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Introduction

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This is a 'go-to' guide for decision makers and professional explorers – of the suitability and applicability of each technology in a variety of geological settings. The guide looks at specific hurdles for de-risking the subsurface, such as hard chalk at seabed, salt and basalt and indicates what the optimal technology combinations are best to overcome them. It also gives an indicative cost required for each technology broadly relative to that of a conventional seismic survey.

The search for both minerals and oil and gas is founded on the ability to understand the subsurface and be able to predict the location of commercial bodies of ore and hydrocarbons; and as we move into the energy transition era, the ability to monitor the behaviour of carbon dioxide stored in underground reservoirs will become more important. Traditionally this skill was the realm of the geologist who mapped the surface rock formations and then extrapolated downwards to create a three-dimensional mental image of the hidden layers of rocks. The realisation that these rocks have differing physical properties led to the development of geophysical measurements to constrain the image of the rock formations deep underground; for example, differences in density led to gravity modelling and differences in resistivity led to the measurements of electrical currents. However, it was the understanding of the acoustic properties of rocks and fluids that was the breakthrough in oil and gas exploration.

Reflection seismic and the ability to create an acoustic image of the subsurface has been the backbone of the hydrocarbon industry and opened up all the offshore continental shelves to oil exploration and development. Continual advances in reflection seismic techniques have led to oil being found in deeper water, underneath salt bodies and in smaller accumulations. This has now become the most important geophysical tool used by exploration and production companies and has been extremely successful in helping to locate and produce oil and gas fields.

But this focus on reflection seismic has been to the detriment of other forms of geophysical measurement. Gravity, magnetic, resistivity and seismicity techniques, collectively called potential field techniques, have tended to be used in isolation and by specialist teams. Each is generally tested and used on a stand-alone basis; there is much reporting and analysis on the physics of each technology and how they should be applied individually.

However, increasingly, there is the appreciation that these technologies used in combination with reflection seismic will provide a better answer, that is, produce a more accurate picture of the subsurface. No single technology can solve the subsurface imaging problem. This is the area that is the focus of the book – how should these geophysical technologies be used, both individually and in combination with other techniques?

The lead authors of the book (Keith Nunn, Matt Luheshi and Hamish Wilson) have assembled a group of industry leading authorities on geophysical technologies, each a master of their respective technology. Each has prepared a chapter on their technology and how the physics works. The key insight and differentiator for the book is the description of how the integration of these technologies with other techniques can enhance our understanding of the subsurface. The authors have worked together to describe how these technologies can be combined to solve specific geoscience problems in subsurface understanding. This volume describes some of these technologies and provides guidelines as to when and where they should be deployed.

The ultimate objective of the book is to present an evidence-based route map of when, where and how to apply these non-conventional geophysical technologies to reduce the exploration and production uncertainty, for conventional oil and gas activity, and to monitor carbon dioxide in reservoirs. Given the specialist nature of these techniques and the fact that they require relatively uncommon expertise, there is a need for a guide for the more generalist practitioner in the field. The route map presented here is a practical technology selection guideline for organisations and individuals working the subsurface. The final chapter of the book describes a 'roadmap to subsurface de-risking' which demonstrates where these specialist tools sit within the tool kit that geoscientists rely on in their day-to-day work.

So in addition to providing an in depth description of each technology, at its heart, this book is a description of when and how to use each technology.

1.1 Introduction to the Technologies of Hydrocarbon Exploration

The oil and gas industry uses technology to create accurate descriptions of the geological architecture of the subsurface. Chapter 2 sets the context for the book and describes the overall process for subsurface analysis in exploration and production (E&P) and introduces where each technology should be used and the problem to be solved. As a company evaluates a given E&P opportunity, or project, money is spent on acquiring and interpreting geophysical measurements (generally reflection seismic) to reduce the uncertainty in our understanding of the subsurface. The focus of the work is to predict the lithologies in the subsurface through measuring their response to various forms of geophysical ‘stimulation’ or their inherent physical characteristics.

The ability of geophysicists to ascribe physical properties to a three-dimensional geological ‘model’, to calculate a synthetic geophysical response and iteratively match this to measured data (seismic, magnetic, etc.), has transformed the exploration process. The ‘model’ closely resembles a three-dimensional picture of the earth. But the ‘model’ is just that, a picture that can create a geophysical response similar to that measured in the field! As a result, explorationists use different techniques to validate, reconcile and improve models before finally committing to expensive drilling. Validating such models using a range of geophysical measures can transform the level of confidence in a geological interpretation.

The resultant geological model is tested through drilling a well which then calibrates the geophysical measurements against the actual lithologies penetrated. The ‘rock physics’ of the lithologies penetrated can be calculated and their geophysical characteristics defined along the wellbore. This information allows the model to be ‘tied to the well’ and updated. The geophysical model is re-created with the new calibration information and the geological prediction refined before the next well is drilled. The process continues through multiple iterations as information is acquired through the exploration process until ultimately, the model approaches the low-risk geological fact.

Today’s process is still predominantly reliant on seismic data. Yet there is a suite of other, geophysics-based technologies that can augment the power of seismic to better understand the subsurface. The core of the book is a review of these geophysical technologies, with the premise that the integrated application of these methods fundamentally enhances our ability to reduce uncertainty in the subsurface. This improved ability to characterise subsurface systems is a real game-changer with applications from exploration through to development and production, off- and onshore.

The ability of reflection seismic technology to image the spatial and stratigraphic distribution of plays and prospects is unsurpassed by any other technique. Other methods such as potential field (gravity and magnetics) tend to be used in basin-wide analysis when seismic is either not available, is too expensive or too difficult to acquire or is compromised because of quality issues. Knowing when and how to use each technology is founded on understanding the underlying physics and what rock or fluid property is being measured (density, resistivity, acoustic impedance, etc.) and its resolution. Clearly these technologies measure changes in these properties. Thus, any use of these technologies has to begin with a view as to what you are looking for and the physical properties of the subsurface environment being studied. In this regard Tables 3.1, 4.1, and 4.2 and Figure 6.2 are critical in showing these physical properties of the different rock types.

Geoscientists reach for potential field tools when, for some reason, seismic of an acceptable quality is not available. Hence opportunities for application of potential field methods have tended to fall into one of the following categories:

- Basin identification and definition at the early stages of exploration
- Structural imaging in zones of poor seismic data (sub-salt or sub-basalt)
- Building velocity models to improve seismic imaging
- Characterisation of reservoir properties in areas where seismic gives ambiguous results

The oil and gas industry is continually looking for the 'holy grail' of detecting hydrocarbons before drilling wells. Many remote sensing techniques have been announced as having 'the answer' but have been of questionable technical validity or value. There are now a number of geoscience technologies that are looking increasingly interesting for geoscientists. Advances in acquisition and processing of potential field and electromagnetic data have improved resolution such that they offer a genuine cost-effective ability to either replace blanket 2D or 3D seismic in onshore frontier basins, or to resolve seismic ambiguity. Acquisition at a fraction of the cost of seismic further adds to the attractiveness of these technologies.

No technology is the 'silver bullet' that proves the presence or absence of hydrocarbons or carbon dioxide; however, if used in the 'right' geological conditions and in combination with other techniques, these technologies can reduce risk and uncertainty. The technology landscape is continually evolving with a large and growing evidence base that is available to test the effectiveness of individual technologies. This evidence base allows rational choices to be made as to when and how to use each technology, and which combinations of technologies produce the best results.

We focus on geophysical technologies and have chosen those that have been proven to work and should be in the mainstream of exploration and production. We have deliberately excluded the more fringe technologies, which in our view are either unproven or lack sufficient evidence of success at this stage to recommend them for frequent use.

1.2 Overview

We start the volume with a description of the overall E&P process and basin analysis in Chapter 2. We outline the problem to be solved at each stage and the ranges of geophysical technologies that can be used. We look at what specific questions or issues the technology is being required to solve and at what stage of the E&P value chain is the question being asked. Starting from basin scale issues that need to be addressed by exploration managers during strategic decision-making about what provinces and plays to enter, through block screening, the high-ranking of prospects and evaluation of wells, with the requirement for finer and finer granularity of data and then onto drilling, development and production. We conclude with a description of the application to subsurface carbon sequestration and the need to monitor the behaviour of carbon dioxide in underground reservoirs. At each stage, we discuss the integrated application of these technologies in relation to the workflow and solutions. This chapter leads into the detailed description of each technology.

The core of the volume consists of six technology-focused chapters (Chapters 3–8):

- Crustal seismic studies
- Gravity and magnetics
- Full Tensor Gradiometry
- Marine electromagnetics (controlled-source electromagnetic and magnetotelluric)
- Ocean bottom nodes
- Microseismic and induced seismicity

The technologies are described in order of decreasing scale as illustrated on Figure 1.1 below. Crustal seismic can identify features at the 100-kilometre scale, while microseismic is used to identify fractures at the 10s of metres scales.

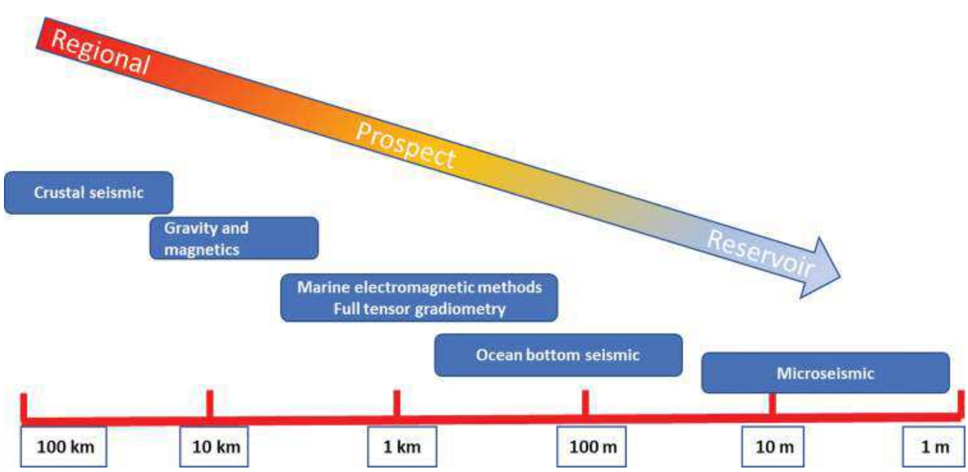

Figure 1.1 The application of technologies and scale.

Each chapter is structured to address the following topics:

- The application and integration of the technology in basin analysis
- History of the technology
- Technical description and basic principles
- How best to apply the technology
- Case examples

In each chapter we have focussed on a discussion of the efficacy of the technology and how it should be applied. We have not reviewed or commented on the companies or vendors who can provide these technologies. Each technology chapter is a stand-alone document.

The concluding piece of our review is the provision of a 'roadmap to subsurface de-risking'. This is presented in Chapter 9. We discuss the optimal way to combine these technologies to reduce uncertainty and risk in exploration and, in some cases, development, production and carbon sequestration ventures.

The book concludes with a glossary and a discussion on units.

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The Hydrocarbon Exploration Process

HAMISH WILSON

2.1 Introduction

The journey to discovering and producing commercial oil and gas starts with an idea in a geologist's mind. This idea will be a conceptual model which explains when and where oil is generated in a source rock, how it is expelled to migrate into reservoirs and finally, where it is trapped. At the outset, this is just an idea. Through effort and a logical process this idea is turned into an opportunity for an oil company, which then spends money and drills exploration wells. Some ideas will be successful: these become projects that attract further investment through to the construction of facilities which then produce oil and gas.

The continued viability of oil and gas as an energy source is dependent on mitigating the carbon impact of using the product. Thus, carbon capture, usage and sequestration (CCUS) is becoming a critical element of the oil industry's future. This involves the search for subsurface storage sites, potentially depleted oil and gas reservoirs or saline aquifers, close to carbon capture hubs. Thus the application of techniques for finding and producing hydrocarbons is being turned towards understanding how to store and manage carbon dioxide in subsurface reservoirs. As with traditional oil and gas exploration, geophysics makes an important contribution to this effort.

The chapter starts with a description of the exploration process: turning an idea, which by definition is uncertain, into an investable opportunity. In overview, the exploration and production (E&P) process is focussed on building a geological model of the subsurface which predicts the presence of hydrocarbons, and through a process of investment, reduces the uncertainty of the model so that the risk of project failure is acceptable.

We describe the staged approach to exploring for, and producing, oil and gas. First, explorers need to be able to screen basins and find potentially prospective hydrocarbon provinces. Following this regional screening, they then need to

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identify specific plays that may contain the elements for a working petroleum system (reservoir, source rocks and seal). Then, following a successful exploration programme that identified hydrocarbons, the next stage appraises the scale and productive characteristics of the discovery to enable the design of an effective, economic development. The traditional final stage is the production of the discovered hydrocarbons, where this is commercially attractive. In many basins the economic life of a reservoir is being extended to allow for the sequestration of carbon dioxide as a vital element in our ability to reduce carbon emissions.

We weave the process for subsurface analysis into the story of basin analysis and introduce the concept of reducing uncertainty and risk of loss at every stage. Our understanding of the geological architecture of the earth's crust is based on very limited data, which means that often a number of widely different possible models could fit the data in any given situation. Taking operational decisions in the context of uncertainty is a risky business that can, and very often does, lead to very large financial losses. For this reason, the industry spends a very considerable amount of effort in trying to reduce uncertainty, and hence risk, in understanding the subsurface setting, a factor critical for commercial success.

E&P geoscientists are skilled and experienced in using a standard approach to identifying and evaluating 'play' systems. The approach is based on an overall workflow that follows a set of logical steps: (1) basin screening, (2) play fairway analysis, (3) prospect definition, (4) exploration drilling, (5) appraisal studies and drilling, (6) field development and finally (7) production management. These stages use a variety of geological and geophysical data, which require thorough and integrated interpretation to develop as accurate a picture of the subsurface as possible.

2.2 Exploration Strategy: Where to Explore?

Discovering new hydrocarbons is still at the heart of the global oil economy. All the hydrocarbons in production today have been found through an exploration programme. And with the global drive to reduce emissions, exploration has to focus on low carbon intensity barrels.

For exploration this means searching for 'better barrels of oil', specifically, oil and gas resources that have lower embedded carbon in their production facilities, lower carbon emissions through their production process and low carbon emissions in their transport to their final market. In addition, the resources have to be produced with minimal environmental damage and have a beneficial social impact (i.e. to maximise the contribution to the UN's 17 Sustainable Development Goals

[United Nations, 2015]). The final constraint is that these resources have to be found at lower cost than before.

The industry is continually challenged to maximise the amount of oil found for a given exploration expenditure. The key metric in exploration is the finding cost per barrel, that is, how much does it cost to find a barrel of oil? Clearly the industry does not wish to waste money. But oil and gas exploration is a risky business in that not all wells find hydrocarbons and a failed well (a dry well) is expensive. The work that is done to 'de-risk' a given well and to choose its location is vital. The industry is continually looking for the least costly way to understand the geology to predict a hydrocarbon accumulation and choose a well location. There is always a tension between a company's investment in 'de-risking' a well and drilling the well itself.

This is where technology comes in. The current mainstay technology for exploration and production is reflection seismic. However, as we argue in this book, there are other geophysical technologies that are cheaper to use and, when used in conjunction with reflection seismic, will give a better answer. These technologies become even more important as companies look to reduce their exploration budgets and find more resources with fewer funds.

The obvious challenge for oil companies is where to look to find the oil and gas resources that match these criteria. Figure 2.1 shows a global map of the world's basins (Roberts and Bally, 2012) and is the starting point for many companies'

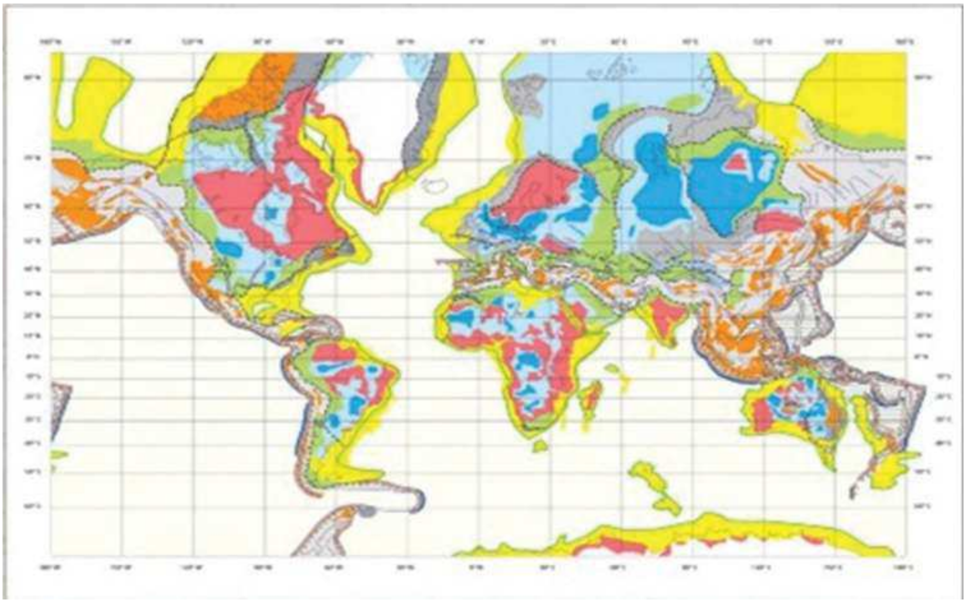

Figure 2.1 The sedimentary basins of the world (Roberts and Bally, 2012).

exploration processes. This shows the wide range of basin types and geographies that are potential exploration targets. The choice of where to look is governed by the company's strategy and the type of exploration it wishes to do.

Exploring in basins that have no discovered hydrocarbons requires different skills, approaches and technology from those for exploring in areas where there are already producing fields and production infrastructure. To guide this thinking, sedimentary basins (and indeed exploration plays[1]) are classed in differing stages of 'maturity' for hydrocarbon extraction (Westwood, personal communication). The industry generally categorises basins into four stages of maturity:

- **Frontier basins** are defined as sedimentary basins that might be of interest to the industry that do not have a commercial oil discovery.
- **Emerging basins** are those in which the hydrocarbon volumes discovered per well continue at the same rate and before the discovery rate starts to decline.
- **Maturing basins** are basins in which the hydrocarbons discovered per well start to decline but before the extended tail which defines the **mature basins**.

There is, of course, an element of subjectivity as to where the latter two categories start and finish. The best way to illustrate the evolving exploration maturity of a basin is using a creaming curve. Figure 2.2 shows typical 'creaming curves' for the basins in the North Sea. This is a graph plotting the cumulative growth of discovered resource (volume of oil and gas commercial discoveries) through time. The graph starts with the first commercial discovery in each basin, noting that in all

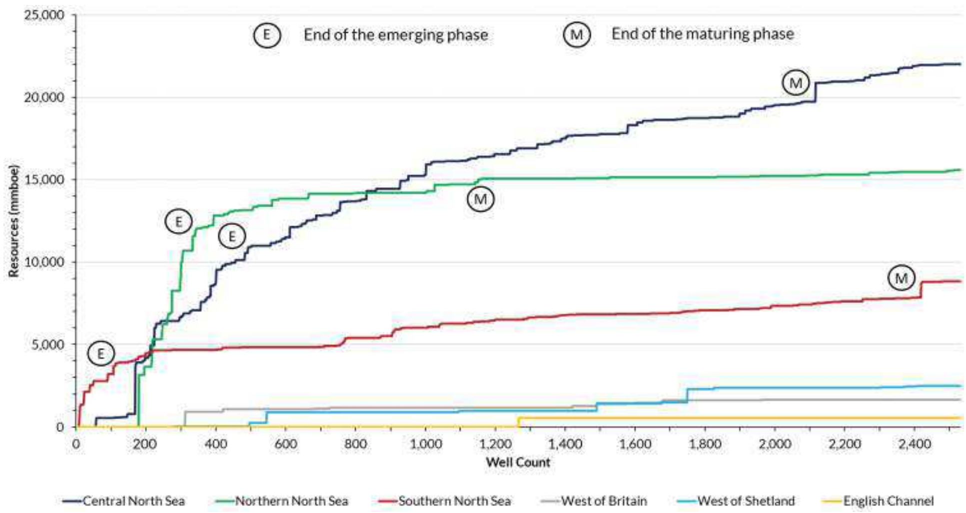

Figure 2.2 Creaming curves for the North Sea showing the transition from the emerging to maturing and mature phases of exploration. (Source: Westwood Global Energy. Used with permission)