HYDROCARBONS
IN BASEMENT FORMATIONS

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Dedication

This book is dedicated to Professor G. V. Chilingar of University of Southern California in recognition of his lifelong teaching that has touched the hearts of thousands of researchers from around the world.

Contents

Foreword

The great Western philosopher, Jean-Jacques Rousseau once wrote: "I would rather be a man of paradoxes than a man of prejudices," as if we are faced with only two options that are: man of uncouth ignorance (who else would entertain paradoxical thinking?) and man of deliberate ignorance (who else would entertain prejudices?) The fact is, modern age is full of examples of such paradoxical and prejudicial thoughts. We are constantly bombarded with fundamentally absurd notions that can be deconstructed with simplest of logic, yet few if any dare question the incessant proclamations of these nonsensical theories as 'laws'. Take, for instance, the centuries old teaching that resources are finite, whereas needs are infinite. Where does that put any engineering solutions of pre-Industrial age era that is based on the principle zero-waste? Yes, it makes the time-tested principle of nature-based approach an absurd concept. Yet, we go ahead and define sustainability as the target for any technology development. Is it possible that we don't understand there is no sustainability without zero-waste or is it that we like to use the word sustainability just because it is fashionable to do so. Then, the case of ad hominem fear mongering that population explosion is the biggest threat to humanity. Before we can catch the breath, we are then told that humans are the greatest creation of all. Then take the case of "grim climate concerns" due to the production of fossil fuel. Why is the fossil fuel all of a sudden a villain. Ah, it's carbon dioxide, we are told. It's as if we are to forget that carbon is the most essential component of plants – the very same plants that is in the core of sustainability of the ecosystem.

I know of no other scientist that has done so much in deconstructing the myths of modern era than Prof. Islam, the lead author of this book. His pioneering work includes the introduction of zero-waste engineering and green petroleum – the terms that were considered to be oxymoron when he first introduced them over a decade ago. In this book, he, along with his co-authors, delve into one of the most controversial topics in petroleum engineering. It was long known, basement reservoirs and everything about them cannot be explained with conventional diagenesis models. However, no one dared take on the problem with an approach that would answer all the questions and solve all the paradoxes. Instead, in line with what has become the hallmark of New science, everyone agreed to disagree and settle for a particular branch of the dogmatic process. Prof. Islam characteristically takes an entirely different approach. This book gets to the root of the problem by advancing an option radically divergent from both the 'petroleum is of organic origin no matter what' and the 'petroleum is of non-organic origin – no matter what'. With this approach, people would no longer be reduced to "choosing" between the equally paradoxical paths.

This is a unique book that describes Geology with the logic of mathematics and engineering with the lucidity of fine arts. There is no fallacy, no resorting to dogma and most importantly there is not a single statement that would lead to a paradox. This book gives a great hope in restoring the time-honoured fact that nature's bounty is infinite and as long human greed is in check, we don't have to worry about energy needs of mankind.

If there is any shortcoming of this book, it is in the fact that it covers only basement reservoirs. One can envision the theories advanced in this book will be able to explain many phenomena, the scientific explanation of which have eluded all scientists – none of whom has been able to answer all the questions, without resorting to dogma. This book is a masterpiece that belongs to every scientist and engineer that aspires to be educated about the most important energy source of human history.

G.V. Chilingar
University of Southern California

1

Introduction

1.1 Summary

Hydrocarbons and their transformations play major roles in sustaining today's civilization. Petroleum fluids are essential for providing chemical and energy sectors with raw materials that are needed for practically all aspects of modern living ranging from transportation to health and medicine. After water, crude oil is the most abundant naturally occurring fluid on earth. However, the modern era has few direct applications of crude oil and practically none of the produced petroleum is processed, either through refining or gas processing, prior to final use. Unfortunately, all modern techniques for refining are also known to be inherently damaging to the environment. In the information age, environmental sustainability has become the most important concern and there is a growing urge to find either an alternative to petroleum fluids or any technology that 'minimizes' the environmental impact. While some progress has been made in developing alternate energy sources, few, if any, present a truly sustainable option. More importantly, no realistic alternate source, sustainable or otherwise, for millions of tons of chemical raw materials for the chemical/medical industries has been suggested. In this regard, basement reservoirs offer an unprecedented opportunity. However, the true benefit of the petroleum fluids produced from basement reservoirs cannot be appreciated without thorough scientific understanding of their nature. This is the first textbook that makes a scientific investigation into the nature of basement rock, the origin of the petroleum that impregnates these rocks and how to properly characterize the behavior of these rock/fluid systems. It is shown with clarity that basement fluids are amenable to sustainable petroleum usage and with careful management skills they can become the hallmark of a sustainable source of both energy and chemical raw materials. This textbook explains the fundamental features of the hydrocarbons in the basement, geological aspects of fractures and types of fractures, and a novel reservoir characterization technique. Two dominant theories of the origin of basement fluids are presented in detail and arguments made in supporting the validity of these theories within a specific domain. It covers almost all seismic techniques including geological techniques, geophysical tools, micro log analysis and borehole techniques, with a focus on fracture networks. A guideline for scientific characterization is presented in order to determine the ranking of petroleum fluids. This book deals with the interpretation and modeling of the fracture network as well as risk analysis and reserve estimation of these kinds of reservoirs.

1.2 Is Sustainable Petroleum Technology Possible?

Even though petroleum continues to be the world's most diverse, efficient, and abundant energy source, due to "grim climate concerns", global initiatives are pointing toward a "go green" mantra. When it comes to defining 'green', numerous schemes are being presented as 'green' even though all it means is the source of energy is not carbon. In fact the 'left', often emboldened with 'scientific evidence', blames carbon for everything, forgetting that carbon is the most essential component of plants. The 'right', on the other hand, deny climate change altogether, stating that it is all part of the natural cycle and there is nothing unusual about the current surge in CO_2 in the atmosphere. Both sides ignore the real science behind the process. The left doesn't recognize the fact that artificial chemicals added during the refining process make the petroleum inherently toxic.

The study of sustainability is a complex science as it involves subsurface and surface, natural and artificial materials, with very high ratio of unknowns over known information (Figure 1.1). Any false step in the

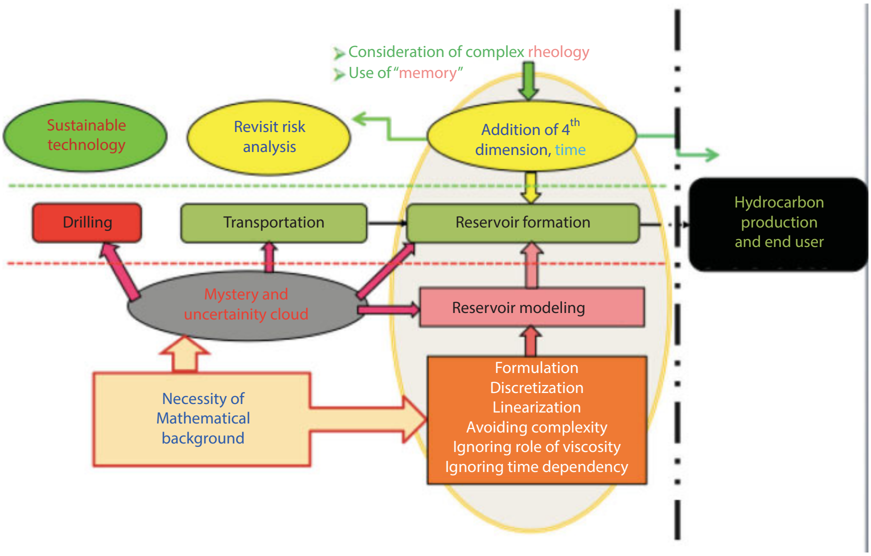

Figure 1.1 Various steps involved in petroleum technology.

process shown in Figure 1.1 can trigger unsustainability. Both the science and the mathematics of the process have been deficient at best.

In 2010, we (Islam *et al.*, 2010) used detailed pathway analysis to identify flaws of various energy production schemes, including petroleum resource development. The source of alteration of CO_2 quality that renders the CO_2 unabsorbable by the ecosystem was identified for each case. CO_2 emission data from the pre-industrial age all the way to the current era are then analyzed, showing a clear correlation between CO_2 concentration in the atmosphere with 'corrupt' CO_2 emission, which itself was a function of the fuel source, the path it travels, isotope numbers, and age of the fuel source. Various energy technologies were ranked based on their long-term sustainability. It was shown that petroleum is the most environmentally benign among the energy sources investigated, followed by biofuel, solar, wind, and nuclear. When the artificial chemicals are replaced with natural substitutes at various phases of petroleum processing, petroleum wastes become useful materials that can be recycled in the ecosystem in a zero-waste mode. Not only the by-products, including CO_2 emissions, are benign, they are in fact beneficial to the environment. Each of these wastes can then become raw materials for value-added new products. Finally the paper offers guidelines for 'greening' of petroleum operations as well as the economics of zero-waste petroleum production and long-term environmental sustainability. So, if petroleum products are benign and offer the greatest hope for sustainable technology, which type of petroleum reservoirs are the best of the best? In this book, we disclose the facts about basement reservoirs and demonstrate that basement reservoir fluids are the most beneficial with the greatest possibility of value addition, as long as their processing is done targeting a particular application, uniquely suited for these fluids. Such a study was only possible after scientific characterization of the rock and fluid system.

1.3 Why is it Important to Know the Origin of Petroleum?

Petroleum fluids are synonymous with 'fossil fuel' or any fluid with organic origin. It turns out, invoking such a premise limits the ability of properly characterizing petroleum fluids, including the true source. This is particularly true for basement reservoirs that are known to have little resemblance to conventional fossil fuel. It is no surprise that oil and gas fields in crystalline basement are discovered mostly by accident, usually when the unassuming operator notices hydrocarbon shows. Yet, these reservoirs can be prolific and the overall estimate of petroleum reserve can go up with revamping of techniques to track basement reservoirs. The standard definition of crystalline basement by petroleum geologists is any metamorphic or igneous rock unconformably overlain by a sedimentary sequence. A somewhat more 'scientific' definition is given by Lartdes *et al.* (1960): "the only major difference between basement rock and the overlying sedimentary rock oil deposits is that in the former case the original oil-yielding formation (source rock) cannot underlie the reservoir." This definition extends the limit of exploratory geological and geophysical studies significantly. However, this definition is still limiting as it suggests that a basement reservoir may be the result of hydrocarbon migration from sedimentary rock to older porous metamorphic or igneous rocks to form a basement reservoir, the likes of which were found in Japan, Mexico and the Maracaibo Basin of Venezuela (Schutter, 2003). As pointed out by Petford & McCafrey (2003), this narration is a mistake. The 1999 Gulf discovery of Suban gas field after penetration sufficiently deeply in the basement rocks proved this point. Similarly, literature is deficient in giving sufficient consideration to mixed convection heating from igneous rocks that can contribute to the maturation process in sediments that have been heated rapidly by magmatic intrusion (e.g., Saxby & Stephenson 1987; Stagpoole & FunnelI 200I; Schutter 2003), making excellent cap rocks (Chert *et al.*, 1999).

The accurate knowledge of the source of the basement oil is pivotal for two reasons. First, this would create an impetus for broadening the exploration base for basement reservoirs. Secondly, the quality of oil will likely be linked to the source and thereby would open up different opportunities for processing for environmental integrity. The possible sources of basement fluids are investigated for both organic (Chapter 2) and non-organic (Chapter 3) origins. Even more significant discussion is presented in Chapter 5 that shows scientific characterization of these reservoirs must include the accurate source of these fluids, in order to properly identify long-term pathways of various components present as well as applicability of the hydrocarbons in question.

1.4 What is the Likelihood of an Organic Source?

Not long ago, an organic source was the only one considered for defining petroleum fluids. Even though igneous rocks posed an interesting dilemma in terms of how organic matters accumulated there, there was no shortage of dogmatic interpretation of geologic history. However, more questions arise than answers exist concerning hydrocarbons in and around igneous rocks. Figure 1.2 shows the distribution of hydrocarbons in and around igneous rocks. This figure shows that the highest reported occurrences are in basalts, followed by andesite and rhyolite tufts and lavas. Although volcanic rocks in this survey constitute close to three-quarters of all hydrocarbon-bearing lithotypes, the majority of production and global reserves appears to be confined predominantly to fractured and weathered granitic rocks (Petford & McCafrey, 2003).

In order to make a non-controversial conclusion regarding the source of this hydrocarbon, one would need to have more data on magma composition as well as the process of hydrocarbon generation in an inorganic setting. However, logical inference allowed us to determine with moderate certainty how much oil is organic in the basement reservoirs.

Chapter 2 establishes a systematic framework for the study of the sources of basement hydrocarbons practical applications that arise. This should include consideration of the relationship to possible source rocks, the maturation history, the possible migration pathways, the possible reservoir characteristics and the type of traps likely to be present. In Chapter 2, the fundamental features of the hydrocarbons in basement reservoirs are discussed, along with the source of hydrocarbon, mechanism of formation and types of basement reservoirs are defined and discussed. Logical explanations are provided for each aspect of the theories presented. Finally, the framework

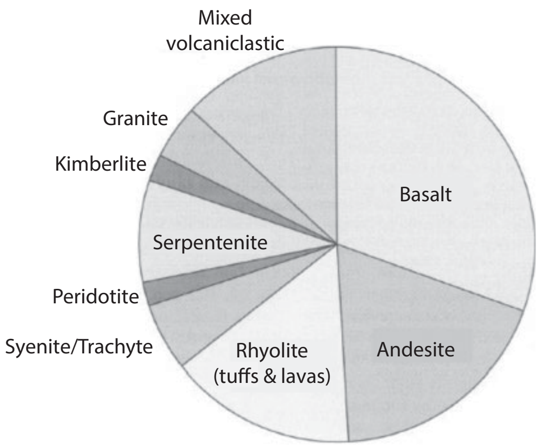

Figure 1.2 The distribution of hydrocarbons in and around igneous rocks according to lithology (from Schutter 2003).

of scientific investigation of the origin of hydrocarbons is laid out in order to facilitate the study of sustainability and the true nature of hydrocarbons.

1.5 What is the Implication of the Abiogenic Theory of Hydrocarbon?

As stated earlier, maturation of organic-rich sediments was considered to be the only source of hydrocarbons in all types of petroleum reservoirs. As early as 1988, Abrajano *et al.* (1988) discussed an alternate origin in conjunction with natural gas seeps in an ophiolite in the Philippines. Under some circumstances, the serpentinization of ultramafic rocks may produce hydrogen from the reaction of olivine with water; if carbon is also present, methane may be the product. The reaction resembles the Fischer-Tropsch reaction for generating synthetic hydrocarbons (Szatmari 1989). Even though this knowledge existed among scientists of the former Soviet Union for many decades, the notion of non-organic origin of oil was dismissed in the West as marginal, 'conspiracy theory'-like notions (Gold and Soter, 1980). Abiotic hydrocarbons from serpentinization or from the mantle may be identified by the anomalous distributions of carbon isotopes and helium isotope ratios (Abrajano *et al.* 1988). Giardini & Melton (1981) stated that hydrocarbons with a $d^{13}C$ value more depleted than -18 %o may be abiogenic in origin. This rediscovery of abiogenic hydrocarbons led a series of studies. Sherwood *et al.* (1988) discussed the origin of CH_4

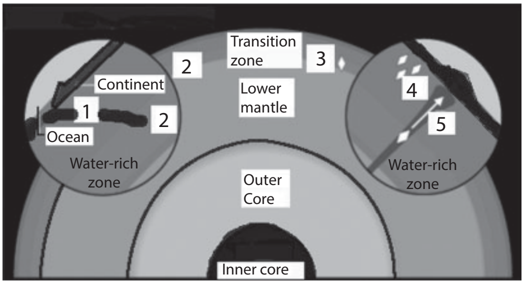

Figure 1.3 Water plays a more significant role in material production than previously anticipated (from the *Guardian*, March 12, 2014).

found in the Precambrian crystalline rocks of the Canadian Shield. They noted that the CH_4 lacked the characteristic isotopic signature of either organic matter or a mantle source. Some of the CH_4 was strongly depleted in deuterium, and some was accompanied by H_2, leading the way to theorize about serpentinization.

Then came the discoveries of the presence of a huge amount of water in the mantle (*Guardian*, 2014) leading Islam (2014) to theorize the formation of hydrocarbon under numerous conditions, virtually making it a continuous process. Islam (2014) argued that the notion of 'clean' energy has to be revised in view of natural processing time for various energy sources. Scientists are still grappling with the origin of the Earth or the universe, some discovering only recently that water was and remains the matrix component for all matter (Pearson *et al.*, 2014). Figure 1.3 shows this depiction. As pointed out by Islam (2014), natural evolution on Earth involved a distinctly different departure point not previously recognized. Pearson *et al.* (2014) observed a 'rough diamond' found along a shallow riverbed in Brazil that unlocked the evidence that a vast "wet zone" deep inside the Earth that could hold as much water as all the world's oceans put together. This discovery is important for two reasons. Water and carbon are both essential for living organisms. They also mark the beginning and end of a life cycle. All natural energy sources have carbon or require carbon to transform energy in usable form (e.g., photosynthesis).

World petroleum reserve takes on a different meaning if the possibility of abiogenic hydrocarbon is added to the equation.

The resource picture becomes even more interesting when the recent discovery of cyanobacteria that may have been active in all known epochs of life on Earth (Sarsekeyeva *et al.*, 2015) is added. All these considerations and discoveries had to be integrated in a logical discussion. This is done in Chapter 3.

1.6 How Important are the Fractures for Basement Reservoirs?

Fractures are very common objects in geological systems. This is particularly true for basement reservoirs. When open, fractures can account for 99% of the fluid flow through the reservoir, whereas closed fractures make a reservoir unproductive, despite use of massive hydraulic fracturing. There has been tremendous progress over the last decades in terms of remote sensing, with a superflux of new techniques in more recent years. In this, the role of seismic data has been phenomenal. For instance, Freudenreich *et al.* (2005) used 3D maps of orientation and density derived from seismic observations. Other authors use geomechanical models in which the fractures grow during the deformation process – a process that can help reconstitute geologic history. There has been a large number of remote sensing tools that can allow detection of fractures. However, an integrated reservoir characterization technique is still lacking. Chapter 4 presents a comprehensive fracture characterization technique that is also practical. It avoids using statistical processing or linearization of data, instead applying scientifically accurate non-linear filters. All available data are integrated in order to create the most likely picture of the fractured formation.

Chapter 5 consolidates the reservoir characterization technique with case studies. It is shown that the practical reservoir characterization tool can help unlock the mysteries of many basement reservoirs and open exploratory opportunities in previously unknown target areas.

1.7 What are we Missing Out?

It is well known that New science has numerous contradictions and unfounded premises that make it difficult to include a new synthesis. If that is the case, how can we trust the currently used reservoir characterization tools that are based on New science?

This aspect needs some elaboration. We used the term, 'New science' innumerable times in our books. The word 'New science' refers to post-Newtonian era that is marked by a focus on tangibles and short-term. In essence, new science promotes a myopic vision, for which the historical background of any event is ignored in favour a time slot that fits the desired outcome of a scientific process. Even though not readily recognized, new science is actually rooted in Dogma science – the ones the likes of Thomas Aquinas introduced. We have demonstrated in our recent books (e.g. Islam *et al.*, 2013, 2015, 2016, 2016a; Islam and Khan, 2012, 2016) how dogmatic notions were preserved by Newton, who claimed to have answers to all research questions. First premises of Newton were not more logical than first premises of Thomas Aquinas, yet Newton as well as post-Newton Newtonian fanatics considered Newton's work as the standard of real science and proceeded to claim the ultimate knowledge has been achieved for everything. In essence, New science added only ignorance and arrogance of the so-called scientists who were no closer to scientific facts and true knowledge than the likes of Thomas Aquinas.

Figure 1.4 demonstrates how the process worked in the Eurocentric culture. In this transition, Albert Einstein and his notion of Quantum mechanics added another level of hubris. Whatever couldn't be explained by Newtonian 'laws' now was claimed to be crystal clear with the arrival of the concept of Quanta. Yet, none of the claims of quantum mechanics could be verified with experiments or even logical discourse. Instead, a great deal of false confidence is added in order to create an illusion that we are climbing the knowledge ladder, while in fact we only thing we are climbing is the arrogance/ignorance curve at a ever increasing faster rate.

Islam (2014) as well as Khan and Islam (2016) introduced a series of discussions of the fundamental science of mass and energy that enables readers to grasp the concept of natural energy and mass. This forms a background for characterizing basement reservoirs with true science without resorting to dogmatic assumptions. Scientific characterization involves ranking in terms of energy contents as well as diversity of applications.

Chapter 6 introduces a scientific characterization technique that uses paradigm shift in its real sense. The outcome is a refreshing new approach that is practical and prepares one for in-depth understanding of the mechanisms involved in petroleum reservoirs in general and basement reservoirs, in particular. The technique relies heavily on whatever is available during the course of the reservoir development and minimizes spending on expensive tools that have little validity in basement reservoirs.

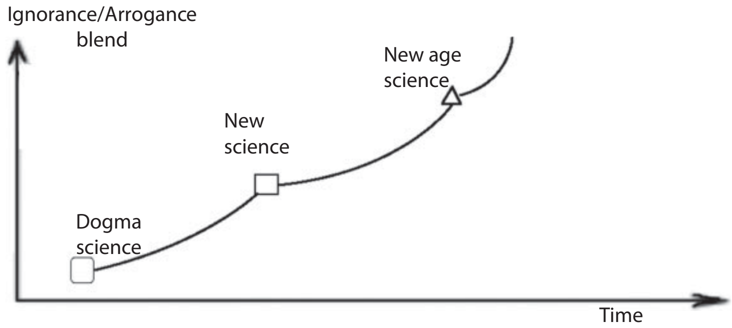

Figure 1.4 New science only added more arrogance, blended with ignorance to Dogma science.

1.8 Predicting the Future?

Everyone wants to predict the future, but how good is the prediction? In reservoir simulation, the principle of GIGO (garbage in and garbage out) is well known (Rose, 2000). This principle implies that the input data have to be accurate for the simulation results to be acceptable. The petroleum industry has established itself as the pioneer of subsurface data collection (Abou-Kassem *et al.*, 2006). Historically, no other discipline has taken so much care in making sure input data are as accurate as the latest technology would allow. The recent superflux of technologies dealing with subsurface mapping, real-time monitoring, and high-speed data transfer is an evidence of the fact that input data in reservoir simulation are not the weak link of reservoir modeling. However, for a modeling process to be meaningful, it must fulfill two criteria, namely, the source has to be true (or real) and the subsequent processing has to be true (Islam *et al.*, 2016). Even though not commonly perceived, modeling comes before execution of any engineering project. The petroleum engineering industry is a champion of modeling. Today, it has the ability to model a reservoir with no less than trillion cells and solve the governing equation within minutes. Only a decade ago, such performance was unthinkable even from supercomputers. The problem is not with the speed or the ability to model billions of grid blocks. The problem is not in collecting data and processing them. In fact, Saudi Arabia has set up massive 4D seismic in reservoirs that don't even employ waterflooding. The problem lies within the fact that none of the unconventional or basement reservoirs follows Darcy's law – the only equation petroleum engineers have used in the last 160 years. Chapter 7 shows how people tried to cope with this crisis and presents a way out, with practical advice on how to model basement reservoirs.

1.9 What is the Actual Potential of Basement Hydrocarbons?

All the chapters lead to answering this question. It places basement reservoirs within the big picture of petroleum resources and provides one with a guideline for exploration, exploitation and final environmental impact of basement reservoirs.

The book closes with a list of references and bibliography. This list contains hundreds of entries spanning over 40 pages.

2

Organic Origin of Basement Hydrocarbons

2.0 Introduction

The majority of hydrocarbons found on Earth naturally occur in the form of crude oil or natural gas. After water, petroleum fluids are the most abundant compounds on Earth (Islam, 2014). When organic matters are decomposed naturally they provide for an abundant source of hydrocarbons.. It is recognized in the literature that there are several specific forms of hydrocarbons:

- **Dry gas**: contains largely methane
- **Wet gas:** contains ethane propane, butane.
- **Condensates:** Hydrocarbon with a molecular weight such that they are gas in the subsurface where temperatures are high, but condense to liquid when they reach cooler, surface temperatures.
- **Liquid hydrocarbons:** commonly known as oil, or crude oil before refining

- **Plastic hydrocarbons:** asphalt
- **Solid hydrocarbons:** coal and kerogen, matter in sediments that is insoluble in normal petroleum solvents.
- **Gas hydrates:** Solids composed of water molecules surrounding gas molecules, usually methane, but also H_2S, CO_2, and other less common gases.

More than 100,000 types of hydrocarbons are known. The main reason for this diversity is that carbon atoms can unite in many different ways to form complex chains or ring frameworks. Different arrangements of atoms yield different molecules.

Basement reservoirs can be found all over the world, but the following countries have significant proven reserve in the basement reservoirs (Figure 2.1).

Algeria, Argentina, Brazil, Canada, Chile, China, Egypt, Former USSR, India, Indonesia, Japan, Korea, Libya, Malaysia, Mexico, Morocco, New Zealand, Peru, Thailand, United Kingdom, United States, Venezuela, Vietnam, and Yemen.

Basement rock can be very old, up to 2.5 billion years of age. It is largely hard rock such as granite. The basement rocks are often highly metamorphosed and complex, with many different types of rock – volcanic, intrusive igneous and metamorphic. They are considered to be older than the time frame of formation of hydrocarbons in petroleum reservoirs. There are several theories on how hydrocarbons ended up in the basement rocks. Each theory has its shortcomings that will be discussed in this chapter.

Figure 2.1 Basement reservoirs are distributed around the world.