Master´s thesis

NTNU
Norwegian University of
Science and Technology
Faculty of Engineering Science and Technology
Department of Production and Quality Engineering

Bjarne Rosvoll Bøklepp

Decision Framework for Petrophysical Data Acquisition in the Development Well Planning Process

NTNU, December 2008

NTNU
Norwegian University of
Science and Technology

Declaration

I hereby declare that this master thesis has been performed in accordance to the regulations provided by the Norwegian University of Science and Technology (NTNU), Trondheim.

Trondheim, 20. December 2008

Bjarne Rosvoll Bøklepp

Abstract

As the Heidrun field has reached a decline from the initial hydrocarbon production plateau, there is an increasing need for alternative well solutions to be able to recover bypassed reserves in a cost effective manner. New wells or drainage points planned are continuously focusing on smaller and often bypassed reserve volumes. As these volumes are getting smaller and hence harder both to identify and to hit, the well planning process is becoming ever more comprehensive and demanding.

As raw or treated sea water and produced water (all having different salinities) is being injected into the reservoir to compensate for reservoir pressure depletion and to increase the total hydrocarbon recovery, the reservoir parameters are altered. Further, movement of fluids (including gas) in the reservoir due to production and injection has changed the properties of the reservoir from its initial state, with a typical two phase fluid system, easily recognized and interpreted by the petrophysicist, into a mixed fluid system containing both oil, fractions of gas and water of unknown or salinity. The previous data acquisition strategy documentation did not cover these newly discovered challenges.

The main objective of this master thesis has been to develop a decision framework for petrophysical data acquisition in the development well planning process. The main intention is to ensure a flexible data acquisition planning process covering both short and long term needs regarding reservoir characterization, while managing new challenges related to the petrophysical interpretation. Further, the process should ensure well placement optimization during the drilling operation, fulfill minimum requirements with regards to data quality and quantity, while minimizing operational risk and time consumption.

As a foundation for the decision framework, an evaluation of the downhole data acquisition methods and techniques available was conducted and an extensive general overview of each method’s advantages and disadvantages was made. Based on the conclusions from this evaluation, the prevailing perception in the industry favoring wireline to Logging While Drilling should be challenged. A stochastic simulation model of the petrophysical evaluation routine was developed and this model generally shows that uncertainty in the input parameters as well as in the model algorithms has just as big impact on the evaluation results as the uncertainties in the raw measurements. Several decision making methods and techniques were evaluated and utilized during several actual well planning processes, from simple flowcharts and decision trees to more complex multi-criteria decision making methods, to test each method’s applicability in the well planning context.

The main conclusion is that data acquisition planning should primarily be based on the premises and the nature of the well to be drilled. Very often, physical limitations and specific well requirements are qualifying one type of data acquisition while disqualifying other methods directly.

Acknowledgements

This post graduate master thesis was carried out together with my daily tasks as petrophysicist and well planning coordinator in the Heidrun Petroleum Technology organization in StatoilHydro. The work has taken place both in the Heidrun Petec offices in Stjørdal, as well as at home in the period March – December 2008.

First of all I would therefore like to thank my colleagues in Heidrun Petec for the assistance, for sharing all that knowledge and the possibility of testing all the ideas and models discussed herein during the ongoing well planning processes using real data and real situations and scenarios. I would also like to thank the different service company representatives for good discussions and patient replies to numerous emails and questions. Further, I must express my gratitude to my supervisor, Professor Marvin Rausand, Department of Production Quality and Engineering (NTNU).

But, most of all I must thank my family for all the support and understanding throughout this busy period. Finally a huge thank you to my dear wife who kept the wheels turning; you are the greatest!

Preface

This thesis report concludes my Master of Management studies at the Norwegian University of Science and Technology (NTNU). The studies were carried out together with my work as a Principal Petrophysicist in the Heidrun asset in StatoilHydro.

In the writing of this thesis, it has been a great advantage to have a broad and multidisciplinary background from the oil industry, covering most sides of well data acquisition, both as a wireline field engineer and later as MWD/LWD specialist in a major oil service company before moving on to StatoilHydro, working as a drilling engineer and currently as a petrophysicist.
The thesis is addressed mainly to petrophysicists, but also to other professionals involved in reservoir characterization and especially development well planning in general.

It is anticipated that readers of this thesis have general knowledge within the area of petroleum technology including drilling operations, reservoir technology and logging operations. Further, it is anticipated that the reader has basic knowledge in petrophysics and well log interpretation like [1, 2] or [3].

This thesis, including the proposed decision framework is designed for the Heidrun development wells and adapted to manage the Heidrun reservoir and its associated distinctive characteristics and challenges.

In this thesis, I have not discussed point 3 in the master project assignment document in detail; *“Evaluate and propose revision of the relevant parts of the governing documentation regarding petrophysical data acquisition planning.”* The reason for this is that the StatoilHydro organization introduces a new well planning process during the first quarter of 2009. At present, there is not much detail available regarding this process, and the Heidrun Petec organization might have to adapt some of the existing routines and documentation to fulfill the new requirements.

Trondheim, Norway 20 December 2008
Bjarne Rosvoll Bøklepp

Table of contents

1 Introduction to the thesis

This chapter describes the background for the master thesis, along with the objectives and limitations. The scientific approach is discussed and the structure of the thesis is outlined.

1.1 Background

The existing petrophysical and geophysical data acquisition requirements for the Heidrun field is described in the *"Reservoir Management Plan Heidrun Field 2007"* [4]. This document is supposed to be updated annually, but the part of the document regarding petrophysical data acquisition has not been significantly changed or updated since 2004. The petrophysical evaluation model however, including the full field reservoir model and the stratigraphic zonation has been revised and updated.

As the Heidrun field has reached a decline from the initial hydrocarbon production plateau, there is an increasing need for alternative well solutions to be able to recover bypassed reserves in a cost effective manner. [5] A thorough well planning process including a flexible data acquisition plan covering both short and long term needs regarding reservoir characterization is crucial.

The reservoir management strategy [4] includes extensive use of water injection to increase the total hydrocarbon recovery of field. As raw or treated sea water and produced water (all having different salinities) is being injected into the reservoir to compensate for reservoir pressure depletion and to mobilize the hydrocarbons in the void space of the reservoir rock, the reservoir parameters are altered. Further, movement of fluids (including gas) in the reservoir due to production and injection has changed the properties of the reservoir from its initial state, with a typical two phase fluid system, easily recognized and interpreted by the petrophysicist, into a mixed fluid system containing both oil, fractions of gas and water of unknown or salinity.

As the existing documentation does not take the new challenges, as well as new technology and new methods fully into account, the document is long overdue for revision.

Further, the existing documentation is, not always specific enough, leaving room for personal interpretation of the requirements and inconsistency from one project to the other. A new decision framework for data acquisition is hence needed, aiming for decisions based on analytical methods and if possible a better quantification of background information.

1.2 Objectives

The main objective of the master thesis project is to develop a decision framework for data acquisition planning adapted to the needs of the decision makers responsible for the petrophysical data acquisition program in new development wells.

More specific objectives are:

1. To give a thorough description of the downhole data acquisition methods and techniques used in well construction – including advantages and limitations of each method.
2. To evaluate the quality of the data acquired, with regards to acquisition technique, measurement type, accuracy and repeatability as a foundation for the decision making.
3. To evaluate and propose revision of the relevant parts of the governing documentation regarding petrophysical data acquisition planning.
4. To identify, describe and evaluate exisiting decision making methods and techniques and propose a new decision framework for petrophysical data acquisition in the development well planning process.
5. To evaluate the decision framework proposed in paragraph 4 and discuss its applicability in the described context.

1.3 Limitations

This project will focus mainly on down hole (sub-surface) data acquisition planning and operations, including LWD/MWD and open hole wireline logging operations.

- Production logging, well data acquisition after production start up and other cased hole activities will be briefly discussed in this project.
- Seismic (surface and cross-well), seabed logging and other surface measured reservoir properties estimation techniques is regarded as geophysical disciplines rather than petrophysical ones and will not be covered in this document.
- Well cores and coring operations are regarded as special activities and a dedicated coring operation project group within the StatoilHydro organization will be involved when needed. Coring is hence not described in detail.

The decision making methods and techniques proposed in a decision framework must comply with the StatoilHydro requirements and governing documentation. Methods and techniques not fulfilling these requirements, and not considered to be of value in a well planning context are not evaluated!

The main target group for the decision framework proposed is petrophysicists, but also the other members of the Well Planning Team (WPT) responsible for the petrophysical data acquisition program in new development wells. The methods described in this thesis are hence focusing on petrophysical data acquisition planning, but could easily be adapted to fit other disciplines participating in the well planning process.

1.4 Scientific approach and scope

The decision framework should adhere to:

Consistency
Well planning is a multidisciplinary team activity. The data acquisition planning framework should aim at concistency from project to project, independent of the team member's personal preferences, competence and experience level.
This objective should be achieved by a designing framework rigid enough to ensure a specific work practice including a set of predefined minimum requirements/deliverables, yet flexible and dynamic enough to ensure that project specific issues and challenges are accounted for.

Redundancy
The framework should allow major uncertainties and risk factors to be identified and classified. Based on this risk register, "What-if" or back-up solutions should be planned and included in the process.

Fulfill minimum data acquisition requirements
Petrophysical data are required and used at different levels in the organization. Different disciplines and subjects as well as different phases in the field's lifespan require different data at different levels of sophistication.
The framework should ensure to the extent possible that the data acquisition plan is covering a set of pre-defined minimum requirements for the different users, for each working discipline and with respect to both short and long term reservoir strategies, as well as authorities', StatoilHydro general requirements and license partner requirements.

Table 1-1 Example of use of petrophysical data in different disciplines. This chart is over-simplified and by far not a complete chart, but intends to show the diversity and complexity of a well planning project.

Discipline	Use of data / requirements
Petrophysicist	Quantitative petrophysics Well evaluation
Geologist	Geological zonation Cross well correlation
Reservoir engineer	Productivity index Flow modelling
Drilling engineer	Optimum well placement Borehole stability
Completion engineer	Well completion (hardware) Completion solution Production intervals
Reservoir management	Full field update Simulation model update Long range plan
Geophysiscist	Seismic tie and calibration Geomechanics
Production engineer	Production profiles Production optimization

Specific project requirements
The framework should further effectively call attention to requirements specific to that well project. This could include, but not limited to

- Geosteering / wellbore placement needs
- Special services / new data acquisition technology qualification
- Limitations due to well design/well concept (length, hole size, tortuosity, and in case of slot recovery, existing well solutions)
- Limitations due to reservoir properties/geology (high temperature and or pressure, unstable formations, faults etc.
- Limitations to drilling assemblies (steerabillity, specific sensor within a critical distance from the drill bit, equipment availability etc.)
- Rig limitations (especially in cases where semi-submersible drilling vessels are utilized, the limitations regarding rig movements, drilling fluid systems capabilities, lifting capacities, deck space etc.)
- Full field data acquisition needs, long range plans and reservoir management requirements

Data acquisition optimization
The framework should aim at optimization of data acquisition programs with regards to

- The projects economic robustness of the project
- HSE perspective
- Cost benefit estimation of the planned data acquisition program.

1.5 Structure of the thesis

Petrophysical data acquisition planning must be considered in the context of the construction process for development wells. A general knowledge of this well planning process and the related StatoilHydro governing documentation is hence needed to confirm that the decision framework is in accordance with company requirements and principles. A description of the general StatoilHydro project development model and the more specific well planning process is therefore included in chapter 2. Chapter 3 describes the role of the petrophysicist and the data acquisition planning process in relation to the well planning process.

Chapter 4 provides a thorough description of the downhole data acquisition methods and techniques used in well construction is given, including the advantages and limitations of each method. Further, the quality of the data acquired, with regards to acquisition technique, measurement type, accuracy and repeatability is evaluated in chapter 5. This evaluation will then be used as a foundation for the decision framework.

Chapter 6 identifies, describes and evaluates existing decision making methods and techniques. This chapter, together with chapters 4 and 5 is then used as a foundation for the proposed new decision framework as presented in chapter 7.

Chapter 8 evaluates the proposed framework and discusses its applicability in the described context before the final conclusions are made.

2 The Well Planning Process

Data acquisition planning is an integrated part of the well planning process. A fundamental knowledge of the well construction process and the essential StatoilHydro governing documentation is needed to assure that the decision framework for petrophysical data acquisition is made in accordance with corporate standards and requirements.

2.1 The StatoilHydro project development model

The general project development framework in StatoilHydro is described in the [6] document. The project model framework is based on the PMI project model [7], as well as national and international best practice supplemented with best practice from the StatoilHydro organization. The purpose of the framework is to provide a set of fundamental principles and a common standard for project management in the organization. This includes a method for structuring and communicating project management knowledge and experience and to give a clear definition of roles and interfaces between the corporate business units and the individual project.
One of the core requirements is that the project development shall be done in accordance with the Capital Value Process (CVP) [8], a decision process that describes the phases, decision gates (DG) and mechanisms established to follow up the project from a project ownership point of view (ref. figure 2.1).
Each investment project runs through defined phases. Between each phase there is a DG that must be passed in order to proceed to the next phase. A DG is a project milestone where a decision shall be made whether the project shall be:

- Continued (DG passed),
- Subject to major changes or further development (before passing DG), normally back to previous DG,
- Terminated (no further development)

The decision gates will generally coincide with phase transitions in the project. Additional approval points are also defined for important project decisions within each project phase.
In a drilling and well construction perspective, the Capital Value Process is further described in the [9] and in the [10] documents.

The exploration and petroleum technology (EaRTh) function [9] covers activities in exploration and petroleum technology, activities which are present in all phases from screening of potential exploration areas, field development, throughout field production and ending with field abandonment

EaRTh is one of several process networks within the organization responsible for introducing and incorporating common work processes. The main disciplines within EaRTh are geophysics, geology, petrophysics, reservoir technology and production technology, and the general EaRTh function describes the requirements to ensure an efficient and cost effective mapping, acquisition, confirmation and exploitation of commercial petroleum accumulations.

[10] defines the StatoilHydro corporate functional requirements to well construction, drilling, completion and well intervention. The main purpose of the drilling and well (D&W) function [10] is to secure that the company's drilling and well activities are carried out in a safe and efficient manner and to secure optimum well performance, based on sound well construction and best available technology for the purpose of reaching the company production targets.

Figure 2.1 summarizes the general Capital Value Process including the project phases, DG's and D&W deliveries.

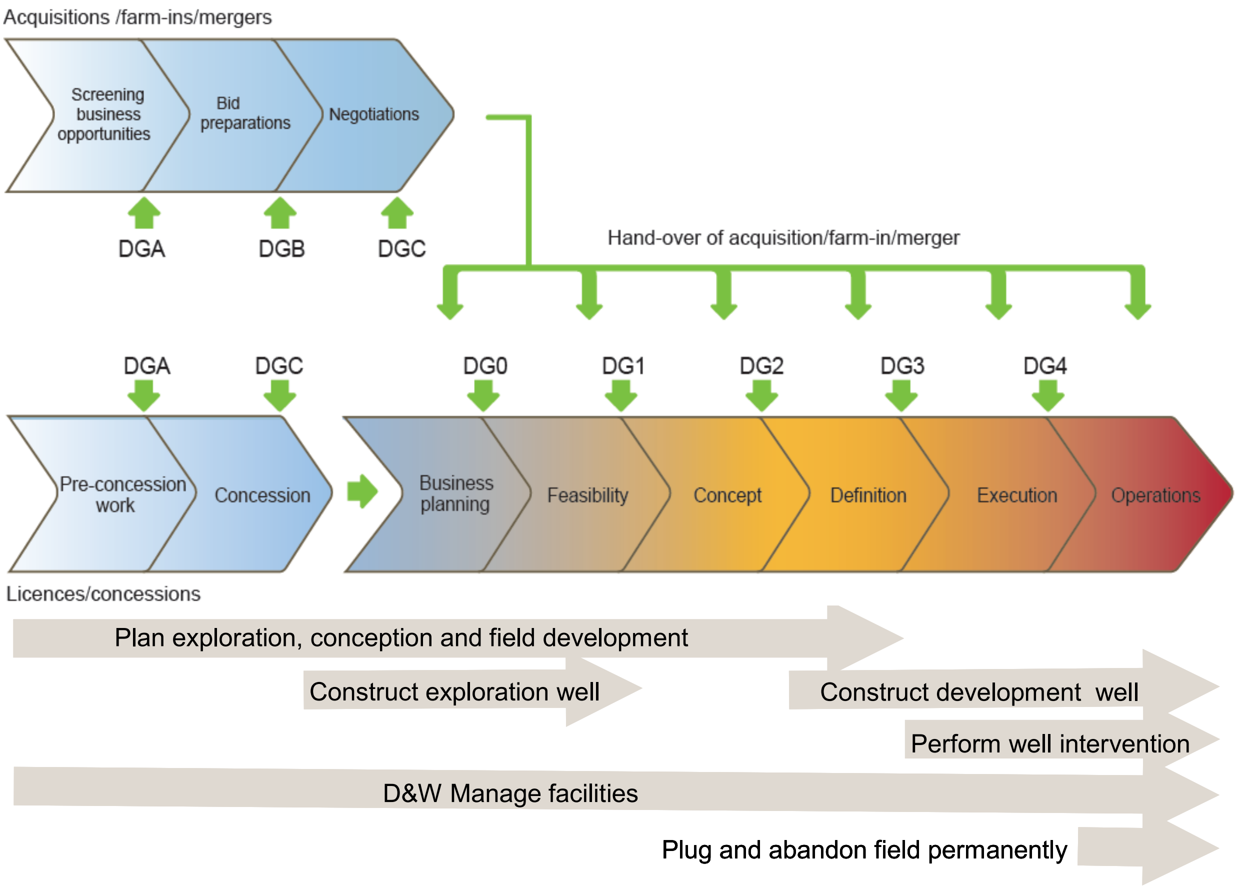


Figure 2-1 CVP process including D&W deliveries (from [8]).

2.2 The well planning process

The well planning process and the requirements is described in several governing documents at several organizational levels within StatoilHydro. At field specific level (the Heidrun field) the most applicable documents and work procedures covering development well planning and construction are the following:

- *"Reservoir Management Plan Heidrun Field 2007"* [4]
- *"Work Process Description for maturing drilling locations in HD PETEK/B&B"* [11]
- *"Construction Process for Development Wells"* [12]

2.2.1 Initial well planning, the TRO process

The document *"Work Process Description for maturing drilling locations in HD Petec/B&B* [11] describes the Targeting Remaining Oil process (TRO). This biennial process ensures a continuous maturing of drilling locations, generation of drilling projects and a prioritised drilling schedule (2-year drilling plan) for the Heidrun field.

2.2.2 Objectives of the TRO process:

TRO will provide the following results for HD Petec / B&B:

- Basis for decision making and drilling projects prioritization
- Quality control and revision of drilling schedule
- Drilling locations matured before start of the well planning process
- Efficient and comprehensive transfer of experience
- Structured and uniform maturing phase
- Orderly and logical risk- and cost management
- Increased utilization of the upside potential in new technology by systematic search for suitable well candidates
- Early warning of complex wells needing increased planning time

The delivery from the TRO prospect phase together with the 2-year drilling schedule is the *well assignment document* that initiates the detailed well planning and drilling process.

2.2.3 Detailed well planning and drilling process

The detailed well planning process is carried out according to the [12] document.
The Well Construction Process is an interdisciplinary work process that commences at the Start-Up Meeting (the formal hand-over of the well assignment document from the TRO-process) and continues until experience transfer and final reports are completed. The goal is to achieve optimum well solutions which have been thoroughly discussed on an interdisciplinary basis and risk assessed in adequate time before the drilling operations commences.
The Construction of Development Wells process is project organized according to [6], and divided into the following three phases:

1. **A Well Planning Phase:** This phase starts when the Well Planning Team is nominated. Requirements for preparatory work are found in checklists. See Chapter 3 and appendices for more details. The phase is divided in two sub-phases:

- The Conceptual Phase: Method selection and development of RTD (the "Recommendation to Drill" document.)
- The Detailed Planning and Engineering Phase: preparing the individual programs including Detailed Operations Procedures.

2. **A Well Operations Phase** which defines the follow-up/support during the actual operations. This phase starts with a Pre-Operations Meeting and ends with a Post Operations Meeting.

3. **A Well Evaluation Phase** which ensures documentation of lessons learned and experience transfer to forthcoming planning and operation projects. This phase includes final reporting and evaluation of the Well Construction Process.

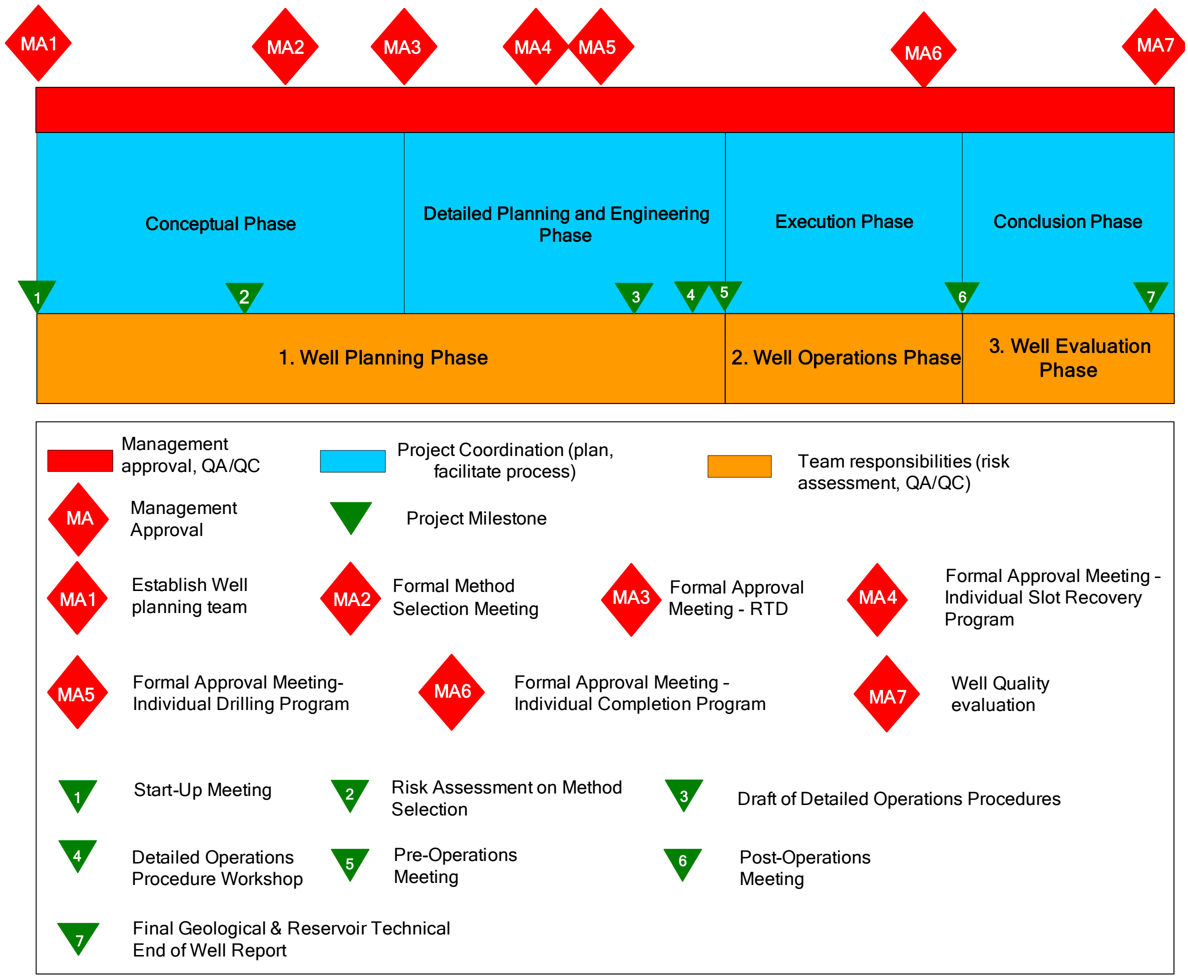


Figure 2-2 Project model for the Well Construction Phase (from [12]).

3 Data acquisition planning

A majority of the decisions made in relation to prospect evaluation and field development and production depend on acquisition of well data of adequate quality and quantity. It is decisive for StatoilHydro to have an auditable methodology for acquisition and quality assurance of these data. The minimum standard to secure this objective is stated in [13]. The document regulates StatoilHydro's world wide geological well data acquisition activities and shall ensure that well data acquisition activities are conducted in accordance with local acts, regulations and agreements, and with company requirements.

3.1 Definition of Geological Well Data Acquisition

Geological Well Data Acquisition is within the organization defined as all activities related to:

- Planning and execution of the well data acquisition program (including data processing, lab analysis etc.) in order to collect necessary information for proper reservoir evaluation and field development.
- Evaluation of all relevant sub-surface information together with data from the well in order to fulfill well objectives.

Examples of Geological Well Data Acquisition include:

- Open/cased hole logging
- Formation pressure measurements
- Proactive well placement (geosteering)
- Formation fluid sampling and analysis
- Fracture pressure measurements
- Pore pressure evaluation
- Coring
- Mud logging
- Biostratigraphy
- Geological samples
- Shallow gas evaluation
- Well production flow testing (WFT) / drillstem testing (DST)
- Seismic and electromagnetic surveying

Petrophysical data acquisition is mainly focusing on the top four subjects (open hole logging, formation pressure measurement/fluid sampling and well placement) and the scope of this thesis is limited to these. Further, the thesis is also limited to the planning phase of petrophysical data acquisition, i.e. the execution and evaluation phase is not a part of the thesis!

3.2 Applicable work process

The general work process described for geological well data acquisition consists of:

- Defining scope of work and objectives (pre planning phase)
- Developing and agreeing on solutions (method selection)
- Performing detailed planning of the work (planning phase)
- Carry out drilling and data acquisition operations in order to satisfy the well objectives (operations phase)
- End of well reporting and experience transfer

3.3 Data acquisition planning in the well planning processes

A draft (proposed) data acquisition plan is included in the well assignment document. Typically, this plan includes a standard data acquisition program only. During the detailed well planning process, data needs and requirements are evaluated and a final data acquisition program is made and included in the RTD document. The planned data acquisition or logging program for a well project is based on requirements at several levels, as well as other needs and wants based on input from the different disciplines in the WPT and the nature of the well itself. This hierarchy of requirements as well as the petrophysical deliveries during the well planning process is shown in figure 3-1.

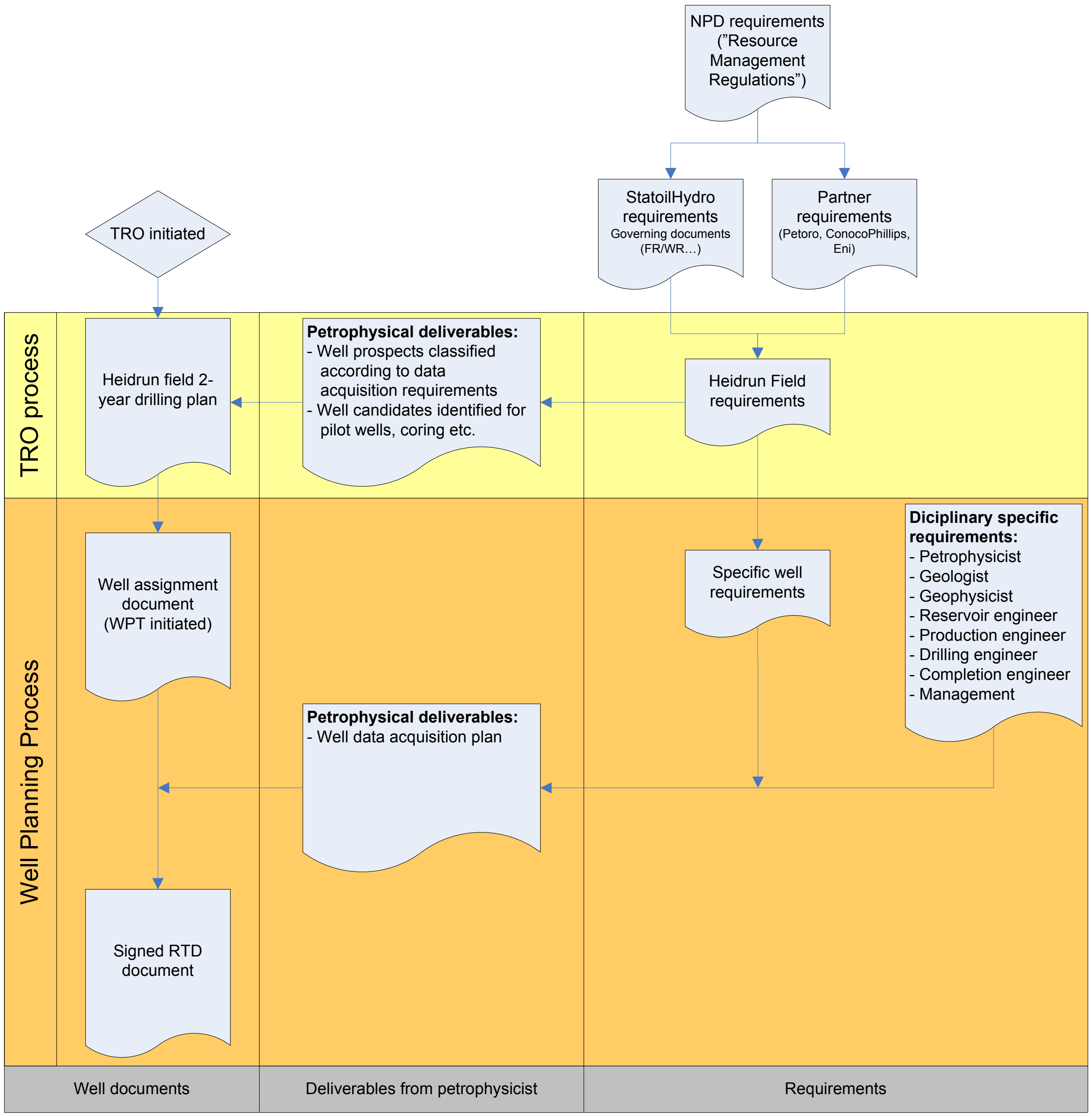


Figure 3-1 Requirements to petrophysical deliverables in the TRO and well planning process.

3.4 The data acquisition planning process

Thesis description bullet #3:
"Evaluate and propose revision of the relevant parts of the governing documentation regarding petrophysical data acquisition planning."

3.4.1 Development of the data acquisition or logging program

The data acquisition program should be based on the prevailing logging contract with the service company and in accordance with applicable local and national laws, regulations and agreements in force. The data acquisition program for a specific well represents a compromise where data necessity and the desire are weighted against operational aspects, risk, economy and time consumption.
The purpose of the well, as well as its length, the well trajectory, borehole and mud properties combined with experience and field knowledge are also important factors to be considered in the planning process [14].

3.4.2 Data acquisition strategy

The objective for the data acquisition strategy is to cover both short and long term needs for data acquisition in new and existing wells in a consistent manner and independent of person.

New wells are categorized as A, B or C-wells regarding data acquisition in open hole.
The petrophysicist participating in the TRO-process will make a temporary data acquisition plan (after consulting with other disciplines). This temporary plan will be used in the well assignment document and sent to the partners.

The final plan for data acquisition is put together by the petrophysicist with input from the other disciplines in the WPT. The data acquisition program is formally approved in the Data Acquisition Formal Choice of Method Meeting and implemented as part of the RTD document.

3.4.3 Classification of type wells for open hole logging

All the wells are classified as either A-, B- or C-wells based on the requirements for data-types and quality in open hole:

A-well:
The data acquisition program is based on the need to make the well (stratigraphic zonation, geosteering and well placement optimization, deciding completion-interval, etc.). Quality and type of data is controlled by these isolated needs.

B-well:
As A-well, but the data will be used for field-evaluation (input to the 3D geomodel) and for planning of future wells in the same area. High quality (quantitative) data are required.

C-well:
As for B-well, but additional acquisition of one or more of the items listed below:
- Logs for calibration of petrophysical field model
- Other logs considered as important
- Cores
- Fluid sample when required

Figure 3-2 proposes the following workflow for well classification:

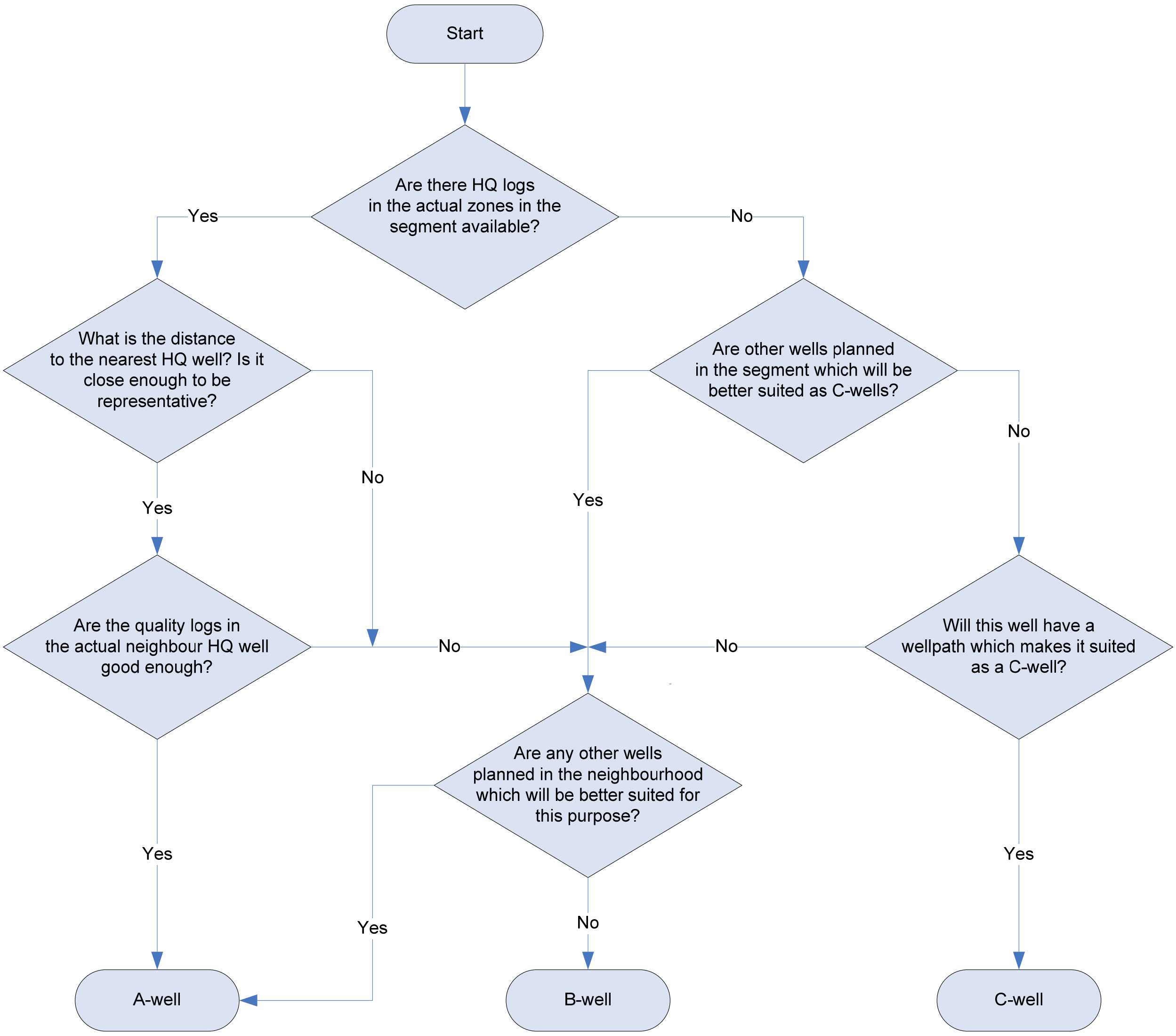


Figure 3-2 Flowchart for classifying wells as type A, B or C (After [15])

4 Technical description – Petrophysics and log measurements

In order to make correct and effective decisions regarding data acquisition planning, a good overview of the methods and techniques used in well description is important for the decision maker. In this section, a description of the relevant downhole data acquisition methods and techniques are given. Further, the most common measurement principles are briefly explained and the advantages and limitation of the measurements as well as the acquisition methods are discussed. The main sources of information are [1, 2, 3, 19, 20] unless other stated.

4.1 Definition/introduction to petrophysics

Petrophysics is the study of rock properties and their interactions with fluids (gases, liquid hydrocarbons, and aqueous solutions). The geologic material forming a reservoir for the accumulation of hydrocarbons in the subsurface must contain a three-dimensional network of interconnected pores in order to store the fluids and allow for their movement within the reservoir. Thus the porosity of the reservoir rocks and their permeability are the most fundamental physical properties with respect to the storage and transmission of fluids. Accurate knowledge of these two properties for any hydrocarbon reservoir, together with the fluid properties, is required for efficient development, management, and prediction of future performance of the hydrocarbon producing field [2].

Petrophysical data acquisition comprises the aspects of collecting the subsurface petrophysical, geophysical and geological information necessary to describe the reservoir. Petrophysical data acquisition planning hence comprises the aspects of optimizing the data acquisition process with regards to:

- Project cost / benefit
- Operational complexity and risk
- Minimum data quality and quantity, requirements and needs
- Long and short term reservoir management requirements
- HSE considerations

4.2 Data acquisition methods

Petrophysical data acquisition is closely related to *logging* [3]. Even though there are other sources of geological and petrophysical information (for example well coring and mud logging), the scope of this thesis is limited to data acquisition from well logging operations.

Reliable economic evaluation of a reservoir requires reasonable knowledge of certain fundamental reservoir properties. Although the rock recovered by coring methods is regarded as the cornerstone of formation evaluation [16], data acquired by wireline or LWD (Logging While Drilling) are more universally available for determining the fundamental reservoir properties.

Well coring operations are highly specialized, high cost, complex drilling operations, generally performed in exploration wells or in dedicated wells in development fields in areas with little geological information or high uncertainty with regards to reservoir properties and recoverable hydrocarbon volumes. Further, coring operations are generally not regarded as routine operations in development fields and require extra resources and expertise during both the planning, execution and evaluation phase of the operation. Coring and core analysis, including the routines for establishing some of the parameters necessary to perform a full *petrophysical evaluation* is described in detail in [16].

4.2.1 Well logs

The continuous recording of a geophysical or petrophysical parameter along a borehole produces a well log. The measurement is performed at reservoir conditions and the value is plotted continuously against depth in the well. The instruments or downhole hardware used to perform the various measurements are referred to as *logging tools.*

The logging tools, ranging from rather simple to highly sophisticated instruments can be combined in numerous ways and run in the well either during the drilling operation as part of the borehole assembly (BHA) or after the well is drilled and the BHA is retrieved from the borehole. Different measurements are performed either simultaneously or in subsequent logging operations and the well logs are interpreted to answer the following:

- Depth and thickness of the reservoir(s) encountered by the wellbore
- Reservoir pressure and temperature
- Lithology
- Porosity
- Oil, water and gas saturation
- Characterization of fluid properties
- Geomechanical properties
- Identify faults and fractures

Together with the three techniques and methods of open hole logging mentioned below, a fourth method, *coiled tubing conveyed logging* should be mentioned. Coiled tubing drilling / data acquisition methods was considered as part of a separate feasibility study [5] that concluded that the method and the existing coiled tubing technology is not suitable for the Heidrun field. Up to present date, coiled tubing has only been utilized for cased hole well intervention work on the Heidrun field. In theory, if future wells were drilled with coiled tubing, it would be very reasonable to perform the logging operations coiled tubing conveyed also. The method will not be further discussed in this thesis.

4.2.1.1 Logging While Drilling (LWD)

Traditionally, petrophysicists were concerned only with wireline logging, that is, the data acquired by running logging tools into the well on a cable from a winch after the hole had been drilled. However, advances in drilling/logging technology have allowed the acquisition of log data via tools placed in the actual drilling/borehole assembly (BHA). This technique is referred to as Logging While Drilling. LWD data may be stored downhole in the tools memory and retrieved when the tool is brought to the surface. Further, processed data, key formation evaluation parameters as well as downhole measured drilling parameters are transmitted back to surface as pressure pulses through the drill string mud column real time while drilling. In a typical operation, both modes will be used, with the memory data superseding the pulsed (real time) data once the tool is retrieved. Initially, this method was considered to present a complication for drilling, as well as additional expense [17]. However, fast technology development and especially the introduction of the 3D rotary steerable drilling system (3D RSS) in the late 1990s has revolutionized the drilling process [18]. Today, downhole measurements including BHA system status and quality checks continuously transmitted back to surface are regarded as paramount, especially in wells with complex wellpaths, small tolerances with regards to drilling targets or low clearance to nearby existing wells.

Since the early 2000s, virtually all reservoir sections drilled on the Heidrun field has been made using the 3D RSS technology, and when discussing LWD data acquisition in this thesis the use of this technology is therefore assumed!

LWD advantages include:

- Real-time information is required for operational reasons, such as steering a well (e.g., a horizontal trajectory) in a particular formation or picking of formation tops, coring points, and/or casing setting depths
- Short time period between the rock is cut (drilled) and logged
- Acquiring data prior to the hole washing out or invasion occurring (borehole quality / logging environment deteriorating with time)
- Safeguarding information if there is a risk of losing the hole
- The trajectory is such as to make wireline acquisition difficult (e.g., in horizontal wells)
- Real-time data like downhole annulus pressure, drill string torque, vibrations and dynamics provided by the LWD tools is very important to understand the drilling process and to get a good quality borehole.

Historically, LWD logging represented some major limitations and drawbacks compared to wireline logging. The technology development in the LWD industry over the last few years has however, reduced the impact of, or removed several of these limiting factors:

- LWD logging was limited by battery life: Depending on the tools in the string, well temperature etc., the tools would work typically between 40 and 90 hours. Modern

LWD BHAs has replaced the batteries by downhole power generators (turbines), driven by the mud flow through the drill string.

- Memory size: Earlier versions of LWD tools had a memory size limited to a few megabytes, or equivalent to a certain amount of hours of logging depending on the tool configuration, the amount of data to be stored and the frequency of the storage. In modern LWD tools, memory size is hardly an issue as the capacity by far exceeds the needs and duration of a typical logging operation.
- Several of the standard wireline services were initially not available as LWD services, or the quality of the LWD acquired was not adequate. Today, most standard services are commercially available, and the measurement quality is comparable to that of wireline.
- Some of the data recorded from LWD may be usable only if the tool string is rotating while drilling, which may not always be the case if a steerable mud motor is being used. In these situations, a reaming while rotating operation to reacquire data over particular intervals was performed if valid data was needed. When using a 3D RSS BHA, the tool string is rotated at all times.
- Initially, BHAs including LWD tools where not very compact, meaning that the distance from the drill bit to the individual sensors were significantly higher than that of wireline. The result is that a certain distance from the bottom of the well is not logged. Modern LWD tools still cannot fully match the compactness of a wireline tool string, but several logs are now available as “at the bit” measurements, while other measurements more often are incorporated in “multi-function” tools bringing all the logging sensors to an acceptable distance behind the bit.
- LWD tool failure: It is a big challenge to develop LWD instruments that are sensitive enough to be wireline comparable and still robust enough to cope with the stresses, vibrations and dynamics of a drilling operation. Further, as the duration of a LWD logging operation could be several days, a wireline operation could done in a few hours. Initially the LWD industry suffered from poor performance or low *mean time between failure* (MTBF), but several actions are taken to increase the LWD performance to an acceptable MTBF.
    - Increased focus on understanding the drilling process and the downhole drilling dynamics. Optimization of the drilling parameters (weight on bit, string rotation speed, correct placement of stabilizers in the BHA etc.) generally decreases downhole vibrations, but also improves the quality of the wellbore and increases the rate of penetration.
    - Implementation of new technology, high capacity digital circuit boards and more compact sensors has drastically reduced the number of parts in the tools.
    - The maintenance program for LWD equipment has improved and is today comparable to that used in the aviation industry.
    - More “multi-function” instruments reduce the number of tools to be connected. (The connections between the tools are regarded as one of the LWD “weak links”.)

4.2.1.2 Wireline open hole logging

Once a section of hole has been drilled, the drilling assembly is pulled out of the hole and there is an opportunity to acquire further openhole logs either via wireline or on the drill string (also referred to as pipe conveyed logging) before the hole is either cased or abandoned. The wireline itself is a high strength steel cable with typically 7 electrical wires in the middle (mono conductor cables exists, but are usually used in cased hole logging operations) conducting electrical power from power supplies at the surface to the downhole instrument and allows high speed data transmission between the instruments and the surface computers. The logging tools are connected to the cable end and lowered into the well. Depth is tracked by means of high precision encoder wheels connected to the cable in front of the wireline winch unit. The logging is performed as the tools are hoisted past the intervals of interest (logged interval) at constant speed and (preferably) constant cable tension.

Wireline logging advantages include:

- In vertical/sub-vertical wells, wireline operations are very quick.
- High precision instruments/high quality log measurements (standard and “niche tools” available for all hole sizes.)
- Depth accuracy better than that of LWD. Proven technology, high reliability tools. Quick turnaround in case of tool failure.

As the wireline tools are lowered into the well, there is a upper limit on the well inclination or deviation from vertical before the tools cannot go further into the well by gravity alone. This angle is typically around 60° but also dependent on other factors like well tortuosity, toolstring configuration, borehole quality and friction between toolstring and borehole. All wireline jobs are simulated well before the actual operation and when in doubt, or when well conditions unquestionably excludes traditional wireline conveyance of the toolstring, other methods like *pipe-conveyed logging* must be used.

4.2.1.3 Pipe-conveyed logging

Pipe-conveyed logging systems makes it possible to deploy tools for wireline logging in highly deviated or horizontal wells and also in hostile environments and deep wells. In such logging environments, the wireline tools could be run on drill pipe. In essence, this is no different from conventional logging. However, there are a number of important considerations. Because of the need to provide electrical contact with the tool string, the normal procedure is to run the tool string in the hole to a certain depth before pumping down a special connector (called a wet-connect) to connect the cable to the tools. Then a side-entry sub (SES) is installed in the drill pipe, which allows the cable to pass from the inside of the drill pipe to the outside. The tool string is then run in hole to the deepest logging point and back out until the SES is back at the surface, typically logging in both directions. The reason the SES is not installed when the tool string is at the surface is partly to save time while running in (and allowing string rotation), and also to avoid the SES (and the logging cable on the outside of the drill string) from going beyond the casing shoe and into open hole. Pipe-conveyed logging is expensive in terms of rig time and is typically used nowadays only where it is not possible to acquire the data via LWD. This includes highly specialized logging services (for example formation fluid sampling and analysis and sidewall coring operations) not available via LWD.

Considerations regarding pipe-conveyed logging

- Time consumption. The time spent from when a well section is drilled until it is cased off and cemented or completed is extended typically by a couple of days if pipe conveyed logging is performed.
- When SES and cable is installed, the drill string cannot be rotated.
- Depth accuracy comparable to that of LWD.
- It is possible to pump through the drill string during the logging operation, but the rates are very limited

4.2.2 Common terms and expressions

Before discussing the different log measurements, some important terms and expressions related to logging and formation evaluation are mentioned. These expressions are regarded as fundamental for the understanding of log responses, log quality and the log evaluation process.

4.2.2.1 Invasion

Under normal drilling conditions, the well is in *overbalance*, meaning that the hydrostatic pressure from the fluid column in the wellbore is higher than the formation pressure. This pressure difference is to some degree causing fluid to flow from the wellbore and into the formation. This process by which mud filtrate (the fluid phase of the drilling fluid), and sometimes whole mud, enters a permeable formation is referred to as invasion. The mud filtrate displaces some or all of the moveable fluids originally in place in the formation, leaving an invaded zone. The invasion depends on formation permeability, degree of overbalance and drilling fluid properties among other factors. The solids in the drilling fluid are generally too big to enter the pore throats of the formation rock, but are instead deposited at the borehole wall building a mudcake. As this mudcake is building up, an impermeable barrier is made and further invasion is stopped. A simplified step-profile invasion model is illustrated in figure 4-1.

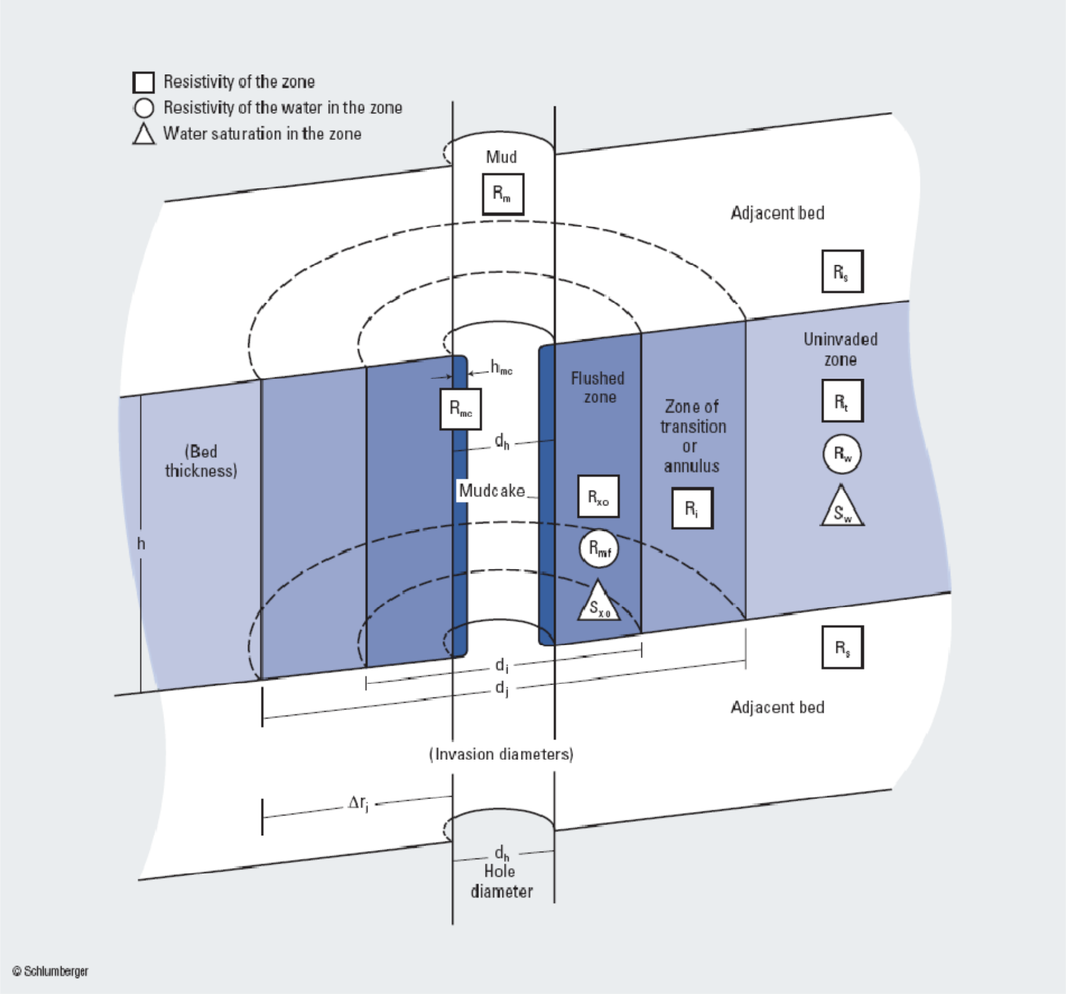


Figure 4-1 Step-profile invasion model (Schlumberger chart book)

4.2.2.2 Depth of investigation

The distance that characterizes how far a logging tool measures into the formation from the face of the tool or the borehole wall is referred to as *depth of investigation*. The depth of investigation summarizes the radial response of the measurement in one or more directions. For nuclear and resistivity measurements, the depth of investigation should be associated with the percentage of signal received from within that depth, typically either 50% or 90%. Most quoted depths of investigation assume a homogeneous formation with certain properties, such as a given resistivity or fluid content. The depths of investigation can vary considerably in inhomogeneous conditions, and at different values of the properties concerned. They should be considered only a qualitative guide to tool response.

For other measurements, the depth of investigation is either well-defined by the tool physics (in the case of nuclear magnetic resonance), or else can be given only approximately, an accurate value being too dependent on formation properties (in the case of acoustic and electromagnetic propagation).

The term is used for all measurements but is most appropriate for azimuthally focused devices such as nuclear logs. For azimuthally symmetric devices such as resistivity logs, the term radius of investigation is more appropriate.

4.2.2.3 Vertical resolution

A distance that characterizes the ability of a logging tool to resolve changes parallel to the tool axis. The word vertical implies a vertical well, but the term is used also at other wellbore deviations. The vertical resolution summarizes the vertical response of the measurement in one or more distances. Most quoted vertical resolutions assume a homogeneous formation with stated properties. Vertical resolutions can vary considerably in more complex conditions, and at different values of the properties concerned. They should be considered only a qualitative guide to tool response.

The theoretical definition of vertical resolution is as follows [19]: *The full width at half maximum of the response of the measurement to an infinitesimally short event. For log deflections whose shapes are Gaussian (normal distributed) with a standard deviation σ,*

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \cdot \exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma} \right)^2 \right] \qquad (1)$$

the vertical resolution, or full width at half maximum (FWHM) is:

$$FWHM = 2\sqrt{2\ln 2} \cdot \sigma \approx 2.35482\sigma \qquad (2)$$

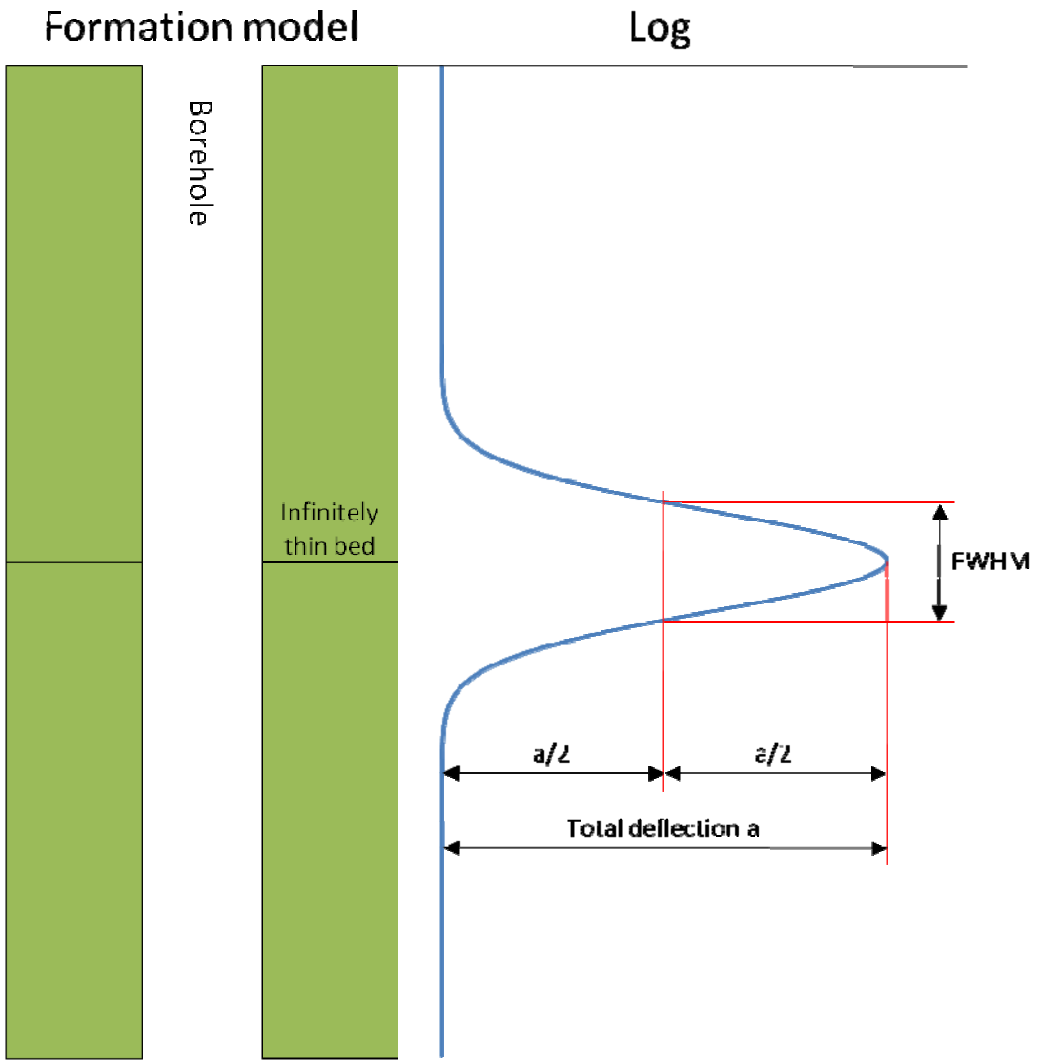


Figure 4-2 Theoretical definition of vertical resolution (after [19]).

In more practical terms (and generally the definition used by the service companies when stating the measurement specifications), the vertical resolution is the minimum bed thickness needed for the measurement to read within a small percentage, typically 10%, of the true value at the center of the bed. The vertical resolutions given in this thesis are all based on this description.

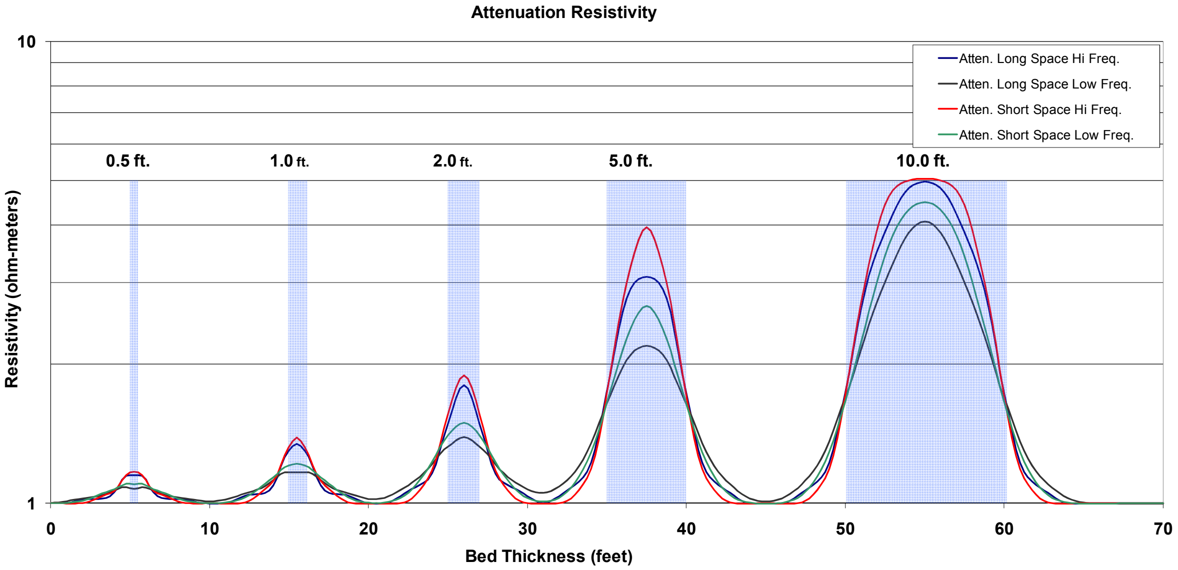


Figure 4-3 Modelled resistivity response (Baker Hughes INTEQ)

Figure 4-3 illustrates a modelled resistivity response in 5 Ohm-m beds at increasing thickness in a 1 Ohm-m shoulder bed. From the chart it is evident that the short-spaced, high frequency curve (red) has the best vertical response in this example, but full bed resolution is achieved only in the 10 ft thick formation and then only by two of four measurements.

Depth of investigation and vertical resolution is dependant on several factors, the most important being measurement type (physics of the measurement), instrument design and geometry and the properties of the formation and the borehole environment in which the measurement is performed. The depth of investigation/vertical resolution values stated in this thesis when describing the common log measurements should therefore used as a rough estimate only. These values are for one specific instrument operating under optimum conditions.

4.2.3 Common log measurements

This chapter gives a short and simplified description of the most common log measurements in the industry. Logging tools are complex instruments and so is the physics behind the measurements. A detailed description of each measurement is not included in the scope of this thesis. The vertical resolution and depth of investigation numbers stated are based on [20], but the corresponding figures for LWD services or from other wireline service providers are very similar unless other stated.

4.2.3.1 Gamma ray

The Gamma ray (GR) log is a measurement of the natural radioactivity of the formations. Radioactive elements tend to concentrate in clays and shales, and due to this the GR log is particularly useful in distinguishing sands from shales (including silts and clays) in siliciclastic environments. Due to its high repeatability, fairly high vertical resolution and insensitivity to the fluids present in the formation it is used to correlate both from one logging run to the next in the same well, but also to correlate the stratigraphy between wells.

Main applications:

- Depth correlation with other logs / other wells in the same field
- Determine stratigraphic profiles
- Estimate shale content in reservoir rock

Vertical resolution:	12 in
Depth of investigation:	24 in

Environmental corrections:

- Borehole diameter (the larger the borehole, the higher the distance from the formation to the GR detector hence decreasing the count rate.)
- Stand-off (distance between tool/detector housing and the formation. Increasing distance causes decreasing count rate.)
- Heavy drilling fluids / high baryte content (barite absorbs gamma rays, decreasing the count rate at the detector.)
- Tool size (a thick collar/tool housing will act as a shielding, reducing the count rate at the detector. Further the outer diameter (OD) of the collar itself has an impact; a larger tool in a relatively small borehole will effectively have a smaller stand-off/distance to the borehole wall and less drilling mud between the detector and the formation.)
- KCl based drilling muds (the natural radiation from the potassium in the drilling fluid will cause an increase in the GR detector count rate.)

4.2.3.2 Natural gamma ray spectroscopy

This tool works on the same principal as the gamma ray, although it also separates the gamma ray counts based on the energy level of each GR count to determine the relative contributions arising from the radioactive isotopes uranium, potassium, and thorium in the formation. Essentially, natural radiation in rocks comes from these three elemental sources only [21]. These data may be used to determine the relative proportions of certain minerals in the formation.

Main applications:

- Define clay content and clay type
- Quantitative definition of natural gamma radiation
- Mineral identification
- Log correlation
- Aid for fracture detection

Vertical resolution:	8 – 12 in
Depth of investigation:	9.5 in

Environmental corrections: Same as for the gamma ray log.

4.2.3.3 Caliper

The caliper log is a measure of the geometry of the borehole. The wireline version is typically using one or several spring loaded or hydraulically pressured arms pushing against the borehole wall. It returns the borehole diameter seen by the tool over either a single or multiple axis. The LWD version of the caliper utilizes different measurement techniques; typically an ultrasonic caliper, but also a density-derived or neutron-derived caliper measurement could be used [22]. The ultrasonic caliper is using a high frequency acoustic transmitter/receiver in a pulse/echo mode to measure the time for an acoustic signal emitted to be reflected from the borehole wall back to the receiver. The acoustic travel time is related to the standoff distance between the sensor and the receiver and the borehole diameter is derived. As the tool is continuously rotated during drilling, a multiple segment radii measurement (also referred to as azimuthal measurement) is possible.

- During drilling, caliper data can be used to monitor the wellbore condition, providing early warning of borehole washouts and impending wellbore instability.
- Provide valuable information about the efficiency of the drill bit and how well it performs in various formations, at various ROPs and various well inclinations not at least during directional
- Undergauge hole intervals due to mud cake build up could indicate permeable zones. (Indirect measurement of the mudcake thickness).
- Undergauge hole due to hole stability / chemical instability between the formation and the drilling mud causing especially clay or shaly formations to swell.
- Overgauge hole due to washouts in soft, brittle or poorly consolidated formations or pressure incompabilities between formation pore pressure and hydrostatic pressure in the well.
- Multi-axis or azimuthal caliper measurements showing elliptical boreholes could provide information about magnitude and direction of geomechanical strain and stress regimes [3].

- For the petrophysicist, the caliper is a very valuable log quality indicator since most log measurements are affected by hole size and quality. Logs acquired over intervals of poor hole conditions are usually of poor quality!

As the caliper measurement is a measurement of the borehole and not related to formation properties the terms vertical resolution and depth of investigation are mot used with the measurement

4.2.3.4 Bulk density

A Cesium source is emitting medium energy (0.66 MeV) gamma rays into the formation. The electrons in the formation/fluids absorbs energy from the gamma rays (in a Compton scattering process) before the scattered gamma-rays reach the tool detectors. The amount and the energy level of the gamma rays detected (typically a short space and a long space detector; referring to the distance from the radioactive source) is proportional to the density of the formation and its containing fluids, also referred to as the *bulk density* of the formation. If the specific gravity of the rock measured (i.e. the matrix density) and the specific gravity of the containing fluids are known, a formation porosity is derived.

The bulk density measurement also includes the PEF (Photoelectric factor) measurement, which under the right circumstances is useful in complex lithology evaluation. The measurement is based on the ratio between the mid-energy and low-energy counts at the tool detectors and gives the effective photoelectric absorption cross section index (Pe) of a formation. This is strongly correlated to the average atomic number (Z) of the constituents of the formation.
The measurement is primarily resonding to the formation matrix composition and the effect of varying porosity and fluid content is low.
One major drawback of the PEF is the effect of barite, a commonly used weighting material in the drilling fluids. As the Pe value of barity is very high compared to that of common rock matrixes, even small amounts will dominate the response of the measurement totally. On the other side, this effect could be used as a fracture indicator, as higher amounts of barite is building up/filling the formation's fractures during the invasion process.

Another important measurement included in the bulk density service is the delta rho ($\Delta\rho$) measurement. Delta rho is a function of the difference between the bulk density measurements from the long space and short space detectors. As the corrected bulk density is calculated from apparent long space density + delta rho, the latter is hence the correction applied to the density measurement. An increasing delta rho value (either positive or negative) is typically indicating poor borehole and/or logging conditions, and the confidence of the bulk density measurement is reduced.
Together with the caliper measurement, delta rho is a very important log quality indicator.

Main applications:

- Bulk formation density
- Formation porosity
- Lithology analysis and mineral identification
- Determination of hydrocarbon density
- Gas detection

- Calculation of acoustic impedance (together with acoustic velocity measurement from sonic logs)

Vertical resolution: 15 in
Depth of investigation: 4 in

Environmental corrections:

- Borehole size and mud weight (as is the case with most logging tools, the density tool is calibrated in a pre-defined environment or standardized values for borehole size and fluid properties. Deviations from these values must be characterized for each tool type to allow for corrections.)

4.2.3.5 Neutron porosity

The "standard" neutron most commonly run is a thermal neutron device. However, newer generation devices often use epithermal neutrons (having the advantage of less salinity dependence) and rely on minitron-type neutron generators rather than chemical sources.

High-energy (fast) neutrons are continuously emitted from a radioactive source in the logging tool into the formation. By interaction with the formation, these neutrons slow down and lose energy until they reach the thermal energy level (< 0.025 eV). Neutrons are primarily slowed down by hydrogen having the approximate same mass. Since hydrogen is found mainly in the formations pore fluids, neutron porosity is derived from the measure of the Hydrogen Index (HI), the number of hydrogen atoms per unit volume divided by the number of hydrogen atoms per unit volume of pure water at surface conditions. The higher the HI in the formation, the more porous the formation is assumed to be. The thermal neutrons are detected at the dual (near and far) proportional detectors in the tool. A porosity is then calculated in terms of a ratio of the near to far count rates. This ratio provides a partial cancellation of borehole effects (refered to as a borehole compensated measurement).

The rock matrix and the type of fluid have an effect on the neutron porosity measurement. Formations with high hydrogen content (hydrogen occurs in clays and hydrated minerals) responds with a high apparent porosity, whereas gas having a low hydrogen density, causes gas interval to have a very low apparent neutron porosity. Due to this, the neutron porosity measurement is not the primary or first choice of porosity, but used together with the bulk density measurement the combination is a very common logging service.

Main applications:

- Differentiating oil or water from gas zones
- Calculate quantitative values for lithology
- Determine shale volume in the rock matrix

Vertical resolution: 12 in
Depth of investigation: 9 in (varies with HI of the formation)

Environmental corrections:

- Lithology (the basic transform of measured ratio to apparent porosity assumes a limestone matrix. If the prevailing matrix is different a correction is needed.)
- Borehole size and stand-off (the water in the drilling increases the HI, resulting in increased apparent porosity.)
- Borehole and formation water salinity (chlorine is an effective neutron absorber, causing the neutron porosity to be too high.)
- Mud weight (increasing mudweight increases the ratio of solids to water resulting in a lower apparent porosity.)
- Temperature (increasing wellbore and formation temperature causes a decreasing HI resulting in a lower apparent porosity.)
- Pressure (increasing hydrostatic and formation pressure causes an increasing HI resulting in a higher apparent porosity.)

Together with the bulk density measurement, neutron porosity measurement is a key measurement in formation evaluation. Due to the versatility in most type of formation rocks, the complementary tool responses and the robustness/simplicity of the measurement, the combination has been by far the most commonly used porosity/lithology indicator in the industry. As virtually all reservoir sections in all wells in the Heidrun field has been logged with the density/neutron combination, the log response and behavior is very well known and even if more sophisticated porosity logs are run, the combination would still be included, mainly for correlation purposes and comparison with existing wells.

4.2.3.6 Resistivity

Resistivity is the ability of a material to resist electrical conduction. Most formations logged for potential oil or gas saturation are made up of rocks which, when dry, will not conduct an electrical current; i.e., the rock matrix is assumed to have zero conductivity or infinite resistivity (not always a valid assumption). Further, an electrical current will flow only through the interstitial water saturating the pore structure of the formation, and then only if the interstitial water contains dissolved salts. If hydrocarbons, being a non-conductive media is displacing parts of the interstitial water, the formation resistivity is increasing. Hence, resistivity is related to hydrocarbon saturation.

A common relationship between resistivity, porosity and water saturation in homogeneous, shale free formations is the Archie equation [23] which is also the equation used in the current Heidrun evaluation model [4]:

$$S_w^n = \frac{a \cdot R_w}{\varphi^m \cdot R_t} \tag{3}$$

Where a (formation factor), m (cementation exponent) and n (saturation exponent) is derived from core analysis, R_w is the resistivity of the formation water determined from different sources (i.e., core data, produced water or water samples from formation testing), φ and R_t is porosity and true formation resistivity from the logs.

Resistivity tools fall into three main categories based on their measurement principles: laterolog and induction type, primarily used in wireline tools and the propagation resistivity type tools used in LWD.

Laterolog tools use low-frequency currents emitted from a transmitting electrode (hence requiring conductive fluids in the well bore) to measure the potential caused by a current source over an array of detectors.

Induction-type tools use primary coils to induce eddy currents in the formation and then a secondary array of coils to measure the magnetic fields caused by these currents. They operate at higher frequencies (multi frequency tools operate at several frequencies simultaneously in the 10 kHz – 150 kHz range) and can be used in both conductive and non-conductive mud systems, for example oil-based mud (OBM) systems.

Propagation resistivity tools emit a high frequency (common frequencies are 400 kHz and 2 MHz) electromagnetic (EM) wave into the formation. The EM wave loses energy as it propagates through the medium. The energy loss depends on the resistivity and the dielectric permittivity of the medium and the energy loss is related to two measurable properties, the amplitude and phase difference as measured by the receivers

Modern resistivity tools are designed to see a range of depths of investigation into the formation where the general rule is that the shallower readings have a better vertical resolution than the deep readings (the volume of media contributing to the measurement signal is increased as the DOI increases). Several computerized vertical resolution and DOI enhanced processing methods are used in the industry (for example deconvolution methods or resolution matching) to improve the measurements.
The DOI is depending on the following:

- Transmitter to receiver distance – increasing distance increases the DOI.
- Frequency – lower output frequencies increases the DOI.
- Attenuation resistivity measurements have higher DOI than phase resistivity measurements
- Formation resistivity – including mud resistivity, invasion profiles, formation water saturation and salinity, porosity and pore interconnectivity.
- Induction and propagation resistivity tools are refered to as “conductivity seeking devices” generally providing an increased DOI with increasing formation resistivity , whereas the laterolog is “resistivity seeking” providing a decreasing DOI with increasing formation resistivity.

Main applications:

- Quantification of water/hydrocarbon saturation
- Identify permeable and non-permeable zones
- Qualitative identification of lithology (for example cemented or clay rich zones)

Vertical resolution:	Depending as described above, 8 in – 48 in
Depth of investigation:	10 in – 120 in

Ultra deep resistivity measurements sensing resistivity contrasts more than 10 m into the formation is developed for LWD. This is not a quantitative measurement, but the technique is designed to geosteer or optimize the well placement for production, for example by keeping the well a certain distance above the oil-water contact [24, 25].

Environmental corrections and effects:

- Anisotropy – the formation might have different properties in different directions, i.e., the log measurement is dependent on relative angle between tool and formation.
- Borehole effects – effects on the log measurement influenced by formation resisitivity to mud resistivity contrast, borehole fluid (mud) salinity and borehole size and shape.
- Dielectric effects – largely a function of the formation dielectric permittivity (i.e., the formations ability to store electric charge.)
- Eccentricity effects – alteration of measurements caused by sensor not being centered in the borehole.
- Invasion – curve separation between curves with different depths of investigation (usually an indication of permeability).
- Horizontal Beds/High Apparent/Effective Dips
- Bed thickness – corrections applied to measurements in thin zones with adjacent (shoulder-) beds with high resistivity contrasts and typically when the thickness of the bed is below the vertical resolution of the measurement.
- Polarization horns – effect characteristic of the propagation resistivity measurement when the borehole is close to parallel (the tool has a low incident angle) to the formation bedding plane and crossing a bed boundary at high resistivity contrast, creating a capacitance charge build-up at the bed boundary, resulting in a over-estimation of the resistivity.

4.2.3.7 Micro resistivity

Micro resistivity tools are designed to measure the formation resistivity in the invaded zone close to the borehole wall. They are generally pad-device measurements where small focused electrodes (same measurement principle as the laterolog measurements) are pushed against the borehole wall, simultaneously providing a caliper measurement. As is the case of the laterolog, the micro resistivity is not suitable in a non-conductive borehole fluid environment, for example in oil-based muds (OBM). The measurement is usually not regarded as a “stand-alone” logging service, but is primarily used for correcting deeper resistivity measurements as well as estimating residual hydrocarbon saturation in the flushed zone (estimating the apparent fluid density used as input in the porosity calculation from bulk density).

Main applications:

- Flushed / invaded zone water saturation estimation
- Invasion correction to deep resistivity measurements
- Detection of beeding features too small to be detected by deep resistivity measurements
- Borehole diameter and rugosity measurement (from auxillary caliper measurement)

Vertical resolution:	0.7 – 3 in
Depth of investigation:	0.5 – 3 in

As the LWD tools cannot use pads or back-up arms to push the sensors against the wall, a different technique is used. The electrodes are mounted on specialized stabilizers in the BHA, providing contact with the borehole wall. For obvious reasons, the diameter of the tool/stabilizer must be smaller than the drilling bit, hence sensor contact with the borehole wall is a challenge. Especially when the sensor is pointing to the highside of the borehole (the “upper” side of the borehole when drilling at high inclinations / close to horizontal.) Another drawback is that the DOI is generally not shallow enough to be valid as a flushed zone measurement. Due to this, the main application for this type of tool is borehole imaging.

Vertical resolution (LWD): 2 – 3 in
Depth of investigation (LWD):11 – 27 in

4.2.3.8 Image logs

One of the big advantages to LWD over logging services is the possibility to create azimuthal or image logs from basic logs. As virtually all reservoir sections today are being drilled with rotary steerable assemblies, the LWD string and logging sensors are being continuously rotated during the logging operation. If the log measurement is focused, covering only a certain part of the borehole circumference, repeated log measurements and a reference to the high side of the borehole could be used to create an image around the borehole, showing the different measurement values in different directions. This technique is especially valuable during complex well placement or geosteering operations where realtime images could indicate if the wellbore is being drilling upwards or downwards in the stratigraphy.

Main applications:

- Geosteering / well placement
- Formation structural and sedimentary dip measurements
- Fracture detection and orientation
- Fault detection and orientation
- Definition and characterization of sedimentary bodies and their boundaries
- Recognition of anisotropy, permeability barriers and permeability paths
- Recognition and evaluation of thinly bedded reservoirs

LWD services including azimuthal / image logs:

- GR
- Bulk density / Photoelectric factor
- Deep resistivity (azimuthal propagation resistivity)
- Shallow resistivity (laterolog micro resistivity)
- Caliper

Wireline services including azimuthal / image logs:

- Microresistivity (both in oil-based and water based mud systems) using multiple focused micro electrode measurements and several (up to six) backup arms
- Rotating ultrasonic transducer (as described in chapter 4.2.3.3) measuring both acoustic travel time and acoustic impedance

Even though there are fewer possibilities for wireline image logging, compared to LWD, wireline has some major advantages:

- Even if LWD can provide images from for example GR and bulk density, the vertical resolution and DOI is the same as for the standard measurements.
- Wireline resistivity images could be produced at very high resolution (0.2 in vertical resolution / 1 in DOI)

- The high data resolution combined with a smoother tool movement along the borehole wall at constant speed and wire tension can provide quantitative formation dip measurements that, at best is qualitative measurements from the LWD images [26].

Other imaging services are available, for example anisotropy and formation stress orientation from acoustic/sonic measurements, but these are regarded as highly specialized services and not further covered by this thesis.

4.2.3.9 Sonic log measurements

Conventional acoustic log data is obtained by the use of one or two transmitters and typically an array of receivers positioned at fixed distances from each other. Sound from the transmitters is coupled through fluids to the borehole wall, where it is refracted along the borehole wall and refracted back across the fluid column to the receivers. The acoustic signal waveform is recorded at each receiver, and the time delay in the signal between the receivers is representative of the distance between them and is a measure of the *acoustic interval transit time* of the formation. Equivalent to the bulk density measurement, knowledge of the lithology and fluid type allows porosity to be calculated by empirical means. Further, the acoustic compressional arrivals of the signal are often compared to later shear arrivals or Stoneley arrivals for more advanced interpretations e.g., to determine the mechanical properties of the rock strata or to derive an estimate of permeability. Comparisons of compressional and shear arrivals are also empirically related to lithology.

Main applications:

- Determination of porosity
- Improve correlation and interpretation of seismic data (acoustic impedance calculated from acoustic and density logs)
- Identify zones of abnormally high pressures
- Resolve difficult correlation problems
- Assist in identifying lithology
- Estimate secondary pore space
- Delineate regional tectonics from acoustic profiles
- Indicate rock mechanical integrity (with density data) / determination of rock mechanical properties i.e., bulk, shear and Young's modulus, Poisson's ratio
- Estimate rock permeability

Vertical resolution:	24 – 48 in (depending on tool type, number of receivers and the distance between the receivers)
Depth of investigation:	Shallow (0 – 9 in) due to physics of measurement (acoustic signal refracted along borehole wall)

Environmental corrections and effects:

- Tool eccentering could create a signal cancellation effect at the receiver end causing a lower signal-to-noise ratio.

- LWD sonic measurements are performed in a lot more dynamic environment and are more exposed to noise than the wireline measurements (drilling/bit noise, mud flow). Increased noise decreases the signal-to-noise ratio.
- When logging parallel / close to parallel with the formation bed boundaries (usually at high inclination), with a velocity contrast (different formations) between the upper and lower side of the borehole, signal-to-noise ratio decreases. The measurement will generally represent the formation with the fastest velocity and give an incorrect indication of the bed thickness.

4.2.3.10 Nuclear Magnetic Resonance

Nuclear Magnetic Resonance (NMR) logging is hardly regarded as a common logging service, but is now commercially available also for LWD and therefore briefly described in this thesis.

NMR is a phenomenon which occurs when the nuclei of certain atoms are immersed in a static magnetic field and exposed to a second oscillating magnetic field. In terms of well logging, NMR measures the amount of moveable versus irreducible fluid. Alignment and dephasing of protons with respect to an external magnetic field controls a process known as nuclear magnetic relaxation. The measurement of the relaxation rate, known as T2 allows the estimation of a rock's internal surface-to-volume ratio. This highly complex measurement is usually not run as a standard service in development wells, but is more commonly used in exploration well logging. It should still be considered in future Heidrun wells, especially in B or C type wells (ref. ch x.x.x Classification of type wells for open hole logging), where NMR could be of high value in addition to more common lithology/porosity indicators like the neutron and density services.
Even though regarded as rather insensitive to borehole size and rugosity and to mudcake thickness, and in theory is capable of performing a direct hydrocarbon characterization independent of formation water resisitivity, the DOI is in general too shallow to be used for hydrocarbon and water saturation determination in permeable zones with moderate to high invasion.

Main applications
- Pore size distribution
- Estimation of grain-size distribution
- Qualitative permeability estimation
- Mineralogy-independent effective porosity
- Total porosity estimation
- Moveable / irreducible fluid saturation (including clay-bound water)

Vertical resolution:	7.5 - 18 in
Depth of investigation:	1.25 - 4 in

4.2.3.11 *Formation pressure/sampling*

Unlike the above described measurements, which all generates a continuous record over an interval of the formation, formation-testing tools are stationary measurements designed to measure the formation pressure and/or acquire formation samples at discrete points.

The far most common formation-testing tools are probe based tools operated by pressing a probe through the mudcake and into the wall of the formation. By opening pretest chambers in the tool and analyzing the fluids and pressures while the chambers are filled, it is possible to determine the true pressure of the formation (as distinct from the mud pressure or the hydrostatic pressure in the borehole). If only formation pressures are required, the pretest chambers are small (typically between 5 and 20 centiliters) and the samples are not retained. For formation sampling, larger chambers are used (ranging from typically 0.45 liter when multi-sampler bottles are used and up to 22.7 liters), and the chambers are sealed for later analysis at the surface [Fundamentals of Formation Testing].

The wireline formation-tester tools can be combined with various modules, allowing different downhole fluid analyses to be performed, like fluid resistivity, gas/oil ratio (GOR) and fluid composition. At present, only simple formation pressure testing is possible with LWD (no sampling / fluid analysis available), leaving enhanced formation testing still as one of the major wireline domains.

Main applications:

- Formation pressure measurement and fluid gradient estimation
- Formation fluid sampling and downhole fluid analysis
- Pretest downhole mobility values (permeability/viscosity)
- Permeability and permeability anisotropy determination away from the well
- In situ stress determination

4.2.4 LWD vs. Wireline comparison

Even though the LWD and Wireline are generally based on the same measurement principles, and have a lot of similarities, there are some large differences that must be taken into account when planning a data acquisition program for a well.

4.2.4.1 *Time since drilled*

Depending on the drilling speed or rate of penetration (ROP) and the sensor offsets (the distance from the drill bit to the different log measuring points on the drill string), the time from the formation is drilled until it is logged may vary from minutes to a few hours (assuming an ongoing drilling operation not interrupted or discontinued). Wireline logging is typically performed after the entire hole section is drilled and the drill string is pulled out of the hole. Depending on the length of the section to be logged, and the duration of the drilling operation, the “time since drilled” for a wireline operation could easily range from less than 24 hours to more than one week.
The time since drilled is affecting the borehole environment in several ways:

- Mud invasion is generally increasing with time
- Chemical reactions between the formation and the drilling fluids; effect increases with time
- Borehole stability issues; effect increases with time

4.2.4.2 Logging environment

LWD measurements are performed under dynamic conditions.

- Ongoing mud invasion
- Drill string/logging sensors are continuously rotated (assuming that 3D RSS BHA is used)
- Noise/vibrations from the drilling process (friction/relative movements between BHA/drill bit and the formation as well as noise from the drilling fluids/cuttings flowing past the sensors)
- Logging speed is limited/determined by the ROP / drilling parameters.

Wireline logging is generally performed under more static conditions.

- Mud invasion has stabilized
- No mud flow/circulation during logging
- Tools are not being rotated or exposed to the noise/vibrations seen in the case of LWD logging
- Logging speed is easily optimized for efficiency and log quality

4.2.4.3 Sensor technology and accuracy

Even though the measurement principles used generally are the same for LWD and wireline tools, certain physical constraints exist for LWD tools compared to wireline tools:

- Being an essential part of the drilling assembly, LWD tools must have the same mechanical robustness as the rest of the drill string. This especially includes requirements with regards to tensile, compressive and torsional strengths, hence the tubulars used for housing the LWD sensors are significantly thicker than their wireline counterparts. This results in a more effective shielding between the formation to be measured and the sensor itself and therefore:
    - Increased attenuation of both emitted and received signals/radiation (acoustic and resistivity measurements).
    - Decreased count rates on instruments detecting radiation (gamma ray, neutron and density measurements).
    - Decreased signal-to-noise ratio as well as increased statistical variation in the measurements decreases measurement accuracy and precision.
    - LWD sensors are further generally restrained physically in design and size as the tubulars in which they are mounted also comprise a certain area of the tools cross section for drilling fluid circulation. Especially instruments containing photomultiplier tubes or crystals detecting radiation are affected by this limitation.

Smaller detectors results in fewer counts detected increasing the statistical variance, hence decreasing measurement accuracy and precision.

- LWD tools are designed to persistently be exposed to shock and vibrations occurring during the drilling operation. Due to this, the requirement to the LWD components regarding robustness, reliability and durability are higher.
- Wireline tools can be run centralized or decentralized (pushed against the side of the wellbore) depending on tool configuration, hole size and the purpose of the logging operation to optimize the sensor placement in the wellbore whereas the drilling assembly is centralized at all times by the use of stabilizers. LWD sensors actually requiring borehole contact is hence typically sidewall mounted on the drill string tubulars, acting both as stabilizers/stand-offs as well as logging instruments.
- One major advantage of the LWD logging tools is that the continuous rotation of the BHA during drilling makes azimuthal measurements possible. Especially in high angle wells, when drilling close to parallel or parallel to the stratigraphy, azimuthal measurements could be of great value, indicating if the well is moving upwards or downwards in the stratigraphy.

4.2.4.4 Depth accuracy

Depth is a fundamental parameter in reservoir characterization. The users of log data rely on precise depths for mapping geological intervals, calibrating seismic depth conversion models and updating geomodels, calculating gross rock volumes, designing well completion procedures etc. If the depth measurement is incorrect, incorrect geologic and economic decisions could result.

LWD measurements as a rule are referenced to the driller’s depth. The driller’s depth is based on a pipe tally – a list of tape measurements made for each joint of pipe lowered into the well. To provide continuous depth for the log data, the movement or height of the block is tracked at the surface. For each distance that the block travels up or down, it is assumed that the bit travels an equal distance out or into the well, provided that the pipe is “out of slips”.

Sources of LWD depth measurement error:

The main causes of LWD depth measurement errors within the wellbore (in decreasing order of magnitude) are [27]:

- Mechanical stretch
- Thermal expansion
- Friction effects
- Rig heave (valid on floating / semi-submersible rigs only)
- Tidal errors (valid on floating / semi-submersible rigs only)
- Pressure effects
- Reference elevation
- Pipe deformation
- Drill-off effect
- Setting slips effect
- Pipe measurement errors

A lot of work has been done on LWD depth improvement [28, 29, 26, 30, 31], and the technology modelling the depth measurement errors described above is commercially available, but still the prevailing standard today is to use the “uncorrected” driller’s depth as reference. There are several explanations to this industry “inertia”:

- Technology still not fully proven.
- LWD depth improvements are separate, non-standard services and hence charged separately.
- Currently, the methods cannot be applied real-time, i.e. the depths are corrected after the operation. This strongly reduces the value of the method.

Wireline depth is derived from a dual encoder wheel measuring the length of cable being run in and out of the hole. The logging is typically performed as pulling out of the hole at constant speed. Cable stretch is modelled and applied by the logging system software by continuously recording both surface tension and cable head tension (the tension at the top of the toolstring).

The logging sequence is generally performed at constant speed and cable tension, providing the best source of reservoir thickness or bed thickness estimation (relative depth), but as the wireline depth tracking system is taking factors like cable stretch and well tortuosity into account, also the absolute depth is usually more accurate than that of LWD (based on driller’s depth) [28, 29].

Pipe conveyed logging comprises both driller’s depth and wireline depth. As the wireline is clamped off at the SES (ref. Ch. 4.2.1.3) and the wireline winch operator is aiming at keeping a constant cable tension throughout the operation. As the wireline tools are run on drill pipe, the sources of depth error are the same as is the case of LWD, hence pipe conveyed logging depth accuracy is comparable to that of LWD.

4.3 Chapter summary and conclusions:

For mature fields, where large amounts of data have been acquired for field specific measured, where well placement is getting increasingly more challenging and critical, real time data acquisition during drilling is more and more crucial. A rapid development of the LWD technology and the evolution of the 3D rotary steerable drilling assembly, has virtually replaced standard wireline measurements and services.
Since wireline is regarded as the “standard” in well logging, the LWD measurements suffer from continuously being compared to those of wireline. Deviations from the standard is very often used in disfavor of the LWD method instead of trying to understand the differences [33] . One of the major drawbacks regarding LWD though, is the depth measurement uncertainty. Even though depth improvement methods are developed and available, these are still not implemented as a standard service.

4.3.1 Conclusions on data acquisition methods and log measurements

All logging tools measure some physical quantities (Count rates, voltages etc.)

- No measurements done are direct measurements of the property.

- In most cases, the measured quantities are not directly applicable for any purpose; quantities of interest are derived by transformations, calculations and calibration routines.

All logging tools average smaller or larger volumes when measuring. This volume is a function of the tool response, mainly described by the tool's depth of investigation and vertical resolution. As a general rule, the vertical resolution decreases (poorer resolution) with increasing depth of investigation.

Due to dynamic processes like mud invasion and formation alteration effects after the formation is drilled, the borehole environment the LWD tool is measuring may be very different from the environment the wireline tool is measuring. Environmental corrections of the measurements due to borehole effects are needed. The magnitude of the correction can be substantial.

A general overview of the differences, the advantages and disadvantages of the different logging methods and the log measurements is needed as a foundation for decision making during the well planning process. Very often, physical limitations and specific well requirements are qualifying one type of data acquisition while disqualifying other methods directly. This includes considering the following factors:

- Planned wellpath inclination and tortuosity
- Need for geosteering / optimized well placement
- Borehole size
- Mud type
- Formation integrity and stability
- High pressure / temperature logging environment requiring special “high temp tools”
- Other hostile environment issues (wells containing H_2S)

The main conclusion is that data acquisition planning should primarily be based on the premises and the nature of the well to be drilled.

4.3.2 Comparison of data acquisition methods

A table summarizing the advantages and disadvantages of the different acquisition methods discussed in this chapter is presented in Appendix C.

4.3.3 Principal uses of borehole data

Table 4-1 summarizes common subsurface data acquisition methods and measurements (not limited to LWD and wireline services only), their potential uses in geological description and reservoir characterization, as well as a general ranking of the quality of the measurement.

Table 4-1 Principal uses of borehole data. After M. Rider (modified by A. Eldøy / B. Bøklepp)

Principal uses of borehole data		Samples			Wireline and LWD													Well testing				Other			
		Cuttings	Whole core	Sidewall core	Gamma Ray	Spectral GR	Sonic	Density	Neutron	Deep Resistivity	Micro Resistivity	Caliper	SP	NMR	Dipmeter	Image Log	Magnetic Field	Well Flow Testing	Formation Pressure While Drilling	Formation Testing/Sampling	Drill Stem Testing	Gas Mud	Seismic (VSP)	Temperature	DBS (Drill Bit Seismic)
General Geology	General Lithology	🟨	🟩	🟨	🟥	🟥	🟧	🟧	🟧	🟥	🟥	🟥			🟧	🟧									
	Volcanics	🟨	🟩	🟨	🟥			🟥	🟥																
	Evaporites	🟨	🟩	🟨	🟧	🟧	🟥	🟥	🟥	🟥	🟥														
	Mineral Identification	🟨	🟩	🟨	🟥	🟧	🟥	🟥	🟥	🟥	🟥														
	Stratigraphic Correlation	🟨	🟨	🟨	🟨	🟥	🟥			🟥	🟥		🟥		🟧	🟧	🟨								
	Formation Dip		🟧												🟩	🟩									
	Faults		🟧												🟨	🟩							🟧		
	Depositional Env./Facies		🟩		🟥	🟥		🟥	🟥	🟥	🟥		🟥			🟧									
Reservoir Geology	Fracture Identification		🟩			🟥	🟧	🟧				🟥				🟨					🟧				
	(Over-) Pressure Identification	🟥					🟧	🟥		🟥	🟥	🟥						🟩	🟩	🟩	🟩	🟨	🟧	🟥	🟧
Geochemistry	Source Rock Identification	🟨	🟩	🟨	🟧	🟧	🟧	🟧		🟧											🟨	🟥			
	Maturity		🟩	🟨																	🟥	🟥		🟧	
Petrophysics	Porosity	🟥	🟩	🟨			🟨	🟩	🟨	🟧	🟥			🟨											
	Permeability	🟥	🟩	🟨	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟥	🟥	🟨				🟨	🟨	🟨	🟩				
	Shale Volume	🟥	🟩	🟨	🟨	🟨		🟧	🟧				🟧	🟨		🟥									
	Fluid Identification	🟥	🟧	🟧			🟥	🟥	🟥					🟨				🟩	🟧	🟩	🟩	🟥		🟥	
	Water Saturation	🟥	🟨	🟧			🟥	🟥	🟥	🟨				🟧											
	Saturation Invaded zone										🟨			🟧											
	Formation Water Salinity						🟥	🟥	🟥	🟥	🟥		🟨					🟧		🟩	🟩				
	Gas Identification						🟥	🟥	🟥	🟥	🟥			🟥				🟩	🟥	🟨	🟩	🟥		🟥	
	Formation Breakout											🟨			🟨	🟩									
Seismic	Interval Velocity						🟨																🟨		🟨
	Acoustic Impedance						🟨	🟨																	
PVT	Fluid Samples		🟨	🟥														🟧		🟩	🟨				

Index:	Best source	🟩
	Quantitative	🟨
	Semi quantitative	🟧
	Qualitative	🟥

5 Data acquisition quality assessment

This chapter evaluates the quality of the data acquired, with regards to data acquisition technique, measurement type, accuracy and repeatability as a foundation for the decision making process.

5.1 Uncertainty assessment

A thorough identification and assessment of the reservoir uncertainties for the prediction of recoverable hydrocarbon volumes and fluid flow performance is of great importance when planning infill development wells. Large uncertainties in reservoir gross volume estimation derive not only from the measurement errors, but also from the way the static reservoir model (the full field geological model) is constructed [33].
The main reservoir model uncertainties are divided into three main areas: geometry, internal heterogeneities and petrophysical properties.

One of the basic concepts in reservoir engineering is the estimation of in place hydrocarbon volumes and further, the recoverable reserves [34]:

$$Reserves = GRV \cdot \phi \cdot (1 - S_w) \cdot NTG \cdot \frac{1}{B_o} \cdot RF \qquad (4)$$

GRV	Gross rock volume = area · height of the (oil/gas filled) reservoir [m^3]. The total volume of the reservoir containing hydrocarbon
Φ	Porosity, the proportion or volume fraction of the rock containing fluids.
S_w	Water saturation, the proportion or volume fraction of the porosity containing water, hence ($1 - S_w$) is the volume fraction of the porosity containing hydrocarbon.
NTG	Net-to-gross, the proportion or volume fraction of the GRV that consists of net reservoir (contains porosity and permeability above a certain cutoff criteria.)
B_o	Oil formation volume factor, a factor used to convert reservoir volumes of oil to

surface (stock tank) conditions.

RF Recovery factor, the reserves as a proportion of the in place hydrocarbon volumes.

In this equation, both the porosity (Φ), the water saturation (S_w) and the Net-to-gross *(NTG)* parameters are derived from log measurements and petrophysical interpretation. Further, also the reservoir thickness or the height of the hydrocarbon column is based on the logs. Poor log response and especially poor depth control could cause the thickness of the reservoir and the hydrocarbon column height to be estimated wrong. It is hence crucial that the quality of the log data used as input into to geomodel is sufficient.

5.2 Definitions of measurement quality

A commonly used definition of quality is *"conformance with specified requirements"* or, as stated by [35]: *"degree to which a set of inherent characteristics fulfils requirements".*

Historically, the quality of logging has been judged on the occurrence or lack of failures and the measurement of rig time. The performance of a logging company was based on its ability to avoid or minimize failures and to reduce the time is involved in logging operations. [19] states that the concept of logging quality should be expanded to total quality, which comprises:

1. Service efficiency (minimization of failures, optimization of rig time).
2. Data quality (intrinsic quality of data).
3. Data relevance (ability of data to describe the formation or to enable the end user to take the correct decisions).

Data quality is closely related to measurement accuracy and repeatability which constitute a certain part of the *petrophysical uncertainty*.

5.3 Sources of petrophysical uncertainty

As discussed earlier (in chapter 4), the petrophysical variables like porosity (Φ), water saturation (S_w) and permeability are not directly measured, but estimated from some physical properties measured in the well, applying some mathematical model of more or less empirical origin with its required parameter values based on physical measurements in the wells, on core material or on other sources. All elements in the petrophysical interpretation process and the process itself, may contribute to the final uncertainty. These contributions may be grouped in the following manner [36]:

- Measurement and measurement condition related uncertainty and errors
- Model and parameter related uncertainty
- Errors due to limitations in logs and petrophysical evaluation routines

5.3.1 Measurement and measurement condition related uncertainty and errors

For a single log measurement, there is a long chain of mathematical and physical tool modeling, calibration and correction of environmental effects to derive the “measured value” from some kind of physical measurement in the logging tool sensors.
Any single measurement has an error, i.e. a difference between the measured and the true value of the property to be measured. The degree of closeness between measured and true value is also referred to as *accuracy*. According to [19] it is generally accepted that there are three types of errors:

1. Systematic errors
2. Random errors
3. Blunders (mistakes)

In a logging context, a systematic error is a reproducible inaccuracy introduced by faulty design, failing equipment, inadequate calibration, inferior procedure or a change in the borehole environment [19, 37]. Systematic errors causes a general bias or offset of the measured value compared to the true value.
By opposition, a random error cannot be reproduced and is mostly imputable to the physics of the measurements. Some random variations around an average measured value is recorded. This random variation defines the *precision* of the measurement. Random errors could be regarded as “noise” in the measurements and the average random error of repeated, identical measurement are decreasing as the number of repeated measurements increases as shown below:

If x_i are the values measured and N the number of different measurements, the mean is calculated:

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{5}$$

The standard deviation σ is calculated:

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2} \tag{6}$$

Finally, the standard (mean) uncertainty σ_m or *precision* is given by:

$$\sigma_m = \frac{\sigma}{\sqrt{N}} \tag{7}$$

[19] is differentiating the terms precision, repeatability and reproducibility with the following definitions:

Repeatability is an in-situ estimation of precision. It is the difference in the magnitude of two measurements made under the same conditions, with the same equipment, same engineer and same environment.

Reproducibility is the difference in magnitude of two measurements made with the same method, but possibly with different equipment and different personnel. Good reproducibility is a crucial attribute for a logging measurement, especially in field wide and multiwell evaluations.

Random errors are generally not a concern in quantitative petrophysics or in-place hydrocarbon volume calculations as the effect is mostly removed when averaging (or “upscaling”) intervals of data for input into the reservoir geological and simulation model [33, 36, 38]. Further, random errors on logs are typically minimized through filtering algorithms.

Mistakes are often measurements with illogical or extreme values and hence usually easily identified and eliminated during the data quality check routines.
The important terms and expressions mentioned so far in this section are summarized and visualized in figure 5-1.

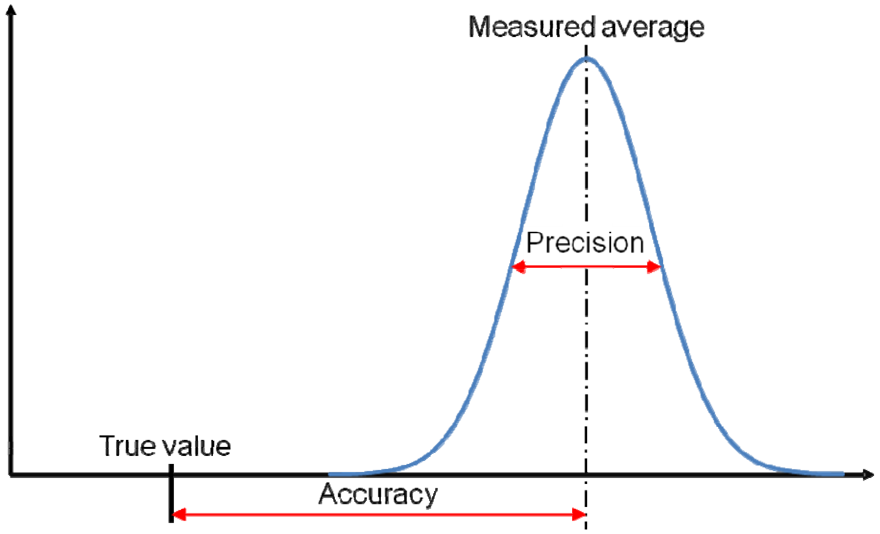


Figure 5-1 Accuracy vs. precision

Comparison of similar measurements/logging instruments from both LWD and Wireline services shows that modern LWD tools are competitive with, or very similar to the specifications of the wireline tools with regards to accuracy and precision. Table 5-1 compares some standard formation evaluation measurements where the LWD and the Wireline counterpart also are comparable when it comes to tool configuration, measurement principles and operating environment (values for precision not defined for all types of measurements by the service providers!) Numbers are stated as is the standard practice in the industry, at one standard deviation. *The service provider and the specific service (tool name) is not included in the table as the LWD specifications for the tools mentioned are not yet made public. Specifications for the wireline tool examples were found in the [20].*

Table 5-1Measurement accuracy and precision for some comparable LWD and Wireline services.

	Density		
	LWD	Wireline	Unit
Measurement range	1.0 - 3.05	1.04 - 3.3	[g/cm3]
Accuracy σ_b	± 0.015	± 0.01	[g/cm3]
Precision	± 0.008	± 0.025	[g/cm3]

	Resistivity (laterolog)		
	LWD	Wireline	Unit
Measurement range	0.2 - 20000	0.2 - 40000	[Ω-m]
Accuracy	± 5%	± 5%	[Ω-m]

	Formation pressure		
	LWD	Wireline	Unit
Measurement range	0 - 20000	750 - 15000	[psi]
Accuracy	± 2.2	± 2	[psi]
Precision	± 0.01	± 0.008	[psi]

	Gamma Ray		
	LWD	Wireline	Unit
Measurement range	0 - 250	0 - 1000	[gAPI]
Accuracy		± 5%	
Accuracy at 10 gAPI	± 3%		
Accuracy at 100 gAPI	± 2		[gAPI]

	Neutron porosity		
	LWD	Wireline	Unit
Measurement range	0 - 100	0 - 60	[p.u.]
Accuracy 0 - 20 p.u.		± 1	[p.u.]
Accuracy 30 p.u.		± 2	[p.u.]
Accuracy 45 p.u.		± 6	[p.u.]
Accuracy < 10 p.u.	± 0.5		[p.u.]
Accuracy > 10 p.u.	± 0.5%		
Precision at 30 p.u.	± 0.9		[p.u.]

5.3.2 Model and parameter related uncertainty

This subject includes the human or the petrophysicist's aspect of petrophysical uncertainty. During the interpretation process a large number of decisions (and often assumptions) must be made, often based on limited information. This includes:

- Validation/corrections/editing of core and log input data.
- Choice of interpretation models and equations for calculating porosity, permeability, water saturation and net-to-gross values. (The equations in the model are typically based on empirical approximations).
- Choice of other input parameters and their validity range needed in the evaluation routine.

The choices described may affect the results significantly, and are thus a major source of uncertainty [36] independently of the data acquisition methods used during the logging operation.

5.3.3 Errors due to limitations in logs and petrophysical evaluation routines

The interpretation models assume that the petrophysical properties of one log increment thick rock layer can be derived by some mathematical manipulations of log measurements associated with that increment. In homogeneous, thick reservoirs this generally holds true, but not in heterogeneous, more complex reservoirs where the thickness of each facies composing the rock volume being measured is smaller than the vertical resolution of the measurement (ref. figure 4-3). If these effects are not accounted or corrected for, they represent a major source of error and uncertainty.

5.4 Estimating petrophysical uncertainty

Two different methods of quantifying petrophysical related uncertainty are commonly proposed [36]:

First order error propagation (Taylor series)
This method is analytical and based on the assumptions that a quantity *f* is a function of *n* independent variables *x*, each with an uncertainty specified by a standard deviation σ. The corresponding standard deviation of *f* can then be estimated by:

$$\sigma f(x_1, x_2, ..x_n) = \{ \sum_{i=1}^{n} (\frac{\partial f}{\partial x_i} \sigma_{x_i})^2 \}^{\frac{1}{2}} \qquad (8)$$

where $\partial f / \partial x_i$ are the partial derivatives of *f* with respect to x_i.
For this approximation to be strictly valid, the individual uncertainties must be independent, symmetrical and have a normal distribution. As many of the uncertainties included in the petrophysical evaluation does not comply with the assumptions above and cannot be used to quantify the uncertainty of the end results (the estimated reservoir properties) from the petrophysical evaluation routines, the method is not very suitable in a well planning context.

Monte Carlo simulations
Monte Carlo simulation is essentially a method of integration [39]. In short, it is a statistical method where an uncertainty spread is generated from many random realizations where the associated uncertainty distribution is applied to each input parameter in the algorithm.
The method is very flexible regarding uncertainty distributions and can handle dependencies between variables by specifying correlation coefficients. Monte Carlo simulations are commonly used in the industry and the preferred and recommended method of subsurface uncertainty analysis in StatoilHydro [38].

A single point (focusing at one single depth) Monte Carlo simulation model of the Heidrun Petrophysical Evaluation was developed as a part of this thesis using Microsoft Excel and the @RISK add-on software from Palisade (www.palisade.com).

Some major drawbacks in the proposed model include:
- Input data (depth of interest) must be selected carefully by the user. The data should be representative of the specific zone of interest and quality checked for resolution and borehole environmental effects (ref. Ch. 5.3.3)
- The uncertainty distribution type and range is not known for all the input parameters.
- Variable dependencies are not always known, and quantifying the correlation coefficients is typically a very subjective process.
- Evaluation model (algorithm) uncertainty is not included in the simulation model (ref. Ch. 5.3.2).

Despite of the stated drawbacks, Monte Carle simulations have a wide range of application in the data acquisition planning context:
- Sensitivity analysis and scenario testing are easily carried out to:
  - Identify the main parameters contributing the most to the total uncertainty.
  - Investigate the robustness of the model predictions.

    - Perform what-if analysis to explore the impact of varying input assumptions and scenarios.
    - Act as an element of quality assurance (unexpected factors sensitivities are recognized and may be further investigated).
- Decision support:
    - Uncertainties and sensitivities are easily visualized and communicated within the well planning team or presented to management.
    - Running a full petrophysical evaluation is time consuming and requires special knowledge and training. The Excel/@RISK evaluation model provides a “quick-look” petrophysical interpretation to support decision making during drilling. (“Is the oil saturation high enough to continue drilling?”)
    - During well planning, effects of different reservoir scenarios can easily be constructed and evaluated, hence simplifying the data acquisition planning process.
- User friendliness:
    - Most members of the well planning teams and the managers are fairly skilled at using spreadsheets. If the model parameters are “tuned” by the petrophysicist, other users could easily use and do simple updates of the model and do their own “quick-look” log interpretations, even if they are not skilled @RISK users.

A single point simulation results of S_w (based on well 6507/7-A-41 A drilled in June 2008) is shown in appendix E.

5.5 Conclusions on data acquisition quality assessment

Based on the log measurement specifications from the service providers, the stated accuracy and precision values are highly comparable between different data acquisition techniques (LWD vs. wireline) for similar measurements. Further, when comparing the magnitude of the log measurement accuracies with the other sources of petrophysical uncertainty (like calibration and operational routines, borehole environmental corrections and borehole quality, evaluation model and parameter uncertainties and measurement as well as evaluation model limitations), log measurement uncertainty constitutes only a small portion of the total uncertainty.

When it comes to evaluating log data quality alone, without considering other important factors like borehole and formation stability, wellpath and well inclination, depth accuracy and other environmental factors affecting the log measurements; modern LWD measurements are fully comparable to those of wireline.

6 Structured review of decision support processes

This chapter identifies, describes and evaluates existing decision making methods and techniques. The review is based on a general literature survey related to decision making and decision support processes as well as experience from StatoilHydro regarding well planning and related decision processes.

6.1 Introduction

Future wells in the Heidrun field are aiming for smaller volumes at increasing reservoir complexity and increasing development cost pr volume. It is hence important to identify and minimize risk and uncertainties by utilizing as much as possible of the existing field data and knowledge, together with making robust well plans and contingency well solutions.
Decision makers in the well planning process therefore need appropriate methods and tools that can support the decision processes. A survey of methods and tools within the field of decision support has been conducted based on the following:

- General literature surveys covering different topics within management, risk and uncertainty assessment and decision making.
- A survey of the StatoilHydro governing documentation, regarding risk and uncertainty management, including requirements, guidelines and best practice documents. [12, 40, 41, 42].

Further, the methods where tested in several real situations during the following:

- Participation as petrophysicist in the TRO process 2008 as well as in several well planning teams.
- Participation as well planning coordinator in two separate well planning teams.

6.2 Decision-making context

The decision-making methods used should be considered in the context of the well planning process. This also implies that the methods used must fulfill the StatoilHydro requirements regarding project and risk management. Further, it is important that the methods considered in a well planning decision framework is fit-for-purpose and easily understood and adapted by the users.

In order to be auditable during the well planning process, also decisions made must be justified, reproducible and recorded. To fulfill these requirements, mainly systematic and analytical decision-making methods are reviewed.

6.3 Decision support systems (DSS)

According to (Power) [43], DSS are interactive computer-based systems intended to help decision makers use communications technologies, data, documents, knowledge and/or models to complete decision process tasks. A formal definition of a DSS as devised by (Marakas) [44], is not necessarily focusing on the computer aspects of the DSS:

> *A decision support system is a system under the control of one or more decision makers that assists in the activity of decision making by providing an organized set of tools intended to impose structure on portions of the decision-making situation and to improve the ultimate effectiveness of the decision outcome.*

Some general benefits and limitations of DSS use includes [44]:

Benefits:
- Extend the decision maker's ability to process information and knowledge
- Extend the decision maker's ability to tackle large-scale, time-consuming, complex problems
- Shorten the time associated with making a decision
- Improving the reliability of a decision process or outcome
- Encourage exploration and discovery on the part of the decision maker
- Reveal new approaches to thinking about a problem space or decision context
- Generate new evidence in support of a decision or confirmation of exisiting assumptions
- Create a strategic or competitive advantage over competing organizations

Limitations:
- DSS cannot yet be designed to contain distinctly human decision-making talents such as creativity, imagination or intuition
- The power of a DSS is limited by the computer system upon which it is running, its design, and the knowledge it possesses at the time of its use
- Language and command interfaces are not yet sophisticated enough to allow for natural language processing of user directives and inquiries
- DSS are normally designed to be narrow in scope of application, thus inhibiting their generalizability to multiple decision-making contexts

Decision Support Systems are generally categorized into five types [43]:

1. **Communication-driven DSS**
   Most communications-driven DSSs are targeted at internal teams, including partners. Its purpose are to help conduct a meeting, or for users to collaborate. The most common technology used to deploy the DSS is a web or client server. Examples: chats and instant messaging softwares, online collaboration and net-meeting systems.
2. **Data-driven DSS**
   Most data-driven DSSs are targeted at managers, staff and also product/service

suppliers. It is used to query a database or data warehouse to seek specific answers for specific purposes. It is deployed via a main frame system, client/server link, or via the web. Examples: computer-based databases that have a query system to check (including the incorporation of data to add value to existing databases.

3. **Document-driven DSS**
   Document-driven DSSs are more common, targeted at a broad base of user groups. The purpose of such a DSS is to search web pages and find documents on a specific set of keywords or search terms. The usual technologies used to set up such DSSs are via the web or a client/server system.
4. **Knowledge-driven DSS:**
   Knowledge-driven DSSs or 'knowledgebase' are they are known, are a catch-all category covering a broad range of systems covering users within the organization setting it up, but may also include others interacting with the organization - for example, consumers of a business. It is essentially used to provide management advice or to choose products/services. The typical deployment technology used to set up such systems could be client/server systems, the web, or software running on stand-alone PCs.
5. **Model-driven DSS**
   Model-driven DSSs are complex systems that help analyse decisions or choose between different options. These are used by managers and staff members of a business, or people who interact with the organization, for a number of purposes depending on how the model is set up - scheduling, decision analyses etc. These DSSs can be deployed via software/hardware in stand-alone PCs, client/server systems, or the web.

Based on the corporate requirements as stated in chapter 6.2, the methods reviewed in this thesis would fall into category 5, model-driven decision support systems. Decision situation in a well planning context involves a finite and usually a small number of alternatives to be evaluated. As is the case with the well planning process in general, model-driven DSS involves analysis of existing data to support the decision-making.

6.4 The decision making process

According to (Sage & Armstrong Jr.) [45], is a *decision* an allocation of resources:
The decision maker makes a decision, by allocation of resources, in order to further the achievement of some objective that is felt to be desirable.

Decision analysis is a structured and formal viewpoint that relates how a course of action would lead to a result. Generally, there are three features of a decision situation that are of importance: a decision to be made and course of action to be taken, the unknown events and outcomes that can affect the result, and the obtained result itself. The decision analysis approach is based on construction of *models*, which represents logical, often mathematical, representations of the relationships among these three features of the decision situation.

A general, sequential process model or decision loop is illustrated in Figure 6-1. This decision process model consists of seven basic steps [43]:

1. Problem definition
2. Decide who should decide
3. Collect information
4. Alternatives identification and evaluation

5. Decision
6. Implementation
7. Assessment and follow-up

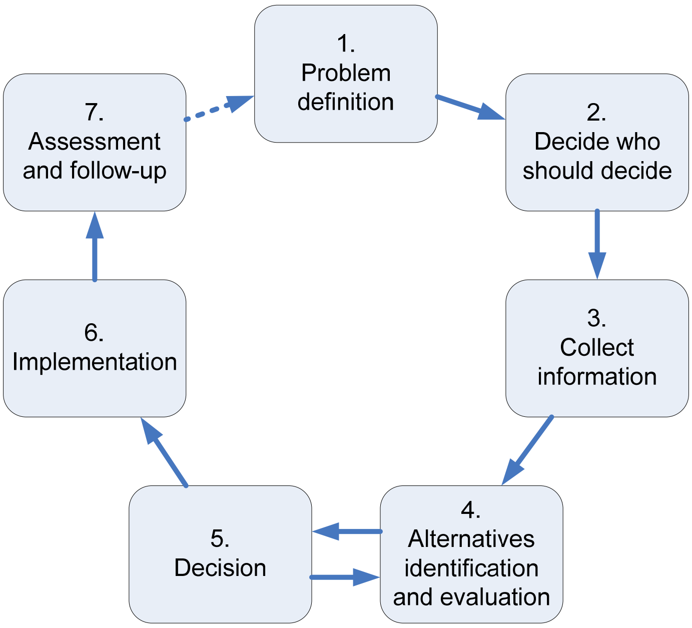
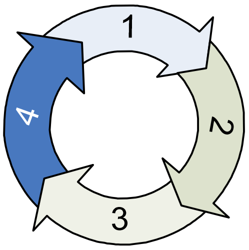


Figure 6-1 A general decision process model (adapted from [43])

A thorough description of this model is done by (Okstad) [46], and it will hence not be discussed in further detail.

According to the StatoilHydro organizational principles [8]: *uncertainty assessment* _is_ *decision support,* and uncertainty management is a fundamental requirement at all levels of the organization [WD0622] [FR08]. The Uncertainty Management Process is, not unlike Figure 6-2, a continuous exercise, but performed in four major steps:



1. Uncertainty identification
2. Uncertainty assessment
3. Response action
4. Response control

Figure 6-2 The StatoilHydro Uncertainty Management Process (from [47]).

The Uncertainty Management Process is an adaption of the *Plan-Do-Check-Act cycle* (as defined by Shewhart and modified by Deming [7]) and requires that uncertainty analysis are performed before all decision gates from DG2 and onwards (ref. figure 2-1), and ad-hoc uncertainty analysis can be initiated within a number of areas throughout the project phases.

6.5 Categorization of decisions

According to (Sage & Armstrong Jr.) [45], decision assessment efforts may be subdivided into five types:

1. Decision under certainty
2. Decision under probabilistic uncertainty
3. Decision under probabilistic imprecision
4. Decision under information imperfection
5. Decision under conflict and cooperation

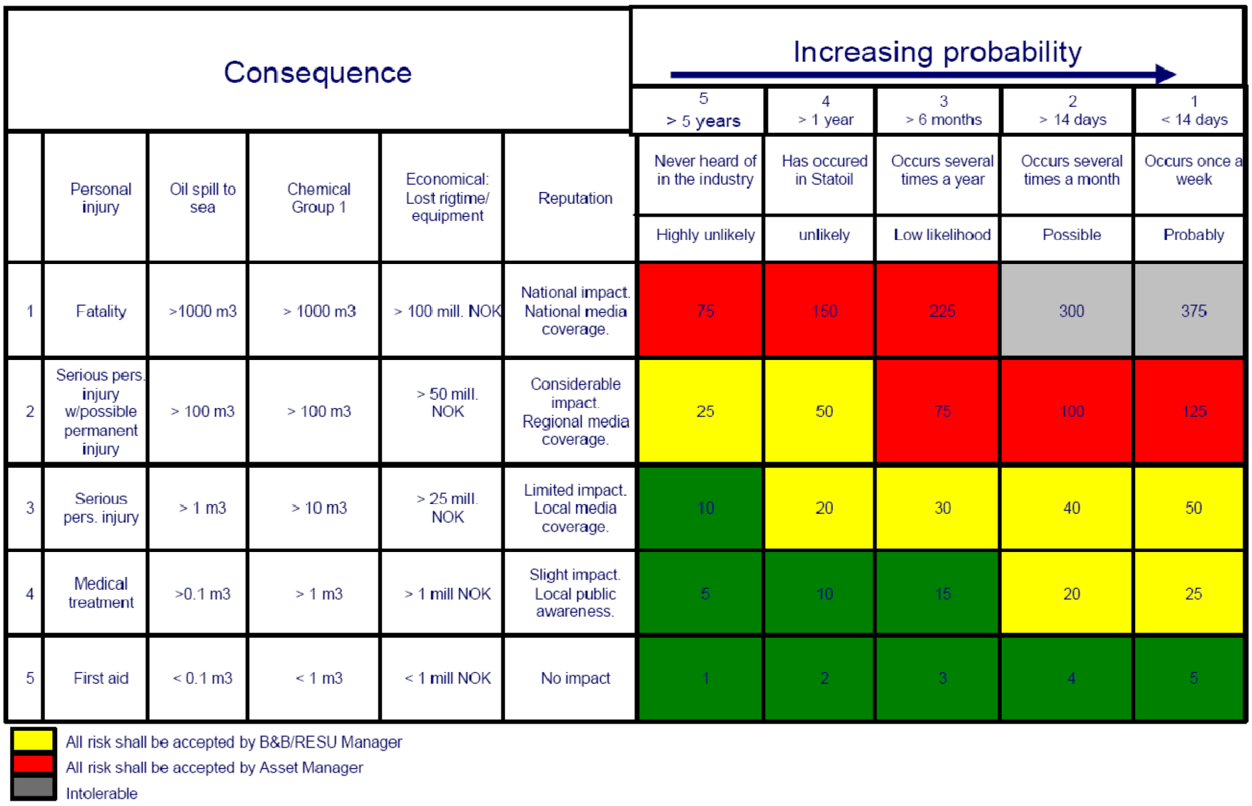
6.5.1 Decision under certainty

Decision under certainty implies that the decision maker has perfect knowledge about the alternative actions and the respective outcomes. Each alternative action results in one and only one outcome and that outcome is sure to occur. Such decisions are simple for a manager to make, but rare. This category is of minor relevance to the current problem context (well planning and subsurface data acquisition) were most decisions are taken under risk or uncertainty.

6.5.2 Decision under probabilistic uncertainty

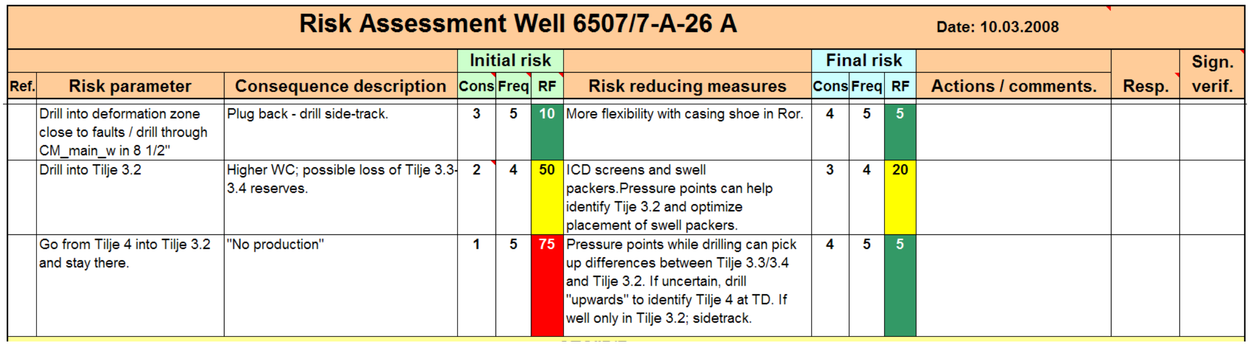
Decision under probabilistic uncertainty are issues in which one of several outcomes can result from a given action. The values of each outcome and the corresponding probabilities for each outcome are known. This category is also referred to as *decision under risk.* In a well planning context, this category is most common in situations where the outcome of the decision is difficult to evaluate quantitatively. Examples are identified hazards related to occupational risk, risk to the environment or risk to the reputation of the company. In such cases qualitative risk assessments methods (for example HAZOP) may be useful to highlight the effects of decisions of a technical or operational character. Table 6-1 shows the StatoilHydro risk matrix used for planning of drilling and well operations:

Table 6-1 Drilling, Well and Production Technology risk acceptance matrix with risk factors (from [42])



Consequence						Increasing probability				
						5 > 5 years	4 > 1 year	3 > 6 months	2 > 14 days	1 < 14 days
	Personal injury	Oil spill to sea	Chemical Group 1	Economical: Lost rigtime/ equipment	Reputation	Never heard of in the industry	Has occured in Statoil	Occurs several times a year	Occurs several times a month	Occurs once a week
						Highly unlikely	unlikely	Low likelihood	Possible	Probably
1	Fatality	>1000 m3	> 1000 m3	> 100 mill. NOK	National impact. National media coverage.	🟥 75	🟥 150	🟥 225	▨ 300	▨ 375
2	Serious pers. injury w/possible permanent injury	> 100 m3	> 100 m3	> 50 mill. NOK	Considerable impact. Regional media coverage.	🟨 25	🟨 50	🟥 75	🟥 100	🟥 125
3	Serious pers. injury	> 1 m3	> 10 m3	> 25 mill. NOK	Limited impact. Local media coverage.	🟩 10	🟨 20	🟨 30	🟨 40	🟨 50
4	Medical treatment	>0.1 m3	> 1 m3	> 1 mill NOK	Slight impact. Local public awareness.	🟩 5	🟩 10	🟩 15	🟨 20	🟨 25
5	First aid	< 0.1 m3	< 1 m3	< 1 mill NOK	No impact	🟩 1	🟩 2	🟩 3	🟩 4	🟩 5

🟨 All risk shall be accepted by B&B/RESU Manager
🟥 All risk shall be accepted by Asset Manager
▨ Intolerable



Risk Assessment Well 6507/7-A-26 A Date: 10.03.2008

			Initial risk				Final risk					
Ref.	Risk parameter	Consequence description	Cons	Freq	RF	Risk reducing measures	Cons	Freq	RF	Actions / comments.	Resp.	Sign. verif.
	Drill into deformation zone close to faults / drill through CM_main_w in 8 1/2"	Plug back - drill side-track.	3	5	🟩 10	More flexibility with casing shoe in Ror.	4	5	🟩 5			
	Drill into Tilje 3.2	Higher WC; possible loss of Tilje 3.3-3.4 reserves.	2	4	🟨 50	ICD screens and swell packers.Pressure points can help identify Tije 3.2 and optimize placement of swell packers.	3	4	🟨 20			
	Go from Tilje 4 into Tilje 3.2 and stay there.	"No production"	1	5	🟥 75	Pressure points while drilling can pick up differences between Tilje 3.3/3.4 and Tilje 3.2. If uncertain, drill "upwards" to identify Tilje 4 at TD. If well only in Tilje 3.2; sidetrack.	4	5	🟩 5			

Figure 6-3 Example from a risk assessment sheet (from StatoilHydro internal document).

Figure 6-3 shows an actual example from a risk assessment during a well planning process, and it indicates how the risk acceptance matrix is used. Due to the geological uncertainty in the area, there is a chance of drilling into the wrong formation (water-filled), hence the consequence would be "No production". The consequence was estimated as a 1 (Economical loss > 100 MNOK) but at the frequency of 5 (Highly unlikely). The 75 point risk factor was a "red" risk, and some action was required to reduce this number. It was then decided to include formation pressures while drilling in the data acquisition program. Based on the extra information provided from these measurement, the wrong formation would be identified at an early stage and the well could be steered back into the right reservoir. After the risk reducing measure was added, the risk factor was reduced to 5 - "green".

Risk assessment advantages includes:

- Well known procedure (standard procedure, standard documentation). Risk assessments are required during the well planning process.
- Risk assessment document is used as a risk register. New risks are added as they are identified during the process. This provides a good overview for the decision makers, and an effective method for communicating identified risk parameters to the management.
- Risk acceptance criteria [48] are established at a corporate level and are the same throughout the organization.

Risk assessment disadvantages include:

- Consequence and probability estimation could be biased by decision makers being subjective.
- Not feasible for decisions not regarding economy or HSE related risks. (How to quantify the impact or consequence of poor data quality?)

6.5.3 Decision under probabilistic imprecision

Decision under probabilistic imprecision are issues in which one of several outcomes can result from a given action depending on the state of nature, and these states occur with unknown or imprecisely specified probabilities. The decision situation structural model is established and is correct. There are outcome uncertainties, and the probabilities associated with the uncertainty parameters are not all known precisely. This category could also be referred to as *Decision under aleatory uncertainty.*

6.5.4 Decision under information imprecision

Decision under information imprecision are issues in which one of several outcomes can result from a given action depending on the state of nature, and these states occur with imperfectly specified possibilities. The decision situation model is established but may not be fully specified. There are outcome uncertainties, and the possibilities associated with these are not all known precisely. Imperfections in knowledge of the utility of the decision maker for the various event outcomes may exist as well. This category could also be referred to as *Decision under epistemic uncertainty.*

6.5.5 Decision under conflict and cooperation issues

Decision under conflict and cooperation issues are those in which there is more than one single decision maker, and where the objectives and activities of one decision maker are not necessarily known to all decision makers. Further, the objectives of the decision makers may differ. This type of decision is not regarded as relevant for the current problem context, and therefore not mentioned further.

6.5.6 Decision under uncertainty

When combining the two types of decisions previously mentioned; decision under probabilistic imprecision and decision under information imprecision, they are commonly referred to as *decision under uncertainty.* The decision-maker does not have enough information to estimate the probability of the potential outcomes. Decision under uncertainty is probably the most challenging type of decision assessment, and unfortunately; most decisions regarding well planning and subsurface activities would fall into this category [BP 3D res modeling].

6.5.6.1 Decision trees

A decision process may involve decision-making over several time periods under conditions of uncertainty, or there may be several succeeding decisions, where decisions to be made are dependent on or determined by the outcome of their predecessors. Decision-making problems of such “dynamic nature” may be visualized and analysed by use of decision trees [44].
A decision tree uses generally two types of nodes: choice or decision nodes (represented as squares) and event or chance nodes (represented as circles). In addition, terminal nodes (or end nodes) are used to represent the end of the decision process (or the end of a particular branch of the decision tree). Terminal nodes are usually represented as short vertical lines, or as in the following example (figure 6-4), as triangles or “arrowheads”.

Some general rules applies for constructing decision trees [44]:

1. Branches extending from a choice node must be constructed so that the decision-maker has only one option.
2. Outcomes from chance nodes are both mutually exclusive (only one of the possible outcomes can occur) and collectively exhaustive (all possible outcomes are represented).
3. All possible paths available are fully mapped in a tree, including all possible choices and uncertainty outcomes.
4. The decision tree must be constructed to depict an accurate chronology of events over time.

From left to right, a typical decision tree begins with a choice node, followed by subsequent choice nodes or uncertainties that must be resolved until the decision tree accounts for all possible paths.

A simple, but informative decision tree for choosing data acquisition method based on expected cost is shown in figure 6-4. The model is prepared in Microsoft Excel and the PrecisionTree add-on software from Palisade.

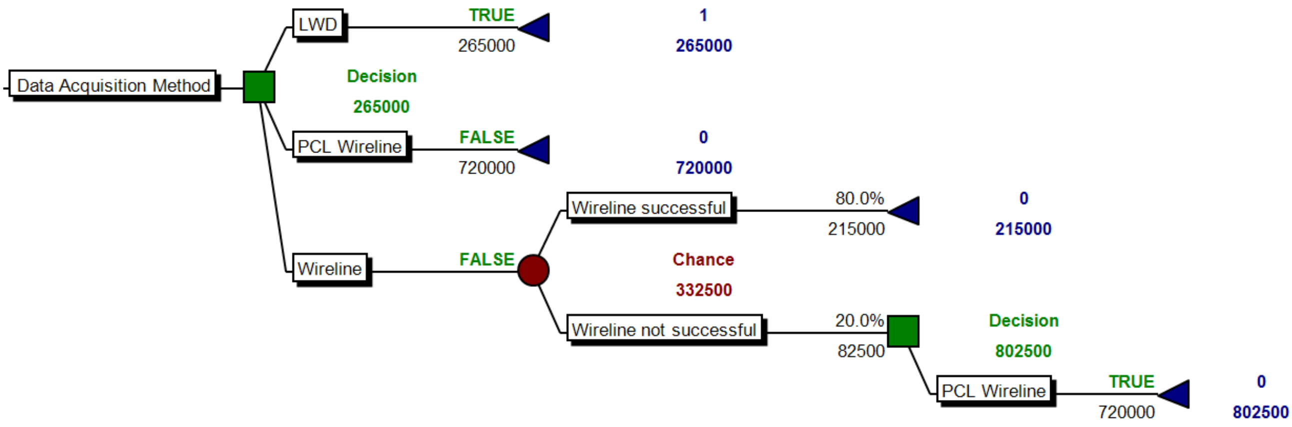


Figure 6-4 Decision tree for choosing data acquisition method based on expected cost.

Table 6-2 Input parameters (unrisked run charges and time estimates for the different data aquisition methods).

Rig cost (24 hour charge)	300000	USD
LWD logging		
Equipment rental / rig up charge	180000	USD
Run / logging charge	35000	USD
Additional rig time due to operation	4	hours
Rig time cost due to operation	50000	USD
Expected cost LWD logging	**265000**	**USD**
Wireline logging		
Equipment rental / rig up charge	50000	USD
Run / logging charge	40000	USD
Additional rig time due to operation	10	hours
Rig time cost due to operation	125000	USD
Expected cost wireline logging	**215000**	**USD**
Pipe conveyed logging		
Equipment rental / rig up charge	80000	USD
Run / logging charge	40000	USD
Additional rig time due to operation	48	hours
Rig time cost due to operation	600000	USD
Expected cost PCL wireline logging	**720000**	**USD**
Cost of unsuccessfull Wireline logging		
Equipment rental / rig up charge	20000	USD
Run / logging charge	24000	USD
Additional rig time due to unsuccessful operation	5	hours
Rig time cost due to unsuccessful operation	62500	USD
Expected cost of unsuccessful operation	**82500**	**USD**
Probability to succeed with wireline (without PCL)	80 %	

The decision tree model is based on the following assumptions:

- Tools are available for all methods considered (LWD, wireline and pipe conveyed logging)
- Data quality is adequate for all methods
- Hole quality/stability is fair.
- LWD and pipe conveyed logging success rate is high (100%)
- Probability for wireline success is depending primarily on wellbore inclination and tortuosity (as the wellbore inclination/tortuosity increases, the probability for success decreases!)
- In case of an unsuccessful wireline operation (not able to get tool string down to the zone of interest):
    - Pipe conveyed logging is to be performed.
    - Wireline run/rig up charge will still be applied for the attempt.

NB! The numbers stated in this example are not real figures as the contract/service prices are confidential. The model presented is generic and hence applicable to most wells. More details could easily be added to the model, but during the well planning phase, the lack of information about the project and the outcome of the well makes a higher degree of detail and sophistication hard to justify and hard to quantify.

Based on the outcome of the decision tree in figure 6-2, the decision-maker can make the following conclusion:

- Wireline has the lowest expected cost (un-risked) of USD 215 000.
- Pipe conveyed logging has by far the highest expected cost, mainly due to the time consumption (USD 720 000).
- After the wireline operation has been risked (since there is a fair chance for not succeeding) , the cost has increased to USD 332 500. In this example, based on cost alone, LWD logging is the best option (USD 265 000).

Decision tree advantages include:

- Decision trees provide a good visual overview of the problem, including the relationship and the timing among the problem elements.
- Decision trees may deal with more complex situations in a compact form.
- The expected value of the input data can be estimated and shown for each decision and accumulated through the tree. This also provides easy measures for sensitivity analysis, e.g., by varying the likelihood probabilities of events.

Disadvantages include [46]:

- As a decision context becomes more complicated, the size of the decision tree will increase exponentially and hence become very complex.
- A common mistake during the decision tree construction process is that decision nodes and chance nodes are placed in the wrong order.
- Incorrect probability values are common as chance probabilities may depend on each other and previous decisions.
- The estimated scenario probabilities are often based on subjective evaluations.
- The residual uncertainty within each scenario might be ignored.
- Every decision represents a discrete set of alternatives.

6.5.6.2 Influence diagrams

An influence diagram is a simple method of graphically modeling a decision [44]. The diagram consists of nodes connected by arrows or directed arcs (figure 6-5). Circle nodes represent events (chance), an activity that results in an outcome that is not necessarily known at the start of the decision process. Rectangular nodes represent decisions (further; rounded-corner rectangular nodes indicate final or intermediate values). Solid arrows point to uncertainties and objectives and represent a relationship of relevance. (indicates that the predecessor is relevant for assessing the value of the succeeding component). Dashed arrows only point to decisions and indicate that a decision was made with knowledge of the outcome of the predecessor node. One characteristic of the influence diagram is that, when properly constructed, it has no cycles; regardless of the starting point in the diagram, no path will lead back to this point – the arrows form a one way path.

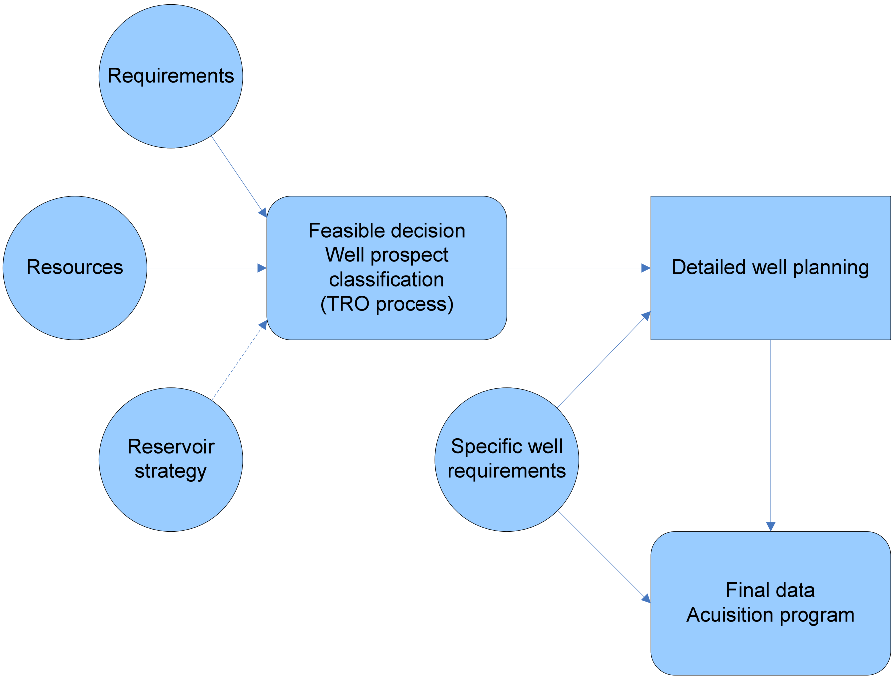


Figure 6-5 Data acquisition planning process presented as simple influence diagram.

Influence diagrams may be used as a simple method for graphically modelling a decision. As such, the diagrams represent what the decision-maker knows or does not know at the particular instant of time. Although the influence diagram is an excellent tool for modelling the structure of a particular decision context, it does not allow for the depiction of many of the details associated with the decision at hand.
Further limitations to the method includes [46]:

- The influence diagram is not a flow chart used to depict a sequence of events in a decision process that leads to the determinated of some decision.
- It is not a precedence diagram that depicts the order in which activities must be executed, nor does it depict the timing of decisions and their consequence in a decision process.

Influence diagrams were found to be of little value in a well planning context due to the limitations mentioned above. Further, influence diagrams provide very little decision support to the managers. In a well planning and operational context, the decision flowcharts are far more useful.

6.5.6.3 Flowcharts

A *flowchart* (even if not described as a separate decision making method) is a structural model of the decision process visualizing the events by different type of nodes, and sequence of events or the event dependencies are shown as arrows.
One of the advantages is that a flowchart can be formalized and approved, for instance ahead of a time critical operation. The time spent decision-making during the operation is hence reduced to a minimum, as the decisions based on the different outcomes are already done.

As is the case with decision trees, a flowchart must be collectively exhaustive, all possible choices and outcomes must be included and it must depict an accurate chronology of the events. An example of a flowchart for selecting data acquisition method is shown in figure 6-6.

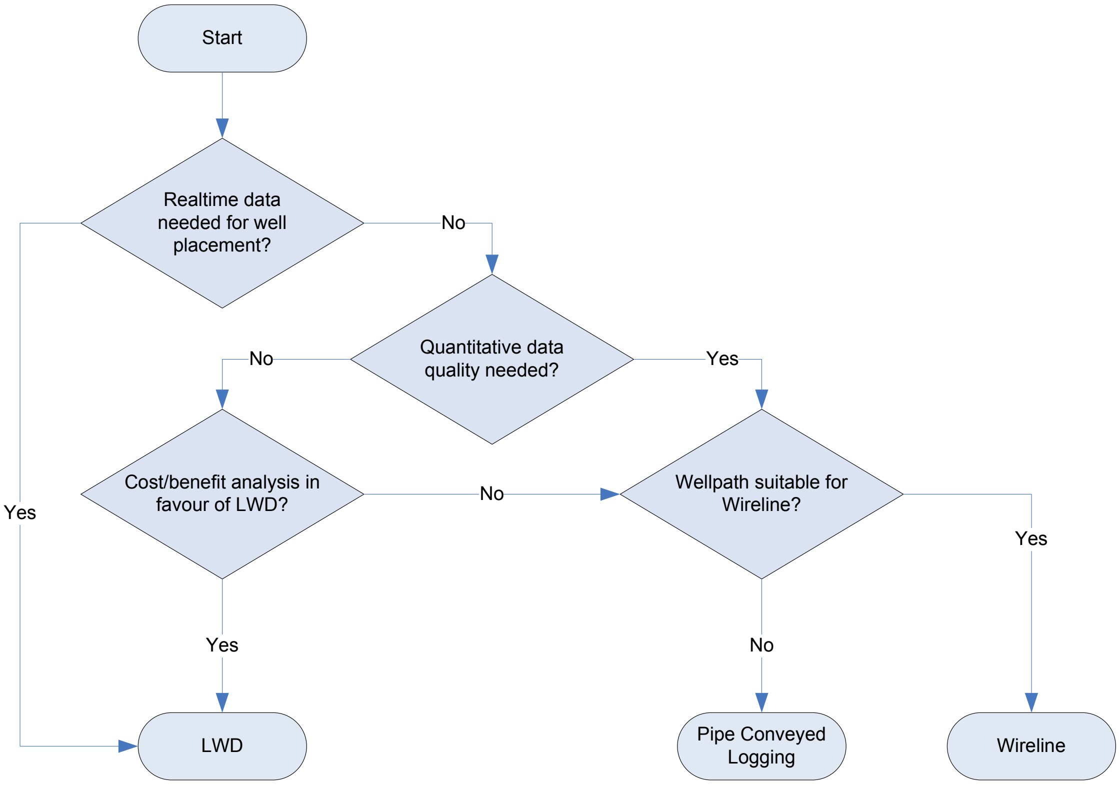


Figure 6-6 Data acquisition method selection flowchart.

In many well planning scenarios, the planned wellpath is a limiting factor, directly disqualifying wireline as a possible data acquisition method. The proposed model (figure 6-6) could be used early in the planning process to highlight obvious well issues.

Note:
The model in figure 6-4 is assuming that no special services/measurement not provided by LWD is required. Further, if realtime data is needed for well placement and high quality data is needed, a separate logging run after the well is drilled must be considered.

6.5.6.4 Simulations

Simulations are regarded as a specialized type of modeling tool, usually needed when the problem under investigation is too complex to be evaluated using optimization models. One of the challenges regarding this method is that most problem structures do not fall into a strictly deterministic or probabilistic realm. Another issue raised is that most quantitative models are simplifications of the reality, while simulation models try to imitate reality with some fewer simplifications.

Simulations, including an example of the applicability in a well planning/petrophysical context as well as the benefits and disadvantages are described in chapter 5.4.

6.6 Multi-Criteria Decision Making

Multi-criteria decision making (MCDM) is associated with multiple attributes (also referred to as multiple "*goals*" or *"decision criteria"*. Or in other words: given a set of alternatives and a set of decision criteria, what is the best alternative?

Although there are several multi-criteria decision methods available, there are many similarities between them. A comparative study of several MCDM methods has been done by (Triantaphyllou) [49].

This thesis is focusing on the Analytical Hierarchy Process (AHP), mainly because it is one of the widely most used methods today, but not at least due to the fact that there are several MCDM software solutions (including free demo-versions) available based on the AHP method.

The AHP method was tested in a data acquisition planning context, using the ExpertChoice 11 software (www.expertchoice.com)

6.6.1 The Analytical Hierarchy Process

The AHP *(Analytical Hierarchy Process)* was developed by Saaty [50]. The process can be characterized as a muti-criteria decision technique that may combine qualitative and qualitative factors in the overall evaluation of alternatives. The two basic features of the AHP are the formulation of the problem as a hierarchy and the judgment in form of pairwise comparisons.

6.6.1.1 *Creating the hierarchy*

The process starts by decomposing a complex, multi-criteria problem into a hierarchy of at least three levels; The hierarchy has at least three levels:

- Top level: Overall goal of the problem / objective
- Middle level: Multiple criteria that define alternatives
- Bottom level: Competing alternatives

where each level consists of a few manageable elements which are further decomposed into another set of elements (the next level of the hierarchy).

Refer to figure 6-7 for an example of a hierarchy of criteria and alternatives as devised by the AHP method. The goal is obtain an optimized data acquisition program based on the four different decision criteria; data quality, HSE perspective, cost and operational complexity issues. The alternatives are (as always): Wireline, pipe conveyed logging and LWD.

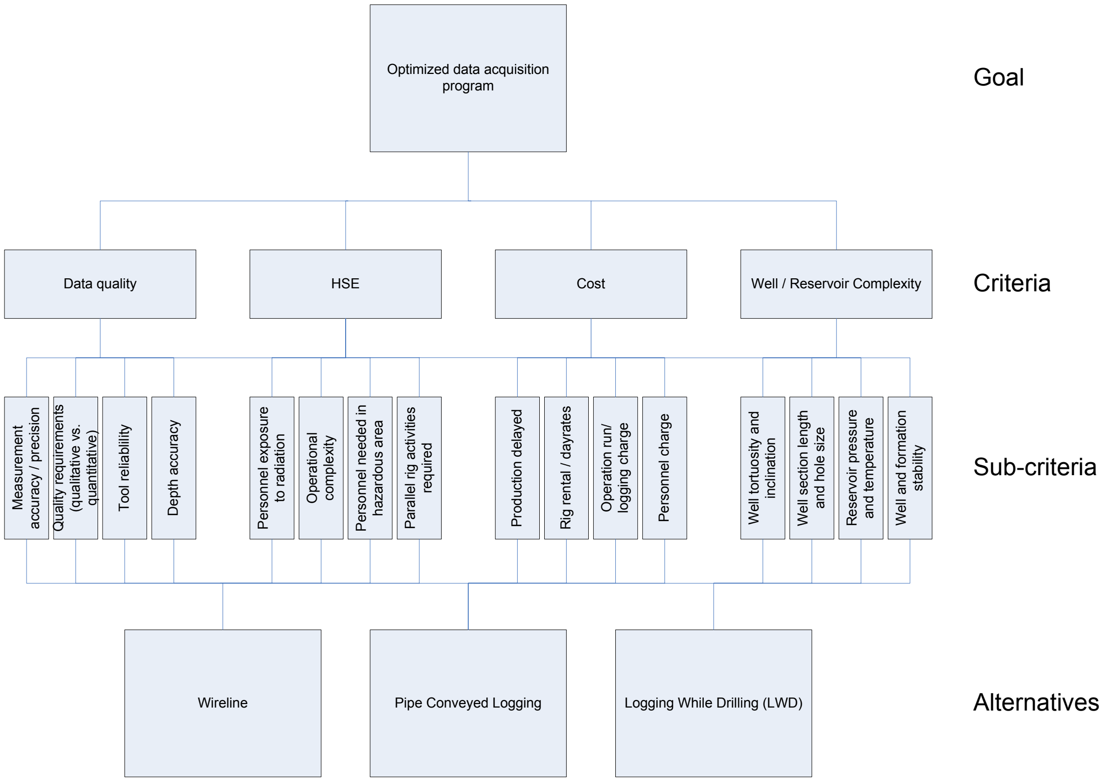


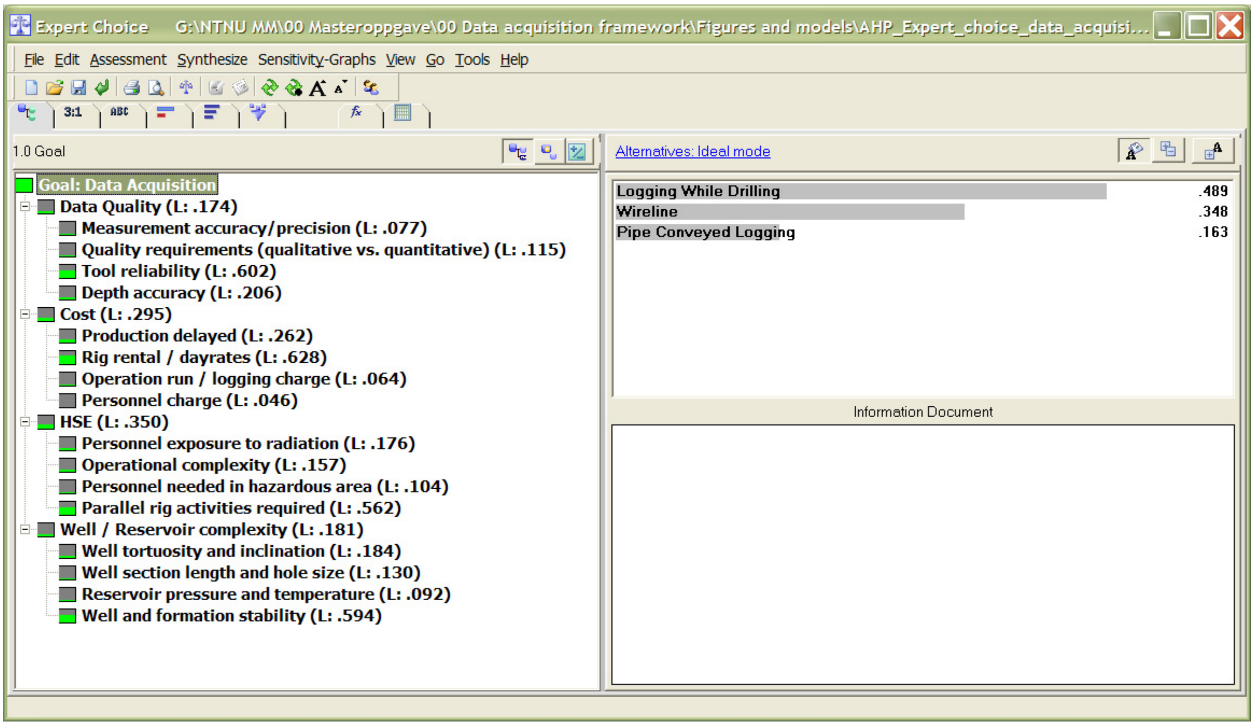
Figure 6-7 Example of a hierarchy of criteria and alternatives as devised by the AHP method.

6.6.1.2 *Comparative judgements*

The next step of the AHP analysis is to assign priorities for each element in the hierarchy. The priorities are set by comparing each set of elements in a pairwise fashion with respect to each of the elements on a higher level. The priorities may be based on objective, quantitative data or on subjective, qualitative judgements.

This procedure is repeated at each level in the hierarchy, comparing each set of elements on the same hierarchy level with respect to each level on the level immediately above until the bottom of the hierarchy is reached (including a pairwise comparison of the alternatives).

Using the hierarchy in figure 6-7, a pairwise comparison of the elements on the Criteria level with respect to the goal, this implies performing (n^2-n)/2 comparisons = 6 comparisons (n = 4). Further, a pairwise comparison of the sub-criteria level with respect to the corresponding element on the criteria level implies another 4 times 6 comparisons (4 criteria, 4 sub-criteria). Finally, a pairwise comparison of the alternatives to each sub-criteria involves another 16 times 3 comparisons.
In total, the fairly simple and small hierarchy proposed requires 6 + 24 + 48 = 48 comparisons.
The pairwise comparison is used to determine the relative importance of each alternative in terms of each criterion. When all judgements are synthesized, a relative *Vector of Overall Priorities* [50] for each element at all hierarchy levels are made, stating the relative importance of that element. The overall principle of the method is that the alternative with the highest priority with respect to the goal is the preferred one.
A screen shot of the main result of a full pairwise comparison of the hierarchy presented above is presented in figure 6-8.



- Goal: Data Acquisition
  - Data Quality (L: .174)
    - Measurement accuracy/precision (L: .077)
    - Quality requirements (qualitative vs. quantitative) (L: .115)
    - Tool reliability (L: .602)
    - Depth accuracy (L: .206)
  - Cost (L: .295)
    - Production delayed (L: .262)
    - Rig rental / dayrates (L: .628)
    - Operation run / logging charge (L: .064)
    - Personnel charge (L: .046)
  - HSE (L: .350)
    - Personnel exposure to radiation (L: .176)
    - Operational complexity (L: .157)
    - Personnel needed in hazardous area (L: .104)
    - Parallel rig activities required (L: .562)
  - Well / Reservoir complexity (L: .181)
    - Well tortuosity and inclination (L: .184)
    - Well section length and hole size (L: .130)
    - Reservoir pressure and temperature (L: .092)
    - Well and formation stability (L: .594)

Logging While Drilling	.489
Wireline	.348
Pipe Conveyed Logging	.163

Figure 6-8 Screen shot from the ExpertChoice software showing the elements of the hierarchy and the calculated Vectors of Priorities.

6.6.1.3 *Conclusions on the AHP method*

According to (Saaty) [50], a decision making approach should have the following characteristics:

- Be simple to construct
- Be adaptable to both groups and individuals
- Be natural to our intuition and general thinking
- Encourage compromise and consensus building

- Not require inordinate specialization to master and communicate.
- The details of the processes leading up to the decision-making process should be easy to review.

The range of application for the AHP method in the well planning context is considered to be low with few of the characteristics mentioned above being descriptive for the process. The process is rather detailed and time consuming, even when the hierarchy is simple. Further, the calculated results are perceived as rather ambiguous and are not easily communicated to the managers. The method is hence not included in the framework.

6.7 Conclusions on decision support processes

A selection of decision-making methods anticipated to be of value in the development well planning process has been reviewed. A subjective comparison of the methods with regards to their applicability in a well planning/data acquisition planning context is shown in table 6-6

Table 6-3 Comparison of reviewed decision making methods.

	Decision trees	Influence diagrams	Flowcharts	Simulations (Monte Carlo)	MCDM (AHP)
Method easy to learn	**	**	**	*	*
Model easy to construct	*	**	**	*	*
Adaptable to the decision context	***	*	***	***	**
User-friendliness	**	**	**	*	*
Results easy to communicate	****	*	**	***	*
Utility value	***	*	**	****	*

* Low
** Moderate
*** High
**** Very high

7 The Framework

This proposes a decision framework for data acquisition in the development well planning process and its applicability in the described context is briefly covered.

7.1 Contribution to the well planning process

Based on the conclusions from the previous chapters, a general data acquisition framework that fits the needs of the Heidrun Petec organization can be constructed. It is evident that a thorough knowledge of the data acquisition processes in general, including the strengths and limitations of the different acquisition methods is important. Very often, physical limitations and specific well requirements are qualifying one type of data acquisition while disqualifying other methods directly. If these limitations and requirements are identified and assessed early in the well planning process, the data acquisition program can be finalized and approved in a short amount of time. The proposed framework proposed is emphasizing these issues.

In situations where the planning process is not that straight forward, the tools and techniques described in this thesis could be utilized to support the planning process and improve the decision-making.

A general workflow representing the final decision framework for data acquisition planning is proposed in table 7-1.

The methods discussed in the proposed framework have been used both in previous and ongoing well planning processes (also shown by the examples and models included in this report), and the methods were found to be useful in the well planning context. Especially, decision trees and Monte Carlo simulation models have shown to have a wide range of application, not only for the petrophysicist, but also for other disciplines in the well planning team.

7.2 The Framework

Table 7-1 Data Acquisition Planning Workflow

TRO Phase	1	Use **Flowchart for classifying wells as type A, B or C** (table 3-2) to classify well prospects according to data acquisition requirements.
	2	Identify well candidates for pilot wells, coring and special data services.
Well Planning Phase	3	Identify and assess specific well requirements and limitations, disqualify acquisition methods and log measurements incompatible with identified constraints. Refer to chapter 4 as well as appendix C, **Comparison of logging methods**.
	4	Identify needs and requirements from other disciplines in the well planning team. Check compatibility with well constraints.
	5	Refer to **Principal uses of borehole data** (table 4-4) to identify what type of services that fulfill the requirements and needs with regards to both data type and quality.
	6	Use the **Data acquisition method selection flowchart** (figure 6-9) to select primary logging method (or disqualify other methods)
	7	Use the **simulation model** to run what-if / sensitivity analysis at expected reservoir conditions. Are conditions expected to provide the requested data quality? If no, should the acquisition program be changed to take this fact into consideration (simplified or extended?)
	8	If more than one option is still qualified (LWD, wireline, pipe conveyed logging) make risked cost estimate using a **decision tree** (figure 6-5) and evaluate the outcome.
	9	Finalize data acquisition program.
Drilling Phase	10	Prepare a **flowchart** describing what to do in case of a tool-failure (when to pull out of hole to change the tools?)
	11	Use the **simulation model** during drilling to perform real-time data quality assessment.

8 Discussions and conclusions

This chapter discusses the main result of the master thesis project and draws some conclusions regarding the application of the framework. Finally, recommendations for further work are outlined.

8.1 Discussion of the main results

The main objective of this master thesis has been to develop a decision framework for petrophysical data acquisition in the development well planning process.
Historically, wireline data has been preferred for input into the reservoir models, and was until the 90s the only method of electrical formation evaluation. The introduction of the MWD in combination with the 3D rotary steerable drilling assembly has revolutionized the drilling process, and the need for formation evaluation data real-time for wellbore optimization and geosteering purposes has made a major push in the direction of replacing wireline with LWD logging services. Still today, wireline is referred to as the standard and generally regarded as superior to LWD when comparing the measurement quality.
A stochastic simulation model of the evaluation routine was developed as part of this thesis and it is showing that in the Heidrun field, when adding the increased reservoir uncertainties due to long time production and injection, model and parameter uncertainty might be adding more to the total uncertainty of the evaluation than the actual measurement itself. Further, the difference in measurement accuracy and precision between the different acquisition methods are marginal, and in many cases often smaller in magnitude than the environmental corrections applied to the measurements. This wireline paradigm should hence, be even more challenged as the quality and reliability of modern LWD tools is comparable to that of wireline. More focus should be put on the borehole and logging environment in which the logs are acquired rather than the stated specifications of the different tools and measurements.

A review of existing decision making methods and techniques was performed and their applicability in the described context was discussed. The conclusion is that model-driven decision support systems, including simulations and decision trees are very useful, whereas influence diagrams and Multi-Criteria Decision making methods are not at all applicable in the well planning context.

A decision framework for petrophysical data acquisition in the well planning process was proposed, and the methods described in the framework has been successfully applied to real situations in several, both previous and ongoing well planning processes.

The final and main conclusion is that data acquisition planning should primarily be based on the premises and the nature of the well to be drilled. Very often, physical limitations and specific well requirements are qualifying one type of data acquisition while disqualifying other methods directly.

8.2 Recommendations for further work

It is always possible to improve models and methods, and so is the case for the current framework. The petrophysicists in Heidrun will definitely continue the development and refinement of the simulation model made as a part of this thesis. (The model showed to have a far wider range of application than first anticipated.) Main topics regarding petrophysical work includes:

- LWD depth improvement.
- Resolution enhancement.
- Evaluation model parameters work to reduce uncertainty.
- Review of current NTG calculation routine.
- Governing documentation updates based on the routines changed.

References

1. Western Atlas International Inc., *Introduction to Wireline Log Analysis,* 1992: Houston, TX.
2. Schlumberger, *Log Interpretation Principles/Applications,* 1991: Sugar Land, TX.
3. Rider, M., *The Geological Interpretation of Well Logs,* 2nd ed.*,* 2002: Whittles Publishing, Scotland.
4. Rekdal, A. et. al., *Reservoir Management Plan Heidrun Field,* 2007: HNO HD PTEK 0147, StatoilHydro internal document.
5. Bøklepp, B., *Feasibility Study – Underbalanced Coiled Tubing Drilling Heidrun TLP*, 2006: HNO HD BB 0369, StatoilHydro internal document.
6. StatoilHydro governing document*, Project development,* Function requirement FR05, Final Ver. 3, valid from 2008-07-01.
7. Project Management Institute (PMI), *A Guide to the Project Management Body of Knowledge,* Third Edition, 2004: Project Management Institute, Four Campus Boulevard, Newtown Square, PA.

8. StatoilHydro governing document, *The StatoilHydro book,* Ver. 1, valid from 2007-11-01.
9. StatoilHydro governing document, *Exploration and petroleum technology,* Function requirement FR01, Final Ver. 2.02, valid from 2007-12-19.
10. StatoilHydro governing document, *Drilling and well technology*, Work process, FR03, Final Ver.3, valid from 2008-04-11.
11. Nordby, L.H., et al., *Work Process Description for maturing drilling locations in HD PETEK / B&B*, 2004: HNO HD PETEK 0101.
12. StatoilHydro advisory document, *Construction Process for Development Wells,* Guideline GL1328, Final Ver. 1, valid from 2008-04-03.

13. StatoilHydro governing document, *Geological well data acquisition acquisition in StatoilHydro,* Work process requirement, WR1192, Final Ver. 2, Valid from 2005-06-21.
14. Forne, O., *Loggkvalitetsmanual,* 1990: RESGEO-49-90, Statoil internal.

15. Muri, H. et. al., *Reservoir Management Plan Heidrun Field,* 2006: HNO HD PTEK 0147, StatoilHydro internal document.
16. Skopec, R.A., *Coring and core analysis, 2007:* PetroSkills, LCC, Tulsa, OK.
17. Darling, T., *Well Logging and Formation Evaluation,* 2005: Elsevier, Oxford, UK.

18. Jones, R.D., et al., *IADC/SPE 112616: Troll West Oilfield Development – How a Giant Gas Field Became the Largest Oil Field in the NCS through Innovative Field and Technology Development,* in IADC/SPE Drilling Conference, 2008, Orlando, FL: Society of Petroleum Engineers (SPE).
19. Theys, T., *Log Data Acquisition and Quality Control,* second edition, 1999: Éditions Technip, Paris.
20. Schlumberger, *Schlumberger Wireline Services Catalogue,* 2007: Schlumberger, Sugar Land, Tx.

21. Adams, J.A., Weaver, C.E., *Thorium-uranium ratios as indicators of sedimentary processes: example of concept of geochemical facies,* 1958: Bull, Am. Assoc. Petrol. Geol. 42(2), 387-430.
22. Oretenzi, L., et al., *SPE 77479: An Integrated Caliper from Neutron, Density and Ultrasonic Azimuthal LWD Data*, in SPE Annual Technical Conference and Exhibition, 2002, San Antonio, TX: Society of Petroleum Engineers (SPE).
23. Archie, G.E., *SPE 942054: The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics,* in SPE 1941: Dallas, TX: Society of Petroleum Engineers (SPE).
24. Iversen, M., et al., *Geosteering using ultradeep resistivity on the Grane Field, Norwegian North Sea, in.* SPWLA 44th Annual Logging Symposium, 2003: Society of Petrophysicists and Well Log Analysts (SPWLA).
25. Gravem, T., et al., *SPE 110340: Combining Advanced Real-Time LWD Answers With Accurate and Flexible 3D Rotary-Steerable System for Proactive Reservoir Navigation,* in. SPE Annual Technical Conference and Exhibition, 2007, Anaheim, CA: Society of Petroleum Engineers (SPE).
26. Bordakov, G.A., et al., *SPE 109972: Improving LWD Image and Formation Evaluation by Utilizing Dynamically Corrected Drilling-Derived LWD depth and Continuous Inclination and Azimuth Measurements,* in. SPE Annual Technical Conference and Exhibition, 2007, Anaheim, CA: Society of Petroleum Engineers (SPE).
27. Stevenson, N., Akram, A., *Kristin SmartDepth* Study 8.5" sections,* 2008: StatoilHydro internal document.
28. Brooks, A., et al., *SPE 95611: Quantification of Depth Accuracy,* in. SPE Annual Technical Conference and Exhibition, 2005, Dallas, TX: Society of Petroleum Engineers (SPE).
29. Pedersen, B.K., et al., *Operational Procedures and Methodology for Improving LWD and Wireline Depth Control, Kristin Field, Norwegian Sea, in.* SPWLA 47th Annual Logging Syposium, 2006, Veracruz, Mexico, Petrophysics Vol. 48, No. 2 (April 2007); p. 90-103. Society of Petrophysicists and Well Log Analysts (SPWLA).
30. Dashevskiy, D., et al., *SPE 103094: Dynamic Depth Correction to Reduce Depth Uncertainty and Improve MWD/LWD Log Quality*, in. SPE Annual Technical Conference and Exhibition, 2006, San Antonio, TX: Society of Petroleum Engineers (SPE).
31. Chia, C.R., et al., *SPE 102175*: *A New Method for Improving LWD Logging Depth,* in. SPE Annual Technical Conference and Exhibition, 2006, San Antonio, TX: Society of Petroleum Engineers (SPE).
32. Tollefsen, E., et al., *SPE 108534: Logging While Drilling Measurements: From Correlation to Evaluation,* International Oil Conference and Exhibition, 2007, Veracruz, Mexico: Society of Petroleum Engineers (SPE).
33. Beucher, H. et al., *The effect of methology on volumetric uncertainty estimation in static reservoir models.* AAPG Bulletin, V. 92, No. 10 (October 2008), pp. 1359-1371.
34. Dake, L.P., *Fundamentals of reservoir engineering.* 1978: Elsevier, Oxford, UK.

35. ISO 9000. 2005. *International Standard ISO 9000 – Quality management systems – Fundamentals and vocabulary,* 3rd edition. International Standards Organization, Geneva.
36. Fylling, A., *SPE 77637: Quantification of Petrophysical Uncertainty and Its Effect on In-Place Volume Estimates: Numerous Challenges and Some Solutions,* in. SPE Annual Technical Conference and Exibition, 2002, San Antonio, TX: Society of Petroleum Engineers (SPE).
37. Dietrich, C.F., *Uncertainty, Calibration and Probability – The Statistics of Scientific and Industrial Measurement,* 2nd edition, 1991, Adam Hilger, NY.
38. Agaev, G.S., et al., *Best practice 3D reservoir modelling* Version 1.0, 2008: StatoilHydro internal document.
39. Jordaan, I., *Decisions under Uncertainty – Probablistic Analysis for Engineering Decisions,* 2005: Cambridge University Press, Cambridge, UK.
40. StatoilHydro governing document, *Planning of Drilling & Well Operations,* Work process requirement, WR0442, Final Ver. 4, Valid from 2005-10-24.
41. StatoilHydro governing document, *Risk management,* Work process, FR08, Final Ver. 2, valid from 2007-10-01.
42. StatoilHydro governing document, *Planning of Drilling & Well Operations,* Work process requirement, WR 0442, Final Ver. 4 Valid from 2005-10-24.
43. Power, D.J., *Decision Support Systems, Concepts and Resources for Managers.* 1st ed., 2002: Quorum Books, Westport, CT.
44. Marakas, G.M., *Decision Support Systems in the 21st Century,* 2nd ed., 2003: Prentice Hall, NJ.
45. Sage, A.P., Armstrong Jr., J.E., *Introduction to Systems Engineering,* 2000: John Wiley & Sons, NY.
46. Okstad, E.H., *Decision Framework for Well Delivery Processes,* 2007: Doctoral Theses at NTNU, Norway.
47. StatoilHydro advisory document, *Uncertainty Management in Project,* Work description, WD 0622, Final Ver. 3, Valid from 2005-12-20.
48. Rausand, M., Høyland, A., *System Reliability Theory, Models, Statistical Methods and Applications.* 2nd ed.2004: Wiley-Interscience, USA.
49. Triantaphyllou, E., *Multi-Critera Decision Making Methods: A Comparative Study,* 2000: Kluwer Academic Publishers, The Netherlands.
50. Saaty T.L., *Decision Making for Leaders. The Analytic Hierarchy Process for Decisions in a Complex World,* New Edition, 2001: RWS Publications, Pittsburg, PA, USA.

Appendix A Introduction to the Heidrun field

The Heidrun Field is located on the Halten Terrace in the Norwegian Sea (Figure A-1). The field was discovered by Conoco in 1985 and started production on October 18th 1995. Heidrun is developed with a floating concrete tension leg platform (TLP). The northern part (Heidrun North) was in January 2000 included in the Heidrun unit. This part of the field is developed with subsea facilities. The Heidrun Unit consist of 2 production licenses, and ConocoPhillips Skandinavia, Petoro, Eni Norge and StatoilHydro hold different shares of the licenses [4].

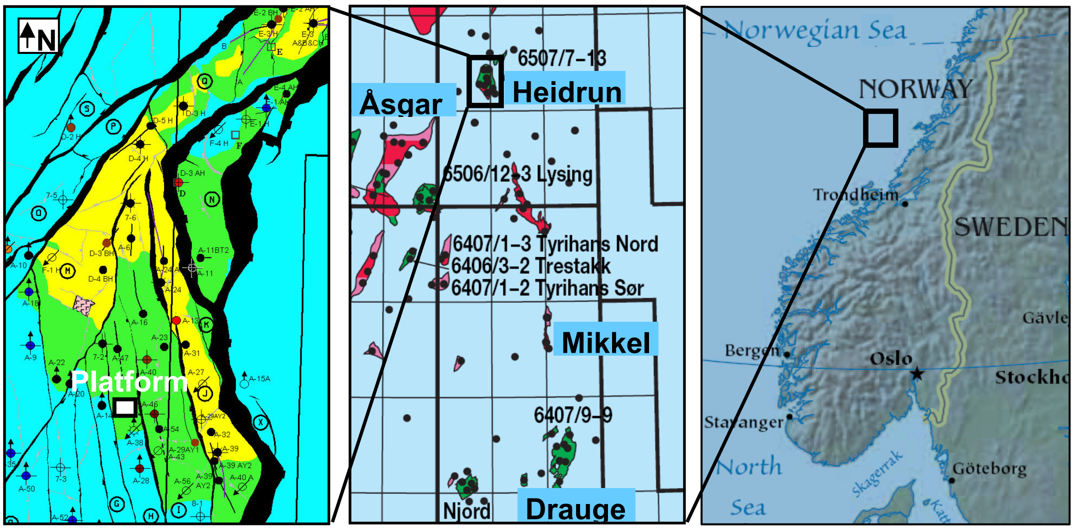


Figure A-1 Heidrun is an oil and gas field located on the Halten Terrace in the Norwegian Sea, north-east of the Åsgard Field. The left figure indicates the original oil (green) and gas (yellow) reserves in the Lower Tilje Formation and Åre Formation.

Total recoverable reserves for the Heidrun field are 186 million Sm^3 of oil and 41.6 billion Sm^3 of gas[1]. As of 01.05.2008, a total of 123.7 million Sm^3 of oil and 8.7 billion Sm^3 of gas have been produced. The gas is exported through Haltenpipe to Tjeldbergodden and through Åsgard Transport pipeline to Kårstø. All excess gas is re-injected into the Fangst formation or used for gas lift.

The Heidrun reservoir consists of sandstones in the reservoir units Fangst Group, the Tilje Formation and the Åre Formation, all of which was deposited in Early and Middle Jurassic age. The reservoir is heavily faulted and compartmentalized by a complex network of faults associated with several stratigraphic barriers. Fangst, which includes the Garn and Ile formations, have good reservoir quality whereas the Tilje and Åre Formations are more complex. The complexity of the field is a challenge when it comes to predicting flow and contact movements. Further, as the Heidrun field is maturing, initial reservoir fluid properties are altered due to hydrocarbon production and water/gas injection and the petrophysical evaluation of the reservoir is becoming more challenging and the interpretation more uncertain.

The Heidrun field has reached a decline from the initial plateau hydrocarbon production (Figure 2) New wells or drainage points planned are continuously focusing on smaller and often bypassed reserve volumes. As these volumes are getting smaller and hence harder both to identify and to hit, the well planning process is becoming more comprehensive and demanding. As the expected hydrocarbon production will continue its decline..

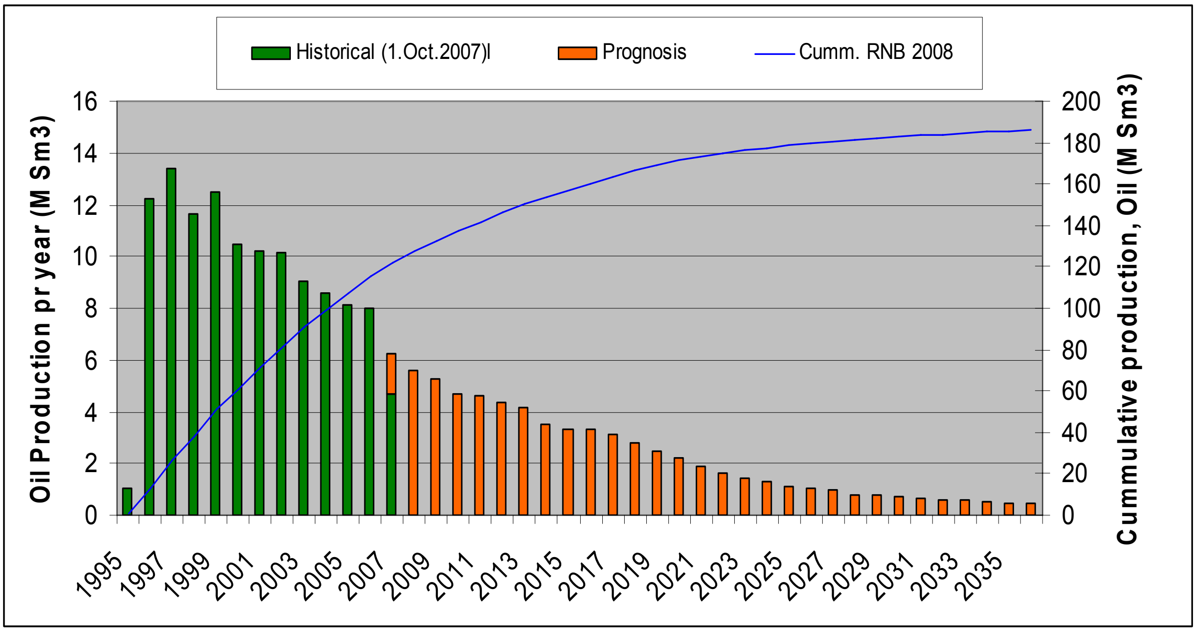


Figure A-2: Heidrun base case profile, oil production. (Source: Reservoir Management Plan Heidrun Field 2007).

Appendix B Acronyms

B&B	Boring & Brønn
BHA	Borehole Assembly
BOP	Blowout Preventer
CVP	Capital Value Process
DDM	Derrick Drilling Machine (Top drive)
DG	Decision Gate
DOI	Depth of investigation
DSS	Decision Support System
DST	Drill Stem Testing
D&W	Drilling & Well
EaRTh	Exploration and Petroleum Technology
EM	Electromagnetic
HD	Heidrun
HSE	Health, Safety & Environment
LWD	Logging While Drilling
MCDM	Multi-Criteria Decision Making
MWD	Measurements While Drilling
NMR	Nuclear Magnetic Resonance
OBM	Oil-Based Mud
OD	Outer Diameter
PETEC	Petroleum Technology
R/A	Radioactive
ROP	Rate of Pentetration (drilling speed)
RTD	Recommendation to Drill
TLP	Tension Leg Platform
TRO	Targeting Remaining Oil
WFT	Well Flow Testing
WL	Wireline
WPT	Well Planning Team

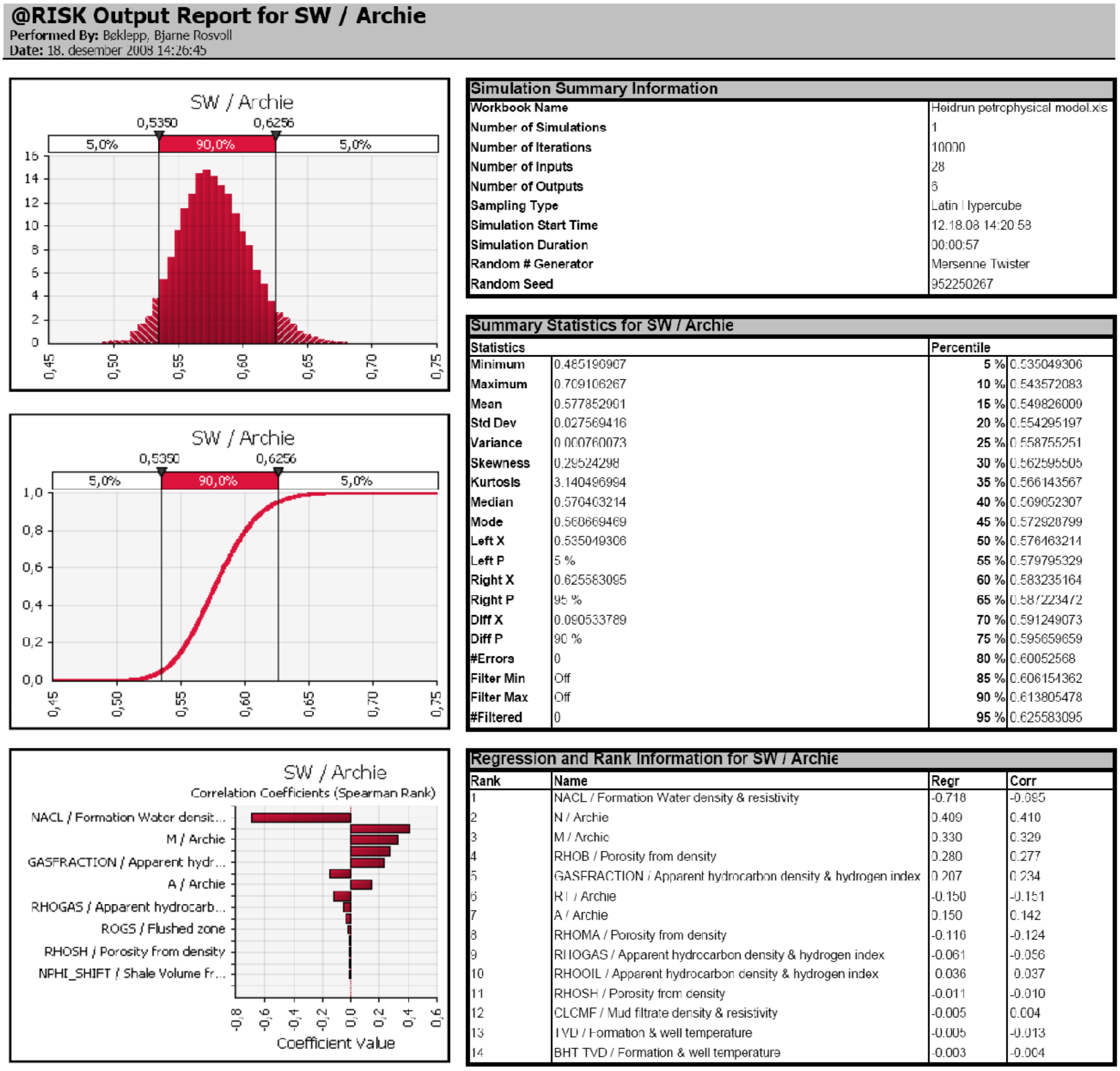
Appendix C Comparison of logging methods

		Wireline		Pipe-conveyed logging (PCL)		Logging While Drilling (LWD)
HSE considerations	+	Neutron R/A source can be replaced with minitron	+	Neutron R/A source can be replaced with minitron	0	Minitron available for a very limited selection of BHAs. R/A sources still common
	-	Sheave wheels and cable rig-up in derrick	-	Sheave wheels and cable rig-up in derrick	+	No extra surface rig up needed
	0	Upper sheave wheel can be hung in top drive	-	Personnel in riding belt on drill floor usually needed during rig up of sheave wheels		
	-	Logging cable over pipe deck. Limitations on crane acticity	-	Logging cable over pipe deck. Limitations on crane acticity		
	-	Risk for breaking logging cable - hHazardous area" on drill floor / around cable.	-	Risk for breaking logging cable - "hazardous area" on drill floor / around cable.		
	-	Extra exposure of personnel on drill floor (longer stay in hazardous area) if fishing (stuck logging string operation)	--	Risk of damaging (pinching or kinking) cable at during operation when setting / pulling slips during pipe connections.		
	-	No well circulation possibilities during the operation	0	Limited circulation possibilities during the operation	+	No limitations on circulation
	+	Well control systems/barriers not impaired during the operation	+	Well control systems/barriers not impaired during the operation	++	Normal drilling routines
Time consumption / Cost	+	Quick to rig up / down	-	Slow to rig up / down	-	Slow to rig up / down additional tools/subs in BHA. Memory downloading on drill floor
	-	Requires several runs due to weight limitations, but decreases complexity of tool string	+	No limitation on weight of tool string	+	No limitation on weight of tool string
	+	Quick to run in and out of the well, quick and continuous (non-stop) logs	-	Very slow to run	+	Included in drilling BHA (logging performed while drilling)
	+	Quick to re-run if tool failure	-	Very slow to re-run if tool failure	-	Very slow to re-run if tool failure
	+	Quick to re-log (if needed)	-	Slow to re-log if needed	-	Very slow to re-log if real time data is needed at high data density. Somewhat faster if only memory data is needed
	+	Monitoring of toolstring status while running in hole (full tool communication)	-	No monitoring of tool string status while running in hole. Tool status not available before cable is connected to tool string	0	Tool string status possible if pumping through drill string at normal flow rates (same as during drilling)
	-	Extra rig time spent on logging	--	A lot of extra rig time spent on logging	+	Little extra rig time spent on logging
					-	Data acquisition may be a limiting factor on drilling rate / ROP

	++ Lowest operational cost of all methods	+ Low operational cost	- High operational cost
Data Quality	+ Good data quality (generally first choice) - Formation alteration possible (long time from formation is drilled until logged) + Good depth control (absolute and relative depth) - Data acquired after well is drilled + Most log measurement types available for all hole sizes + Continuous logging through entire interval (constant speed / cable stretch) - No images from Density / GR / deep Resistivity + Static logging environment + Mud invasion stabilized	+ Good data quality - Formation alteration possible (long time from formation is drilled until logged) 0 Fair absolute depth control - Data acquired after well is drilled + Most log measurement types available for all hole sizes - Discontinuous logging (stop to make pipe connections) - No images from Density / GR / deep Resistivity + Static logging environment + Mud invasion stabilized	+ Generally good data quality + Formation alteration minimized (short time from formation is drilled until logged) 0 Fair absolute depth control ++ Data acquired while drilling allowing proactive use of the data for well optimization - All tool types not available for all hole sizes - Discontinuous logging (stop to make pipe connections) + Image logs from Density / GR / deep Resistivity possible - No fluid sampling / downhole fluid analysis available - Poor quality of shear sonic measurements - Dynamic logging environment 0 Mud invasion possibly very shallow, but unknown/ongoing
Data Quality / Tool power	+ Continuous supply of power from the surface throughout the operation. + Stable / constant output from power supplies + Generally not limited by power	+ Continuous supply of power from the surface throughout the operation. + Stable / constant output from power supplies + Generally not limited by power	- Discontinuous power (from downhole turbine). Tools are switched off when pumps are off, i.e. tools rebooted at each pipe connection. - Power output somewhat fluctuating (depending on and varying with flowrate). Internal tool power control/adjustments more challenging. - Potentially limited by power (max turbine output) if several high-power consuming services are run in combination - Limited operating time if batteries are used instead of turbines. Battery lifetime/output also highly dependant on downhole temperature.

Resources	- Lot of extra equipment on rig; wireline/winch unit, rig-up equipment. Deck space needed - Full wireline crew (6 persons) - Other (parallel) rig activities restrained due to lack of deck space / extended hazardous zone area during cable operations	- Lot of extra equipment on rig; wireline/winch unit, rig-up and PCL equipment. Deck space needed - Full wireline crew (6 persons) + additional PCL specialist - Other (parallel) rig activities restrained due to lack of deck space / extended hazardous zone area during cable operations	+ No additional surface equipment needed + Normal crew is 2 persons (MWD operators, on the rig during drilling anyway) + 1 LWD specialist
Stuck tool / fishing operations	- Limited possibility to work/pull on toolstring when mechanically stuck (limited by max pull on logging cable) - Cable differential stuck; Fishing operation required - Cable key-seating in soft formations; Fishing operation required - Probability for experiencing sticky hole conditions / borehole collapse increases with time open hole is exposed	- Overpull limited by toolstring tensile/compressive strength (much lower than the rest of the drill string) + No cable exposed to open hole -- Probability for experiencing sticky hole conditions / borehole collapse increases with time open hole is exposed	+ LWD toolstring of same mechanical strength as the rest of the drill string; Overpull not limited by LWD + Drilling jars / accelerators included as part of the drill string + No logging cable in the hole + Open hole time exposure is minimized
Well issues / borehole stability	- Long time from section is drilled until casing/completion string is run (increased risk of deteriorated borehole and hence hampering succeeding well operations) + Reduced need for rat hole due to shorter tool strings / sensors closer to bottom of toolstring. (Assuming several runs if a lot of data is to be acquired)	-- Long time from section is drilled until casing/completion string is run (increased risk of deteriorated borehole and hence hampering succeeding well operations) - May need to drill long rat hole to acquire all data due to long toolstring / high sensor offsets from bottom of toolstring	+ Little extra time from section is drilled until casing/completion string is run - May need to drill long rat hole to acquire all data due to long BHA / high sensor offset from bottom of BHA

Appendix E Uncertainty assessment of the Heidrun Petrophysical Evaluation model



@RISK Output Report for SW / Archie

Performed By: Bøklepp, Bjarne Rosvoll

Date: 18. desember 2008 14:26:45

Simulation Summary Information

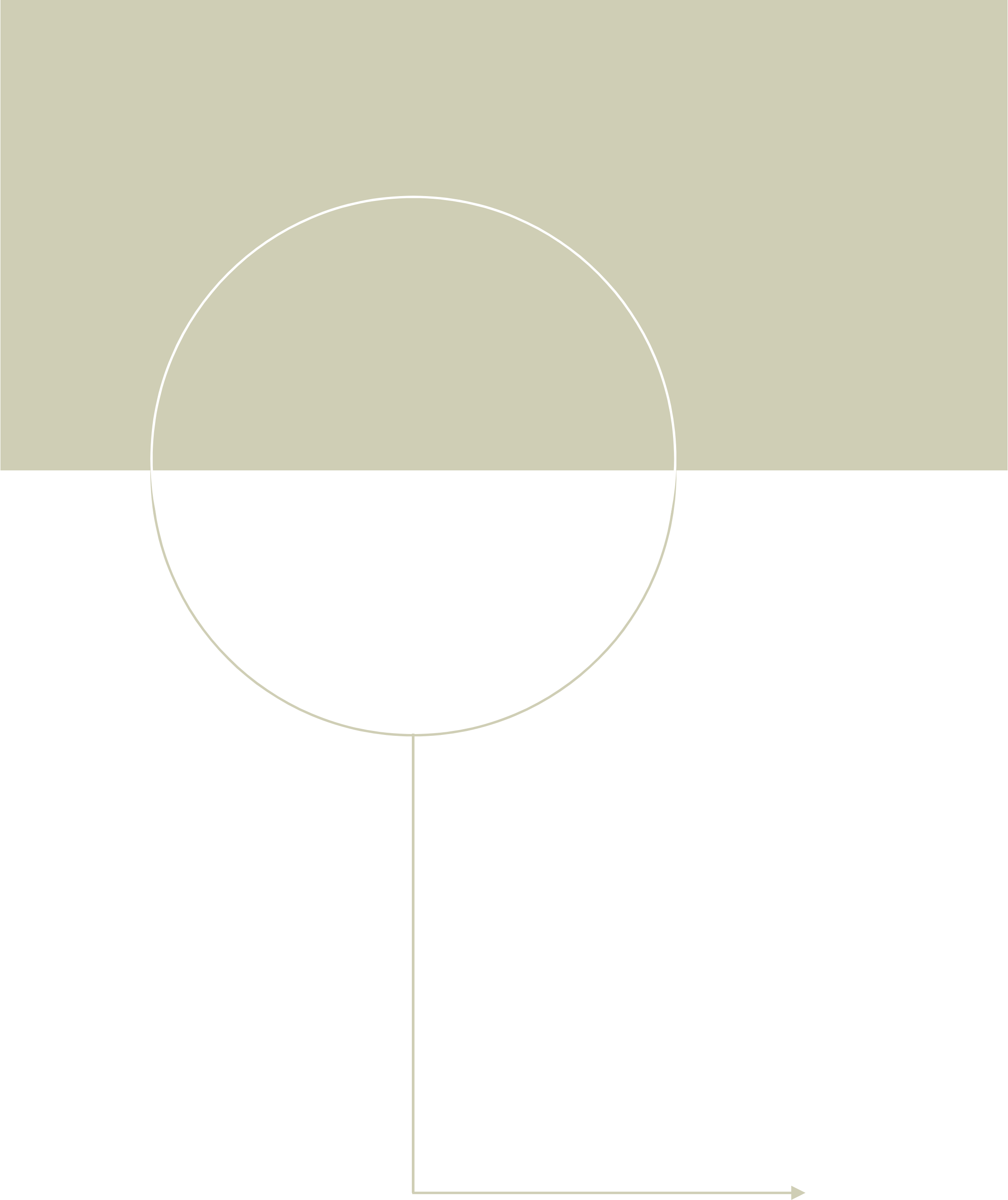
Workbook Name	Heidrun petrophysical model.xls
Number of Simulations	1
Number of Iterations	10000
Number of Inputs	28
Number of Outputs	6
Sampling Type	Latin Hypercube
Simulation Start Time	12.18.08 14:20:58
Simulation Duration	00:00:57
Random # Generator	Mersenne Twister
Random Seed	952250267

Summary Statistics for SW / Archie

Statistics		**Percentile**	
Minimum	0.485196967	**5 %**	0.535049306
Maximum	0.709106267	**10 %**	0.543572083
Mean	0.577852991	**15 %**	0.549826009
Std Dev	0.027569416	**20 %**	0.554295197
Variance	0.000760073	**25 %**	0.558755251
Skewness	0.29524298	**30 %**	0.562595505
Kurtosis	3.140496994	**35 %**	0.566143567
Median	0.576463214	**40 %**	0.569652307
Mode	0.568669469	**45 %**	0.572928799
Left X	0.535049306	**50 %**	0.576463214
Left P	5 %	**55 %**	0.579795329
Right X	0.625583095	**60 %**	0.583235164
Right P	95 %	**65 %**	0.587223472
Diff X	0.090533789	**70 %**	0.591249073
Diff P	90 %	**75 %**	0.595659659
#Errors	0	**80 %**	0.60052568
Filter Min	Off	**85 %**	0.606154362
Filter Max	Off	**90 %**	0.613805478
#Filtered	0	**95 %**	0.625583095

Regression and Rank Information for SW / Archie

Rank	**Name**	**Regr**	**Corr**
1	NACL / Formation Water density & resistivity	-0.718	-0.695
2	N / Archie	0.409	0.410
3	M / Archie	0.330	0.329
4	RHOB / Porosity from density	0.280	0.277
5	GASFRACTION / Apparent hydrocarbon density & hydrogen index	0.207	0.234
6	RT / Archie	-0.150	-0.151
7	A / Archie	0.150	0.142
8	RHOMA / Porosity from density	-0.116	-0.124
9	RHOGAS / Apparent hydrocarbon density & hydrogen index	-0.061	-0.056
10	RHOOIL / Apparent hydrocarbon density & hydrogen index	0.036	0.037
11	RHOSH / Porosity from density	-0.011	-0.010
12	CLCMF / Mud filtrate density & resistivity	-0.005	0.004
13	TVD / Formation & well temperature	-0.005	-0.013
14	BHT TVD / Formation & well temperature	-0.003	-0.004



NTNU
Norwegian University of
Science and Technology