Introduction to
Exploration Geophysics
with Recent Advances

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The purpose of this book is to give an introduction to exploration geophysics. Geophysicists explore the earth by making physical measurements at the surface. They use these measurements to map subsurface rocks and their fluids at all scales, and to describe the subsurface rocks in physical terms – velocity, density, electrical resistivity, magnetism, and so on. In this book we explain how geophysics is used to ‘look into’ the earth and how geophysical technologies help us to understand the solid subsurface beneath our feet.

The book is derived from articles in the column ‘Recent Advances in Technology’ in the interdisciplinary magazine GEO ExPro, which the authors have been writing since 2007. Each article is based on our research and experience, with help from internet sources as well as from several colleagues from industry and academia who have contributed as guest authors.

Each technical subject has its own chapter, and can be read independently of other chapters, but to make it easier to read, we have prepared an introductory chapter called ‘Looking into the Earth’, which outlines the scope of geophysical methods and gives an overview demonstrating how everything in petroleum geophysics is interrelated. We focus on basic principles and from there explain the recent advances within various exploration techniques, hopefully in an easy way with limited use of equations but with many examples.

We acknowledge that the area of application of geophysical methods is very wide, and much has had to be omitted. It is inevitable that our selection of topics has prejudice resulting from personal interest and experience, which has led to a bias towards descriptions and examples based on our extensive expertise in the marine seismic industry in north-west Europe.

The chapters are:

1. **Looking into the Earth**: an introduction to geophysics and geophysical exploration methods, including seismics, electromagnetics, gravimetry and magnetometry and use of satellite data, followed by illustrative data examples of how geophysics is used to look into the earth. We show how rock physics can translate geophysical observations into reservoir properties.

2. **Elements of Seismic Surveying**: a brief history of seismic and, in particular, seismic surveying in the North Sea. We introduce four-component ocean-bottom seismic surveying and imaging, as well as wide and full azimuth seismic surveying. In Codes and Ciphers we look at ways of decoding nature’s disorder, and use that to discuss simultaneous sources as one avenue to improving the way geophysicists deliver high-quality data while maintaining viability in a cost-focused market.

3. **Marine Seismic Sources and Sounds in the Sea**: we summarise salient points for geoscientists who need to sharpen their rusty skills in seismic source technology. We give you a feeling for decibels in air and water; discuss the effect seismic sources may have on marine life; and present sound and sound modelling in the sea.

4. **Reservoir Monitoring Technology**: a review of the use of time-lapse (4D) seismic for reservoir monitoring and an introduction to the noble art of analysing data. We discuss typical monitoring parameters: fluid saturation, reservoir pressure, and reservoir compaction. Rapid implementation of 4D technology has led to increased hydrocarbon production through infill drilling. It is also effective in the early detection of unwanted and unforeseen reservoir developments, such as gas breakthrough and sudden pressure increases. Finally, we present several field examples from Life of Field Seismic (LoFS) / Permanent Reservoir Monitoring (PRM) over Valhall, Ekofisk, Snorre and Grane.

5. **Broadband Seismic Technology and Beyond**: an introduction to what broadband seismic is, what this technology has to offer, and the various broadband technologies that have recently been commercialised; and we describe how seismic ghosts can be exorcised.

6. **Gravity and Magnetics for Hydrocarbon Exploration**: how unexplored sedimentary basins can be unravelled by gravity, and how gravity and magnetics are used in cross-disciplinary workflows for hydrocarbon exploration.

7. **Supercomputers for Beginners**: an introduction to supercomputers: how to design parallel software, what is GPU-accelerated processing, supercomputers and seismic imaging, and quantum computers.

8. **Gas Hydrates**: gas hydrates have been often mentioned as an important possible source of natural gas. We give simple explanations of what gas hydrates are, where they can be found on Earth and what their physical properties are. We also discuss the possibilities of gas hydrates on Mars and elsewhere in outer space.
9. **Dwelling on the Mysteries of Space**: this last chapter looks at the monsters, marvels and machinery of the universe, and some important discoveries that have led the way to mind-boggling and fascinating questions at the cutting edge of physics today: from Big Bang to our solar system; observations of hot Jupiters, which have opened the possibility that our solar system was not born in the configuration that we see today; and gravity waves, which give us a new window on the universe, back at the beginning of time. Final answers cannot be given, but the chosen topics show where the physical sciences are making contributions and are affecting our thinking and understanding of the world.

The book is designed primarily to reach students of all academic levels, including those at high school, college and university, as well as geo-students who plan to enrol in exploration geophysics graduate programmes. The authors also hope that the book will be a resource for those just entering the industry as well as for experienced professionals who are interested in learning more.

*Lasse Amundsen and Martin Landro*

*Trondheim, 1 April 2017*

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has been a professor at the Norwegian University of Science and Technology (NTNU) since 1998. He received a M.Sc. (1983) and a Ph.D. (1986) in physics from the Norwegian University of Science and Technology. From 1986 to 1989 he worked at SERES A/S and from 1989 to 1996 he was employed at IKU Petroleum Research as a research geophysicist and manager. From 1996 to 1998, he worked as a specialist at Statoil’s research centre in Trondheim, before joining NTNU. He received the Norman Falcon award from EAGE in 2000 and the award for best paper in *Geophysics* in 2001. In 2004 he received the Norwegian Geophysical award, and in 2007 Statoil’s researcher prize. He received the SINTEF award for outstanding pedagogical activity in 2009. In 2010 he received the Louis Cagniard award from EAGE and in 2011 the Eni award (New Frontiers in Hydrocarbons), followed by the Conrad Schlumberger award from EAGE in 2012. Landro’s research interests include seismic inversion, marine seismic acquisition, and 4D and 4C seismic, including geophysical monitoring of CO2 storage. In 2014 he received the IOR award from the Norwegian Petroleum Directorate. He is a member of EAGE, SEG, The Norwegian Academy of Technological Sciences and The Royal Norwegian Society of Sciences and Letters.

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Chapter 1

Looking into the Earth

Live as if you were to die tomorrow. Learn as if you were to live forever.
Mahatma Gandhi

Marine seismic survey geometry superimposed on top of the city of Oslo. This picture serves to illustrate the main components and the size of a conventional 3D marine seismic acquisition system, referred to as the largest moving man-made object on Earth. The vessel tows two airgun source arrays with three sub-array strings in each (white lines). In 2010, seismic vessels typically towed in the order of 10 streamers (yellow lines), 6,000m long, with 100m separation between the streamers. Today, we are seeing a range of streamer spreads, formatted to optimise survey productivity. The most advanced vessels can deploy up to 24 streamers, 10 km in length. As the streamers get longer, the recording time for any one shot must also increase in order to capture the returning signal at the longer source-receiver offsets.
1.1 Introduction

The world’s oil and gas – collectively known as petroleum, which is Latin for ‘rock oil’ – is formed from countless dead microscopic marine organisms like plankton, algae and bacteria. They piled up on the seabed as thick sludge and, together with plants and dead animals (including occasionally turtles, crocodiles and dinosaurs), were gradually buried by the minerals and sediments that accumulated on top of them. Bacteria then rotted the organisms into substances called kerogen (from Greek kero, κηρός ‘wax’ and -gen, γένεση ‘birth’). Over millions of years, as this kerogen was buried beneath several kilometres of sediments, heat and pressure cooked them into oil and gas. The ‘oil window’ is found in the 60–120°C interval (approximately 2–4 km depth), while the ‘gas window’ is found in the 100–200°C interval (about 3–6 km depth).

In north-west Europe, the Kimmeridge Clay Formation, deposited around 150 million years ago, is the most economically important unit of such rocks, being the major source rock for oil fields in the North Sea hydrocarbon province. The Kimmeridge Clay, named after the village of Kimmeridge on the Dorset coast of England, is also exposed as grey cliffs on the Dorset coast, forming part of the Jurassic Coast World Heritage Site.

Although there is evidence for the non-organic origin...
of methane gas, the majority of geoscientists consider oil and
gas found in sedimentary basins to originate from source
rocks. Without these, all the other components and processes
needed to form hydrocarbons become irrelevant. The source
rock’s hydrocarbon-generating potential is directly related to
its volume (thickness times areal extent), organic richness and
thermal maturity (exposure to heat over time).

In the Earth’s history, most rich source rocks were deposited
during six time periods that favoured their deposition and
preservation, starting with the Silurian (444–416 million
years ago, or Ma), including the above mentioned Late Jurassic
(165–145 Ma) up to the Oligocene–Miocene period (34–5 Ma)
(see Figure 1.4).

Since oil and gas are relatively low density compared

![Figure 1.4: The geological time scale is used by earth scientists to describe the timing and relationships between events that have occurred throughout the 4.6 billion years of Earth’s history. It is organised into intervals based on important changes that have been seen in the geologic record. The largest defined unit of time is the eon. Eons then are divided into eras, which in turn are divided into periods, epochs and ages. Eons, periods and epochs are usually named after places on Earth where the rocks of those times were first discovered. More specifically, eras or ‘chapters’ in Earth’s history are separated according to the nature of life they contained. Eons begin and end with dramatic changes in the types of animals and plants living on Earth. Periods are based upon the nature of the rocks and fossils found there.

Life on Earth started 3.5 billion years ago. During the Cambrian period of the Palaeozoic era, shellfishes and corals developed. In the Silurian period, around 435 million years ago, the first land plants, swamp trees and primitive reptiles evolved, and around 225 million years ago during the Triassic period the dinosaurs came on the scene. The Jurassic saw the first mammals and birds. Around 2 million years ago, in the Pliocene, Homo habilis appeared – the first human species to be given the genus name Homo, meaning ‘man’. Because of the geological record we know that continental drift – the movement of the plates on the earth’s crust – resulted in the current position of the continents. Further, we know that the geological record contains evidence of several extinctions, including the Cretaceous–Paleogene (K–Pg) extinction event that marks the end of the Cretaceous and the beginning of the Paleogene 65 million years ago, when more than half of the earth’s species were obliterated, including the dinosaurs. Scientists have two main hypotheses to possibly explain this extinction: an extra-terrestrial impact, such as a huge meteorite or an asteroid, or a massive bout of volcanism. A layer of rock rich in the metal iridium dated to the extinction event is found all over the world, on land and in the oceans. Iridium is rare on Earth but is commonly found in meteorites. Later in this chapter you will read the story of the Chicxulub crater, found during geophysical surveying over Mexico’s Yucatán Peninsula, and dated to 65 million years ago.
Chapter 2

Elements of Seismic Surveying

Whoever is ignorant of the past remains forever a child. For what is the worth of human life, unless it is woven into the life of our ancestors by the records of history?

Marcus Tullius Cicero (106–43 BCE, Roman statesman, lawyer, scholar and writer)

An artist’s impression of a modern marine seismic survey seen from below. The seismic vessel is towing several long streamers. The two sources, fired in a flip-flop manner, consist of three subarrays each. A deflector (door) is visible on the right-hand side of the picture. Such a door is shown in more detail in Figure 1.27.
The origin of the term ‘seismic’ is the Greek word ‘seismos’, which means shaking. Earthquakes were in Greek called ‘seismos tes ges’, literally shaking of the Earth. The first known use of the word seismic is from 1858, and the terms seismic and seismology started to be used around the middle of the 19th century.

In a broad sense, seismology is defined as the science of the study of earthquakes: their generation (source) and the vibration and propagation of seismic waves inside the Earth, and the various types of instruments used to measure seismic motion.

The earliest known seismic instrument to detect earthquake motion was the seismoscope, invented by the Chinese scholar, Zhang Heng, as early as AD 132. The seismoscope was cylindrical in shape with eight dragon heads arranged around its upper circumference, each with a ball in its mouth. Below were eight frogs, each directly under a dragon’s head. When an earthquake occurred, its motion would cause a pendulumfastened to the base of the vase to swing. The pendulum would knock a ball, which dropped and was caught in a frog’s mouth, generating a sound. Which mouth it dropped into indicated the direction from which the earthquake came.

Exploration seismic deals with the use of man-generated acoustic or elastic waves to locate mineral resources, water, geothermal reservoirs, archaeological sites, as well as hydrocarbons. The different methods of seismology are applied and have been refined to serve special purposes. This is especially true for seismic exploration for oil and gas, where technology has developed rapidly.

Broadly speaking, the major elements of seismic exploration technology that enable geoscientists to ‘see’ underground many kilometres below the surface in order to explore, develop and produce hydrocarbons are:

1. Seismic acquisition technologies: a variety of survey techniques are available to address specific geophysical and geological objectives.
2. Seismic imaging technologies: complex algorithms are used to process and analyse the vast amounts of acquired data utilising massive computing power (supercomputers).
3. Visualisation and integration with other data.

Here we give a brief history of seismic surveying. Readers with more appetite for the history of seismic technologies are referred to Sheriff and Geldart (1995) and Lawyer et al. (2001). The remaining sections in this chapter will focus on the link between seismic acquisition geometry and seismic imaging, where we will focus on imaging from ocean-bottom seismic surveys, subsalt imaging developments in the Gulf of Mexico, and will suggest new surveying geometries that could significantly improve seismic imaging.
Chapter 3

Marine Seismic Sources and Sounds in the Sea

If learning the truth is the scientist’s goal... then he must make himself the enemy of all that he reads.

Ibn al-Haytham (965–1040)

This chapter on marine seismic sources will summarise salient points for geoscientists who need to sharpen their rusty skills in seismic source technology and sound in the sea. It will also discuss the effect seismic sources have on marine life.
3.1 Airguns for Non-Experts
The airgun has long been the most popular marine seismic source.

Double, double, toil and trouble; airguns fire and ocean bubble.
With apologies to Shakespeare’s three witches in Macbeth, and thanks to our colleagues Bill Dragoset and Jan Langhammer.

A seismic source is defined as any device which releases energy into the earth in the form of seismic waves. The major source type in marine exploration is the airgun array, which since the 1970s has been by far the most popular. The airgun can be described as a chamber of compressed air that is released rapidly into the surrounding water to create an acoustic pulse. The airgun is the most commonly used source because the pulses are predictable, repeatable and controllable, it uses compressed air which is cheap and readily available, and it has only a minor impact on marine life.

3.1.1 Size and Geometry
An airgun volume is measured in litres (l) or more commonly, by the conservative petroleum geophysicist, in cubic inches (in³). Typical volumes of individual airguns used by the exploration industry vary from 20 in³ (0.3 litres) to 800 in³ (13.1 litres), while academic seismic refraction studies can use volumes up to 1,600 in³ (26.2 litres). An airgun array consists of 3–6 subarrays called strings, each string containing 6–8 individual guns, so that the array usually involves between 18 and 48 guns, although in special cases as many as 100 guns an array can be used. The airgun array volume is the sum of the volumes of each gun, and is typically in the range 3,000–8,000 in³ (49.2–131.6 litres).

The airguns hang in the sea beneath floats between 3m and 10m below the sea surface, generally at about 6m, except in refraction studies when a deeper deployment is needed. The gun pressure most commonly used by the seismic industry is 2,000 psi (138 bar). During a survey the guns fire every 10–15 seconds. It is common to arrange several (2–4) airguns in a cluster, with the guns so close together that they behave as a larger single gun. The main purpose of clustering is to improve signal characteristics, since the bubble motion (see Section 3.1.2.1) is reduced by this configuration.

The energy sent out by airgun arrays is predominantly directed vertically downwards. The broad band of frequencies from the array form a pulse with peak-to-peak amplitude in the range 14–28 bar-m, corresponding to 243–249 dB re 1 μPa-m vertically downward. The amplitude levels emitted horizontally tend to be 15–24 dB lower. These numbers are frequency dependent. By filtering out high frequencies there is less deviation between amplitude levels vertically and horizontally.

Here, ‘dB re 1 μPa-m’ means decibel value peak-to-peak relative to the reference pressure one micropascal at a reference distance of one metre. Confusing units? Read the box on definitions and for a guide of the physical principles of airguns and the basic sound measurement units. Our focus for the moment is on the vertically downward travelling ‘far-field’ signature of an airgun array as this signature provides a quantitative measure of the array’s performance.

3.1.2 Bubble Oscillations
When compressed air is suddenly released into the water an oscillating bubble forms. This process is described in Parkes and Hatton (1986):

“Initially, the pressure inside the bubble greatly exceeds the hydrostatic (external) pressure. The air bubble then expands well beyond the point at which the internal and hydrostatic pressures are equal. When the expansion ceases, the internal bubble pressure is below the hydrostatic pressure, so that the bubble starts to collapse. The collapse overshoots the equilibrium position and the cycle starts once again. The bubble continues to oscillate, with a period typically in the range of tens to hundreds of milliseconds.”

The oscillation is stopped due to frictional forces, and the buoyancy of the bubble causes it to break the sea surface. If
Chapter 4

Reservoir Monitoring Technology

Repeat your mistakes.
Rodney Calvert (1944–2007)

The Grane field demonstrates the permanent reservoir monitoring (PRM) setup. The water depth is 130m, and the receiver cables are trenched into the seabed with a separation distance of 300m between them. The in-line distance between receivers is 50m. A vessel towing two sources is used for PRM at both the Snorre and the Grane fields.
4.1 An Introduction to 4D Seismic

This introduction is partially based on Chapter 19 in Petroleum Geoscience (edited by K. Bjørlykke) and on unpublished material we have gathered from work at Statoil and at NTNU over two decades.

4D, or time-lapse, seismic is a phrase used to describe the process of using two or more seismic surveys acquired over the same area or field to find changes that have occurred over calendar time. For hydrocarbon reservoirs, these changes might represent production related changes such as pore pressure, temperature or fluid saturation. 4D seismic might also be used to monitor seasonal changes (near surface effects), earthquakes (before and after) or, for instance, underground storage of CO2.

As a common reservoir monitoring tool today, 4D seismic has gone through a tremendous development over the past three decades. In the beginning monitoring was done by repeating 2D seismic lines, and then by repeating large 3D surveys. Today, several fields can be monitored by trenched receiver cables at the seafloor, enabling frequent and close to continuous reservoir monitoring. The benefit of this development is two-fold: increased hydrocarbon production by infill drilling, and early detection of unwanted and unforeseen reservoir developments, such as gas breakthrough and sudden pressure increases.

The first 4D commercial seismic surveys were acquired in America in the early 1980s for heavy oil fields. Heavy oil is viscous, and steam injection was used as a way to heat the oil and thereby reduce the viscosity. In this way the oil migration towards the producing wells was improved, and oil production increased. During the heating process, the P-wave velocity of the oil decreased, and this change was clearly observed on repeated seismic data acquired before and after the heating process. The major breakthrough for commercial 4D seismic acquisition in the North Sea was the Gullfaks 4D study launched by Statoil in 1995. By comparing seismic data before and after the start of production, Statoil identified several (about 20) targets that were undrained. Statoil estimated the added value of this study to be of the order of US$ 1 billion.

4.1.1 An Early North Sea 4D – Still Alive!

One of the first 4D studies performed in the North Sea, however, had a more dramatic background: an underground blowout that Saga Petroleum encountered when drilling exploration well 2/4-14, which occurred in January 1989, and lasted for almost a year. During this period, Saga Petroleum acquired several 2D seismic lines close to the well. Figure 4.2 shows a vertical cross-section from the 3D seismic data that was acquired in 1991, two years after the blowout. We can clearly see vertical chimneys along the two vertical well bores. The chimney in well 14 is more pronounced and stretches further into the overburden, compared to well 15.

When we use time-lapse seismic data as shown in Figure 4.3, we clearly see huge and dramatic changes in the overburden. At 520 ms (two-way traveltime) we observe a new event that is hardly visible on the 1988 data. This is interpreted as gas leaking vertically outside well 14 from a leakage point through the casing at approximately 900m depth, and into a thin and almost horizontal sand layer at approximately 490m depth. Figure 4.3 shows a clear example of the most common interpretation.

Figure 4.1: Artistic view of the rotated Jurassic fault blocks constituting the Gullfaks reservoir (left). Solid black lines represent wells; light brown-yellow layers represent sandstones, and blue-grey layers represent shales. The right-hand figure illustrates the connection between the top reservoir sandstone layer (dashed red line) and the corresponding seismic response before and after ten years of production. The original oil-water contact is shown as a dashed green line on the time-lapse seismic data, clearly demonstrating the production effect on the data. Also notice the decreased traveltime for the seismic event below the oil-water contact. This reduction in velocity is caused by water replacing oil in the lower part of the reservoir rock.

Figure 4.2: Vertical cross-section of a seismic line acquired in 1991 (after the blowout) intersecting the blowout well (2/4-14) and the relief well (2/4-15). Notice the gas accumulation along the vertical well paths of both wells, and the horizontal accumulation of gas (leaking from the well and marked by the red arrow).

Figure 4.3: Time-lapse seismic data acquired before and after the blowout. Notice the dramatic change in velocity and the new event at 520 ms (two-way traveltime) indicating gas leakage vertically outside well 14.
Chapter 5

Broadband Seismic Technology and Beyond

You know what the issue is with this world? Everyone wants some magical solution to their problem and everyone refuses to believe in magic.

From Alice’s Adventures in Wonderland – a novel written in 1865 by English mathematician Charles Lutwidge Dodgson (1832–1898) under the pseudonym Lewis Carroll.

Once a new technology rolls over you, if you’re not part of the steamroller, you’re part of the road. One such new technology is broadband seismic. Want to be part of the steamroller or the road? In this chapter, we give you an introduction to what broadband seismic has to offer.
5.1 The Drive for Better Bandwidth and Resolution

This section gives an introduction to resolution and the benefits of hunting for low frequencies in particular.

Technology presumes there’s just one right way to do things and there never is.
Robert M. Pirsig (1928–), American writer and philosopher

Most people think of broadband with regard to telecommunications, in which a wide band of frequencies is available to transmit information. This large number of frequencies means that information can be multiplexed and sent on many different frequencies or channels within the band concurrently, allowing more information to be transmitted in a given amount of time (much as more lanes on a highway allow more cars to travel on it at the same time).

In seismic exploration broadband refers to a wider band of frequencies being recorded and utilised than in conventional seismic exploration. In the marine case the conventional acquisition system is said to give a useable bandwidth of typically between 8–80 Hz, whereas broadband seismic systems are claimed to give useable frequencies from as low as 2.5 Hz up to 200 Hz or more for shallow targets. On land, marine vibrators today can produce signal frequencies down to 1.5 Hz.

In this chapter we will discuss the seismic vendors’ various new broadband solutions – a combination of leading equipment, unique acquisition techniques and proprietary data processing technology. As the quote at the start of this section says, it is fair to state that there is not one right way to do things. Each of the vendor’s solutions has unique capabilities.

5.1.1 Organ Pipes
Did you know that organ pipes have gone through a technological development similar to that of broadband.

Figure 5.1: The world’s largest pipe organ was built between May 1929 and December 1932 by the Midmer-Losh Organ Company of Merrick, Long Island, New York. It weighs 150 tons, boasts seven manuals and has 1,439 stop keys, 1,255 speaking stops, 455 ranks, and 33,112 pipes! The most impressive stop on the organ would have to be the 16 ft Ophicleide, which is the world’s loudest stop. This stop has six times the volume of the loudest train whistle.
seismic? The frequency $f$ of an organ pipe is $f = \frac{v}{\lambda}$, where $v$ is the speed of sound in air (340 m/s) and $\lambda$ is the wavelength. Let $L$ be the length of the pipe. The longest possible wavelength equals $2L$ and $4L$ for open and closed pipes respectively. The maximum wavelength thus is $\lambda = 4L$, and the corresponding minimum frequency equals $f = \frac{v}{4L}$.

One of the biggest organs in the world is the Boardwalk Hall Auditorium organ in Atlantic City. It is equipped with 33,112 pipes, and the biggest pipe has a length of 64 ft. This is an open pipe so the corresponding lowest frequency is around 8 Hz. A closed pipe of the same length would give a lower frequency of 4 Hz.

But the story does not stop at 4 Hz. The lowest produced note is obtained by combining a stopped 64 ft and stopped 422/3 ft pipe to produce a resultant 256 ft pipe which gives 2 Hz! This is far below the threshold of the human ear, which is approximately 16 Hz. So what is the point in this focus on low frequencies for organ pipes? Can we feel the low frequencies directly on our body, or is it a combination of hearing and body feeling?

Anyhow, there is a strong similarity between the design of big organ pipes and today’s developments in broadband seismic. As geophysicists, we would be thrilled if our marine seismic system produced frequencies truly from 2 Hz and upwards. We would want to activate all the pipes of the organ in Atlantic City, and especially the big pipes! The low frequencies are of particular interest for deep imaging, inversion and high-end interpretation.

### 5.1.2 Temporal Resolution

Improving bandwidth and resolution has been a priority since the early days of the seismic method – to see thinner beds, to image smaller faults, and to detect lateral changes in lithology. Although sometimes used synonymously, the terms bandwidth and resolution actually represent different concepts. Bandwidth describes simply the breadth of frequencies comprising a spectrum. This is often expressed in terms of octaves.

Commonly referred to in music, an octave is the interval between one frequency and another with half or double its frequency. As an example, the frequency range from $f_1$ to $f_2 > f_1$ represents one octave if $f_2 = 2f_1$. The range from 4 to 8 Hz represents one octave of bandwidth, as do ranges 8–16 Hz, and 16–32 Hz. Also, the range from $f_1$ to $f_2 < f_1$ represents one octave if $f_2 = f_1/2$.

In a classic empirical study, Kallweit and Wood (1982) found a useful relationship between bandwidth and resolution. For a zero-phase wavelet with at least two octaves of bandwidth, they showed that the temporal resolution $T_{\text{r}}$ in the noise-free case could be expressed as $T_{\text{r}} = \frac{1}{1.5f_{\max}}$, where $f_{\max}$ is the maximum frequency in the wavelet. Other definitions are possible, but for two octaves or more of bandwidth the clue is that one can approximately relate temporal resolution to the highest, and only the highest, frequency of a wavelet. This leads to some very useful and quite accurate predictions. Examples are that wavelet breadth is $T_{\text{b}} = \frac{1}{0.7f_{\max}}$ and peak-to-trough is $T_{\text{PT}} = \frac{1}{1.4f_{\max}}$.

Figure 5.2 demonstrates the expected improvement in resolution associated with increasing $f_{\max}$. We see that when the maximum frequency value is increased while holding $f_{\min}$ fixed, sharper temporal wavelets are obtained. Meanwhile, the right side of the figure shows three more temporal wavelets where the $f_{\min}$ value is changed while holding $f_{\max}$ fixed. We see that the main lobe shows hardly any change while the side lobes diminish as $f_{\min}$ is lowered. Thus, filling in the low frequencies gives wavelets with less pronounced side lobe amplitudes. It is attractive because it is smoother, and with less side lobe energy in the wavelet it is unlikely that a small-amplitude event will be lost amid the side lobes from neighbouring, large-amplitude reflections.

Figure 5.2: Temporal resolution. Left: Resolution increases with the maximum frequency. The number of octaves is 2, 3 and 4 for the black, blue and red spectra, respectively. Right: Resolution is relatively insensitive to the minimum frequency. The number of octaves are 2, 3 and 4, but the resolution is the same. A key learning is that side lobe reduction is obtained by adding low frequencies.
Chapter 6

Gravity and Magnetics for Hydrocarbon Exploration

Pick a flower on Earth and you move the farthest star.
Paul A. M. Dirac (1902–1984)

This gravity anomaly map shows where the Earth’s gravity field differs from a simplified model that assumes the Earth is perfectly smooth and featureless. Gravity anomalies are often due to unusual concentrations of mass in a region. For example, the presence of mountain ranges will cause the gravitational force to be stronger than it would be on a featureless planet — yielding a positive gravity anomaly. Positive anomalies are coloured yellow, orange, or red. Conversely, the presence of ocean trenches or even the depression of the landmass that was caused by the presence of glaciers millennia ago can cause negative gravity anomalies. Negative anomalies are coloured in shades of blue.
6.1 Gravity for Hydrocarbon Exploration

Can an unexplored sedimentary basin be unravelled by gravity? How can gravity in cross-disciplinary workflows estimate the base of salt domes and gas saturation in shallow sedimentary traps? There are many uses for gravity measurements in hydrocarbon exploration.

Gravity. It’s not just a good idea. It’s the Law.
Gerry Mooney (1977)

Thanks to Newton’s Law of universal gravitation, you are safely standing on earth and not flying off into space. The gravitational attraction between two masses increases as their mass expands and decreases as the distance between them grows. For you, this means that you are one mass and mother Earth is another mass — luckily a big one, which attracts you.

From the geological viewpoint, all subsurface rocks are part of the earth’s mass. They cause an attraction on a test-mass, spring-mounted in a gravimeter, the instrument that measures gravity. Just the size of a car battery, it can be located on seismic vessels, aeroplanes or simply on the ground. Tiny deviations from the average gravity force caused by density variations in subsurface rocks are called gravity anomalies. The density of a rock relates to its mineral composition and pore space: sediments, for example, possess low densities, increasing with compaction towards crystalline rocks like granites. Higher on the density scale are mafic rocks like gabbros and basalts; and densest of all are ultramafic mantle rocks.

Gravity anomalies are a composite expression of all the subsurface densities and as such contain a clue to the subsurface geology. The task of an interpreter is to find a reasonable density distribution that matches the gravity anomalies and other geological data. This procedure, known as gravity modelling, can be done simply along a profile or in a more advanced fashion on gridded or triangulated surfaces or even using voxels. Once a basic subsurface geometry has been established and density ranges for the expected rocks are set, the fun begins: grab a body or a point in the model, move it with your cursor, see the immediate change in the gravity in your program and play this game towards a model that matches the gravity (Figure 6.2).

Alternatively, you can let an inversion algorithm do the work, by telling the program which points it is allowed to move, or which density it can change, and it will find the solution with the best gravity match. This leads to a familiar concern regarding the inherent ambiguity in gravity interpretation, since both unrealistic and reasonable models can generate exactly the same gravity anomaly. The most important strategy to tame the ‘beast’ of ambiguity is to utilise constraints, such as the geometry of layers interpreted from seismic, densities from geological databases, or geological models or analogues. Gravity will always provide a solution space, hopefully narrow enough to provide the missing piece of the puzzle. It can be used to supplement seismic data and geological models with unknown quantities or to create an initial coarse structural model of an unexplored basin.

Let’s look at three important tasks where gravity can make an impact in hydrocarbon exploration.

6.1.1 Basin Structure in Early Exploration

Early basin exploration suffers from a lack of geological information due to scarce seismic coverage. Gravity interpretation can address open questions of basin geometry, sedimentary thickness and direction of structural trends, as illustrated in the synthetic model in Figure 6.3, consisting of crystalline basement and sediments, where the clue is the contrasting density. Gravity anomalies and vertical gradients have been computed, the latter representing a highpass filtered gravity version, which enhances details of the shallow structure better than
Chapter 7

Supercomputers for Beginners

Guest Contributor: Børge Arntsen, NTNU

Computers are like humans – they do everything except think.
John von Neumann (1903–1957)

Computers are more powerful than humans in executing simple step-by-step instructions. Humans are more powerful than computers in handling tasks that are not easily broken into simple steps. A computer as powerful as the human brain would be able to perform about 38,000 trillion operations per second and hold about 3.584 TB of memory.
7.1 Introducing Supercomputers

Supercomputers help geophysicists to analyse vast amounts of seismic data faster and more accurately in their search for oil and gas. Seismic surveying is a merger of big data and big computing, and the seismic industry is expected to be an early adopter of new and fast computing technologies. Majors like Total, Eni and BP have rolled out mega-supercomputing centres for seismic imaging. In March 2015, PGS installed a five-petaflop supercomputer, the most powerful in the seismic industry. By 2020 we will have exaflop computers doing a quintillion \(10^{18}\) calculations per second. This section is an introduction to supercomputers using high-level explanations.

Anonymous

Cutting-edge research and development (R&D) is a competitive differentiator for many organisations, allowing them to attract leading talent and solve some of the world’s largest challenges. Supercomputing is revolutionising the types of problems we are able to solve in all branches of the physical sciences. Almost every university and major E&P company hosts some kind of supercomputing architecture. The primary application of supercomputing in E&P is seismic imaging, while secondary applications are reservoir simulation and basin simulation. The availability of computing resources is only going to increase in the future and as a result it is important to know the primary concepts behind supercomputing.

Figure 7.1: The #2 system in 2016’s TOP500 was Tianhe-2 (which means Milky Way-2), a supercomputer developed by China’s National University of Defence Technology at a cost of 2.4 billion yuan ($390 million). Its performance of 54.9 petaflops (quadrillions of calculations per second) is used for simulation, analysis, and government security applications. It has 125 cabinets housing 16,000 computer nodes with a total of 3,120,000 compute cores, and each of those nodes possesses 88 gigabytes of memory. Powerful computers also use more electricity; at peak power consumption, it draws 17.6 MW of power, with the water cooling system bringing that up to 24 MW. The electricity bill for Tianhe-2 runs at 400,000–600,000 yuan ($65,000–$100,000) a day. The computer complex occupies 720 m² of space. The #1 system in 2016 was also Chinese: Sunway TaihuLight, at 125.4 petaflops. The US is responding to China’s lead by developing the supercomputer Summit, claimed to be operational in 2018, at 200 petaflops.
7.1.1 What is a Supercomputer?

The official definition of a supercomputer is a computer that leads the world in terms of processing capacity—speed of calculation—at the time of its introduction. It is an extremely fast computer which has, at present, a number-crunching power measured in hundreds of billions of floating point operations. Today’s supercomputer is destined to become tomorrow’s ‘regular’ computer. For many, a better definition of supercomputer may be any computer that is only one generation behind what you really need!

Supercomputers are made up of many smaller computers—sometimes thousands of them—connected via fast local network connections. Those smaller computers work as an ‘army of ants’ to solve difficult scientific or engineering calculations very fast. Supercomputers are built for very specific purposes. To fully exploit their computational capabilities, computer scientists have to spend months, if not years, writing or rewriting software codes to train the machine to do the job efficiently.

Supercomputers are expensive, with the top 100 or so machines in the world costing upwards of US$20 million each.

The terms supercomputing and high-performance computing (HPC) are sometimes used interchangeably. HPC is the use of supercomputers and parallel processing techniques for solving complex computational problems.

The first scientific supercomputer was ENIAC (Electronic Numerical Integrator and Computer), constructed at the University of Pennsylvania in 1945 (see Figure 7.2). It was about 25m long and weighed 30 tons. Two famous recent supercomputers are IBM’s Deep Blue machine from 1997, which was built specifically to play chess (against Russian grand master Garry Kasparov), and IBM’s Watson machine (named for IBM’s founder, Thomas Watson, and his son), engineered to play the game Jeopardy.

7.1.2 Computer Speed

The definition of a supercomputer is defined by processing speed. Computer speed is measured in Floating Point Operations Per Second (FLOPS). Floating point is a way to represent real numbers (not integers) in a computer. A floating
7.4 Quantum Computers

The 2012 Nobel Prize in Physics was awarded to Serge Haroche and David Wineland for Quantum Entanglement, which is a phenomenon that enables the manipulation and measurement of individual quantum systems without destroying them. This may pave the way for superfast computers, called quantum computers. Some of the smartest physicists, mathematicians and information theorists today are driving this development. Quantum computers may find applications in inverse problems, like those which the industry is trying to solve in geophysics. Give it 20–30 years, and you will have quantum computer desktops.

God does not play dice with the universe.
Albert Einstein

Will we ever have the amount of computing power that we need or want? What is the next era of computing? If we agree with Moore’s Law, the years 2020–2030 will find the circuits on a microprocessor measured on an atomic scale. The logical next step will be to develop quantum computers, which tap directly into the field of quantum mechanics to speed computation. As of 2016, the development of quantum computers is still in its infancy, but experiments have been carried out in which quantum computational operations were executed on a very small number of quantum bits. Academic research labs and universities around the world and companies such as IBM, NASA, Google, Microsoft and Lockheed Martin have been working on the basic building blocks of a quantum computer for some years. But most people, like us, do not really understand what quantum computing is and isn’t. We will not even attempt to give a full explanation, but only an introduction.

Recall that a conventional computer stores information as 0s or 1s. Most real numbers are stored with a set of 64 zeroes or ones—i.e. bits. However, the quantum computer uses quantum bits, or qubits – which can be a 1 or a 0 or both at the same time, a condition known as a superposition. Qubits represent particles – atoms, ions, photons or electrons – and their respective control devices work together to act as computer memory and a processor. Because qubits can exist in quantum superposition, or multiple states simultaneously, the quantum computer has the potential to be millions of times more powerful than today’s most powerful supercomputers. But – of

Figure 7.13: Sorry Albert, but it looks like the universe is one big dice game. Recent studies have confirmed that the ‘spooky action at a distance’ that so upset Einstein — the notion that two entangled particles separated by long distances can instantly affect each other — has been proven to work.
Chapter 8

Gas Hydrates

Robert Frost (1874–1963)

Gas hydrates are naturally occurring ‘ice-like’ combinations of natural gas and water that have the potential to provide an immense resource of natural gas from the world’s oceans and polar regions. Gas hydrates are known to be widespread in permafrost regions and beneath the sea in sediments of outer continental margins. It is generally accepted that the volume of natural gas contained in the world’s gas hydrate accumulations greatly exceeds that of known gas reserves. There is also growing evidence that natural gas can be produced from gas hydrates with existing conventional oil and gas production technology.
8.1 Burning Ice

Scientists have known and studied natural gas hydrates for decades. Vast deposits of hydrates have been found in both the permafrost and the continental shelves of the oceans of the world. Natural gas hydrates also exist in the universe. Hydrates have played an important role during formation of planets, and our atmosphere and hydrosphere. Want to know more? Read on!

Curiosity is always the starting point for solutions to a problem.
Galileo Galilei (1564–1642)

In this chapter we will explain in a simple way what gas hydrates are, where they can be found in nature, and what their physical properties are. Natural gas hydrates are a potential source of energy and may play a role in climate change and geological hazards. Therefore a number of countries, including Japan, USA, India, China, Korea and Germany, have national programmes for studying gas hydrates and the potential for industrial production of natural gas from them.

8.1.1 Gas Hydrates
You are familiar with ice: it is cold, hard, slippery, and buoyant. You can find icebergs and ice floes on the surface of the ocean in polar regions. But there is another, higher-pressure form of ice trapped at and beneath the seafloor that is far less familiar. This ice, which is known as gas hydrate, is created by the reaction of gas – predominantly methane – with water at low temperature and high pressure to form a crystalline solid. Such compounds are a common occurrence buried in permafrost and continental slope sediments around the world’s oceans. To create methane hydrate, the water and gas combine in a ratio of six molecules of water to one of gas. The gas draws in the water molecules to form a cage within which the methane molecule flutters in a strange molecular dance, feeling the attraction and pull of the hard ice walls of its prison, but without ever touching them.

Most natural gas hydrate appears to be in this structure, with methane as the trapped guest molecule, although alternative structures have also been identified, with guest molecules such as isobutane and propane, as well as lighter hydrocarbons.

Gas hydrates provide an extremely effective way of storing natural gas or methane (CH₄). At standard atmospheric temperature (20°C) and pressure (1 atm) conditions, 1 m³ of gas is replaced by the hydrate 164 m³ of water. Gas hydrate is therefore a potentially valuable energy resource.

Figure 8.1: The wild mountain landscape of Siberian taiga along the Lena River in Lenskie Stolby National Nature Park, Yakutia, Russia.
of solid methane hydrate is equivalent to 160 m$^3$ of free gas. Although global estimates range widely by more than two orders of magnitude, the most cited value is that of Kvenvolden in 1988, at 2x10$^{16}$ m$^3$ of gas, or 10,000 gigatons of carbon. In comparison, estimates for the known combined reserves of conventional hydrocarbons (natural gas, oil, coal) are about half that value.

8.1.2 Doubted by Experts

Yakutia, or the Sakha Republic, is a vast unexplored region of Siberia in the north-east of Russia. It is one of the rare places left on Earth where large expanses of wild nature – mountains, rivers, lakes, forests, tundra – have been left untouched by civilisation.

Yakutia is located in a permafrost zone, although the climate is continental, with summer temperatures in July in the city of Yakutsk reaching 40°C, as hot as Tokyo, while in winter it goes down to -50°C. Yakutia is where we find the Cold Pole, the coldest place in the northern hemisphere, where in 1924 the lowest ever temperature for our hemisphere, -71.2°C, was recorded. Here, beyond the Arctic Circle, the night lasts all winter, and the day all summer.

It is 1963, and Yuri Makogon, then at the Moscow Oil-Gas Gubkin Institute with a fresh MSc degree in petroleum engineering (now recently retired from Texas A&M University), is staying in the north-western part of Yakutia. He participates in the drilling of the Markhinskaya well, down to 1,800m where the temperature is 3.8°C. The well reveals a section of rock at 0°C temperature at a depth of 1,450m, although the permafrost ends at around 1,200m. Yuri recognises that this section of the rock matches hydrate formation conditions. He hypothesises the possibility that gas hydrates can exist and accumulate in such cold layers. His hydrate hypothesis is seriously doubted by the experts, and the idea needs experimental verification, so in 1965 Yuri experimentally proves that gas hydrates may accumulate as large natural deposits in porous rock. In 1969 this discovery is formally recognised and registered in the USSR. Yuri is today recognised as the first person to discover that hydrates of natural gas can accumulate as deposits in nature.

8.1.3 Easy Rapid Process

Monterey Canyon is a submarine canyon in Monterey Bay, California. It begins at the middle of the Monterey Bay, and extends 153 km into the Pacific Ocean where it terminates at the Monterey Canyon submarine fan, reaching depths of up to 3,600m below surface level at its deepest. The canyon’s depth and nutrient availability due to the regular influx of nutrient-rich sediment provide a habitat suitable for many marine life forms.

In 1996, the remotely operated vehicle (ROV) Ventana comes to rest in the Monterey Bay Canyon at a water depth of 910m where the temperature is 4°C. Operated by scientists from Monterey Bay Aquarium Research Institute, Stanford University, and the US Geological Survey, an amount of methane is injected into the water and bottom sediments. Within minutes, this mixture of gas and water forms into a solidified block, bright white and fluffy. The experiment shows not only that methane hydrate formation is possible in natural seawater but that the process is extremely easy and rapid, so long as the pressure and temperature conditions are right. Prior calculations had shown that the local hydrographic conditions gave an upper limit of 525m for the pressure-temperature (P-T) boundary defining methane hydrate formation at this site, and thus the experiment takes place well within the stability range for this reaction to occur.

8.1.4 An Unusual Catch

Barkley Canyon is located off Vancouver Island, Canada, on the northern Cascadia Margin accretionary prism. The...
Chapter 9

Dwelling on the Mysteries of Space

Pumbaa: “Timon, ever wonder what those sparkly dots are up there?”
Timon: “Pumbaa, I don’t wonder; I know.”
Pumbaa: “Oh. What are they?”
Timon: “They’re fireflies that got stuck up in that bluish-black thing.”
Pumbaa: “Oh, gee. I always thought they were balls of gas burning billions of miles away.”
Timon: “Pumbaa, with you, everything’s gas.”
The Lion King (1994)

Ever since humans first looked up at the sky, they have wondered about the monsters, marvels and machinery of the universe. In this chapter we explore how the universe began; we investigate the mysterious force known as ‘dark energy’ and the enigmatic and invisible ‘dark matter’ which may even be lurking near the Earth; we delve into how galaxies, stars and planets are born, and we check out the building blocks of our solar system. We look into why heavy elements are found on Earth, and how water came to our ‘Blue Planet’. And finally we wonder what will be the fate of our Earth, our sun, one of countless stars, and our universe.
The Universe Through Time

Guest Contributors: Christine and Birgitte Reisaæter Amundsen

The universe begins 13.7 billion years ago with an event known as the Big Bang in a very high energy and immensely hot environment. Both time and space are created in this event. The universe passes through many different epochs, where most activity and change takes place in the first second.

In a tiny fraction of a second, 10⁻³⁴ seconds after the Big Bang, the cosmos goes through a superfast expansion called ‘inflation’, expanding from the size of an atom to that of a grapefruit. At 10⁻³² seconds (s), the universe is a seething, hot soup of electrons, quarks, and other particles created spontaneously out of pure energy; the temperature is 10²⁷°C. At 10⁻⁴ s and a temperature of 10¹³°C quarks clump into protons and neutrons. By three minutes the universe is a 10⁸°C superhot fog, and protons and neutrons combine to form the first atomic nuclei – mostly hydrogen nuclei (single protons) and nuclei of helium-4 (comprising 2 protons and 2 neutrons), along with tiny fractions of other light isotopes.

Nothing much then happens as 300,000 years go by and the universe cools to around 6,000°C (about the surface temperature of our sun). Now electrons combine with protons and neutrons to form the first atoms, 75% hydrogen and 25% helium. From 300,000 to 150 million years, the universe is literally in the Dark Age; although photons exist, no stars have yet formed to give off light. After some hundred million years, the temperature is -200°C and gravity makes hydrogen and helium gas coalesce to form giant clouds. Matter clumps together forming the first proto-galaxies and, within them, smaller dense clumps of gas start to collapse under their own gravity, becoming hot enough to trigger nuclear fusion between hydrogen atoms, thus giving birth to the very first stars. The lights are on!

Nuclear fusion in stars forms heavier elements such as carbon, oxygen, silicon and iron. The first stars are supermassive ones, a hundred times more massive than our sun. They are short-lived, however, and explode in massive supernova events creating even heavier elements, sending material into space ready to be used in future generations of stars and planets. After a few billion years more, the rate of expansion of the universe begins to accelerate, caused by a mysterious force known as ‘dark energy’, the nature of which is unknown.

At nine billion years, the solar system forms. Our sun, its eight planets, and all the asteroids, comets and Kuiper Belt objects (e.g., Pluto) and Oort Cloud objects form from the debris left behind by earlier generations of stars. Ten billion years after the Big Bang, the first life appears on Earth in the form of simple cells, perhaps after impacting comets and asteroids contributed organic molecules to Earth. Life spreads across the globe.

Today, the expansion of the universe and the recycling of star material into new stars continue. The visible universe contains trillions of galaxies, each comprising billions of stars. The characteristic temperature of the universe is approximately -270°C, or more exactly 2.725 K (Kelvin) above absolute zero according to the latest measurements obtained by looking at the cosmic microwave background (CMB). The ‘standard model’ of the make-up of the universe suggests that it is made of 70% dark energy that permeates all of space and tends to increase the rate of expansion of the universe; 26% dark matter, an extremely hard-to-detect unknown substance which emits no light, heat, radio waves, nor any other kind of radiation; and 4% normal matter, which is the matter we can see. Within our own Milky Way, thousands of exoplanets have been discovered orbiting other stars. From Earth, we are trying to unravel the mysteries of the cosmos, and we are asking: is anybody out there?

In one to two billion years from now, the sun is significantly brighter. On Earth a runaway greenhouse effect is triggered, and our planet is heating up. Life on Earth is impossible but luckily in the Kuiper Belt formerly icy worlds are melting, so that liquid water is present beyond the orbit of Pluto. Perhaps Eris, a trans-Neptunian object, is our new home? After five billion years, the sun enters into the red giant phase of its evolution, and it consumes Mercury, Venus and Earth, before it shrivels into a white dwarf. In seven billion years from now the Milky Way and Andromeda have merged to form a huge galaxy, with its bright core dominating the night sky. Now, the future is not so clear. Will the universe collapse and end with a Big Crunch, or expand forever, becoming increasingly cold and empty? The Big Crunch model is a possibility if the average density of the universe is sufficiently large to stop the expansion, so that it begins the process of collapsing onto itself. In this way, the universe resets, and it may trigger the next Big Bang – like the mythical Phoenix, in death it is reborn. The Big Freeze model is an end-result if the average density of the universe is not enough to stop the expansion and it continues to expand at an ever increasing speed. It will steadily get colder and colder until the temperature throughout the universe reaches absolute zero. Galaxies, stars and matter are pulled so far apart that the stars would eventually lose access to the raw material needed for star formation. This leaves the universe to its ultimate fate as cold, dead, empty space, containing only radiation. When the last star is extinguished, the lights go out for good.
About the guest contributors: Christine and Birgitte Reisæter Amundsen

We are 16-year-old twin girls who have lots of interests and hobbies, and we love learning about anything. In 2016, when we started at Thora Storm high school in Trondheim, we explored the net to find entertaining and educational documentary films about our favourite topics. Accidentally, we discovered the 2014 American science documentary television series *Cosmos: A Spacetime Odyssey*, which addresses the big questions about the solar system and the universe. It uses extensive computer-generated graphics and animation which appeal not just to those interested in the cosmos. Being fascinated by this and wanting to learn a bit more, we checked out popular science stories on nasa.gov, universetoday.com, space.com and theplanets.org as well as Wikipedia.

We discussed our learnings and questions with our father, who also became interested in the topic. To cut a long story short, we were invited to put together recent knowledge of the mysteries, monsters, marvels and machinery of our universe, and contribute to the writing of this chapter.

What is surprising to us after this study is the number of questions that science does not know the answer to. It would be really fun, when we finish our education, to contribute to solving the big questions. Did the universe start with the Big Bang, or has it existed forever? What is dark matter? Is there extraterrestrial life, or are we the best that creation has to offer? And – what will be the ultimate fate of Earth and our universe?

Figure 9.1: Christine and Birgitte Reisæter Amundsen
9.1 From Big Bang to Our Solar System and Beyond

Look up at the stars and not down at your feet. Try to make sense of what you see, and wonder about what makes the universe exist. Be curious.

Stephen Hawking (1942–)

9.1.1 From the Big Bang to Today

The word universe is defined as everything that physically exists: the entirety of space and time, all forms of matter and energy, and the physical laws that govern them.

The question that has been puzzling mankind for millions of years back since our ancestors developed on Earth is how was the universe created? Today, the consensus among scientists is that in the beginning everything in existence is thought to have occupied a single point, or singularity, of infinite high temperature and density and infinitely strong gravity. Then, matter and energy exploded outwards, covering distances millions of light years every fraction of a second. The time when the universe officially began to expand in this Big Bang model is estimated by general relativity to have occurred 13.7 billion years ago. Interpretations of astronomical observations indicate that the age of the universe is 13.73 (± 0.12) billion years, and that the diameter of the observable universe is at least 93 billion light-years, or 8.8 × 10^23 km.

The universe as we know it started with the Big Bang. The cosmic ‘inflation’ epoch, lasting from 10^{-36} seconds (s) to 10^{-32} s, had a kind of repulsive gravity that kick-started the universe. In this period there was practically no matter or radiation. The universe was dominated by energy inherent to space itself, and it expanded exponentially. Things were pushed apart rather than attracted in an extremely rapid (exponential) expansion of the very early universe flattening out any large-scale inhomogeneities in temperature and density, rapidly creating a large cosmos out of a much smaller one. The outwards

Figure 9.2: Panoramic view of the entire near-infrared sky reveals the distribution of galaxies beyond the Milky Way (centre). The observable universe – the part of the universe that is visible to us on Earth – contains about 2 trillion galaxies. The galaxies are colour-coded by redshift with numbers in parentheses. Astronomers use the term ‘redshift’ when describing how far away a distant galaxy is. To understand what a redshift is, imagine a police car with its siren on going by. As the sound waves from the siren move toward you, they are compressed into higher frequency sound waves (increased pitch). As the siren moves away from you, its sound waves are stretched into lower frequencies (decrease in pitch). This shifting of frequencies is what is known as the Doppler effect. In the same way as for sound, the frequency of light when observed can be lower than the frequency of light emitted at the source. Specifically, the spectrum of light emitted by distant galaxies moving fast away from us is shifted to lower frequencies – towards the red end of the spectrum – when compared to the spectrum of closer stars. This is the redshift phenomenon, interpretable as the galaxies are moving away from us; and more distant galaxies are moving away from us faster. This result, called Hubble’s Law, is expected for an expanding universe, and is another piece of evidence in support of the Big Bang model. Hubble’s Law states a proportionality between the distance D to a galaxy and its observed velocity v away from us: D=v/H₀, where H₀ is the Hubble constant, generally believed to be in the range of 45–90 km/s/Mpc (Mpc represents megaparsec, or 1 million parsecs, when 1 parsec (pc) = ~3.26 light-years or 31 trillion km). The fact that we on Earth see other galaxies moving away from us does not imply that we are the centre of the universe. All galaxies will see other galaxies moving away from them in an expanding universe. A rising loaf of raisin bread is a good visual model: each raisin will see all other raisins moving away from it as the loaf expands.
inflation made the universe enlarge itself by a factor of $\sim 10^{26}$, meaning that it was a 100 trillion times larger than it had been less than a second before. In another tiny fraction of a second, inflation slowed down to a more leisurely rate of expansion that continues to this day but is accelerating. The universe cooled to allow the formation of subatomic particles, and later simple atoms. These became the building blocks for the universe. Giant clouds of these primordial elements later coalesced through gravity to form stars and galaxies. The Big Bang model explains the origin of all known matter, the laws of physics, and accounts for the expansion of the universe as well as a broad range of other phenomena, including the abundance of light elements, the cosmic microwave background (CMB) radiation, and Hubble’s Law.

CMB radiation is the residual heat of creation from the time there was a firestorm of radiation and elementary particles – or the afterglow of the Big Bang – streaming through space like the heat from a sun-warmed rock, reradiated at night. When this cosmic background light was released around 380,000 years after the Big Bang in a universe at a temperature of about 3,000°C, it was as hot and bright as the surface of a star, but as the universe expanded CMB cooled to its present-day temperature, measured by radio telescopes at about 2.73 degrees above absolute zero. CMB radiation fills the universe and can be detected in every direction. In 1963 the American radio astronomers Arno Penzias and Robert Wilson were studying faint microwave signals from the Milky Way galaxy when they found a mysterious noise of unknown origin. It soon turned out that the noise was CMB signal, left over from the early stage in the development of the universe. This accidental discovery is today considered a landmark test of the Big Bang model of the universe, and earned the discoverers the 1978 Nobel Prize in Physics.

### 9.1.2 Dark Energy and Dark Matter

However, with the development of the Big Bang model a number of mysteries and problems have arisen. Two mysteries that are still under intense investigation by cosmologists and astrophysicists are dark energy and dark matter.

In 2011, the Nobel Prize in Physics was awarded to the astrophysicists Saul Perlmutter, Brian P. Schmidt and Adam G. Riess, for their 1998 discovery that the universe is expanding at an accelerating pace. It was a very unexpected discovery, and something was causing it. Physicists came up with the idea that something is an enigmatic force, called dark energy, which is working against the gravitational forces that are trying to pull the universe inward. The exact explanation for dark energy is a mystery, but we know how much dark energy there is because we know how it affects the expansion of the universe. The widespread acceptance is that the universe is 70% dark energy.

As Einstein’s famous equation tells us, energy equals mass multiplied by the speed of light squared ($E=mc^2$), so the concepts of matter and energy are intrinsically linked. If the universe contains 70% dark energy, this leaves 30% to other mass-energy content. The normal matter that we can account for and explain with all our experiments and instruments, is only 4%. This leaves mass-energy of 26% to a mystery substance called “dark matter”. In terms of total mass, dark matter
constitutes 87% of the mass in the universe. Let us discuss dark matter.

In galaxy clusters – huge conglomerations of galaxies – the normal matter, like the atoms that make up the stars and planets, is primarily in the form of hot gas and stars. They present the largest structures in the universe held together by gravity. In 1933, astronomer Fritz Zwicky, while examining the motion of the Coma Cluster, concluded there was not enough visible matter to hold these fast-moving galaxies together. The Coma Cluster is about 330 million light-years from Earth and today is known to contain several thousand galaxies, each housing billions of stars. Zwicky proposed that something invisible was producing additional gravity out there in space. He dubbed this unknown substance dark matter. Unseen dark matter? Astronomers at the time considered his claim to be a crazy idea, just as they had Zwicky’s first proposals of stars made of neutrons and galactic cosmic rays. But in the 1970s astronomer Vera Rubin together with instrument maker Kent Ford confirmed Zwicky’s dark matter findings. She observed that galaxies are rotating so fast that they would fly apart, if the gravity of their observable stars was all that was holding them together. But they are not flying apart, and therefore, a huge amount of unseen mass must be holding them together – at least ten times as much mass as can be accounted for by the visible stars. Although Rubin’s work was initially met with scepticism, her results have been confirmed over subsequent decades. Her observations were the strongest evidence at that time for the existence of dark matter.

Currently, we know that dark matter is hypothetical matter that does not emit or absorb light, but whose presence can be inferred from gravitational effects on visible matter. If it sent out light or electromagnetic radiation, we would see it. If it absorbed light, we would be able to see it as shadows against the background. It is abundant, making up about 26% of the universe’s total mass and energy.

Physicists have postulated that dark matter is made up of a new and as yet unknown elementary particle that only interacts weakly with other known particles, thereby making it difficult to detect. This weakly interacting massive particle (WIMP) can only interact through gravity and the weak force. WIMPs