; with GR and FMI also from 114 to 500 meters; and with XPT and GR from 396.4 to 475.5 meters of depth.

Although the entire recorded logs were in good quality, the conventional gamma ray (GR) log is discovered to be a poor indicator of clays in the formations penetrated in İkihöyük wells. Since the difference in reading of sand and shale was very small, GR log did not directly help effective determination of clay volume (V_{clay}) in these wells. To overcome such drawback it is advised by this study the spectral GR tool be run in the wells drilled in the Northern part of Thrace Basin. Consequently, the V_{clay} content in Lower Danişmen and Osmancık intervals is determined by integrated use of SP, GR, Sonic, Neutron and Density Log responses.

6.1. Analyses of İkihöyük-1 Open Hole Logs

Overall, all recorded logs in İkihöyük-1 well were good in quality and showed that the bore hole was in good condition. Therefore, the logs allowed not only fair to good estimation of clay content, formation pressure, fluid mobility and saturations but also adequate identification of gas saturated intervals. The recorded log data and their analysis results in terms of water saturation, porosity, and lithology, are shown along with the perforated intervals in the composite log, presented in **Figure 6.1**, particularly for L. Danişmen and Osmancık formations.

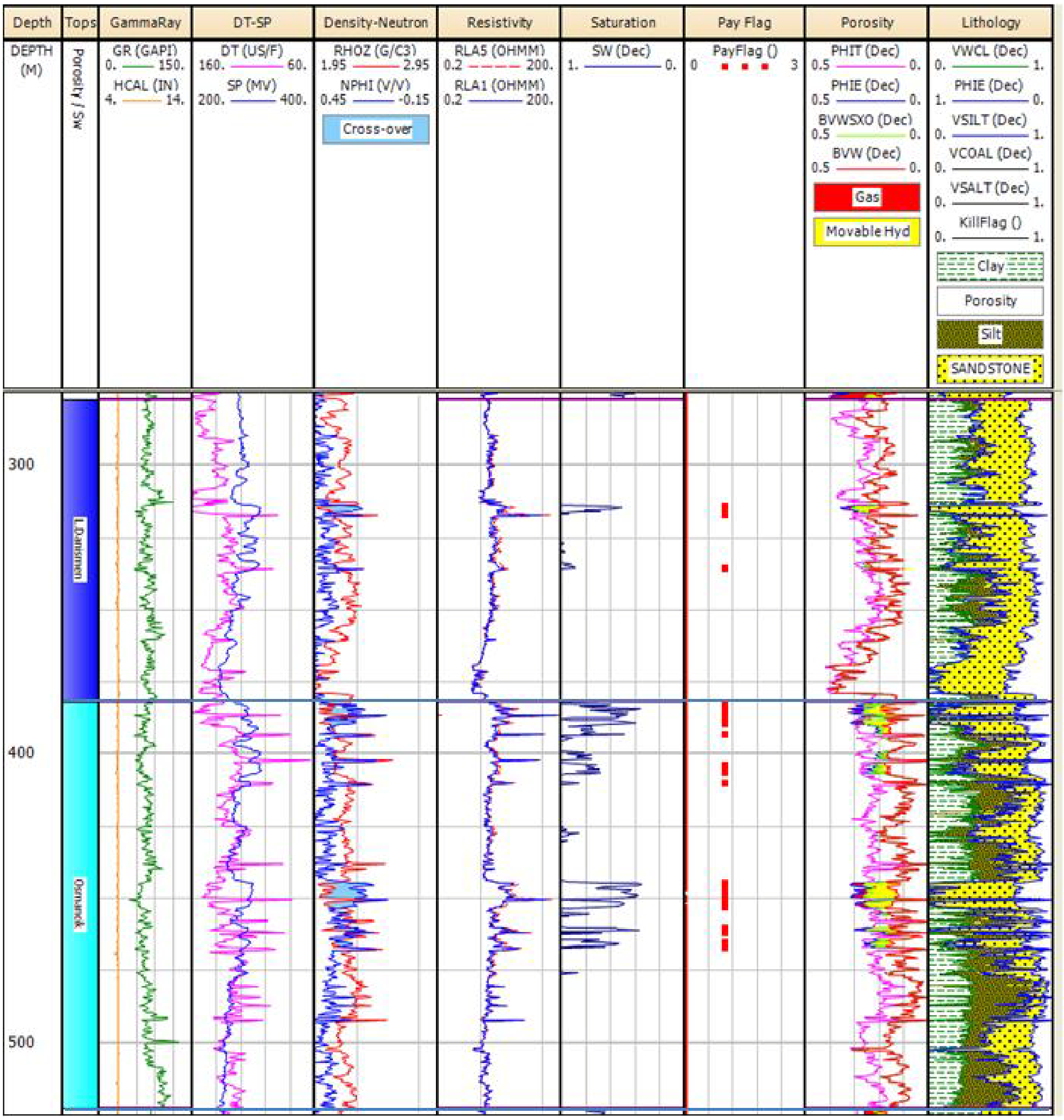

Figure 6.1 : The Raw Data and Analysis of Open Hole Logs for İkihöyük-1 well.

In **Figure 6.1**, the lithology track indicates the mineral volumes in the sequential order of clay, silt, and sandstone. The width of the track represents the total (bulk) volume of the formation. The white area between the right edge of the track and the last mineral curve, which is for sandstone, indicates the magnitude of porosity.

Archie's saturation equation, as given in Eqn.6.1, is used in conjunction with the Density Porosity Model to estimate the water saturation at each depth.

$$S_w = \left(\frac{a\, R_w}{R_t\, \phi^m} \right)^{\frac{1}{n}} \qquad (6.1)$$

Eqn.6.1 the tortuosity factor of a = 1.65 and the cementation exponent of m = 1.33 are used as characteristic values for the shaly sands of both Lower Danişmen and Osmancık sequences (Asquith, 1980). Based on this analysis the variation of water saturation with depth is plotted by a solid line in dark blue color in the “Saturation” track in **Figure 6.1**. Note that the low water saturation zones correspond to the Density-Neutron logs cross-over areas in blue color in the “Density-Neutron” track and indicate the gas saturated zones.

Porosity track also shows the effective and total porosity with bulk water volume, BVW, Sxo bulk volume, BVSXO. The separation between BVW and BVSXO indicates the movable hydrocarbon and that between the effective porosity (PHIE) line and BVSXO shows the gas containing zone.

SP curve and 0.254 ohm-m at 13°C of Rmf value were used for the water resistivity (Rw) calculation. **Figure 6.2** illustrates the results of Rw determination using Pickett plot analysis. The red line in **Figure 6.2** indicates the 100 % water saturated zone and the blue lines from left to right shows 50 %, 30 %, and 20 % water saturation. Rw values were determined as 0.329 ohm-m. The formation water salinity was measured to be 15000 ppm for this interpretation.

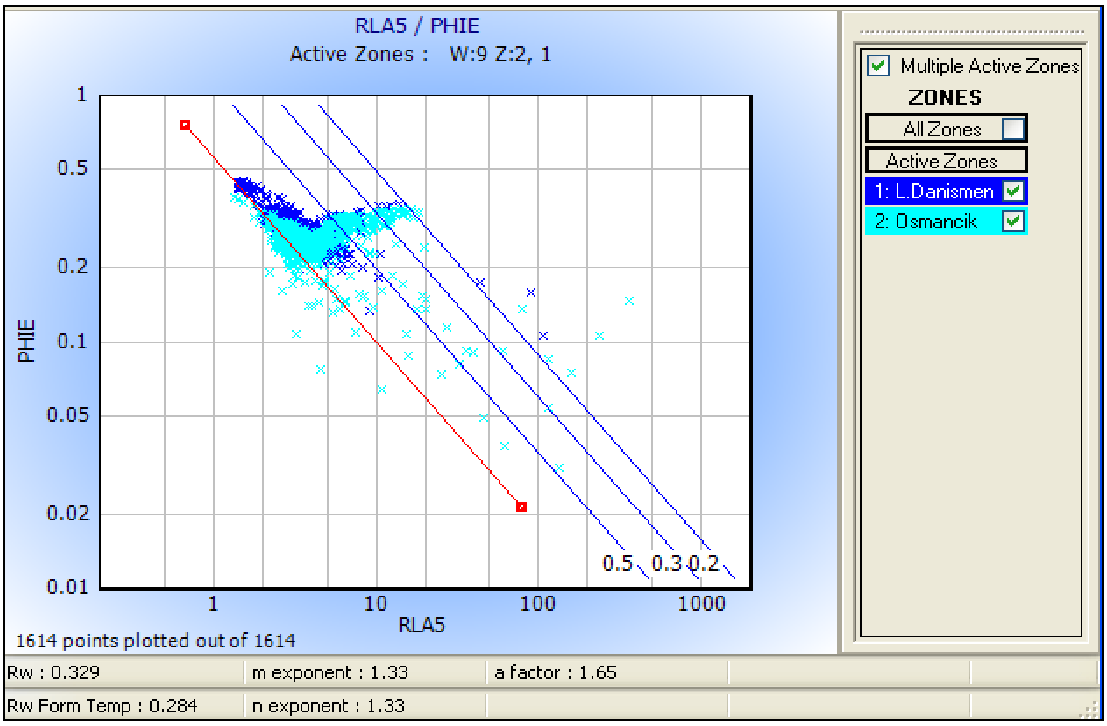

Figure 6.2 : The Pickett Plot Analysis for the Logs of İkihöyük-1 well.

Deep resistivity, RLA5, and shallow resistivity, RLA1, logs shown in Resistivity track also read higher resistivity values in these potential zones and have more separation between deep and shallow resistivity. The separation between deep and shallow resistivity indicates higher permeable interval.

DT (sonic) log measures the interval transit time and depend on both lithology and porosity. The interval transit time of a formation is increased due to the presence of hydrocarbons as seen in DT log response in **Figure 6.1**.

Finally, good amount of gas containing intervals, which exhibit an average porosity of 30 percent and an average water-saturation of 41 percent, have been identified and shown in the Pay Flag track in **Figure 6.1** and **Table 6.1**. These zones are located at the depth intervals of 314 to 317 meters in Lower Danişmen, and of 383 to 390 meters, 444 to 453 meters, 460 to 463 meters, and 465 to 467 meters in Osmancık successions.

6.2. Analyses of İkihöyük-2 Open Hole Logs

Also in İkihöyük-2 well all recorded logs in were good in quality and showed good bore hole condition. Therefore, the logs allowed fair to good estimation of clay content, formation pressure, fluid mobility and saturations. Adequate identification of gas saturated intervals was also determined. The recorded log data and their analysis results in terms of water saturation, porosity, and lithology, are shown along with the perforated intervals in the composite log, presented in **Figure 6.3**, for Lower Danişmen and Osmancık formations.

In **Figure 6.3**, the lithology track indicates the mineral volumes in the sequential order of clay, silt, and sandstone. The width of the track represents the total (bulk) volume of the formation. The white area between the right edge of the track and the last mineral curve, which is for sandstone, indicates the magnitude of porosity.

In analyzing the İkihöyük-2 logs, again, Archie's saturation equation in Eqn.6.1 is used in conjunction with the Density Porosity Model to estimate the water saturation at each depth. The same values of tortuosity factor of a = 1.65 and the cementation exponent of m = 1.33 are used as characteristic values for the shaly sands of both Lower Danişmen and Osmancık sequences (Asquith, 1980).

Reservoir Summary

Zn #	Zone Name	Top	Bottom	Gross	Net	N/G	Av Phi	Av Sw	Av Vcl Ari	Phi*H	PhiSo*H
1	L.Danismen	277.00	380.00	103.00	87.33	0.848	0.207	0.948	0.219	18.05	0.95
2	Osmancik	380.00	523.00	143.00	116.47	0.814	0.191	0.822	0.212	22.22	3.95
	All Zones	**277.00**	**523.00**	**246.00**	**203.80**	**0.828**	**0.198**	**0.878**	**0.215**	**40.28**	**4.90**

Pay Summary

Zn #	Zone Name	Top	Bottom	Gross	Net	N/G	Av Phi	Av Sw	Av Vcl Ari	Phi*H	PhiSo*H
1	L.Danismen	277.00	380.00	103.00	2.74	0.027	0.312	0.401	0.000	0.86	0.51
2	Osmancik	380.00	523.00	143.00	16.76	0.117	0.298	0.408	0.007	4.99	2.95
	All Zones	**277.00**	**523.00**	**246.00**	**19.51**	**0.079**	**0.300**	**0.407**	**0.006**	**5.85**	**3.47**

Cutoffs Used

Zn #	Zone Name	Top	Bottom	Min. Height	Phi PHIE	Sw SW	Vcl VWCL
	Reservoir						
1	L.Danismen	277.00	380.00	0	>= 0.1		<= 0.5
2	Osmancik	380.00	523.00	0	>= 0.1		<= 0.5
	Pay						
1	L.Danismen	277.00	380.00	0	>= 0.1	<= 0.6	<= 0.5
2	Osmancik	380.00	523.00	0	>= 0.1	<= 0.6	<= 0.5

Depth Units : m

Table 6.1: The Summary of Reservoir Results for İkihöyük-1 well.

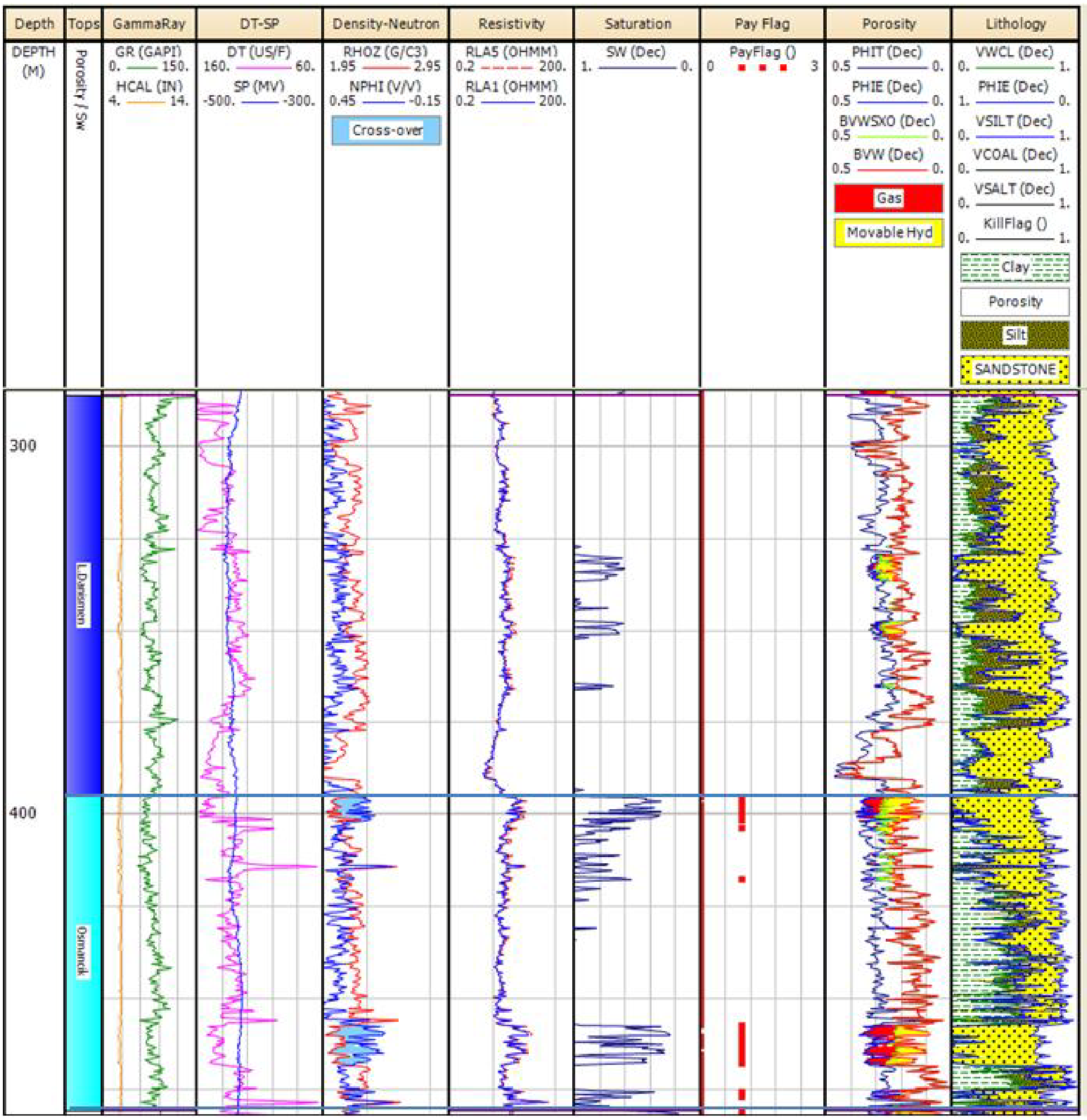

Figure 6.3: The Raw Data and Analysis of Open Hole Logs for İkihöyük-2 well.

Based on this analysis the variation of water saturation with depth is plotted by a solid line in dark blue color in the “Saturation” track in **Figure 6.3**. As in the case of İkihöyük-1 well, here the low water saturation zones correspond to the Density-Neutron logs cross-over areas in blue color in the “Density-Neutron” track and indicate the gas saturated zones.

Porosity track also shows the effective and total porosity with bulk water volume, BVW, Sxo bulk volume, BVSXO. The separation between BVW and BVSXO indicates the movable hydrocarbon and that between the effective porosity (PHIE) line and BVSXO shows the gas containing zone.

SP curve and 0.254 ohm-m at 13°C of Rmf value were used for the water resistivity (Rw) calculation. **Figure 6.4** illustrates the results of Rw determination using Pickett plot analysis. The red line in **Figure 6.4** indicates the 100 % water saturated zone and the blue lines from left to right shows 50 %, 30 %, and 20 % water saturation. Rw values were determined as 0. 472 ohm-m. The formation water salinity was measured to be 12000 ppm for this interpretation.

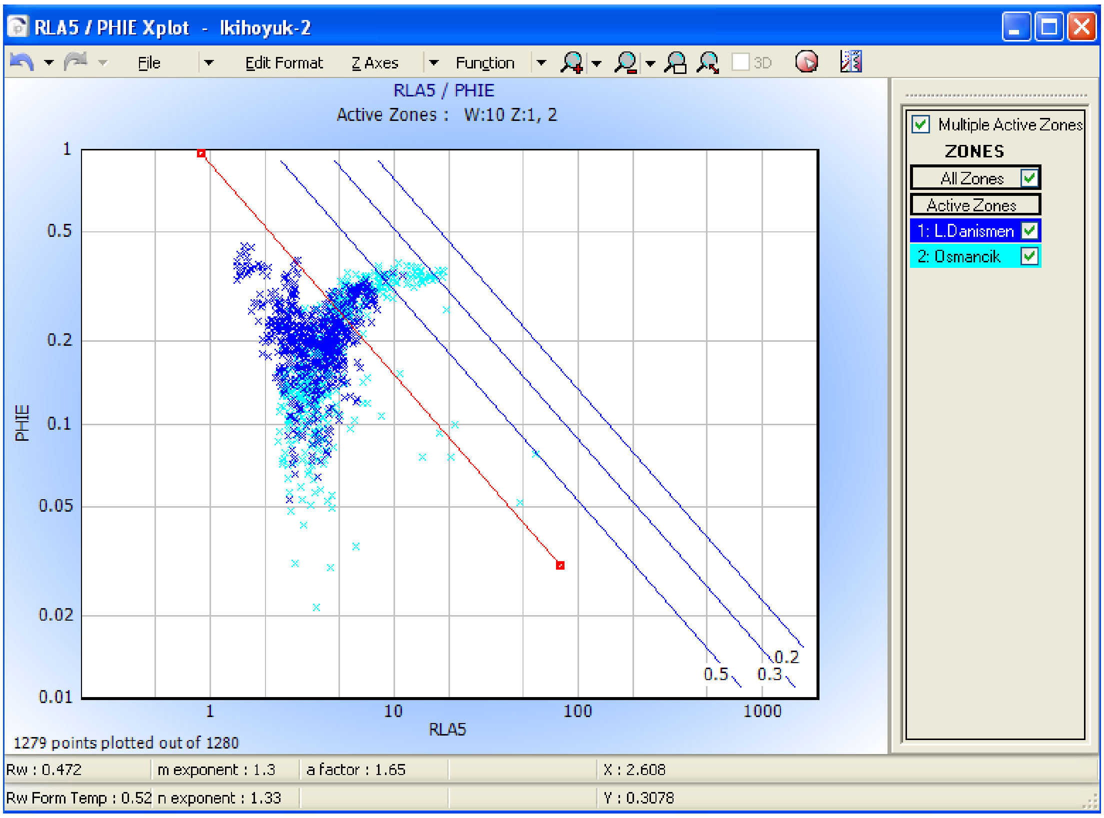

Figure 6.4: The Pickett Plot Analysis for the Logs of İkihöyük-2 well.

As in the case of İkihöyük-1 well, deep resistivity, RLA5, and shallow resistivity, RLA1, logs shown in Resistivity track read higher resistivity values in potential gas zones and indicate higher permeability interval by exhibiting larger separation. The increase in interval transit time of DT (sonic) log is due to the presence of hydrocarbon gas, as seen in DT log response in **Figure 6.3**.

Finally, good amount of gas containing intervals, which exhibit an average porosity of 33 percent and an average water-saturation of 42 percent, have been identified and shown in the Pay Flag track in **Figure 6.3** and **Table 6.2**. These zones are located at the depth intervals of 394 to 404 meters, 457 to 468 meters, and 475 to 478 meters in Osmancık formation.

Reservoir Summary

Zn #	Zone Name	Top	Bottom	Gross	Net	N/G	Av Phi	Av Sw	Av Vcl Ari	Phi*H	PhiSo*H
1	L.Danismen	286.00	396.00	110.00	105.58	0.960	0.220	0.955	0.151	23.25	1.04
2	Osmancik	396.00	481.00	85.00	72.20	0.849	0.227	0.775	0.222	16.36	3.68
	All Zones	**286.00**	**481.00**	**195.00**	**177.78**	**0.912**	**0.223**	**0.881**	**0.180**	**39.61**	**4.72**

Pay Summary

Zn #	Zone Name	Top	Bottom	Gross	Net	N/G	Av Phi	Av Sw	Av Vcl Ari	Phi*H	PhiSo*H
1	L.Danismen	286.00	396.00	110.00	0.60	0.005	0.346	0.441	0.000	0.21	0.12
2	Osmancik	396.00	481.00	85.00	14.64	0.172	0.337	0.425	0.002	4.93	2.83
	All Zones	**286.00**	**481.00**	**195.00**	**15.24**	**0.078**	**0.337**	**0.426**	**0.002**	**5.13**	**2.95**

Cutoffs Used

Zn #	Zone Name	Top	Bottom	Min. Height	Phi PHIE	Sw SW	Vcl VWCL
	Reservoir						
1	L.Danismen	286.00	396.00	0	>= 0.1		<= 0.5
2	Osmancik	396.00	481.00	0	>= 0.1		<= 0.5
	Pay						
1	L.Danismen	286.00	396.00	0	>= 0.1	<= 0.6	<= 0.5
2	Osmancik	396.00	481.00	0	>= 0.1	<= 0.6	<= 0.5

Depth Units : m

Table 6.2: The Summary of Reservoir Results for İkihöyük-2 well.

7. WELL TESTS AND INTERPRETATIONS

Upon the confirmation of gas producing potential at perforated zones in İkihöyük reservoirs, a flow-after-flow type gas deliverability test and a pressure buildup test were conducted in both İkihöyük-1 and İkihöyük-2 wells. It should be noted that a static pressure and temperature survey was conducted after the flow-after-flow tests. The measured data sets and the results of various analyses of the tests are presented below for both wells of İkihöyük-1 and İkihöyük-2.

7.1. The Deliverability Test and Static Gradient Survey in İkihöyük-1 Well

Initially a gas deliverability test in the form of the flow-after-flow test was conducted in İkihöyük-1 well to start at 13:00 hours on 23.05.2008 and end at 06:59 hours on 26.05.2008. The test was consisted of eight consecutive periods, of which three were shut-in and the rest were flow periods. The gathered data is presented in **Table 7.1** and the recorded pressures and flow rates are plotted against the elapsed time in **Figure 7.1**.

During the flow periods of the test the well was flowed about 3 hours on four different-size chokes, which were 26/64”, 24/64”, 28/64”, 32/64”, for the extended period of 6 hours on 32/64” choke, sequentially. At the end of the flow periods the well was shut in for 42 hours for the observation of pressure build-up. Entire pressure and temperature data were recorded using the digital gauge for detailed and accurate interpretation of the test results.

As seen in **Table 7.1**, the bottom-hole temperature was constant at 99°F, indicating no Joule-Thomson (cooling) effect occurred during the flow from the reservoir into the wellbore. On the other hand, the tubing head temperature initially increased from the static 67°F to 83°F, possibly due to the depletion of stored warm gas in the wellbore, and then decreased steadily with increasing choke size and flow rate, probably due to the gas expansion with flow up through the wellbore. The overall temperature behavior indicated a successful test with no significant problems.

Table 7.1: The Summary of Flow-After-Flow Test for İkihöyük-1 Well.

Duration (hours)	Choke Size (inches)	Tubing Head Pressure (psia)	Tubing Head Temp. (°F)	Bottom Hole Pressure (psia)	Bottom Hole Temp. (°F)	Static Pressure (psia)	Static Temp. (°F)	Diff. Pressure (in of water)	Ambient Temp. (°F)	Gas Rate	
										Scf/d	Scm/d
3.03	-	576	67	592	99	Shut-in					
2.99	26/64	550	83	568	99	69	83	121	75	1,502,360	42,542
2.99	-	577	67	592	99	Shut-in					
3.01	24/64	555	62	571	99	111	71	49	58	1,143,154	32,371
2.99	28/64	526	61	549	99	133	88	159	57	2,198,828	62,264
2.99	32/64	506	61	537	99	133	83	71	63	2,730,841	77,329
6.00	38/64	471	79	509	99	149	73	115	79	3,800,041	107,605
42.00	-	568	62	582	99	Shut-in					

Initial shut-in bottom hole pressure : 592.01 psia	Initial shut-in well head tubing pressure : 578 psia (not stabilized)
Final shut-in bottom hole pressure : 582.052 psia	Final shut-in well head tubing pressure : 568 psia

Produced fluid during test	Reservoir Temperature is 99°F at 457 m
Gas : 1,891,040 scf	Specific gravity of gas was assumed 0.5592 for flow calc.
Condensate : 0 bbl	Orifice base factor is 460.79 @ 26-24-28/64 chokes
Water : 0 bbl	Orifice base factor is 842.12 @ 32-38/64 chokes

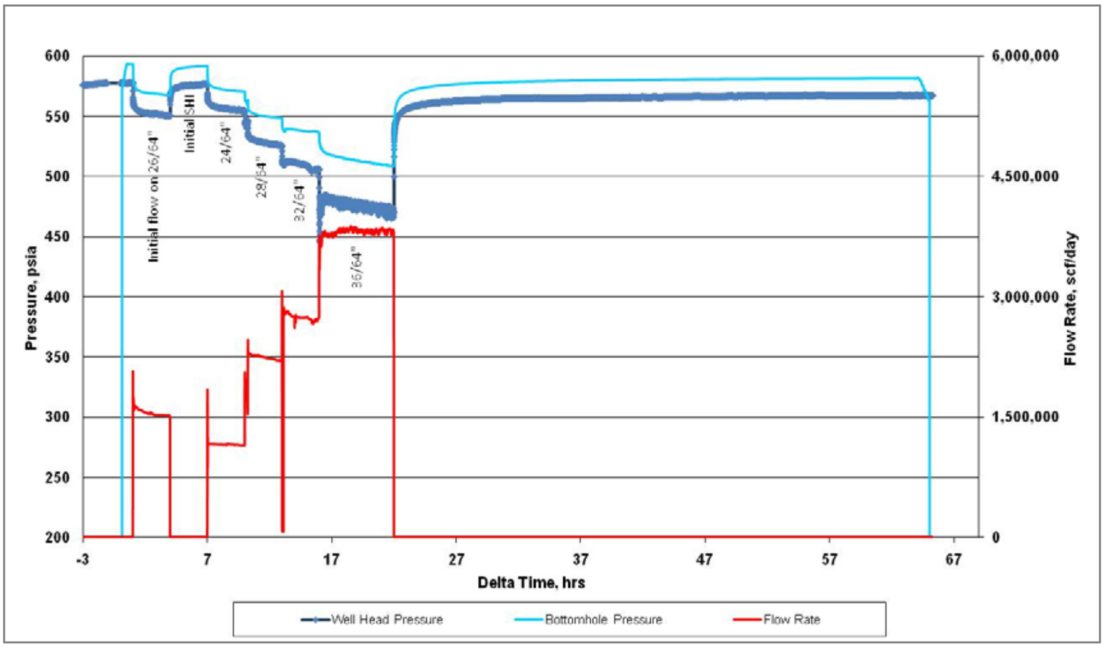

Figure 7.1: The Measured Pressure and Flow Rate Data Against the Time Elapsed During the Flow-After-Flow Test in İkihöyük-1 Well.

Both bottom hole and tubing head pressures followed a similar trend during the test and decreased steadily with increasing choke size and flow rate. However, neither of those pressures reached their initial levels and stayed constant at about 10 psi below the initial pressure, after the final shut-in period following the extended flow period. Such behavior may be reflection of the achievement of pseudo-steady state flow regime and, therefore, can be attributed to either the reservoir being rather small or the existence of flow barriers around the drainage volume of the well. During the flow periods no liquid was produced or accumulation was detected in the wellbore.

Gas Composition Analysis

Six gas samples were taken from the surface heater/seperator during the flow-after-flow test. The produced gas was dry and mainly methane and a gas composition analysis was conducted on 4 representative gas samples, during the flow through the 38/64" choke. The produced gas is found to be composed of 97.71 percent Methane (CH_4), 0.07 percent Ethane (C_2H_6), 0.03 percent carbon dioxide (CO_2) and 2.19 percent nitrogen (N_2). The specific gravity and compressibility factor, z, of the gas mixture were measured to be 0.5645 and 0.9981, respectively, at standard conditions. Note that the pressure in the sample bomb was 200 psia initially and was 60 psia at the end of the test.

Static Pressure and Temperature Gradient Survey

After the flow-after-flow test a static pressure and temperature gradient survey was conducted. The results of this survey are tabulated in **Table 7.2** and plotted in **Figures 7.2** and **7.3**. As seen in **Table 7.2**, the pressure and temperature gradients are found to be 0.032 psia/m and 0.011°F/m, respectively.

Table 7.2: Static Pressure and Temperature Gradient Survey Conducted to Follow the Flow-After-Flow Test in İkihöyük-1 Well.

Time	Measured	Depth*	TVD*	Pressure	Temperature	Pressure Gradient	Temperature Gradient
(hours)		(m)	(m)	(psia)	(°F)	(psia/m)	(°F/m)
64.23	Static	457.00	457.00	582.064	99.479		
64.33	Static	465.02	465.02	582.319	99.566	0.032	0.011
64.41	Static	450.87	450.87	581.896	99.513	0.03	0.004
64.53	Static	399.95	399.95	579.962	97.865	0.038	0.032
64.69	Static	300.01	300.01	576.018	92.111	0.039	0.058
64.86	Static	199.97	199.97	572.041	84.055	0.04	0.081
65.02	Static	99.95	99.95	568.0	75.926	0.04	0.081
65.20	Static	0.00	0.00	563.967	68.284	0.04	0.076
		465.02	**465.02**	**582.319**	**99.566**	**0.032**	**0.011**

* measured from KB (Kelly Bushing.)

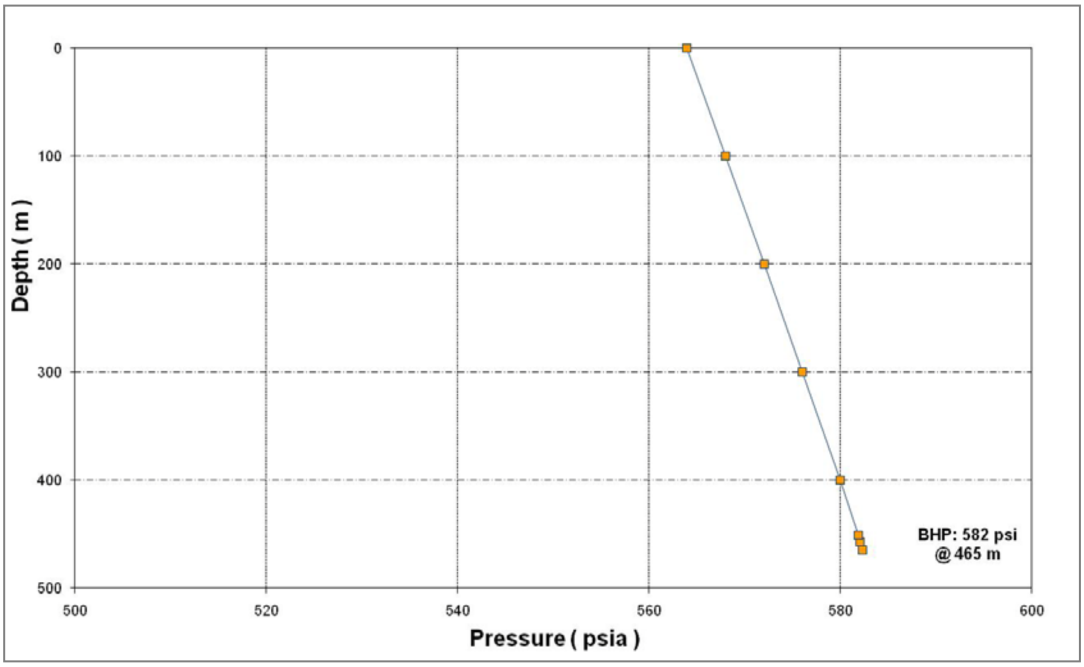

Figure 7.2: The Results of Static Pressure Gradient Survey in Well İkihöyük-1.

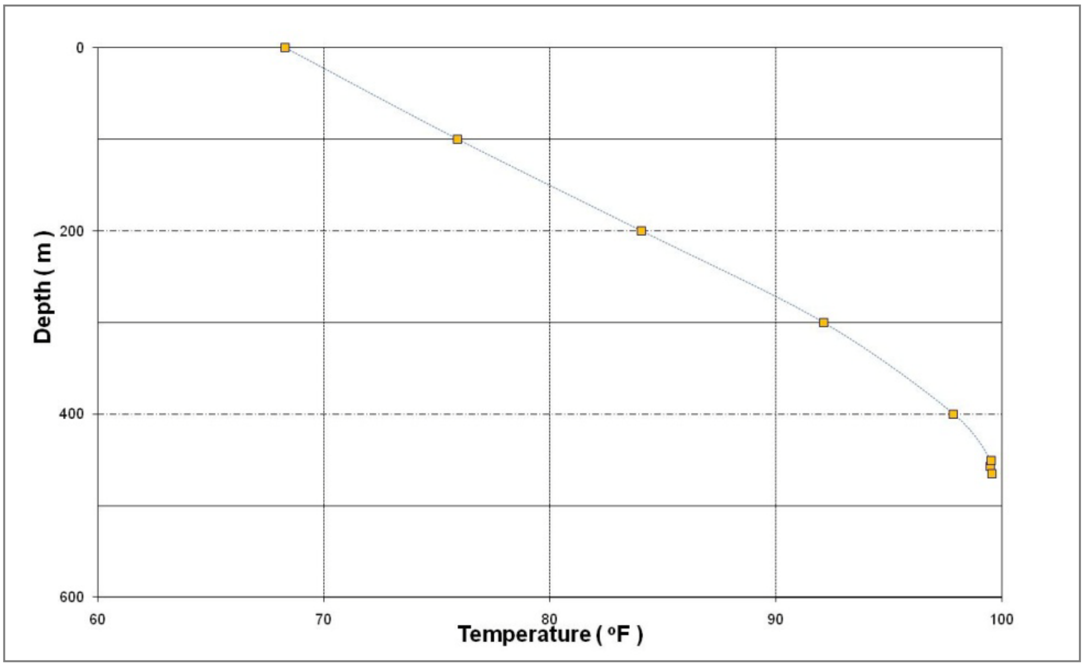

Figure 7.3: The Results of Static Temperature Gradient Survey in Well İkihöyük-1.

Deliverability (Flow-After-Flow) Test Analysis

In analyzing the deliverability (flow-after-flow) test, conducted in Well İkihöyük-1, the conventional Rawlins and Schellhardt equation, given as below, is used.

$$q_{sc} = C\left(P_e^2 - P_{wf}^2\right)^n \quad \text{.......} \quad (7.1)$$

where;

q_{sc} : flow rate at standard conditions, MM scf/d

P_e : stabilized reservoir pressure obtained from shut-in, psia

P_{wf} : bottom hole (sand face) flowing pressure, psia

C : coefficient that describes the position of the stabilized deliverability line,

n : exponent describing the inverse of the stabilized deliverability line (varies from 0.5 for turbulent flow to 1 for laminar flow)

In the application of this method, the difference between square of reservoir pressure and square of bottom-hole pressure are plotted against the corresponding flow rate, both on logarithmic scales, as seen in **Figure 7.4**. Then, the parameters of "C" and "n" characterizing well productivity are calculated as C = 0.007745 and n = 0.535 from this plot. Hence, the Rawlins and Schellhardt equation for the well became,

$$q_{sc} = 0.007745\left(P_e^2 - P_{wf}^2\right)^{0.535} \quad \text{.......} \quad (7.2)$$

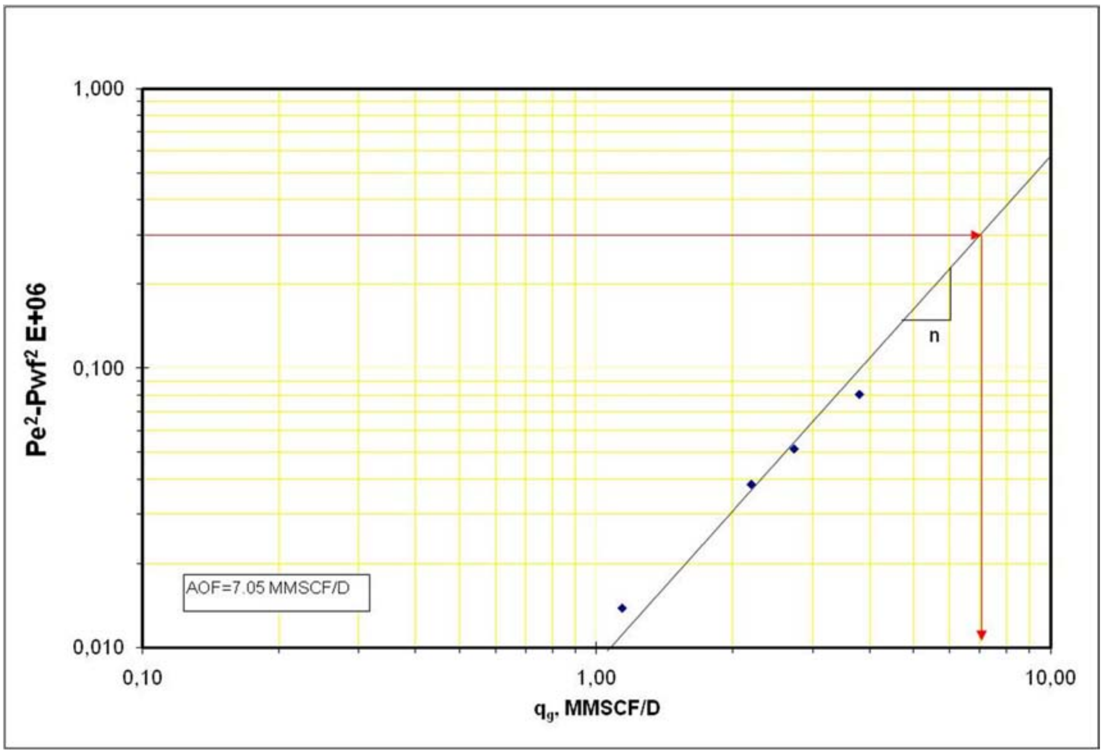

Figure 7.4: The Rawlins and Schellhardt Plot for the Analysis of Deliverability (Flow-After-Flow) Test Conducted in Well İkihöyük-1.

Once the parameters of "C" and "n" are obtained, the absolute open flow (AOF) potential of İkihöyük-1 well is calculated to be AOF = 7.05 MMscf/day (or 199,660 m^3/day) by assigning zero to the bottom hole (sand face) flowing pressure. Note that AOF is a hypothetical maximum flow rate and the well cannot produce at this flow rate in reality.

7.2. The Pressure Build-Up Test İkihöyük-1 Well

The analysis of the pressure build-up test in İkihöyük-1 well was performed using the PTA software by Ryder Scott Engineering. Both the type curve matching and the Horner plot and methods were employed in analyzing the data. Before the type-curve-matching analysis, a diagnostic analysis is performed.

Diagnostic Analysis

The diagnostic plot analysis helps to determine the wellbore storage coefficient for the well, the type of flow regime and permeability in the drainage volume of the well. In diagnostic analysis the pseudo pressure and the derivative of pseudo pressure are plotted against the time elapsed during the test, as shown in **Figure 7.5**. The wellbore storage coefficient is determined to be C = 0.9996 bbls/psi. The radius of investigation (or the radius drainage area) is estimated to be 226 meters (743 ft), in where the flow regime is found to be radial with the permeability of k = 51.21 md. The transmissivity of the reservoir is, then, calculated as kh = 2662.85 md-ft.

Type Curve Matching

The type-curve-matching has become the core method in the modern pressure transient test analysis. In type-curve matching a theoretical curve reflecting various flow regimes is matched to the field measured test data. Type curve matching is used to identify the various flow regimes that exist during a transient test and calculate the reservoir properties from the measured test data. The advantage of type curve matching, using the pressure and pressure derivative, is to identify the flow regimes encountered during a test of the reservoir and, accordingly, to predict the reservoir performance under various producing strategies. The type-curve-matching technique also yields quantitative information about the formation and well properties.

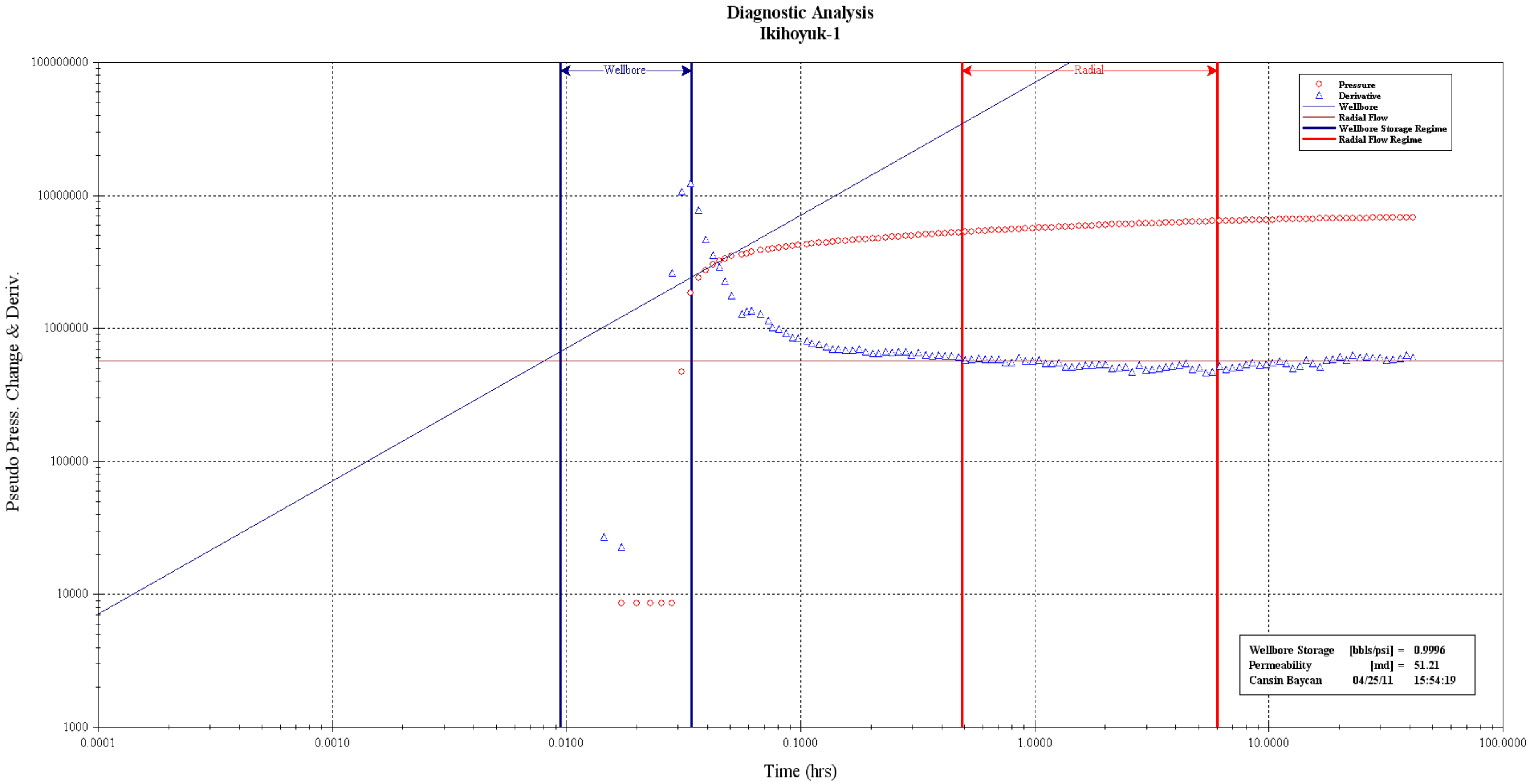

Figure 7.5: Diagnostic Plot Analysis of Pressure Build-Up Test in Well İkihöyük-1.

The graphical presentation of the automatic type-curve-matching, performed on the PTA software, is illustrated in **Figure 7.6**. In this analysis the dimensionless pressure and its derivative are plotted against the ratio of dimensionless time to dimensionless wellbore storage coefficient. For the initial reservoir pressure of P_i = 583.5 psia, the type-curve-matching analysis yielded the wellbore storage coefficient to be C = 0.38 bbls/psi and the radius of investigation (or the radius drainage area) to be 239.58 meters (786.037 ft), in where the flow regime is found to be radial with the permeability of k = 57.3 md. The transmissivity of the reservoir is calculated to be kh = 2979.6 md-ft. The skin around the well is estimated to be -1.2, indicating no damage around the well bore.

According to type-curve-matching results there was a no-flow boundary 310 ft away from the wellbore on East direction. Such flow boundary effect is slightly visible from the increasing behavior with about ½ slope of the derivative of dimensionless pressure, plotted in solid line in magenta color, in **Figure 7.6**. The detection of a flow boundary in type-curve-matching analysis of the well test can be considered as the confirmation of the claim of the existence of faults around the well by the seismic interpretation in this study, as illustrated in **Figure 4.3**, previously. Note that the estimated distance of no-flow boundary fault to the wellbore is also calculated from the seismic interpretation, in this study.

Horner Plot Analysis

The graphical presentation of the Horner plot, performed on the PTA software, is illustrated in **Figure 7.7**. In this analysis the pseudo pressure is plotted against the Horner time ratio of $(t_p + \Delta t)/\Delta t$, where t_p being the production time prior to the test. According to the Horner plot analysis the average reservoir pressure (p*) is estimated to be 583.3 psia and the permeability within the well drainage volume is determined to be 54.97 md. The manually-fit slope of the curve is calculated as m = -1213000 $psia^2$/cp/cycle. The transmissivity of the reservoir is calculated to be kh = 2858.22 md-ft. The skin around the well is estimated to be -1.49, also indicating no damage around the well bore. Note that the Horner plot indicates the infinite homogeneous reservoir behavior; at the first glance. However, a careful inspection of the upper part of the curve seems to reflect that the well felt the no-flow boundary.

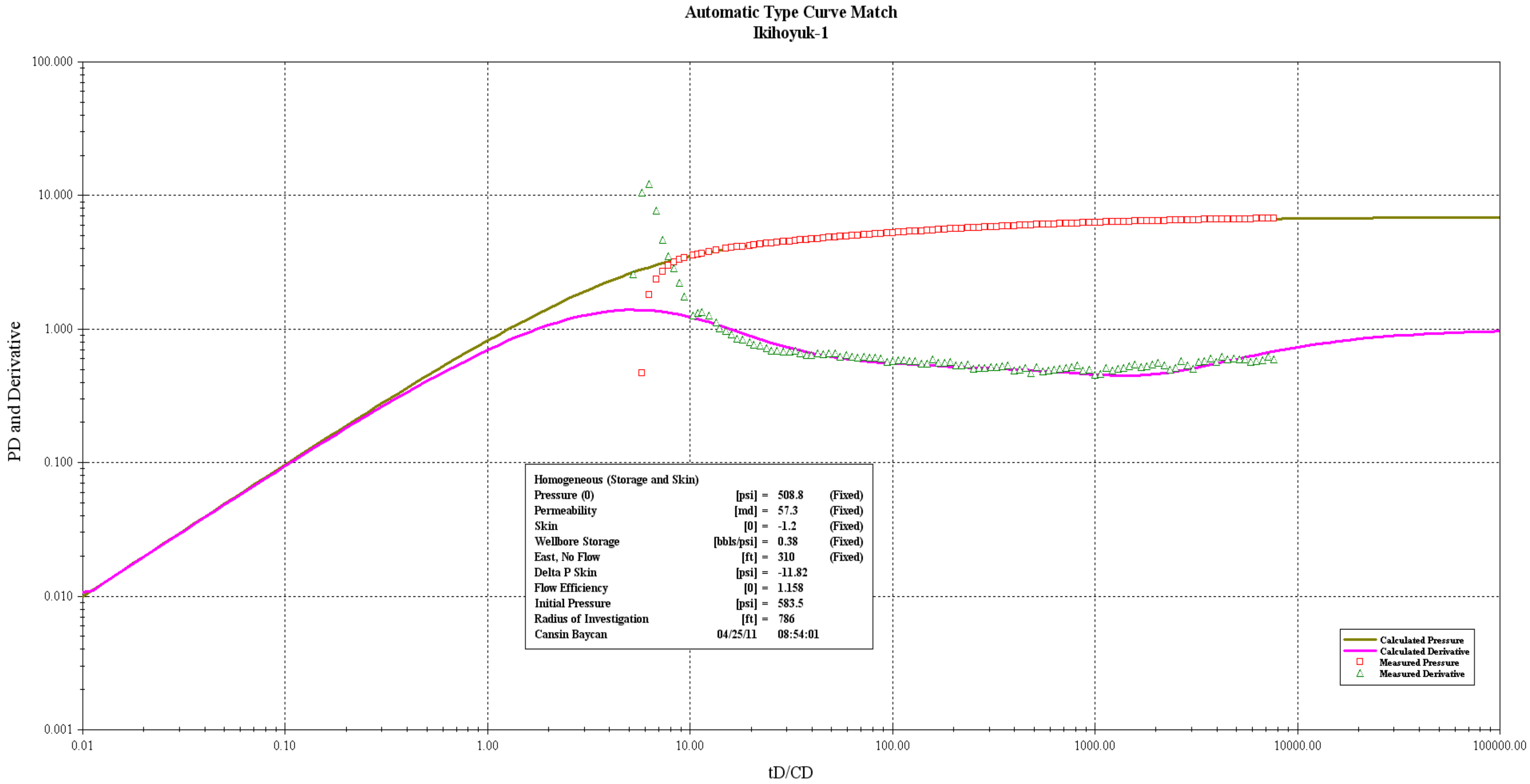

Figure 7.6: The Type-Curve-Matching Analysis of Pressure Build-Up Test in Well İkihöyük-1.

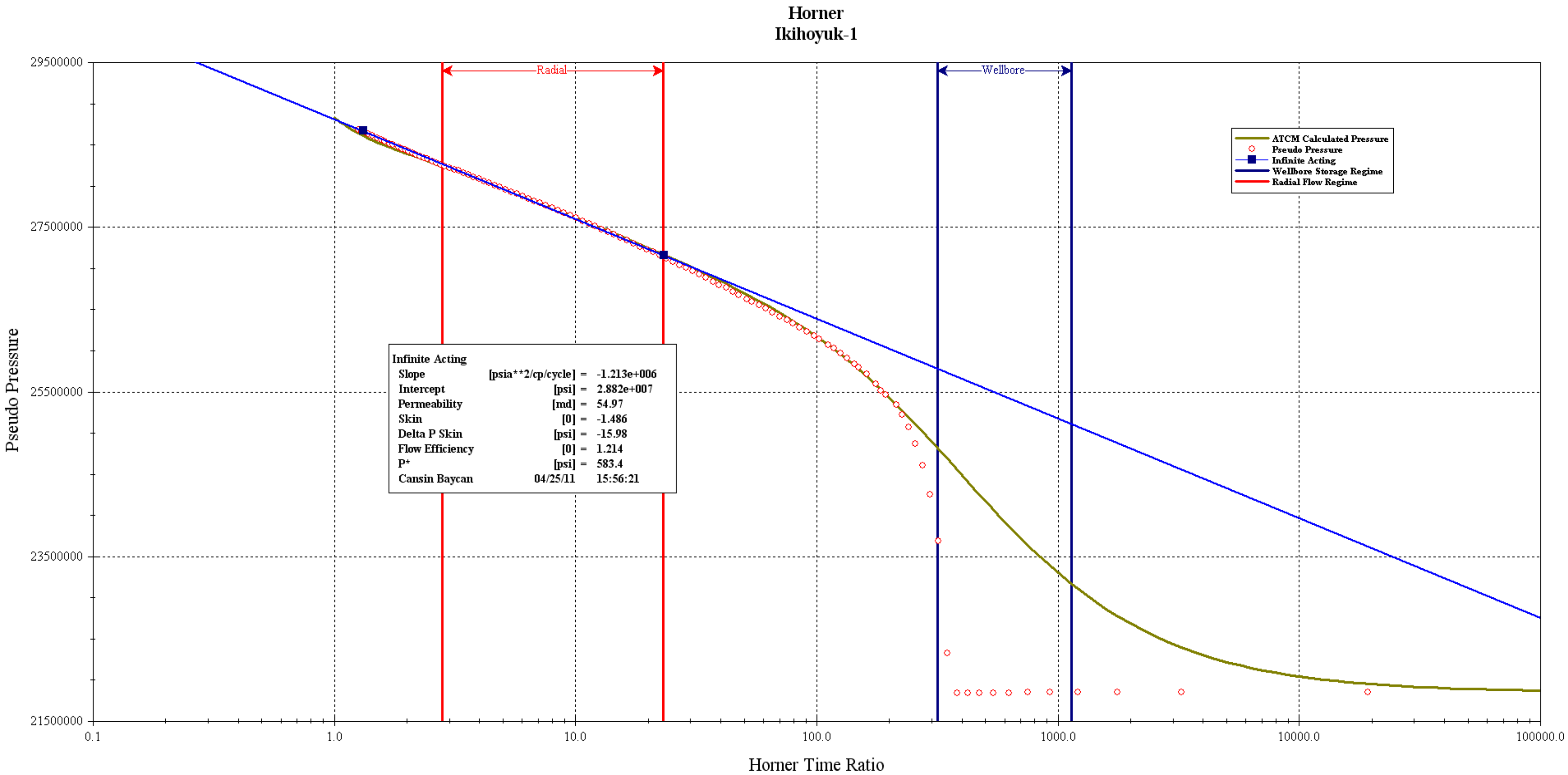

Figure 7.7: Horner Plot Analysis of Pressure Build-Up Test in Well İkihöyük-1.

The extrapolated reservoir pressure in the Horner plot is 583.3 psia, which is 8.5 psia less than the initial pressure of 592 psia measured by XPT tool at 445 meters of depth. This difference in initial pressure must be due to the pressure equilibration among the five zones tested together in commingled flow into the wellbore, since 1.89 MM scf of gas was flared during the test. Otherwise the reservoir gas reserve would be much smaller and not realistic. Still, however, having an extrapolated pressure of 583.5 psia as compared to 592.0 psia XPT pressure at 445 m is difficult to explain since the shallowest perforation depth is 444.29 m. According to the Horner analysis the radius of investigation (or the radius drainage area) is 786 ft, which provided the gas reserve estimation of a minimum of 571 MMM scf of gas-in-place for the connate water saturation of S_w = 0.47, the porosity of ϕ = 0.277, and the net pay thickness of h_{net}:52 ft. The results of well test analyses showed that the flow in reservoir had not reached the pseudo-steady state flow by the end of the test.

At the end of the test, upon completing the final shut-in period, the well was flowed at a much higher separator pressure (approximately 300 psi) for short durations to prove that this did not cause any decrease in the rates.

7.3. The Deliverability Test and Static Gradient Survey in İkihöyük-2 Well

Initially a gas deliverability test in the form of the flow-after-flow test was conducted in İkihöyük-2 well to start at 21:45 hours on 13.06.2009 and end at 09:03 hours on 16.06.2009. The test was consisted of eight consecutive periods, of which three were shut-in and the rest were flow periods. After the first shut-in and before the first flow periods a cleaning flow was performed due to the stuck gauge at the well head. The fluctuations in tubing head pressure are normal, with the effect of this clean out flow. The gathered data is presented in **Table 7.3** and the recorded pressures and flow rates are plotted against the elapsed time in **Figure 7.8**.

During the flow periods of the test the well was flowed about 3 hours on four different-size chokes, which were 32/64”, 28/64”, 36/64”, 42/64”, for the extended period of 6 hours on 48/64” choke, sequentially. At the end of the flow periods the well was shut in for 35.06 hours for the observation of pressure build-up. Entire pressure and temperature data were recorded using the digital gauge for detailed and accurate interpretation of the test results.

Table 7.3: The Summary of Flow-After-Flow Test for İkihöyük-2 Well.

Duration (hours)	Choke Size (inches)	Tubing Head Pressure (psia)	Annulus Pressure (psia)	Bottom Hole Pressure (psia)	Bottom Hole Temp. (°F)	Static Pressure (psia)	Static Temp. (°F)	Diff. Pressure (in of water)	Ambient Temp. (°F)	Gas Rate	
										Scf/d	Scm/d
-	-	591	588	607	92	Shut-in					
0.17	64/64	211	471	487	98	Cleaning flow after stuck gauge at the well head					
3.08	32/64	505	532	550	99	95	58	129	65	3,042,919	86,166
6.01	-	583	580	605	99	Shut-in					
2.98	28/64	521	538	558	99	109	63	70	77	2,458,391	69,614
3.00	36/64	477	517	535	99	158	70	106	86	3,669,734	103,915
3.00	42/64	431	498	515	98	196	74	133	85	4,546,370	128,739
6.00	48/64	399	481	497	98	212	72	142	69	4,747,416	134,432
35.06	-	580	577	596	99	Shut-in					

Initial shut-in bottom hole pressure : 607.29 psia	Initial shut-in well head tubing pressure : 591.10 psia
Final shut-in bottom hole pressure : 595.96 psia	Final shut-in well head tubing pressure : 579.55 psia

Produced fluid during test	Reservoir Temperature is 99°F at 455 m
Gas : 2,947,000 scf	Specific gravity of gas was assumed 0.559 for flow calc.
Condensate : 0 bbl	Orifice base factor is 849.41
Water :9 (= 2+4+3) bbls	Down hole gauge run depth @ 455 m from KB

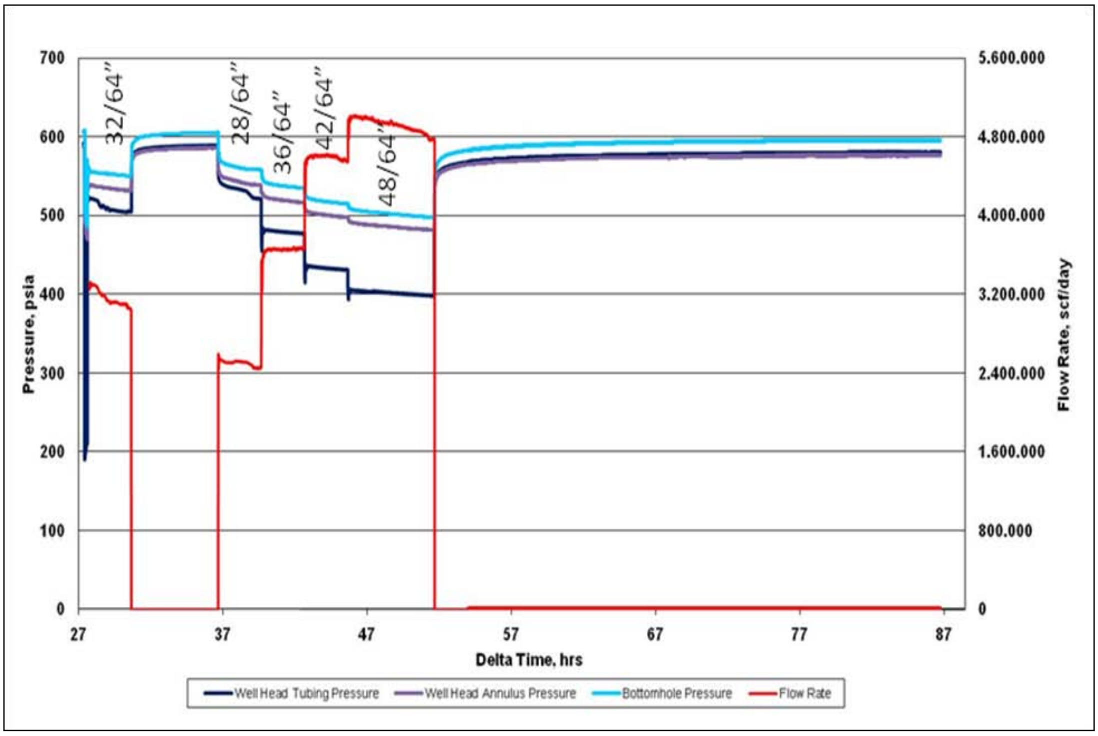

Figure 7.8: The Measured Pressure and Flow Rate Data Against the Time Elapsed During the Flow-After-Flow Test in İkihöyük-2 Well.

As seen in **Table 7.3**, the bottom-hole temperature was almost constant at 99°F, indicating no Joule-Thomson (cooling) effect occurred during the flow from the reservoir into the wellbore. The tubing head temperatures during the test are not either recorded or disclosed. Neither of the pressures at bottom hole, tubing-head, and annulus reached their initial levels and stayed constant at about 10 psi below the initial pressure, after the final shut-in period. Such behavior may be reflection of the achievement of pseudo-steady state flow regime and, therefore, can be attributed to either the reservoir being rather small or the existence of flow barriers around the drainage volume of the well.

A total of 9 bbls of water was produced during the flow periods of the test, 2 bbls on 36/64" choke, 4 bbls on 42/64" choke, and 3 bbls on 48/64" choke. The water production was probably from the deepest zone that indicated limited water entry. Note that the test was conducted when the perforated intervals of 457.5 to 465.45 meters, 466 to 468.44 meters, 475.36 to 477.8 meters, and 479.3 to 481.43 meters were all open to the wellbore.

Gas Composition Analysis

Ten gas samples were taken from the surface heater/seperator during the flow-after-flow test. The produced gas was dry and mainly methane and a mixture of gases from all open 4 zones tested. A gas composition analysis was conducted on the gas samples, during the flow through the 48/64" choke. The produced gas is found to be composed of 99.19 percent Methane (CH_4), 0.08 percent Ethane (C_2H_6), 0.04 percent carbon dioxide (CO_2) and 0.69 percent nitrogen (N_2). The specific gravity and compressibility factor, z, of the gas mixture were measured to be 0.5583 and 0.9980, respectively, at standard conditions.

Static Pressure and Temperature Gradient Survey

After the flow-after-flow test a static pressure and temperature gradient survey was conducted. The results of this survey are tabulated in **Table 7.4** and plotted in **Figures 7.9** and **7.10**. As seen in **Table 7.4**, the pressure and temperature gradients are found to be 0.041 psia/m and 0.048°F/m, respectively. The static pressure gradient survey at the end of the test proved that no additional liquid accumulation in the wellbore occurred. **Figure 7.9** shows that the static pressure at the depth of 455 meters was measured as 596 psia. As in the case of İkihöyük-1 well, somewhat minor non-linearity was observed in temperatures at the bottom parts of the wellbore.

Table 7.4: Static Pressure and Temperature Gradient Survey Conducted to Follow the Flow-After-Flow Test in İkihöyük-2 Well.

Time	Measured	Depth*	TVD*	Pressure	Temperature	Pressure Gradient	Temperature Gradient
(hours)		(m)	(m)	(psia)	(°F)	(psia/m)	(°F/m)
3749.23	Static	455	455	595.96	98.99		
3752.93	Static	440	440	595.37	98.81	0.040	0.012
3756.83	Static	420	420	594.59	98.26	0.039	0.027
3760.63	Static	400	400	593.78	97.53	0.041	0.037
3764.53	Static	380	380	592.98	96.56	0.040	0.048
3768.63	Static	350	350	591.78	94.96	0.040	0.053
3773.53	Static	300	300	589.74	92.23	0.041	0.055
3779.83	Static	200	200	585.65	85.58	0.041	0.067
3785.78	Static	100	100	581.53	78.51	0.041	0.071
38139.28	Static	0	0	577.36	72.66	0.042	0.058
		455	**455**	**595.96**	**99.566**	**0.041**	**0.048**

* measured from KB (Kelly Bushing.)

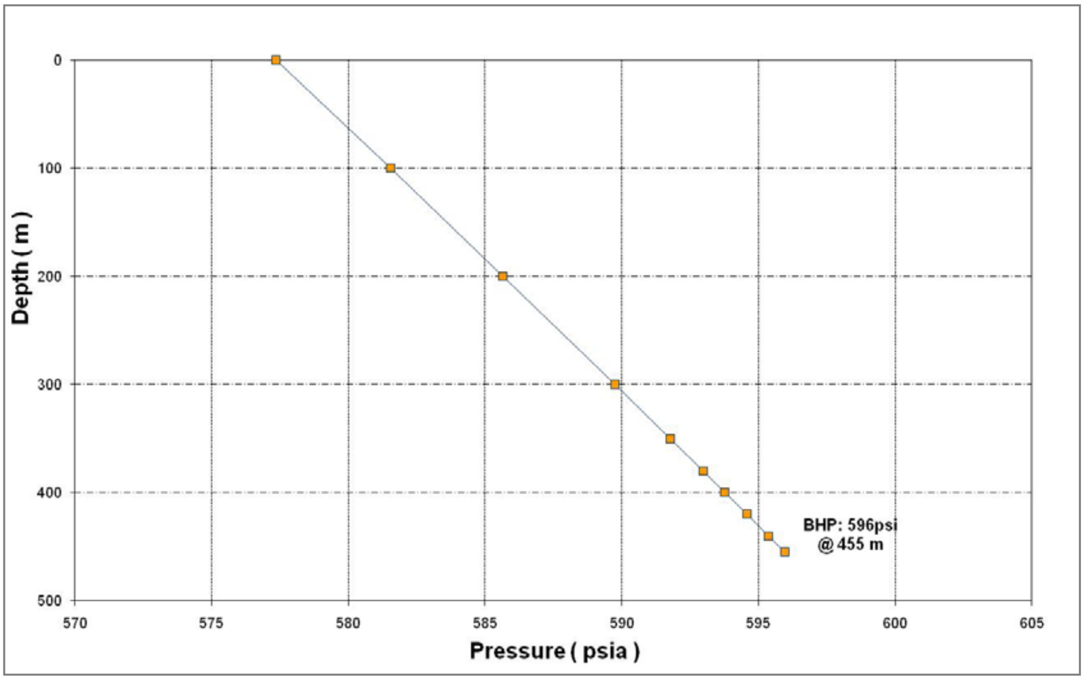

Figure 7.9: The Results of Static Pressure Gradient Survey in Well İkihöyük-2.

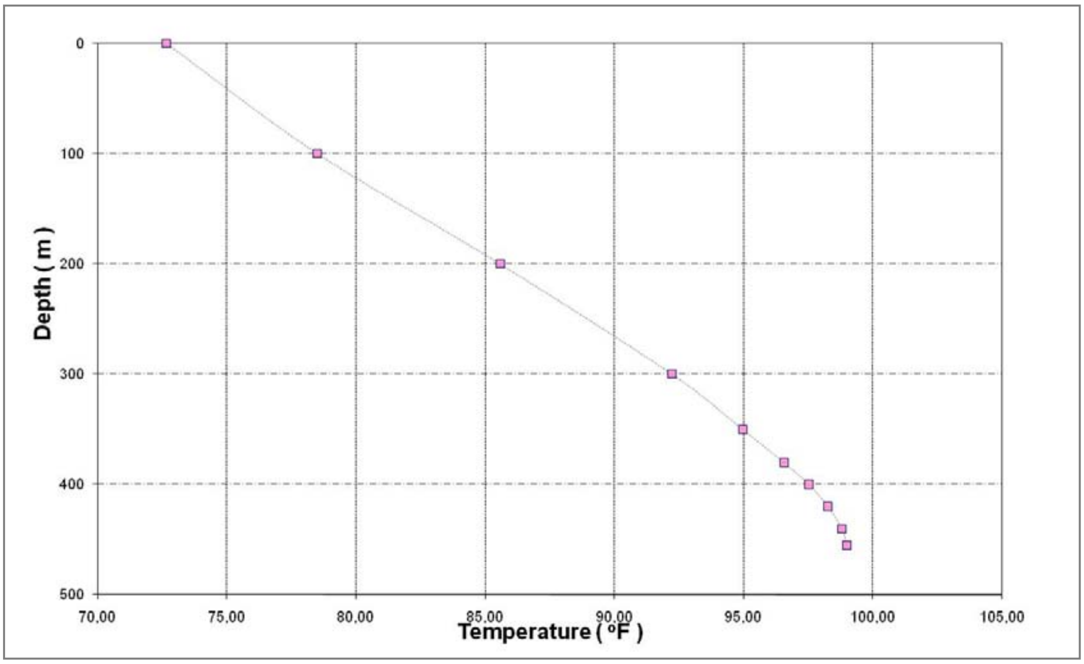

Figure 7.10: The Results of Static Temperature Gradient Survey in Well İkihöyük-2.

Deliverability (Flow-After-Flow) Test Analysis

In analyzing the deliverability (flow-after-flow) test, conducted in Well İkihöyük-2, the conventional Rawlins and Schellhardt equation, Eqn.7.1, is also used.

In the application of this method, the difference between square of reservoir pressure and square of bottom-hole pressure are plotted against the corresponding flow rate, both on logarithmic scales, as seen in **Figure 7.11**. Then, the parameters of "C" and "n" characterizing well productivity are calculated as C = 5.95×10^{-5} and n = 0.98 from this plot. Hence, the Rawlins and Schellhardt equation for the well became,

$$q_{sc} = 5.95 \times 10^{-5} \left(P_e^2 - P_{wf}^2\right)^{0.98} \quad \text{(7.3)}$$

Once the parameters of "C" and "n" are obtained, the absolute open flow (AOF) potential of İkihöyük-2 well is calculated to be AOF = 16.19 MMscf/day (or 458,510 m^3/day) by assigning zero to the bottom hole (sand face) flowing pressure. Note that AOF is a hypothetical maximum flow rate and the well cannot produce at this flow rate in reality. The graphical estimation of AOF is marked on **Figure 7.11**.

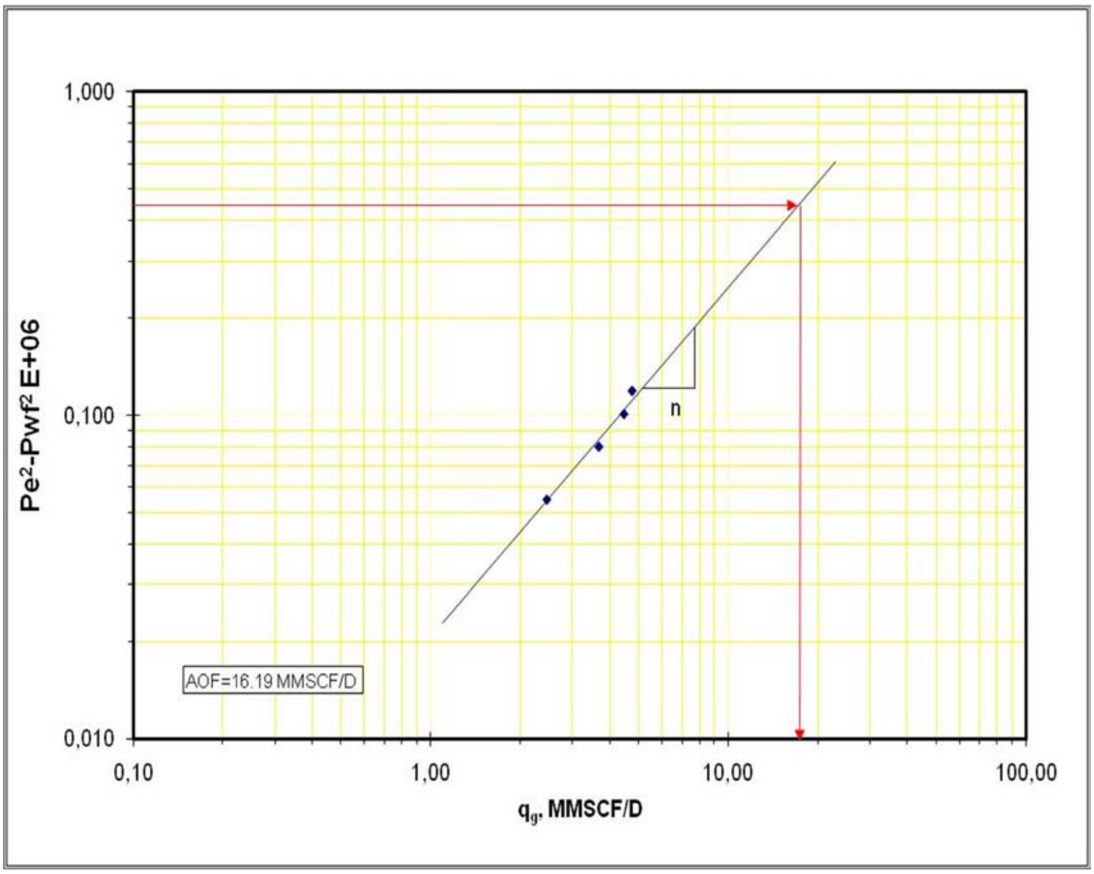

Figure 7.11: The Rawlins and Schellhardt Plot for the Analysis of Deliverability (Flow-After-Flow) Test Conducted in Well İkihöyük-2.

7.4. The Pressure Build-Up Test İkihöyük-2 Well

The analysis of the pressure build-up test in İkihöyük-1 well was also performed using the PTA software by Ryder Scott Engineering. Both the type curve matching and the Horner plot and methods were employed in analyzing the data. Before the type-curve-matching analysis, a diagnostic analysis is performed.

Diagnostic Analysis

In diagnostic analysis the pseudo pressure and the derivative of pseudo pressure are plotted against the time elapsed during the test, as shown in **Figure 7.12**. The flow regime is found to be radial with the permeability of k = 68.58 md. As seen from **Figure 7.12**, at least one no-flow boundary is detected by the derivative of pseudo pressure after the radial flow behavior.

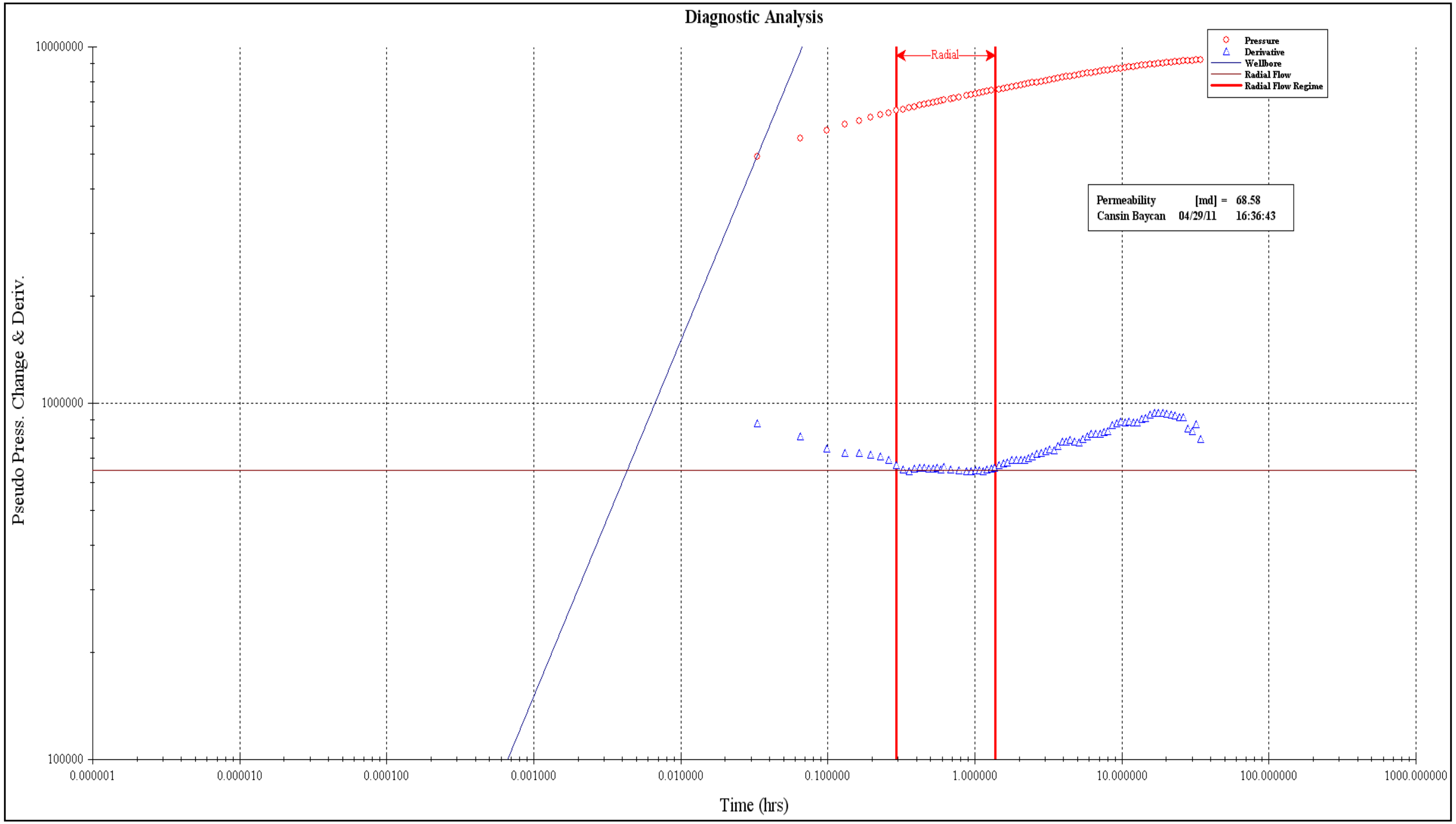

Figure 7.12: Diagnostic Plot Analysis of Pressure Build-Up Test in Well İkihöyük-2.

Type Curve Matching

The graphical presentation of the automatic type-curve-matching, performed on the PTA software, for the pressure build-up test in Well İkihöyük-2 is illustrated in **Figure 7.13**. For the initial reservoir pressure of 602.4 psia, the type-curve-matching analysis yielded the wellbore storage coefficient to be C = 0.1793 bbls/psi and the radius of investigation (or of the drainage area) to be 248 meters (813.8 ft), in where the flow regime is found to be radial with the permeability of k = 67.73 md. The skin factor is estimated to be s = -0.42, indicating no damage around the well bore.

According to type-curve-matching results there were two no-flow boundaries away from the wellbore; one is 170.17 meters (558.3 ft) on the East direction and the other is 51.42 meters (168.7 ft) on the West direction. Such no-flow boundary effect is clearly visible from the increasing behavior with about ½ slope of the derivative of the dimensionless pressure, plotted in dashed line in magenta color, in **Figure 7.13**. Therefore, the reservoir seems to be a channel type. The detection of two no-flow boundaries in type-curve-matching can be considered as the confirmation of the claim of the existence of faults around the well by the seismic interpretation in this study, as illustrated in **Figure 4.3**, previously. The estimated distances of no-flow boundaries to İkihöyük-2 well are also nearly estimated in the seismic interpretation.

Horner Plot Analysis

The graphical presentation of the Horner plot, performed on the PTA software, is illustrated in **Figure 7.14**. In this analysis the pseudo pressure is plotted against the Horner time ratio of $(t_p + \Delta t)/\Delta t$, where t_p being the production time prior to the test. According to the Horner plot analysis the average reservoir pressure (p*) is estimated to be 597.9 psia and the permeability, within the well drainage volume during the test, is determined to be 61.12 md. The slope of the curve, which was manually fit, is calculated as m = -1667000 $psia^2$/cp/cycle. The skin around the well is estimated to be -0.95, also indicating no damage around the well bore. If upper part of the curve in Horner plot is inspected carefully, it can be seen that the well had felt the no-flow boundaries. A minimum of 294 MMscf of gas-in-place is calculated in the drainage volume of the well for 50 percent gas saturation of, 42 ft net thickness, and 27 percent porosity. This gas volume should not be taken as the total gas-in-place.

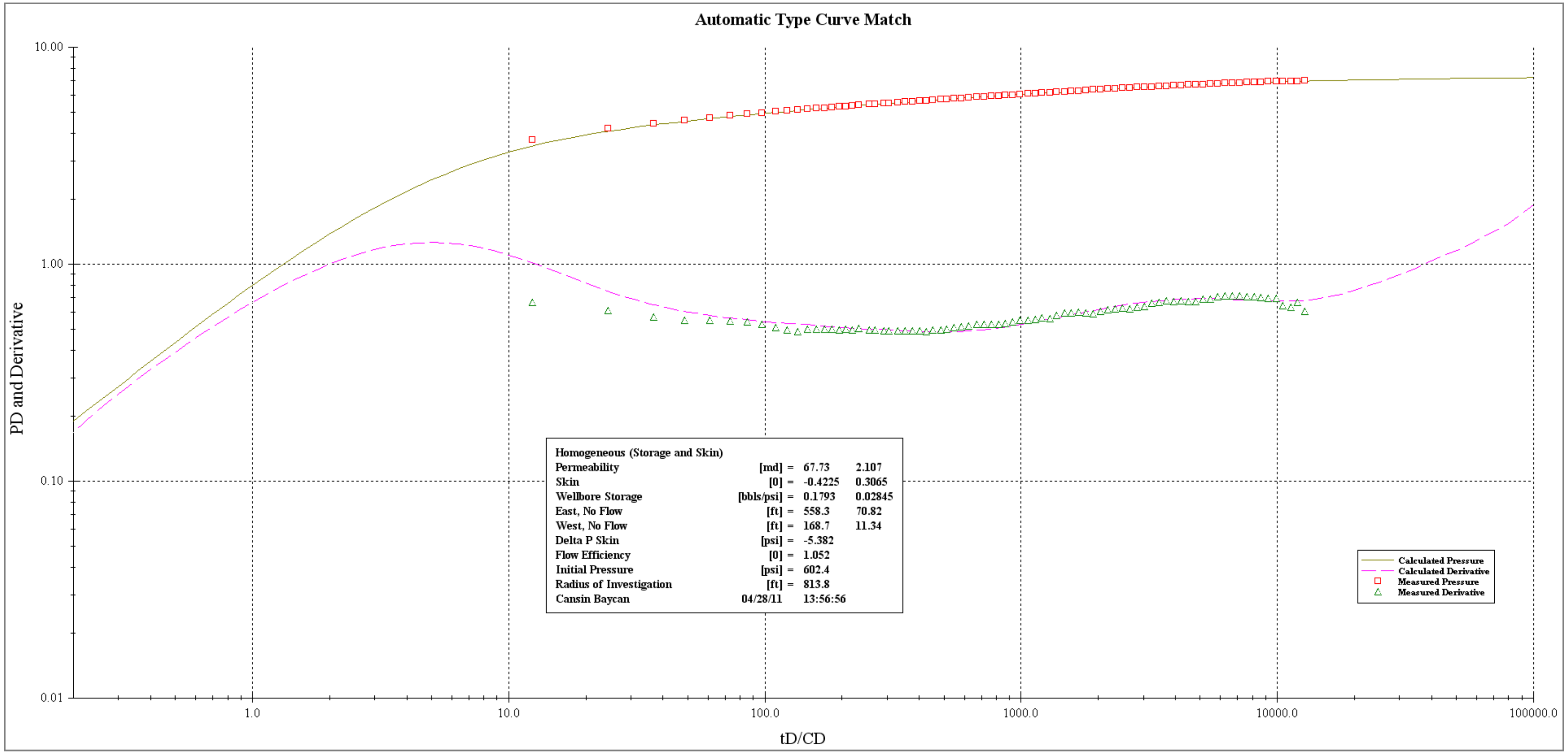

Figure 7.13: The Type-Curve-Matching Analysis of Pressure Build-Up Test in Well İkihöyük-2.

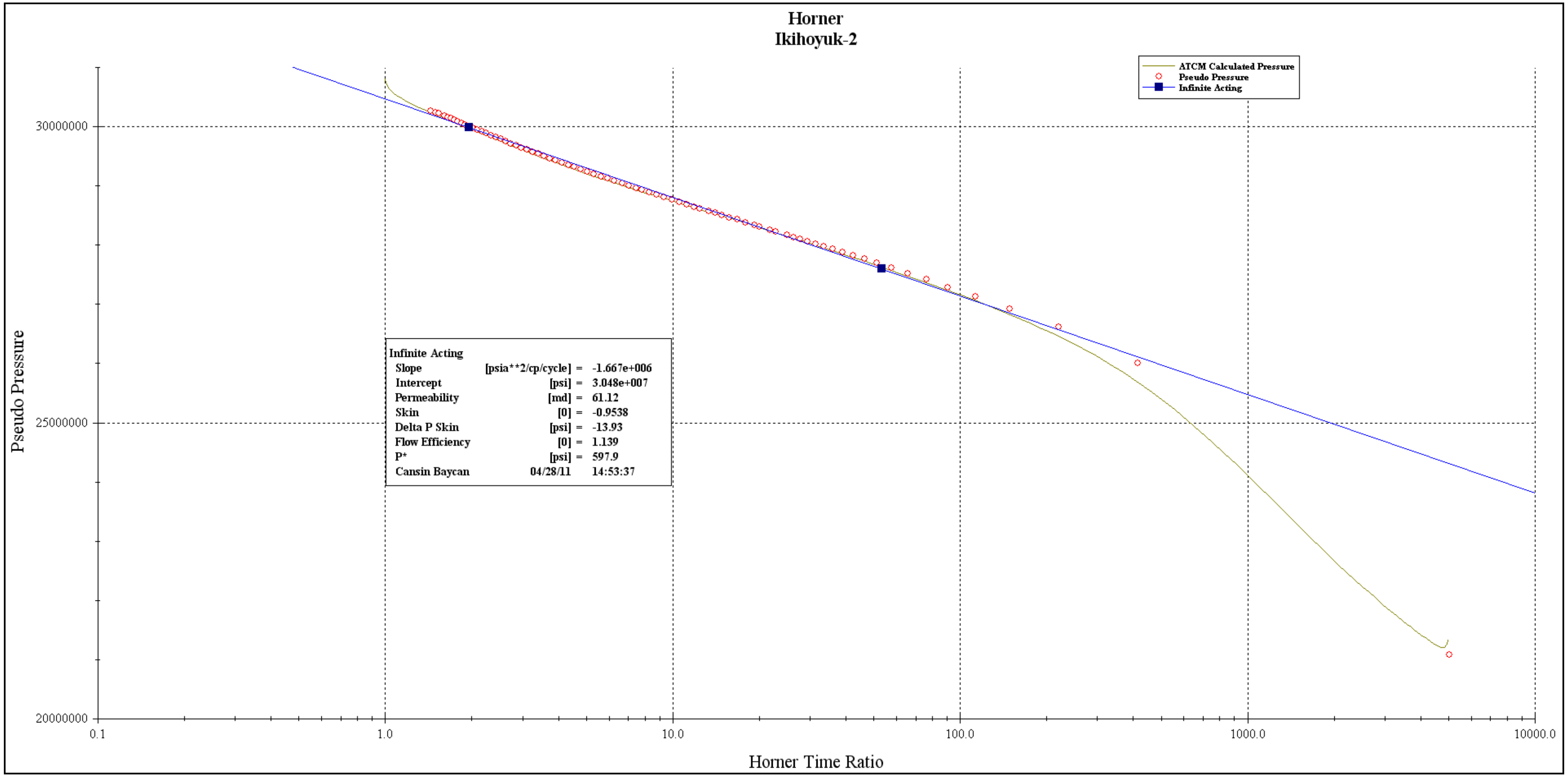

Figure 7.14: Horner Plot Analysis of Pressure Build-Up Test in Well İkihöyük-2.

8. GAS RESERVE CALCULATIONS

The gas reserves in both İkihöyük structures are estimated using the “p/z” plot method, derived from the classical material balance equation for a dry gas reservoir. The classic material balance expresses a relationship between the amount of gas produced and the average reservoir pressure. When there is no production, the pressure equals to initial reservoir pressure. Although not pratically possible, if the entire gas in the reservoir is produced, the pressure in the reservoir should become zero. In the case where the reservoir acts like a tank and there is no external pressure maintenance, the relationship between the reservoir pressure and the cumulative production is approximately linear for dry gas reservoirs. The material balance equation for dry gas reservoirs can be expressed as a linear relationship between the “p/z” and the cumulative prıoduction, G_p. Therefore, the OGIP (original-gas-in-place) can be obtained at the initial value of “P/z”, i.e. P_i/z_i. Deviations from the straight line may be the indication of either external recharge or offset drainage, or abnormally high pressured reservoir.

In order to generate a traditional P/z plot, the well is shut-in at several points along its producing life and the average reservoir pressure is obtained for each point from a properly conducted buildup test and interpretation. The duration of the shut-in is often not long enough to directly measure current average reservoir pressure. Consequently, extrapolation of the build-up data and correction of the extrapolated pressure to obtain the average reservoir pressure are required. As a result, problems with testing and interpretation comprise some of the key causes of erratic pressure data often observed in material balance plots. (L. Mattar, R. McNeil, 1998)

8.1. Recoverable Gas Reserve Estimation for İkihöyük-1

According to the test results on 26th of May 2009, the bottom hole pressure (BHP) was measured as 583.5 psia at 99.6°F at the depth of 444.29 meters. The gas spesific gravity of 0.5645 and the compressibility factor, z, of 0.938 were determined using the previously given gas composition. On the 10th of May 2010 the well was shut in for running the Slickline unit and the bottom hole pressure was measured to be 321 psia. The temperature assumed to be the same at the same depth in the reservoir and the z factor for those conditions is calculated to be 0.966. The cumulative gas production was 0.035 B scf as of 10th of May 2010. Using these data a P/z versus G_p (cumulative gas recovery) plot is generated, as seen in **Figure 8.1**.

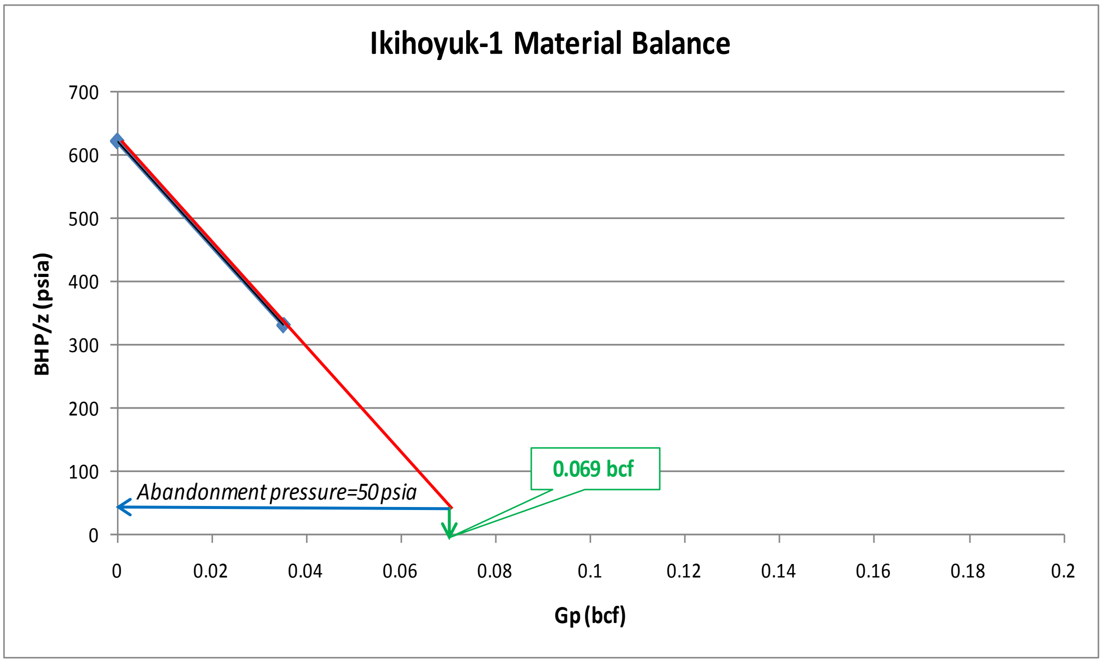

Figure 8.1: P/z Versus Gp Plot for İkihöyük-1 Reservoir.

As seen in **Figure 8.1**, the ultimate gas recovery (UR) for İkihöyük-1 reservoir is estimated to be G_p = 0.069 B scf for the abandonment pressure of 50 psia, which is equal to the pipeline pressure. Note that the P/z value at the abandonment pressure is almost equal to the pressure of 50 psia. Thus, the remaining reserve is determined to be 0.28 B scf as of 10th of May 2010. Contrary to such estimation of recoverable gas reserve, the actual total gas produced from İkihöyük-1 reservoir has been 0.089 B scf, till the well was abandoned. Therefore, 22.47 percent error was committed in the estimation of recoverable gas reserve.

8.2. Recoverable Gas Reserve Estimation for İkihöyük-2

According to the test results on 16th of June 2009, the BHP was measured as 605.3 psia at 99°F at the depth of 455 meters. The gas spesific gravity of 0.558 and the compressibility factor, z, of 0.934 were determined using the previously given gas composition. On the 10th of June 2010 the well was shut in, but the bottom hole pressure could not be measured by the Slickline unit. Instead, however, the BHP was is calculated to be 258.2 psia, from the tubing head pressure of 240 psia with the assumtion of no significant water accumulation in the wellbore. The temperature assumed to be the same at the same depth in the reservoir and the z factor for those conditions is calculated to be 0.971. The cumulative gas production was 0.063 B scf as of 10th of June 2010. Using these data a P/z versus G_p (cumulative gas recovery) plot is generated, as seen in **Figure 8.2**.

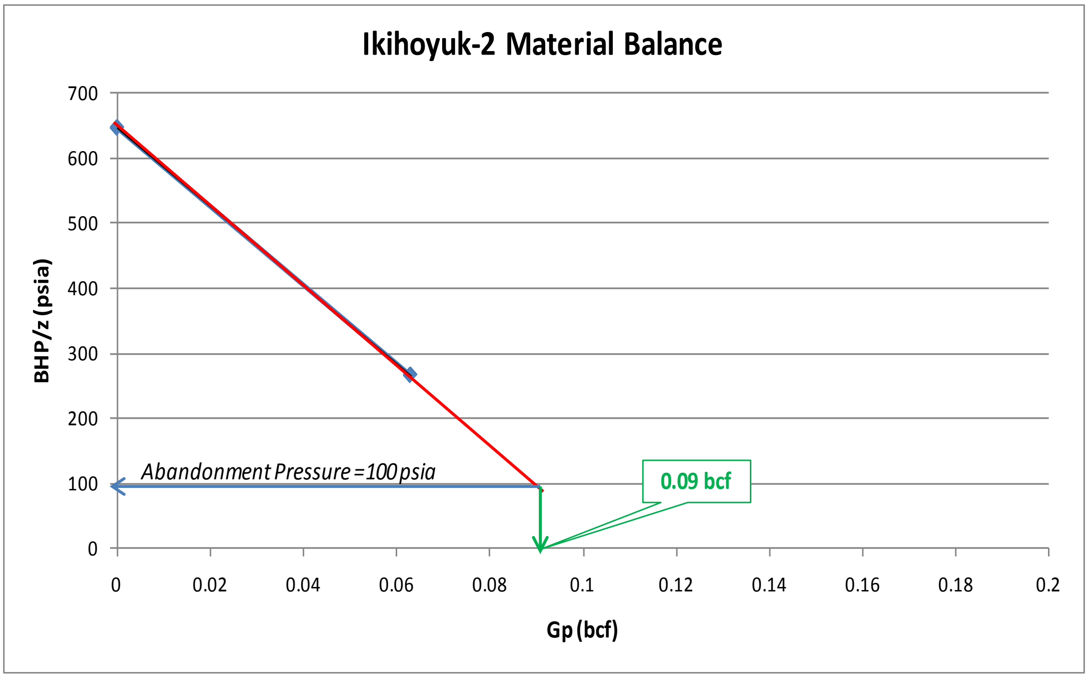

Figure 8.2: P/z Versus Gp Plot for İkihöyük-2 Reservoir.

As seen in **Figure 8.2**, the ultimate gas recovery (UR) for İkihöyük-2 reservoir is estimated to be G_p = 0.09 B scf for the abandonment pressure of 100 psia, which is equal to the pipeline pressure. Note that the P/z value at the abandonment pressure is almost equal to the pressure of 100 psia. Thus, the remaining reserve is determined to be 0.27 B scf as of 10th of June 2010. Since the actual total gas produced from İkihöyük-2 reservoir has been 0.087 B scf, till the well was abandoned, the error committed in the estimation of recoverable gas reserve was only 2.45 percent. With such result, it can be said that the recoverable reserve estimation for İkihöyük-2 reservoir was very good.

Using the estimated total gas reserves the total drainage area was calculated to be 0.06 square kilometers for İkihöyük-1 reservoir and 0.052 square kilometers for İkihöyük-2 reservoir. When these drainage areas are compared with the seismic interpretation results, it is found that these two reservoirs were not in hydrodynamic communication. Such outcome is directly supported by the bottom hole pressure measurements and the analysis results of the well tests, as given in Section 7 of this thesis study.

9. CONCLUSIONS

A study integrating the geological, geophysical, and engineering data and analyses is performed to identify the sedimentary depositional environment, the stratigraphic sedimentary cycles, their areal extent, and to determine the existence, reserves, and the gas deliverability capacity of gas reservoirs within Danişmen and Osmancık formations in İkihöyük gas field, located in the northern Thrace basin. In the geological part of the work, the application of sequence stratigraphy to identify the stratigraphic cycles of sedimentary units was the main emphasis. In the geophysical part of the work, the concentration was on the analysis and interpretation of the strong amplitude anomalies of the vertical velocity of seismic waves, obtained from the first 3D seismic survey application in the lease area of Concession 3839. In the engineering part of the work, the analysis of well logs and both the transient and deliverability well tests were the essential elements that led to the estimation of reserves.

1. It is determined that both Danişmen and Osmancık sandstones were deposited in a fluvial deltaic depositional environment with the upward coarsening of the sequence stratigraphic cycles.

2. It is determined and proven by the actual production that the main gas zones and reservoirs were in the top of upward coarsening/sequence stratigraphic cycles of Danişmen and Osmancık sandstones in the lease area. The application of sequence stratigraphic analysis has revealed the areal extension of individual reservoir sands in the study area.

3. In both Danişmen and Osmancık formations the reservoir quality parameters, such as porosity and permeability, are found to change rapidly in short distances.

4. The developed method, utilizing the large-scale analysis and interpretation of the strong amplitude anomalies in 3D seismic data, is proven to be very useful for detecting the gas filled zones of the well developed reservoirs.

5. The well test interpretation results confirmed the pressure difference of 22 psi between the two wells that was detected during the completion of wells. In addition

to such pressure difference the difference in permeability, determined by well test analyses, is interpreted as the existence of a flow barrier that leads to the occurrence of two separate but neighboring gas reservoirs with the rapid change of reservoir rock properties in such fluvial deltaic depositional environment.

6. The well test analysis for İkihoyuk-2 well indicated the presence of two flow boundaries on both sides of the well and, therefore, İkihoyuk-2 reservoir is likely to be channel sand.

7. The drainage area of both wells are determined using actual total produced gas volume and found to be in very close agreement with the volumetric estimate that was calculated from synsedimentary fault controlled area.

8. The recoverable gas reserves, estimated by P/z versus G_p plot analysis for the gas producing zones that were penetrated by both wells, are found to be 0.069 B scf with 22.47 percent error for İkihöyük-1 reservoir and to be 0.09 B scf with 2.45 percent error for İkihöyük-2 reservoir, with a recovery factor of 75 percent.

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