

https://dspace.org/

# The assessment of exploration processes in the Upstream Industry to increase exploration efficiency and promote accelerated drilling decisions.

**Tshikovhi, Rilwele Mikovhe Muditambi**

**2024**
University of the Witwatersrand, Johannesburg
https://hdl.handle.net/10539/45582

Tshikovhi, Rilwele Mikovhe Muditambi . (2024). The assessment of exploration processes in the Upstream Industry to increase exploration efficiency and promote accelerated drilling decisions. [Master`s dissertation, University of the Witwatersrand, Johannesburg]. WIReDSpace. https://hdl.handle.net/10539/45582

Downloaded from a DSpace repository. https://dspace.org/




# *The assessment of exploration processes in the Upstream Industry to increase exploration efficiency and promote accelerated drilling decisions.*

***Rilwele Tshikovhi***

(Student number: 309170)

School of Mechanical, Industrial and Aeronautical Engineering

University of the Witwatersrand

Johannesburg, South Africa.

**Supervisor: Dr A Botha**

A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in partial fulfilment of the requirements for the degree of Master of Science in Engineering.

*08 July 2024*

## Declaration

I, Rilwele Tshikovhi declare that the research report submitted to the University of the Witwatersrand, in fulfilment of the requirements for the degree of Master of Science in Engineering is my own unaided work except where I have explicitly indicated otherwise.

Signed: 

Date: 08 July 2024

**Abstract**

During petroleum exploration, petroleum companies (operators) require efficient hydrocarbon detection and delineation methods to locate petroleum prospects and promote drilling (Selley, 1998). The two pre-drill surveys under investigation in this study are seismic surveys and controlled source electro-magnetic (CSEM) surveys which are used to study the subsurface during offshore petroleum exploration. Drilling dry holes is inevitable, however, a proper and thorough prospect evaluation can significantly increase the chance of success of a prospect (Milkov & Samis, 2020). The purpose of the research is to evaluate seismic and CSEM surveys as secondary hydrocarbon detection tools used to recommend drilling, and to also determine if any of these methods can encourage accelerated drilling decisions and significantly reduce exploration risk.

A total of 49 seismic-based samples and 41 CSEM-based samples were used in the study. Survey anomalies were assessed against drilling results to determine the predictive strength of each survey. The Chi-test confirmed that there is a significant association between survey anomalies and attributes such as well results, predictive strength, fluid type and trap style. The researcher analysed the two datasets to determine the probability of an anomaly in each survey and the chance of success if each well is drill based on these surveys. The presence of an anomaly was defined as a positive anomaly (PA) and the absence of an anomaly was defined as a negative anomaly (NA). Fluid type and trap style were used to analyse the predictive ability of the survey anomalies. Seismic and CSEM surveys have indicated a high probability of discovering charged reservoirs in a structural trap as compared to stratigraphic traps, however, CSEM is slightly better than seismic surveys in defining these reservoirs. Both surveys have a low probability of predicting a charged stratigraphic reservoir, although seismic surveys have indicated higher chance of success as compared to CSEM. Positive anomalies observed in both surveys proved to be good indicators of gas-bearing reservoirs as compared to other hydrocarbon fluid. CSEM has a slightly higher chance of predicting oil than seismic surveys.

A simplified process mapping for the current offshore exploration processes was conducted. A decision tree was used to analyse seismic and CSEM surveys as secondary tools with emphasis given to their hydrocarbon detection capabilities. Bayesian Theorem was used to calculate the posterior probabilities given that a well is drilled on a positive

anomaly. The same was applied for wells drilled on negative anomalies. The results have indicated that CSEM has a higher probability of detecting hydrocarbon accumulations as compared to seismic surveys.

**Acknowledgements**

I would like to extend my gratitude to my Supervisor Prof Andries Botha for the dedication and guidance throughout my research. I wish to thank the two companies that supplied the data and all relevant material; without this support, the research would not have been possible. I would also like to thank my family for the continuous support and motivation. Lastly, I want to thank the Postgraduate Merit Award (University of the Witwatersrand) for the financial support.

“Musi tshifhinga tsho teaho tshi tshi swika, Nn̓e Yahavee ndi d̓o ita uri hezwo zwi mbo d̓o vha hone”

Yesaya 60:22

**Table of Contents**

Declaration ..... i

Abstract ..... ii

Acknowledgements ..... iv

List of figures ..... vii

List of tables ..... ix

Abbreviations ..... xi

1. Introduction ..... 1

1.1. Research Background ..... 1

1.2. Motivation ..... 2

1.3. Research Question ..... 3

1.4. Research Objectives ..... 3

2. Literature Review ..... 5

2.1. Introduction ..... 5

2.2. Petroleum Reservoir ..... 5

2.3. The Upstream Life Cycle ..... 7

2.4. Seismic Surveys ..... 8

2.5. Controlled Source Electro-Magnetic Surveys ..... 10

2.6. Seismic surveys and CSEM as decision tools ..... 13

2.7. Dry Hole Analysis ..... 14

2.8. Direct Hydrocarbon Indicators ..... 20

2.9. Pitfalls ..... 21

2.10. Statistics ..... 23

2.10.1. Descriptive Statistics ..... 23

2.10.2. Inferential Statistics ..... 23

2.11. Decision Tree analysis ..... 25

2.12. Gaps in current studies ..... 31

3. Methodology ..... 32

3.1. Research Design ..... 32
3.1.1. Ethical Issues/Clearance ..... 32
3.1.2. Validity And Reliability ..... 33
3.1.2.1. Validity ..... 33
3.1.2.2. Reliability ..... 34
3.2. Sampling ..... 35
3.3. Instrumentation ..... 35
3.4. Data collection and analysis procedures ..... 36
4. Results ..... 39
5. Discussion ..... 71
5.1. Process Mapping ..... 71
5.2. Predictive strength ..... 72
5.3. Technology Advancement ..... 74
5.4. Decision Tree Analysis ..... 75
5.5. Research Limitation ..... 75
5.6. Recommendations for Future Work ..... 76
6. Conclusion ..... 76
7. References ..... 78
8. Appendices ..... 82

## List of figures

Figure 1:Different types of petroleum traps (Najoui, et al., 2018). ..... 6

Figure 2: Strength of Seismic and CSEM surveys in structure and fluid detection (EMGS, 2021). ..... 6

Figure 3: Upstream life cycle (Cairn Energy, 2014) ..... 7

Figure 4: Seismic profile with a bright anomaly (Nanda, 2016). ..... 10

Figure 5: Reservoir on seismic (left) and CSEM (right) profiles (Fanavoll, et al., 2014). 11

Figure 6: Results of the look back study (Karman, et al., 2013). ..... 12

Figure 7: CSEM inversion using CGG L-BFGS code (Price, et al., 2019). ..... 13

Figure 8: CSEM inversion using the EMGS TTI BFGS code (Price, et al., 2019). ..... 13

Figure 9: Seismic versus CSEM for investment decisions (Zweidler, et al., 2015). ..... 14

Figure 10: Success and failure examples for top seal (Milkov & Samis, 2020). ..... 15

Figure 11: Success and failure examples for lateral and bottom seal (Milkov & Samis, 2020). ..... 16

Figure 12: Success and failure examples for the presence of reservoir (Milkov & Samis, 2020). ..... 17

Figure 13: Success and Failure examples for reservoir deliverability (Milkov & Samis, 2020). ..... 17

Figure 14: Success and failure examples for the presence of mature source rocks (Milkov & Samis, 2020). ..... 18

Figure 15: Success and failure examples for the migration of hydrocarbons (Milkov & Samis, 2020). ..... 19

Figure 16: Decision tree applied in failed segments (Milkov & Samis, 2020). ..... 20

Figure 17: DHI anomalies in the X structure with Well X1 testing positive for gas and Well X3 dry (Rowi, et al., 2020). ..... 22

Figure 18: Goferboke decision tree (Perera, 2018). ..... 27

Figure 19: Initial expected value without consideration of additional data (Foum, 2018). 28

Figure 20: Four possible outcomes of a CSEM survey (Foum, 2018).....29

Figure 21: Probability of each branch give 90% reliability of the survey. .....30

Figure 22: Revised Expected Monetary Value using the new probabilities given that the survey was conducted and resulted in an anomaly.....31

Figure 23: Process mapping showing the exploration processes (Cairn Energy, 2014). 40

Figure 24: Successful and unsuccessful well results from sample group. .....46

Figure 25: Anomalies assessment looking at false negative and positive as well as true negative and positive. .....48

Figure 26: (A) Seismic: Positive anomalies versus negative anomalies, (B) Seismic Positive anomalies showing the true positives and false positive. .....49

Figure 27: (A) CSEM: Positive anomalies versus negative anomalies, (B) CSEM: Positive anomalies showing the true positives and false positive. .....49

Figure 28: True versus false predictions from sample group. .....51

Figure 29: Well results categorized into various trap style. .....54

Figure 30: Well results classified into different fluid type.....57

Figure 31: True and false prediction for seismic surveys classified into different years to track technology advancement. .....59

Figure 32: True and false prediction for CSEM surveys classified into different years to track technology advancement. .....59

Figure 33: Decision tree computed from the calculated probabilities and agreed costs. 70

## List of tables

Table 1: Summary of causes of seismic DHI pitfalls, DHI types and quality control techniques to assist in assessing the DHI pre-drill (Nixon, et al., 2018).....21

Table 2: Prior probabilities from the Goferbroke Case (Perera, 2018). .....26

Table 3: The payoff table from the Goferbroke Case showing maximax and maximin. 26

Table 4: Bayes Decision Rule for the Goferbroke Case (Perera, 2018).....27

Table 5: Data received from each participating companies.....35

Table 6: Additional information requested from Company A and Company B. .....36

Table 7: SWOT analysis of seismic survey and CSEM.....42

Table 8: Seismic samples selected for the study. .....44

Table 9: CSEM Samples selected for the study.....45

Table 10: Observed frequency of the successful and unsuccessful well results. .....47

Table 11: Expected frequency of the successful and unsuccessful well results.....47

Table 12: Observed frequency of the anomalies assessment.....49

Table 13: Expected frequency of the anomalies assessment. .....50

Table 14: Observed frequency of the true and false predictions. .....52

Table 15: Expected frequency of the true and false predictions.....52

Table 16: Observed frequency of the trap style. .....54

Table 17: Expected frequency of the trap style. .....55

Table 18: Observed frequency of the fluid type.....57

Table 19: Expected frequency of the fluid type. .....58

Table 20: Calculated P(PA) and P(NA) for seismic and CSEM data.....60

Table 21: Summary showing the successful versus unsuccessful well results. .....61

Table 22: Chance of success of seismic surveys and CSEM. .....61

Table 23: Calculated COS given that the survey was conducted, and an anomaly was observed. .....63

Table 24: Calculated COS and COF given that the survey was conducted, and no anomaly was observed. .....64

Table 25: Survey costs with the relevant sources. ..... 64

Table 26: Well cost and minimum commercial size (Africa Energy Corp, 2020). ..... 65

Table 27: Input data for decision tree analysis. ..... 65

Table 28: Summary of payoff for each alternative. ..... 67

Table 29 Expected value calculations for "acquire seismic" alternative. ..... 68

Table 30: Expected value calculations for "acquire CSEM" alternative. ..... 69

Table 31:Expected value calculations for "don’t acquire secondary survey". ..... 69

**Abbreviations**

CSEM: Controlled source electro-magnetic

DHI= Direct hydrocarbon Indicators

HC=Hydrocarbons

PA=Positive anomaly

NA=Negative anomaly

COS=Chance of Success

COF=Chance of Failure

TP=True Positive

FP=False Positive

TN=True Negative

FN=False Negative

TOC=Total organic carbon

HI= Hydrogen Index

EV=Expected Value

EP= Expected payoff

EVPI= Expected Value of Perfect Information

EM=Electro-Magnetic

MM=Million

B=Billion

MMbbl=Million barrels of oil

BBOE=Billion barrels of oil equivalent

G&G=Geological and Geophysical

# CHAPTER 1

## 1. Introduction

### 1.1. Research Background

The petroleum exploitation life cycle begins with petroleum exploration where various surveys are employed to identify potential petroleum resources and reserves (Selley, 1998). These surveys can suggest the existence of hydrocarbons (oil or gas) in a specific prospect and may also indicate an approximate size of the reservoir (Hesthammer, et al., 2010) and (Rowi, et al., 2020). The next stage after interpretation of the survey results is drilling a well, which is the only way to confirm the existence of hydrocarbons in the relevant prospects. Drilling results can either be successful if the well tests positive for hydrocarbons or unsuccessful if the well shows no indications of hydrocarbons (Milkov & Samis, 2020). This research is targeting the Upstream Industry (petroleum exploration and production), looking mainly at the survey technologies applied prior to drilling. The purpose of the research is to evaluate the use of Controlled Source Electro-Magnetic (CSEM) surveys and seismic surveys which are the two main survey methods used for hydrocarbon detection during petroleum exploration. In the study, these surveys will be classified as secondary seismic surveys assuming a potential area has been identified through acquisition and interpretation of the primary seismic survey. The primary survey is used to identify a prospective area, and thereafter, a secondary survey targeting that area will be acquired and interpreted. If the results are positive, the Geological and Geophysical (G&G) team may recommend drilling (Cairn Energy, 2014). This research study will assess the two secondary pre-drill methods to see if any of these processes encourages accelerated drilling decisions.

The questions that this research will be addressing is:

- Which exploration survey method/technology is the most efficient for ensuring successful drilling and increasing exploration efficiency?
- Do both surveys (seismic and CSEM) determine hydrocarbon accumulations successfully? if yes, are these surveys equally reliable in determining reservoirs.

The study assessed two pre-drill surveys used in petroleum exploration, with an aim to increases the chance of success in drilling a hydrocarbon-bearing well for the benefit of operators. CSEM and seismic results were validated by actual well result to confirm if their predictions were correct; the seismic-based drilling and CSEM-based drilling processes

were analysed and compared. Statistical methods were used to analyse and propose improvement to the current exploration processes from acquisition, interpretation all the way to discovery.

## 1.2. Motivation

Petroleum exploration is a cost intensive, high risk operation that requires expensive machinery and a high level of expertise (Suslick & Schiozer, 2004). Operators require the most cost-effective hydrocarbon detection and delineation methods to ensure early success and to limit costs (Hesthammer, et al., 2010). When an oil and gas exploration company approach a new prospective area, the location of hydrocarbons is not always certain. Operators will acquire the relevant surveys to study the subsurface geology and predict hydrocarbon accumulations (Selley, 1998). As a result, drilling a well can either test positive for oil and/or gas or result in a dry hole. Most of the time, several dry holes may be drilled before an actual oil or gas discovery is made (Milkov & Samis, 2020).

Most companies spend a considerable amount of time interpreting geological and geophysical data to ensure that the drilling process is successful to avoid financial loss. In underexplored and frontier areas, this drilling process may be delayed until such a time that the operator is confident enough to drill. This level of confidence is achieved through intensive studies of the area as well as integration with analogues studies to compare the prospective area with other hydrocarbon prone areas of a similar geological setting.

Seismic and CSEM surveys are geophysical methods that provide G&G information about the sub-surface. These methods can be used to identify hydrocarbon-charged reservoirs. Other petroleum elements crucial in the accumulation of hydrocarbons such as source, migration pathways, trap and seal may also be mapped from these surveys. The most common method used in petroleum exploration is seismic surveys (Selley, 1998). Some of the anomalies observed in seismic profiles can be mistaken for hydrocarbon indicators, these can be seismic pitfalls such as brine-saturated sandstones or volcanics (Nixon, et al., 2018). The less common method used is CSEM which is sensitive to hydrocarbon saturation and volumes (Fanavoll, et al., 2014).

The evaluation of seismic and CSEM surveys will provide insight on how to optimize pre-drill processes and recommend efficient ways to encourage early drilling and reduce exploration risks. Dry holes are a big loss to the company; hence, it is a priority to apply relevant de-risking technologies to reduce these failure cases (Milkov & Samis, 2020).

## 1.3. Research Question

The main research question addressed is: How does CSEM and seismic surveys compare in detecting hydrocarbon accumulations, is one method more effective than the other?

The sub questions are as follows:

- Based on the presence or absence of anomalies, how do true and false hydrocarbon predictions compare for each survey?
- Are the hydrocarbon detection capabilities of CSEM and seismic surveys influenced by the type of hydrocarbon fluid contained in the reservoir?
- Which trap style (stratigraphic or structural) can easily be identified by seismic and CSEM surveys?
- Using the Bayes Decision Rule, what is the probability of discovering hydrocarbon after drilling a survey anomaly?
- What is the chance of success for drilling on seismic or CSEM surveys without an anomaly?

## 1.4. Research Objectives

The main objective is to use both descriptive statistics and hypothesis testing to compare CSEM and seismic surveys capabilities in detecting hydrocarbons.

The sub objectives are as follow:

- To check the reliability of each survey through assessing positive anomalies and the corresponding drilling results.
- To check if each survey can predict oil and gas equally, or whether one hydrocarbon fluid is easily identified as compared to the other.
- To determine which trap style (stratigraphic or structural) is easier to identify using survey anomalies.

- To determine seismic and CSEM pitfalls that result in dry wells.
- To determine which pre-drill survey can increase exploration efficiency and accelerate drilling decisions though assessing the probability of success for each survey.

## 2. Literature Review

### 2.1. Introduction

Petroleum exploration focuses on conducting a proper prospect evaluation to help review the economic viability of each prospective area. These evaluation studies cover various aspects of a prospect looking at all elements that are necessary for petroleum to accumulate (Selley, 1998). Even after establishing that such elements are present in a particular area, their effectiveness must also be taken into consideration. A good example of this is that fault detection and mapping is not sufficient to rank a prospect, the effects of fault on the accumulation of hydrocarbons should also be investigated (Nanda, 2016). Seismic surveys were first used in the 1920's; and contributed significantly to the success of petroleum exploration in the oil and gas industry. Seismic surveys employ remote sensing techniques to image the subsurface in varying depths ranging from several metres to kilometres. Seismic survey uses acoustic energy released by a localized source; this energy travels in the subsurface where changes in rock properties are recorded by receivers on the surface (Bakker, 2002). CSEM uses resistivity to map hydrocarbon-saturated reservoirs in the subsurface; Although this technology may indicate specific rock types, it is not an effective tool in stratigraphic interpretation. Seismic surveys use acoustic energy to map the subsurface geology and structures whereas CSEM uses resistivity to map the subsurface and to distinguish the type of fluids contained in the reservoir (Hesthammer, et al., 2010).

### 2.2. Petroleum Reservoir

Several elements are required to form a conventional petroleum reservoir. The first element is a source rock, usually a shale that host organic material from dead organisms in the sea or in lakes. With the suitable pressure and temperatures, the organic matter is converted into oil or gas. The generated hydrocarbons are less dense than water and they tend to move upwards along pathways such as faults until they encounter an impermeable layer of rock. A seal is an important part of accumulation; above any reservoir is an impermeable rock which blocks the petroleum fluids from migrating up to the surface. Hydrocarbons will accumulate in traps; a trap can be structural and/or stratigraphic in nature. Structural traps (*Figure 1*B, C and D) refer to a trapping mechanism where the geometry of the reservoir is responsible for the accumulation of hydrocarbons; folding and faulting may lead to fault and fold structures that allow containment of hydrocarbons. A stratigraphic trap (*Figure 1*A)

results from the change in rock type, blocking petroleum fluids from moving upward. When both structural and stratigraphic characteristics are exhibited in one trap; this is referred to as a combination trap (Fanchi, 2010).

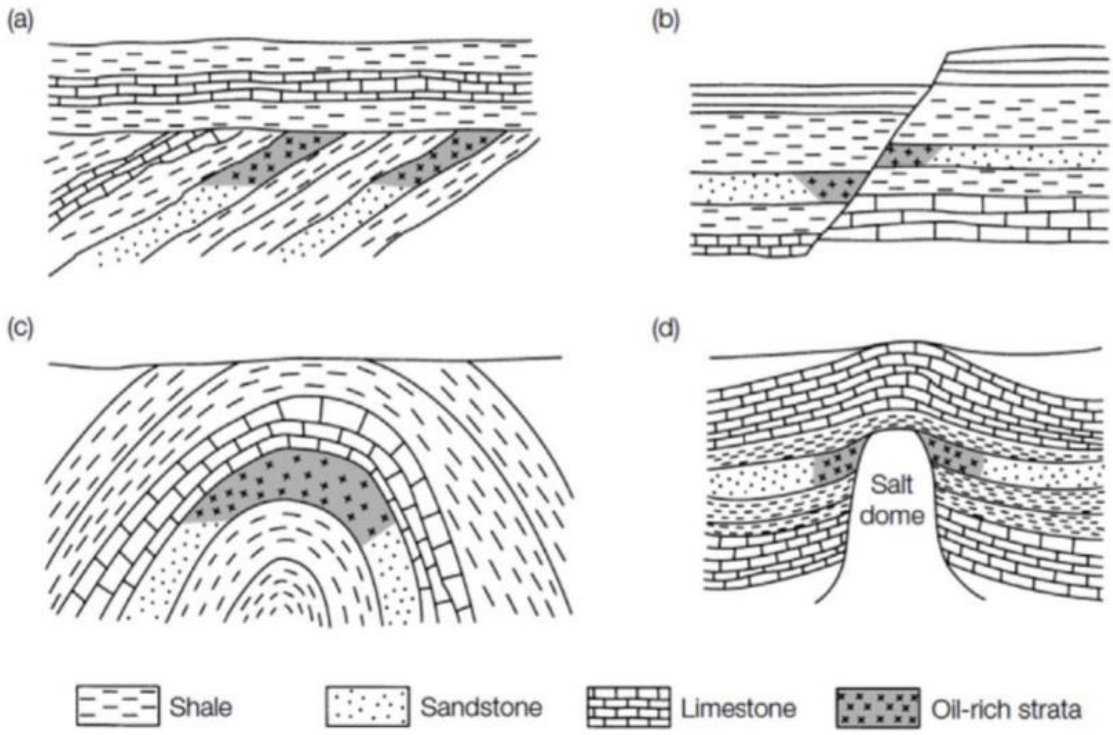


Figure 1:Different types of petroleum traps (Najoui, et al., 2018).

Seismic surveys are generally thought to be strong in structure detection assisting with identification of the trap and reservoir and CSEM is thought to be strong in fluid related detection with identification of charge, seal and volumes (Figure 2).

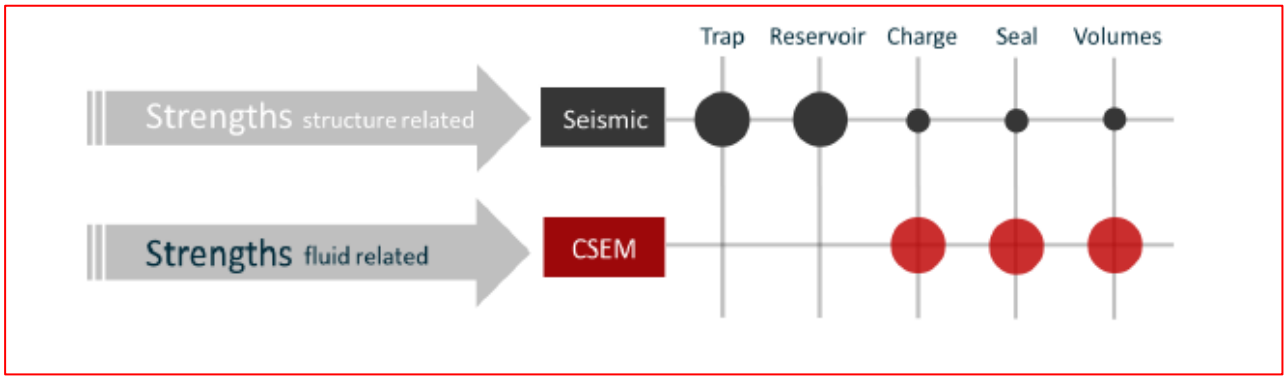


Figure 2: Strength of Seismic and CSEM surveys in structure and fluid detection (EMGS, 2021).

## 2.3. The Upstream Life Cycle

The petroleum exploration and production life cycle has been divided into different stages starting with due diligence all the way to production (Cairn Energy, 2014).




Figure 3: Upstream life cycle (Cairn Energy, 2014)

I. Due diligence: Before a company can apply for an exploration licence or farm-in to an existing project, the company will carry out a risk-screening process and then decide whether to go ahead with the investment.

II. Prequalification: The company will apply for an exploration right. All the required documents with information such as legal status, financial capability, technical capabilities, health, safety & environment management will be submitted to the relevant authorities.

III. Exploration seismic: The operator may carry out seismic surveys to understand the subsurface. Potential hydrocarbon-charged reservoirs may be identified in these surveys.

IV. Site survey: Before drilling commences, site surveys are conducted to further understand the reservoir and proposed drilling location. This stage may involve fetching geological samples from seabed and carrying out additional seismic surveys.

V. Exploration drilling: Exploration wells are drilled to confirm hydrocarbon accumulations.

VI. Appraisal drilling: If oil or gas indications are encountered in the reservoir during the exploration phase, the prospect will be appraised through additional drilling to further understand the reservoir (size, characteristics, performance).

VII. Development: If the appraisal results indicate a commercially and technically viable hydrocarbon field, field development will commence.

VIII. Production: This is the final stage which involves the production of oil and/or gas

## 2.4. Seismic Surveys

Seismic surveys use acoustic energy to map the subsurface and locate hydrocarbons (Hesthammer, et al., 2010). Compressional and shear waves are the two seismic body waves that propagates through solid rock. These waves encounter boundaries of rocks with different physical properties, resulting in reflections, diffractions, absorption, scattering and refractions. When the incident waves hit the rock boundary between two different rock types, some of the incident waves are reflected to the surface and some are transmitted further down into the underlying rock units. The seismic waves can be measured in amplitude and velocity, which are the most important seismic properties during petroleum exploration (Nanda, 2016). Amplitudes and velocities will differ according to rock and fluid types; therefore, the rock properties and fluid properties can be derived from seismic profiles.

Rock properties that affect seismic character are as follows:

- Elasticity: The resistance of a rock to stress; the main elastic moduli that determines seismic velocities is the bulk modulus (k) and shear modulus (μ) depending on the type of wave. The compressional waves (P-waves) are influenced by both the bulk modulus and the shear modulus, but the shear waves (S-waves) are mainly influenced by the shear modulus. The elastic moduli can be simplified by the following illustration: hard rock has a high bulk modulus since it is difficult to compress which results in a high velocity; but a soft rock has a lower elastic modulus which results in low velocity (Nanda, 2016).
- Bulk Density: The density of the rock and fluid contained in pore spaces. The density of a rock increases with depth, due to compaction. Highly compacted intervals exhibit high densities and under-compacted intervals tend to have lower densities (Nanda, 2016).
- Porosity: The spaces between the rock particles in a rock volume. High porosity results in lowered densities (Nanda, 2016).
- Textures: The textures may be described according to grainsizes, roundness, sorting and cementation. The elasticity and density of a rock is reliant on texture of the rock ranging from grain contacts, sizes and roundness (Nanda, 2016).
- Fractures and cracks: Open fractures and cracks in a rock influences the seismic properties; the fractured porosity lowers velocity and impedance. Micro fractures

may negatively affect the reservoir evaluation since they exhibit a lower velocity which assumes good permeability which may be false; larger fracture may exhibit better permeability (Nanda, 2016).

Fluid properties that affect seismic characteristics are as follows:

- Fluid and saturation: The pores in the rocks are usually filled with fluids. A saturated rock is affected by the compressional waves, the shear waves may be negligible. In a water-saturated reservoir, water will resist the stress resulting in increased velocities but generally lower than the tight rocks. Oil-saturated reservoir rock will tend to show lower velocities compared to brine-reservoir rocks, due to the low bulk density of oil. Gas-saturated reservoir rocks exhibit an even lower bulk modulus and density as compared to both brine- and oil-saturated reservoir rock. Lowered seismic velocities due to gas saturation is highly notable, especially in shallow depths resulting in bright anomalies (Nanda, 2016), see Figure 4.
- Viscosity: Elasticity and density increase with viscosity of oil; heavy oil exhibits a high bulk modulus (Nanda, 2016).
- Pressure: There are two vertical stresses that act on a rock beneath the surface: overburden stress and fluid pressure. The overburden stress relates to gravity and fluid pressure relates buoyancy; these forces act downwards and upwards respectively. The overburden pressure reduces the porosity, but the fluid pressure promotes retention of pores spaces. Effective pressure is the difference between overburden and fluid pressure; and this pressure may influence seismic properties. Effective pressure generally increases with depth which results in increased elasticity and density (Nanda, 2016).
- Temperature: Increased temperature influences the viscosity and elasticity; seismic properties will decrease in water and gas but decrease even more in oil (Nanda, 2016).

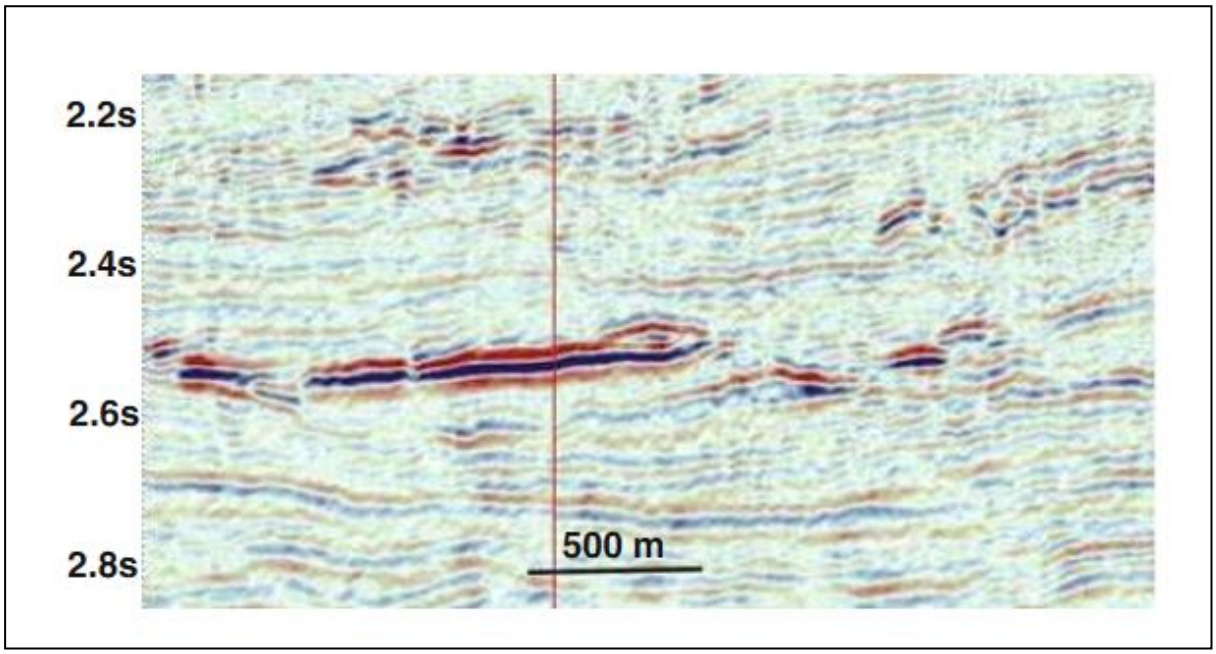


Figure 4: Seismic profile with a bright anomaly (Nanda, 2016).

Seismic reflection forms as a result of the contrast between two rock types. These reflections comprise different attributes like amplitude, phase, polarity, arrival time and velocity. Seismic interpretation workflow starts off by structural interpretation (structure), stratigraphic interpretation (rock and fluid properties), seismic stratigraphy interpretation (depositional systems and tectonics styles) and seismic sequence stratigraphy interpretation (log and core data with seismic interpretation). Different lithologies, fluid types and structures can be observed during seismic interpretation which makes it a very important tool during hydrocarbon exploration (Nanda, 2016).

### 2.5. Controlled Source Electro-Magnetic Surveys

CSEM relies on the distribution of electrical resistivity in the subsurface which determines the fluid content in lithologies. This physical property allows geoscientists to distinguish brine reservoirs (water-saturated) from hydrocarbon-saturated reservoirs (Fanavoll, et al., 2014). High resistivity on CSEM profiles may indicate hydrocarbon saturated areas which helps in detecting and delineating hydrocarbon resources (Hesthammer, et al., 2010). CSEM can identify hydrocarbon accumulations in traps and stratigraphic layers (varying in thickness) with high resistivity as compared to the surrounding lithologies. In Figure 5, reservoir intervals are mapped (green and yellow) on a seismic profile to the left and the same reservoirs are identified as CSEM anomalies showing as a bright red to yellow signature to the right (Fanavoll, et al., 2014). CSEM anomalies are not only limited to hydrocarbon saturated reservoirs; some lithologies that exhibit a high resistivity signature

are volcanics, salts, basement and carbonates. These lithologies are to be observed during interpretation, hence the geologist assigned in that specific area should understand the geology prior interpretation for proper results. This technology must be used in conjunction with other geophysical tools like seismic profiles and geological tools such as well data to get efficient results. CSEM is usually incorporated in risking of prospect once a potential area is identified; this will assist operators to make an improved decision during the exploration phase (Fanavoll, et al., 2014).

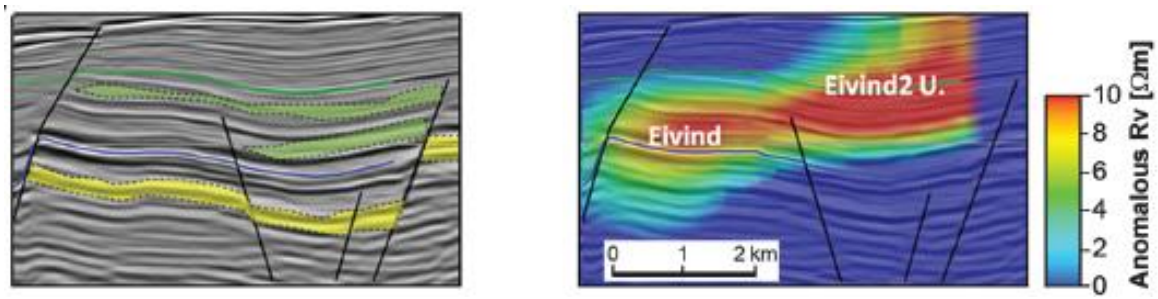


Figure 5: Reservoir on seismic (left) and CSEM (right) profiles (Fanavoll, et al., 2014).

Hesthammer, et al. (2010) assessed CSEM results and associated well data. In the publication, the number of wells associated with CSEM was 86 in total: 36 calibration surveys were assessed against well data with an aim to test the technology and 50 exploration wells were drilled after CSEM data was acquired. From the 36 calibration surveys; 22 surveys were acquired over hydrocarbon discoveries, 19 (86%) of these surveys indicate an CSEM anomaly as expected. The remaining 14 calibration surveys were shot over prospects that have tested negative for hydrocarbons, 13 (93%) of these surveys had no significant anomalies as expected (Hesthammer, et al., 2010). Out of the 50 exploration wells drilled, 30 were drilled on an CSEM anomaly of which 21 resulted in hydrocarbon discoveries. The remaining 20 were drilled in areas without an CSEM anomaly, of which 7 resulted in hydrocarbon discoveries. For all exploration wells drilled, there was a 70% success rate associated with CSEM anomalies and 35% success rate drilled in prospects without anomalies. This concludes that the average success rate of prospects with CSEM anomalies are double the success rate of prospects without anomalies. Although the success stories have been well documented in literature; the failure cases of CSEM application are not as well documented which makes it difficult to investigate why certain cases have failed in the past. The current hesitation in adopting the technology can be attributed to lack of understanding rather than the reliability of the technology (Hesthammer, et al., 2010).

In 2013, Shell conducted a lookback study aimed at evaluating the successful application of CSEM. Shell has applied this technology over numerous existing discoveries and prospects. The lookback study includes 37 cases of drilled prospects with the associated CSEM over different geological settings (Karman, et al., 2013). These wells were assessed based on acquisition details, workflow and interpretation results. Most of the ambiguous results were acquired before feasibility studies which is now common practice. As shown in Figure 6, the well results show 80% true positive results, with 83% true negative results (Karman, et al., 2013).

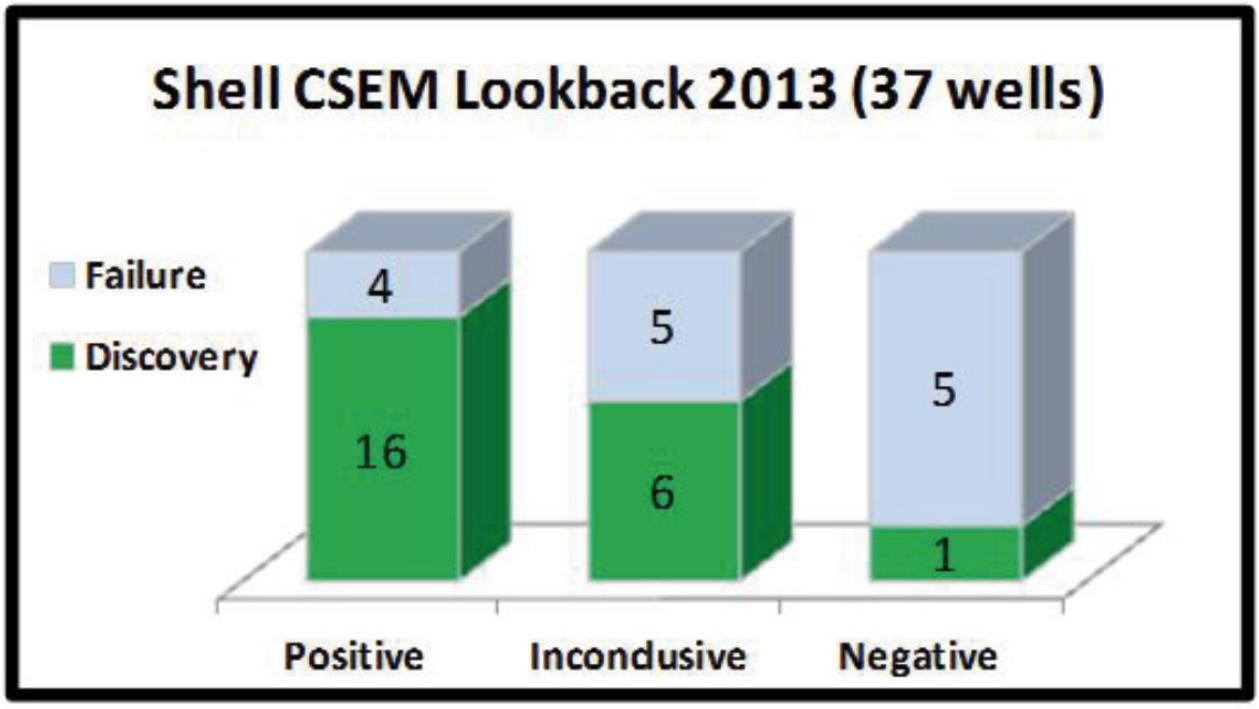


Figure 6: Results of the look back study (Karman, et al., 2013).

Numerous studies have been done on the success rate of CSEM. In a recent publication (Price, et al., 2019), benchmark studies have been conducted using available multiclient data over existing discoveries, sub-economic discoveries as well a failure cases. The study aimed at better understanding success and failure cases within the study area. Throughout this study, CSEM predictive strength as well as pitfalls and failure modes where investigated. During these studies, all available data such as seismic and well results were incorporated to fully understand the results. Old CSEM data was re-calibrated and reprocessed using recent techniques (Common Source Point) to ensure consistency with data of different vintages. The methodology was kept as simple as possible, 3D seismic inversion with no reference to seismic and well results. Two inversion codes were used during the study: L-BFGS (CGG's software) and TTI BFGS (EMGS latest Gauss-Newton

Code). The secondary objective of the study was to compare the two inversion codes, which if applied correctly, can address imaging challenges related to structure or geology. Looking at the images below; CSEM inversion based on the TTI BFGS code (Figure 8) gives better reservoir imaging than L-BFGS code (Figure 7) in this instance. L-BFGS has a lot of artefacts which has reduced the quality of reservoir imaging (Price, et al., 2019).

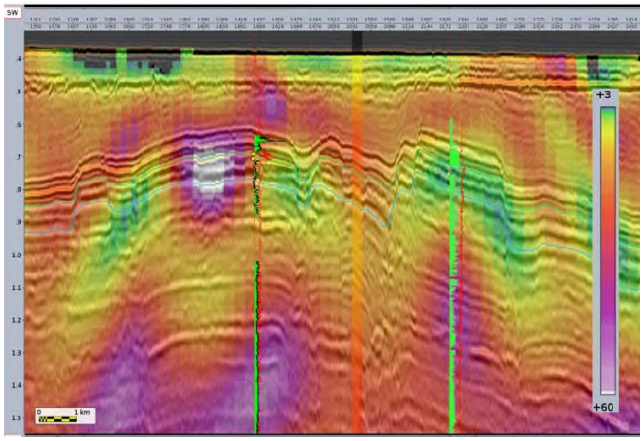


Figure 7: CSEM inversion using CGG L-BFGS code (Price, et al., 2019).

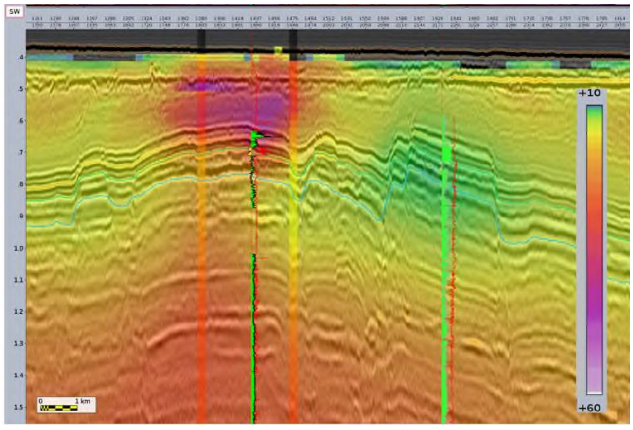


Figure 8: CSEM inversion using the EMGS TTI BFGS code (Price, et al., 2019).

### 2.6. Seismic and CSEM surveys as decision tools

Investment decisions in the Upstream Industry are dependent on geological interpretation and associated levels of uncertainty. A lot of geological tools are used to get as much information about the subsurface. Operators will determine how much information will be required to reduce the uncertainty and make that decision. The cost of information of each dataset acquired should be balanced with the value it brings in the decision-making process. Although seismic-based drilling is the most common, studies have shown that uncertainty is greatly reduced by the presence of CSEM data in a prospective area (Zweidler, et al., 2015) , see Figure 9.

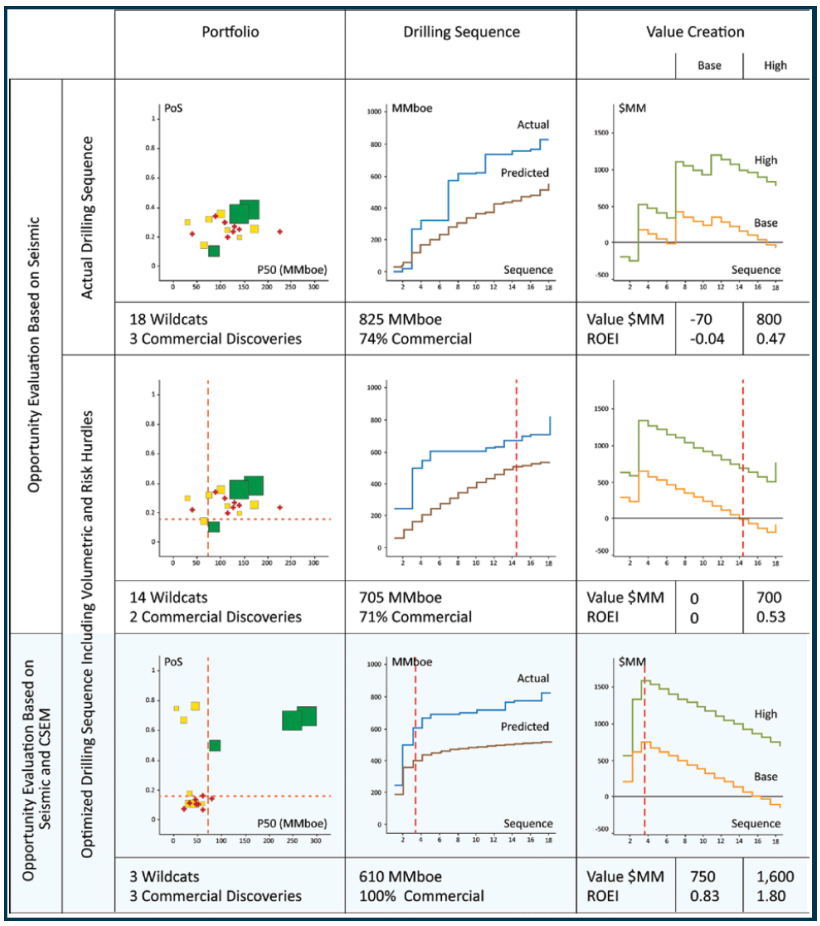


Figure 9: Seismic versus CSEM for investment decisions (Zweidler, et al., 2015).

## 2.7. Dry Hole Analysis

Post-drill (Post-mortem) analysis studies can significantly contribute towards understanding the dry hole disasters that most operators face during exploration. Such studies can be used as exploration wisdom to promote future drilling success by studying why these processes fail in the first place (Milkov & Samis, 2020). The first dry well to be drilled in the United States was the Grandin Well, which was also drilled around the same time as the first commercial well (Drake Well). Both wells were targeting the same play system. This first dry hole revealed the drilling risk associated with petroleum exploration. Post-drill studies become beneficial if they are used as a basis to either drill another exploration well or abandon the whole project. Most operators prefer not to invest in failure cases; once a dry well is drilled, most often they ignore the results and continue with other projects. Dry holes usually threaten the credibility of companies and the relevant technical team; this stigma hinders the efforts made towards post-drill reviews (Milkov & Samis, 2020).

Studies of well failures in peer-reviewed literature is limited, whereas the success cases are in abundance. The special attention given to successful discoveries alone results in

incorrect conclusions. Both failures and successes should be given the same attention to fully understand petroleum exploration. Companies also need to embrace past failures and consider mistakes in current exploration models as normal. These lessons learnt can serve as direction to future successes. The subsurface is quite complex and can never be fully understood; dry holes remain inevitable especially in frontier areas. Geologically, failing of a well can be attributed to lack of seal, closure, reservoir, or mature source (Milkov & Samis, 2020). In Figure 10, possible success and failure cases are illustrated. For petroleum fluids to accumulate properly, a trap where these fluids accumulate needs to exist and an efficient seal need to stop these fluids from leakage. In Figure 10A, a reservoir (sandstone), a seal (shale) and domal trap is present; this condition is suitable for the significant accumulation of petroleum fluids. The same applies in Figure 10B where a fault trap and a seal (salt) are present, this is another possible success case. Two possible failure cases illustrated in Figure 10C and D where a reservoir (sandstone) and trap (domal trap and fault trap respectively) are present, but no effective seal exists.

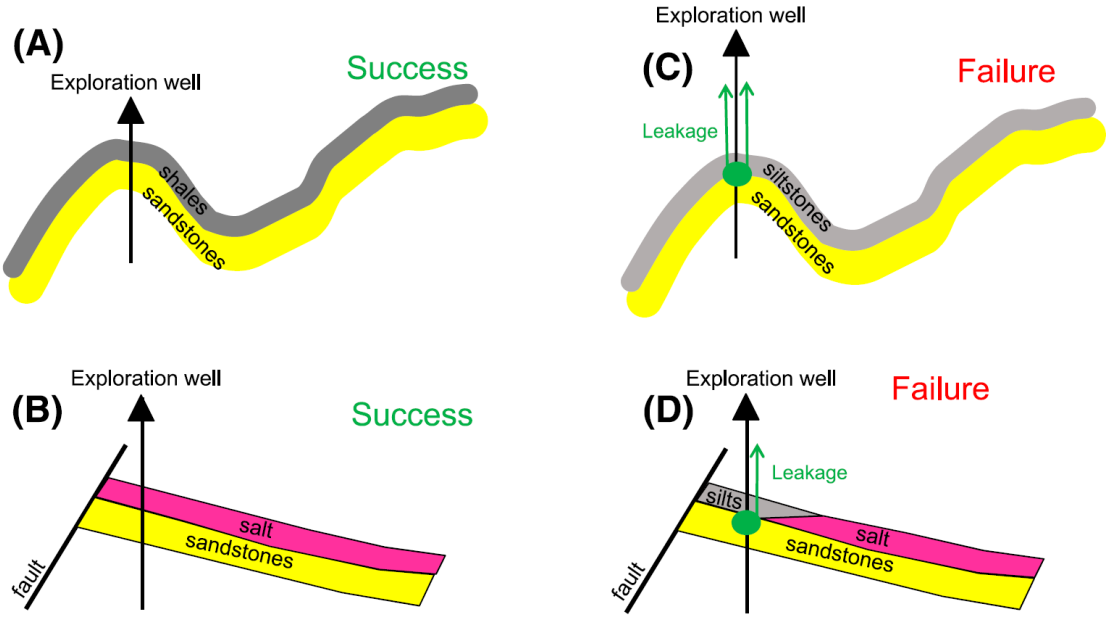


Figure 10: Success and failure examples for top seal (Milkov & Samis, 2020).

In Figure 11A and D, success cases are illustrated; both examples have an effective top seal, reservoir and a trap which is fault-bound in A and stratigraphic in D. In addition to the stratigraphic trap, a bottom seal is required to seal the reservoir and prevent leakage. Cases B and C are failure cases of fault traps associated with faults that are not sealing resulting

in a leakage, and cases E and F are failure cases of stratigraphic trap where bottom seal is not effective.

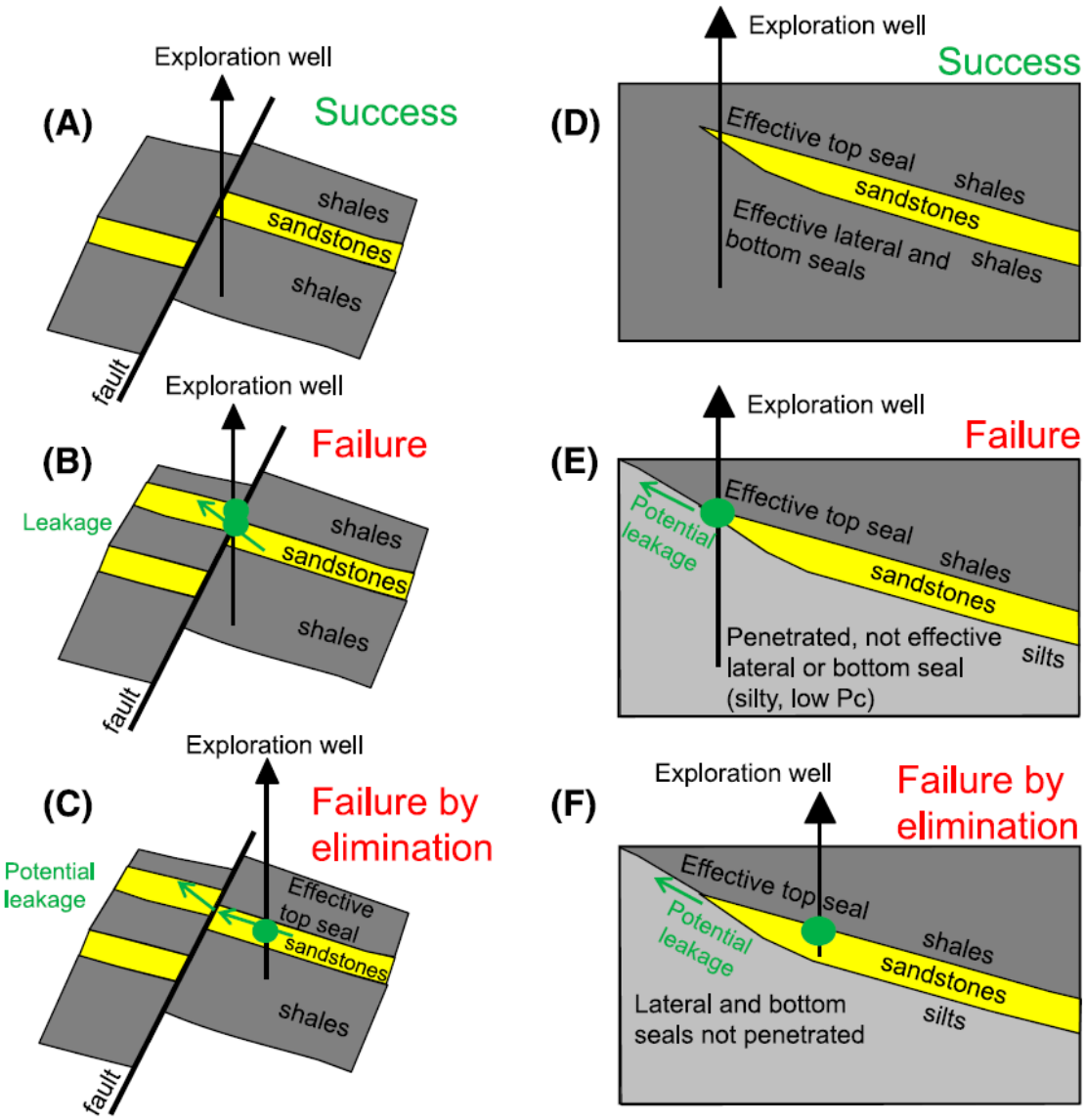


Figure 11: Success and failure examples for lateral and bottom seal (Milkov & Samis, 2020).

The success or failure of a reservoir can be attributed to the presence or absence of a reservoir respectively. In Figure 12A, the presence of sandstone as a suitable reservoir results in a success case whereas in Figure 12B, the targeted interval is shales (not a suitable reservoir) which results in a failure case.

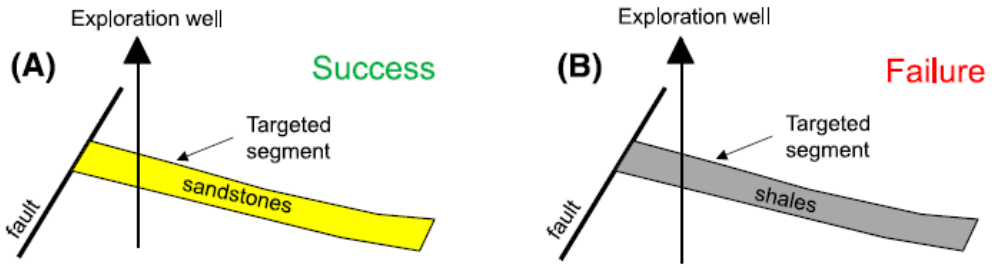


Figure 12: Success and failure examples for the presence of reservoir (Milkov & Samis, 2020).

Another criterion that can distinguish a prospect into a failure and success case is the reservoir deliverability. Figure 13A is a success case since it comprises a good sandstone reservoir; whereas Figure 13B has a low quality reservoir due to cementation and Figure 13C has heavy oil with no flow. Both cases B and C are regarded failure cases due to non-movable petroleum fluids.

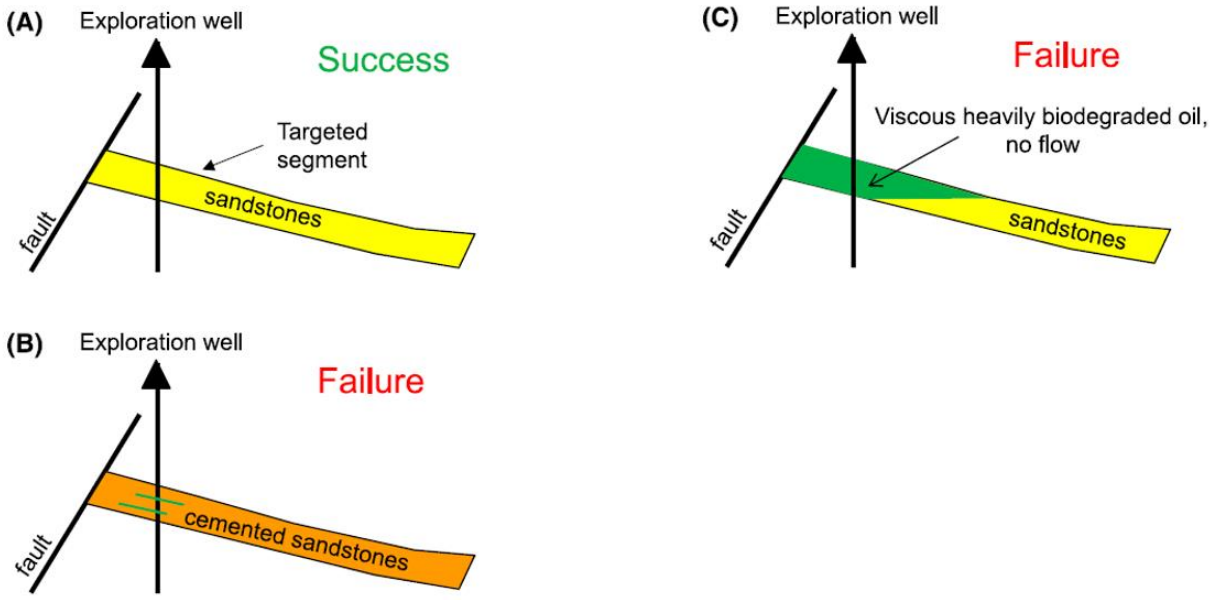


Figure 13: Success and Failure examples for reservoir deliverability (Milkov & Samis, 2020).

Figure 14A and C are success cases comprising mature source rocks capable of generating petroleum fluids; this results in hydrocarbon charged reservoirs. Case B represents a failure

case caused by low total organic carbon (TOC) and low hydrogen index (HI) shales whereas Case D represents a failure case resulting from immature source rocks.

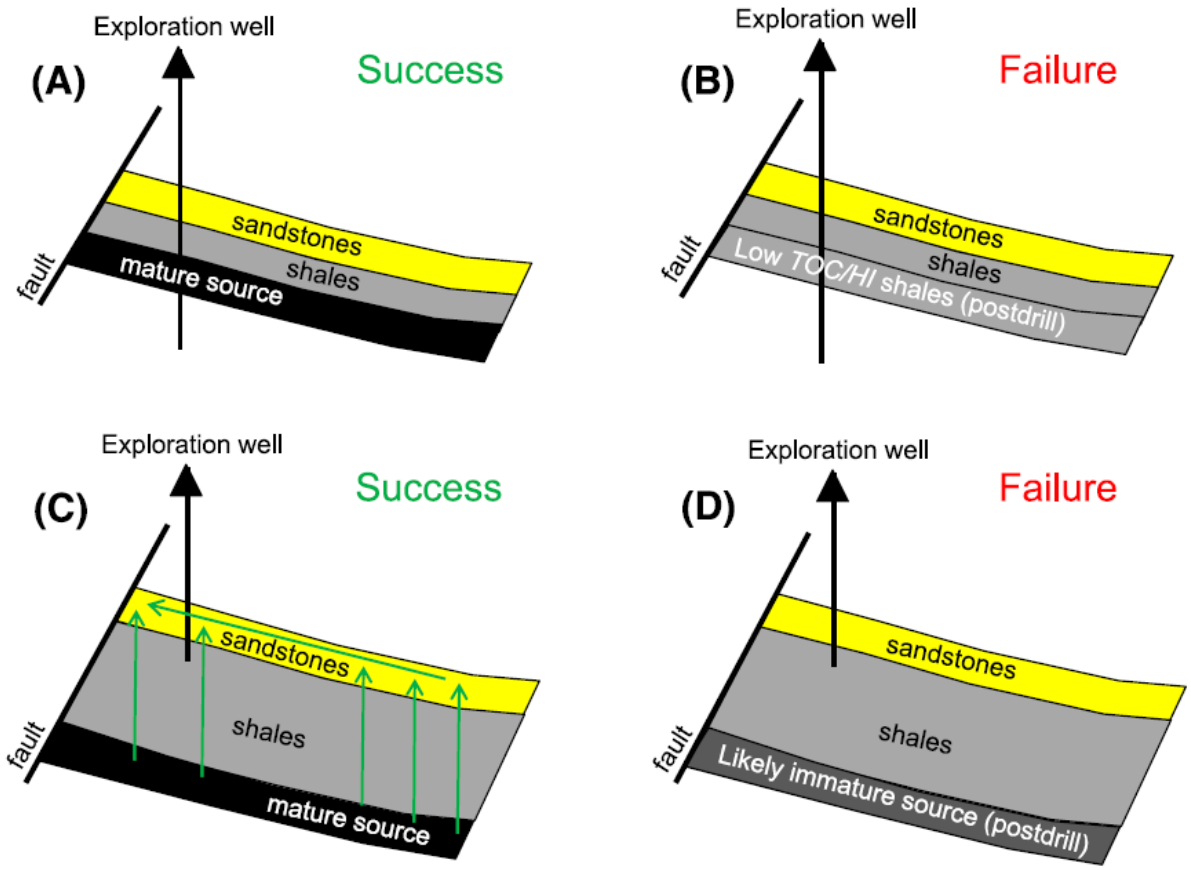


Figure 14: Success and failure examples for the presence of mature source rocks (Milkov & Samis, 2020).

Migration is a crucial element in the accumulation of hydrocarbons in a trap. In Figure 15A and C (Time 2), the green dots represent hydrocarbon shows, which suggests that petroleum fluids migrated from the source to the reservoir. In Figure 15B, petroleum fluids generated in the sources rock were lost during migration. In Figure 15C (Time1), the petroleum migrated before a structure could form which resulted in a failure case.

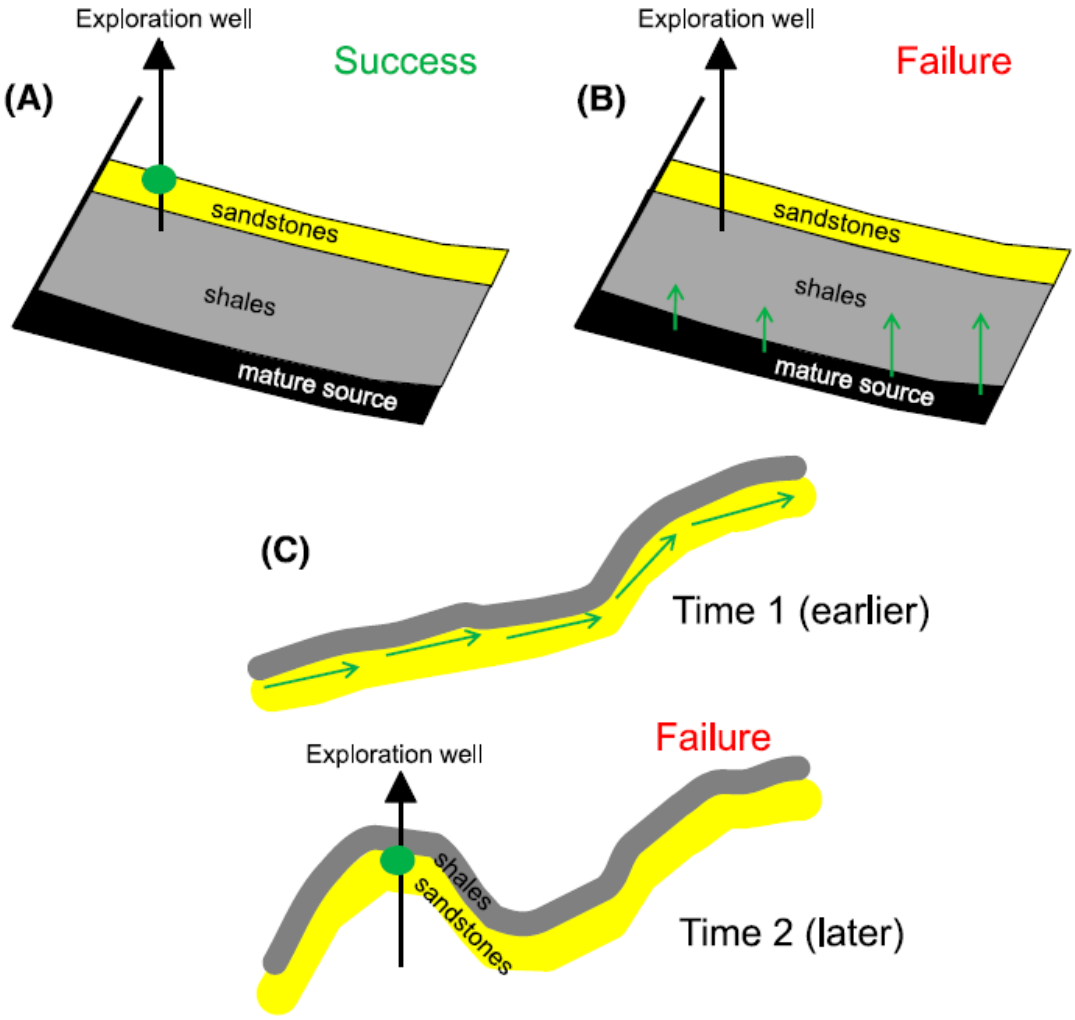


Figure 15: Success and failure examples for the migration of hydrocarbons (Milkov & Samis, 2020).

In the dry hole analysis studies, a decision tree (see Figure 16) may be used to determine the failure mode for the relevant conventional hydrocarbon prospects (Milkov & Samis, 2020). Each failed segment can be studied individually, and the reason of failure may be determined from the tree.

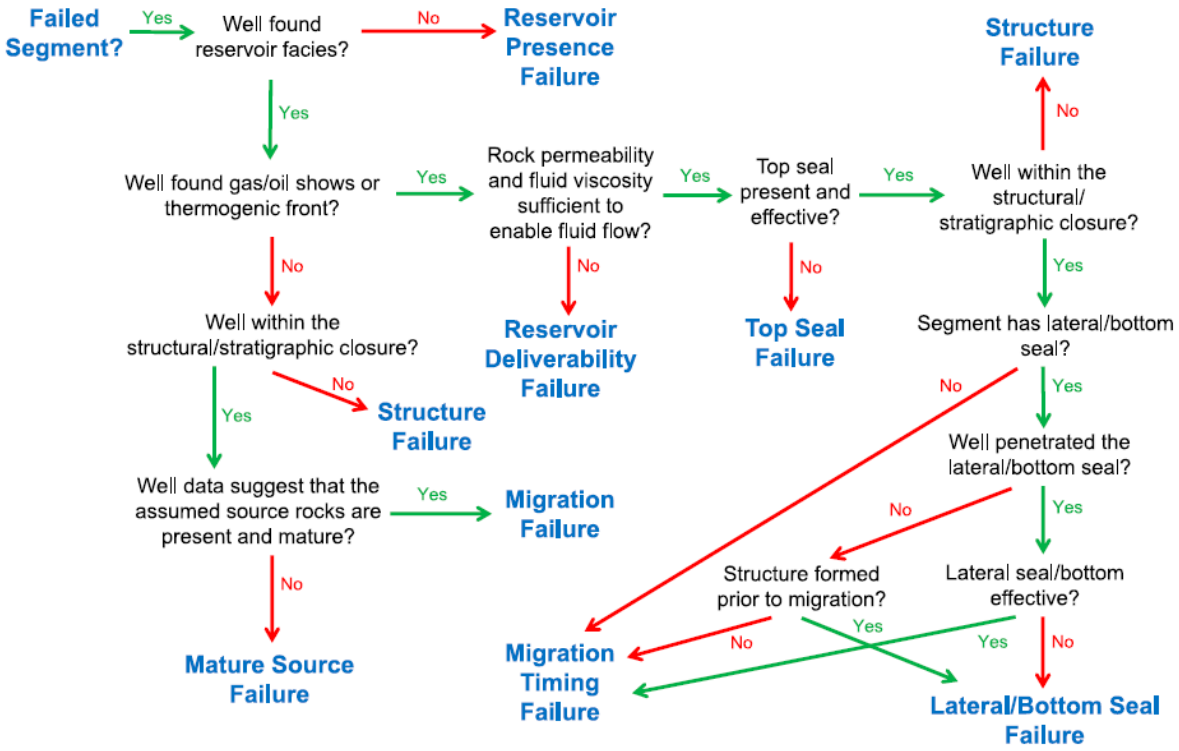


Figure 16: Decision tree applied in failed segments (Milkov & Samis, 2020).

## 2.8. Direct Hydrocarbon Indicators

Seismic anomalies were first used to predict hydrocarbon accumulation in 1970. It was observed that most hydrocarbon traps could possibly be associated with bright amplitude anomalies, these anomalies were later referred to as Direct Hydrocarbon Indicators (DHI) (Rowi, et al., 2020). DHIs imply the presence of hydrocarbons, these anomalies significantly reduce risk and have led to may successful discoveries. Seismic DHIs are anomalous seismic attributes (Nixon, et al., 2018) used to track hydrocarbon accumulations using amplitude anomalies such as bright spots, flat spots, polarity reversals and dim spots (Rowi, et al., 2020). Although DHIs are identified by their anomalous character (Nixon, et al., 2018), the following conditions are necessary in validating the DHI anomaly:

- Good seismic quality, preferably 3D. The reservoir interval should be imaged properly with compromise from geological features such as igneous bodies, carbonates and salt.
- A plausible geological model supporting a hydrocarbon trap.

In CSEM, DHIs are resistivity anomalies observed in CSEM data using different inversion techniques to distinguish a saturated reservoir from the surrounding geology (Price, et al., 2019). To ensure proper interpretation of DHIs, these anomalies need to be interpreted

according to the local geology and be incorporated with geological risking and historical results. DHIs are a basis for good drilling decisions and often guard against poor decisions too. A DHI is only genuine if supported by a valid geological model (Nixon, et al., 2018).

### 2.9. Pitfalls

DHI pitfalls are DHI lookalike anomalies caused by geological scenarios that do not contain hydrocarbons (Nixon, et al., 2018). These anomalies are not completely infallible, and any misinterpretation will result in exploration failures. DHIs are very difficult to classify as some cases may be falsely categorized as hydrocarbon-bearing units (Nixon, et al., 2018). As a result, some drilled anomalies have resulted in dry holes (Rowi, et al., 2020).

#### I. Seismic DHI Pitfalls

Seismic DHI pitfall may result from low gas saturation in reservoirs, diagenetic effects and seismic responses of inert gases such as carbon dioxide and nitrogen (see Table 1) which may not be easily distinguishable from hydrocarbons (Nixon, et al., 2018).

Table 1: Summary of causes of seismic DHI pitfalls, DHI types and quality control techniques to assist in assessing the DHI pre-drill (Nixon, et al., 2018).

| Causes of DHI False Positive | DHI Type | Pre-drill QC |
|---|---|---|
| Low saturation residual gas | Attribute Conformance with depth, Flat Spot, Phase Change, Amplitude Consistency, AVO Anomaly | Unable to differentiate between high saturation gas (moveable) and low saturation gas (residual) |
| Diagenetic effects | Attribute Conformance, Flat-spot, Phase Change, Amplitude Consistency, AVO Anomaly | Check for potential diagenetic effects e.g. opal CT, devitrification of volcaniclastics |
| Cross-cutting multiple energy | Flat Spot | Multiple event extends beyond prospect closure area |
| Unconformity surface | Flat Spot | Unconformity unlikely restricted to prospect closure area |
| Gas Hydrates | Flat Spot | Temperature/Depth dependent - restricted to narrow overburden range |
| Manipulation of colour bar dynamic range or inappropriate windowing of attributes | Amplitude Consistency | Assess data using full dynamic range over discrete target intervals |
| Brightening due to seismic tuning | Amplitude Consistency, AVO Anomaly | Seismic forward modelling |
| Shale on Shale AVO | AVO Anomaly | No conformance with depth structure |
| Brine sand gives Class 3 AVO response | AVO Anomaly | No conformance with depth structure |

A good example of a DHI pitfall is found within the East Java Basin in a structural high containing limestone. DHI anomalies were used to assess the X Structure which led to the drilling of Well X1 which tested positive for gas and Well X2 which resulted in a dry hole; the two wells were targeting the same DHI anomaly and reservoir (Rowi, et al., 2020). After a post-mortem analysis, it was concluded that the seismic pitfall is related to low hydrocarbon saturation. A reservoir that has low gas saturation (approx. <5%) and a

reservoir with up to 100% gas saturation will have a similar DHI response. Reservoirs with low gas saturation are automatically dry wells whereas high saturation reservoirs tend to be successful (Rowi, et al., 2020).

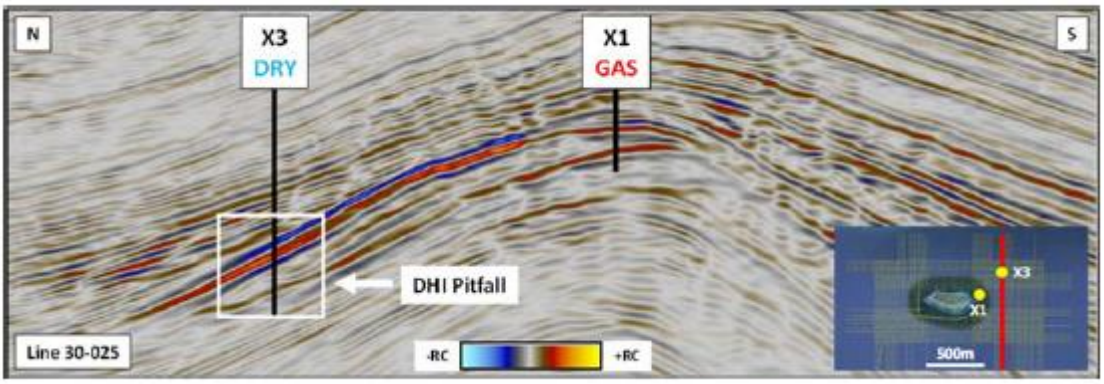


Figure 17: DHI anomalies in the X structure with Well X1 testing positive for gas and Well X3 dry (Rowi, et al., 2020).

Another seismic pitfall was observed in a deep-seated thin layered reservoir within the Talang Akar Formation. Seismic processing may affect the imaging of data in deeper levels which may result in seismic pitfalls (Oktariena & Triyoso, 2016).

II. CSEM Pitfalls

There is a risk of drilling a dry well on a CSEM anomaly. These cases are referred to as false positive (CSEM DHI pitfalls). The risk can be lowered by a good understanding of the measurements and integration with any other geophysical instruments (Fanavoll, et al., 2010). CSEM is sensitive to commerciality of a hydrocarbon field; however, it is not sensitive to minimum-sized prospects. CSEM may not be able to distinguish a low-gas saturated reservoir from a brine reservoir (Fanavoll, et al., 2010). In problematic areas with high resistive layer such as salt and volcanic, the incorporation of magnetic or H-field in the inversion is important to properly interpret the CSEM anomalies (Price, et al., 2019).

## 2.10. Statistics

Statistics is a way of studying data; this involves data collection, description, analysis and usually results in a certain conclusion (Ross, 2010).

### 2.10.1. Descriptive Statistics

Descriptive Statistics presents data in an organized, summarized and understandable manner. The data is represented in a form of central location and measure of variability (spread) (DeCoursey, 2003).

- Central Location refers to the central position of a set of data: Mean (arithmetic and geometric), Median and Mode.
- Measure of variability refers to the spread of a set of data: Range, standard deviation and variance (DeCoursey, 2003).

### 2.10.2. Inferential Statistics

Inferential statistics infers conclusions about a population from studying a representative sample (DeCoursey, 2003).

Hypothesis Test:

A statistical hypothesis is an assumption made on one or more populations. The process of making a decision about a hypothesis is referred to as hypothesis testing (Montgomery & Runger, 2002). A hypothesis testing begins with a null hypothesis $H_0$, this is a specific baseline statement that is tested which will either take a form of “no effect” or “no difference”. An alternative hypothesis ($H_1$) denies the null hypothesis (Kaur, 2016). During hypothesis testing, rejection of the null hypothesis leads to the acceptance of the alternative hypothesis e.g.:

$H_0$: “x = y.”

$H_1$: “x≠y” → (Two tailed)

A two-tailed test considers two directions were x< y or x> y (Kaur, 2016).

The main steps to follow when testing hypothesis is as follows (Remenyi, et al., 2009):

- State the null hypothesis as well as the alternative hypothesis.
- Define the suitable level of significance (1%, 5%, 10%).
- Determine the type of tool suitable for your test (t, Z, F, Chi Square, Anova).
- Calculate the test statics value using the selected tool.

- Compare the calculated t value with the table value (Critical t).

The Critical t value is derived from the Student's t-distribution and is compared to the calculated test statistic to determine whether to accept or reject the null hypothesis (DeCoursey, 2003). If the calculated value is less than the table value (Critical t), accept the null hypothesis; but if the calculated value is greater than the table value, reject the null hypothesis (Kaur, 2016).

Chi-square test is a non-parametric statistical tool that provides information on the significance of difference observed in nominal data (Zibran, 2007). This significance test is also known to be a distribution free test (McHugh, 2013) .

Chi-square assumptions are as follows (McHugh, 2013):

I. Cell data should be in the form of frequencies or counts.
II. The variable categories are mutually exclusive.
III. Each subject must strictly contribute to one cell in $X^2$.
IV. The test can only be applied on study group that are independent. If the groups are related, different test should be used.
V. The two variables must be categorical or ordinal in nature.
VI. The expected value should not be less than 1, this assumption is likely to be true if the number of samples are equal.

The following equation is used to calculate the value in a cell:

$$\text{Expected cell frequency} = \frac{(\text{row total}) * (\text{column total})}{grand\ total\ of\ all\ cells}$$

Chi square can be calculated by the following equation:

$$\sum X^2_{i=j} = \frac{(O-E)^2}{E}$$

Where:
O=Observed (relates to the actual data)
E=Expected Value
$X^2$=Chi-square value in cell
i=j relates to all cells, from the first (i) to last (j)

Degrees of freedom is calculated as follows:
df=(r-1)(c-1)

Where

r=rows

c=columns ( (Zibran, 2007)

## 2.11. Decision Tree analysis

There is a lot of uncertainty associated with decision analysis, assuming every company is likely to view risk with the same attitude. The assumption made is that decision makers will prefer to choose a decision based on the highest expected value of profit (Hammond, 1967). Decision tree analysis is characterized by decision alternatives with associated payoffs represented by a decision tree (probability distributions). The ultimate decision may be based on the expected value criterion. This aims at either maximizing or minimizing the expected profits and costs respectively (Taha, 2017). The decision analysis is mainly useful in deciding whether to make an immediate decision or to do some form of testing to reduce the uncertainty associated with that decision. When the decision alternatives and state of nature with associated probabilities are known, you can calculate the payoffs under these different circumstances. A good example to demonstrate the decision analysis is the Goferbroke case study.

The Goferbroke Company owns land that potentially has oil. A geologist consultant seems to believe there is a one out of four chances that there is oil. Due to the consultant's report, another company took an interest on the land and decided to put an offer to buy the land from Goferbroke. Geobroke has an option to either sell the land or keep the land and drill for oil. The drilling campaign cost $100 000. If drilling the land is successful for oil, the expected revenue is $800 000. Considering the drilling cost ($100 000), the company will make a profit of $700 000. If no oil is found, the company will incur a loss of $100 000. Another option that can be considered before deciding whether to drill or sell is conducting a seismic survey of land to reduce the uncertainty associated with the decision. The company's financial standing is not that good, hence a loss of $100 000 would make significant damage to the company profile.

The decision maker can be an individual or groups tasked with making a decision. There are different alternatives or options. Different factors can potentially affect the outcome of the decision. These factors determine the results of the decision executed. The possible outcomes are referred to as possible state of nature. The decision maker will have

information about the probability of the state of nature, these are referred to as prior probabilities. The payoff is often monetary in value and represent a quantitative measure of the decision outcome.

Table 2: Prior probabilities from the Goferbroke Case (Perera, 2018).

| State of nature | Prior Probabilities |
|---|---|
| Land contains oil | 0.25 |
| Land is dry | 0.75 |

Source: Perera, 2018

Table 3: The payoff table from the Goferbroke Case showing maximax and maximin.

| | State of Nature | | | |
|---|---|---|---|---|
| Alternative | Oil | Dry | Maximum in row | Minimum in row |
| Drill for oil | $700 000 | -$100 000 | $700 000 ←Maximax | -$100 000 |
| Sell the land | $90 000 | $90 000 | $90 000 | $90 000 ←Maximin |
| Prior probabilities | 0.25 | 0.75 | | |

Source: Perera, 2018

The maximax criterion is a decision criterion that only focus on “the best that can happen”. The criterion starts off with identifying the maximum payoff in all the state of nature for each alternative; thereafter, the maximum payoff will be chosen. Looking at Table 3, the maximax is $700 000. The maximin criterion focuses on the worst-case scenario. This criterion begins with identifying the minimum payoff from all state of nature for each alternative, the maximum out of all these minimum payoffs are selected, see Table 3. The maximum likelihood criterion deals with the “most likely state of nature”. This criterion begins with the identification of the state of nature with the highest prior probability. Within that selected state of nature, the largest payoff will be chosen. Looking at Table 3, the highest prior probability is 0.75; and within that specific state of nature (dry), the largest payoff is $ 90 000. The Bayes Decision Rule considers all state of nature and associated probabilities. For each alternative, the payoff is multiplied by the prior probability. These products are summed up resulting in a weighted average referred to as the expected payoff (EP). The largest payoff is selected, Table 4 (Perera, 2018).

Table 4: Bayes Decision Rule for the Goferbroke Case (Perera, 2018).

| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 1 | **Bayes' Decision Rule for the Goferbroke Co.** | | | | | |
| 2 | | | | | | |
| 3 | | **Payoff Table** | State of Nature | | | Expected |
| 4 | | Alternative | Oil | Dry | | Payoff |
| 5 | | Drill | 700 | -100 | | 100 |
| 6 | | Sell | 90 | 90 | | 90 |
| 7 | | | | | | |
| 8 | | Prior Probability | 0.25 | 0.75 | | |

Using the Bayes decision rule, a decision tree can be used to analyse the problem graphically (Perera, 2018). The decision tree consists of nodes and branches. The nodes are made up of squares which represent decision points, and circles which represents chance events (Taha, 2017).

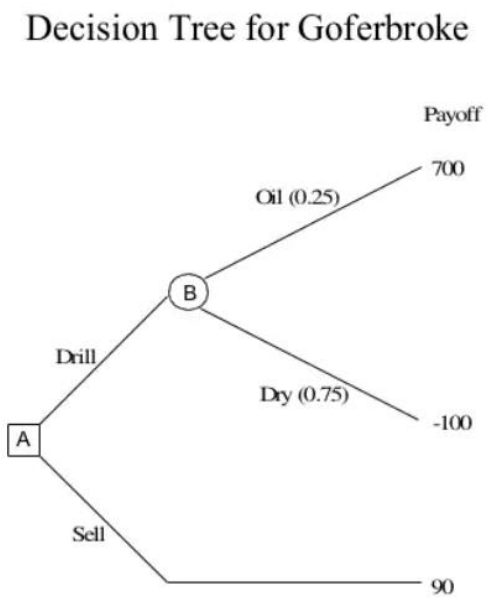


Figure 18: Goferboke decision tree (Perera, 2018).

Is it important to obtain more information to decrease the uncertainty around the decision? The best way to answer that question is by determining the “true state of nature” with perfect information (Perera, 2018).

EP (with perfect information) = EP of true state of nature

EP (without perfect information) = EP using Bayes decision rule with associated prior probabilities

The expected value of perfect information (EVPI) is as follows:

EVPI = EP (with perfect information) and EP (without perfect information) (Rothery, et al., 2020).

Bayes Theorem in justifying a geophysical survey.

Bayes Theorem defines the probability of an event based on prior probabilities that are likely to be related to the event (Foum, 2018). The Bayes Theorem states the following "Probability of A given that B has occurred = (Probability of B if A is true) * Original Probability of A) / Probability of B" which is represented as follows (Rangangatha, et al., 2018):

$P(A \mid B) = (P(B \mid A) * P(A))/P(B)$

An example of how Bayes Theorem was used to justify a CSEM survey:

A team of geologists have identified a potentially hydrocarbon-charged structure using available data. The chance of success (COS) which is defined as the probability of discovering producible hydrocarbons volume (Foum, 2018) was estimated to be 25%. If the project is successful, the economic value of the project is +$100MM, which is the sum of cash-flows. The cost of drilling a dry well is -$30MM. The expected monetary value (EMV) is +$2.5MM as shown in Figure 19.

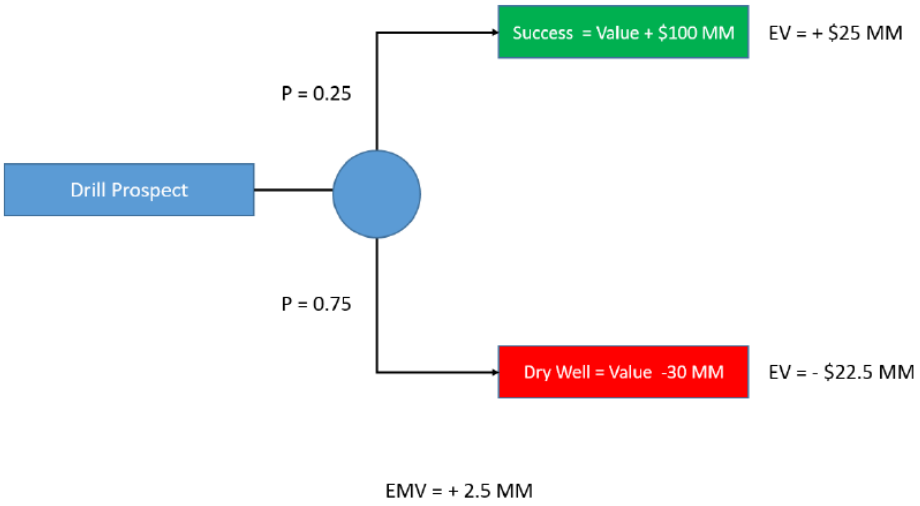


Figure 19: Initial expected value without consideration of additional data (Foum, 2018).

The Exploration Manager asked the geoscience team to investigate ways of polarising the risk. Some other companies have drilled in the same play and have employed CSEM to polarise the risk. CSEM anomalies that were drilled have generally been successful, whereas those without anomalies were likely to fail. The team conducted a feasibility study, the results indicated a 90% reliability on the play using this technique. There are four possible outcomes of the survey: True Positive, False Positive, True Negative and False Negative (Figure 20). The chance of success (COS) is the probability of discovering producible volume of hydrocarbons (Foum, 2018).

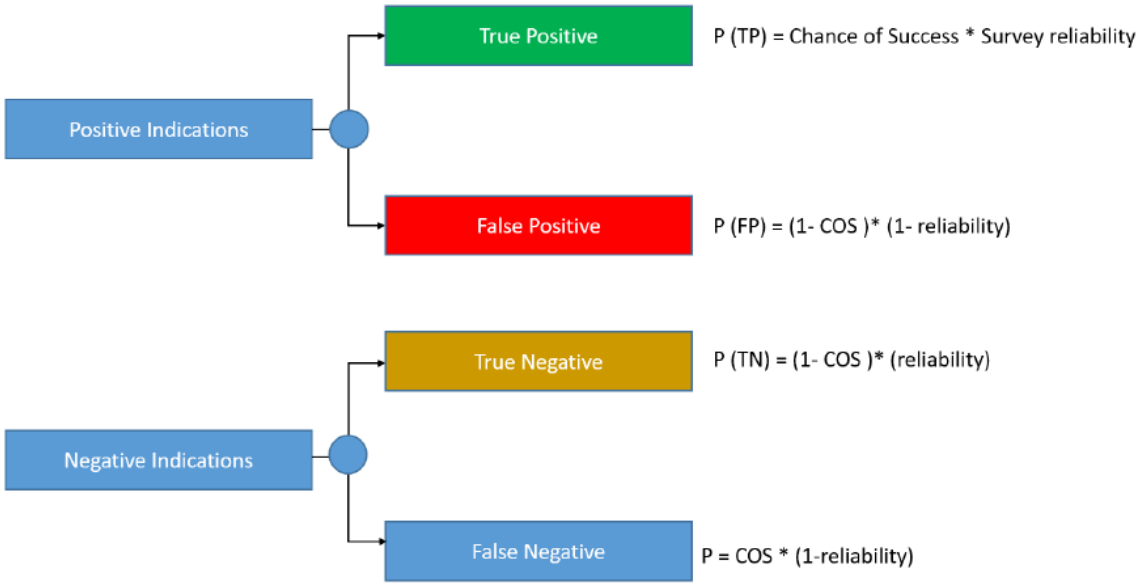


Figure 20: Four possible outcomes of a CSEM survey (Foum, 2018).

With the additional data supplied, the probability of each branch was calculated as shown in Figure 21. For instance, the probability of a True Positive=COS*reliability which will result in the following P(TP)=0.25*0.9=0.225. The probability of a false positive=(1-COS) *(1-reliability) which will result in the following: P(FP)=0.75*0.1=0.075. The probability of a True negative=(1-COS) *(reliability) which will result in the following: P(TN)=0.75*0.9=0.675. The probability of a false negative=(COS)*(1-Reliability) which will result in the following: P(FN)=0.25*0.1=0.025.

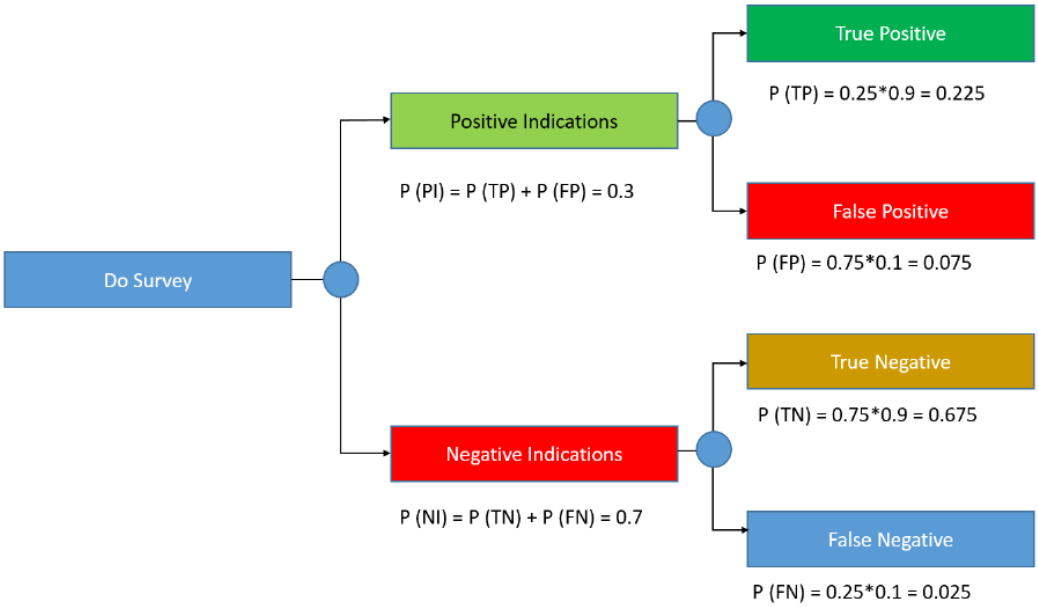


Figure 21: Probability of each branch give 90% reliability of the survey.

If the survey has been conducted and resulted in an anomaly (DHI), the new chance of success can be calculated by the following equation:

Bayes Theorem: $P(A|B) = (P(B|A) * P(A))/P(B)$

$P(A) = COS = 0.25$

$P(B) = Anomaly = 0.3$

$B|A = Reliability = 0.9$

If anomaly has been observed, the revised COS will be as follows:

$P(A|B) = (0.9*0.25)/0.3 = 0.75$

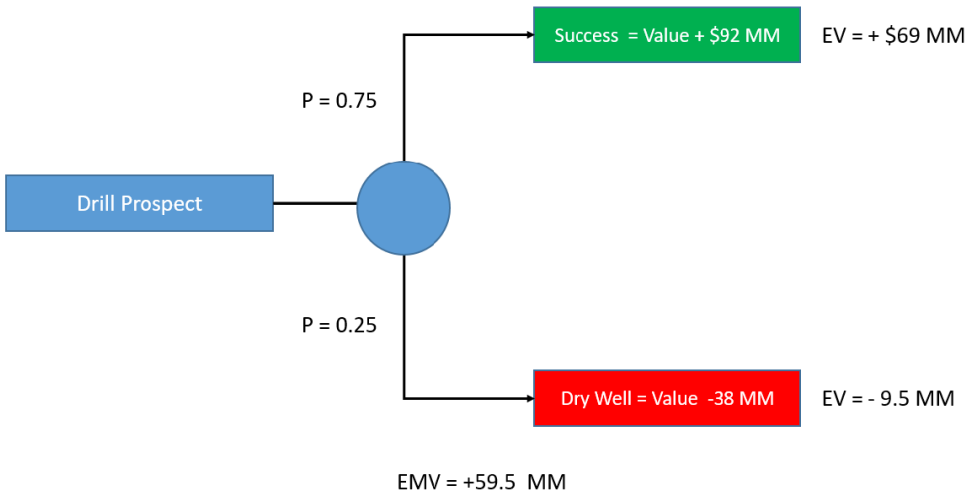


Figure 22: Revised Expected Monetary Value using the new probabilities given that the survey was conducted and resulted in an anomaly.

## 2.12. Gaps in current studies

The upstream industry faces major challenges in finding significant petroleum discoveries for exploration and exploitation. Seismic surveys are extensively used in petroleum exploration whereas CSEM application has seen limited application across the industry (Hesthammer, et al., 2010). Most studies have previously concentrated on seismic-based discoveries, looking mainly at direct hydrocarbon indicators on seismic profiles. Some of the studies focus on CSEM performance, with a statistical evaluation of well results in an area with CSEM data coverage. These results focused mainly on whether the wells have been drilled on an anomaly or not (Hesthammer, et al., 2010).

The survey results were classified as either true positive or a false positive if that survey had an anomaly, and true negative or false negative for surveys results without an anomaly (Berre, et al., 2020). The research investigated the effectiveness of the two surveys in hydrocarbon detection using fluid type and trap style. Each of the surveys were assessed to see if one of the surveys best identifies a certain hydrocarbon-saturated trap better than the other survey, e.g., the strength of seismic surveys in predicting saturated structural trap versus stratigraphic, and likewise for CSEM. The survey strength in predicting a specific hydrocarbon fluid was also investigated, e.g., the strength of seismic surveys in predicting gas versus predicting oil, and likewise for CSEM.

# 3. Methodology

## 3.1. Research Design

The most appropriate design for this study is the quantitative research method. The research is a study based on historical exploration data. The aim of the research is to test a theory through evaluating seismic-based drilling and CSEM-based drilling to check exploration effectiveness for the two methods. Statistical tools were used to analyse these exploration processes and to improve efficiency through process improvement. The research investigates the reliability of each technology through collecting CSEM-based results and seismic-based results and assessing the performance of CSEM against the performance of seismic surveys in hydrocarbon detection. The performance was tested by studying the number of drilled wells yielding hydrocarbons versus dry wells. The drilling results analysed were classified as successful or unsuccessful. The successful wells were categorized into different fluid types such as gas, oil and condensate to check if certain fluid types are easier to identify in seismic or CSEM. Successful wells were further grouped into trap style to check if structural or stratigraphic traps are easier to identify on seismic or CSEM profiles. Chi-square tests on Excel (CHISQ.TEST) were used to check if the seismic and CSEM samples are statistically significant, and to determine if one method is better than the other in hydrocarbon detection. Wells were divided into different age intervals to see if there is a relationship between age of survey and success of survey; this would help track the advancement of technology with years. Decision tree analysis using Tree Plan (Add-in) on Excel was used to evaluate which hydrocarbon detection tool to prioritize for accelerated drilling decisions.

### 3.1.1. Ethical Issues/Clearance

Permission to access and use data in the research was formally requested from the relevant companies. An ethics clearance application was made to the university and a waiver was granted thereof. The ethical clearance reference number is MIAEC 120/20w. As stated in the application, all confidential information was protected by the researcher. Participating companies will be given access to the research upon completion.

**Right to privacy**

All participant's "right of privacy" was observed. The nature and quality of performance for the two participating companies was kept confidential. The two companies are referred to using numbers and alphabets e.g., Company A, Company B and so forth; and the relevant data supplied was referred to as well 1, well 2, well 3 etc. As requested by company B, no spudding date (date of which drilling began) was published in the research project. Process time for each method was calculated through subtracting the spudding date and end of survey date; the results were published in the research project. The researcher ensured that no computer hackers accessed sensitive information from the participating companies (Leedy & Ormrod, 2016).

**Honesty with Professional Colleagues**

The researcher has ensured honesty in reporting the results without misleading others. The researcher refrained from any sort of misrepresentation of work done. The researcher did not fabricate information with an aim to support a specific conclusion, as this act will be classified as scientific fraud. The researcher acknowledged ideas or words belonging to someone else as failure to do so serves as plagiarism (Leedy & Ormrod, 2016).

### 3.1.2. Validity And Reliability

#### 3.1.2.1. Validity

Validity is the degree of which the methodology measures what it is intended to measure as per the purpose of research (Leedy & Ormrod, 2016). Survey performance was measured using seismic-based and CSEM-based data to determined which method is the most efficient in hydrocarbon detection. The hydrocarbon detection capabilities were investigated using the well results, anomalies, age of survey, hydrocarbon fluid type and trap style to see if these attributes have any relevance to the type of survey used. The accuracy of each method was validated by real well data.

**Face validity** is the degree of which the methodology appears to measure a specific characteristic (Leedy & Ormrod, 2016). The CSEM-based results and seismic-based

results collected gave conclusive results in terms of effectiveness of both technologies regardless of geological complexities. Process variation was supposed to be analysed through comparing process time for the seismic-based drilling and CSEM-based drilling processes. This method proved invalid after some of the processes measured from survey to drilling resulted in a negative value (these negative results were due to surveys acquired after drilling).

**Content validity** is the degree of which the methodology will have a representative sample that covers all crucial aspects of the research (Leedy & Ormrod, 2016). The seismic-based samples and CSEM-based samples are representative of the general population as random selection methods have been applied during sample selection. The random sample function "=RAND ()" in Excel was used on both seismic and CSEM datasets.

**Criterion validity** is the degree to which results of a measurement will correspond with another related element (Leedy & Ormrod, 2016). The purpose of the research is to evaluate the effectiveness of each survey; however, the most common type of hydrocarbon fluids (oil or gas) discovered by company A and company B can also be extracted.

**Construct Validity**: The degree to which a methodology can measure an element that is assumed to exist but cannot be observed directly (Leedy & Ormrod, 2016). The data analysis of all samples measured the chance of success of both methods which are reliant on geophysics (mathematics and physics) to determine real geology. CSEM uses resistivity to determine the fluid contents and seismic surveys use acoustic energy to determine geology and fluid content. Oil or gas is assumed to exist, and that is only validated with real well data.

#### 3.1.2.2. Reliability

Reliability refers to how reliable the methodology is, in yielding the same results if repeated; this is also referred to as reproducibility (Leedy & Ormrod, 2016). The methodology consists of standardized steps in data collection, sampling and analysis, which makes the reproducibility of results possible.

**Interrater reliability**: The degree to which two or more people will give the same results when evaluating the same element (Leedy & Ormrod, 2016). When given the same data, two or more people will be able to reproduce the results.

**Test-retest reliability**: The degree to which a method will give similar results if conducted by the same people in a different occasion (Leedy & Ormrod, 2016). The reliability in result may be affected if there is a time lapse, since both two technologies are advancing and becoming more accurate. CSEM and seismic surveys in 2020 are expected to yield better results than in 1995 due to improvement in technology.

**Equivalent forms reliability**: The degree to which two different versions will give the similar results (Leedy & Ormrod, 2016). The instruments used to evaluate the data will not be affected by difference in versions if the data set remains the same.

**Internal consistency reliability**: The degree to which all steps in a single method will give the same results (Leedy & Ormrod, 2016). Internal consistency reliability was achieved by standardizing each step of all methods employed.

### 3.2. Sampling

Company A submitted 49 wells and Company B submitted 41 wells. Due to limited amount of data, the researcher used all the available samples in the analysis. As mentioned above, the data to be used in the study is 49 seismic-based data and 41 CSEM-based data.

### 3.3. Instrumentation

The researcher received a list of exploration wells from Company A and Company B; all these wells were captured in a spreadsheet. A total of 49 samples were selected from Company A and 41 samples from Company B. The researcher requested the following information of the 30 selected wells from each company:

Table 5: Data received from each participating companies.

| | Company A | Company B |
|---|---|---|
| Well status (dry/gas/oil/condensate) | Required | Required |
| Date of acquisition of seismic | Required | Required |
| Date of acquisition of CSEM | Required | Required |

| | | |
|---|---|---|
| Fluid type | Required | Required |
| Trap style | Required | Required |
| Spudding date | Required | Required |

In addition to the above, the researcher also requested the following information about the anomalies and drilling results: True Positive, False Positive, True Negative and False Negative from each survey.

Table 6: Additional information requested from Company A and Company B.

| Well results | Anomalies assessment | CSEM: Direct Hydrocarbon Indicators | Seismic: Direct Hydrocarbon Indicators |
|---|---|---|---|
| Successful well (oil, gas or condensate) | True Positive | | |
| | False Negative | | |
| Unsuccessful (dry) | True Negative | | |
| | False Positive | | |

### 3.4. Data collection and analysis procedures

All seismic-based data was collected from Company A and all CSEM-based data was collected from Company B. All samples have been submitted with the following relevant information: Well name, well status, spud date, survey date, fluid type and trap style. The well results (successful and unsuccessful) and fluid type (oil, gas or condensate) was derived from the well status. The process time in months was calculated using the following formula: [(Spudding date – End of survey date) /30]/12.

Process maps for the current exploration processes will be generated. Data analysis started off with grouping the successful and unsuccessful wells from both the seismic and CSEM dataset; these groups were plotted on multiple bar graphs. These graphs were used to determine which survey has the highest number of successful wells and which survey has the highest number of unsuccessful wells. The dataset was also grouped according to the anomalies: true positive, true negatives, false positive and false negatives. These groups were plotted on multiple bar graphs. These bar graphs

were used to compare the true and false predictions of both surveys. Using the true predictions (true negative and true positive anomalies), samples were grouped and plotted into different trap styles to determine if a specific survey predicts one type of hydrocarbon trap better than the other one. Using all the successful wells (true positive and false negatives), samples were grouped according to fluid type to determine if one survey predicts a specific fluid better than the other. All “gas and condensate” samples were classified as “gas “and all “oil and condensate” samples as oil. Additionally, hypothesis testing using the Chi-square tests were used to check if the seismic and CSEM data was statistically significant.

The observed frequency was captured on an Excel worksheet. The expected cell frequency was calculated using the following formula:

$$Expected\ cell\ frequency = \frac{\text{(row total) x (column total)}}{\text{(grand total of all cells)}}$$

Chi-Square was calculated using the following formula:

$$\sum X_{i=j}^{2} = \frac{(O-E)^2}{E}$$

Using the observed and expected frequency, the CHISQ.TEST function on Excel was used to get the p-value.

$H_0$: There is a no significant association between seismic and CSEM data.
P value<0.05 Reject $H_0$
P value>0.05 Accept $H_0$

Technological advancement was tracked by plotting the true predictions and false prediction into different age intervals to see if the success of drilling is related to newer technology. The different surveys were interpreted independently looking at whether there is a pattern observed in the graphs that suggests technological advancement with age. The decision tree analysis was the approach used to analyse the two surveys to see which tool needs to prioritize in the hydrocarbon detection phase. The main petroleum element considered in this stage is the reservoir. If a reliable hydrocarbon

detection tool is utilized, this can significantly increase the chance of success. The decision tree assessed the value of information of seismic and CSEM surveys as secondary tools focusing mainly on their hydrocarbon detection capabilities. The Bayes Theorem was applied in calculating the posterior probabilities, focusing on drilling based on direct hydrocarbon indicators (anomalies). The decision tree was computed using Tree Plan Add-in on Excel. A swot analysis was conducted on both methods to investigate the strength, weakness, opportunities and threats of the two technologies.

## 4. Results

Process mapping from primary survey acquisition to drilling is illustrated in the diagram below (Figure 23). The first column represents the start of the process which is a primary 2D seismic survey. The second column represent the various secondary surveys such as additional 2D or 3D seismic surveys and/or 2D or 3D CSEM surveys. After acquiring these additional surveys, the operators must make a decision from the results of the surveys. If the results are positive the operator may decide to drill; but if the results are negative, the operator may decide to abandon prospect. The last column is the end of the process which is drilling where the results will confirm if there are any hydrocarbons within the prospect or not.

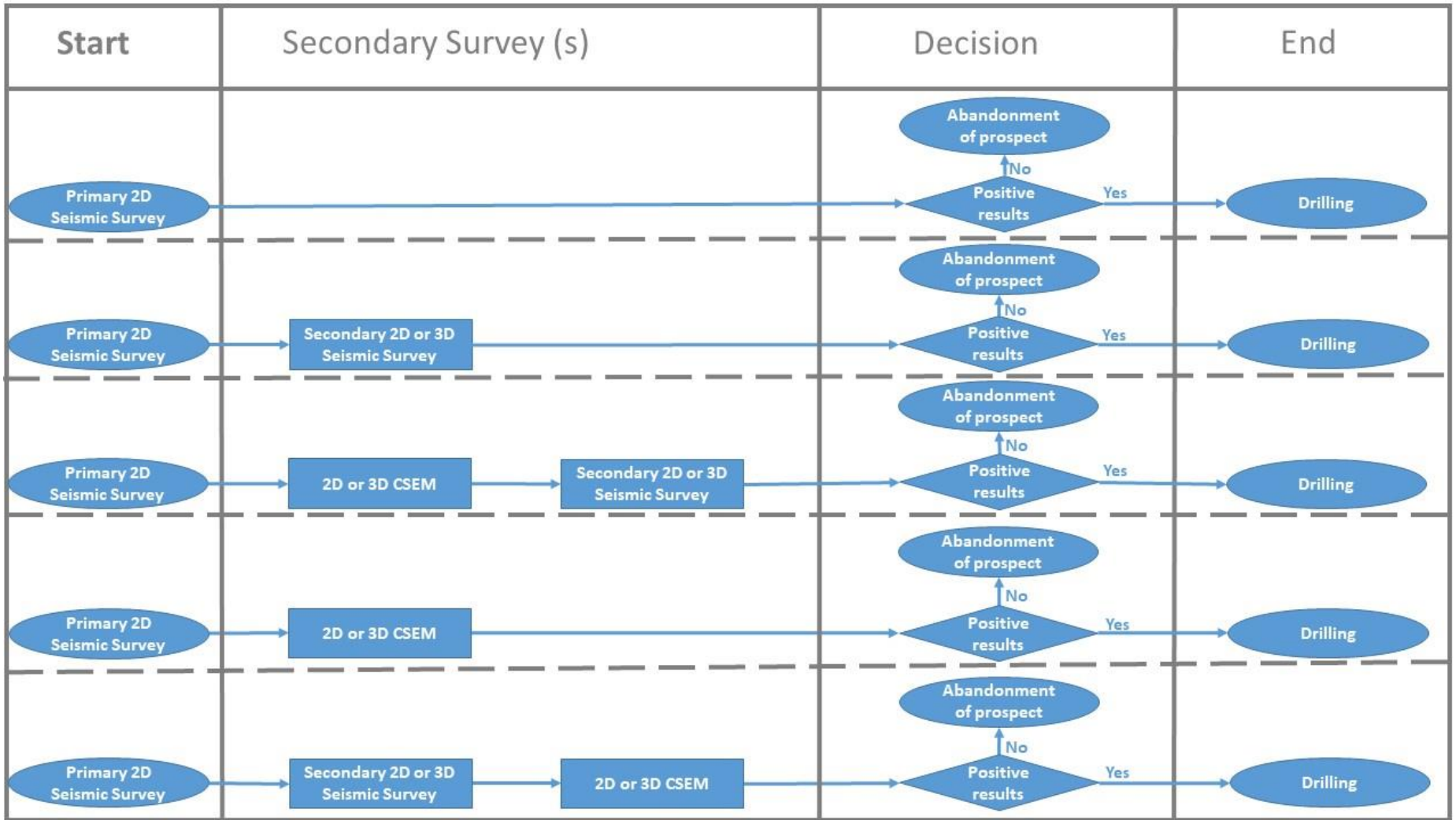


Figure 23: Process mapping showing the exploration processes (Cairn Energy, 2014).

Five processes have been mapped (Figure 23); these processes may vary according to different operators and specific needs for that prospect. The primary survey suggests the existence of hydrocarbons, different secondary survey(s) will be employed to further evaluate the prospect. The first process begins with primary 2D seismic survey. If the results are positive, the operator may decide to drill for hydrocarbons and if the results are negative, the operator may abandon prospect. The second process begins with a primary survey; if the results are positive, an additional 2D or 3D seismic survey is acquired. If the secondary seismic survey is positive, the operator will drill, however, if the results are negative the operator will abandon the prospect.

The third process begins with a primary seismic survey; if the results are positive, 2D or 3D CSEM survey is acquired. If the CSEM supports the existence of hydrocarbons, additional 2D or 3D survey is acquired to further evaluate the prospects. If the results of the secondary surveys are positive; the operator will drill; however, if the results are negative, the operator may abandon the prospect. The fourth process begins with a primary seismic survey; if the results are positive, 2D or 3D CSEM survey is acquired. If the CSEM results are positive, the operator will drill and if the results are negative, the operator may abandon the prospects. The last process begins with a primary seismic survey; if the results are positive, additional 2D or 3D seismic survey is acquired. If the secondary seismic survey supports the existence of hydrocarbons, an additional 2D or 3D CSEM survey is acquired to further evaluate the prospects. If the results of the secondary surveys are positive; the operator will drill; however, if the results are negative, the operator may abandon the prospect.

A SWOT analysis summarizing the strengths, weaknesses, opportunities and threats of each survey was tabulated as shown below (Table 7).

Table 7: SWOT analysis of seismic survey and CSEM.

| Strengths | |
|---|---|
| Seismic | CSEM |
| • Sensitivity to structure<br>• Provides a better understanding of the trap and reservoir | • Sensitivity to commerciality (volume and high saturation) of a hydrocarbon field<br>• Provides a better understanding of the charge |
| Weaknesses | |
| Seismic | CSEM |
| • Low saturated reservoirs that result in dry wells will have the same DHI anomaly as high saturated reservoirs that are commercial<br>• Processing effects for deeper targets<br>• DHI anomaly from non-hydrocarbon gases<br>• Seismic tuning | • Minimal Size may not be detected<br>• Low gas saturation has similar response to a brine reservoir<br>• Provides limited understanding of the lithologies and structure |
| Opportunities | |
| Seismic | CSEM |
| • Technological advancement in acquisition<br>• Data reprocessing to improve imaging | • Technological advancement in acquisition<br>• Data reprocessing to improve imaging |
| Threats | |
| Seismic | CSEM |
| • Pitfalls leading to dry wells.<br>• Environmental concerns | • Pitfalls leading to dry wells. |

| | |
|---|---|
| • False negative leading to abandoning a hydrocarbon saturated reservoir | • False negative leading to abandoning a hydrocarbon saturated reservoir |

From the data supplied by company A and Company B, 49 and 41 were used in the analysis (Table 8 and Table 9).The samples were categorized according to fluid type, well results, anomalies, trap type, survey year and process time as shown in Table 8 and Table 9.

Table 8: Seismic samples selected for the study.

| Name | Fluid Type | Well results | Anomalies | Trap Type | Survey year | Process Time (Months) |
|---|---|---|---|---|---|---|
| Well 1 | Gas | Successful | True Positive | Stratigraphic | 2001 | 2.21 |
| Well 2 | Gas | Successful | True Positive | Structural and stratigraphic | 1990 | 4.09 |
| Well 3 | Gas | Successful | True Positive | Structural | 1986 | 12.74 |
| Well 4 | Dry | Unsuccessful | False positive | Structural | 1976 | 2.76 |
| Well 5 | Oil | Successful | True Positive | Stuctural | 1969 | 4.56 |
| Well 6 | Dry | Unsuccessful | False Positive | Stratigraphic | 1996 | 2.26 |
| Well 7 | Dry | Unsuccessful | False positive | Structural | 1983 | 2.09 |
| Well 8 | Gas | Successful | True positive | Structural and stratigraphic | 1975 | 1.88 |
| Well 9 | Dry | Unsuccessful | False positive | Structural | 1976 | 2.09 |
| Well 10 | Dry | Unsuccessful | False Positive | Stratigraphic | 1988 | 2.28 |
| Well 11 | Dry | Unsuccessful | False positive | Structural | 1975 | 1.56 |
| Well 12 | Dry | Unsuccessful | False positive | Structural and stratigraphic | 1984 | 2.64 |
| Well 13 | Dry | Unsuccessful | True negative | Stuctural | 1969 | 4.43 |
| Well 14 | Dry | Unsuccessful | False positive | Stuctural | 1969 | 3.32 |
| Well 15 | Gas | Successful | False negative | Structural and stratigraphic | 1976 | 0.95 |
| Well 16 | Dry | Unsuccessful | False positive | Structural | 1969 | 1.68 |
| Well 17 | Gas | Successful | False negative | Structural | 1974 | 3.83 |
| Well 18 | Dry | Unsuccessful | False positive | Structural and stratigraphic | 2001 | 2.06 |
| Well 19 | Dry | Unsuccessful | True negative | Structural and stratigraphic | 1982 | 3.06 |
| Well 20 | Dry | Unsuccessful | False positive | Stratigraphic | 1976 | 1.38 |
| Well 21 | Dry | Unsuccessful | False positive | Structural | 1978 | 9.98 |
| Well 22 | Dry | Unsuccessful | False positive | Stratigraphic | 1993 | 10.46 |
| Well 23 | Dry | Unsuccessful | False positive | Stratigraphic | 1990 | 10.85 |
| Well 24 | Oil | Successful | True positive | Structural and stratigraphic | 1983 | 6.81 |
| Well 25 | Oil | Successful | True positive | Structural | 1970 | 2.94 |
| Well 26 | Dry | Unsuccessful | False positive | Stratigraphic | 1979 | 1.90 |
| Well 27 | Dry | Unsuccessful | True negative | Stratigraphic | 1984 | 2.74 |
| Well 28 | Dry | Unsuccessful | False positive | Structural | 1980 | 2.77 |
| Well 29 | Dry | Unsuccessful | False positive | Structural | 1975 | 1.59 |
| Well 30 | Dry | Unsuccessful | False positive | Stratigraphic | 1989 | 10.68 |
| Well31 | Dry | Unsuccessful | True  negative | Structural | 1969 | 4.34 |
| Well32 | Dry | Unsuccessful | False positive | Structural | 1984 | 2.58 |
| Well33 | Dry | Unsuccessful | False positive | Structural | 1968 | 2.74 |
| Well34 | Dry | Unsuccessful | False positive | Structural | 1967 | 6.11 |
| Well35 | Dry | Unsuccessful | True  negative | Stratigraphic | 1976 | 2.17 |
| Well36 | Dry | Unsuccessful | True  negative | Structural and stratigraphic | 1981 | 0.79 |
| Well37 | Dry | Unsuccessful | True  negative | Structural and stratigraphic | 1981 | 0.76 |
| Well38 | Oil | Successful | True positive | Stratigraphic | 1968 | 0.50 |
| Well39 | Gas | Successful | True positive | Structural | 1998 | 0.51 |
| Well40 | Dry | Unsuccessful | True  negative | Structural | 1969 | 1.59 |
| Well41 | Dry | Unsuccessful | False positive | Structural | 1975 | 1.58 |
| Well42 | Dry | Unsuccessful | True  negative | Structural | 1991 | 12.41 |
| Well43 | Dry | Unsuccessful | True  negative | Structural | 1976 | 2.76 |
| Well44 | Dry | Unsuccessful | True  negative | Structural | 1983 | 2.00 |
| Well45 | Dry | Unsuccessful | False positive | Structural | 1971 | 2.06 |
| Well46 | Gas | Successful | True positive | Stratigraphic | 1980 | 2.68 |
| Well47 | Dry | Unsuccessful | True  negative | Structural and stratigraphic | 1968 | 2.39 |
| Well48 | Gas | Successful | True positive | Structural and stratigraphic | 1968 | 2.65 |
| Well49 | Dry | Unsuccessful | False positive | Stuctural | 1989 | 31.99 |

Table 9: CSEM Samples selected for the study.

| Name | Fluid Type | Well results | Anomalies | Trap Type | Survey year | Process Time |
|---|---|---|---|---|---|---|
| Well 1 | Gas | Successful | False Negative | structural | 2014 | -0.9 |
| Well 2 | Gas | Successful | True positive | stratigraphic | 2010 | 4.2 |
| Well 3 | Dry | Unsuccessful | True negative | structural | 2004 | 4.7 |
| Well 4 | Gas | Successful | True positive | stratigraphic | 2004 | 4.7 |
| Well 5 | Gas | Successful | True positive | structural | 2011 | 0.5 |
| Well 6 | Oil/gas | Successful | True positive | structural | 2008 | 3.5 |
| Well 7 | Oil/gas | Successful | True positive | structural | 2010 | 1.3 |
| Well 8 | Oil | Successful | True positive | structural | 2008 | 5.1 |
| Well 9 | Gas | Successful | True positive | structural | 2015 | 1.7 |
| Well 10 | Oil/gas | Successful | True positive | structural | 2008 | 24.8 |
| Well 11 | Oil/gas | Successful | True positive | stratigraphic | 2007 | 0.2 |
| Well 12 | Gas | Successful | False negative | structural | 2016 | -35.3 |
| Well 13 | Gas | Successful | True positive | structural | 2008 | 2.9 |
| Well 14 | Gas | Successful | True positive | structural | 2010 | 4.1 |
| Well 15 | Gas | Successful | False negative | structural | 2015 | -28.4 |
| Well 16 | Oil/gas | Successful | True positive | structural | 2011 | 0.8 |
| Well 17 | Oil | Successful | True positive | structural | 2012 | -12.1 |
| Well 18 | Gas | Successful | True positive | structural | 2006 | 0.2 |
| Well 19 | Dry | Unsuccessful | True negative | structural | 2014 | 3.8 |
| Well 20 | Dry | Unsuccessful | False positive | structural | 2012 | 5.6 |
| Well 21 | Dry | Unsuccessful | False positive | stratigraphic | 2016 | 2.7 |
| Well 22 | Dry | Unsuccessful | True negative | structural | 2004 | -3.0 |
| Well 23 | Dry | Unsuccessful | True negative | stuctural | 2008 | 12.2 |
| Well 24 | Dry | Unsuccessful | True negative | structural | 2012 | 8.2 |
| Well 25 | Dry | Unsuccessful | True negative | structural | 2013 | 5.2 |
| Well 26 | Dry | Unsuccessful | True negative | stratigraphic | 2016 | 3.9 |
| Well 27 | Dry | Unsuccessful | True negative | structural | 2011 | 0.7 |
| Well 28 | Dry | Unsuccessful | True negative | structural | 2011 | 2.2 |
| Well 29 | Dry | Unsuccessful | True negative | structural | 2015 | -38.2 |
| Well 30 | Dry | Unsuccessful | False positive | structural | 2009 | 0.9 |
| Well 31 | Dry | Unsuccessful | True negative | structural | 2014 | 5.6 |
| Well 32 | Oil | Successful | False negative | stratigraphic | 2008 | 9.3 |
| Well 33 | Gas | Successful | False negative | structural | 2014 | 3.2 |
| Well 34 | Dry | Unsuccessful | False positive | structural | 2010 | 2.4 |
| Well 35 | Gas | Successful | True positive | structural | 2008 | 3.0 |
| Well 36 | Oil/gas | Successful | True positive | structural | 2010 | 3.2 |
| Well 37 | Oil/gas | Successful | True positive | structural | 2004 | 0.8 |
| Well 38 | Gas | Successful | False negative | structural | 2008 | 6.8 |
| Well 39 | Oil | Successful | True positive | structural | 2008 | 5.8 |
| Well 40 | Oil/gas | Successful | True positive | structural | 2016 | 0.7 |
| Well 41 | Gas | Successful | False negative | structural | 2010 | 3.2 |

The data analysis began with plotting the well results to see successful wells versus unsuccessful wells for both datasets. Successful wells were classified as all wells that tested positive for hydrocarbons (gas, condensate and oil) whereas dry wells do not contain any commercial or movable hydrocarbons. From the 49 seismic well results, 13 were successful and 36 were unsuccessful (Figure 24). These results have indicated a 27 % chance of success for all wells drilled on seismic surveys regardless of whether it is drilled based on an anomaly or not. Furthermore, 26 CSEM wells were successful and the remaining 15 wells were unsuccessful. From these results, there is a 63% chance of success of all wells drilled on CSEM surveys regardless of whether the wells were drilled on a positive or negative anomaly.




Figure 24: Successful and unsuccessful well results from sample group.

Hypothesis testing: Chi-square tests (see Table 10 and Table 11)

$H_0$: There is a no significant association between the type of survey used and the well results.

Table 10: Observed frequency of the successful and unsuccessful well results.

| Observed | Successful | Unsuccessful | Grand Total |
|---|---|---|---|
| Well results-Seismic | 13 | 36 | 49 |
| Well results-CSEM | 26 | 15 | 41 |
| Grand Total | 39 | 51 | 90 |

The expected value for each cell was calculated as follows:

$$\text{Expected cell frequency} = \frac{(\text{row total}) * (\text{column total})}{grand\ total\ of\ all\ cells}$$

$E_1$= (49*39)/90=21.23

$E_2$= (49*51)/90=27.77

$E_3$= (41*39)/90=17.77

$E_4$= (41*51)/90=23.23

Table 11: Expected frequency of the successful and unsuccessful well results.

| Expected | Successful | Unsuccessful | Grand Total |
|---|---|---|---|
| Well results-Seismic | 21.23 | 27.77 | 49 |
| Well results-CSEM | 17.77 | 23.23 | 41 |
| Grand Total | 39 | 51 | 90 |

$$\sum X^2_{i=j} = \frac{(O-E)^2}{E}$$

$X^2$= [(13-21.23)$^2$/21.13] + [(36-27.77)$^2$/27.77]+[(26-17.77)$^2$/17.77]+ [(15-23.23)$^2$/23.23]

$X^2$= 3.19+2.44+3.81+2.92

$X^2$=12.37

df= (r-1)(c-1)

df= (2-1)(2-1) =1

Significance level: 0.05

P-Value: 0.000437

0.000437<0.05 $H_0$ Rejected

There is a significant association between the type of survey used and the well results. The number of successful and unsuccessful wells are dependent on whether the survey is a seismic or CSEM survey. These samples are statistically significant.

The seismic and CSEM surveys may results in an anomaly that is suggestive of hydrocarbons; or “no anomaly” which may be associated with a non-saturated reservoir or other lithologies. The assessment of anomalies (Figure 25) began with categorizing all anomalies as either true positive or false positive, which results in successful and unsuccessful, wells respectively. All samples that did not have anomalies were categorized as true negative or false negative, which result in unsuccessful and successful wells respectively. From the positive anomalies observed, the true positive and false positive for the seismic results were 31% and 69% respectively (Figure 26B); Alternatively, the true positive and false positive for the CSEM results were 83% and 17% respectively (Figure 27B).

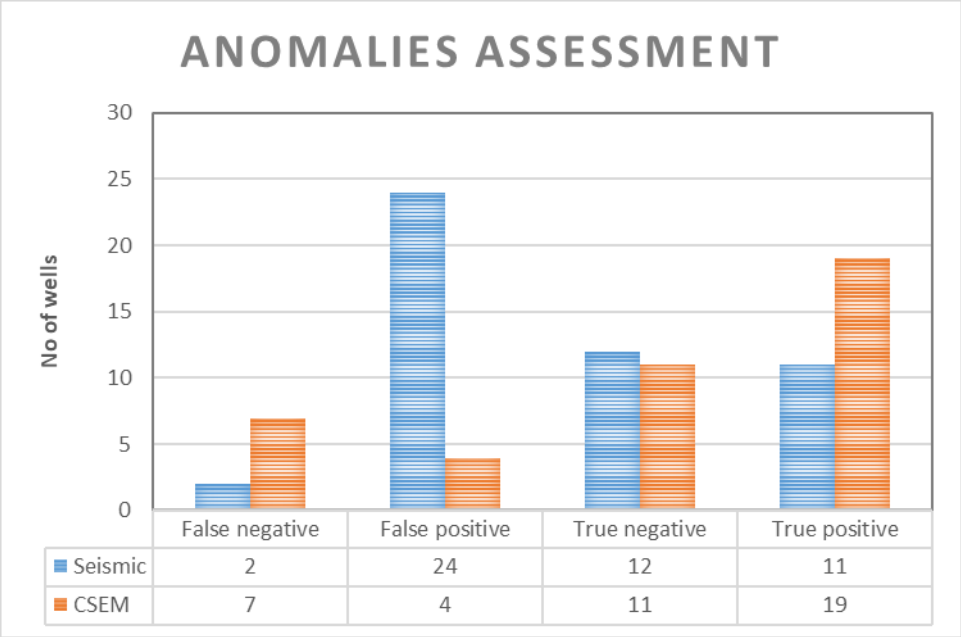


Figure 25: Anomalies assessment looking at false negative and positive as well as true negative and positive.

The data indicates that 71 % of the seismic profiles had positive anomalies (Figure 26A), and the remaining 29% had negative anomalies (25% true negatives and 4% false negatives). Additionally, 31% of the positive anomalies discovered hydrocarbons and 69% resulted in dry wells (Figure 26B).

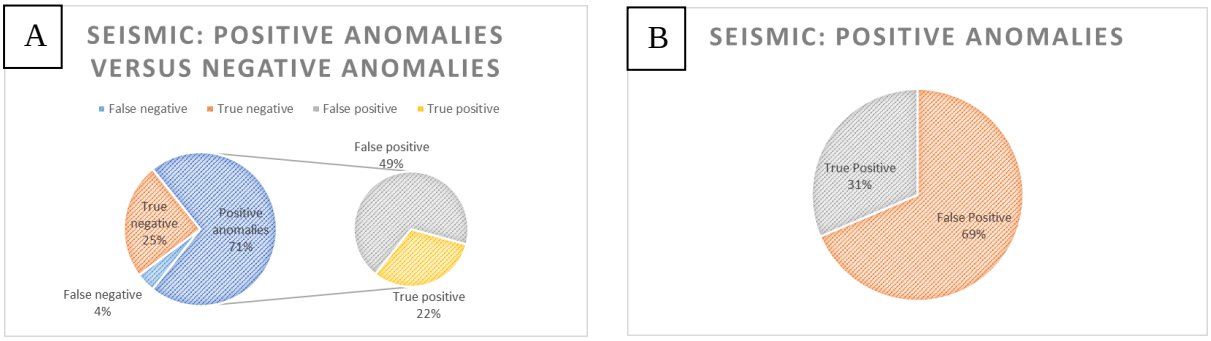


Figure 26: (A) Seismic: Positive anomalies versus negative anomalies, (B) Seismic Positive anomalies showing the true positives and false positive.

Looking at the CSEM data, 56 % of the CSEM profiles had positive anomalies (Figure 27A), and the remaining 44% had negative anomalies (27% true negatives and 17% false negatives). Additionally, 83% of the positive anomalies discovered hydrocarbons and 17% resulted in dry wells (Figure 27B).

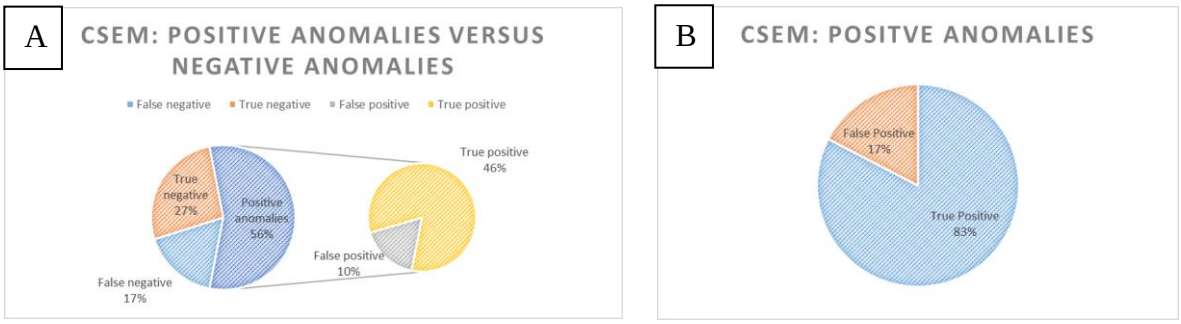


Figure 27: (A) CSEM: Positive anomalies versus negative anomalies, (B) CSEM: Positive anomalies showing the true positives and false positive.

Hypothesis testing: Chi-square tests (see Table 12 and Table 13)

$H_0$: There is a no significant association between the survey anomalies observed and the well results.

Table 12: Observed frequency of the anomalies assessment.

| Observed | False Negative | False positive | True Negative | True Positive | Total |
|---|---|---|---|---|---|
| Seismic | 2 | 24 | 12 | 11 | 49 |
| CSEM | 7 | 4 | 11 | 19 | 41 |
| Total | 9 | 28 | 23 | 30 | 90 |

The expected value for each cell was calculated as follows:

$$\text{Expected cell frequency} = \frac{(\text{row total}) * (\text{column total})}{grand\ total\ of\ all\ cells}$$

$E_1$= (49*9)/90=4.90

$E_2$= (49*28)/90=15.24

$E_3$= (49*23)/90=12.52

$E_4$= (49*30)/90=16.33

$E_5$= (41*9)/90= 4.10

$E_6$= (41*28)/90=12.76

$E_7$= (41*23)/90=10.48

E8= (41*30)/90=13.67

Table 13: Expected frequency of the anomalies assessment.

| Expected | False Negative | False positive | True Negative | True Positive | Total |
|---|---|---|---|---|---|
| Seismic | 4.90 | 15.24 | 12.52 | 16.33 | 49 |
| CSEM | 4.10 | 12.76 | 10.48 | 13.67 | 41 |
| Total | 9 | 28 | 23 | 30 | 90 |

$$\sum X^2_{i=j} = \frac{(O-E)^2}{E}$$

$X^2$= [(2-4.90)$^2$/4.90] + [(24-15.24)$^2$/15.24]+[(12-12.52)$^2$/12.52]+ [(11-16.33)$^2$/16.33]+ [(7-4.10)$^2$/4.10] + [(4-12.76)$^2$/12.76]+[(11-10.48)$^2$/10.48]+ [(19-13.67)$^2$/13.67]

$X^2$= 1.71+5.03+0.02+1.74+2.05+6.01+0.03+2.08

$X^2$=18.68

df= (r-1)(c-1)

df= (2-1)(4-1)=3

Significance level: 0.05

P-Value: 0.00031886

0.00031886<0.05 $H_0$ Rejected

There is a significant association between the survey anomalies observed and the well results. The number of false negative, false positive, true negative and true positive are dependent on whether the survey is a seismic or CSEM survey. These samples are statistically significant.

True predictions comprise well results that correspond to the relevant survey anomalies such as true positives and true negatives; these are successful wells drilled on positives anomalies and unsuccessful wells drilled on negative anomalies respectively. False predictions comprise well results that do not correspond to the survey results such as false positive and false negative; these are unsuccessful wells drilled on positive anomalies and successful well drilled on negative anomalies. Figure 28 shows well results classified as true prediction and false prediction for seismic and CSEM surveys. Looking at the plots, 47% of the seismic results are true predictions and the remaining 53% represent false predictions, whereas 73% of the CSEM results are true predictions and the remaining 27 % are false predictions.

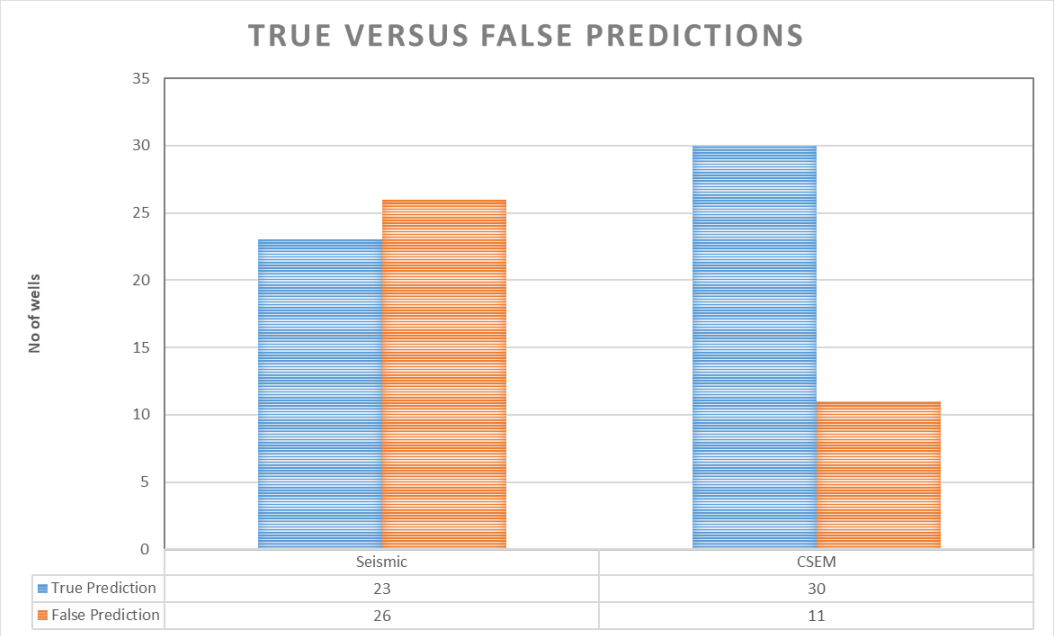


Figure 28: True versus false predictions from sample group.

Hypothesis testing: Chi-square tests (see Table 14 and Table 15)

$H_0$: There is no significant association between the type of survey used and the prediction capabilities of positive and negative anomalies.

Table 14: Observed frequency of the true and false predictions.

| Observed | True Prediction | False Prediction | Total |
|---|---|---|---|
| Seismic | 23 | 26 | 49 |
| CSEM | 30 | 11 | 41 |
| Total | 53 | 37 | 90 |

The expected value for each cell was calculated as follows:

$$\text{Expected cell frequency} = \frac{(\text{row total}) * (\text{column total})}{grand\ total\ of\ all\ cells}$$

$E_1$= (49*53)/90=28.86

$E_2$= (49*37)/90=20.14

$E_3$= (41*53)/90=24.14

$E_4$= (41*37)/90=16.86

Table 15: Expected frequency of the true and false predictions.

| Expected | True Prediction | False Prediction | Total |
|---|---|---|---|
| Seismic | 28.86 | 20.14 | 49 |
| CSEM | 24.14 | 16.86 | 41 |
| Total | 53 | 37 | 90 |

$$\sum X_{i=j}^2 = \frac{(O-E)^2}{E}$$

$X^2$= [(23-28.86)$^2$/28.86] + [(26-20.14)$^2$/20.14]+[(30-24.14)$^2$/24.14]+ [(11-16.86)$^2$/16.86]

$X^2$= 1.19+1.70+1.42+2.03

$X^2$= 6.34

df= (r-1)(c-1)

df= (2-1)(2-1)=1

Significance level: 0.05
P-Value: 0.01177373
0.01177373<0.05 $H_0$ Rejected

There a significant association between the type of survey used and the prediction capabilities of positive and negative anomalies. The number of true and false predictions are dependent on whether the survey is a seismic or CSEM survey. These samples are statistically significant.

The trap styles were categorized into stratigraphic, structural as well as structural & stratigraphic trap (Figure 29). A “structural & stratigraphic trap” refers to a trap that exhibits both a structural and stratigraphic nature. True positives were assessed to see if a specific trap style that tested positive for hydrocarbons will be easily identified by anomalies. True negatives were also assessed to see if a specific trap style without anomalies can be used to discourage drilling to avoid dry holes. These true negatives represent prospect that did not have an anomaly and resulted in dry holes. The analysis allows a reliability check to see if one of the surveys best identifies a certain hydrocarbon-saturated trap (stratigraphic and/or structural) better than the other survey. Looking at CSEM true positives, 84% and 16% of the samples have correctly predicted hydrocarbon on a structural and stratigraphic trap respectively (Figure 29). Seismic true positives have indicated that 36.5% and 27% of the samples have correctly predicted hydrocarbons in a structural and stratigraphic trap respectively; the remaining 36.5% of the samples have successful predicted hydrocarbon in a structural & stratigraphic trap respectively (Figure 29).

True negatives have also been assessed to see if the results correspond with unsuccessful wells; and to see if the absence of an anomaly in a specific trap style can be used to disprove hydrocarbon accumulation assuming these prospects do not contain hydrocarbons. The results will be used to check whether brine-saturated reservoirs can be picked up by survey profiles with no anomalies. Looking at the CSEM true negatives, 91% and 9% of the samples have correctly predicted that there is no hydrocarbon on the structural and stratigraphic trap respectively (Figure 29). Seismic

true negatives have indicated that 50% of the samples have correctly predicted that there are no hydrocarbons on the structural traps, and 17% predicted that there are no hydrocarbons in the stratigraphic traps. The remaining 33% of samples have successful predicted that the structural & stratigraphic traps will have no hydrocarbons (Figure 29).

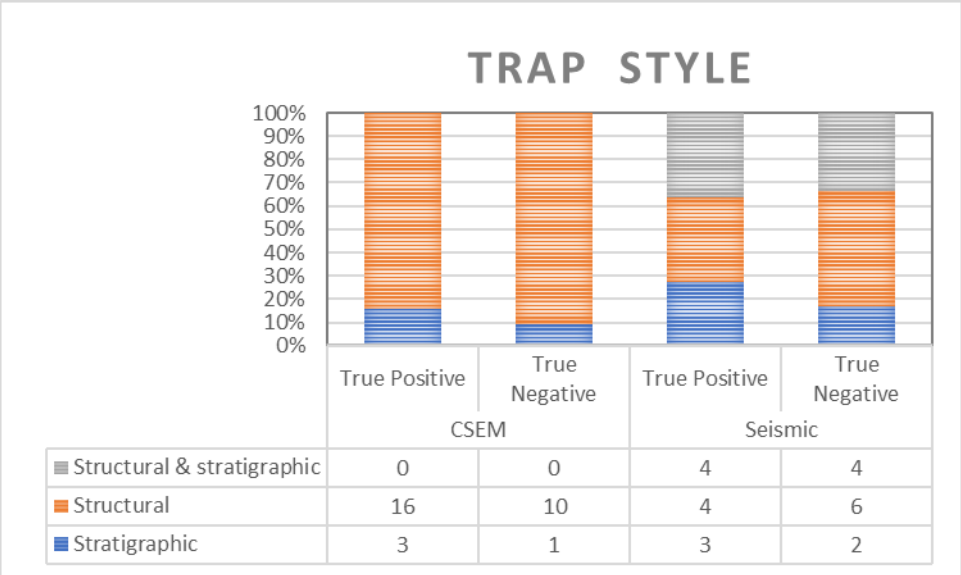


Figure 29: Well results categorized into various trap style.

Hypothesis testing: Chi-square tests (see Table 16 and Table 17)

$H_0$: There is a no significant association between the survey anomalies and the trap style with associated well results.

Table 16: Observed frequency of the trap style.

| Observed | Stratigraphic | Structural | Structural and stratigraphic | Total |
|---|---|---|---|---|
| Seismic-True Positive | 3 | 4 | 4 | 11 |
| Seismic-True Negative | 2 | 6 | 4 | 12 |
| CSEM- True Positive | 3 | 16 | 0 | 19 |
| CSEM-True Negative | 1 | 10 | 0 | 11 |
| Total | 9 | 36 | 8 | 53 |

The expected value for each cell was calculated as follows:

$$\text{Expected cell frequency} = \frac{(\text{row total}) * (\text{column total})}{grand\ total\ of\ all\ cells}$$

$E_1$= (11*9)/ 53=1.87

$E_2$= (11*36)/ 53=7.47

$E_3$= (11*8)/ 53=1.66

$E_4$= (12*9)/ 53=2.04

$E_5$= (12*36)/ 53=8.15

$E_6$= (12*8)/ 53=1.81

$E_7$= (19*9)/ 53=3.23

$E_8$= (19*36)/ 53=12.91

$E_9$= (19*8)/ 53=2.87

$E_{10}$= (11*9)/ 53=1.87

$E_{11}$= (11*36)/ 53=7.47

$E_{12}$= (11*8)/ 53=1.66

Table 17: Expected frequency of the trap style.

| Expected | Stratigraphic | Structural | Structural and stratigraphic | Total |
|---|---|---|---|---|
| Seismic-True Positive | 1.87 | 7.47 | 1.66 | 11 |
| Seismic-True Negative | 2.04 | 8.15 | 1.81 | 12 |
| CSEM- True Positive | 3.23 | 12.91 | 2.87 | 19 |
| CSEM-True Negative | 1.87 | 7.47 | 1.66 | 11 |
| Total | 9 | 36 | 8 | 53 |

$$\sum X^2_{i=j} = \frac{(O-E)^2}{E}$$

$X^2$= [(3-1.87)$^2$/1.87] + [(4-7.47)$^2$/7.47]+[(4-1.66)$^2$/1.66]+ [(2-2.04)$^2$/2.04]+ [(6-8.15)$^2$/8.15] + [(4-1.81)$^2$/1.81]+[(3-3.23)$^2$/3.23]+ [(16-12.91)$^2$/12.91] + [(0-2.87)$^2$/2.87] + [(1-1.87)$^2$/1.87] + [(10-7.47)$^2$/7.47] + [(0-1.66)$^2$/1.66]

$X^2$= 0.69+1.61+3.30+0.00+0.57+2.64+0.02+0.74+2.87+0.40+0.86+1.66

$X^2 = 15.35$

df= (r-1)(c-1)

df= (4-1)(3-1)=6

Significance level: 0.05

P-Value: 0.017676109

0.017676109<0.05 $H_0$ Rejected

There a significant association between the survey anomalies and the trap style with associated well results. The type of trap and well results are dependent on whether the wells have been drilled on a seismic or CSEM anomaly. These samples are statistically significant.

All success wells have been classified as either true positives which are wells drilled on anomalies and tested positive for hydrocarbon, or false negative for all wells testing positive for hydrocarbons after being drilled on a profile with no anomalies. Figure 30 has indicated that 42%, 16% and 42% of the CSEM surveys properly predicted gas, oil, and oil & gas respectively. Looking at seismic surveys, 64% have properly predicted gas, while the remaining 36% properly predicted oil. Some seismic surveys did not have anomalies but still tested positive for hydrocarbons; all these samples assisted in checking which hydrocarbons are difficult to see in seismic profiles. Looking at the false negatives, 86% and 14% of gas and oil could not be identified by anomalies. CSEM false negatives showed that all samples that could not be identified using anomalies are all gas cases.

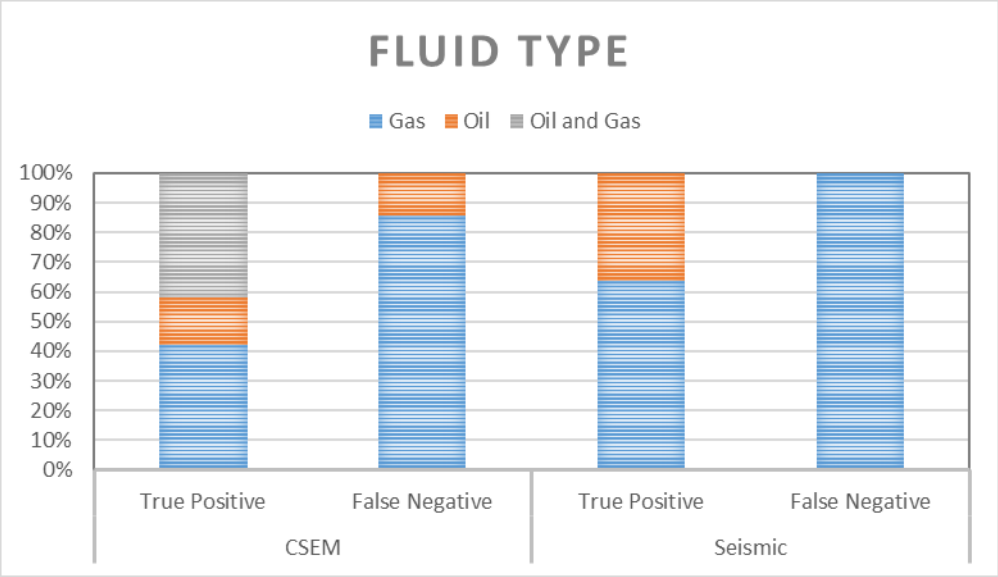


Figure 30: Well results classified into different fluid type.

Hypothesis testing: Chi-square test (see Table 18 and Table 19)

$H_0$: There is a no significant association between the survey anomalies and fluid type.

Table 18: Observed frequency of the fluid type.

| Observed | Gas | Oil | Oil and Gas | Total |
|---|---|---|---|---|
| CSEM-True Positive | 8 | 3 | 8 | 19 |
| CSEM- False Negative | 6 | 1 | 0 | 7 |
| Seismic-True Positive | 7 | 4 | 0 | 11 |
| Seismic-False Negative | 2 | 0 | 0 | 2 |
| Total | 23 | 8 | 8 | 39 |

The expected value for each cell was calculated as follows:

$$\text{Expected cell frequency} = \frac{(\text{row total}) * (\text{column total})}{grand\ total\ of\ all\ cells}$$

$E_1$= (19*23)/ 39=11.21

$E_2$= (19*8)/ 39=3.90

$E_3$= (19*8/ 39=3.90

$E_4$= (7*23)/ 39=4.13

$E_5$= (7*8)/ 39=1.44

$E_6$= (7*8/ 39=1.44

$E_7$= (11*23)/ 39=6.49

$E_8$= (11*8)/ 39=2.26

$E_9$= (11*8/ 39=2.26

$E_{10}$= (2*23)/ 39=1.18

$E_{11}$= (2*8)/ 39=0.41

$E_{12}$= (2*8/ 39=0.41

Table 19: Expected frequency of the fluid type.

| Expected | Gas | Oil | Oil and Gas | Total |
|---|---|---|---|---|
| CSEM-True Positive | 11.21 | 3.90 | 3.90 | 19 |
| CSEM- False Negative | 4.13 | 1.44 | 1.44 | 7 |
| Seismic-True Positive | 6.49 | 2.26 | 2.26 | 11 |
| Seismic-False Negative | 1.18 | 0.41 | 0.41 | 2 |
| Total | 23 | 8 | 8 | 39 |

$$\sum X_{i=j}^2 = \frac{(O-E)^2}{E}$$

$X^2$= [(8-11.21)$^2$/11.21] + [(3-3.90)$^2$/3.90]+[(8-3.90)$^2$/3.90]+ [(6-4.13)$^2$/4.13]+ [(1-1.44)$^2$/1.44] + [(0-1.44)$^2$/1.44]+[(7-6.49)$^2$/6.49]+ [(4-2.26)$^2$/2.26] + [(0-2.26)$^2$/2.26] + [(2-1.18)$^2$/1.18] + [(0-0.41)$^2$/0.41] + [(0-0.41)$^2$/0.41]

$X^2$= 0.92+0.21+4.32+0.85+0.13+1.44+0.04+1.35+2.26+0.57+0.41+0.41

$X^2$=12.90

df=(r-1)(c-1)

df= (4-1)(3-1)=6

Significance level: 0.05

P-Value: 0.04474334

0.04474334<0.05 $H_0$ Rejected

There is a significant association between the survey anomalies and fluid type. The fluid type is dependent on whether the well is drilled on a seismic or CSEM anomaly. These samples are statistically significant.

For the seismic technology advancement analysis, plots were prepared as shown in Figure 31. Two plots have been generated for each survey; these plots represent two different age intervals. The main aim for the plots is to see if there is an increase in successful wells over time in order to determine the effect of technology advancement. Looking at the seismic plots, there is no specific trend picked up in both the 5-year interval (Figure 31A) and 10-year interval (Figure 31B). The CSEM plots has a general decrease in true predictions with time (Figure 32A and B).

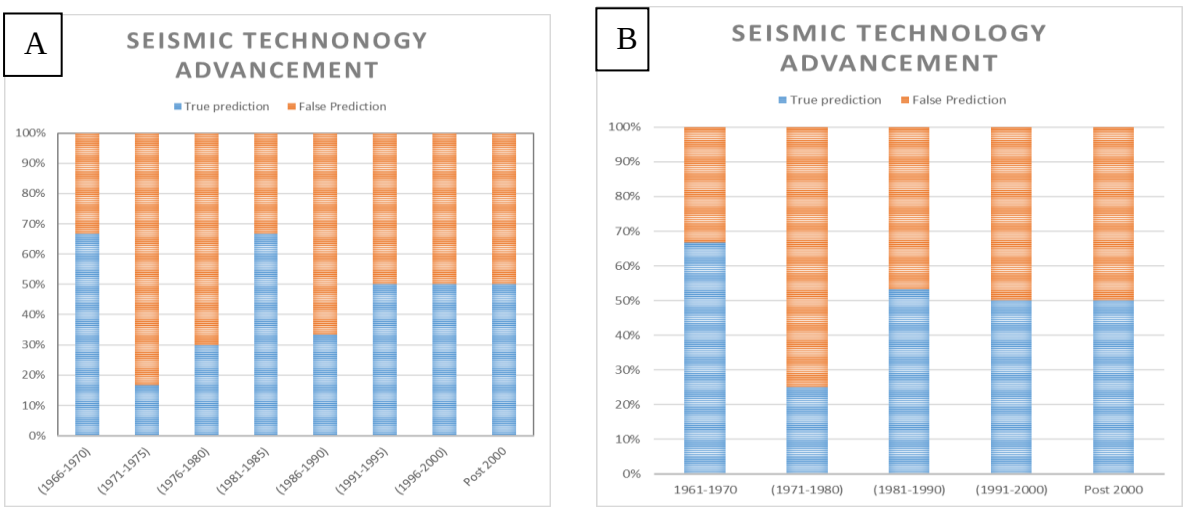


Figure 31: True and false prediction for seismic surveys classified into different years to track technology advancement.

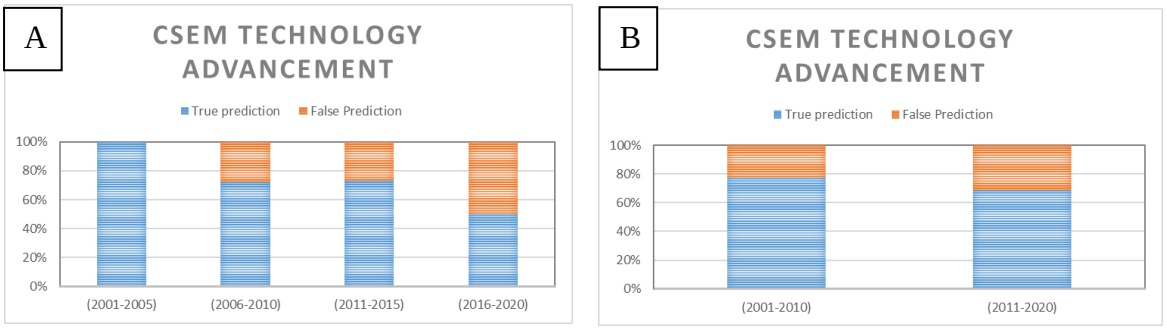


Figure 32: True and false prediction for CSEM surveys classified into different years to track technology advancement.

Decision trees were used to assess drilling based on secondary seismic surveys as well as drilling based on CSEM surveys to see the value of information for secondary surveys. Assuming the primary survey has been conducted and a prospective area has been identified, three alternatives can be considered before drilling:

I. Do not acquire additional data, drill on existing seismic data.
II. Acquire secondary seismic surveys before drilling.
III. Acquire CSEM survey before drilling.

P(PA) is the probability of a positive anomaly, this value was calculated by adding all positive anomalies (TP+FP), divided by the total number of samples. The P(NA) is the probability of a negative anomaly, this value was calculated by adding all the negative anomalies (TN+FN), divided by the total number of samples. These results are summarized in Table 20.

**P(PA)=(TP+FP)/ No. of samples**

Seismic: P(PA)= (11+24)/49=0.71

CSEM: P(PA)= (19+4)/41=0.56

**P(NA) =(TN+FN)/ No. of samples**

Seismic: P(NA)= (12+2)/49=0.29

CSEM: P(NA)= (11+7)/41=0.44

Table 20: Calculated P(PA) and P(NA) for seismic and CSEM data

| Initial Probability | Seismic | CSEM |
|---|---|---|
| P(PA) | 0.71 | 0.56 |
| P(NA) | 0.29 | 0.44 |

From the data set, the following information was extracted:

Table 21: Summary showing the successful versus unsuccessful well results.

| | Seismic | CSEM | |
|---|---|---|---|
| True Positive (TP) | 11 | 19 | Successful |
| False Negative (FN) | 2 | 7 | |
| True Negative (TN) | 12 | 11 | Unsuccessful |
| False Positive (FP) | 24 | 4 | |
| Total | 49 | 41 | |

The COS was calculated through summing up all the successful wells from each survey and dividing it by the number of samples. These results disregarded the occurrence of an anomaly, see Table 22.

**COS=(TP+FN)/ No. of samples**

Seismic: COS= (11+2)/49=0.27

CSEM: COS= (19+7)/41=0.63

**COF=1-COS**

Seismic: 1-COS=1-0.27=0.73

CSEM: 1-COS=1-0.63=0.37

Table 22: Chance of success of seismic surveys and CSEM.

| Well results (Successful versus unsuccessful | Seismic | CSEM |
|---|---|---|
| COS | 0.27 | 0.63 |
| 1-COS | 0.73 | 0.37 |

Given that:

**P(HC)=(TP+FN)/ No. of samples**

Seismic: P(HC)= (11+2)/49=0.27

CSEM: P(HC= (19+7)/41=0.63

**P (No HC)=(TN+FP)/ No. of samples**

Seismic: P (No HC) =(12+24)/49=0.73

CSEM: P (No HC) =(11+4)/41=0.37

**P(Anomaly)=(TP+FP)/ No. of samples**

Seismic: P(Anomaly)=(11+24)/49=0.71

CSEM: P(Anomaly)=(19+4)/41=0.56

**P(No Anomaly)=(TN+FN)/ No. of samples**

Seismic: P(No Amomaly)=(12+2)/49=0.29

CSEM: P(No Amomaly)=(11+7)/41=0.44

**P(Anomaly I HC) = TP/(TP+FN)**

Seismic: P(Anomaly I HC)11/(11+2)=0.85

CSEM: P(Anomaly I HC)=19/(19+7)=0.73

**P(Anomaly I No HC) = FP/(FP+TN)**

Seismic:  P(Anomaly I No HC)=24/(24+12)=0.67

CSEM: P(Anomaly I No HC)=4/(4+11)=0.27

**P(No Anomaly I no HC) = TN/(TN+FP)**

Seismic:  P(No Anomaly I no HC) =12/(12+24)=0.33

CSEM: P(No Anomaly I no HC) =11/(11+4)=0.73

**P(No Anomaly I HC) = FN/(FN+TP)**

Seismic: P(No Anomaly I HC) =2/(2+11)=0.15

CSEM: P(No Anomaly I HC) = 7/(7+19)=0.27

| Probabilities | Seismic | CSEM |
|---|---|---|
| P(HC) | 0.30 | 0.57 |
| P (No HC) | 0.70 | 0.43 |
| P (Anomaly) | 0.83 | 0.57 |
| P (No Amomaly) | 0.17 | 0.43 |
| P (Anomaly I HC) | 0.78 | 0.82 |
| P (Anomaly I No HC) | 0.86 | 0.23 |
| P (No Anomaly I no HC) | 0.14 | 0.77 |
| P (No Anomaly I HC) | 0.22 | 0.18 |

If the survey has been done and an anomaly is observed, the following COS can be derived using Bayes Theorem:

P(AIB)=(P(BIA)*P(A))/P(B)

**P(HC I Anomaly)= P (Anomaly I HC)*P(HC)/P(Anomaly)**

Seismic: P(HC I Anomaly)=(0.85*0.27)/0.71=0.31

CSEM: P(HC I Anomaly)=(0.73*0.63)/0.56=0.83

The following COF can be derived:

**P(No HC I Anomaly)= P (Anomaly I No HC)*P(No HC)/P(Anomaly)**

Seismic: P(No HC I Anomaly)=(0.67*0.73)/0.71=0.69

CSEM: P(No HC I Anomaly)=(0.27*0.37)/0.56=0.17

Table 23: Calculated COS given that the survey was conducted, and an anomaly was observed.

| Survey | Initial COS | Initial COF | Calculated COS | Calculated COF |
|---|---|---|---|---|
| Seismic | 0.27 | 0.73 | 0.31 | 0.69 |
| CSEM | 0.63 | 0.37 | 0.83 | 0.17 |

If the survey has been done and a negative anomaly is observed, the following COS can be derived using the Bayes Theorem:

**P(AIB)=(P(BIA)*P(A))/P(B)**

**P(HC I No Anomaly)= P (No Anomaly I HC)*P(HC)/P(No Anomaly)**

Seismic: (0.15*0.27)/0.29= 0.14

CSEM: (0.27*0.63)/0.44= 0.39

**P(No HC I No Anomaly)= P (No Anomaly I No HC)*P(No HC)/P(No Anomaly)**

Seismic: (0.33*0.73)/0.29= 0.86

CSEM: (0.73*0.37)/0.44= 0.61

Table 24: Calculated COS and COF given that the survey was conducted, and no anomaly was observed.

| Survey | Initial COS | Initial COF | Calculated COS | Calculated COF |
|---|---|---|---|---|
| Seismic | 0.27 | 0.73 | 0.14 | 0.86 |
| CSEM | 0.63 | 0.37 | 0.39 | 0.61 |

The following CSEM and seismic survey costs were captured in Table 25 and the agreed values were used in the decision tree.

Table 25: Survey costs with the relevant sources.

| | Cost | Agreed cost | Source |
|---|---|---|---|
| 1. Seismic survey | $13 MM - $15 MM | $14MM | (Energy Industry Review, 2020) |
| 2. CSEM | $6MM-$10MM | 8MM | (Foum, 2018) |

Due to limited access to cost information from service providers and operators, water depth, minimum commercial size, well costs and prospect size were extracted from Africa Energy Corp (2020); and from there, the agreed values were used in the decision tree (Table 26).

Table 26: Well cost and minimum commercial size (Africa Energy Corp, 2020).

| Water depth | Min commercial size | Well Costs |
|---|---|---|
| 150 m | < 50 MMbbl at $60/bbl | ~$21 MM |
| 548 m | ~110 MMbbl at $60/bbl | ~$28 MM |
| 1432 m | ~350 MMbbl at $60/bbl | ~$150 MM |
| Agreed values | ~110 MMbbl at $60/bbl | ~$28 MM |

The prospect size used in the analysis is an average of the values extracted from Africa Energy Corp (2020) which are 359 MMbbl, 124MMbbl and 1 Bboe. The agreed prospect size is 494 MMbbl which is an average of the 3 prospect sizes. To get the value of the project, 60$/bbl was used to convert these hydrocarbon fields to monetary value:

Field size: 494MMbbl

Current oil price (OilPrice.com, 2022): $101.4/bbl (as opposed to the price in 2020 which was $60/bbl)

Monetary value: 494MMbbl*$101.4/bbl= $50 B

The decision tree input values have been summarized in the Table 27. Please note that the COF and 1-COF is calculated based on drilling on a negative anomaly and can be disregarded assuming operators will prefer drilling on an anomaly; operators may still decide to drill on a negative anomaly, so this alternative was considered on the decision tree.

Table 27: Input data for decision tree analysis.

| | | |
|---|---|---|
| Seismic Probabilities | P(PA) | 0.71 |
| | P(NA) | 0.29 |
| | P(HC I Anomaly) | 0.31 |
| | P(No HC I Anomaly | 0.69 |
| | P(HC I No Anomaly) | 0.14 |
| | P(No HC I No Anomaly) | 0.86 |
| CSEM Probabilities | P(PA) | 0.56 |
| | P(NA) | 0.44 |
| | P(HC I Anomaly) | 0.83 |
| | P(No HC I Anomaly | 0.17 |
| | P(HC I No Anomaly) | 0.39 |
| | P(No HC I No Anomaly) | 0.61 |
| Costs | Seismic survey | $14MM |
| | CSEM survey | $8MM |
| | Drilling | $28MM |
| | Field Value | 50 000MM |

From the compiled information, a decision tree was computed using Tree Plan Add-in on Excel. The decision tree assumes that the primary seismic survey has been conducted and the decision maker is faced with a decision to conduct a secondary survey to further study the reservoir or to proceed with making a decision without any additional survey. The decision tree results (Figure 33) are based on Bayes Theorem taking into account both scenarios where a survey is conducted, and a positive anomaly is observed as well as where a survey is conducted, and a negative anomaly is observed.

The payoffs were summarized in the Table 28**Error! Reference source not found.**. These payoffs are used to calculate the expected value of each alternative, see Table 29, 30 and 40 (refer to Appendix A). Please note that the payoffs are not affected by the presence of anomalies. These are dependent on the discovery of hydrocarbons (revenue), the surveys costs and the drilling cost. Please see Appendix A.

Table 28: Summary of payoff for each alternative.

| Alternative | Action | Results | Payoffs (Million $) |
|---|---|---|---|
| Acquire seismic survey | Prospect drilled | Hydrocarbons | 49958 |
| | Prospect drilled | No Hydrocarbons | -42 |
| | Prospect not drilled | No Hydrocarbons | -14 |
| Acquire CSEM survey | Prospect drilled | Hydrocarbons | 49964 |
| | Prospect drilled | No Hydrocarbons | -36 |
| | Prospect not drilled | No Hydrocarbons | -8 |
| Do not acquire secondary survey | Prospect drilled | Hydrocarbons | 49972 |
| | Prospect drilled | No Hydrocarbons | -28 |
| | Prospect not drilled | No Hydrocarbons | 0 |

The expected value of “acquire seismic survey”, “acquire CSEM survey”, “do not acquire secondary survey” alternatives were calculated, please see Table 29, Table 30 and Table 31 for the summary of calculations.

Table 29 Expected value calculations for "acquire seismic" alternative.

| Seismic | | Payoff | Probabilities | (Payoff*Probabilities) | EV1 | Highest EV1 | Probabilities | (Highest EV1*Probabilities) | EV2 |
|---|---|---|---|---|---|---|---|---|---|
| Positive Anomaly | Drill | 49958 | 0.31 | 15487 | 15458 | 15458 | 0.71 | 10975.18 | 12993 |
| | | -42 | 0.69 | -29 | | | | | |
| | Don't drill | -14 | - | -14 | -14 | | | | |
| Negative Anomaly | Drill | 49958 | 0.14 | 6994 | 6958 | 6958 | 0.29 | 2017.82 | |
| | | -42 | 0.86 | -36 | | | | | |
| | Don't drill | -14 | - | -14 | -14 | | | | |

Table 30: Expected value calculations for "acquire CSEM" alternative.

| CSEM | | Payoff | Probabilities | (Payoff*Probabilities) | EV1 | Highest EV1 | Probabilities | (Highest EV1*Probabilities) | EV2 |
|---|---|---|---|---|---|---|---|---|---|
| Positive Anomaly | Drill | 49964 | 0.83 | 41470.12 | 41464 | 41464 | 0.56 | 23219.84 | 31784 |
| | | -36 | 0.17 | -6.12 | | | | | |
| | Don't drill | -8 | - | -8 | -8 | | | | |
| Negative Anomaly | Drill | 49964 | 0.39 | 19485.96 | 19464 | 19464 | 0.44 | 8564.16 | |
| | | -36 | 0.61 | -21.96 | | | | | |
| | Don't drill | -8 | - | -8 | -8 | | | | |

Table 31:Expected value calculations for "don't acquire secondary survey".

| | | Payoff | Probabilities | (Payoff*Probabilities) | EV | Highest EV |
|---|---|---|---|---|---|---|
| No survey | Drill | 49972 | 0.27 | 13492.44 | 13472 | 13472 |
| | | -28 | 0.73 | -20.44 | | |
| | Don't drill | 0 | - | 0 | 0 | |

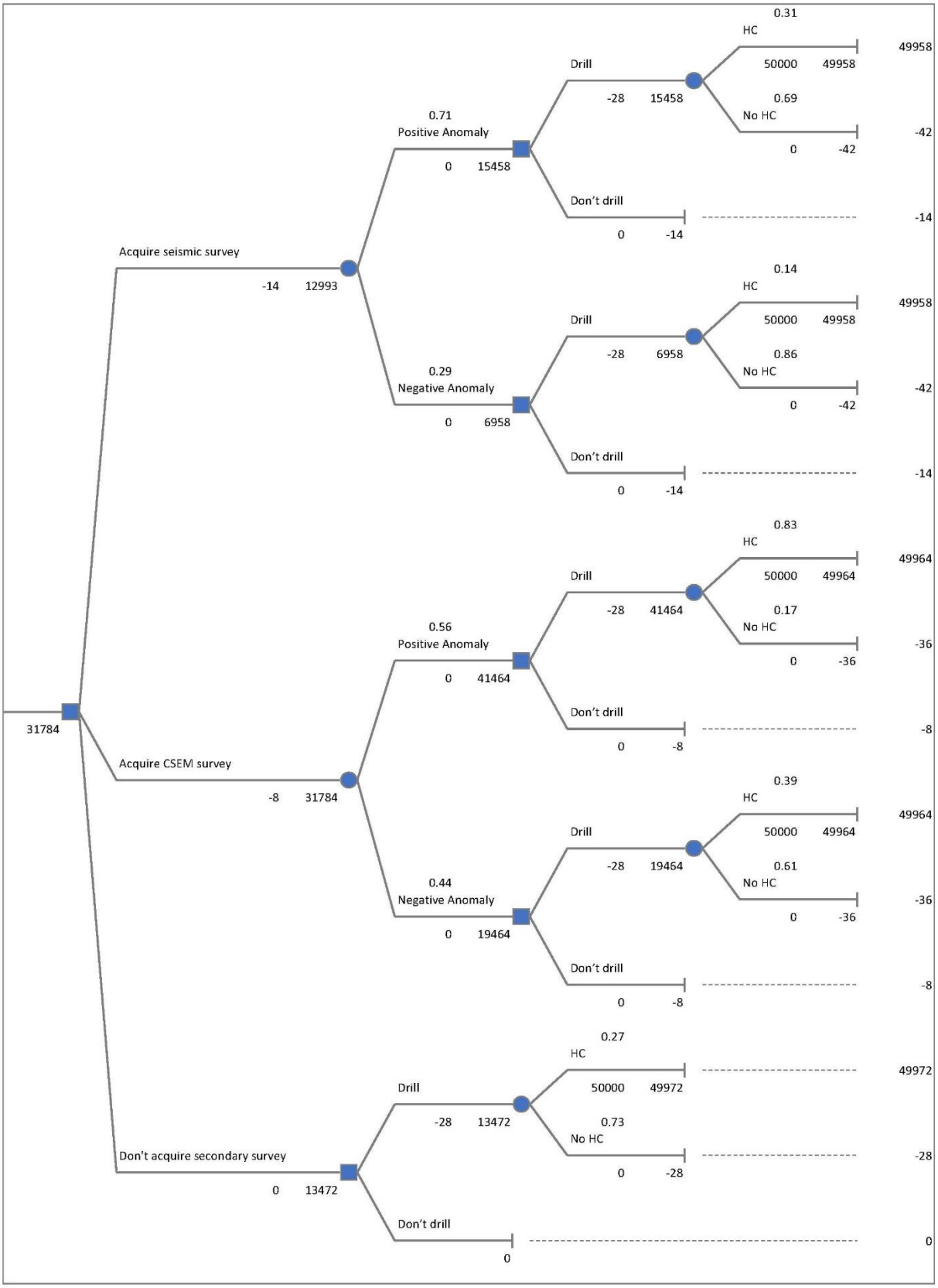


Figure 33: Decision tree computed from the calculated probabilities and agreed costs.

# 5. Discussion

## 5.1. Process Mapping

The process mapping results (Figure 23) represents the offshore exploration processes starting from the acquisition of the first survey until drilling. The main surveys discussed in this exercise are seismic surveys and CSEM, with the very first seismic survey acquired defined as the primary 2D seismic survey. The primary seismic survey is an essential survey necessary to recommend any additional surveys to further understand the prospect or suggest drilling during exploration phase, this is defined as the start of the process. The secondary surveys are defined as a single unit, with either one survey or two surveys. This may depend on the need to acquire more information about a defined prospect that needs to be upgraded to a drillable prospect.

The choice of secondary survey is based on the needs of that specific prospect or area as recommended by the G&G team. In the case of reservoir detection needs, additional secondary surveys are acquired to better image the reservoir and related elements. These profiles may target a specific feature or petroleum element, with acquisition parameters design to improve imaging as opposed to the initial survey conducted. These results may provide a better understanding of the reservoir and other petroleum elements (source, trap, migration pathways and seal). After the results, an operator may be able to recommend or discourage drilling. CSEM may be used to evaluate a prospect and increase the chance of success before drilling. This survey will either support or oppose the primary seismic survey results. After these results, an operator may be able to recommend or discourage drilling. The number and type of secondary surveys will depend on an operator, the G&G team will be able to suggest which one is required for that specific project, and why it is necessary.

## 5.2. Predictive strength

The first step of the data analysis started off by comparing the successful well results against the unsuccessful well results. In Figure 24, 27% of the seismic surveys and 63% of the CSEM surveys have resulted in successful wells. The well results plot disregards anomalies: the aim is to check the reliability of drilling based on each survey. Figure 24 shows that most operators that have acquired CSEM are likely to have a 63% success rate whereas any well drilled on seismic data alone (regardless of whether its primary or secondary) is likely to have a 27% success rate. This suggest that wells drilled on CSEM surveys have a higher chance of success than wells drilled on seismic surveys. The Chi Square tests results indicate that there is a significant association between seismic and CSEM well results. This means that the data is reliable to confirm these assumptions.

When an operator sees an anomaly on seismic or CSEM data, that feature can be associated with a specific rock-type or hydrocarbon charged intervals. If these anomalies are classified as DHIs, drilling can either confirm or disprove the existence of DHI's. Looking closely at the positive anomalies (Figure 25), the seismic data shows that an operator has 71% chance of seeing an anomaly on a seismic profile whereas with CSEM data, there is a 56 % chance of seeing anomalies. Out of the positive anomalies drilled, 31% of the seismic surveys (Figure 26B) and 83% of CSEM surveys (Figure 27B) discovered hydrocarbons. Although seismic surveys have a very high number of anomalies, the survey also has a high number of pitfalls as compared to CSEM surveys. The CSEM anomalies are more likely to discover hydrocarbons as compared to seismic surveys. When a seismic anomaly recommends drilling a prospect, there is a very high risk of not discovering hydrocarbons; but if additional CSEM data is acquired, the chances of finding hydrocarbons are significantly increased. The Chi Square tests results indicate that there is a significant association between seismic and CSEM anomalies. This means that the data is reliable to confirm these assumptions.

The prediction plots (Figure 28) focused on whether the surveys correctly predicted hydrocarbon saturated reservoir and non-hydrocarbon bearing lithologies. If an anomaly correctly predicted hydrocarbons and if a survey with no anomalies resulted in a dry well, then both surveys were classified as true prediction; whereas surveys with anomalies that resulted in dry wells and surveys with no anomalies resulted in successful wells were classified as false prediction. According to the data, seismic surveys have a 47% prediction strength, whereas the CSEM had a significantly higher predictive strength of 73 %. There is a significantly higher number of pitfalls in seismic surveys, this can be attributed to the low sensitivity of survey in distinguishing brine saturated reservoirs and other lithologies from hydrocarbon charges reservoirs. CSEM has higher sensitivity to hydrocarbon fluid content than seismic, even though seismic surveys may better define structure and different rock types. Although both surveys are relevant in studying the reservoir elements, CSEM excels more in identifying charged reservoirs as opposed to other petroleum elements such as migration pathways, seal and source. The Chi Square tests results indicate that there is a significant association between seismic and CSEM “true and false” predictions. This means that the data is reliable to confirm these assumptions.

The trap style (Figure 29) attributes were used in further analysing the predictive strength of the surveys to check if a specific survey should be preferred in searching for a specific fluid type and when dealing with a specific trap style. CSEM has an 84% chance of predicting a charged reservoir within a structural trap, whereas seismic has a lower chance of 36.5%. On the seismic data, an additional 36.5% chance has predicted a charged reservoir in both stratigraphic and structural trap. As structural traps will significantly increase the appearance of hydrocarbons on a profile where the accumulation of petroleum will be more localized than extensive, this 43% of hydrocarbons discovered on structural traps can be bumped up to 73% if summed up with the 36.5% of hydrocarbons discover in both structural and stratigraphic traps. This means that CSEM can predict a charged reservoir in structural trap 11% more than seismic surveys can. The results also indicate that you are likely to identify a charged structural trap rather than a charged stratigraphic trap. CSEM data indicated that structural traps that do not have an anomaly are highly unlikely to discover hydrocarbon with a 91% chance of failure. Seismic data indicated that structural and stratigraphic traps exhibit 50% and 17% chance of failure when no anomaly is

observed. Additionally, there is a 33% chance of failure on structural & stratigraphic traps in prospects with no anomalies. The Chi Square tests results indicate that there is a significant association between seismic and CSEM trap-style results. This means that the data is reliable to confirm these assumptions.

The Fluid type plot (Figure 30) shows that there is a very high chance to discover gas in both seismic surveys and CSEM surveys. This suggests that both surveys can be used effectively to explore for gas. Both surveys have exhibited a good chance of predicting gas when an anomaly is observed, with 42% and 63% of the successful wells from the CSEM and seismic samples discovering gas respectively. Condensates were classified as oil since these occur in liquid form beneath the surface and are therefore expected to have a similar signature. Looking at identification of oil using anomalies, 16% of the CSEM samples and 36% of the seismic samples discovered oil (accounting for both oil and condensate). Additionally, there is a 42% chance of CSEM anomalies successfully identifying oil & gas. From the results, seismic surveys are more likely to discover oil than CSEM surveys. The samples that did contain anomalies but still discovered hydrocarbons are 100% gas-bearing reservoirs for seismic surveys, these results are inconclusive as they cannot be compared with other hydrocarbon fluids or against the two surveys investigated. CSEM has indicated that 86% and 14% of profiles without anomalies resulted in gas and oil. Such results suggests that oil is unlikely to be missed by the absence of an anomaly. The Chi Square tests results indicate that there is no significant association between seismic and CSEM “true and false” predictions. The data may not be reliable in confirming these assumptions.

### 5.3. Technology Advancement

Both the CSEM and seismic plot have proved not to be reliable in interpreting technology advancement as the number of samples in CSEM and seismic will vary in different time intervals. The sample size is too small to conduct such an analysis as some intervals have 1 sample while another interval may have up to 13 samples. In an interval that has one sample, if the sample is categorized as false prediction, this assumes that 100% of the interval is false negative. This interpretation would not be representative of the dataset as one sample cannot give conclusive results. The

absence of drilling during that timeframe could be attributed to political issues, oil prices and the fiscal regime and other matters ( (Suslick & Schiozer, 2004). Due to limited number of samples, these data cannot contribute to the analysis as the reliability of the assessment will require a larger sample group to be representative.

## 5.4. Decision Tree Analysis

The decision tree considered four different outcomes: true positives, false positives, true negatives and false negatives. The probabilities of positive and negative anomalies were calculated using these four outcomes. The probability of discovering hydrocarbons given that an anomaly has been observed (P(HC I Anomaly)) is 31% and 83% for seismic and CSEM surveys respectively. The results correspond to the findings in Hesthammer, et al. (2010), which is 35% for seismic surveys and 75% for CSEM. From the agreed well and survey costs as well as the hypothetical field and field value (using the following conversion: $101.4/bbl), the decision tree was computed. The decision tree (Figure 33) suggests that CSEM provides significant information that may assist in drilling decisions. The decision tree indicates that CSEM has a high probability of detecting hydrocarbons than seismic surveys. While considering secondary surveys, acquiring CSEM might provide information that can increase the COS significantly.

## 5.5. Research Limitation

Company A and Company B provided the 49 seismic-based and 41 CSEM-based results respectively. Due to the limited amount of data available, the researcher used all 90 samples in the analysis. Some of the CSEM surveys were acquired post drilling, this proved to be limiting as process variation studies were to be based on acquisition to drilling under the assumption that the surveys were acquired pre-drill. Due to such limitations, the process variation studies could not be carried out. Each method requires G&G interpretation, the level of expertise is thought to affect the drilling results with the assumption that a much more experienced G&G team is likely to interpret these surveys better than a team with limited knowledge and experience. The analysis assumes that all G&G teams will identify an anomaly in the same manner, and recommend drilling thereafter, disregarding variation due to the difference in interpretation from on team to another.

### 5.6. Recommendations for Future Work

Given that hydrocarbon accumulations occur in different stratigraphic levels, future work can investigate the effects of depth on the reliability of seismic and CSEM anomalies. The research could provide insight on the sensitivity of each survey, assisting operators to understand if imaging quality varies with depth. This study can be achieved through comparing false prediction and true prediction observed in different stratigraphic levels.

## 6. Conclusion

CSEM is more efficient in differentiating fluid types rather than lithologies, whereas seismic surveys may better define structure and different rock types. Seismic surveys tend to give a better understanding of the geology, the lithological changes, charge and reservoir properties which is paramount in mapping prospective areas. Although seismic and CSEM surveys contribute significantly to defining the reservoir, the study analysed the survey capabilities in identifying hydrocarbon accumulations, distinguishing hydrocarbon fluid and trap style using survey anomalies. Recommendations to drill based on a seismic anomaly have a higher risk compared to recommendations based on CSEM anomalies. From the findings of the study, the following observations were made: Both CSEM and seismic surveys are likely to identify charged reservoir within a structural trap than in a stratigraphic trap. This may be attributed to how localised and extensive a structural trap is, as compared to a continuous stratigraphic trap that may range in thicknesses. Although both surveys can identify a charged structural reservoir effectively, CSEM can predict charged structural reservoirs slightly better than seismic surveys. Although both surveys are not that effective in identifying a stratigraphic trap, seismic surveys have a higher probability. The CSEM data indicated that structural traps that do not have an anomaly are highly unlikely to discover hydrocarbon with a 90% chance of failure. This means that an operator can discourage drilling if the prospect is a structural trap with no anomalies. The seismic data is inconclusive as the structural and stratigraphic traps exhibit the same chance of failure in prospects with no anomalies. Both surveys are very good in predicting gas-bearing reservoirs as compared to other hydrocarbon fluid. CSEM has a slightly higher chance of predicting oil (given that condensate reservoirs

are classified as oil reservoirs). The hypothesis testing has indicated that there is an association between survey anomalies and attributes like well results, fluid type and trap style. The decision tree analysis suggests that CSEM is more effective in hydrocarbon detection than seismic surveys. CSEM serves as a good secondary survey to consider for hydrocarbon detection during petroleum exploration; employing this secondary survey may accelerated drilling decisions and increase the chance of success.

## 7. References


Africa Energy Corp, 2020. *Funded Near-Term, High-Impact Exploration*.

Bakker, P., 2002. *Image structure analysis for seismic interpretation,* Netherlands.

Berre, L., Morten, J., Baillie, G. & Nerland, E., 2020. Experience on controlled-source electromagnetic performance for exploration in Norway. 8(4), pp. SQ25-SQ37.

Cairn Energy, 2014. Petro Bazaar. [Online]
Available at: https://petrobazaar.com/oil-and-gas-exploration-and-production-life-cycle-11146.html
[Accessed 04 09 2022].

DeCoursey, W., 2003. *Statistics and Probability for Engineering Applications.* United States of America: Elsevier.

EMGS, 2021. *Embedding CSEM in the exploration workflow,* Oslo: EMGS.

Energy Industry Review, 2020. *Energy Industry Review.* [Online]
Available at: https://energyindustryreview.com/oil-gas/3-d-seismic-survey-data-acquisition-over-entire-etame-marin-block-completed/
[Accessed 12 July 2022].

Fanavoll, S., Danielsen, J., EMGS, Hesthammer, J, Stefatos, A., Rocksource., 2010. *False negatives and positives in the interpretation of EM data.* Denver, SEG.

Fanavoll, S., Gabrielsen, P. & Ellingsrud, S., 2014. *CSEM as a tool for better exploration decisions: Case studies from the Barents Sea, Norwegian Continental Shelf,* Norway.

Fanchi, J., 2010. *Integrated Reservoir Asset Management: Principles and Best Practices.* Burlington: Gulf Professional Publishing.

Foum, A., 2018. *Using Bayes Theorem to Determine the Value of Information in Justifying a Geophysical Survey*.

Hammond, J., 1967. *Better Decisions with Preference Theory,* Havard Business Review.

Hesthammer, J., Fanavoll, S., Stefatos, A., Danielsen, J.E., Boulaenko, M., 2010. CSEM performance in light of well results. In: *The Leading Edge*, pp. 258-264.

Hesthammer, J., Stefatos, A., Boulaenko, M., Vereshagin, A., Gelting, P., Wedberg, T., Maxwell, G., 2010. CSEM technology as a value driver for hydrocarbon exploration. *Marine and Petroleum Geology,* 27(9), pp. 1872-1884.

Karman, G., Ramirez, D., Voon, J. & Rosenquist, L., 2013. *More than a decade of CSEM in Shell: a global look back study.* Oslo, Norsk Geologisk Forening (NGF).

Kaur, J., 2016. Techniques Used in Hypothesis Testing in Research Methodology – A Review. *International Journal of Science and Research (IJSR),* 4(5), pp. 362-365.

Leedy, P. & Ormrod, J., 2016. *Practical research: Planning and Design.* 11th ed. New Jersey: Pearson Educational International and Prentice Hall.

McHugh, 2013. The Chi-square test of independence. *Biochemia Medica,* 23(2), pp. 143-149.

Milkov, A. & Navidi, W., 2020. Randomness, serendipity, and luck in petroleum exploration. *AAPG Bulletin,,* 104(1), p. 145–176.

Milkov, A. & Samis, J., 2020. Turning dry holes from disasters to exploration wisdom: Decision tree to determine the key failure mode for segments in conventional petroleum prospects. *AAPG Bulletin,* 104(2), pp. 449-475.

Montgomery, A. & Runger, G., 2002. *Applied Statistics and Probability for Engineers.* 3rd ed. John Wiley & Sons, Inc.

Najoui, Z., Riazanoff, S., Deffontaines, B. & Xavier, J., 2018. Estimated location of the seafloor sources of marine natural oil seeps from sea surface outbreaks: A new "source path procedure" applied to the northern Gulf of Mexico. *Marine and Petroleum Geology,* Issue 91, pp. 190-201.

Nanda, N., 2016. *Seismic Data Interpretation and Evaluation for Hydrocarbon Exploration and Production, A Practitioner's Guide.* Springer.

Nixon, S., Hallam, T. & Constantine, A., 2018. *Ranking DHI attributes for effective prospect risk assessment applied to Otway Basin, Australia.* Sydney, Petroleum Exploration Soceity of Australia (PESA).

OilPrice.com, 2022. *OilPrice.com.* [Online]
Available at: https://oilprice.com/
[Accessed 12 July 2022].

Oktariena, M. & Triyoso, W., 2016. *Gabor Deconvolution as Preliminary Method to Reduce Pitfall in Deeper Target Seismic Data,* Bandung: IOP Publishing.

Perera, C., 2018. *Slideshare.* [Online]
Available at: https://www.slideshare.net/mckhm/analysis-2018
[Accessed 14 December 2021].

Price, A.; Total; Twarz, C.; Gabrielsen, P; EMGS, 2019. Building confidence in CSEM for exploration - Benchmarking. *SEG International Exposition and 89th Annual Meeting*, pp. 1095-1099.

Remenyi, D., Onofrei, G. & English, J., 2009. *An Introduction to Statistics using Microsoft Excel.* 1st ed. United Kingdom: Academic Publishing Limited.

Ross, S., 2010. *Introductory Statistics.* 3rd ed. California: Academic Press, Elsevier.

Rothery, C. et al., 2020. *Value of Information Analytical Methods: Report 2 of the ISPOR Value of Information Analysis Emerging Good Practices Task Force,* United Kingdom: Elservier.

Rowi, V., Haris, A. & Riyanto, A., 2020. *Direct hydrocarbon indicator (DHI) pitfall assessment in prospecting pliocene globigerina biogenic gas play in "X structure", Madura Strait, East Java Basin..* Indonesia, IOP Publishing.

Selley, R., 1998. *Elements of Petroleum Geology.* 2nd ed. California: Academic Press.

Suslick, S. & Schiozer, D., 2004. Risk analysis applied to petroleum exploration and production: an overview. *Journal of Petroleum Science and Engineering,* 44(1-2), pp. 1-9.

Taha, H., 2017. *Operations Research: An Introduction.* 10th ed. Harlow, England: Pearson.

Zibran, M., 2007. *CHI-Squared Test of Independence,* Calgary: Department of Computer Science, University of Calgary.

Zweidler, D., Baltar, D. & Barker, N., 2015. Additional Data Helps Investment Decisions. *AAPG Explorer*, November, pp. 42-43.

## 8. Appendices

**Appendix A**: Pay off calculations for the different alternatives.

I. Acquire seismic survey.

**Payoffs:**

- If hydrocarbons are discovered after acquiring a seismic survey and drilling:
  50 000MM (Expected revenue)-14MM (Cost of survey)-28MM (Cost of drilling) = 49958MM
- If no hydrocarbons are discovered after acquiring a seismic survey and drilling:
  0MM (Expected revenue)-14MM (Cost of survey)-28MM Cost of drilling) = -42MM
- If no hydrocarbons are discovered after acquiring a seismic survey (without drilling):
  0MM (Expected revenue)-14MM (Cost of survey) = -14MM

II. Acquire CSEM survey.

**Payoffs:**

- If hydrocarbons are discovered after acquiring a CSEM survey and drilling:
  50 000MM (Expected revenue)-8 MM (Cost of survey)-28MM (Cost of drilling) = 49964MM
- If no hydrocarbons are discovered after acquiring a CSEM survey and drilling:
  0MM (Expected revenue)-8MM (Cost of survey)-28MM (Cost of drilling) = -36MM
- If no hydrocarbons are discovered after acquiring a CSEM survey (without drilling):
  0MM (Expected revenue)-8MM (Cost of survey) = -8MM

III. Do not acquire secondary survey.

**Payoffs:**

- If hydrocarbons are discovered after drilling without secondary survey:
  50 000MM (Expected revenue) -28MM (Cost of drilling) = 49972MM
- If no hydrocarbons are discovered after drilling without secondary survey:
  0MM (Expected revenue)-28MM (Cost of drilling) = -28MM

- If no hydrocarbons are discovered and no drilling or survey is acquired, the payoff will be 0MM.