AN INVESTIGATION OF THE LEAK-OFF TESTS CONDUCTED IN OIL AND NATURAL GAS WELLS DRILLED IN THRACE BASIN

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ABSTRACT

AN INVESTIGATION OF THE LEAK-OFF TESTS CONDUCTED IN OIL AND NATURAL GAS WELLS DRILLED IN THRACE BASIN

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This study aims to analyze the leak-off tests carried out in the Thrace Basin of Turkey by Turkish Petroleum Corporation and find any relationship that may exist between leak-off test results and drilled formations as well as drilling parameters, such as mud weight, depth.

The analysis of 77 leak-off tests indicated that there is no close correlation between the mud weight of test fluid and equivalent mud weight (fracture gradient) if the test is carried out within impermeable sections. On the other hand, the correlation between mud weight and equivalent mud weight increase while running the test within permeable-productive zones. It is also found that the leak-off test results are not dependent on the depth but the formation to be tested.

The analyzed leak-off test results from Thrace Basin showed that the fracture gradient is not the limiting factor to set the casing of any section unless a gas show is observed during drilling operation which occurred only in 5 wells out of 78 wells analyzed.

Keywords: Leak-off test, fracture gradient, Thrace Basin, equivalent mud weight

ÖZ

TRAKYA BASENİNDE KAZILMIŞ OLAN PETROL VE DOĞAL GAZ KUYULARINDA YAPILAN LEAK-OFF TESTLERİNİN İNCELENMESİ

Kayael, Burak

Yüksek Lisans, Petrol ve Doğal Gaz Mühendisliği Bölümü

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Bu çalışma, TPAO'nun Türkiye'nin Trakya Baseninde yapmış olduğu leak-off testleri analiz etmeyi ve leak off test sonuçları ile kazılan formasyonlar ve çamur ağırlığı, derinlik gibi sondaj parametreleri arasında olması muhtemel ilişkiyi bulmayı amaçlamaktadır.

İncelenen 77 leak-off test sonucu, testin geçirgen olmayan jeolojik formasyonlarda yapılması durumunda çamur ağırlığı ve eşdeğer çamur ağırlığı (çatlatma basıncı) arasında ilişki bulunmadığını göstermiştir. Bununla birlikte testin geçirgen/üretken jeolojik formasyonlarda yapıldığı durumlarda çamur ağırlığı ve eşdeğer çamur ağırlığı arasındaki bağlantı artmaktadır. Bulunan bir diğer sonuç da leak-off test sonuçlarının testin yapıldığı derinlik yerine formasyona bağlı olduğudur.

Trakya Baseni'nde yapılmış olan leak-off test sonuçlarının incelenmesi sonucunda, çatlatma basıncının sondaj operasyonları sırasında herhangi bir gaz belirtisi olmadığı sürece yeni bir kuyu muhafaza dizisinin inişi için geçerli sebep olmadığı görülmüştür. Bu durum incelenen 78 kuyu içerisinden sadece 5 tanesi içinde gerçekleşmiştir.

Anahtar Kelimeler: Leak-off test, çatlama basıncı, Trakya Baseni, eşdeğer çamur ağırlığı

To My Parents

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NOMENCLATURE

BHA = Bottom hole assembly

bpm = Barrels per minute

D = Depth (below rotary table), m

ECD = Equivalent circulating density, ppg,

EMW = Equivalent mud weight, ppg

ESD = Equivalent static density, ppg

FV = Funnel viscosity

LWD = Logging while drilling

MW = Mud weight, ppg

MW_{in} = Mud weight getting into well, ppg

MW_{out} = Mud weight getting out of well, ppg

OBG = Overburden gradient

P_h = Hydrostatic pressure, psi

P_{lo} = Leak-off pressure, psi

PV = Plastic viscosity

SPP = Standpipe pressure, psi

TD = Total depth, m

YP = Yield point

CHAPTER 1

INTRODUCTION

Drilling Engineering is one of the main branches of Petroleum and Natural Gas Engineering. This branch includes all activities for bringing a well-qualified wellbore for exploration and production operations in oil and natural gas industry.

As technology improves many new techniques emerge for drilling engineering purposes. These new technologies help drilling activities to occur faster and easier, but still there are some conventional methods which keep their validity. One of these methods is Leak-off Test.

Leak-off test is applied to determine the fracture gradient at depth where the test is run. The main reason for determining the fracture gradient is to forecast upcoming drilling operations and drilling parameters. Fracture gradient which is detected via leak-off test will be the limit for drilling parameters of next hole section. Leak-off test result (fracture gradient) affects;

1. Well design,
2. Mud weight for next hole section,
3. Kick tolerance (well control limit).

As all of these three effects will directly dictate how drilling operations go on, leak-off test, its procedure and results should be studied and understood carefully. In an opposite case leak-off test can guide drilling engineers or well planning engineers in a wrong way, which may end up with chaotic consequences. These chaotic consequences may be stuck pipe, severe fluid losses, a kick or even a blowout.

In this study, the purpose is to find a relation between results of leak-off tests conducted in oil and natural gas wells in Thrace Basin. Ceylan, Danişmen, Ergene, Mezardere and Osmancık formations were studied to reveal any present relation between investigated leak-off test results and some variables. Each formation was investigated by itself to get formation specific results. More than hundred wells were studied and their composite logs, daily drilling reports, final drilling reports and mud logging reports were analyzed. Each well's lithology column was drawn to compare each formation's thickness with other related wells.

For leak-off test results analysis; first of all each well's specific data were collected. These data sets consist of test depth, mud weight, equivalent mud weight (leak-off test result) and mud rheological properties. After collecting these data, they were interpreted to calculate new data sets like fracture gradient and differential mud weight. Each result calculated were compared with historical data written in daily drilling reports and final drilling reports to eliminate any possible inconsistencies. At final stage all results were put together to gather a relation between studied wells and their data.

The reason for selecting Thrace Basin is the necessity of Turkish Petroleum Corporation (TPAO). As Thrace Basin has mostly gas fields, it requires special treatment during planning and execution of drilling activities. This study was initiated by TPAO's request for such research. Thrace Basin having a uniform structure in most of its area was a facilitating factor for choosing this region. Thrace Basin is not over faulted like South-East Turkey, where many oil fields exist. This comparison brought Thrace Basin one step further.

CHAPTER 2

THEORY

Leak-off test is a test used to determine the strength or fracture pressure of an open formation below the casing shoe which is drilled right after the casing is run. The test is done by shutting in the well and pumping fluid into wellbore until the fluid enters the formation through permeable paths or by fracturing it. The results of leak-off test show the maximum mud weight that can be used or maximum pressure that can be applied during the drilling operations at that well section.

2.1. What is Leak-Off Test (LOT)?

In wildcat and exploratory drilling, one of the most important challenges for well planning and drilling engineering is the ambiguity of limits for drilling parameters. As limited data is present for field (seismic results, preliminary pressure and geological studies) all additional information that can be gathered during drilling operation are critical for a successful ongoing operation.

One of the most critical information that should be continuously watched is wellbore's Pore Pressure – Fracture Gradient (PPFG) acts. An instantaneous increase in pore pressure (PP) may cause a kick or eventually a mud weight (MW) increase. A kick will lead operator company to a well control operation which will cause non – productive time and extra costs. No matter a kick occurs or not mud weight should be increased to keep safety margin above pore pressure. As mud weight increases hydrostatic pressure in the wellbore increases naturally. This increase affects each point of wellbore including casings, liners and open hole. Since the overburden gradient of a well increases as depth increases, the fracture gradient is affected proportionally from this change. Wellbore is enforced by setting a casing and cementing it. This makes the formation just below last casing's shoe as the weakest point of a wellbore, in normal conditions. Normal conditions define the case where no permeable/productive zone is penetrated where drilling fluid can be lost. The hydrostatic pressure at this point should not exceed the fracture gradient value. If it exceeds there will be losses, partial or complete, which may again end up with a kick.

To prevent above hazards the fracture gradient at last casing's shoe should be well known and pore pressure should be watch continuously. There are different ways of tracking pore pressure during drilling. One of the most common ways of observing pore pressure increase is chasing formation cavings on shale shakers. Any presence of cavings in disposed cuttings shows an increase in pore pressure and should be concluded as hydrostatic pressure in open hole is less than pore pressure. Another way to track the pore pressure is Trip Gas or Connection Gas readings. If gas readings at surface increases during tripping out of hole this should be interpreted as Trip Gas, which means hydrostatic pressure in open hole is above pore pressure but too close to it. When tripping out of hole Swab Effect will decrease the hydrostatic pressure and any present gas will enter into wellbore. Also if Equivalent Static Density (ESD) is insufficient to hold pore pressure but Equivalent Circulating Density (ECD), Equation 2.1, can hold it with additional pressures, any gas presence in wellbore will show up (when circulation stops) as Connection Gas and gas readings at surface will increase significantly.

$$ECD = ESD + \frac{SPP}{0{,}052 * D * 3{,}281} \qquad (2.1)$$

Most up to date method for pore pressure prediction is interpreting LWD readings. Sonic and resistivity readings can be used to predict any change in pore pressure. In spite of pore pressure prediction, fracture gradient can only be predicted by some mechanical tests.

Generic name of these tests is Pressure Integrity Tests (PIT) or pump-in/flow -back test (Soliman and Daneshy, 1991). Pressure Integrity Tests are divided into three types: Formation Integrity Test (FIT), Leak-Off Test (LOT) and Extended Leak-off Test (ELOT or XLOT). Main differences between these tests are their ending point pressures and their durations (Raaen and Brudy, 2001).

In FIT, newly drilled formation will be pressurized up to a predefined pressure and hold that pressure for a determined period of time. This predefined pressure is calculated according to a mud weight that needs to be maintained to drill the hole section. For example if 10 ppg MW is thought to be enough for drilling a hole section, formation below previous casing shoe (at 2500 m) can be tested to 4,265 psi (~4300 psi). Equation 2.2 shows the details of hydrostatic pressure calculation. The pressure will be kept at 4,270 psi for 2-3 minutes to ensure exposed formation can handle adequate pressure.

$$P_h = 0{,}052 * MW * D * 3{,}281 \tag{2.2}$$

LOT is generally run when there are uncertainties about fracture gradient of a field or quality of previous casing’s cementing job. Newly drilled formation will be pressurized up to a pressure where formation breaks down. The pump is shut down and the pressure vs. pumped volume graph is observed for determined period of time. Figure 1 shows a sample LOT graph. The test fluid starts to be pumped with a constant rate until massive breakdown occurs at open hole and pressure drops.

Interval between the points C and D shows the loss of friction and pressure fall-off due to filtration (Wojtanowicz and Zhou, 2001).

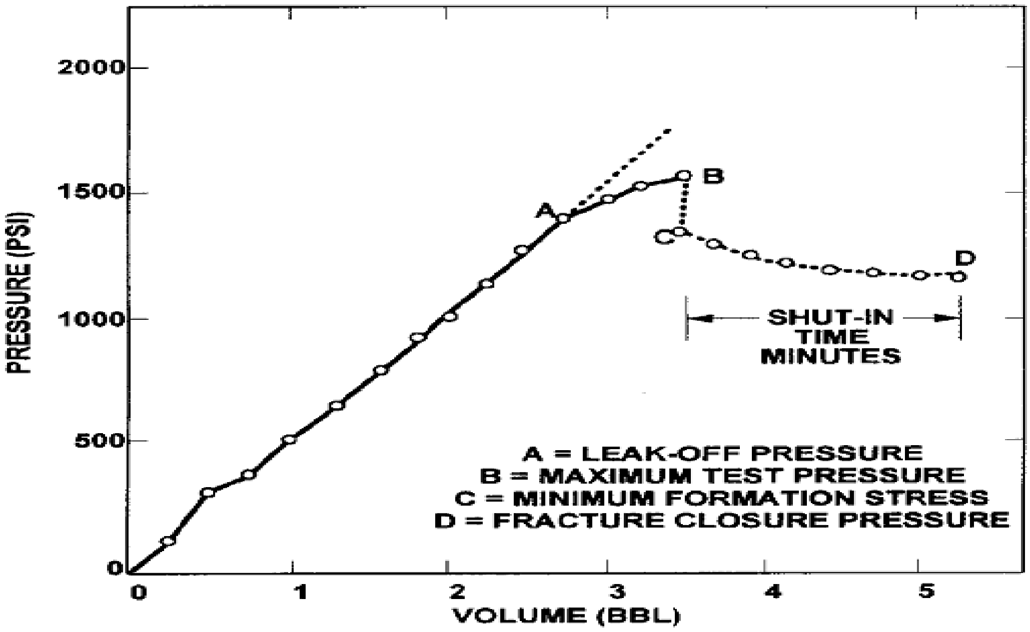

Figure 1 A sample graph for leak-off test (LOT) (Postler, 1997)

ELOT is a new type of PIT that is being used in recent years. Main difference from a LOT is the number of repeating cycles. In ELOT a classical LOT is followed by at least two more pressurization cycles. This test gives a more certain result for fracture gradient but is still uncommon in oil industry. A sample ELOT graph is given in the Figure 2 below.

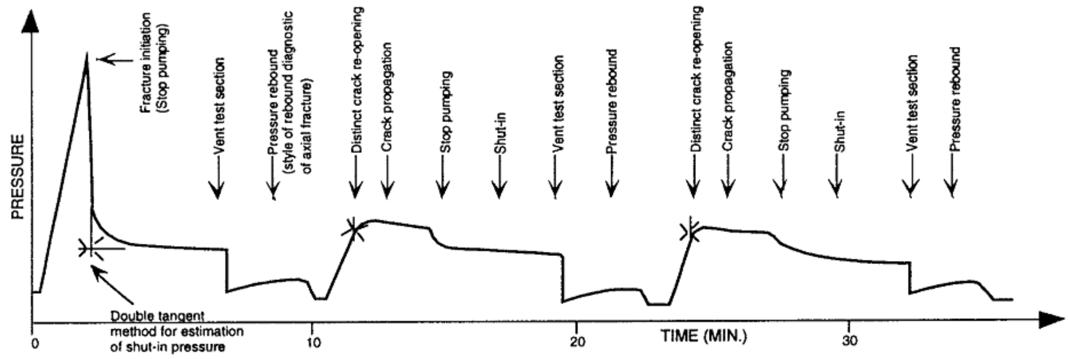

Figure 2 A sample graph for extended leak-off test (ELOT) (Addis, et al., 1998)

All PITs, including LOT, give a result in units of pressure. This pressure is the maximum pressure which the previous casing shoe can withstand. The pressure value is used to calculate the maximum mud weight that can be used in that hole section. This maximum value is calculated using EMW formula. Equation 2.3 shows the relationship between EMW and leak-off pressure (P_{lo}).

$$\text{EMW} = \text{MW} + \frac{P_{lo}}{0{,}052 * D * 3{,}281} \qquad (2.3)$$

This EMW value is highly critical for drilling operation as if necessary leak-off value cannot be reached, some additional cement squeeze operations will be mandatory. As its nature, there are many factors affecting each LOT run. Some can be listed as test fluid type, shoe cement quality and formation to be tested. Detailed information will be given in the section of ‘Factors That Affect LOT’.

LOTs are also used for stress estimation at certain depth. Breckels and van Eekelen (1982) suggest that formation stress is directly dependent on depth. That stress estimation can be used for exploration and drilling planning, including sealing capacity of faults, mud weight design, fracture gradient estimation, wellbore stability, well array planning and the development of fractured reservoirs. Additionally sand production, reduction of production rate and reservoir compaction and subsidence can be counted as dictations of stress (Addis, 1998).

Although LOT results may be used for stress estimation there are some weak points for being a perfect source for it. Firstly, lack of a standardized methodology for performing LOT is the main handicap of the oil industry. Secondly, the main approach of executing LOT in shales eliminates the chance of using LOT as stress estimation tool in other formations like sandstones or limestones. Finally, as a LOT is not designed for being an exact way for determining formation stresses, its mechanics and interpretation methods seem unsuitable for such kind of evaluation (Addis, 1998)

2.2. What is Pore Pressure – Fracture Gradient (PPFG)?

While discussing LOT issue, PPFG topic should be carefully studied. Main reason for running a LOT is to understand the relation between pore pressure and fracture gradient correctly. If LOT is run correctly and can be commented on carefully, it will give many hints for upcoming drilling operations.

Schlumberger Oilfield Glossary defines these two terms as following: Pore pressure is the pressure of fluids within the pores of a reservoir, usually hydrostatic pressure, or the pressure exerted by a column of water from the formation's depth to sea level (Schlumberger, 2011a). Fracture gradient is the pressure required to induce fractures in rock at a given depth (Schlumberger, 2011b).

To understand pore pressure – fracture gradient relation of a possible hydrocarbon bearing field, some works should be done before starting to drill. Firstly, 2D or 3D seismic gives the initial idea about field's PPFG curves. Secondly, any available offset wells around field should be examined for any past experiences for similar formations or hazards. Any mud weight, kick or loss records give a clue for the field. If the field is totally wildcat, then the seismic data is the only guide for PPFG studies. After studying few years on raw seismic data, seismic velocity results can be gathered which gives an idea about possible formations. A sample PPFG graph is shown in the Figure 3 below.

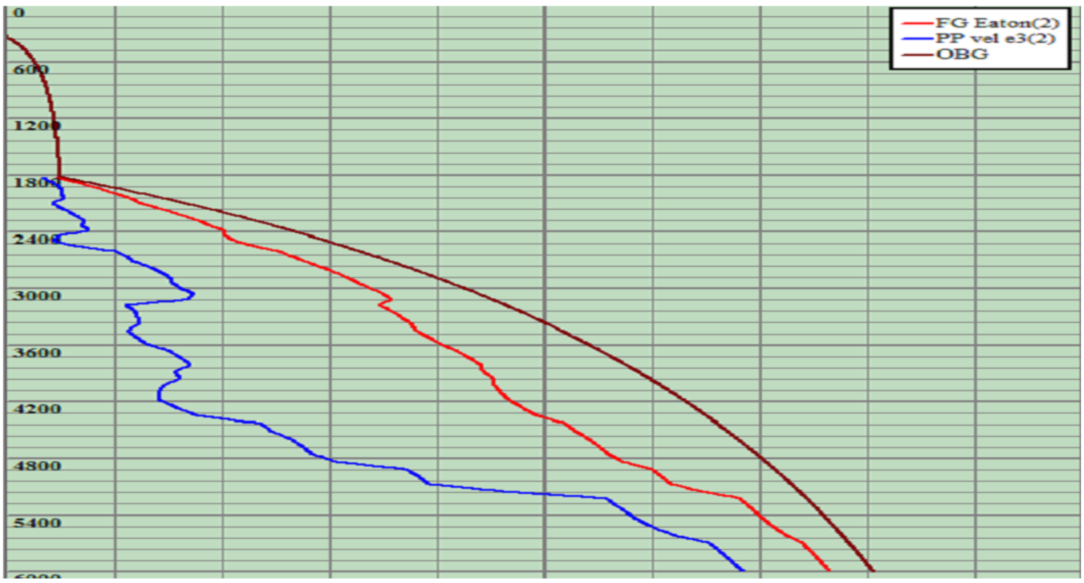

Figure 3 A sample PPFG graph that shows pore pressure, fracture gradient and overburden gradient (TPAO, 2011a)

After having a PPFG graph, next step for drilling is to plan casing or liner setting depths. The most basic way to determine casing setting depths is to draw some 'stairs like lines' between pore pressure and fracture gradient curves. The horizontal lines point out the casing setting depths while vertical ones show the hole section lengths. Naturally, such basic study will be independent of any formation properties and technical limits. Any formation characteristic like high permeability forces drilling team to set casing before its planned depth. Also technical issues like landing string specifications or surge pressures may also limit casing setting depths. As this thesis is not directly focused on casing design, those limitations will not be discussed in a detailed way.

As pore pressure and fracture gradient curves get closer, like in deep water environment, number of casings and liners increase (Simmons and Rau, 1988). As nature of drilling, each casing set in well decreases the wellbore diameter. So this diameter decrease will bring some hydraulic difficulties and may cause some operational problems. As a disadvantage of setting more casings, the number of critical operations increase, which results in longer operational days and higher cost.

A LOT result will affect the casing design as it will enforce horizontal and vertical lines in a casing design graph. As an open hole can go up to a pore pressure equal to previous casing shoe's fracture gradient, each LOT done after casing running operation will determine how much each hole section can go further. LOT result will dictate the maximum mud weight that can be used in upcoming hole section. Rezmer-Cooper, et al. (2000) suggests 0.3 ppg margin between mud weight and fracture gradient. If LOT result is lower than what was expected, a shorter open hole section can be drilled before setting a new casing. This will lead the operator company to set more casings which may cause not reaching projected TD. This may cause the drilling campaign to end before testing any predetermined targets in the well. Eventually, although millions of dollars was paid for the operation; any of the project‘s goals would not be reached.

2.3. How a LOT Is Executed?

LOT is a critical step for drilling operation, so preliminary works for a LOT should be done carefully. Same care should be taken during the testing period for eliminating any possible misalignments or any confusion. Postler (1997) listed the procedure for a LOT as below.

1. Have a realistic LOT result scenario: Before running a leak-off test possible fracture gradient should be studied by well planning engineers and G&G (geological & geophysical) specialists. Knowing expected results makes it easier for drilling engineers to comment on previous cementing operation quality or test result's sensitivity. Cautiously studied PPFG graphs will prevent any unnecessary LOT repeats or squeeze operations.

2. Be sure to have properly rigged up equipment: One of the key points of having a correct LOT run is to have correctly arranged testing system. Firstly, a smoothly working "Cement Pump" should be ready to be worked with. The reason for not picking regular rig pumps is their high capacity. Regular rig pumps are not preferred for LOT as they cannot handle low pumping rates, which are necessary for LOT. Cement pumps can easily pump 1/4 bpm or 1/2 bpm which are common pumping rates in oil industry. Secondly all rig lines should be perfectly sealed to eliminate any leaks in the system. Any possible leaking line cannot handle high pressures during LOT, therefore pressure drop will occur before the formation breaks down. Finally a good working pressure gauge is a must for having a realistic result from LOT.

3. Run test with clean, uniform testing fluid: To be sure that the result of a LOT is correct and reliable, testing fluid should be pure and proper for testing. As a certain height of cement column and few meters of new formation will be drilled before executing the LOT, the drilling fluid (also the testing fluid) will be contaminated by cement and cuttings. Especially, cement affects the rheological properties of testing fluid. It changes its compressibility or other characteristics. There are several methods for checking if the testing fluid is pure enough or not. Most technological way is to use LWD tools which senses hydrostatic pressure at well. If ESD value is equal to mud weight getting into the well, then testing fluid is ready to be used for LOT. Another way to check pureness of testing fluid is a manual procedure. If LWD is not present in BHA the mud technician and/or mud engineer can compare MW_{in} and MW_{out}. If they are equal to each other it means all cuttings and cement traces were filtered from the testing fluid. In either techniques mud technician and/or mud engineers should check and approve the rheological properties.

4. Pumping period: To have a proper LOT result, there are many key points that should be followed during pumping process. One of the most important elements during pumping is stability of pump rate. Cementing unit used for LOT should work efficiently and pump the testing fluid in same pump rate during whole test. Another important factor that should be checked continuously is pumping rate's itself. It should not be so high because of the risk of masking the real leak-off value. All items that affect LOT and that should be followed will be explained in the chapter of 'Factors That Affect LOT'.

5. Plot data during the test: Correctly plotting the 'pressure versus pumped volume' graph is one of the most critical parts of the LOT procedure. If a mistake is made during plotting of graph, it may affect whole well's upcoming operations as it will determine future sections' lengths. Each

operator company has its own LOT pumping policy so the graph plotting should be done according to their policy. Main difference between various companies' graphs is the unit pumping rate range. If a company refers to pressure readings per each 1/2 bbl, the LOT pressure versus pumped volume should be plotted with respect to that pump rate. Nowadays there are two different ways to record the pumping pressures and plotting related LOT graph. First method, which is executed via new generation cementing units, uses compatible software that can sense the pumping rates and pumping pressures. This kind of software can plot LOT graphs simultaneously as operation goes on and is mostly used in offshore operations. Second method can be called manual plotting and is generally preferred at onshore wells. As many onshore cementing units do not have compatible software, which can sense the pressures and pumping rates, drilling engineers or technicians record the pumping pressures from pressure gauge and plot it with dedicated office software like Microsoft Excel.

6. When to stop pumping: Determining when to stop pumping test fluid is vital. If pumping continues longer than it should, the formation will be fractured uncontrollably. Pumping should be stopped at any time after pumping pressure starts to decrease. If pumping is not stopped after observing pressure drop, the pressure will increase after a period of stability. At a certain point of this increase the formation will break down permanently where plastic rock deformation occurs (Mitchell, 1995). This plastic rock deformation will make fractures worse, which will decrease the leak-off value. A low value of leak-off means shorter hole sections and eventually more casing runs. Figure 4 shows an example for explaining how excess pumping affects the formation. A shut-in period, which shows if formation and cement can hold the pressure or not, follows the pumping procedure.

7. Shut-in period: Like pumping rate, each operator company has its own shut-in period policy. This period may change between 5 – 15 minutes. Usually 10

minutes waiting period seems enough for many operators to observe the quality of LOT results and cement bond at previous casing's shoe. If any cement channel is present, the pressure will drop significantly after pumps go off. Cement channel(s) forms a connection between the shoe level and another shallower hole section. Since, fracture gradient increases as depth increases, shallower hole sections have lower fracture gradient values. This connection via cement channel(s) will transport the pressure to weaker formations (shallow sections), so the leak-off value will be detected as shallow section's leak-off value rather than casing shoe depth. Any present cement channel(s) should be plugged by cement squeeze operation(s). Even if there is one cement channel, one cement squeeze operation may not be enough to plug it. After each cement squeeze operation, LOT is run again to see if operation plugged the channel or not. Once the cement channel(s) is plugged and necessary leak-off value is gathered, regular drilling operations may continue.

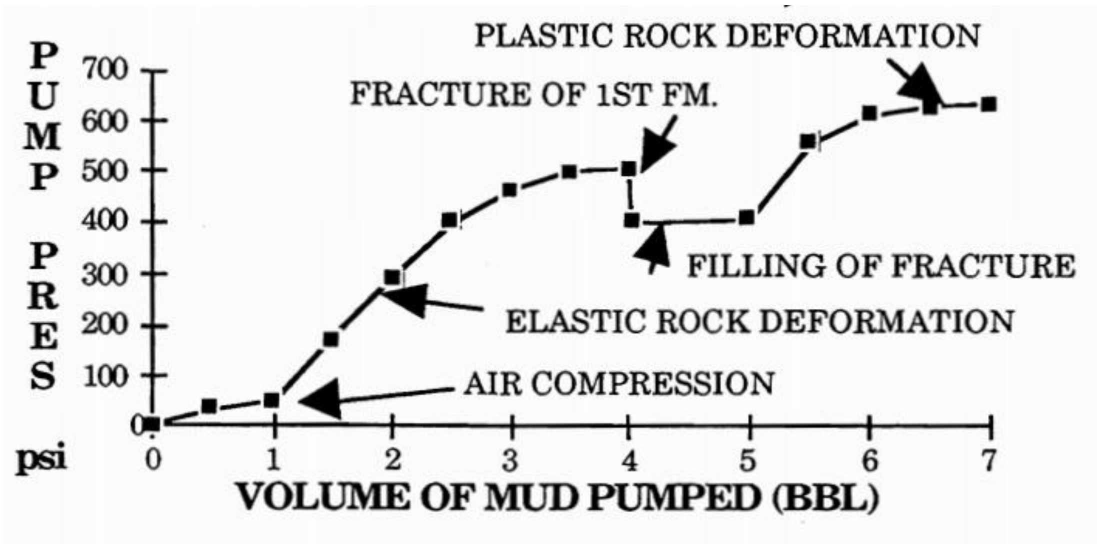

Figure 4 Graph showing effect of excess mud pumping during leak-off test (Mitchell, 1995)

2.4. Factors Affecting the Results of LOT

There are many factors that affect the LOT results. Some of these factors can be controlled by test executers and some of them cannot be done. Factors affecting the results of LOT are categorized into two and listed below in detail, based on the study of Postler (1997).

2.4.1. Factors that cannot be controlled:

a. Rock properties: The cement tensile strength and the bond between cement and casing string are usually greater than the bond between cement and wellbore wall. This is caused by the presence of mud cake (Zhou and Wojtanowicz, 1999). Since the newly drilled formations tensile strength will be weaker than cement tensile strength and cement bonds, can also be called as weakest section in tested system, it will be first one to be broken.

   Most of the formation types act as they are elastic until they are massively broken. While LOT procedure is going on, “initiation fracture pressure” is reached and the hole will be fractured for the first time. A bending in the linear increase at pressure graph should be interpreted as reaching to initiation fracture pressure (minimum principle stress) (Lin, et al., 2008; Rocha, et al., 2004). Then, pressure continues to increase up to “extension fracture pressure” where the already formed factures tend to extend and a significant decrease in pressure at LOT plot is observed (Fig. 4). Detournay and Carbonell (1994) indicate that in certain circumstances initiation fracture pressure and extension fracture pressure may be identical, but these conditions rarely occur.

Formations like salt and very unconsolidated shales “fail plastically rather than in brittle elastic failures”, and especially salt can start deforming plastically at levels of 10 – 20 % of its ultimate strength (Barker and Meeks, 2003).

As different types of formations have their unique characteristics, these properties are uncontrollable. Therefore, if all other conditions are optimum for the LOT, then formation rock properties will be the limiting factor for the leak-off test value.

b. Fractures at wellbore: By drilling operations’ nature the mud weight inside the well fluctuates continuously during drilling. This fluctuation may be caused by variable drilling rates or poor cutting removal capacity. The fluctuation in mud weight directly affects the hydrostatic pressure applied on wellbore. When the sum of hydrostatic pressure and the applied pressure (pressure occurred by pumping) exceeds the compressive strength, there will be pressure difference which tends to expand the wellbore. This expansion movement will cause some fractures or cracks. These formed fractures or cracks tend to act like weak formations during the leak-off test.

   Another way for having fractures at well is the formation’s itself. Some unconsolidated rocks may have naturally occurred fractures, cracks or vugs inside of them. Naturally occurred fractures and faults are listed by Altun, et al. (2001) as one of the factors influencing the results leak-off test. If a casing or liner needs to be set in these kinds of formations, the pressure build-up may end early during LOT.

c. Formation characteristics: Permeability is one of the most important factors affecting the LOT result. A permeable rock, like sandstone, has a lower break-down pressure than an impermeable one, like shale, has. If possible, casings or liners should not be set to highly permeable zones. If this is not possible, a high leak-off value should not be expected.

d. Test fluid properties: A test fluid is needed for LOT and this test fluid is the drilling fluid which is used during drilling operations. As a realistic leak-off value is needed for drilling and any possible well control situation, the drilling fluid needs to be used in LOT.

Since drilling fluid's rheological properties and other characteristics are enforced by the formations being drilled, the leak-off value is affected by these properties. For example, if a well with highly reactive shale formation is being drilled, most probably an oil-based mud is chosen because of its positive effects of reactive formations. However, oil-based mud is classified as a penetrating fluid, which causes a lower leak-off value. If a water-based mud is used instead of an oil-based one, because of its low penetrating property it will give a higher leak-off value under same conditions. IADC (International Association of Drilling Contractors) deepwater guidelines state that leak-off test results obtained by water-based mud may be 0,5 - 0,7 ppg higher than results obtained by oil-based mud (Rezmer-Cooper, 2000).

Another fluid characteristic affecting the leak-off results is viscosity. As viscosity increases, the pressure drop in the fracture increases. Viscous muds cause a time delay between the initiation and extension fracture pressures.

2.4.2. Factors that can be controlled:

The two affecting factors that can be controlled are explained as follows (Postler, 1997).

a. Pumping rate: The basic logic behind the LOT is pressurizing newly drilled formations up to limit where they start to fail. Since this pressurizing up process is done by pumping fluid down into well, pumping is the most important factor that affects the leak-off value.

   First of all, pumping rate is very critical. As previously mentioned each operator company has its own LOT pumping policy. 1/4 bpm pumping rate is preferred for impermeable zones, whereas 1/2 bpm is generally applied for permeable zones. The reason for picking slow pumping rates is to prevent any "masking" caused by high pumping rates. The higher the pumping rate, the higher the apparent leak-off value will be. Another reason for using slow rate is to observe how formation will act during long and slow circulations, like well control operations. Figure 5 shows an example how pumping rate affects the leak-off pressure.

   Another critical issue about pumping is the stability of pumping rate. Any fluctuations in pumping rate may cause a change in slope at pressure graph earlier than real leak-off pressure, which will lead a misinterpretation.

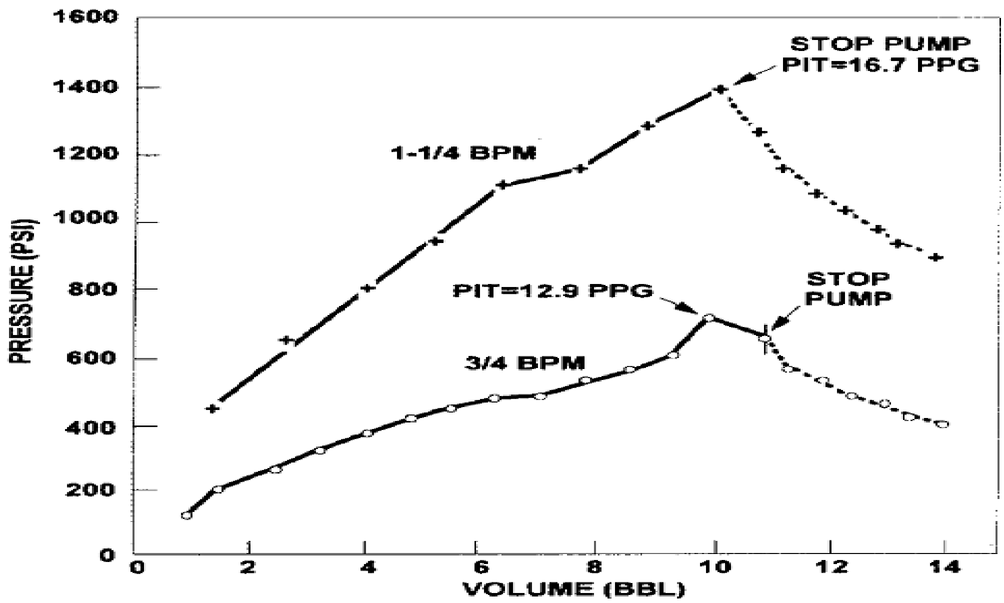

Figure 5 A hypothetical graph that shows effect of pump rate on leak-off test result (Postler, 1997)

b. Cement channels: A cement channel is a fluid path that let testing fluid pass through or around the cement to shallower zones which have lower fracture gradient. Cement channel is the most probable reason for low leak-off results. Generally, poorly directed cementing operations will end up with one or more cement channels. Another reason for having cement channel at casing shoe is inadequate centralization. As centralizers make sure that casing string is fixed at the center of the wellbore, they should be placed in casing string properly and in sufficient number. If centralization is not done carefully, casing string may lean on the wellbore and cement slurry will not be distributed equally inside the well.

One LOT result is not enough to comment on cement channel presence. LOT should be repeated to ensure that cement channel exists. A second test is necessary to observe if low leak-off result is caused by formation effects or by a cement channel. Postler (1997) states that +/- 0.5 ppg EMW difference between the actual and the predicted leak-off values can be considered as normal. Once difference between real leak-off value and predicted one is higher than 0.5 ppg, then a cement channel presence should be suspected.

There are few types of cement channels which are listed below.

i. Large and open cement channel: A large and open cement channel will not change any detail in a LOT graph but the leak-off value, which will be significantly lower than predicted value. There will be a deviation in pressure graph like in a normal LOT graph, but this deviation will be observed at a lower pressure value than it should be. Since a large and open channel directly transfers the pressure to weaker zones, the leak-off value will be interpreted to be lower than its normal value. A significant difference between predicted and tested leak-off values will give an idea about presence of a large and open cement channel. The effect of a large and open cement channel to a LOT graph is shown in the Figure 6 below.

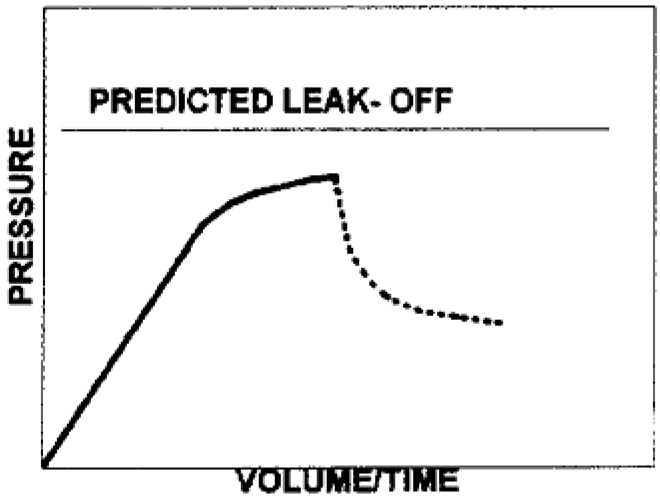

Figure 6 A sample graph showing the effect of large and open cement channel (Postler, 1997)

ii. Small and open cement channel: Differently from a large and open cement channel, deviation on pressure graph is observed twice during the pressurizing up period. The first one happens because of the low fracture gradient of shallower zones, when the second one is caused by the fracture gradient of formation at casing shoe. The reason for observing two different leak-offs is the characteristic of channel. Since a small channel restricts the flow, it lets the pressure build-up continue until the formation at shoe is broken. Figure 7 presents an example for the effect of a small and open cement channel.

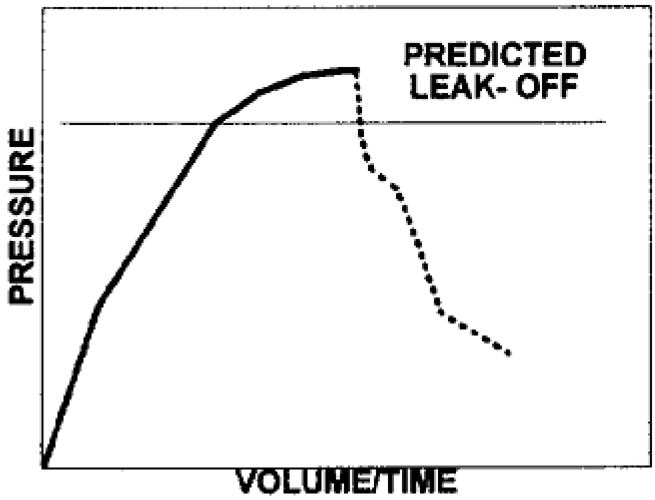

Figure 7 A sample graph showing effect of small and open cement channel (Postler, 1997)

iii. Plugged channel: Sometimes a cement channel is plugged by a plugging material like gelled mud. This plugging material blocks the cement channel until the already built pressure eliminates it and unplugs the channel. The pressure build-up continues until the plugging material is eliminated, which may not occur immediately. Once the channel is unplugged the weaker zone will be exposed to LOT pressure which causes a pressure drop because of weaker zone's low fracture gradient. After pressure drop is observed and pumps are stopped, the shut-in pressure will drop significantly which will show the major difference between final pumping pressure and weaker zone's breakdown pressure. After LOT plot indicates the presence of a plugged channel, a second LOT should be run to understand the characteristics of the channel, whether it is a large one or a small one. The following Figure 8 illustrates the example for the effect of a plugged cement channel.

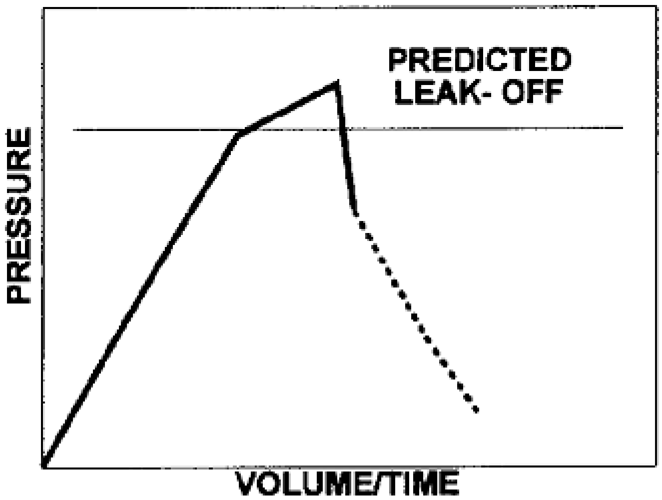

Figure 8 A sample graph showing effect of plugged cement channel (Postler, 1997)

Any cement channel should be filled up with cement by a squeeze operation, even if the leak-off result is enough for drilling. As soon as it is interpreted that a cement channel is present at casing shoe area, it should be immediately plugged. Because once it has been exposed to pressure during drilling, it may get worse and cause mud losses.

During drilling operations the operator may need to increase the mud weight because of a kick or instantaneously increasing pore pressure. While increasing the mud weight, the equivalent circulating density and annular hydrostatic pressure will increase proportionally. As equivalent circulating density increases it will get closer to shallower zone's fracture gradient, which is linked to the open hole via cement channel.

2.5. The Interpretation of a LOT

After a successful LOT process, next step is to evaluate this LOT to get realistic results. Correct interpretation lets operator to simulate how fracture gradient system acts, which will help upcoming operations. According to Postler (1997), a LOT interpretation includes following steps:

1. Estimate the leak-off: Once LOT graph is plotted; it gives a rough idea about the leak-off value. Draw the best fit line over the data starting from the second data point (the first one is usually affected by the air in mud and pumping system) to the point where a decrease occurs in the pressure increase slope. The end of this line shows the "minimum" leak-off value.

2. Evaluate leak-off pressure: The test result should be accepted if it is higher than the predicted leak-off value (within a range of 1/2 ppg). If pressure is lower than the predicted value, a cement channel may exist. To confirm the test result test may be repeated. It should be noted that leak-off prediction value may be incorrect; therefore it should be re-evaluated before deciding to run a squeeze job.

3. Evaluate shut-in: The shut-in curve of the leak-off test should be checked and carefully evaluated. The first inflection in shut-in data indicates the "Minimum Horizontal Stress". The evaluated leak-off value should be higher than MHS (Minimum Horizontal Stress). If any opposite indications are observed, the leak-off value can be ignored. If gauge pressure at MHS ≥ gauge pressure at leak-off, the result can be accepted. If gauge pressure at MHS < gauge pressure at leak-off, or if shut-in pressure does not level off above zero, a cement channel may exist. Re-running the test will help to confirm results. Most fractures require more than 10 minutes to get closed, especially in shales. Because of this, the shut-in period should be monitored for around 30 minutes (Kunze and Steiger, 1992).

4. Check for cement channels: Cement channels can be identified by observing following indications: the leak-off EMW is more than 1/2 ppg lower than predicted value, gauge pressure at MHS < 1/2 gauge pressure at leak-off or shut-in pressure does not level-off.

5. When in doubt, re-test: Apply the correct pump rate (if original pump rate is acceptable use the same rate again). Re-test, until the changes are apparent in the plot; and then evaluate the final unimproved PIT.

CHAPTER 3

STATEMENT OF PROBLEM

Leak-off tests are the tests commonly carried out to find the fracture gradient of a formation during drilling operations. The information obtained from these tests is utilized to estimate the maximum permissible mud weight that can be used during the drilling of a section. Although it is a common test that was carried by Turkish Petroleum Corporation long years both in South Eastern Anatolia and Thrace Basins of Turkey, there is no study to find the relationship between the test results and test parameters, such as mud weight of test fluid, depth and lithology of formation.

This study aims to collect the necessary leak-off test data from the archives of Turkish Petroleum Corporation, analyze the test results, group them and find the relationship between the test results and test parameters, if any.

CHAPTER 4

PROCESSED DATA

4.1. General Data

This part of thesis explains the details of data sets used for the current analysis. These data are gathered from TPAO Drilling Department archives (TPAO, 2011b) and processed internally. Each data set contains specific leak-off test information such as test depth, mud weight at test time, equivalent mud weight, mud rheological properties, etc.

The methodology followed during data collection process started with receiving an already formed leak-off test data list from TPAO Drilling Department’s Program and Optimization Directorate. This list was formed by well planning engineers as collecting separate leak-off data from several oil and natural gas wells drilled in Thrace Basin. The initial list was containing around fifty wells and most of the listed data was required to be checked by going over the sources for those data.

Initial process for checking the sources was achieving all reports of listed wells. Each drilled well has its own archive folder and this folder contains final drilling report, daily drilling reports, mud logging logs, composite logs, final well completion report and production report (only for producing wells). These reports were reviewed to confirm the data collected in original list. Unfortunately some of well folders do not contain mentioned reports. First step followed was to read final drilling reports to check if listed leak-off tests were mentioned or not. If yes, the final test rating (equivalent mud weight in ppcf or testing pressure in psi) was compared with listed data. In case of confirmation through information in final drilling report, the listed data were marked as confirmed.

Second step, where daily drilling reports were used, contains two different purposes. Primary one is to check unconfirmed listed data, through daily drilling reports. This would eliminate any problems of wells not having final drilling report or not having leak-off data mentioned in final drilling reports. Auxiliary aim was to re-confirm leak-off data which were written in list and confirmed via final drilling reports.

After confirming listed leak-off data through final drilling report or daily drilling reports, next step was to check the processing and evaluation procedures followed by drilling engineers who run the tests. Most common mistake done by drilling engineers is to consider top point of pressure graph as leak-off point. Edwards, et al. (1998) confirms that leak-off point is the point where the pressure-time plot deviates from linearity. Details of evaluation of leak-off test graph were explained in Section 2.5 LOT Interpretation. If a test performance graph was attached to final drilling report, it is easier to re-interpret the performed test. What was done in this step is to re-evaluate each present graph and change leak-off data recorded if necessary.

During data collection period, one other major data collected was mud weight values at test depths. The reason for pick mud weight data is to compare all relevant data between different wells and see if there is any relation between mud weights used and leak-off test results gathered. There are two main sources for mud weight data; daily drilling reports and mud logging logs. As evaluated wells were drilled in a spread time period (starting from 1981 to 2011), some data may be missing in daily drilling reports, especially for older wells. At this point mud logging logs were used as they show each and every detail about mud properties and drilling parameters.

While investigating for mud weight data to set a relationship between mud properties and leak-off results, an idea of analyzing mud rheological properties arose. The main purpose for collecting mud rheological data is the effect of some rheological properties on leak-off test result. Postler (1997) indicates that higher the drilling fluid viscosity, higher the delay time between fracture initiation and break-down point. Collected mud rheological properties are FV, PV, YP and pH.

One of the most important data collected during thesis work was casing setting depth. Setting depth is directly relevant to leak-off test results because as depth increases the overburden pressure of formations increase so do fracture gradient. Setting depth data is used to compare leak-off test results between wells with close casing setting depths. If two casing strings are set to similar depths in same formation it is expected to have results in leak-off test that are run in both wells. If one of either result differs significantly from the other, significantly different one should be investigated for wrong test procedures, default in interpretation or mistyping in records. There are two different sources for casing setting depth; daily drilling reports or well composite logs. Well composite logs show details about already drilled formations and their descriptions, exact formation contacts, any present faults in well, etc. Composite logs were used to confirm the casing setting depths by double checking with daily drilling reports or final drilling reports. To standardize casing setting depths rotary kelly bushing height and altitude of wells were subtracted from total depths. By doing this all starting depths was set to sea level so that all wells can be compared evenly.

Another data set collected through thesis work was formation thicknesses in each well. As Thrace Basin has a quite big area, in some parts of it some top formations eroded. This causes other formations to be in shallower depths which will eventually cause them having lower overburden gradient. Lower overburden gradient will bring lower fracture gradient which will naturally decrease leak-off test results.

Standardized depths were also applied in formation thicknesses. As starting point of formations change by standardization, their thicknesses also differ slightly.

4.2. Why Thrace Basin Was Selected?

The main reason for selecting Thrace Basin is because of its uniform structure in all over the Thrace peninsula. From Edirne to İstanbul all wells have same formation distribution unless they have reverse faults passing through them. Even a reverse fault passes through them it only makes two consequent formations get into other one mostly for few hundred meters. Only few of the examined wells for each specific formation had reverse fault causing this conjunction.

The main difference between Thrace Basin and other oil/gas fields is uniformity. South Eastern Turkey which contains many oil and gas fields in it has a complex and though structure. Even too close wells may differ in formation basis. This difference is caused by over faulting which affects whole region. This property directly affects all drilling operations and campaigns as too many uncertainties may occur during drilling.

4.3. How Were The Wells Picked?

Throughout all studies of this thesis work hundreds of well data and reports were examined and evaluated. All of them were drilled in Thrace Basin in a time period starting from 1960s to present. This wide range limited the accessibility to well data for some wells. The limitation is caused by either missing files or unwritten information in reports or change in drilling engineering approach.

During this study it was decided to keep source data list as wide as possible to have strong statistical results. This direct logic ignores the quality of data collected, assuming all of them are correct and valuable. Every well where one or more leak-off test(s) run were added to database list. Leak-off tests are mostly run in exploration wells in onshore operations. This eliminates most of the appraisal and production wells to be a candidate for database. Few of listed well contain inconsistent information in their files or reports. Unless those inconsistencies were eliminated, suspicious well data was not added to database. By doing this, shadowy data were intended to be crossed out.

4.4. Formations Seen in Thrace Basin

There are five different formations evaluated during this thesis work; Ceylan, Danişmen, Ergene, Mezardere and Osmancık. Below the main characteristics of mentioned formations are listed (Siyako, 2006). Figure 9 shows a generic stratigraphical cross-section of Thrace Basin.

4.4.1. Ergene

Ergene formation was firstly defined by Boer (1954 as cited in Siyako, 2006). Ergene formation consists of sandstone, claystone and milestone. It is mostly rich in plant and vertebrate fossils. Its age is Upper-Miocene.

4.4.2. Danişmen

Danişmen Formation was firstly defined by Boer (1954 cited in Siyako, 2006) and by Beer and Wright (1960 cited in Siyako, 2006). But this definition also included the Osmancık Formation in it. Ünal (1967 cited in Siyako, 2006) was the first one to define “Danişmen Shale”. Kasar et.al (1983 cited in Siyako, 2006) defined Danişmen as “Formation” because of homogeneity. Danişmen formation mostly consists of clay, claystone, sandstone and coal. Rarely it contains tuffite and limestone in it. Its age is Late-Oligocene.

4.4.3. Osmancık

It was firstly defined by Holmes (1961 cited in Siyako, 2006) in Ceylan-1 and Osmancık-1 oil wells, as "Osmancık - Ceylan Sandstone". Ünal (1967 cited in Siyako, 2006) described this unit as "Osmancık Sandstone" but Kasar et. al (1983 cited in Siyako, 2006) defined it as "Osmancık Formation" because of being non-homogeneous. It mostly consists of sandstone and shale. Limestone and tuffite are some other lithologies which are observed in Osmancık formation. Its age is Oligocene.

4.4.4. Mezardere

Ünal (1967 cited in Siyako, 2006) was the first one to define "Mezardere Shale" in Mezardere-1 well. Mezardere belongs to Yenimuhacir Group. Kasar et. al (1983 cited in Siyako, 2006) defined this unit as "Mezardere Formation", relying on having different lithologies than shales in it. It contains shale, marl and rarely sandstone layers in it. Its age is Late Eocene – Early Oligocene.

4.4.5. Ceylan

Ünal (1967 cited in Siyako, 2006) firstly defined "Ceylan Shales" in Northern Thrace wells. It was described as "Ceylan Formation" by Keskin (1974 cited in Siyako, 2006) again in Northern Thrace wells. Ceylan formation consists of mostly marl, shale, clayey limestone and rarely turbiditic sandstone-shale and tuffite. Its age is Late-Eocene.

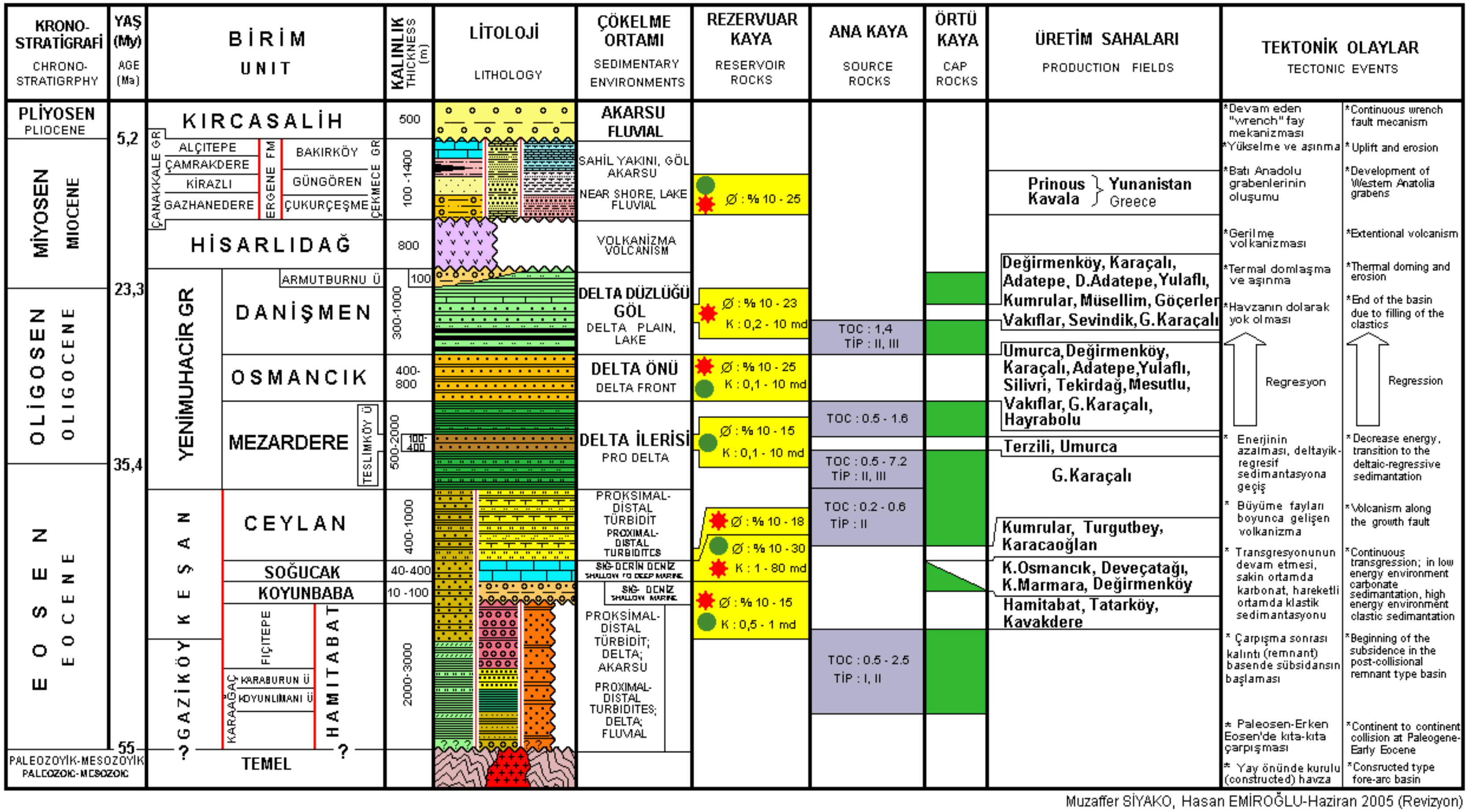

Figure 9 Stratigraphical cross-section of Thrace Basin (TPAO, 2011a)

4.5. Which Method Was Used To Interpret Wells' Data?

After each well data was collected and distributed finely, the next step was to establish a method for interpreting the relation between wells and leak-off test results. Many ways were tried out to set a process for distributing wells. In all methods ppcf unit was preferred for mud weight and equivalent mud weight as it provides more sensitive results compared to ppg unit.

First of all, idea of grouping relatively close wells together was arisen. All wells were marked on map to see how far the wells from each other. At the end of this practice the result was not so promising, only two gas fields (V. gas field and K. gas field) with around 10 wells in each of them. As this will eliminate many of the wells in different and remote fields, this idea become useless for this thesis' purpose (Fig. 10).

Secondly, all data was distributed in two dimensional graphs, like MW vs. EMW, Depth vs. EMW, FV vs. PV, etc. As graphs formed some correlation between identified data was observed. At this point all graph combinations were modeled in MW - EMW - Depth group and PV – YP – FV – pH group. This means first group and second group were simulated internally for all two dimensional graph combinations (Fig. 11 & Fig. 12). Two dimensional graphs were drawn as plots containing all geological formations' data in same graph.

After some discussions about the limitations caused by using two dimensional graphs, it was decided to use depth as fixed third axis to form three dimensional graphs. It was thought to be more useful to visualize relationship between similar wells, but difficulty in visualizing three dimensional graphs on two dimensional screen/paper eliminated chance of data evaluation in different perspectives (Fig. 13). Three dimensional graphs were created for each geological formation separately.

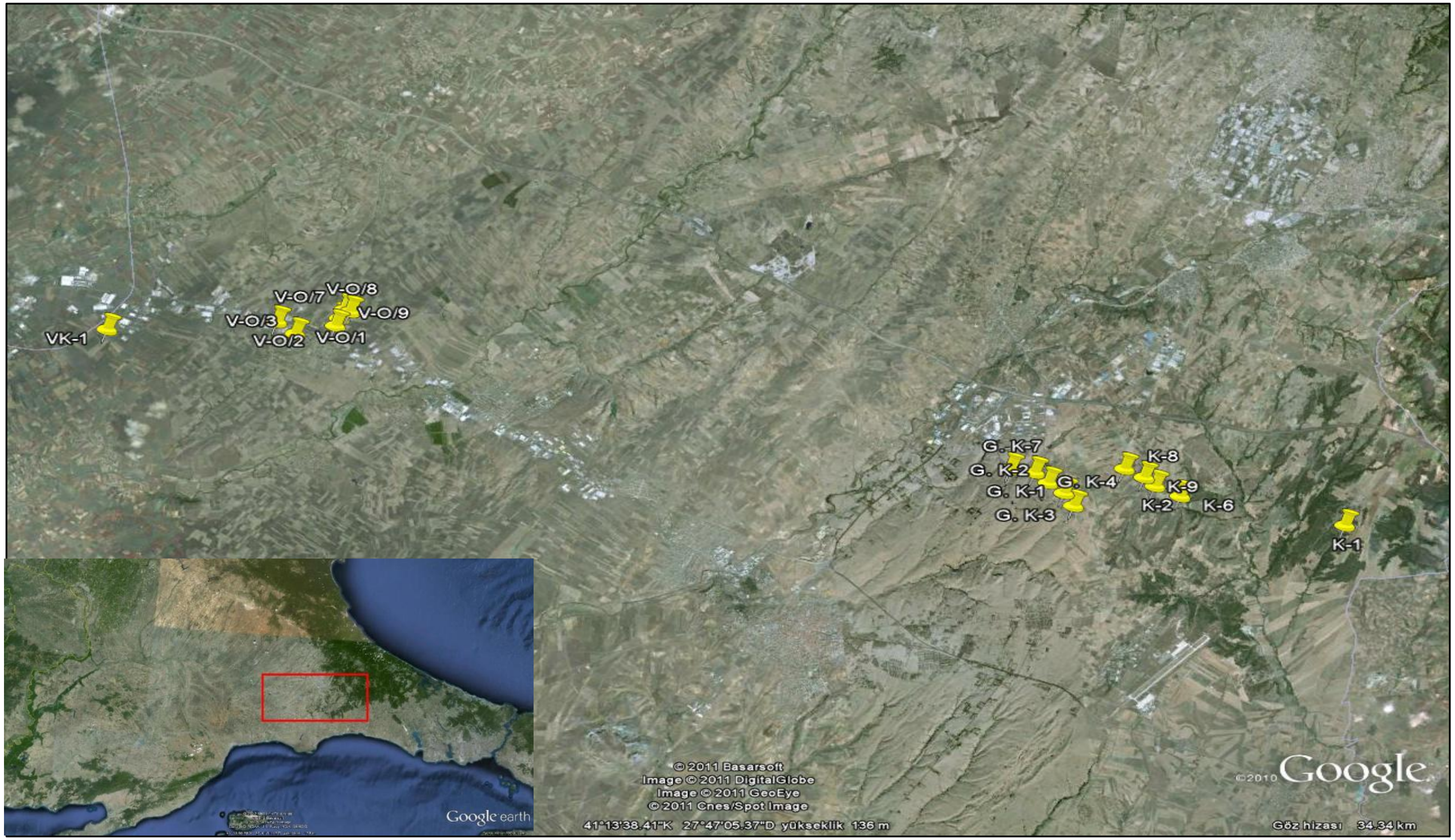

Figure 10 Map of two gas fields having close wells internally

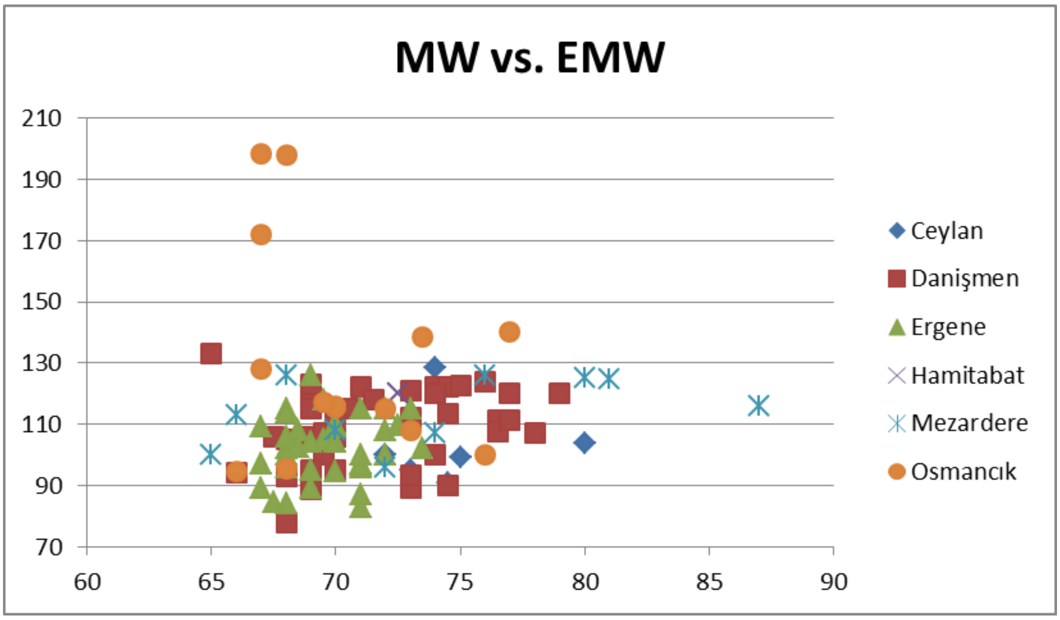

Figure 11 An example of statistical scatter graph (MW vs. EMW)

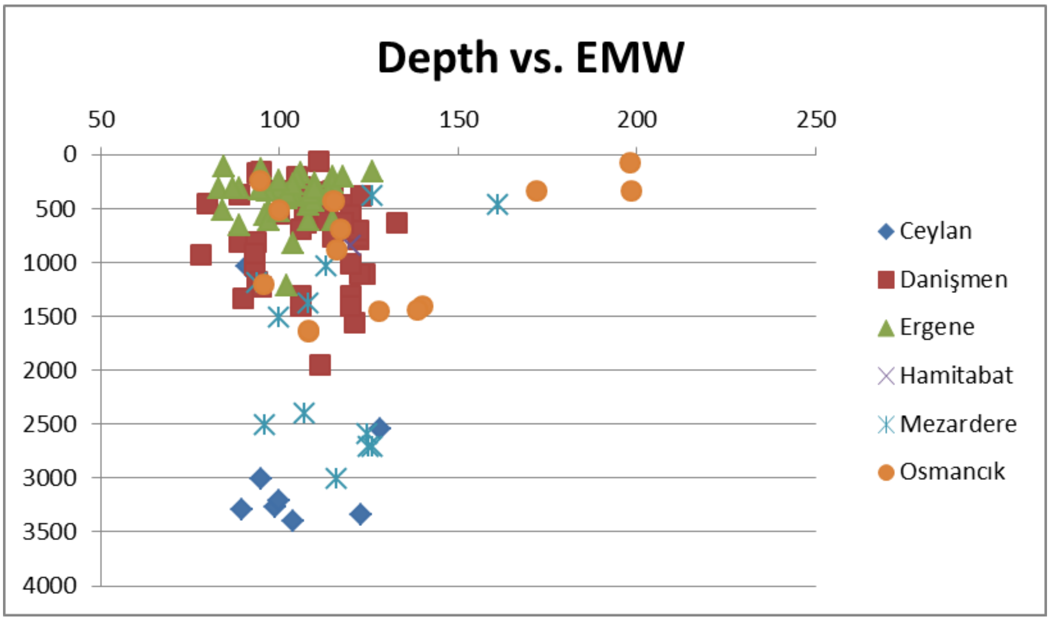

Figure 12 An example of statistical scatter graph (Depth vs. EMW)

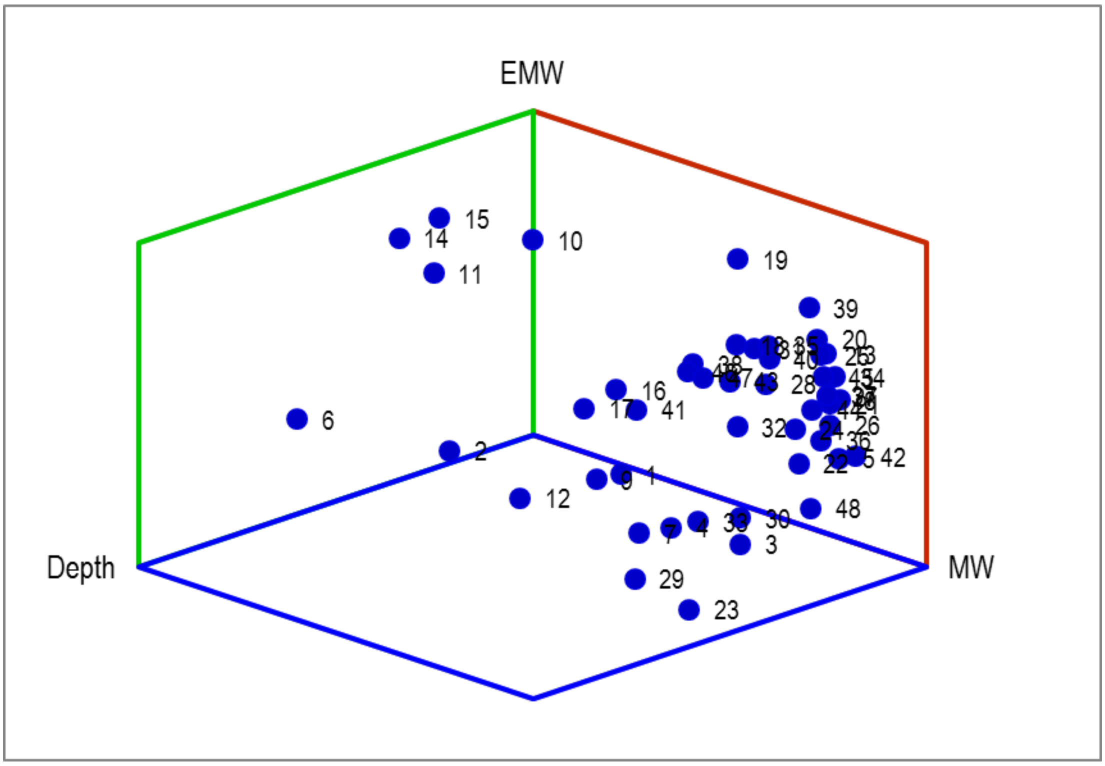

Figure 13 An example of 3D statistical scatter graph (Depth - MW - EMW)

As it can be observed easily none of the above methods cover wells' coordinate data. None of them could help to enlighten the relation between the wells' location on map and MW, EMW or other data. The study was directed to find a better method to find relation between all data collected throughout this study. After some discussions, it was decided to create a cross-section of Thrace Basin. This method was applied for each separate formation data set without combining all wells' data.

The method can be simply explained as, for each formation data set, marking wells' locations on map and drawing a mid-line passing through them. Wells were numbered according to their alphabetical order. Same well in different formation data sets was shown with same number to maintain consistency throughout the study. The reason for drawing such a line is to eliminate any far wells (15 km limit was used for this study) that may deflect the general trend of wells. Wells which are out of 15 km range were shown with letters on maps. Below is an example for drawing a mid-line through a set of wells (Fig. 14).

Next step is to create a cross-section chart passing through the mid-line. As nature of mid-line, most of the wells are not exactly on mid-line. To form a cross-sectional chart, projection of each non-linear well was plotted on mid-line. By doing this every well was flagged on mid-line. The cross-section chart should show the total depths, formation thicknesses and mud weights used; for determining any present relationship between the location of well, formation depth, mud weight used and test result. A sample cross-section chart can be found below (Fig. 15).

Final step for processing collected well data is to evaluate the final result of studies. As result (cross-section chart) include many variables in it (relative well location, formation thicknesses, mud weights used to drill sections and equivalent mud weight), it should show any existing relationship between investigated parameters.

Correlation function was used to prove any existing connection/relation between two variables like depth, mud weight or equivalent mud weight. It shall be reminded that correlation value is between -1 and 1. The closer the value to any of the ends the higher dependent relation between two compared variables is observed. As result value gets closer to 0 it means there is a low dependency between compared variables. Two different correlations were investigated, between depth and EMW and between test MW and EMW. The wells that were eliminated in mid-line method were not considered in correlation calculations.

$$Correl\ \ X,Y\ = \frac{N\sum xy - (\sum x)(\sum y)}{N\sum x^2 -\ \sum x\ ^2\ [N\sum y^2 -\ \sum y\ ^2]} \tag{4.1}$$

Where:

N = number of pairs of investigated parameters

$\sum xy$ = sum of the products of paired parameters

$\sum x$ = sum of x parameters

$\sum y$ = sum of y parameters

$\sum x^2$ = sum of squared x parameters

$\sum y^2$ = sum of squared y parameters

A sample calculation for correlation function:

Data set:

Well #	Test MW	EMW
1	72	96
2	81	124,5
3	74	107
4	87	115,92
5	110	123
6	76	126
7	80	103,7
8	75	110

Step 1: $\frac{8*74651.54-655*906.12}{\sqrt{(8*54691-429025)(8*103461.39-821053.45)}}$

Step 2: $\frac{597212.32-593508.6}{\sqrt{(437528-429025)(827691.12-821053.45)}}$

Step 3: $\frac{3703.72}{\sqrt{56440.1}}$

Step 4: $\frac{3703.72}{7512.663}$

Result: 0.492998

After chasing for relation between depth and EMW and test MW and EMW some evaluation was done to investigate if leak-off test results were used properly in drilling operations or not. The method used for this investigation is to compare the equivalent mud weight with mud weight range between casing run where used leak-off test was executed and next casing run. This range shows how effective leak-off test results were used to optimize drilling operations. The study mainly focused on if drilling after each casing operation continued up to technical limit caused by leak-off test result or was ended earlier. Each wells' leak-off test result, test mud weight and maximum mud weight used in next hole section is set on chart to observe if used mud weight values were close to equivalent mud weight values or not.

It should be noted that no stress data were available for investigated wells. In this thesis no study was done for stress estimation of investigated wells.

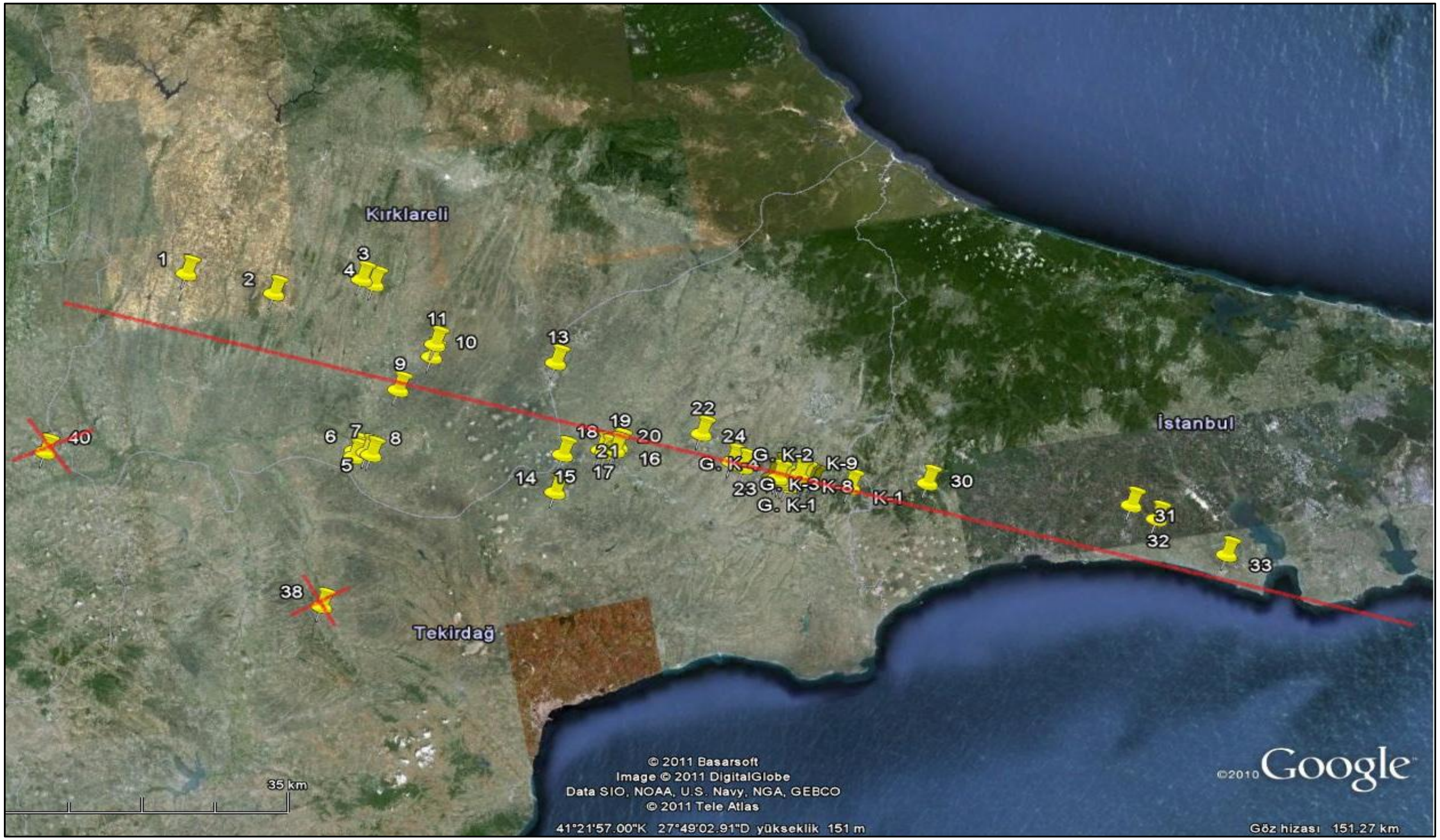

Figure 14 A sample map showing mid-line drawn and eliminated wells

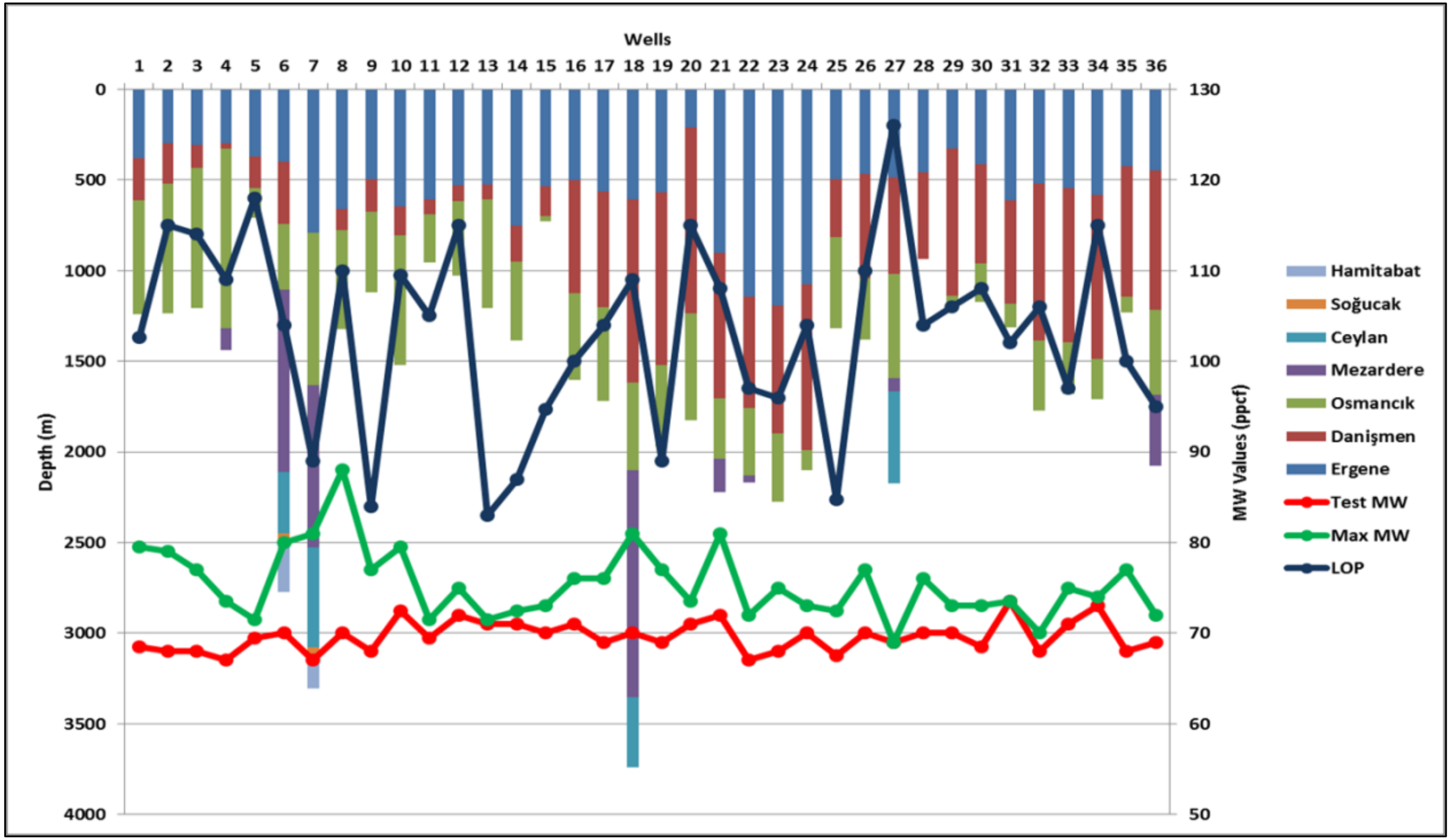

Figure 15 A sample cross-section of wells showing formation thicknesses

CHAPTER 5

RESULTS AND DISCUSSIONS

All studies of this thesis work were directly dedicated to find a relation between leak-off test results gathered in oil/natural gas wells in Thrace Basin and test depth and test mud weight. During data searching, data collection, filtration and evaluation many interesting results arose. These results should be the first step for other more detailed studies about Thrace Basin's properties and activities in Thrace Basin.

5.1. General Results and Discussions

It is hard to generate general results for whole Thrace Basin area, as it includes an area of 133.080 km^2 with many reservoirs in it. One other reason for having difficulty to raise a common model/result for area is because of data used. All collected leak-off test data were acquired from different sub-areas of Thrace Basin and from different geological formations, which have completely different characteristics. As different places on earth have different pressure behaviors no one should expect a generic modeling for whole Thrace Basin area. Rather than working for such results, this study focuses on generating models/results for each different geological formation.

For each different evaluated formation, a conclusion chart has been produced, which intends to show any possible relation between collected well data. It should be noted that some data are directly relevant to well's conditions but some are speculative because of its dependency on interpreter's comments. This directly affects the results and may cause prognosed model/result to deviate. Below are the formation specific results.

5.2. Formation Specific Results and Discussions

5.2.1. Ergene Formation

Ergene formation mostly consists of claystone and sandstone in it. In most of Thrace peninsula Ergene formation is observed at surface, in case it was not eroded in geological timeline. Generally it was eroded in south-east section of Thrace peninsula (as gets close to İstanbul). Detailed definition and explanation of Ergene formation had been given in Section 4.4.1. Figure 16 shows the wells used and eliminated for Ergene formation study.

While investigating the relationship between mud weights used during LOT and equivalent mud weights an unexpected result was observed (Fig. 17). It was revealed that there is a little relation between mud weight used in LOT and equivalent mud weight (result of LOT). It can easily be seen at Figure 18 that the test mud weights differ between 67 ppcf and 73 ppcf which is not a big difference. Hence the equivalent mud weights differ between 83 ppcf and 126 ppcf. The difference between two separate fluctuation models shows the weak connection between mud weight and equivalent mud weight. This misconnection is also proven by correlation function run between these two variables. The result is 0.209 which directly shows low relation level.

Another unexpected result was observed in relation between depth and equivalent mud weight. It is expected to have higher equivalent mud weight values as depth increases in same formation but the results move in opposite way. In Figure 18 it can easily be seen that the equivalent mud weight does not change linearly as depth changes. Same equivalent mud weight can be calculated in 274m in one well and 818m in another one. Also different LOT results (equivalent mud weight) can be calculated in close depths. For example in well #13 83 ppcf equivalent mud weight was gathered at 307m where in well #2 115 ppcf was gathered in 367m. This kind of big difference is not expected in such short depth differences. Correlation function run for depth and equivalent mud weight gives result of -0.134, which directly shows the significant weakness in connection between depth and equivalent mud weight.

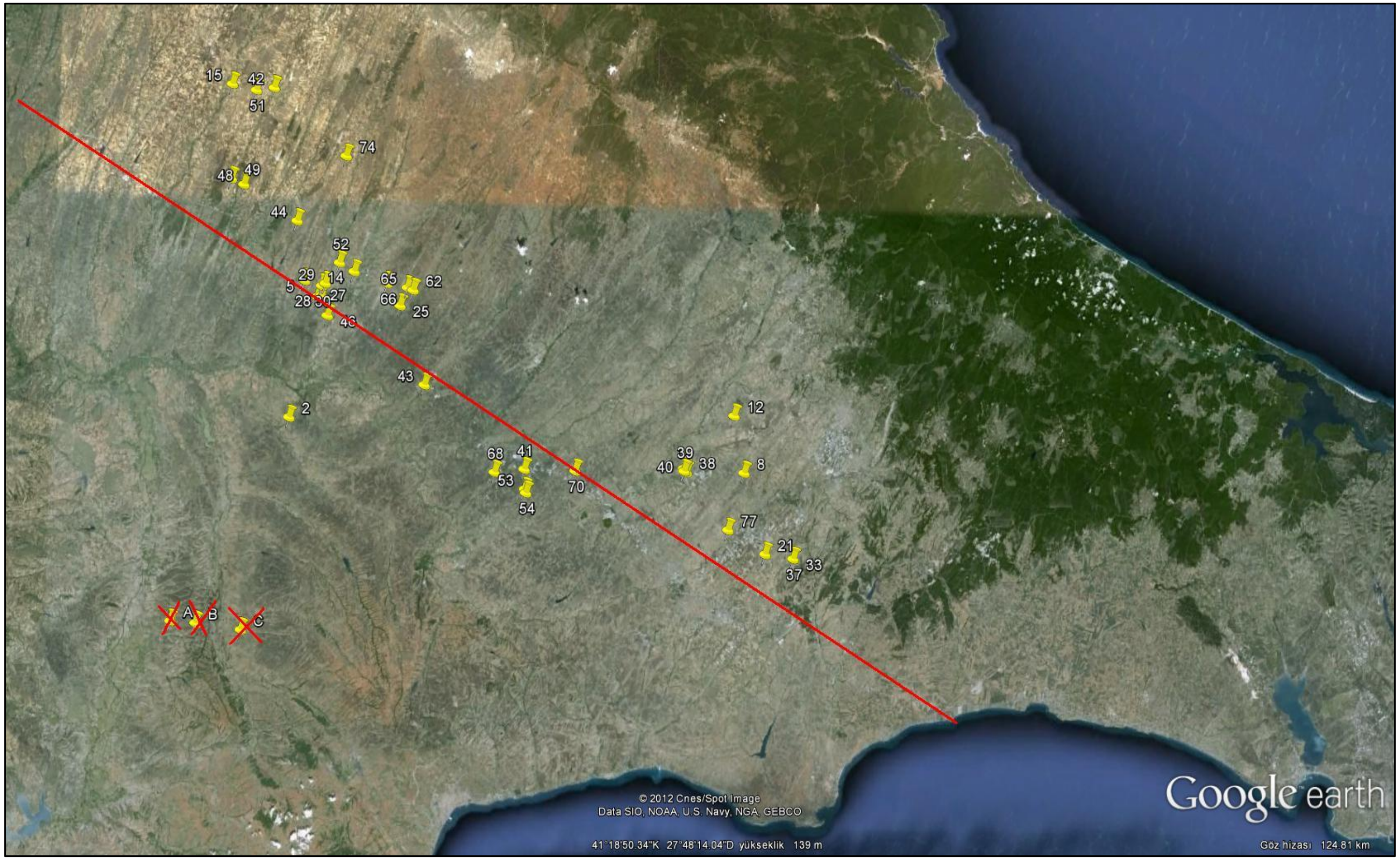

Figure 16 Map showing used and eliminated wells for Ergene formation

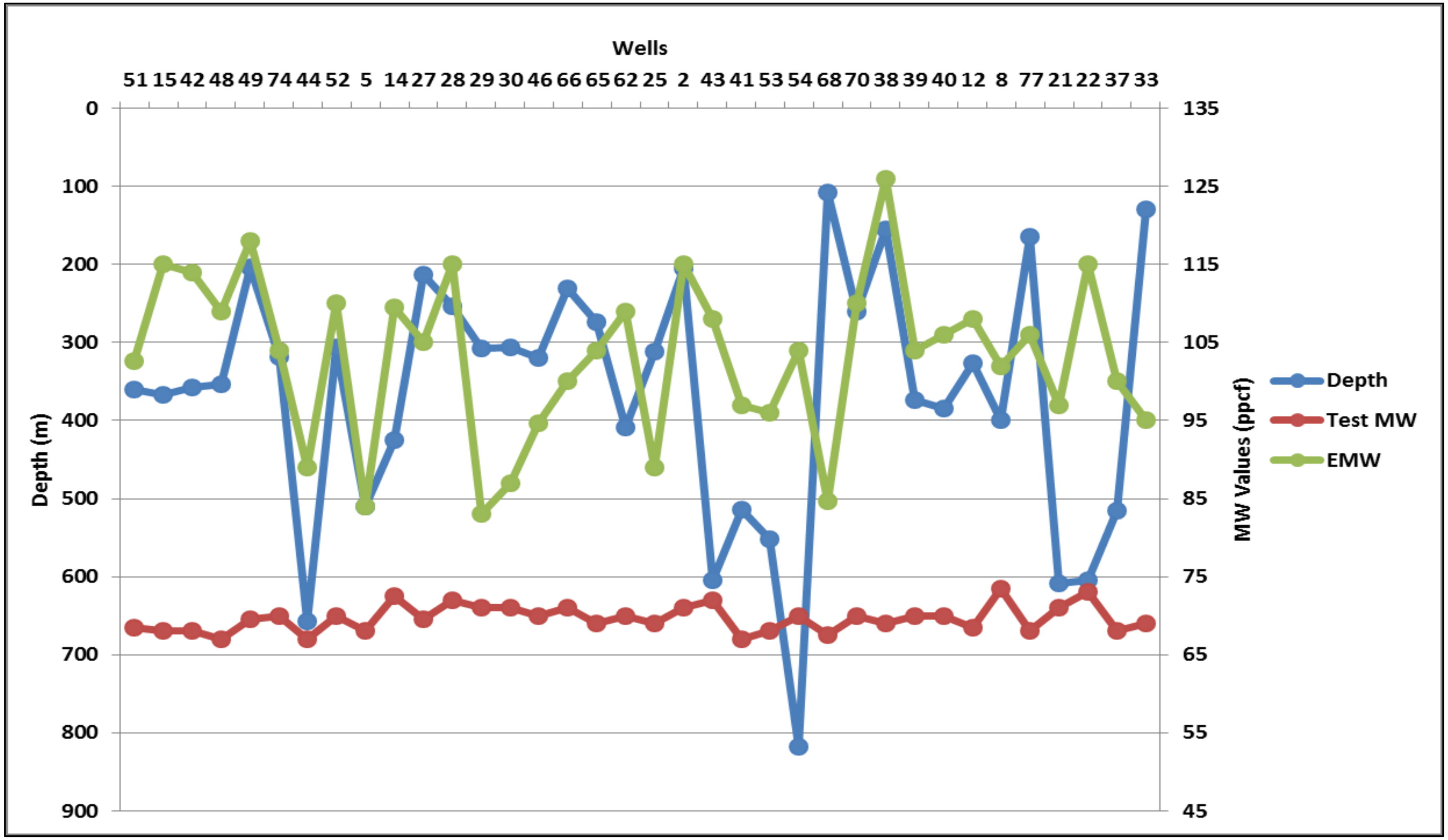

Figure 17 Chart showing relation between MW - EMW and Depth – EMW in Ergene formation

After investigating any existing relationship between depth and equivalent mud weight and test mud weight and equivalent mud weight next study was executed about evaluating drilling activities done after investigated leak-off tests.

As Ergene formation is the first formation to be drilled mud weights used during drilling operations were not high generally. Average value for maximum used mud weight is 75 ppcf where average leak-off pressure value is 103 ppcf. In Figure 18 it can be seen that closest difference between maximum mud weight used and equivalent mud weight is in well #8 and it is 22 ppcf, which corresponds to a significant difference in drilling terminology. This difference observed in all wells investigated in Ergene data set clearly shows that drilling operations did not need to push drilling parameters to limits, which is equivalent mud weight in this case. Since Ergene is the shallowest formation and following formation, Danişmen, is not a possible hydrocarbon bearing formation, drilling operators did not need to increase mud weight, which is possibly an economic decision. None of the data should be investigated without considering practical issues of drilling. If drilling program derived by geological targets and instantaneous drilling conditions force drilling operators to set casing earlier than reaching to fracture gradient limit of previous casing shoe then the operation should be done accordingly. Casing shoe fracture gradient is not the only criteria for casing running, especially at onshore wells.

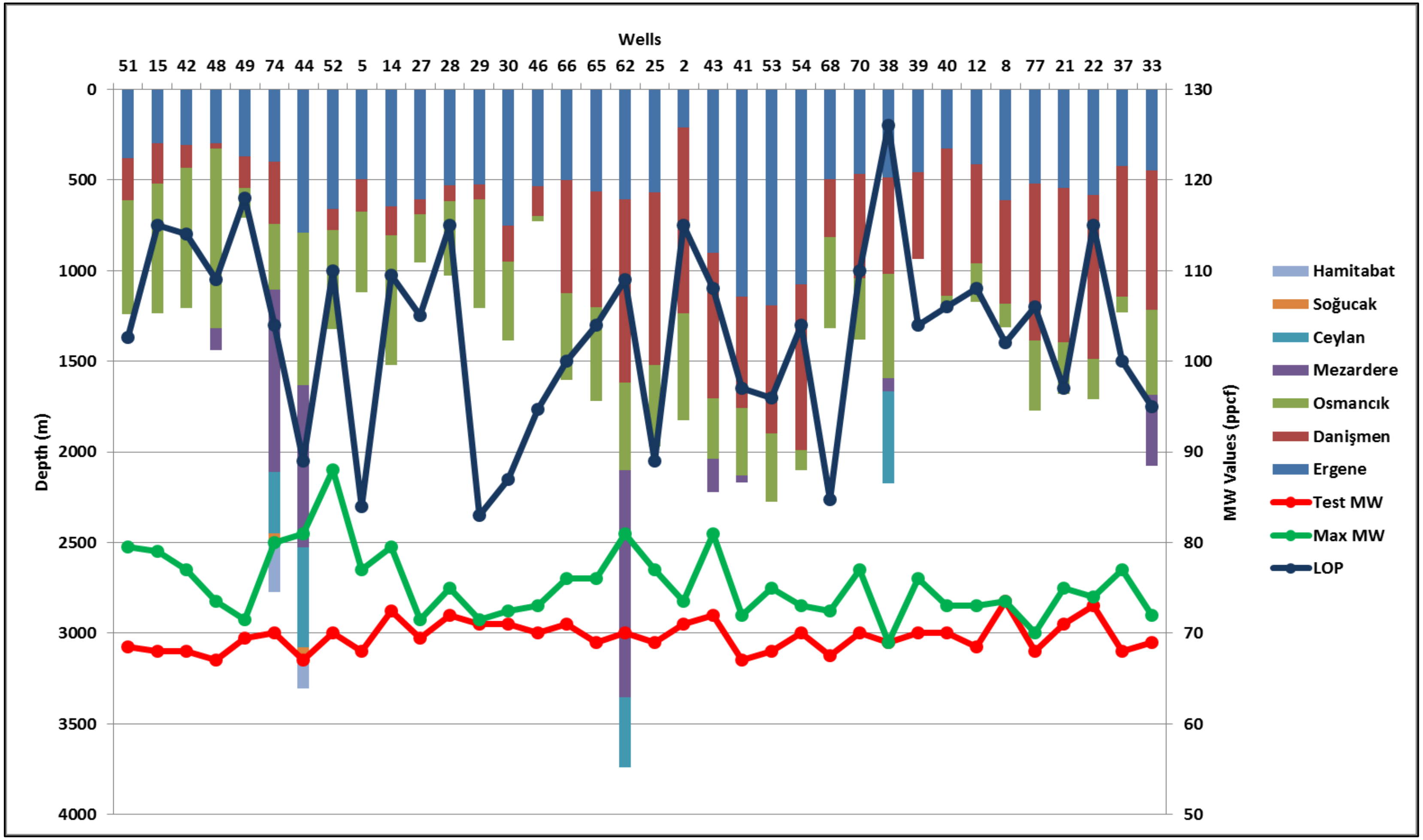

Figure 18 Chart showing details for wells where LOT was run in Ergene formation

5.2.2. Danişmen Formation

Danişmen formation usually consists of sandstones, coal layers, shale and claystone in it. It is generally observed after drilling Ergene formation which is at the top of all other formations unless erosion happened in geological history. It is a non-hydrocarbon bearing formation which sometimes acts as seal for lower reservoirs. Detailed definition and explanation of Danişmen formation had been given in Section 4.4.2. Figure 19 shows the wells used and eliminated for Danişmen formation study.

As studies were steered to evaluate the relationship between mud weights used and equivalent mud weights (leak-off test results) in Danişmen formation, it was discovered that there is no significant relationship between these two terms. It can easily be seen in Figure 20 how different both of them change independently. It should be noted that the equivalent mud weight values may have changed if any other drilling engineer had interpreted them. It is highly dependent on how leak-off test was run or who interpreted the results. In this study all collected and reviewed data were considered as correct, so all results and discussions should be judged by reader accordingly. Another proof for not having direct relationship between mud weight and equivalent mud weight is correlation value between leak-off test mud weight and equivalent mud weight. Correlation value was calculated as 0.193 which shows a little inter-connection between these two parameters.

Another interesting result from studies was about relation between depth and equivalent mud weight. It is expected to have higher equivalent mud weights as leak-off tests are conducted get deeper. But it can be observed that equivalent mud weight values do not change much when depth changes significantly (Fig. 20). For example in well #14 the test depth was 1,946 m but the equivalent mud weight was still 111.4 ppcf, which was observed in shallower parts of other wells. Correlation value of 0.0083 also exposes this misalignment between these two parameters.

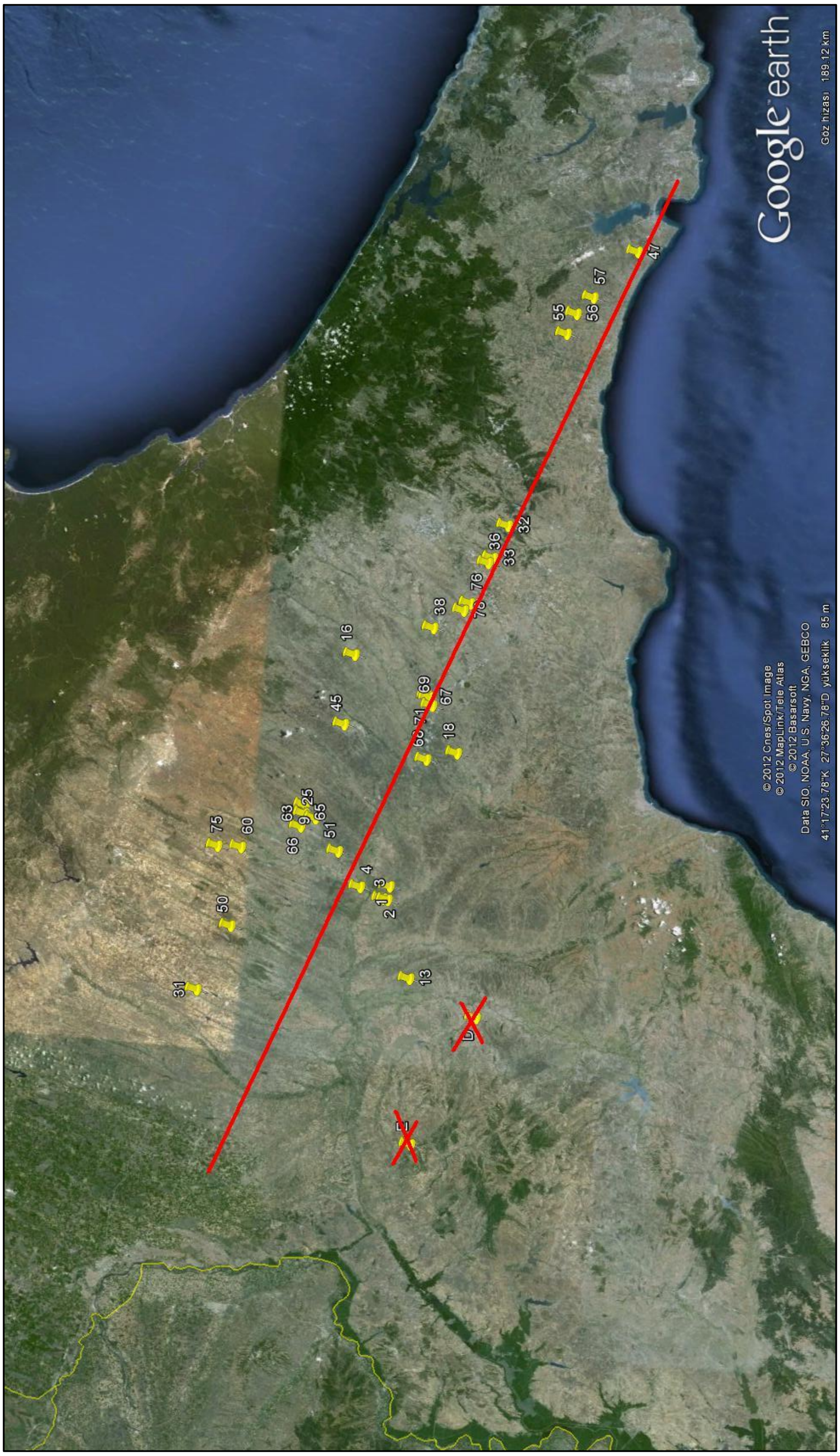

Figure 19 Map showing used and eliminated wells for Danişmen formation

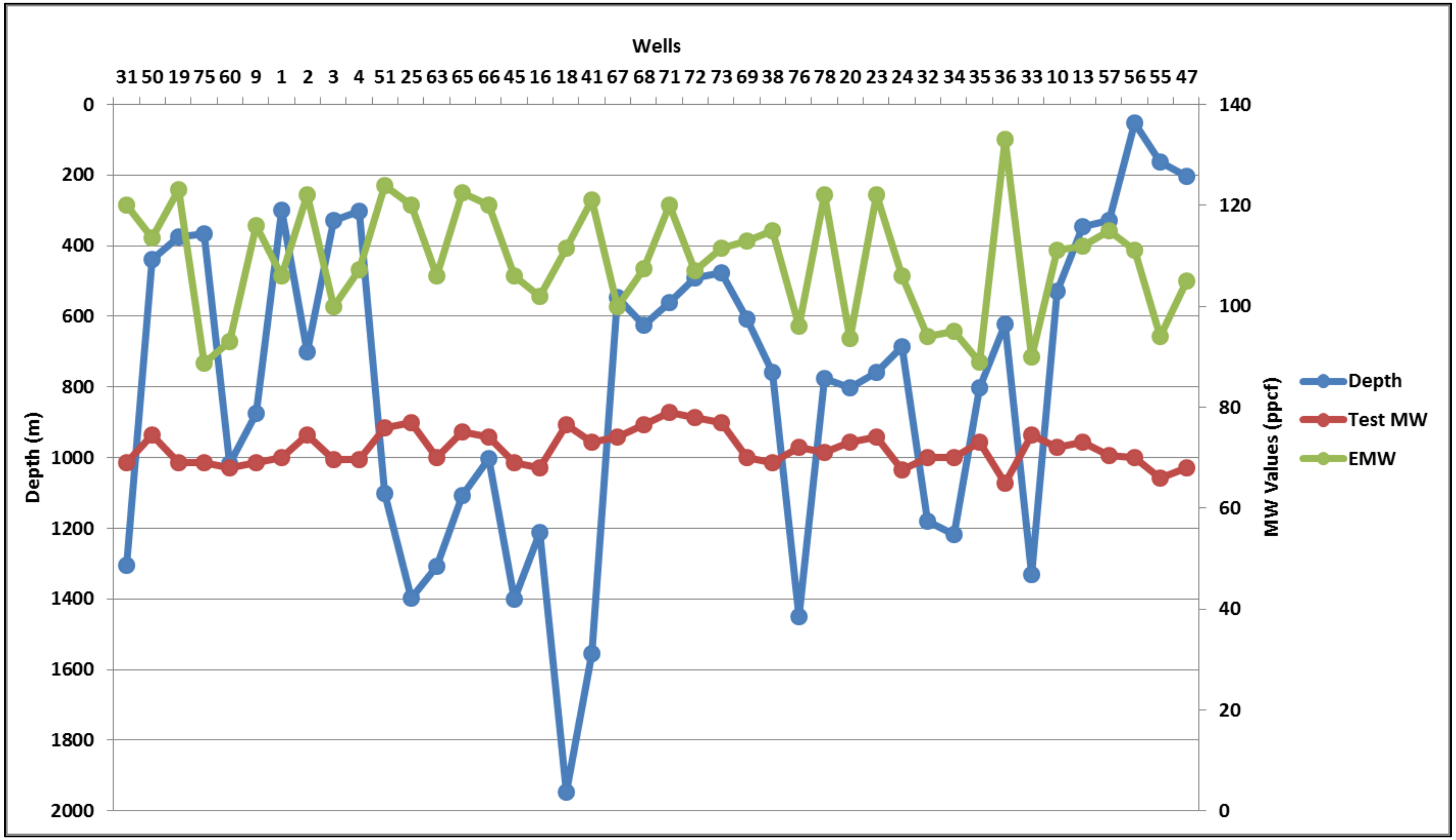

Figure 20 Chart showing relation between MW - EMW and Depth – EMW in Danişmen formation

For investigating drilling activities done after setting a casing in Danişmen formation leak-off test results and mud weights used until next casing run were studied. Main criteria of investigation was comparing maximum mud weight used in that hole section and equivalent mud weight, looking for if mud weight values are close enough to leak-off test results to dictate running a new casing string.

Just as in Ergene formation, maximum used mud weight values in Danişmen formation are also lower than equivalent mud weight values. The main difference between investigated Ergene wells and Danişmen wells is having less mud weight difference in Danişmen wells. Main driving force for using higher mud weight values is having Osmancık formation as consequent geological formation. Osmancık formation is the main hydrocarbon bearing formation in Thrace Basin. Especially this decrease in mud weight values are observed in wells drilled in gas fields.

In Figure 21 it can easily be seen that in wells #20, #21, #22, #23 and #24 maximum used mud weights are quite close to equivalent mud weights values gathered from leak-off tests. When these wells were investigated it was observed that these wells belong to a producing gas field and the reason for increasing mud weight was crucial because of having continuous gas influx. Smallest difference between mud weight and leak-off test result was observed at well #34, which is another gas producing well.

It should also be noted that in well #35the equivalent mud weight is significantly higher than close wells (wells #32, #33, #34 and #36). This may show a misinterpretation.

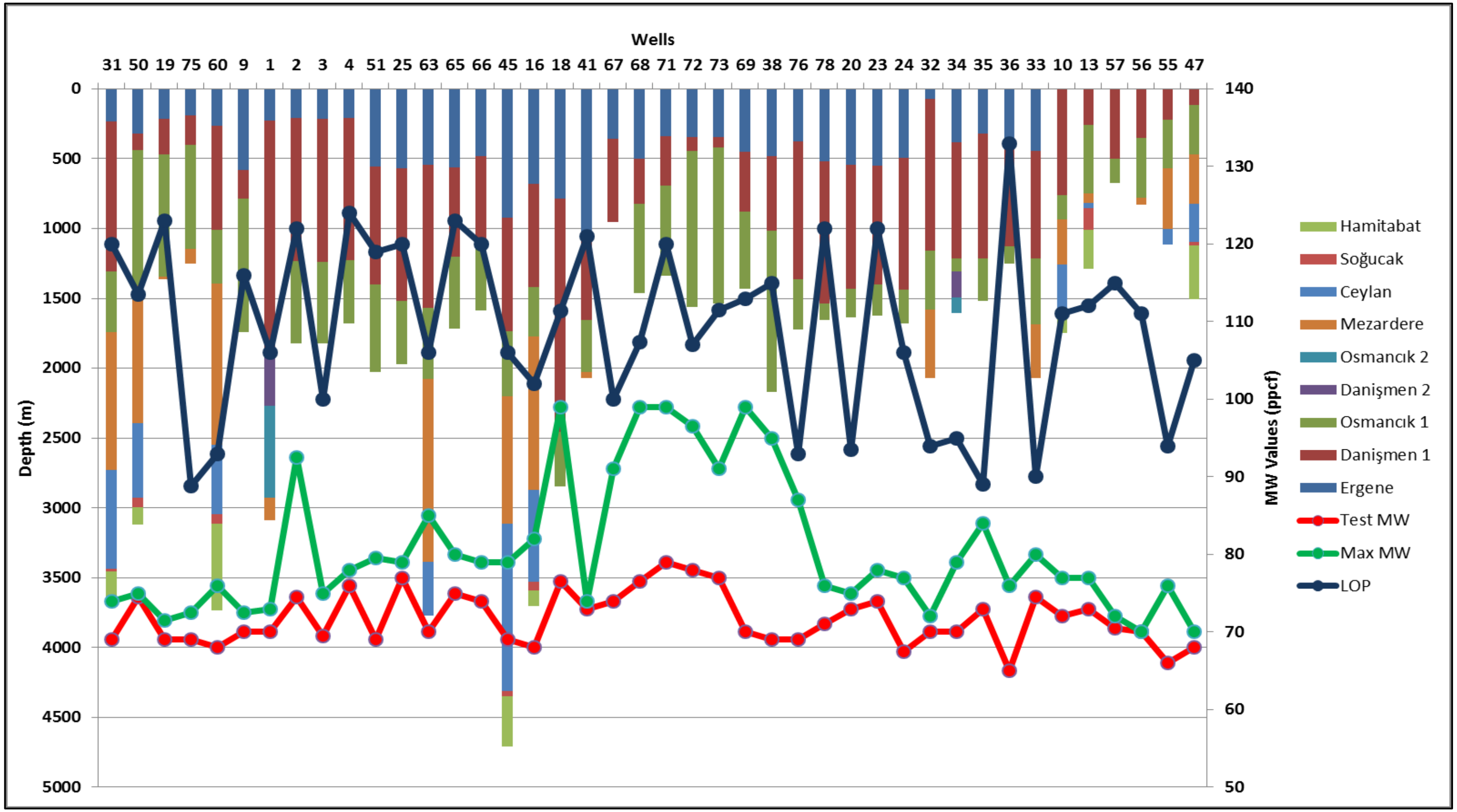

Figure 21 Chart showing details for wells where LOT was run in Danişmen formation

(Osmancık 2 and Mezardere 2 shows the interbedded formations)

5.2.3. Osmancık Formation

Osmancık formation mostly consists of sandstone and shale in it. It is drilled after Danişmen formation. Even Ergene and Danişmen formations may have been eroded Osmancık formation was observed in all wells that were investigated in this study. As Osmancık is a possible hydrocarbon bearing formation mostly casing is set before entering into it during drilling operations. This causes less data for LOT which requires casing set into formation. Detailed definition and explanation of Osmancık formation had been given in Section 4.4.3. Figure 22 shows the wells used and eliminated for Osmancık formation study.

During studies on wells where casing set into Osmancık formation, it was observed that the relation between test mud weight and LOT result (equivalent mud weight) is stronger than Ergene and Danişmen formations. The examined 9 wells showed a 0.42 result for correlation between these two parameters. This is significantly higher than previous two formations where the relations were low. Figure 23 shows the relation between test mud weight and equivalent mud weight. As it can be observed from the chart test mud weights are changing in a range of 66 ppcf and 77 ppcf where equivalent mud weights are between 95 ppcf and 140 ppcf.

Another interesting result from study on Osmancık formation is about relationship between test depth and equivalent mud weight (LOT result). In previous two formations (Ergene and Danişmen) the relation between depth and equivalent mud weight were very low where in Osmancık formation this is directly in an opposite way. The result of correlation function between depth and equivalent mud weight is 0.526 which is a significantly high value showing a strong connection. In Figure 23 it can easily be observed that the equivalent mud weight increases where the test depth is deeper than other investigated wells.

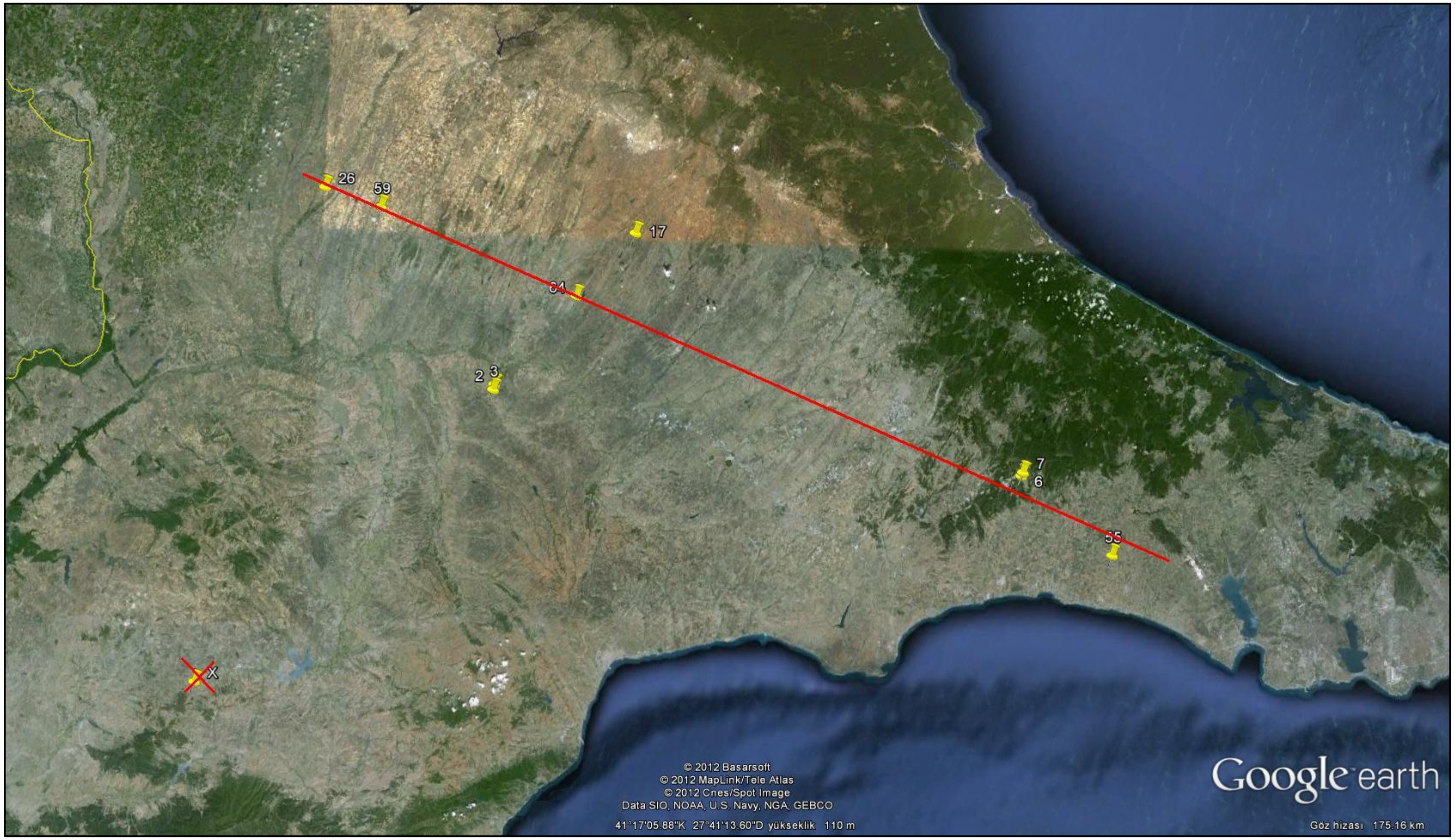

Figure 22 Map showing used and eliminated wells for Osmancık formation

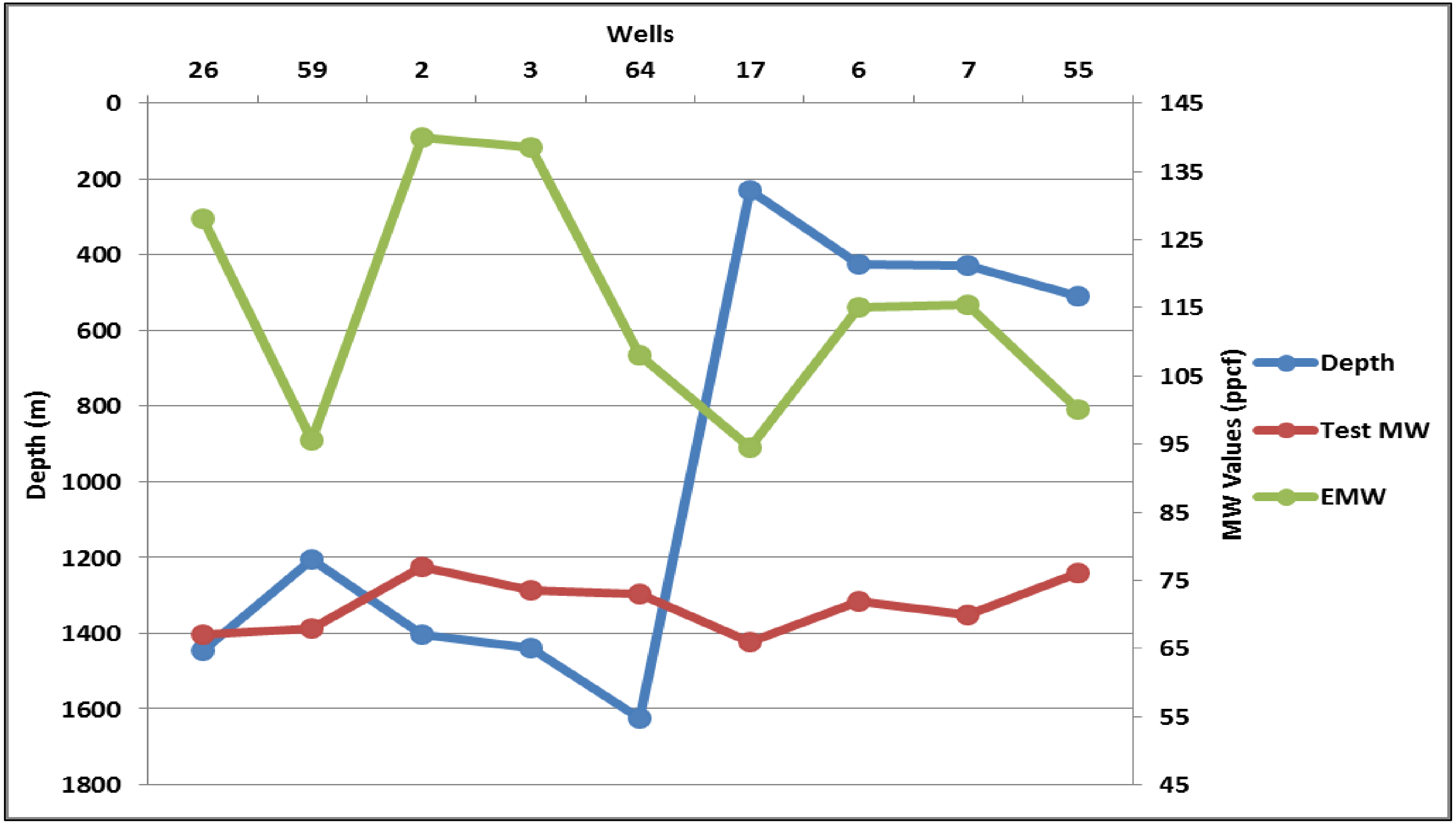

Figure 23 Chart showing relation between MW - EMW and Depth – EMW in Osmancık formation

A comparison was done between equivalent mud weight values calculated in leak-off tests in Osmancık formation and mud weight range used in next hole section just as in previous two formations. There was a disadvantage of Osmancık. This disadvantage was having less number of wells where a casing string was set in Osmancık formation. As Osmancık was main potential hydrocarbon bearing formation in Thrace Basin casing strings are run before entering into it or after exiting it. When daily drilling reports and drilling programs were read it was observed that there are two main reasons for setting casing in Osmancık formation. First of them is compulsory running because of low penetration issues during drilling. Second reason was programmed running for deep wells. It was planned to set casing into Osmancık to support upcoming drilling phases. This kind of setting are observed in deep exploration wells drilled to find hydrocarbon potential of Thrace Basin.

In 9 wells investigated for Osmancık formation it can be observed that maximum mud weights used are lower than leak-off test results except well #5 (Fig. 24). When records were investigated about drilling activities done in these 8 wells (except well #5) it was observed that mud weights lower than leak-off test result was adequate for drilling in safety margins. In daily reports of well #5 it was recorded that it was an obligation to increase drilling fluid weight because of gas traces seen during drilling. As it can be observed at Figure 24 max mud weight used and equivalent mud weight are same (108 ppcf). No mud loss recorded during drilling of this hole section so it can be commented that leak-off test result was evaluated correctly by drilling engineers who was in charge at well #5. If leak-off test graph was evaluated wrongly and overestimated this would have seen as mud losses.

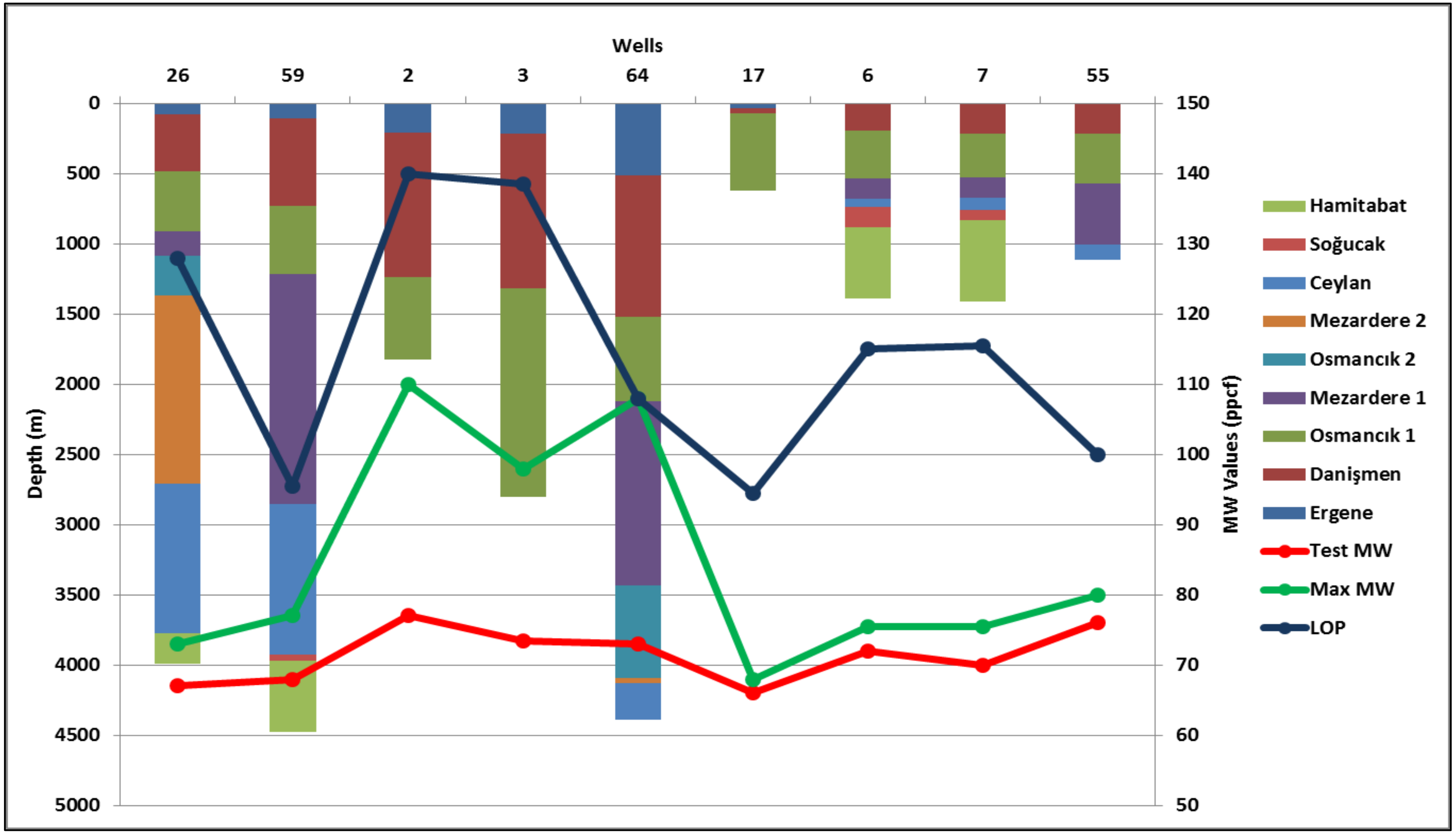

Figure 24 Chart showing details for wells where LOT was run in Osmancık formation (Osmancık 2 and Mezardere 2 shows the interbedded formations)

5.2.4. Mezardere Formation

Mezardere formation mostly consists of shale and marl in it. Some sandstone additions were observed in some wells throughout Thrace peninsula. It is mostly drilled after Osmancık formation but in some wells it got into Osmancık formation because of reverse faults. Detailed definition and explanation of Mezardere formation had been given in Section 4.4.4. As Mezardere is not a potentially hydrocarbon bearing formation and relatively deeper than conventional Thrace reservoirs the data set for it was limited. Figure 25 shows the wells used and eliminated for Mezardere formation study.

During investigating the relation between test mud weight and LOT result (equivalent mud weight) for Mezardere formation, it was discovered that these two parameters are strongly combined to each other. As it can be seen from Figure 26 equivalent mud weight is acting similar to test mud weight. Correlation function proves this strong relation with a result of 0.493.

During the study on Mezardere formation it was once again observed that how interpretation of leak-off test is important on results. Majority of the data set shows strong relation between depth and equivalent mud weight where well #7's equivalent mud weight value is totally an exception. It can be seen on Figure 26 the depth is effective on equivalent mud weight. In wells #3, #4 and #5 it can easily be observed that as depth increases equivalent mud weight also increases. But in well #7 even depth increases significantly the equivalent mud weight decreases. This may have been caused by some misinterpretation or cementing problem. When all eight wells are used to calculate a correlation coefficient the result is 0.155, which is a very low value for connectivity of two parameters. Once we omit well #7's data and re-calculate correlation coefficient the result becomes 0.522 which proves the misinterpretation on leak-off test result at well #7. This second result also shows a strong connection between depth and equivalent mud weight for Mezardere.

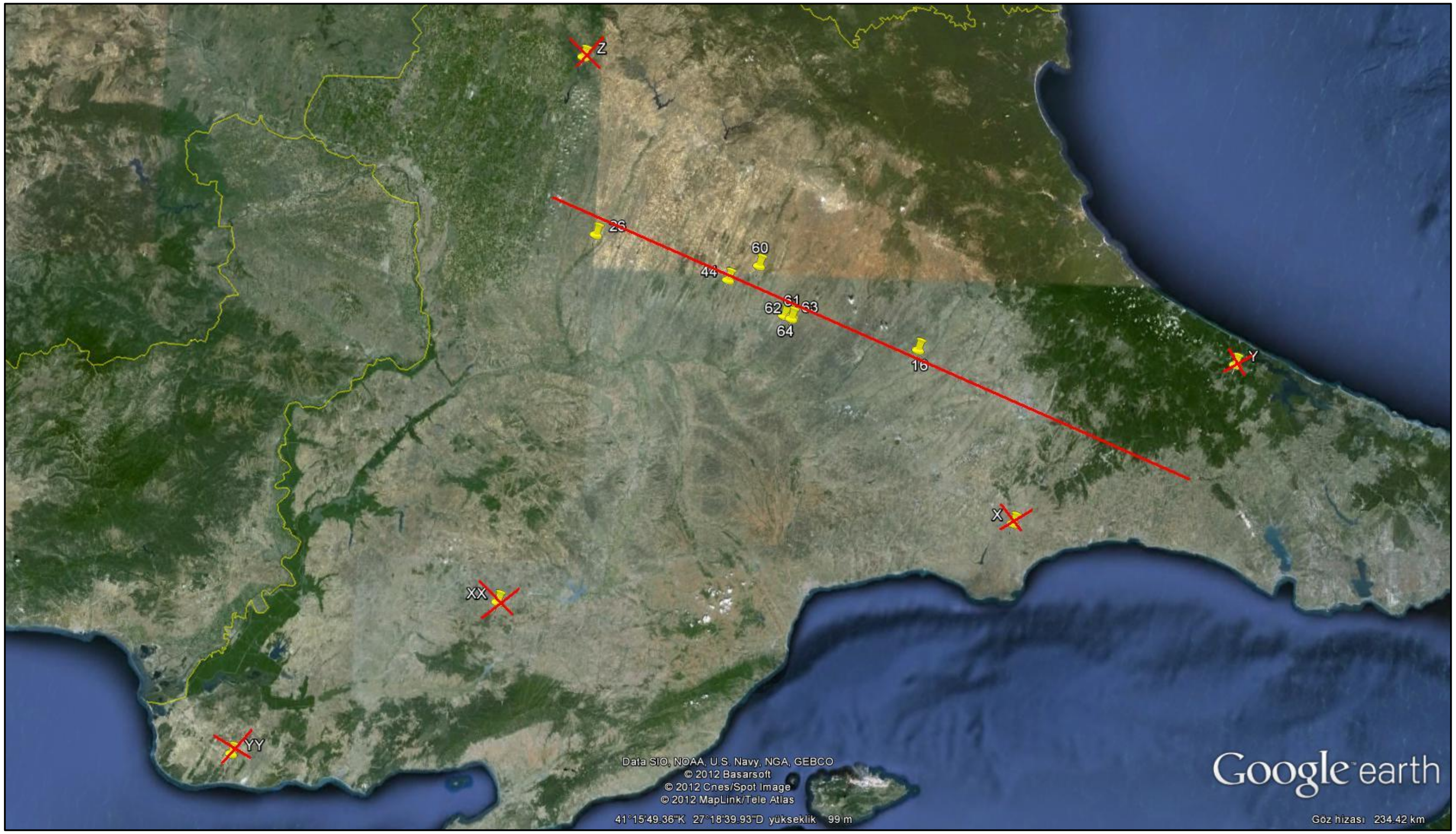

Figure 25 Map showing used and eliminated wells for Mezardere formation

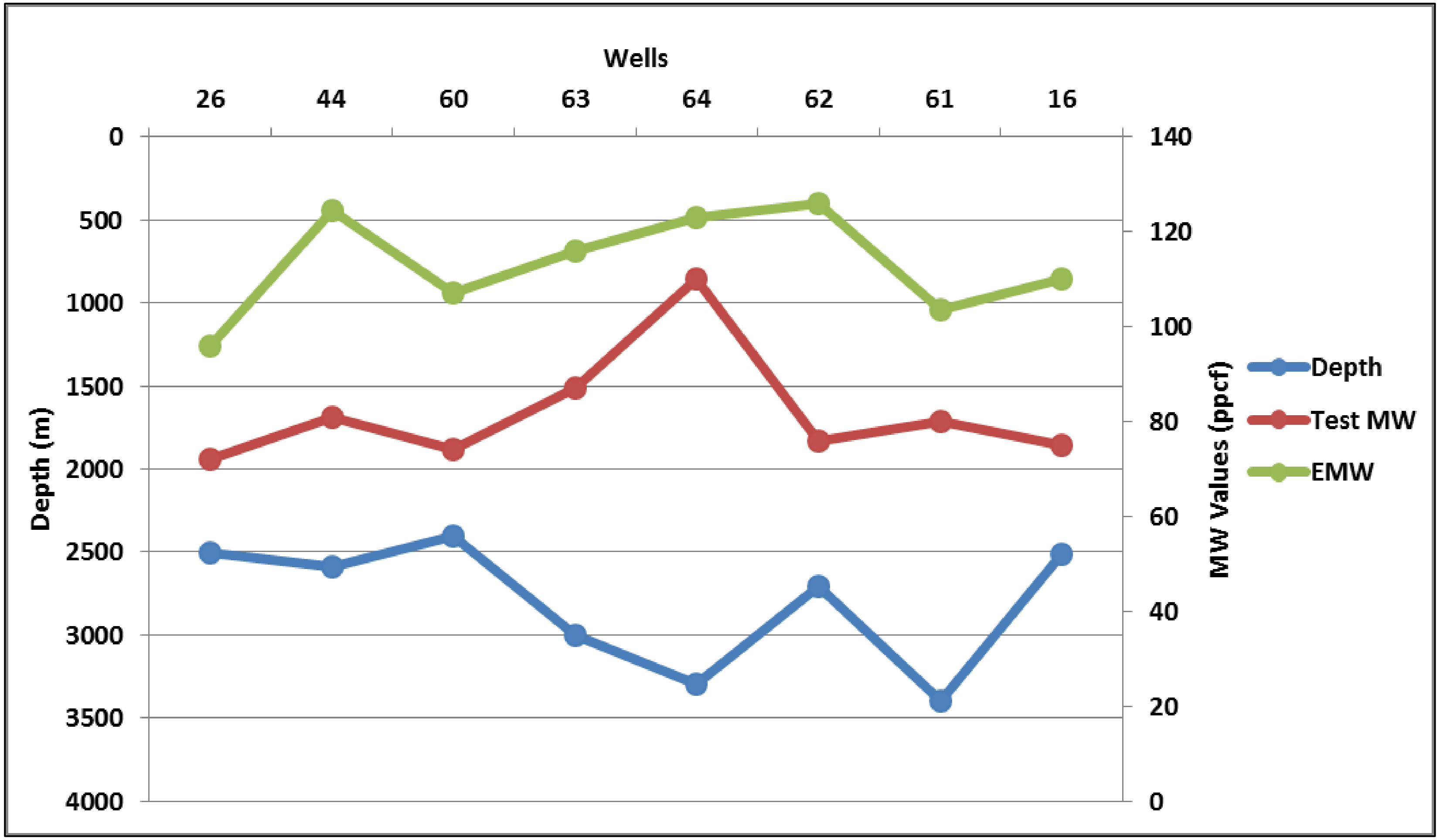

Figure 26 Chart showing relation between MW - EMW and Depth – EMW in Mezardere formation

After evaluating relation of depth and mud weight with leak-off test result the study was steered to investigation of drilling operations done during studied wells. Same method was applied to these 8 wells which a casing string was set in Mezardere formation and leak-off test was run. As Figure 27 clearly shows and previously explained in Formations Seen in Thrace Basin section Mezardere formation is observed in deep parts of Thrace peninsula and it is a non-hydrocarbon bearing formation it was mostly drilled in elder wells which were drilled in early exploration campaigns in Thrace Basin. This is the major reason for having limited number of wells investigated. Only 8 wells were appropriate in 13 wells total to be included in this study.

As it can be observed in Figure 27 in wells #4, #5, #6 and #7 drilling engineers needed to increase mud weights to complete drilling next hole sections. Figure 25 shows that these wells are located closely to each other and when records were examined for these wells it was observed that these wells belong to a natural gas field. Another property for this field is having high pore pressure values. This property directly explains why high mud weight values were used in these 4 wells. Other 4 wells are observed to be relatively easier to be drilled in manner of drilling parameters because low mud weights were enough to drill investigated hole sections.

In well #4 maximum mud weight used (118ppcf) was higher than leak-off test result (116 ppcf). Daily drilling reports record that mud losses encountered during drilling with 118 ppcf and it was needed to decrease mud weight back to 115 ppcf. This solution cured the mud loss issue. In wells #5 and #6 maximum mud weights used are significantly close to leak-off test results. No mud loss recorded investigated hole sections so this can be commented as calculated equivalent mud weights were correct and not overestimated. In well #7 maximum mud weight used was 116 ppcf where leak-off test result was 104 ppcf. In normal conditions it should be expected to have mud losses caused by pressure difference created by this mud weight difference but no mud loss was recorded in this hole section. This leads us to comment that this leak-off test was interpreted wrongly. This misinterpretation can also be proved by comparing the leak-off test result of well #7 with wells #4, #5 and #6. The reason for comparing these 4 wells is because of having all of them in same field and leak-off tests conducted in these 4 wells are in similar depths. Figure 27 clearly shows that leak-off test result of well #7 is significantly low than other 3 wells. This comparison shows that leak-off test was misinterpreted in well #7. Bad cement quality is not considered because if that case occurs there should have been mud losses when drilling fluid weight exceeded leak-off test result.

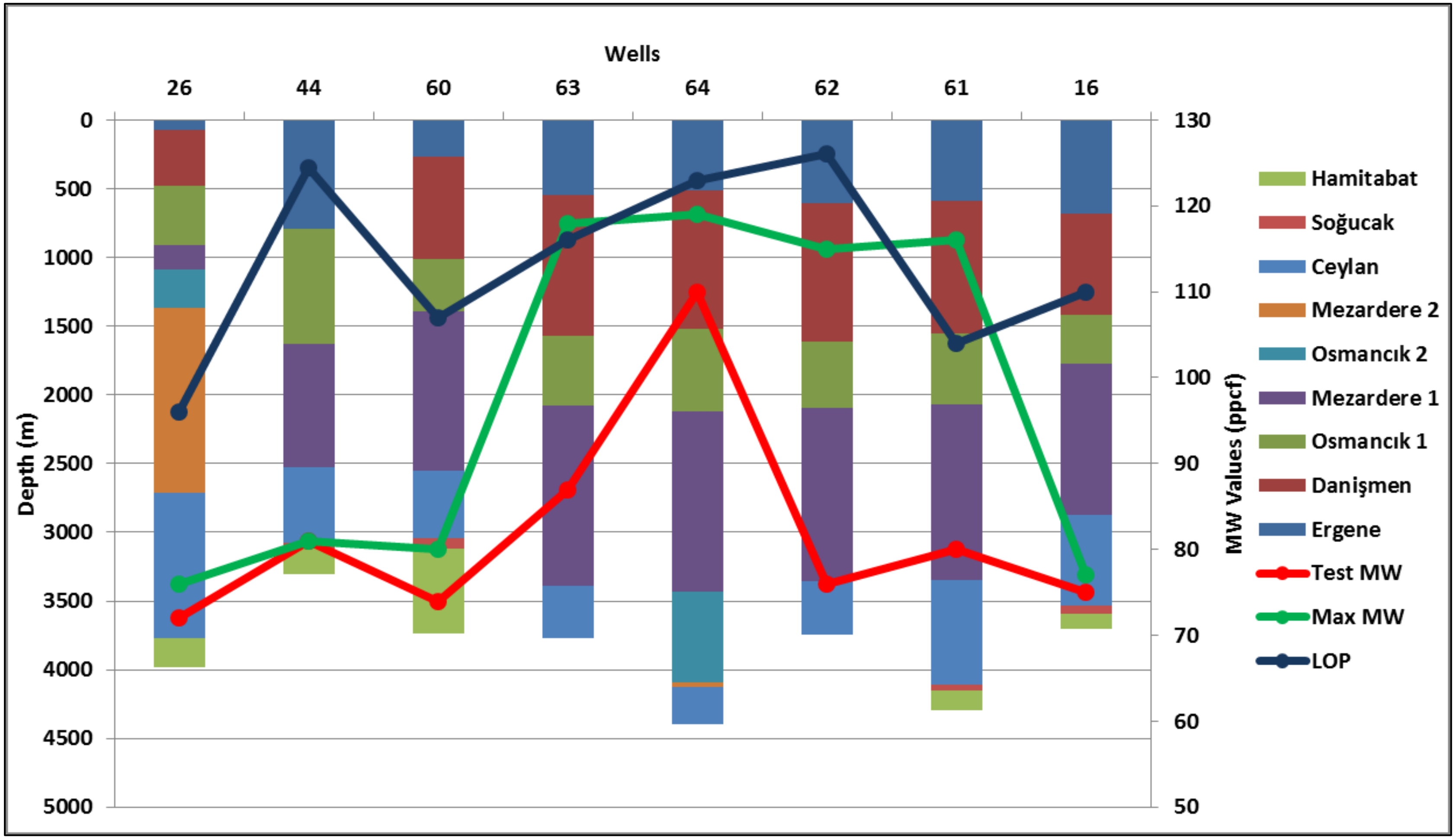

Figure 27 Chart showing details for wells where LOT was run in Mezardere formation (Osmancık 2 and Mezardere 2 shows the interbedded formations)

5.2.5. Ceylan Formation

Ceylan formation mostly consists of marl, shale, limestone and sometimes tuffite. Ceylan formation is not a potential hydrocarbon bearing formation. It was formed in older ages in geological history and is drilled below Mezardere formation. Detailed definition and explanation of Ceylan formation had been given in Section 4.4.5. As Ceylan formation does not have hydrocarbon potential it was mostly drilled in early drilling campaigns in Thrace Basin at deep wells. This causes a limited data set for this study. There were 7 wells appropriate to be investigated for Ceylan formation. Figure 28 shows the wells used and eliminated for Ergene formation study.

While investigating the relation between test mud weight and equivalent mud weight it was observed that there is not a strong connection between these two parameters. Figure 29 shows how these two parameters change independently. In well #3 equivalent mud weight increases drastically when test mud weight is almost same with other studied wells. Another example for weak connection is well #6. Despite the test mud weight is highest in investigated Ceylan specific wells the equivalent mud weight is lowest in value. Correlation function gives a result of 0.255 which proves the weak connection between test mud weight and equivalent mud weight.

There is a weaker connection between depth and equivalent mud weight. It can easily be seen at Figure 29 that equivalent mud weight is independent of depth. In deepest well investigated, well #6, the equivalent mud weight is lowest. Correlation function gave a result of -0.035 which is almost 0. This directly shows there is no connection between depth and equivalent mud weight for Ceylan formation.

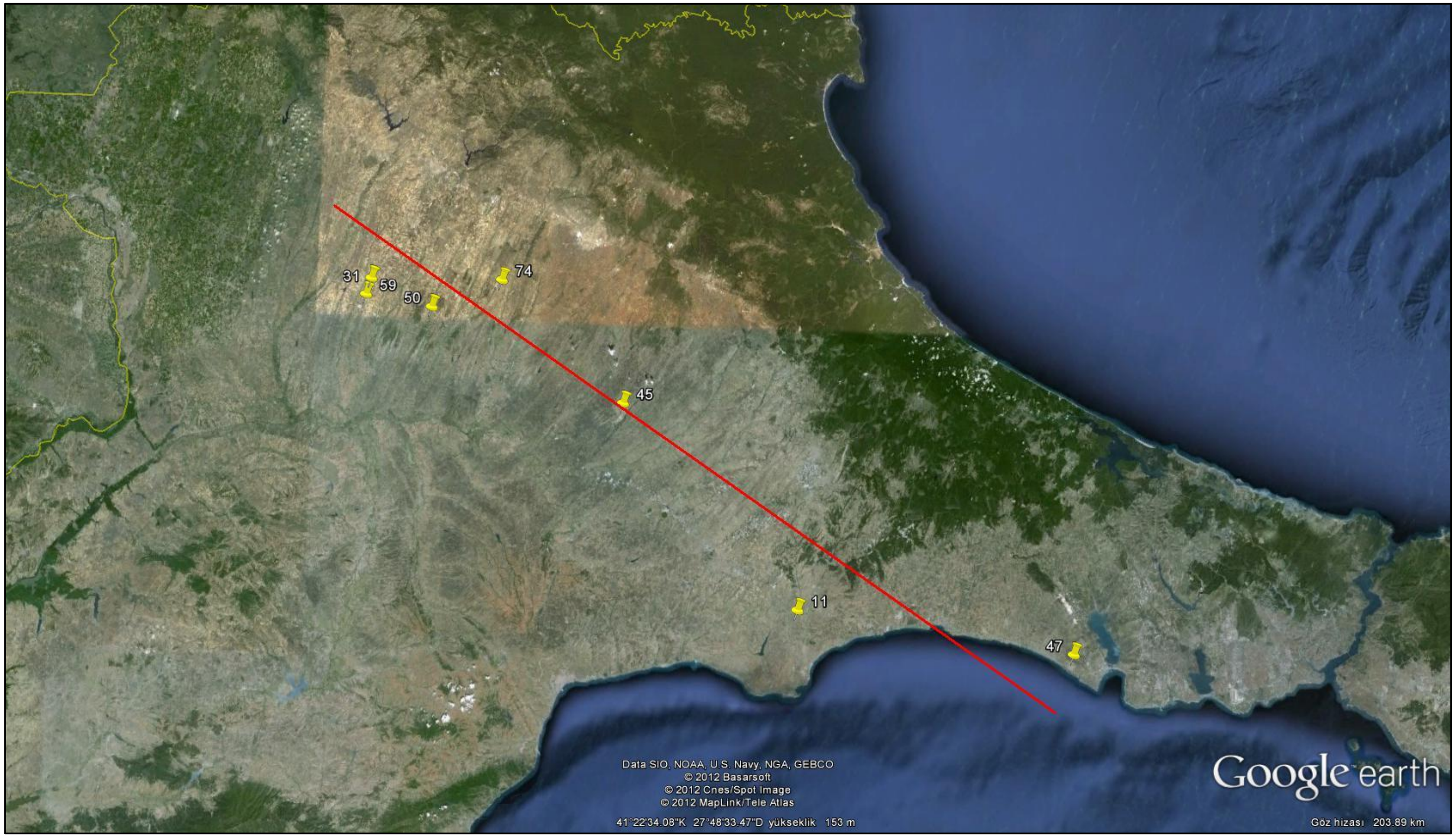

Figure 28 Map showing used and eliminated wells for Ceylan formation

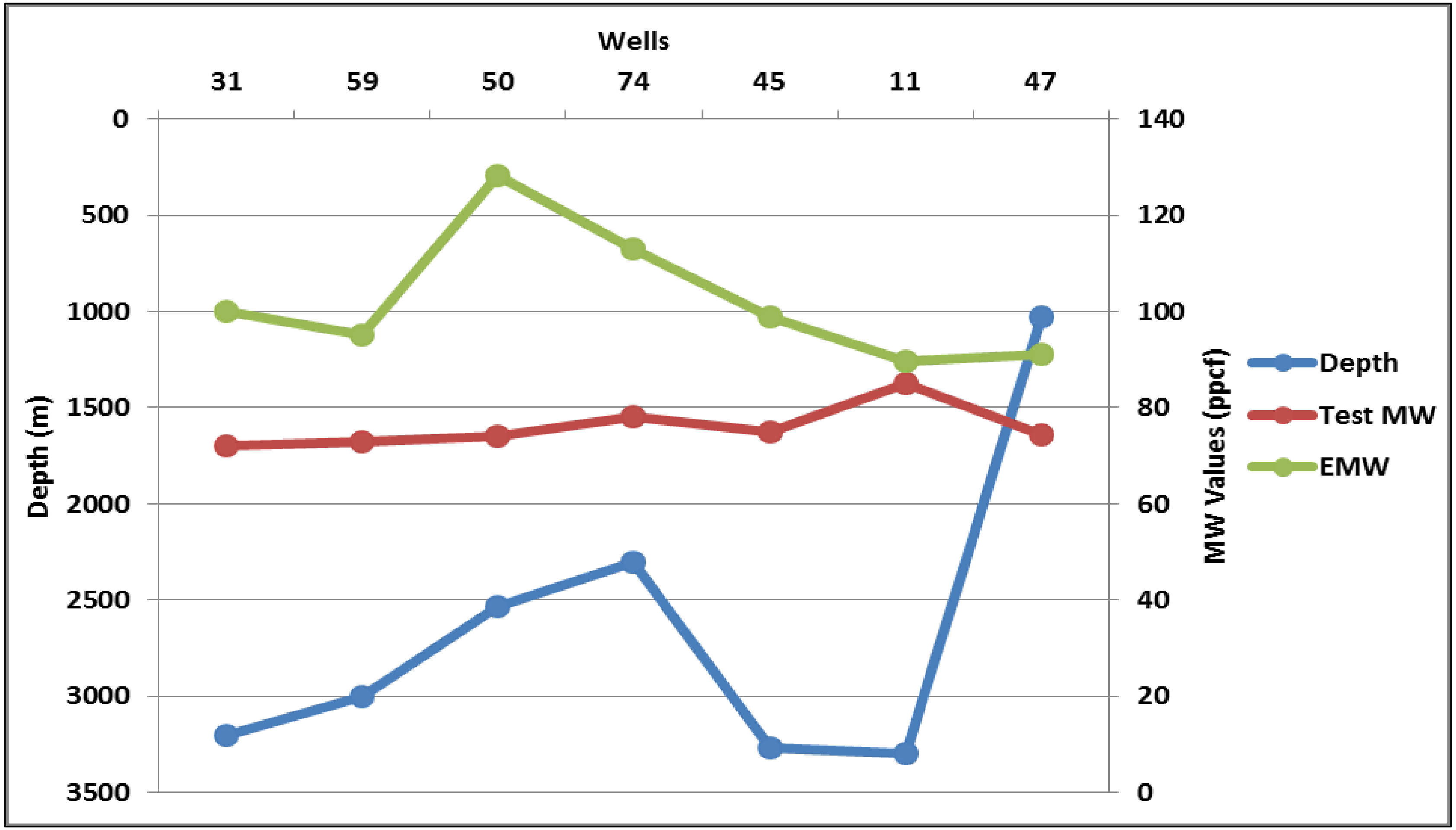

Figure 29 Chart showing relation between MW - EMW and Depth – EMW in Ceylan formation

After investigating the relation between depth and leak-off test result and test mud weight and leak-off test result next step was to evaluate if leak-off test result were the limiting factor for drilling or not. 7 picked wells were used to evaluate mentioned limitation.

As it can be observed on Figure 30 maximum mud weights used in examined 7 wells are lower than leak-off test results. Only in 2 of them, wells #5 and #6, mud weight got close to equivalent mud weight value. In the light of these values it can be concluded that drilling conditions in Ceylan formation and consequent formations should not be so hard. But it should be reminded that this conclusion is valid for studied wells.

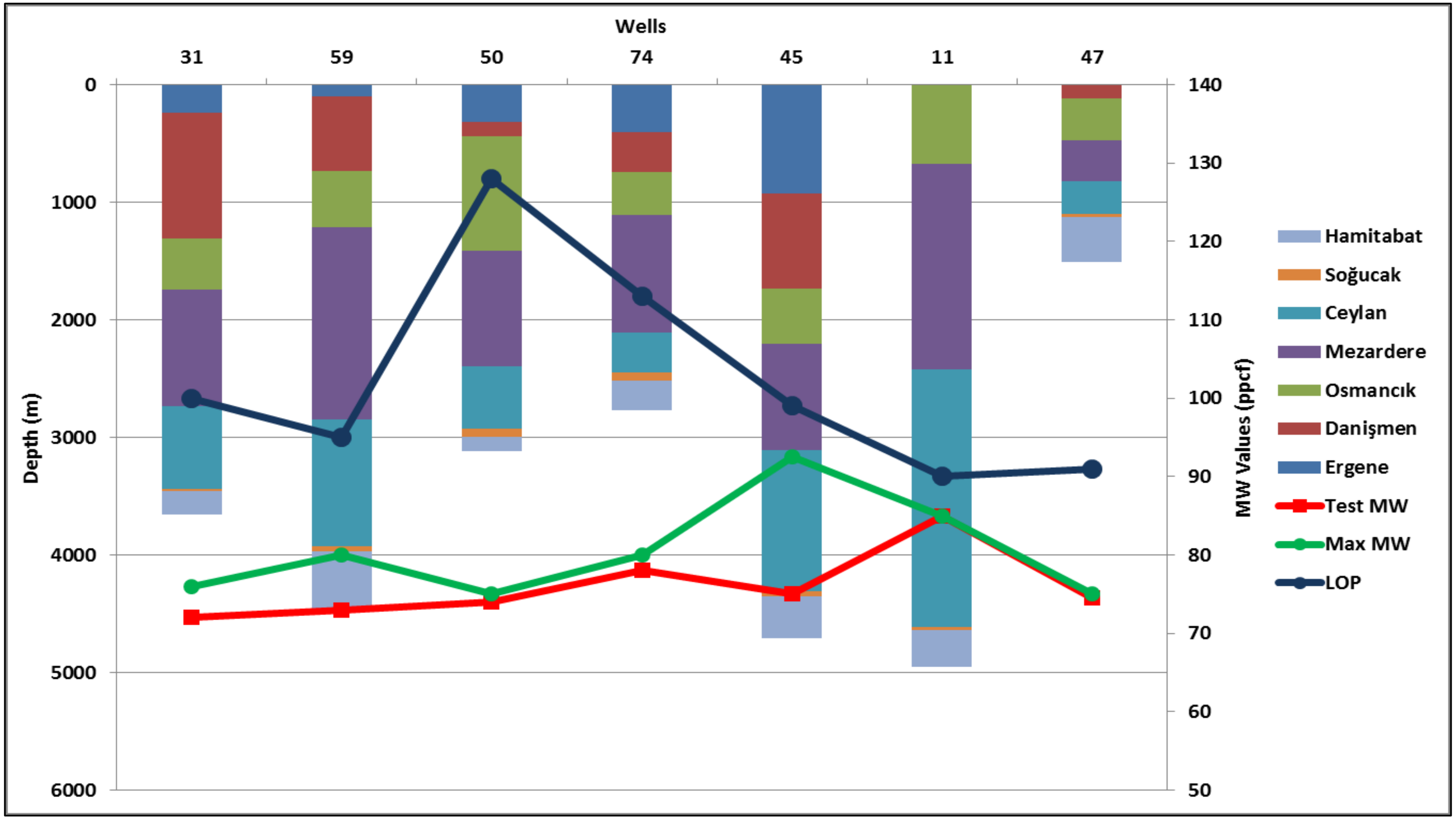

Figure 30 Chart showing details for wells where LOT was run in Ceylan formation

CHAPTER 6

CONCLUSIONS

This thesis work mainly focuses on leak-off tests conducted in Thrace Basin and their results. Its main purpose is to reveal any existing relationship between the well conditions and the leak-off test results. Many different wells were analyzed and the ones where the leak-off test was run were collected in a specially created list. Main mud properties (mud weight and mud rheological properties) were listed for wells where applicable. All collected data were evaluated to eliminate any possible inconsistency in evaluated data. Collected data were filtered according to the formations where the leak-off test was run. This filtering process enabled to evaluate different formations internally. Following conclusions are acquired from the results of this study:

- It was shown that the leak-off test result is not directly related with the mud weight used. Different leak-off test results were encountered even though similar mud weights had been used. In addition to this, similar leak-off test results were encountered with significantly different mud weights.

- Opposite to what was expected, the leak-off test results are not directly proportional to test depth. When comparing two tests conducted in the same formation but in two different wells, it was observed that the deeper sections of the first well may have a similar leak-off result with the shallower sections of the second well.

- The results of this study show that as permeable lithology content in tested formation increases, fracture gradient's dependency on the depth and mud weight increases. Osmancık formation, a formation with mostly sandstone, and Mezardere formation, a formation with mostly limestone, are proved to be more dependent on depth and mud weight with correlation results.

- It was concluded that it is difficult to create a general leak-off test result for each formation. Processed data showed that using close wells could be more appropriate rather than using all wells in a specific formation. Close wells give more accurate estimations for the leak-off test performance. Since close wells have similar formation contact depths and similar geological properties (faults, overburden gradient, etc.), the leak-off test results can be forecasted by investigating close wells' leak-off test data.

- It was concluded that the hole sections were ended before the operation parameters reach to their equivalent mud weight limit. Most of the investigated hole sections were ended up because of reaching to target depth or having hydrocarbon shows. These reasons were effective in ending up hole sections before reaching to equivalent mud weight limits. This situation, not reaching to equivalent mud weight value, can be related with well compressed formations with high overburden gradient. Onshore environment provides better compressed formations when compared to offshore environments. This difference may be a factor for not reaching to the leak-off test results as a drilling limit.

To sum up, the leak-off test is an important reference for drilling operations, and many studies in the literature have investigated whether there is a direct relationship between the leak-off test results and drilling parameters. Although some studies have indicated a link between test results and drilling parameters, this study shows that the leak-off test results gathered in Thrace Basin are not strongly connected to test mud weight and depth, which are the two parameters investigated in this study as they are believed to be two of the effective parameters on the leak-off test results. Additionally, according to this study the drilling operations in Thrace Basin were stopped before drilling parameters reach their limits, calculated via leak-off tests. This proves that the other factors are more effective on drilling operations than the leak-off test results.

CHAPTER 7

RECOMMENDATIONS

In the light of listed conclusions in previous chapter following recommendations are suggested:

- Turkish Petroleum Corporation (TPAO) should create standardized leak-off test (LOT) procedures and interpretation process. This standardization will provide realistic test results and fracture gradient estimations.

- A similar study should be repeated for a different basin or field. This new study will allow a comparison between already collected results/conclusions and new results/conclusions. The comparison results will give an idea about generalizing drawn conclusions for all LOT results.

- It is recommended that permeable lithologies should be chosen to make a correlation between LOT results and parameters depth and test mud weight.

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