PETROLEUM GEOSCIENCE

JON G. GLUYAS | RICHARD E. SWARBRICK

SECOND EDITION

WILEY Blackwell

Petroleum Geoscience

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Preface to Second Edition

The first edition of *Petroleum Geoscience* was published in 2004 having taken 10 years to write. This second edition was requested by the publishers in 2009 and again it has taken 10 years to update and write. During the time we took to write the first edition there were incremental changes to the petroleum industry, many of which we incorporated into the text as they happened. However, since 2004 the petroleum industry has undergone two radical changes as well as the incremental changes associated with improvements in technology.

The production of shale-oil and shale-gas (sometimes referred to as "unconventional" hydrocarbons) has changed the world in terms of the relationship between supply and demand for petroleum and in turn this has influenced global energy politics.

The production and combustion of petroleum and coal has changed the world in terms of the concentration of carbon dioxide in the atmosphere – now almost double pre-industrial levels. As a consequence our climate is changing. We must use less petroleum and mitigate the effects of that which is used if we are to maintain a habitable planet for all of humanity.

We will address both climate change and shale-oil/shale-gas in this preface but first let us reflect on some profound changes in our own employment circumstances in these past 10 years.

JG was in 2004 a director of Acorn Oil and Gas, a company he helped found. By late 2005 Acorn had been sold and a new company, Fairfield Energy formed. Fairfield inherited from Acorn the abandoned Maureen Field in the Central North Sea, a field of interest to a start-up company wishing to use Maureen for the geo-storage of carbon dioxide (carbon capture and storage, CCS) from a planned new power station on Teesside, north east England. The power plant was not built but industrial support for a new post at Durham University, the chair in Geoenergy and CCS, led JG to switch from industry to academia in 2009 and join the Earth Sciences Department at Durham University where he has since served as Head of Department, Dean of Knowledge Exchange, and Executive Director of the Durham Energy Institute.

RS was Reader in Petroleum Geology at Durham University in 2004, but also Founder and Managing Director of a small university start-up company, GeoPressure Technology. In 2005 he moved to work full-time with GeoPressure Technology located on the university Science site. Later GeoPressure Technology merged with Ikon Science and from 2010–2013 RS was the Global Director of GeoPressure & Geomechanics at Ikon Science. In 2013 RS left to set up his own consultancy and training company, but he is planning to retire from paid employment soon!

In the 16 years, since the first edition of this book was published, the USA has switched from being the world's largest importer of petroleum and derivative products to a modest exporter of petroleum liquids and liquified gas. This in turn led to a collapse in oil prices between 2014 and 2016 (and collateral fall in the value of coal) as competition for global market share led OPEC to try to regain the upper hand. The switch of the USA from importer to exporter of petroleum is also mirrored by the USA's foreign policy from expansive and global to introverted – it no longer needs to buy the petroleum produced by other countries.

The turnaround in petroleum production in the USA comes from the development of shale-gas and shale oil, principally facilitated by development of hydrofracturing along horizontal wells. Gas and oil are now produced from rocks, mainly hydrocarbon source rocks, once considered too impermeable to flow. Advances in drilling and completion technology have opened up vast areas of the USA (and Canada) for exploitation of this hard-to-produce resource. Other countries such as Argentina and China are beginning to exploit their resources too, but all are around 20 years behind the USA. Given the vast areas yet to be exploited in the USA and other countries it would seem the shale-gas and shale-oil revolution is a long way from being finished.

While much of the world still craves petroleum and other energy-dense fuels such as coal, the damage to the Earth's atmosphere from burning fossils fuels has become only too apparent. Carbon dioxide released to the atmosphere from burning coal, oil, and gas has led to a near doubling of the concentration of CO_2 in the atmosphere (now at >400 ppm) since the beginning of the industrial revolution. The increase in CO_2 and other greenhouse gases such as methane (vented and accidental leakage) is driving climate change and in particular global warming and ocean acidification. In the most recent report form the Intergovernmental Panel on Climate Change (2018) we are faced with the stark reality that humanity has little more than a decade to decarbonize its energy industry or face the irreversible consequences of increased temperatures, rising sea-levels, and significant losses of biodiversity.

And so, the largest change to occur for the petroleum industry is one of perception. To many, especially in the developed parts of the world, fossil fuels (oil, coal, and gas) are seen as bad – enemies of the environment. Greenpeace, Friends of the Earth, and other environmental lobby and projection groups have gone mainstream and in 2019 Extinction Rebellion emerged as a new force in the quest to minimize climate change. The response of many multinational oil giants as well as some of the even larger national petroleum companies has been enlightening. Business models are changing, such companies are describing themselves as "energy companies" rather than oil companies and while this may be regarded as superficial given that most expenditure still goes into finding and producing petroleum, new business streams are emerging, not least the Oil and Gas Climate Initiative (OGCI). Formed from oil majors, OGCI will begin to capture and bury carbon dioxide in industrial quantities, something that most national governments have failed to do. It seems unlikely that enough will be done to prevent major impacts from climate change – time will tell.

The problem with lessening humanity's dependence on petroleum consumption is that it has underpinned almost everything we do as a modern society. The energy density of oil and gas and the ease with which it is transported make it the energy product of choice for most applications, including transport and heating/cooling. In energy terms, petroleum is energy dense, much more so than geothermal fluids, a windy day, a lithium battery, or the sun shining upon our PV panels: it is difficult not to choose petroleum for one's energy needs. That said, and driven by real concerns about the impacts climate change will bring, carbon capture and storage, solar and geothermal energy will emerge as important energy vectors in a rapidly changing market. We have included geothermal energy and CCS sections within our new final chapter. Beyond petroleum, former petroleum geoscientists will be in demand to help realize the worth of hot water, develop storage space for CO_2, and deliver the basic materials for a cleaner world.

Preface to First Edition

Wemet at AAPG London 1992 and, unknown to each other at the time, we were both facing similar problems with respect to teaching petroleum geoscience within the industry (J.G.) and academia (R.S.). The main problem was the paucity of published information on the basics of the applied science—how the geoscientist working in industry does his or her job, and with which other disciplines the geoscientist interacts. R.S. had already taken steps to remedythis with a proposal for a book on petroleum geoscience sent to Blackwell. The proposal was well received by reviewers and the then editor Simon Rallison. Simon sought an industry-based coauthor and found one in J.G. At that time, J.G. was teaching internal courses at BP to drillers, reservoir engineers, petroleum engineers, and budding geophysicists with a physics background. Simon's invitation was accepted and by early 1994 work had begun. It seemed like a good idea at the time, but the petroleum industry was changing fast, nowhere more so than in the application of geophysics, stratigraphicgeology, and reservoir modeling. The use of 3D seismic surveys was changing from being rare to commonplace, 4D time-lapse seismic was being introduced, and multi-component seismic data was also beginning to find common use. Derivativeseismic data were also coming to the fore, with the use of acoustic impedance, amplitude versus offset, and the like. The application of sequencestratigraphic principles was becoming the norm. Reservoir models were increasing in complexity manifold, and they were beginning to incorporate much more geologic information than had hitherto been possible. Along side the technological changes, there were also changes in the business as a whole. Frontier exploration was becoming less dominant, and many geoscientists were finding themselves involved in the rehabilitation of old oilfields as new geographies opened in the former Soviet Union and South America. It was tough to keep pace with these changes in respect of writing this book, but as the writing progressed it became even clearer that information on the above changes was not available in textbooks. We hope to have captured it for you! This book is written for final-year undergraduates, postgraduate M.Sc. and Ph.D. students, and non-geologic technical staff within the petroleum industry.

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Producing a second edition of *Petroleum Geoscience* has been a long, arduous and at times thankless journey, unassisted by numerous changes in computer hardware and software since the first edition was produced. With help from Wiley we eventually managed to track down image files of the original figures but for many they were originally constructed using software that no longer exists, or at least was not accessible to us. Editing was not an option. We had to start from scratch. We thank Antony Sami and a string of earlier editors at Wiley for digging deep into archives inherited from Blackwell to find most of the original material.

Mike Bowman (long-term BP employee and now retired) was a huge help with the first edition and he was on hand to supply most of the material we needed for the new Thunder Horse case history in Chapter 4. We also need to thank senior staff at Lundin for verifying the material used in the Johan Sverdrup case history (Chapter 3) and at Tullow for the review of the information used in the Jubilee case history (Chapter 3).

The biggest thanks though go to Theresa Gluyas and Alison Swarbrick, our wives. That we have now completed the second edition is down to their support, encouragement, and at times well-directed instructions to, “get on with it,” thank you!

1

Introduction

1.1 The Aim and Format of the Book

The aim of this book is to introduce petroleum geoscience to geologists, be they senior undergraduates or postgraduates, and to non-geologists (petrophysicists, reservoir engineers, petroleum engineers, drilling engineers, and environmental scientists) working in the petroleum industry. We define petroleum geoscience as the disciplines of geology and geophysics applied to understanding the origin and distribution and properties of petroleum and petroleum-bearing rocks. The book will deliver the fundamentals of petroleum geoscience and allow the reader to put such information into practice.

The format of the book follows the path known within the oil industry as the "value chain." This value chain leads the reader from frontier exploration through discovery to petroleum production. Such an approach is true to the way in which industry works; it allows the science to evolve naturally from a start point of few data to an end point of many data. It also allows us to work from the larger basin scale to the smaller pore scale, and from the initial superficial analysis of a petroleum-bearing basin to the detailed reservoir description.

Case histories are used to support the concepts and methods described in the chapters. Each case history is a complete story in itself. However, the case histories also form part of the value chain theme. Specific emphasis is placed upon the problems presented by exploration for and production of petroleum. The importance and value of data are examined, as are the costs, both in time and money, of obtaining data.

1.2 Background

Petroleum geoscience is intimately linked with making money, indeed profit. The role of the petroleum geoscientist, whether in a state oil company, a massive multinational company, or a small independent company, is to find petroleum (oil and hydrocarbon gas) and help produce it so that it can be sold.

In years past, geoscientists overwhelmingly dominated the bit of the industry that explores for petroleum – they have boldly gone to impenetrable jungles, to scorching deserts, and to hostile seas in the search for petroleum. Getting the oil and gas out of the ground – that is, production – was left largely to engineers.

Today, the situation is different. Geoscience is still a key part of the exploration process, but finding oil and gas is more difficult than it used to be. There are many fewer giant oilfields to be discovered. The geoscientists now need to work with drilling engineers, reservoir engineers, petroleum engineers, commercial experts, and facilities engineers to determine

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whether the petroleum that might be discovered is likely to be economical to produce as crude oil for market.

Geoscientists now also play an important role in the production of petroleum. Oilfields and gasfields are not simply tanks waiting to be emptied. They are complex three-dimensional (3D) shapes with internal structures that will make petroleum extraction anything but simple. The geoscientist will help describe the reservoir and the trapped fluids. Geoscientists will also help determine future drilling locations and use information from petroleum production to help the interpretation of reservoir architecture.

1.3 What Is in this Book

This book is aimed at satisfying the needs of undergraduates who wish to learn about the application of geoscience in the petroleum industry. It is also aimed at nongeoscientists (petrophysicists, reservoir engineers, and drilling engineers) who, on account of their role in the old industry, need to find out more about how geologists and geophysicists ply their trade.

The book is divided into seven chapters. The first chapter introduces both the book and the role of petroleum geoscience and geoscientists in industry. It also includes a section on the chemistry of oil. Chapter 2 examines the tools used by petroleum geoscientists. It is brief, since we intend only to introduce the "tools of the trade." More detail will be given in the body of the later chapters and in the case histories as needed.

Chapters 3 through 7 comprise the main part of the book. Chapters 3 and 4 cover exploration. We have chosen to divide exploration into two chapters for two reasons. To include all of the petroleum geoscience associated with exploration in one chapter would have been to create a massive tome. Moreover, it is possible to divide the exploration geoscience activity into basin description and petroleum exploration. Chapter 3 contains the basin description, with the addition of material on acreage acquisition and a section on possible shortcuts to finding petroleum. The final section of Chapter 3 is about petroleum source rocks, where they occur, and why they occur. Chapter 4 opens with sections on the other key components of petroleum geoscience; that is, the petroleum seal, the petroleum reservoir, and the petroleum trap. The second half of Chapter 4 examines the spatial and temporal relationships between reservoir and seal geometries and migrating petroleum. Risk (the likelihood of a particular outcome) and uncertainty (the range of values for a particular outcome) are both intrinsic parts of any exploration, or indeed appraisal, program. These too are examined.

Once a discovery of petroleum has been made, it is necessary to find out how much petroleum has been found and how easily oil or gas will flow from the field. This is appraisal, which is treated in Chapter 5. During appraisal, a decision will be made on whether to develop and produce the field under investigation. The geoscience activity associated with development and production is covered in Chapter 6. Since publication of the first edition in 2003, the term unconventional petroleum has come into common usage within the industry and particularly within the news media and we have recognized this by extracting material on unconventional petroleum from Chapter 6 and adding new material to produce Chapter 7.

1.4 What Is Not in this Book

The book introduces petroleum geoscience, a discipline of geoscience that embraces many individual and specialist strands of earth science. We deal with aspects of all these strands, but these important topics – such as basin analysis, stratigraphy, sedimentology, diagenesis, petrophysics, reservoir simulation, and others – are not covered in great detail. Where appropriate, the reader is guided to the main texts in these sub-disciplines and there are also suggestions for further reading.

1.5 Key Terms and Concepts

The source, seal, trap, reservoir, and timing (of petroleum migration) are sometimes known as the “magic five ingredients” without which a basin cannot become a petroleum province (Figure 1.1). Here, we introduce these and other essential properties, before examining each aspect in more detail in the chapters that follow.

1.5.1 Petroleum

Petroleum is a mixture of hydrocarbon molecules and lesser quantities of other organic molecules containing sulfur, oxygen, nitrogen, and some metals. The term includes both oil and hydrocarbon gas. The density of liquid petroleum (oil) is commonly less than that of water and the oil is naturally buoyant. So-called heavy (high specific gravity) oils and tars may be denser than water. Some light (low specific gravity) oils are less viscous than water, while most oils are more viscous than water. The composition of petroleum and its properties are given in Section 1.6.

1.5.2 The Source

A source rock is a sedimentary rock that contains sufficient organic matter such that when it is buried and heated it will produce petroleum (oil and gas). High concentrations of organic matter tend to occur in sediments that accumulate in areas of high organic matter productivity and stagnant water. Environments of high productivity can include nutrient rich coastal upwellings, swamps, shallow seas, and lakes. However, much of the dead organic matter generated in such systems is scavenged and recycled within the biological cycle. To preserve organic matter, the oxygen contents of the bottom waters and interstitial waters of the sediment need to be very low or zero. Such conditions can be created by overproduction of organic matter, or in environments where poor water circulation leads to stagnation.

Different sorts of organic matter yield different sorts of petroleum. Organic matter rich in soft and waxy tissues, such as that found in algae, commonly yields oil with associated gas on maturation (heating), while gas alone tends

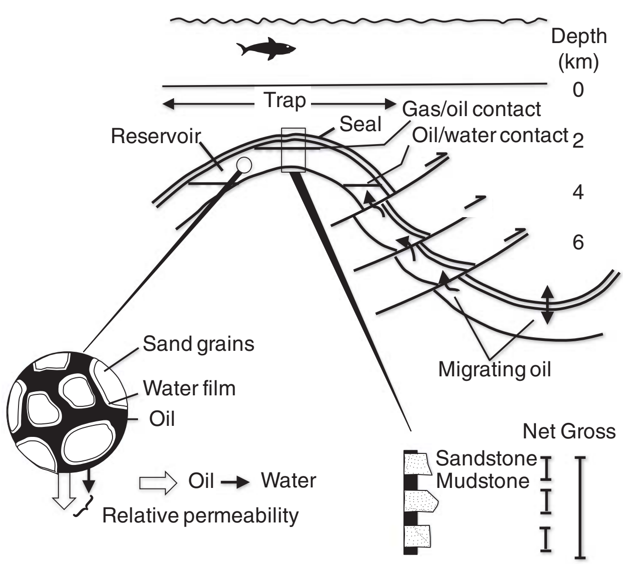

Figure 1.1 A cartoon cross-section of part of a petroleum-bearing basin. Most of the “key terms” described in the text are shown pictorially.

to be derived from the maturation of woody tissues. Even oil-prone source rocks yield gas when elevated to high temperatures during burial. A detailed description of source rocks and source rock development can be found in Section 3.7. Most source rocks expel petroleum as it is generated. However, all source rocks retain at least some of the petroleum generated and it is typically these which may be exploited as the so-called unconventional shale-gas and shale-oil deposits.

1.5.3 The Seal

Oil and gas are less dense than water and, as such, once they migrate from the source rock they tend to rise within the sedimentary rock column. The petroleum fluids will continue to rise under buoyancy until they reach a seal. Seals tend to be fine-grained or crystalline, low-permeability rocks. Typical examples include mudstone/shale, cemented limestones, cherts, anhydrite, and salt (halite). As such, many source rocks may also be high-quality seals. Seals to fluid flow can also develop along fault planes, faulted zones, and fractures.

The presence of a seal or seals is critical for the development of accumulations of petroleum in the subsurface. In the absence of seals, petroleum will continue to rise until it reaches the Earth's surface. Here, surface chemical processes including bacterial activity will destroy the petroleum. Although seals are critical for the development of petroleum pools, none are perfect. All leak. This natural phenomenon of petroleum seepage through seals can provide a shortcut to discovering petroleum. Seals and seal mechanisms are described in Section 4.2.

1.5.4 The Trap

The term "trap" is simply a description of the geometry of the sealed petroleum-bearing container (Section 4.5). Buoyant petroleum rising through a pile of sedimentary rocks will not be trapped even in the presence of seals if the seals are, in gross geometric terms, concave-up. Petroleum will simply flow along the base of the seal until the edge of the seal is reached, and then it will continue upwards toward the surface. A trivial analogy, albeit inverted, is to pour coffee onto an upturned cup. The coffee will flow over but not into the cup. However, if the seal is concave-down it will capture any petroleum that migrates into it.

The simplest trapping configurations are domes (four-way dip-closed anticlines) and fault blocks. However, if the distribution of seals is complex, it follows that the trap geometry will also be complex. The mapping and remapping of trap geometry is a fundamental part of petroleum geoscience at the exploration, appraisal, and even production phases of petroleum exploration.

1.5.5 The Reservoir

A reservoir is the rock plus void space contained in a trap. Traps rarely enclose large voids filled with petroleum; oil-filled caves, for example, are uncommon. Instead, the trap contains a porous and permeable reservoir rock. The petroleum together with some water occurs in the pore spaces between the grains (or crystals) in the rock. Reservoir rocks are most commonly sandstones or carbonates, although source rocks themselves can act as reservoirs as can more exotic lithologies such as fractured granites and gneiss. Viable reservoirs occur in many different shapes and sizes, and their internal properties (porosity and permeability) also vary enormously (Section 4.3).

1.5.6 The Timing of Petroleum Migration

We have already introduced the concept of buoyant petroleum migrating upward from the source rock toward the Earth's surface. Seals in suitable trapping geometries will arrest migration of the petroleum. When exploring for petroleum it is important to consider the timing of petroleum migration relative to the time of deposition of the reservoir/seal combinations and the creation of structure within the basin. If migration of petroleum occurs before deposition of a suitable reservoir/seal combination, then the petroleum will not be trapped. If petroleum migrates before structuring in the basin creates suitable trap geometries, then the petroleum will not be trapped. In order to determine whether the reservoir, seal, and trap are available to arrest migrating petroleum, it is necessary to reconstruct the geologic history of the area under investigation. Petroleum migration is examined in Section 4.4.

1.5.7 Porous Rock and Porosity

A porous rock has the capacity to hold fluid. By definition, reservoirs must be porous. Porosity is the void space in the rock, reported either as a fraction of one or as a percentage. Most reservoirs contain >0% to <40% porosity.

1.5.8 Permeable Rock and Permeability

A permeable rock has the capacity to transmit fluid. A viable reservoir needs to be permeable or the petroleum will not be extracted. By definition, a seal needs to be largely impermeable to petroleum. Permeability is a measure of the degree to which fluid can be transmitted. The unit for permeability used in the petroleum industry is the darcy (D), although the permeability of many reservoirs is measured in millidarcies (mD). Typically, the permeability of reservoirs is 10 D or less. At the lower end, gas may be produced from reservoirs of 0.1 mD, while oil reservoirs need to be 10× or 100× more permeable. The darcy is not an SI unit but like other measures of permeability its units are the same as area and it is equivalent to $9.689\,233 \times 10^{-13}$ m^2.

1.5.9 Relative Permeability

Most reservoirs contain both oil and water in an intimate mixture. A consequence of there being more than one fluid in the pore system is that neither water nor oil will flow as readily as if there were only one phase. Such relative permeability varies as a function of fluid phase abundance.

1.5.10 Net to Gross and Net Pay

A reservoir commonly contains a mixture of nonreservoir lithologies (rocks) such as mudstone or evaporite minerals interbedded with the reservoir lithology, commonly sandstone or limestone. The ratio of the porous and permeable interval to the nonporous and/or nonpermeable interval is called the "net to gross." Net pay is the portion of the net reservoir containing petroleum and from which petroleum will flow.

1.5.11 Water Saturation

A petroleum-bearing reservoir always contains some water. The quantity of water is commonly expressed as a fraction or percentage of the pore space. There are, of course, comparable terms for oil and gas.

1.5.12 Formation Volume Factor

The formation volume factor is the volume of the petroleum in the trap divided by the volume of the same mass of petroleum at the Earth's surface under conditions of standard temperature and pressure (25 °C and 1 atm). The increase in pressure at depth means that gas occupies less volume in the subsurface. However, the situation differs for most oils which shrink when raised from the trap to the surface. This is because most oils contain dissolved gas and as the pressure is lowered there comes a pressure known as the bubble point when gas starts to exsolve. The gas expands and in consequence the oil shrinks.

Most oils have formation volume factors of between 1 and 2. Gases typically have formation volume factors of 0.003–0.01. The inverse of these figures for gas are commonly quoted and called the gas expansion factor.

1.5.13 The Gas to Oil Ratio

The gas that is exsolved when oil is raised from the trap to the surface is produced alongside the oil. The proportion of gas and oil in the produced fluid at stock tank conditions (i.e. surface temperature and pressure) is known as the gas to oil ratio (or "GOR").

1.5.14 Timescales

In a book written by geoscientists about geoscience, but intended for at least some non-geoscientists, it is important to point out the difference between what is meant by *time* to a geoscientist and to a nongeoscientist. At around 4.5×10^9 years (10^9 = 1US billion), the Earth is old. The oldest rocks from which oil has been generated are a mere half a billion years old or thereabouts, though pre-Cambrian crustalline basement rocks are known to reservoir oil and gas. At the other end of the timescale; maturation migration and trapping of oil can occur quickly, at least in a geologic sense. Some of the oil in the southern Caspian Sea and some of the oil in eastern Venezuela are found in reservoir sands that are only a few million years old. Had *Australopithecus* wandered from Africa a little sooner, he would have been able to witness the deposition of sands that now host major oilfields in Venezuela and Azerbaijan. Thus, although a complete cycle of petroleum maturation, migration, and trapping can occur in a few million years – almost a geologic instant – that same instant covers all of recorded human history and most of that deduced from paleoanthropology.

Geologic time is divided, using a hierarchical scheme, into a variety of named units. The basic unit in this scheme is the period (individual periods lasted between 10 million and 100 million years). The sequence of periods with their attendant subdivisions and supra-divisions makes up the stratigraphic column (Figure 1.2).

1.5.15 The Units Used in this Book

For the most part, metric units are used in this book. Imperial terms appear where the original source data are in imperial measurements. However, the terms "barrels of oil" (bbl) and "standard cubic feet of gas" (scf) are generally employed in this book because they are used much more commonly than their metric equivalents. In these instances, the metric equivalents are bracketed (see the unit conversions in Table 1.1).

1.6 The Chemistry of Petroleum

Petroleum is a mixture of hydrocarbons and other organic compounds that together dictate its chemical and physical properties. For example, typical oil from the Brent Field in the UK North Sea contains an average of 26 000 pure compounds. This oil will easily flow through the reservoir rock to reach a wellbore, and flow to the surface and along pipelines, up to 1000 km long, to the refinery. By contrast, oil found in parts of the Los Angeles basin (e.g. the Wilmington Field) is viscous and it needs to be heated by steam for it to flow. It would be too viscous to flow down a conventional pipeline, and it is refined at a surface installation above the oilfield. In a gross sense, it is possible to determine the physical properties of the petroleum if its chemical constituents are known. Thus we now review the main groups of hydrocarbon and associated compounds.

Hydrocarbons are molecules composed of hydrogen (H) and carbon (C) bonded together. Petroleum also contains lesser quantities of organic molecules that contain nitrogen (N), oxygen (O), and sulfur (S). Small but significant quantities of organometallic compounds (commonly with vanadium and nickel) are also present, as are a large array of elements in trace quantities. Examples of small and simple hydrocarbons include methane (CH_4),

(a)

Era	Sub-era	Period / Sub-period	Epoch	Stage	Age (Ma)	Stage abbr.	Intervals (Ma)	
Paleozoic		Devonian	15 D3 Late	Famennian	367.0	Fam	4.5	46
				Frasnian	377.4	Frs	10.4	
			9 D2 Middle	Givetian	380.8	Giv	3.4	
				Eifelian	386.0	Eif	5.2	
			22 D1 Early	Emsian	390.4	Ems	4.4	
				Pragian	396.3	Pra	5.9	
		46 D		Lochkovian	408.5	Lok	12.2	
		Silurian	S4 Pridoli Prd		410.7	Prd	2.2	31
			13 S3 Ludlow Lud	Ludfordian	415.1	Ldf	4.4	
				Gorstian	424.0	Gor	8.9	
			6.5 S2 Wenlock Wen	Gleedonian	425.4	Gle	1.4	
				Whitwellian	426.1	Whi	0.7	
				Sheinwoodian	430.4	She	4.3	
			8.5 S1 Llandovery Lly	Telychian	432.6	Tel	2.2	
				Aeronian	436.9	Aer	4.3	
		31 S		Rhuddanian	439.0	Rhu	2.1	
	Ordovician	Bala	4 Ashgill Ash	Hirnantian	439.5	Hir	0.5	71
				Rawtheyan	440.1	Raw	0.6	
				Cautleyan	440.6	Cau	0.5	
				Pusgillian	443.1	Pus	2.5	
			21 Caradoc Crd	Onnian	444.0	Onn	0.9	
				Actonian	444.5	Act	0.5	
				Marshbrookian	447.1	Mrb	2.6	
				Longvillian	449.7	Lon	2.6	
				Soudleyan	457.5	Sou	7.8	
				Hamagian	462.3	Har	4.8	
		25 Bal		Costonian	463.9	Cos	1.6	
		Dyfed	4.5 Llandeilo Llo	Late	465.4	Llo 3	1.5	
				Mid	467.0	Llo 2	1.6	
				Early	468.6	Llo 1	1.6	
			7.5 Llanvirn Lln	Late	472.7	Lln 2	4.1	
		12 Dfd		Early	476.1	Lln 1	3.4	
		Canadian	Arenig		493.0	Arg	17.0	
	71 O	34 Cnd	Tremadoc		510.0	Tre	17.0	
	Cambrian		7 Merioneth Mer	Dolgellian	514.1	Dol	4.1	60
				Maentwrogian	517.2	Mnt	3.1	
			19 St. David's StD	Menevian	530.2	Men	13.0	
				Solvan	536.0	Sol	5.8	
			34 Caerfai Crf	Lenian	554	Len	18.0	
				Atdabanian	560	Atb	6.0	
325 Pz	60 E			Tommotian	570	Tom	10.0	

Eon	Age	Era	Period	Epoch / Stage	Stage	Age (Ma)	Stage abbr.	Intervals (Ma)	
Proterozoic Pt1		Sinian	Vendian	20 Ediacara Edi	Poundian	580	Pou	10.0	40
					Wonokan	590	Won	10.0	
			40 V	20 Varanger Var	Mortensnes	600	Mor	10.0	
					Smalfjord	610	Sma	10.0	
		230 Z	Sturtian			800	Stu	190	
Pt2	1000	Riphean		Karatau		1050	Kar	250	
				Yurmatin		1350	Yur	300	
		850 Rlf		Burzyan		1650	Buz	300	
Pt3	1600	Animikean				2200	Ani	550	
		Huronian				2450	Hur	250	
Archean	2500	Randian				2800	Ran	350	
		Swazian				3500	Swz	700	
		Isuan				3800	Isu	300	
		Hadean		Early Imbrian		3850	Imb	50	
				Nectarian		3950	Nec	100	
				Basin Groups 1–9		4150	BG1-9	200	
Priscoan	4000	760 Hde		Cryptic		4560	Cry	410	

Figure 1.2 A stratigraphic time scale. Source: Gradstein and Ogg 2004. Reproduced with permission of John Wiley & Sons.

(b)

Era	Sub-era / Period	Sub-period	Epoch			Stage	Age (Ma)	Stage abbr.	Intervals (Ma)	
Cenozoic 65 Cz	Quaternary or Pleistogene 1.64		Holocene				0.01	Hol	0.01	
			Pleistocene				1.64	Ple	1.63	
	Tertiary 63 TT	Neogene 22 Ng	Pliocene Pli		2	Placenzian	3.40	Pia	3.6	22
					1	Zanclian	5.2	Zan		
			Miocene 18.1 Mio		3	Messinian	6.7	Mes	5.2	
						Tortonian	10.4	Tor		
					2	Serravallian	14.2	Srv	5.9	
						Langhian	16.3	Lan		
					1	Burdigalian	21.5	Bur	7.0	
						Aquitanian	23.3	Agt		
		Paleogene 42 Pg	Oligocene 12.1 Oli		2	Chattian	29.3	Cht	6.0	42
					1	Rupelian	35.4	Rup	6.1	
			Eocene 21.1 Eoc		3	Priabonian	38.6	Prb	3.2	
					2	Bartonian	42.1	Brt	11.4	
						Lutetian	50.0	Lut		
					1	Ypresian	56.5	Ypr	6.5	
			Paleocene 8.5 Pal		2	Thanetian	60.5	Tha	4.0	
					1	Danian	65.0	Dan	4.5	
Mesozoic 180 Mz	Cretaceous 81 K		Gulf K_2 32 Gul	Senonian 23.5 Sen		Maastrichtian	74.0	Maa	9.0	81
						Campanian	83.0	Cmp	9.0	
						Santonian	86.6	San	3.6	
						Coniacian	88.5	Con	1.9	
				Gallic 43.3 Gal		Turonian	90.4	Tur	1.9	
						Cenomanian	97.0	Cen	6.6	
			Early K_1 49			Albian	112.0	Alb	15.0	
						Aptian	124.5	Apt	12.5	
						Barremian	131.8	Brm	7.3	
				Neocomian 13.8 Neo		Hauterivian	135.0	Hau	3.2	
						Valanginian	140.7	Vlg	5.7	
						Berriasian	145.6	Ber	4.9	
	Jurassic 62 J		Malm J_3 11.5 Mal			Tithonian	152.1	Tth	6.5	62
						Kimmeridgian	154.7	Kim	2.6	
						Oxfordian	157.1	Oxf	2.4	
			Dogger J_2 20.9 Dog			Callovian	161.3	Clv	4.2	
						Bathonian	166.1	Bth	4.8	
						Bajocian	173.5	Baj	7.4	
						Aalenian	178.0	Aal	4.5	
			Lias J_1 30.0 Lia			Toarcian	187.0	Toa	9.0	
						Pliensbachian	194.5	Plb	7.5	
						Sinemurian	203.5	Sin	9.0	
						Hettangian	208.0	Het	4.5	
	Triassic 37 Tr		Tr_3 27 Late			Rhaetian	209.5	Rht	1.5	37
						Norian	223.4	Nor	13.9	
						Carnian	235.0	Crn	11.6	
			Tr_2 6 Mid			Ladinian	239.5	Lad	4.5	
						Anisian	241.1	Ans	1.6	
			Scythian Tr_1 4 Scy			Spathian	241.9	Spa	0.8	
						Nammalian	243.4	Nml	1.5	
						Griesbachian	245.0	Gri	1.6	
Paleozoic	Permian 45 P		Zechstein 11 Zec			Changxingian	247.5	Chx	2.5	45
						Longtanian	250.0	Lgt	2.5	
						Capitanian	252.5	Cap	2.5	
						Wordian	255.0	Wor	2.5	
						Ufimian	256.1	Ufi	1.1	
			Rotliegend 34 Rot			Kungurian	259.7	Kun	3.6	
						Artinskian	268.8	Art	9.1	
						Sakmarian	281.5	Sak	12.7	
						Asselian	290.0	Ass	8.5	
	Carboniferous 73 C	Pennsylvanian 33 C_2	Gzelian 5 Gze	Stephanian 13 Ste		Noginskian	293.6	Nog	3.6	33
						Klazminskian	295.1	Kla	1.5	
			Kasimovian 8 Kas			Dorogomilovskian	298.3	Dor	3.2	
						Chamovnicheskian	299.9	Chv	1.6	
						Krevyakinskian	303.0	Kre	3.1	
			Moscovian 8 Mos	Westphalian 15 Wes		Myachkovskian	305.0	Mya	2.0	
						Podolskian	307.1	Pod	2.1	
						Kashirskian	309.2	Ksk	2.1	
						Vereiskian	311.3	Vrk	2.1	
			Bashkirian 12 Bsh			Melekesskian	313.4	Mel	2.1	
						Cheremshanskian	318.3	Che	4.9	
				Namurian 15 Nam		Yeadonian	320.6	Yea	2.3	
						Marsdenian	321.5	Mrd	0.9	
						Kinderscoutian	322.8	Kin	1.3	
		Mississippian 40 C_1	Serpukhovian 10 Spk			Alportian	325.6	Alp	2.8	40
						Chokierian	328.3	Cho	2.7	
						Arnsbergian	331.1	Arn	2.8	
						Pendleian	332.9	Pnd	1.8	
			Visean 17 Vis			Brigantian	336.0	Bri	3.1	
						Asbian	339.4	Asb	3.4	
						Holkerian	342.8	Hlk	3.4	
						Arundian	345.0	Aru	2.2	
						Chadian	349.5	Chd	4.5	
			Tournaisian 13 Tou			Ivorian	353.8	Ivo	4.3	
						Hastarian	362.5	Has	8.7	

Figure 1.2 (*Continued*)