1 Introduction

The energy of the mind is the essence of life

Aristotle

In this book we explore flow processes in permeable rocks which are important for the energy industry and the environment. As well as the oil and gas industry, flows in porous rocks are key for geothermal energy production, CO_2 sequestration, interseasonal heat storage and the geological disposal of nuclear waste. The motivation for the book stems from the flourishing interest in energy systems and the use of such energy, much of which relies on fluids. As well as being the raw material, for example oil and gas, fluids can transport the energy, as occurs in geothermal systems and in some cases the product of energy consumption, namely CO_2, can be sequestered in the ground to reduce atmospheric emissions from burning fossil fuels. Flow in permeable rocks impacts the nuclear industry, with the challenges of geological disposal of radioactive waste and especially the potential for dispersal of such waste through the subsurface. Contamination of groundwater systems can also arise from spillages for example of non-aqueous phase petroleum liquids (NAPLs).

There are many classic texts on flow in porous media, and the recovery of oil, including those by Muskat (1937), Bear (1972), Phillips (1991) and Lake (1991). However, recently, there has been a resurgence of interest in a number of new fundamental physical problems relating to flow in porous media. These arise for a number of factors. First, it is becoming increasingly challenging to recover the remaining oil and gas reserves. The challenges arise as operators work in more extreme environments as they search for increasingly high temperature and high pressure deep reservoirs of viscous oil; shale gas is being recovered from very low permeability rocks; very heavy oil is being recovered from tar sands; and operators are exploring in difficult deep water and arctic environments. However, developing effective secondary and tertiary recovery of oil from existing fields through injection of water and chemicals is also likely to be key to enabling the continued effective recovery of hydrocarbons from existing fields, especially as global energy consumption rises and oil demand approaches the global production capacity. Furthermore, although there have been spectacular advances in geophysical imaging of reservoirs using seismic waves, the remote and harsh environments of new oil provinces leads to increased cost of exploration wells and other data-acquisition systems. This emphasises the importance of developing models of flow in permeable rock which can help inform decisions by reflecting uncertainty in the architecture of and potential production from oil fields.

Other challenges for flow in permeable rocks are associated with the emerging science of CO_2 sequestration, where there is interest in the fate of CO_2 injected into the subsurface, both on the short timescale of injection, and on the longer timescale of hundreds to thousands of years when buoyancy forces dominate the flow. Related to this, there are important questions about the dispersal of contaminants in the subsurface, especially concerning potential geological waste repositories designed for the long-term storage of radioactive waste. Knowledge of flow patterns and contaminant dispersal by these flows can be key for risk assessment.

Flows in porous media are also of importance for the renewable energy industry, including the challenge of geothermal heat production from the circulation of fluids through hot, permeable rock. Here, we explore the transport and dispersal of heat, both as a liquid and a vapour, following liquid injection into the system. We also study the role of convection on the fate of liquid injected for geothermal energy recovery. These issues are strongly coupled with challenges of aquifer thermal energy storage.

The objective of this book is to introduce simplified quantitative models, in some cases supported by experiment, to help to understand some of the different fluid mechanical processes which arise in porous rocks. Many of the flows described above are so complex and ill-constrained by data about the specific geological formations that it is very difficult to simulate the flows in detail. In many cases, the detailed structure of the rock, at the scale of the layers and other heterogeneities in the formation, is unavailable and so only relatively coarse, averaged models are available to describe the flow. These models are often informed by the structure of analogue rocks visible at the surface. Many of the parameters relating to the rock structure can only be constrained probabilistically, owing to the difficulty and expense of measuring such properties far below the surface. The idealised modelling approach proposed herein, which focuses on quantifying specific physical flow processes, enables discussion and illustration of the impact of geological uncertainties on the flow. Indeed, in Chapter 4, with a series of very simple models, we outline some of the challenges related to assessing uncertainty and the ultimate use of models to help inform decisions.

The book has been arranged in a series of themes to reflect some of the above challenges. First, we start with a simplified introduction to the complexity and diversity of geological formations which constitute the rocks involved in oil and gas recovery, CO_2 sequestration and geothermal heat recovery. This leads to the challenge of developing models of the effective large-scale flow properties within a formation as these tend to be strongly controlled by individual geological layers and the interaction between these layers. We illustrate how the geological complexity of a reservoir can impact the effectiveness of the displacement of fluid through the reservoir by the injection of water. We then explore how the predictions of simplified models depend on the geological parameterisation and how the sensitivity of models to these parameters might be determined, identifying that the boundary conditions are key. In Chapter 5, we turn to a discussion of dispersion by pressure-driven flow in porous media. This topic has been very thoroughly studied, and there have been many substantial books describing the processes from the pore scale to the scale of the macroscopic heterogeneities in the formation. The present physically based account is designed to illustrate some of the different phenomena, and to develop simplified scaling rules to assess the likely magnitude of the dispersion in some idealised systems. We then describe the classical process of viscous instability, whereby less viscous fluid develops a fingering pattern through a more viscous fluid rather than displacing the more viscous fluid with a planar front; this presents a fundamental challenge for oil recovery, and we illustrate how the associated instability pervades many fluid–fluid displacement problems in porous rock, including a fascinating erosional instability when liquid is injected into unconsolidated sand. In Chapter 7, we introduce immiscible flow in porous media, and describe how, in a two-phase flow, there is an asymmetry between the resistance experienced by the wetting and non-wetting phases. This leads to prediction of the classical Buckley–Leverett shock front, across which there is a jump in the saturation of the wetting fluid in the pore space, across an advancing wetting front in which the upstream pore space may be largely occupied with, for example, water to a flow downstream which is dominated by the non-wetting phase, for example oil. There are again many excellent texts which explore two- and three-phase flow dynamics in porous media in detail (Bear, 1972; Lake, 1991). We focus much of the continuing discussion in the present book on the dynamics of fronts and fluid–fluid interfaces. We first explore the dynamics of thermal fronts and reaction fronts as building blocks to describe the dynamics of gelling polymer fronts. Such fronts are likely to have a growing importance in enhanced recovery, and we illustrate some of the effects of using gels in layered geological strata. In Chapter 9, we turn to buoyancy-driven flows, and explore how buoyancy forces tend to localise interface instabilities into a single gravity dominated flow. We then develop various models of buoyancy-driven flows to illustrate the processes associated with CO_2 sequestration, including capillary retention and leakage across layer boundaries. In Chapter 10, we discuss the possible influence of heterogeneity in the geological structure of a formation in dispersing such buoyancy-driven flows, a process which is key for CO_2 dispersal and possible hydrogen gas release from geological waste repositories. In Chapter 11, we turn to the transport of thermal energy, and illustrate how injection of liquid into superheated rock can lead to vaporisation, while the injection into warm rock can lead to heating and a change in the buoyancy of the flow, producing a range of complex patterns of water flood with associated changes in the efficiency of heat recovery from the system. In Chapter 12, we return to hydrocarbon production, but focus on the dynamics of gas production, for which the compressibility of the system is key. We illustrate how important cross-layer flows between high and low permeability rock can be for enhancing the production of gas, and discuss the analogous benefits of fracturing the formation normal to the well in very low permeability systems.

Before launching into the fluid mechanics of these different processes, it is of interest to describe present energy resource production. This provides context for the very substantial challenge of maintaining present rates of energy supply, and the need for new technology in the oil and gas industry in order to continue to develop hydrocarbons at scale, while also building up the technology base and infrastructure for renewable energy and CO_2 sequestration.

1.1 The energy context

Interest in energy resources arises from concerns about security of energy supply and its maintenance over the next few decades; abatement of carbon emissions from those sources which are hydrocarbon based; the challenge of supplying a material fraction of the energy base from renewable resources; and the more efficient usage of energy, so the output in productivity per unit of fuel is increased. Although projections of energy consumption depend on many interrelated factors the historical data shown in Figure 1.1 indicate that there has been a nearly linear increase in global energy supply over the past four decades, with the last decade occurring in a post-Kyoto Protocol world (Figure 1.1). It is not unreasonable to assert that over the next few decades there is likely to be further growth in demand. Feeding this demand requires the development of new energy sources. Energy supplies today are largely sourced from hydrocarbons, as seen in Figure 1.1. Over 80% of global energy is derived from fossil fuels and the remaining sources are dominated by nuclear and hydroelectric.

Before considering the challenges and opportunities for continued hydrocarbon production, and the need for managing the associated CO_2 emissions it is worth reflecting on the other sources of energy.

Nuclear energy is a viable alternative to hydrocarbons, and can provide a nearly carbon-free energy source. However, there are challenges for the global growth of nuclear power, including the large upfront cost and timescale to bring new nuclear online, and the environmental concerns relating to accidents. In addition, there is a long-term challenge of the storage of the waste. Many countries have adopted a strategy of using a geological repository, whereby the waste will be stored in a low permeability part of the subsurface. As part of these plans, there is considerable research effort underway to explore the possible interaction of such waste with subsurface flow processes over the very long time comparable to several half lives of the radioactive material.

Hydroelectric power generation already makes a substantial contribution to global energy supply and, for example, in South America and China contributes a significant

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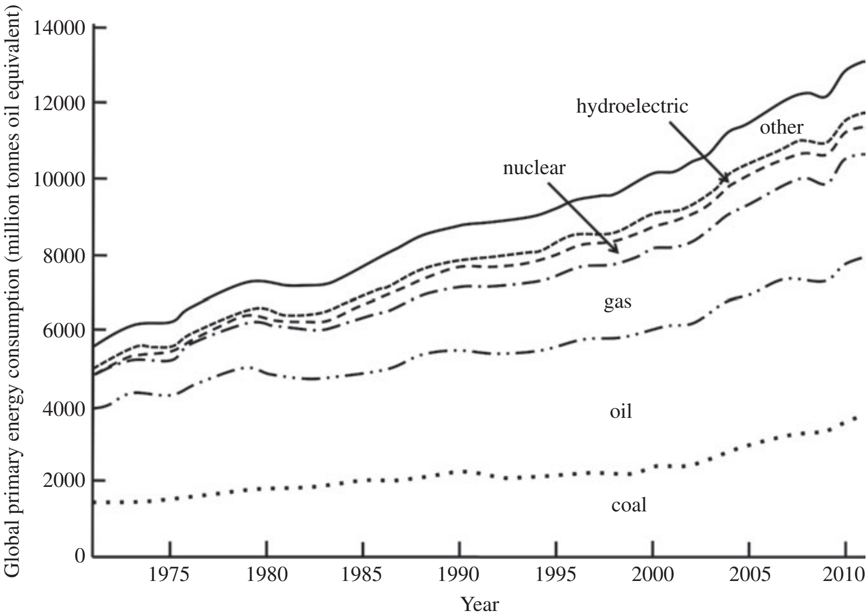

Figure 1.1 Breakdown of the global primary energy supply by fuel type. From 1970 to 2010 there is a near linear rise in total consumption with time, with oil, coal and gas accounting for over 85% of the total supply. Data from BP Statistical Review of Energy (2013). 'Other' which includes wind, solar and biomass is gradually increasing.

amount of energy, in part through large river-dam systems. Other renewable energy sources, such as wind and solar, presently only account for a relatively small fraction of the whole energy supply. However, this is a rapidly growing sector of the energy industry and installed capacity is increasing (Figure 1.1) although this is likely a multi-decadal process. A further challenge for such sources of power is associated with possible storage, to level out the somewhat intermittent supply. Here, battery technology or other storage systems can play an important role, and we consider some challenges of aquifer thermal energy storage systems in Chapter 11. Geothermal energy could also play a very significant role. At a large scale, there are several high temperature systems, with the Geysers in northern California and Larderello in Tuscany, Italy, being two examples with potential electrical power generating capacity of order 1000 MW, and very many lower temperature systems providing thermal energy for direct use in heating. Biofuel technology has made enormous progress, and there are major plants generating bioethanol as a transport fuel, with, for example, Brazil fuelling a substantial fraction of its car fleet through bioethanol from sugar cane. Tidal and wave power is less well developed, but at EMEC, offshore Orkney (www.pelamiswave.com) there are new installations being developed with the Pelamis wave system and submarine tidal turbines, although they are a relatively minor part of the global energy supply. With all these renewable energy sources, cost is a key factor in order that they are competitive.

Given the present mix of energy supply, and the associated infrastructure which is built around this energy supply, it is likely that we will continue to produce and use hydrocarbons over several decades, even if it was straightforward to replace the supply with alternative sources of power. One of the key drivers for renewable energy is associated with carbon emissions produced by burning fossil fuels. Although an aspiration would be to move all supply to renewable energy sources, the time required for this to become a material reality on a global scale may be decades. There are two important ways of reducing emissions associated with the likely use of fossil fuels during this period while the renewable energy supply grows. First, there could be a switch from coal to gas for power generation. Coal is a very substantial part of the energy supply but when used for power generation it produces nearly 1.5–2.0 times the CO_2 emissions per kilowatt hour of electric power that is produced by natural gas. Switching from coal- to gas-fired power stations could therefore have an enormous impact on CO_2 emissions, as has happened recently in the United States. Second, CO_2 produced at power stations, and other large consumers of fossil fuels, can be captured and geosequestered underground into deep saline aquifers. This would reduce the continued supply of CO_2 to the atmosphere, although incurring a substantial cost in infrastructure.

However, underpinning the above arguments is the assertion that the supply of hydrocarbons is readily maintained. The continued supply of hydrocarbons, and especially liquid hydrocarbons, at present production rates is not straightforward and will rely heavily on new technology. Hydrocarbon reserves can be categorised into different groups, called conventional and unconventional. Conventional resources describe reservoirs with good quality rock and fluid oil, which can be recovered using techniques available today.

In typical oil fields, initial approval to develop the field may be based on an aspiration to extract 30–40% of the oil, while the technical limit, based on the effect of capillary retention, for example, may indicate that up to 80% may be recovered. The effects of layering, heterogeneities and compartmentalisation of the field can lead to significant challenges in recovering this secondary oil, as described in Chapter 3. However, it is possible to produce considerably more of the resource. There are examples in the North Sea where over 70% of the intial oil in place has been produced, including the Fortes field. In achieving high recovery rates, much technology has been developed and applied relating to (i) lower cost and horizontal drilling technology, to enable a larger surface area of the well to be located within oil-bearing horizons; (ii) seismic imaging of oil fields before and during their production which can enable improved three-dimensional characterisation of the reservoir and identification of regions of the reservoir in which there has been little flow, which may be targets for infill drilling, (iii) use of surfactants and polymers in water injected into the field to enhance the recovery of the residual oil. All of these techniques can benefit from knowledge of the dynamics of flow in permeable rock, and this forms the first major set of topics of the book, including discussion of the effects of the macroscopic and microscopic structure of the rock formation on the flow, and the intermingling or dispersion of an injected fluid through the original reservoir fluid (Chapters 3–7).

Challenges in the development of oil from new oil fields are often associated with their being located in more remote or hostile environments: new fields may be deeper in the ground, under deeper bodies of water and in many potential reservoirs, the oil may be very viscous, contained in low permeability rocks or loose-packed sand requiring considerable post-extraction processing. Data about the detailed structure of these remote fields may be limited up to the point of development, owing to the cost and inaccessibility, and this introduces risk, which increases the cost and impacts the likelihood of their successful development. The early sections of this volume are concerned with describing some of the difficulties of oil recovery, especially relating to water flooding. In large part, this is a result of the complex structure of these reservoir rocks and the difficulty of driving liquids through the different geological layers in a formation; it also depends on the pore-scale structure and the capillary forces which ultimately retain a fraction of the oil within the pores.

Data available in the BP Statistical Review of Energy and information available from the IEA suggests that up to the present day, the world has used about 1000 billion barrels of oil. However, there are very substantial resources remaining. As well as the significant volume of conventional resources which are still to be developed, which exceeds that already produced, there are enormous volumes of non-coventional resources for which new approaches are required to produce the hydrocarbons. One fascinating example of a so-called non-conventional resource is shale gas: here, gas is bound within extremely low permeability rock. By fracturing the rock in the subsurface, around a well, a fraction of the gas can be released, and with sufficient fracture area, this leads to economic rates of recovery of the gas. This has transformed the US gas market, supplying nearly 40% of US gas requirements, and illustrates the power of technology in opening up new resources.

Some of the major non-conventional oil resources include heavy oil and bitumen deposits in the Canadian and Venezuelan tar sands, where estimates suggest that about another 1 billion barrels of oil may exist. Oil shales are rocks containing high levels (tens of per cent) of organic material which were deposited in shallow seas in anoxic conditions, but which have not been buried to sufficient depth within the Earth to pyrolise. By heating these resources to temperatures of 400–500°C, the bitumen can be converted into hydrocarbons; technology for this is at a very early stage of development, but the Green River Basin in Colorado, USA, may contain 500–1000 billion barrels of oil. Perhaps one of the most intruiging unconventional resources are the methane hydrates, which consist of ice type structures within which methane is trapped. These hydrates are stable at the pressure and temperature conditions found in shallow marine sediments and the permafrost. The resources of such hydrates are thought to be very substantial, of the same order as conventional hydrocarbons, but there remain major challenges in the extraction technology before these become

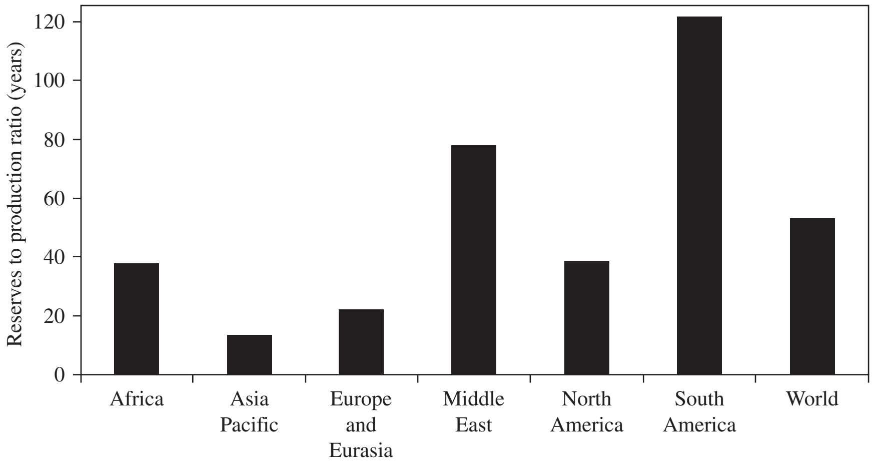

Figure 1.2 Illustration of the reserves to production ratio of oil in different parts of the world, illustrating the number of years of remaining proved resource based on present day production rates. Data from BP Statistical Review of Energy 2013. The total global resources are much larger than the proved reserves shown here.

material energy resources. In particular, the dissociation of the gas and the ice requires latent heat, and this typically leads to freezing of the surrounding permeable layer, thereby suppressing flow of the methane. Also, in some areas, the methane hydrates play a key geotechnical role in supporting the geological strata, and if they dissociate, then slope instability may ensue.

In the short term, the major source of oil production is likely to be that which still remains in existing oil fields, with exploration focusing on the habitat of the oil within the reservoir after the initial phases of oil recovery. Much of the resource is located in the Middle East, where there are some very large reservoirs in carbonate rocks. There are also very significant ongoing oil production developments around the globe, including deep-water offshore West Africa, the Brazilian offshore deposits, the North Sea and the Gulf of Mexico, as well as northern Canada and Alaska. The potential resource base around the globe is often characterised by the reserves to production ratio, where reserves represent those resources which can be recovered economically using known technology. Figure 1.2 illustrates that many of the oil-producing centres round the globe have many decades of future production based on present rates.

As well as the many challenges of oil recovery through water flooding and related techniques, there are a number of related problems in the emerging technology of carbon sequestration. Carbon sequestration is the process of capturing CO_2 from combustion of hydrocarbons and injecting it into subsurface aquifers to reduce the emissions of CO_2 directly into the atmosphere (Figure 1.3). There are still numerous challenges for its implementation and in particular the establishment of a viable economic framework to grow an industry able to inject large volumes of CO_2 into the subsurface. Also the

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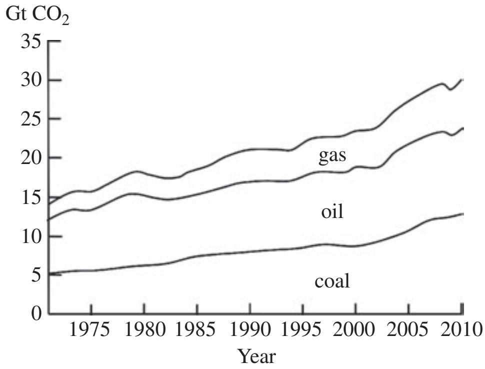

Figure 1.3 Illustration of the source of greenhouse gas emissions associated with use of primary energy. Data from BP Statistical Review of Energy, 2013. The increasing use of coal has led to an increase in coal-related emissions.

assessment of the risk that a significant fraction of sequestered CO_2 may escape from the storage reservoir back to the surface or to subsurface potable aquifers, with the associated problems of cross-contamination is critical. We address some of the technical challenges of modelling and monitoring the fate of the CO_2 during and after injection. Again, fluid mechanics lies at the heart of this process, with the motion of CO_2 often being dominated by buoyancy forces as the plumes ascend through the geological strata or spread horizontally along the strata (Chapters 9 and 10). Some of the processes which control the dispersal of CO_2 in the subsurface are also in operation in the dispersal of plumes of dense non-aqueous phase liquid (DNAPL) following a spillage, and in the migration of plumes of buoyant hydrogen gas which may be emitted from geological waste repositories, and we consider the implications of buoyancy-driven flow for these applications as well (Chapter 10).

Geothermal power involves the recovery of thermal energy from the subsurface, often by pumping cold water into the rock and recovering hot water. Again this is a fluid mechanical process, but involves the migration of thermal fronts, and often mineralisation fronts, as the injected water heats up and in supercritical systems boils. There are significant reserves globally, although at present those which provide substantial sources of energy tend to be strongly coupled to geologically active regions, such as Iceland and New Zealand. In superheated geothermal systems, such as the Geysers in Santa Rosa, northern California and the Lardarello field in Tuscany, cold water is injected into the system to generate additional steam through heating from the rock. This leads to some fascinating phase change problems, which we explore in Chapter 11. There is also interest in using aquifers for interseasonal thermal energy storage, for improving power station efficiency and also for levelling load from intermittent renewable energy sources such as wind. We consider some challenges associated with this in terms of the fluid dynamics of injection and production of water to transport thermal energy.

In Chapter 12, we discuss flow in gas fields, initially considering conventional gas, but then extending the models to account for shale gas. In gas fields, often the pressure is allowed to fall as gas is produced. This can lead to a gradual waning of the flow over time which may introduce other challenges, such as suppression of the gas production if water flows into the production wells from the formation, increasing the backpressure in the field. We examine how gas flows through layered strata, in which the flow path from deep in the reservoir to the well is typically dominated by the flow through high permeability pathways, while the main source of the gas may be in the low permeability matrix surrounding these high permeability channels. The models are also useful in building understanding of the production of gas from very low permeability rocks which are fractured during development, and can be developed to account for the release of adsorbed gas as the formation is decompressed; this is relevant for the production of shale-gas reservoirs.