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SUSTAINABLE ENERGY ENGINEERING

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# RESERVOIR CHARACTERIZATION

## FUNDAMENTALS AND APPLICATIONS

FRED AMINZADEH



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# **Reservoir Characterization**

## **Fundamentals and Applications**

**Fred Aminzadeh**



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# Foreword

What is reservoir characterization? As you will see from this book, this is a very advanced topic so let's break it down a bit and start from the basics. What is a reservoir? This is 'a place where something is kept in store'. And what is characterization? That is 'to describe the character or quality' all according to the Webster dictionary. So, we are arrived at: 'describe the character of something that's kept in store'. It seems relatively benign and easy but 'the devil is in the details' is perhaps the best way to get the readers intrigued and immersed in this topic. So, we are left wondering what are these details where the devil resides? And here starts the story.....

In fact, a better wording would be 'Subsurface Reservoir Characterization' or SRC. There have been on the order of thousands of studies in reservoir characterization over the life time of this field. As such, this topic has evolved and matured with many learnings. As illustrated in this book, there are now well established and tested workflows SRC and I'd like to go over some aspects of these understandings and workflows.

First, it is key to understand that SRC is a continuously changing, multi-discipline and multi-scale topic. For continuously changing a good example would be the recent impact of say machine learning methods. I have learned that if our data quality is good enough and there are physical relationships between reservoir data and properties, machine learning can be an excellent way to quickly uncover relationships in a multi-variable universe. However, once again, even here, the devil is in the details.... Multi-discipline is a word we easily use but have difficulty implementing. In many projects the geologist is

tasked with building a static reservoir model and then passing it on to the reservoir engineer to build a dynamic model and history match production. However, it has been challenging to form a loop versus a linear workflow or for the dynamic model to be updated with new static information or cover a range of possible models that fit the data..... As for multi-scale, the discipline involves integration of data from a wide range of data, say, nanometer (electron microscope), to centimeter (cutting and core samples), to decimeter (well log), to meter (seismic) scale. Spatially most of these data are acquired within a small portion of one or several wells and geophysical data gives the capability to extrapolate away from the wells with lower resolution. Due to uncertainties in the data, rapid variations in the subsurface, and sparse sampling multi-scale integration can be a challenging task. There is a good discussion of “SURE Challenge” in the book where the author addresses the above mentioned challenges of integration involving multitude of data set with different Scale, Unvertainty, Resoultion and Environemnet. It is suggested that different AI and Data Analytics techniques may be best equipped to handle the SURE Challenge.

The second component can be categorized into input data quality (informally ‘garbage in, garbage out’). Any workflow that is lets say cutting edge cant work without high quality input data. Further, it may cause mis-interpretation that a workflow is ‘not’ a good workflow or appropriate simply because the input data was the culprit. The input data in fact starts from data acquisition, then to data processing and finally to data interpretation and integration. One of the pitfalls along the way is to simply obtain the data as an interpreter and not be aware of lets say the ‘history’. An example would be to apply amplitude based seismic analysis to data that non-amplitude preserving processing

was applied to (Automatic Gain Control or AGC would be a simple example). However, the same could be happening with say well-log or production data. The good news is that over time in every SRC related discipline data quality has been improving with not only better tools but also more frequent data acquisition during the life of a reservoir. Further, over time we have learned to build much better processing tools that provide high quality data for the integration component. The net result of this has improved our ability to conduct integrated studies and quantitative products. One example of this near to my heart is joint seismic inversion of PP reflected waves with PS (or converted) reflected waves from a reservoir. We have seen that with improved acquisition and processing, the joint PP/PS inversion can substantially improve pre-stack seismic inversion providing a stable S-impedance as well as a P-impedance that can provide valuable information such as formation properties, porosity, Total Organic Carbon (TOC,) fluid types, and time-lapse reservoir pressure and saturation changes over the life of the reservoir. Such improvements are going on in all the subsurface disciplines thanks to modern acquisition and more diverse data with higher quality.

This book is an excellent resource for beginners in SRC to get an overview of the topic and for expert to study most recent advances in their own and related disciplines. The book covers a wide range of topics from conventional to unconventional reservoirs, from geology to geophysics to petroleum engineering, from laboratory measurements to field applications, from deterministic to statistical methods, from primary depletion to EOR with CO<sub>2</sub> injection, from static to dynamic SRC, as well as use of AI for reservoir characterization. In the end, SRC requires best practices to be implemented to be value generating. This books certainly provides the necessary best practices.

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## **Preface**

An important step in exploration development, monitoring, and management a reservoir as well optimizing production and planning for post primary production decisions is reservoir characterization. Upon the completion of the preliminary task of reservoir characterization, and as we continue to produce from the reservoir or use different methods to stimulate it, many of its properties change. This requires updating the reservoir model, bringing up the concept of dynamic reservoir characterization. To achieve this goal, we incorporate the newly acquired petrophysical, seismic, micro seismic and production data. The updated model would be a better representative of the status of the reservoir. Both static reservoir properties, such as porosity, permeability, and facies type; and dynamic reservoir properties, such as pressure, fluid saturation, and temperature, needs to be updated as more field data become available.

Among the reason for focusing on reservoir characterization is the fact based on the estimates by experts, more than 95% of the world's oil production in the 21<sup>st</sup> century will come from existing fields. This will require significant improvements in the current recovery rates of less than 50% in most reservoirs. Improved secondary and tertiary recovery through enhanced recovery of oil and gas require by better understanding and monitoring of the reservoir will be an important element of the much-needed increase in the recovery factor. Increased production will be made possible only through effective dynamic reservoir characterization.

We need to recognize the fact that reservoir characterization is a multidisciplinary field. It attempts to

describe petroleum deposits and the nature of the rocks that contain hydrocarbons using a variety of data types. Reservoir characterization relies on expertise from petroleum engineers, geologists, geochemists, petrophysicists, and of course geophysicists, The integration of information from these fields, with the aid of advanced data analysis techniques as well as artificial intelligence (AI) based methods will make our reservoir models more accurate and the updating process much faster.

This book will provide a comprehensive body of technical material on different aspects of reservoir characterization. It is divided into 7 parts: [Part 1](#) is an introductory chapter covering the general concepts, of reservoir characterization. It includes an overview of what is meant by reservoir characterization as it is applied in different stages of its life, from exploration to post primary production stages. It also highlights the challenges of data integration of different data types, the previously mentioned dynamic reservoir characterization, and reservoir stimulation for enhanced oil (or gas) recovery.

[Part 2](#) deals with general issues on reservoir characterization and anomaly detection. It is comprised of 7 chapters on different related topics such as: (1) Comparison between estimated shear wave velocity and elastic modulus at in situ pressure condition (2) Anomaly detection (3) geochemical analysis on characterization of carbonate source-derived hydrocarbons, (4) MWD mud pulse telemetry, (5) Use of Monte Carlo clustering to detect geologic anomalies, (6) Gas-sand predictors using dissimilarity analysis, and (7) Fluid flow tests distorted by wellbore storage effects. [Part 3](#) is dedicated to reservoir permeability detection, being one of the most important reservoir properties. What are covered here are three different techniques. Two of them involves use of two

different machine learning techniques to predict permeability, namely, exponential/multiplicative and Monte Carlo/committee machines. The other chapter discusses geoscience criteria identifying high gas permeability zones.

One of the reasons for reservoir characterization is to assess the recoverable reserves in the reservoir. [Part 4](#) addresses reserves evaluation and decision-making issues. The first chapter of this part discusses foundation for science-based decision making, using data from the Gulf of Mexico. The next chapter in [Part 4](#) investigates decline trends in a reservoir using Bootstrap and Monte Carlo modeling. This Part concludes with a typical production, reserves, and valuation method used in an oil and gas company.

Given the tremendous success with the development and production from shale reservoirs over the last 2 decades, [Part 5](#) is dedicated to the unconventional reservoirs. The chapters in [Part 5](#) include: (1) Optimization of Gas-Drilling in Unconventional Tight-Sand Reservoirs, (2) Predicting the Fluid Temperature Profile in Drilling Gas Hydrates Reservoirs, (3) Distinguishing between brine and gas-saturated shaly formations, and (4) Influence of shale mechanical properties on water content effects.

[Part 6](#) is about enhanced oil recovery. It covers EOR with hydrophilic nanofluids, as well as CO<sub>2</sub>-EOR Flow Simulation for the Tensleep Formation using 3D seismic data. [Part 7](#) is the concluding section, highlighting new advances in reservoir characterization. It discusses the recent application of machine learning in reservoir characterization. It also discusses the future trends in reservoir characterization and the impact of data explosion associated with the real time reservoir monitoring and reservoir surveillance. It also describes how the “Big Data” concepts and data analytics techniques will play a role in

the next generation reservoir characterization technology developments.

It should be understood reservoir characterization is an evolving technology. It is our hope that this volume will be a meaningful addition to the current body of literature and will help pave the way for further advances on the subject matter in the future.

**Fred Aminzadeh**  
Santa Barbara, California  
September 22, 2021

# **Part 1**

# **INTRODUCTION**

# 1

## **Reservoir Characterization: Fundamental and Applications - An Overview**

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### ***Abstract***

This article provides a brief overview of reservoir characterization at different stages of a field from exploration to development to production and post primary production. It demonstrates the challenges associated with integration of different data types. It also shows how “Dynamic Reservoir Characterization” can assist in monitoring of the field for various well stimulation processes such as enhanced oil recovery as well as reservoir stimulation. Different sections of this entry attempt to highlight different aspects of reservoir characterization, as an exploration tool, development tool, production tool and monitoring tool. As reservoirs age, different measures are taken to extend their productive life. This includes different types of reservoir stimulation and enhanced oil (or gas) recovery.

***Keywords:*** Reservoir characterization, data integration challenges, 3D/4D seismic, micro-seismic data, reservoir monitoring, dynamic reservoir characterization, rock physics and enhanced oil recovery (EOR)

## **1.1 Introduction to Reservoir Characterization?**

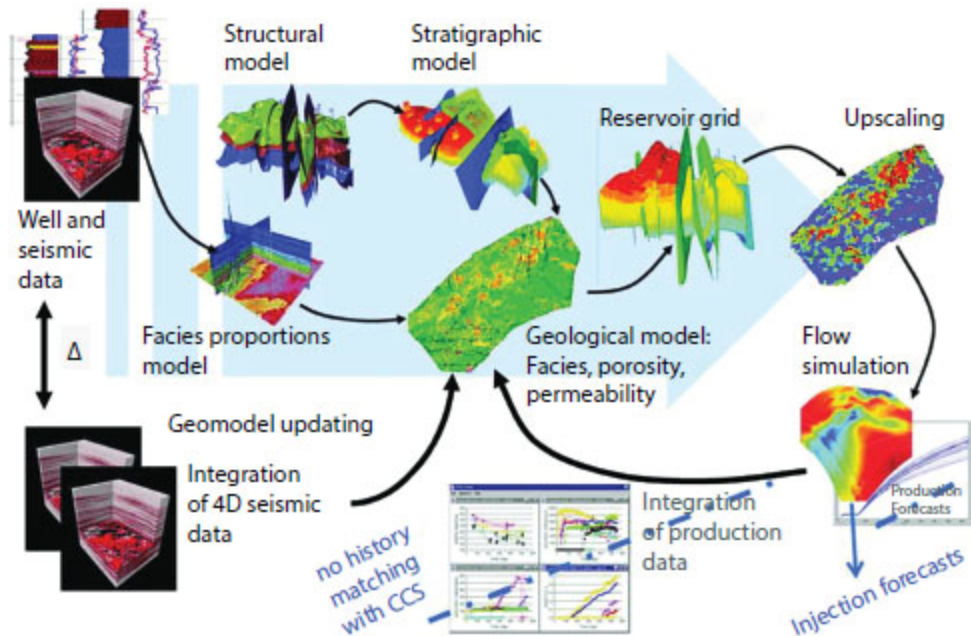
As discussed in Aminzadeh and Dasgupta [2], Reservoir Characterization is to assess reservoir condition and its properties using the available data from core/log data to seismic and production data. This is done to assist in delineating or describing a reservoir. Reservoir characterization and modeling have become increasingly important for optimizing field development.

Reservoir valuation and producing from a field demands a realistic description of the reservoir, requiring an integrated reservoir characterization and modeling. An integrated approach for reservoir modeling bridges the traditional disciplinary divides and tears down interdisciplinary barriers, leading to better handling of uncertainties and improvement of the reservoir model for field development. Integrated reservoir management requires better characterization of the reservoir and it is imperative to a successful operation throughout the life of the reservoir. Dynamic reservoir characterization is to understand the changes in reservoir properties to monitor its performance as we produce from reservoir and/or stimulate the reservoir to enhance production. This is accomplished by the analysis of data from combination of different sources, to extract additional information about the *in-situ* conditions of the reservoir, including the formation temperature, pressure, and the properties of the oil, gas, and brine. Other reservoir properties that can affect measured data are density, hydrocarbon viscosity, stresses, and fractures. We start with the reservoir description process that generates models of reservoir architecture, lithologies and facies. The geometry of the flow units is established, physical rock properties such as porosities and permeabilities of flow layers. Three properties are related to the pore space: porosity--the fraction of the entire volume part occupied by pores, cracks and fractures, internal surface: the magnitude of the

surface of pores as related to the rock mass pore volume and controls interface-effects at the boundary grain - pore fluid, permeability: the ability to flow fluid through rock pores. Porosity and specific internal surface are scalar properties, permeability is a tensor.

[Figure 1.1](#) shows integration of reservoir structure or architecture and reservoir detailed properties from calibration with well data for the reservoir model. Reservoir description is an iterative process and need.

Different aspects of [Figure 1.1](#), from the input data to the process (well data, seismic data, production data, etc.) will be discussed in [Section 1.2](#) on the data requirements. The difficulties associated with the integration of different data sources will be addressed in [Section 1.3](#), under “SURE Challenge”. In [Section 1.4](#) we discuss different aspects of reservoir characterizations in different stages of reservoir life. The exploration and development stage deal with preliminary determination of the reservoir structural model, stratigraphic and facies models. This is followed by the production phase with a focus on porosity, permeability and fluid saturation, involving reservoir/flow simulation and history matching. The recovery stages involve injection of water/CO<sub>2</sub> or steam to increase production. We discuss Dynamic Reservoir Characterization (DRC) in [Section 1.5](#). We note that 4D seismic and microseismic data play an important role in geo-model updating monitoring production and the EOR/reservoir stimulation process. [Sections 1.6](#) goes into more details on rock physics and reservoir modeling and how reservoir characterization can be used as an input to reservoir simulation and help with enhanced oil recovery and other well stimulation processes.



**Figure 1.1** Different components of reservoir characterization, from Fornel and Estublier [5].

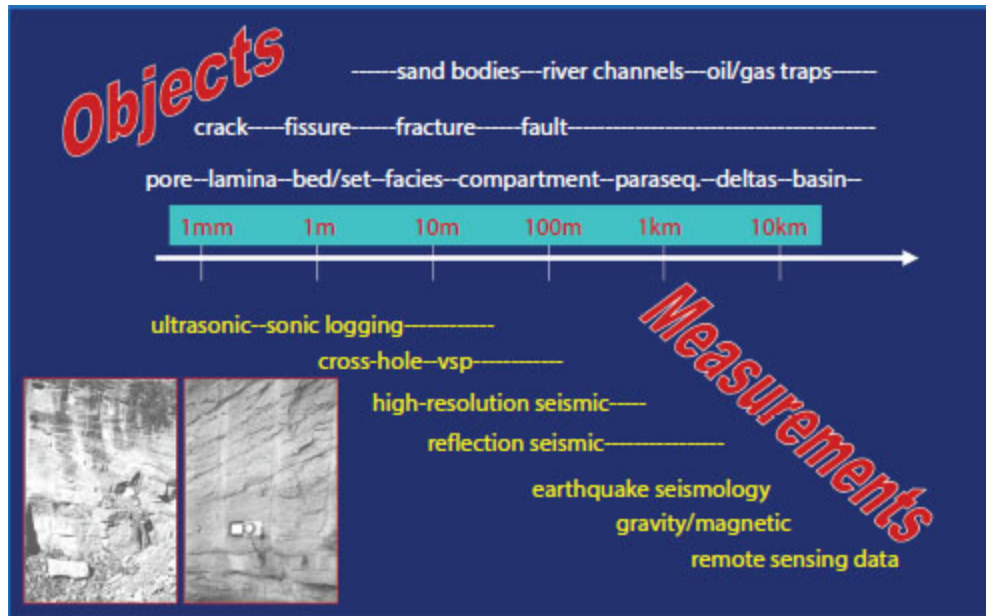
## 1.2 Data Requirements for Reservoir Characterization

Well data provides vertically high-resolution model at the well location, however, the distribution of well in a field are sparse. Combining well information with geophysical and geological data allows the necessary constraints for extrapolating high resolution well data beyond where they are measured thus increasing the coverage. For every phase of the reservoir life cycle from discovery to development to operating to maturity and well stimulation (enhanced oil recovery) phase, geophysical tools are used to create reservoir model with the associated properties and update the model based new data collected.

Integration of geophysical data with geologic data, and engineering measurements improves our understanding of the reservoir, reduces uncertainties and mitigates the risk. The detailed spatial coverage offered are calibrated with

analysis of well logs, pressure tests, cores, fracture system, geologic depositional knowledge and other information from appraisal wells. 3D seismic is the primary geophysical technique used to create the original reservoir models. 4D seismic (time lapse data) and other new measurements (micro-seismic, new log/pressure data and production data help create updated (dynamic) reservoir model. In addition, gravity, controlled source EM, borehole measurements such as vertical seismic profiling-VSP, borehole gravimeter-BRGM, cross well seismic, cross well EM are also used to build the original and updated reservoir models.

The required information for the petroleum engineers and geologists includes subsurface lithology, net pay, porosity, permeability, reservoir fluid-fill, fluid contacts, reservoir pressure and stress regime. Geophysical tools infer reservoir properties from the measured physical observations by blending these with measurements made at the wells like well logs, well tests and core analyses. During the field appraisal and development stages, understanding of the reservoir matrix properties and fluid distribution within the reservoir are of great importance.



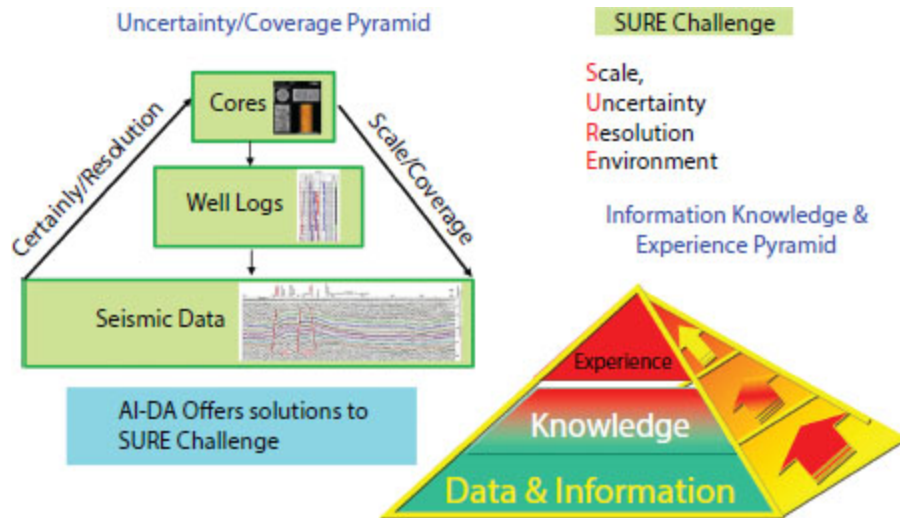
**Figure 1.2** Wide range of physical scale for different data types associated with different geological and reservoir features.

## 1.3 SURE Challenge

The ultimate goal is not only to identify and delineate hydrocarbon charged in reservoirs, but also to quantitatively determine the volume and distribution of oil and gas it contains and quantify the associated uncertainty. No single measurement has the required response to achieve this. It is therefore essential to integrate the various types of data to a common earth model. This information includes seismic data, various types of well data, and geologic concepts. The challenge is to integrate measurements that are of different Scale, Uncertainty, Resolution, and Environment or the SURE Challenge as was introduced by Aminzadeh [1] and further elaborated at Aminzadeh and Dasgupta [2] and Aminzadeh [3]. The entire process of exploration for reservoirs to its abandonment involves acquisition and analysis of different types of data. These data types are associated with an enormous range of

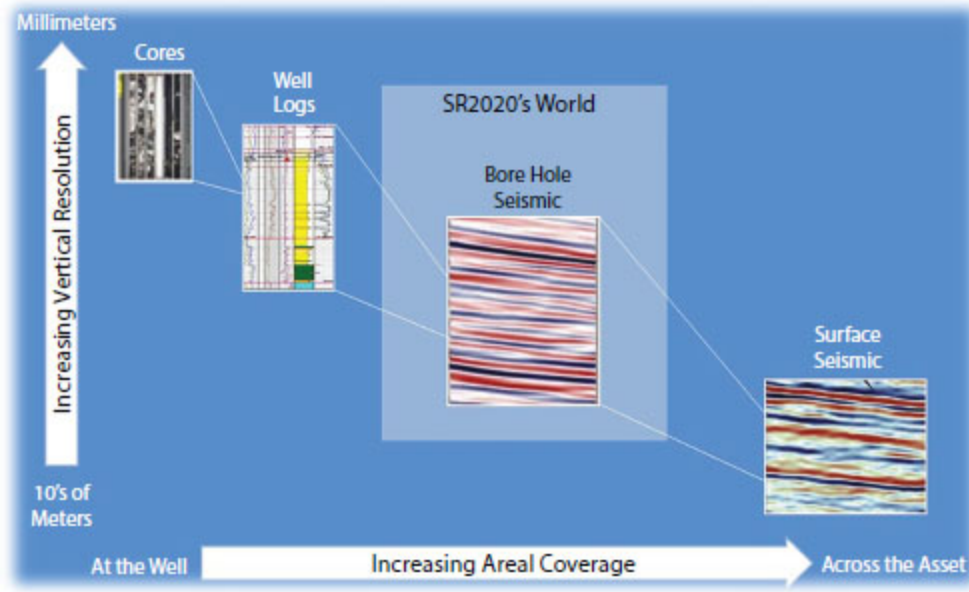
scale as shown in [Figure 1.2](#). This spans ultra-sonic measurements of pores of the order of 1 millimeter to remote sensing measurements of basins of over 10 Kilometers wide. Examples of many other data measurements for many other objects that lie in between all the features are shown in this figure.

Admittedly not all the data types are integrated at the same time. Nevertheless, Scale and the wide range of differences for different data types is one of the challenges in reservoir characterizations. To make the matter more complicated is the fact that different data types are associated with different levels of uncertainties. For example, the direct measurements of rock properties from the core data may involve little uncertainty. The petrophysical information from well log data may be associated with somewhat more uncertainty. The seismic data used to ascertain reservoir properties, for their indirect nature of measurements involve much more uncertainty. Thus, Uncertainty level and its variations with respect to different data types is poses another challenge in data integration.



**Figure 1.3** SURE Challenge: Having to deal with the wide ranges of Scale, Uncertainty, Resolution and Environment of different data types when integrating them, (from Aminzadeh [3]).

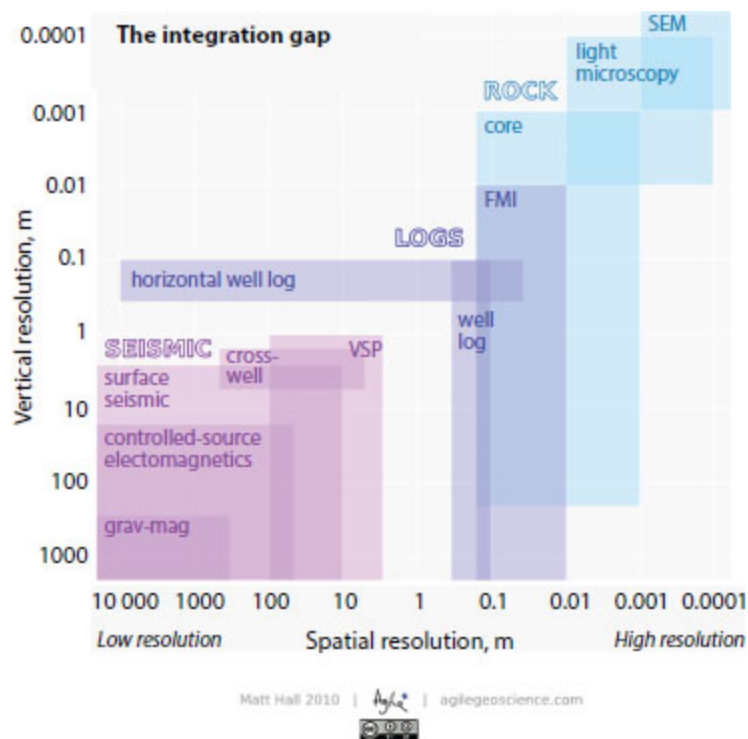
In addition, having different data types with vastly different underlying Resolution, also poses a challenge for data fusion. The resolving power of different data types is drastically different. As shown in [Figure 1.3](#), some data types have very high resolving power. For example, while well log data can resolve a reservoir unit of under an inch, seismic data, generally speaking, may not be able to resolve a reservoir under 30 feet. Finally, the effectiveness and usefulness of different data types are impacted by the geological conditions and reservoir “Environment”. This can be associated with different reservoir types (carbonate, clastic, unconventional, heavy oil,) or different reservoir conditions (High Pressure/High Temperature, or reservoir depth (shallow water, Deep, or Ultra Deep Water.)



**Figure 1.4** Areal coverage of well data is complemented by the larger areal sampling of the geophysical methods. VSP vertical seismic profile and Crosswell seismic fill a resolution “gap” between sonic log measurements and vertical seismic profiles. Courtesy of SR2020 (now Optasens).

We refer to these four key challenges: Scale, Uncertainty, Resolution and Environment as: the SURE Challenges. Top left side of [Figure 1.3](#) illustrates three key data types: core, well log and seismic data. We will refer to it as a data pyramid. The base of the pyramid is the seismic with very large coverage but with limited resolution and lesser level of certainty. The top of the pyramid is the core data with very little coverage (only at a particular well location involving a fraction of the well) but with high level of certainty and resolution. Effective integration of all the data types, in spite of the SURE challenge is what reservoir characterization is all about. As we will show in the last chapter artificial intelligence and data analytics can play a key role in offering solutions to the SURE challenge.

The bottom right-hand side in [Figure 1.3](#) shows an upside-down pyramid comprised of a different aspect of integration. That is, vast amount of data needs to be combined with some technical knowledge and experience to perform effective data mining and ultimately reservoir characterization. As an aside, it must be pointed out that borehole geophysical data (e.g. Vertical Seismic Profile and Cross-Well data) fills the gap between core data and well log data on one side of the scale and 3D seismic data on the other side.



**Figure 1.5** Vertical and spatial resolution of various geophysical, well logs and laboratory measurements. From [www.agilegeoscience.com](http://www.agilegeoscience.com) (left), and Optaense (right).

In general. The resolution of different data types for reservoir characterization and description varies considerably. [Figure 1.5](#) illustrate such a large variability for core to log to borehole geophysics and seismic, gravity magnetics data and control source electromagnetics, among others. This further demonstrates the importance

finding a solution to the “SURE Challenge” for reservoir characterization and other E&P problems. Also, see Ma *et al.* [8] addressing integration of seismic and geologic data for modeling petrophysical properties.

## **1.4 Reservoir Characterization in the Exploration, Development and Production Phases**

Reservoir characterization has different focus in different phase of the life of a field. In what follows we briefly highlight the main objective of Reservoir Characterization in Exploration, Development, Production (primary recovery) and Production Enhancement (secondary and tertiary recovery) phase. For the very reason, the notion of reservoir characterization often times means different thing to geologists, geophysicists and reservoir engineers. This is primarily due to the fact that their primary focus is different phases of life of the field.

### **1.4.1 Exploration Stage/Development Stage**

The pre-development (exploration) phase requires delineation of the reservoir limits and assessment of its economic feasibility. Development stage requires somewhat more accurate assessment of the reservoir extent, better appraisal of the economic viability of the reservoir and placement of new wells for further delineation of the reservoir. More detailed depth imaging using advanced geophysical methods, borehole geophysics applications as well as fault seal analysis, and better understanding of reservoir compartmentalization are some of the objectives of reservoir characterization at this stage. At this stage it is necessary to determine the reservoir drive mechanism and the size and strength of the aquifer. At the development

phase, reservoir continuity rather than reservoir delineation becomes the focus. The focus in this phase is to identify the structural extension or truncation beyond well control in order to minimize the drilling of dry holes. While the pre-development and development phase require considerable attention to reservoir characterization. Geophysicists construct an initial model by correlating lithology, porosity, net pay thickness and other properties at the well location using seismic attributes from surface 3D seismic, VSP and synthetic seismograms. The initial model is then updated by computing seismic attributes between the wells in order to predict reservoir properties in 3D. Seismic attributes like acoustic impedance, variations in amplitudes, frequencies, interval velocities and instantaneous phase are applied in the computation.

### **1.4.2 Primary Production Stage**

As the primary production of the reservoir begins, the goal is to position wells at optimal locations that would maximize hydrocarbon recovery. During secondary recovery and then enhanced recovery process, the engineer's objective is to maximize the volume of hydrocarbon contacted by injected fluids. This is to achieve maximum volumetric sweep efficiency for fluid production. To minimize cost and risk, engineers attempt to predict reservoir performance—for both planning and evaluation of hydrocarbon recovery projects. Reservoir description in terms of reservoir architecture, flow paths, and fluid-flow parameters are the key to reservoir engineering. Accurate prediction of reservoir production performance is predicated primarily on how well the reservoir heterogeneities are understood and have been modeled and applied for fluid-flow simulation. This stage requires integration of reservoir characterization models with reservoir simulation, history matching for production

optimization. Reservoir management process conducts reservoir related studies and applies the results from fluid flow modeling in defining, updating and optimizing a development plan for producing the reservoir and forecast the production profile. This phase also involves optimization and management of reservoir performance evaluation, surveillance of fluid flow and changes in the reservoir that result in changes in the original distribution of physical properties. The optimization criteria can change during the life cycle of a producing reservoir. Managing the reservoir depletion is a dynamic process and the reservoir engineers constantly react and adapt to the changes as they evolve. Dynamic characterization is a representation of the fluid flow in a static reservoir model and needs to be validated with reservoir performance data.

### **1.4.3 Secondary/Tertiary Production Stage**

When the reservoir ages, intervention to increase production through reservoir stimulation and enhanced oil (or gas) recovery becomes necessary. Here, the main objective shifts to plan the production and injection, develop an optimum secondary/tertiary recovery mechanism and plan for infill drilling well locations to maximize recovery rate and deliver oil and gas at the planned rate and to extend the economic producing life of the reservoir as much as possible. The finite resources that are available are applied to plan and optimize the economic recovery of oil and gas from the reservoir. Petroleum engineers are responsible for planning and executing the development and of petroleum reserves. They seek to maximize petroleum recovery from the reservoirs. Effective use of reservoir characterization and reservoir model updating play an important role in this process. This is accomplished by incorporating physical property measurements of the reservoir rock and fluid properties

that describes the reservoir architecture and its initial fluid distribution to make an optimum production and reservoir stimulation plan. 4D seismic and/or micro-seismic monitoring plays a role in assessing the effectiveness of well different well stimulation approaches (for example EOR, artificial lift or hydraulic fracturing), giving rise to the importance of “dynamic reservoir characterization” at this stage.

Engineers need to monitor the reservoir state of pressure, temperature and fluid distribution during the producing life of a reservoir. This information could 1) identify situations within the reservoir which may potentially impact oil and gas recovery, and 2) locate problems that can cause undesirable leakage or entry into wellbore. If these situations are not corrected in a timely manner, irreversible damage might occur to the reservoir affecting the ultimate oil and gas recovery. Inter-well monitoring of production and injection processes using geophysical techniques also allow improvement of field development plans and optimize reservoir management. Field scale monitoring of reservoir drainage patterns would improve the recovery factor.

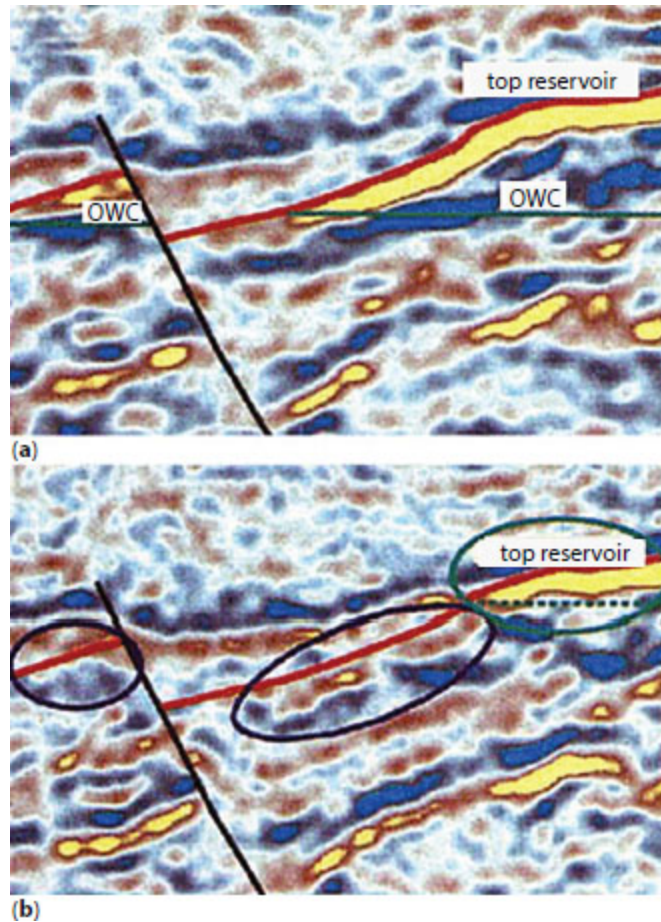
## **1.5 Dynamic Reservoir Characterization (DRC)**

Both in the primary and post-primary production phases, we need to have an updated characterization of the reservoir. We will refer to this as DRC. DRC can play a key role in production optimization and monitoring of effectiveness of the EOR operation or hydraulic fracturing. It can help surveillance of fluid flow which is an essential part of reservoir management process. Likewise, changes in the reservoir pressure distribution is also helpful to make important reservoir management decisions. Among many data sets that are used to monitor fluid, pressure and

other reservoir properties is 4D seismic and Microearthquake data. For some examples, see Kosco [7], Maity [9] and Maleki [10].

### **1.5.1 4D Seismic for DRC**

Changes in the reservoir fluids or pressure distribution can be imaged by 4D. This is based on the impact of fluid saturation and reservoir pressure on the changes in compressional and shear wave velocities of seismic waves. A simplistic idea is to directly subtract two 3D seismic volumes of acquired in say successive years. This is often referred to as 4D seismic, with the fourth dimension being the time lapse between the two 3D seismic surveys. An example of time lapse seismic is in [Figure 1.6](#). As the reservoir is produced, the distribution of the fluid properties changes with time but the reservoir rock frame properties remain constant during the producing life of the reservoir. Therefore, by repeating the seismic measurements i.e., acquiring time lapse seismic data and computing the differences in the seismic attributes between the measurements the changes in the distribution of reservoir fluid properties between wells could often be detected.



**Figure 1.6** Time-lapse seismic response changes caused by different positions of oil-water contact (OWC) in Gullfaks field Tarbert reservoir. (a) Oil-water contact level before production and (b) after production for 10 years. Zones with changes in seismic impedance are circled. <http://accessscience.com>.

The changes in time lapse seismic data are due to the acoustic impedance variation (in this case, mostly the compressional velocity change), caused by the reservoir production or other changes (such as water or CO<sub>2</sub> injection in the EOR process). Acoustic impedance is the product of velocity ( $V$ ) and density ( $\rho$ ), for time lapse seismic amplitudes are influenced by the incompressibility ( $K_{\text{rock}}$ ) of the reservoir rock and the production-generated changes in the incompressibility of the pore fluids ( $\Delta K_{\text{fluids}}$ ).