

B. P. Tissot · D. H. Welte

Petroleum Formation and Occurrence

Second Revised and Enlarged Edition

With 327 Figures

Springer-Verlag
Berlin Heidelberg New York Tokyo 1984



Contents

Part I Production and Accumulation of Organic Matter: A Geological Perspective

<i>Chapter 1</i>	Production and Accumulation of Organic Matter: The Organic Carbon Cycle	3
1.1	Photosynthesis – The Basis for Mass Production of Organic Matter	3
1.2	The Organic Carbon Budget During the History of the Earth	7
1.3	The Organic Carbon Budget in the Black Sea	11
	Summary and Conclusion	13
<i>Chapter 2</i>	Evolution of the Biosphere	14
2.1	Phytoplankton and Bacteria	14
2.2	Higher Plants	17
2.3	Geological History of the Biosphere	19
	Summary and Conclusion	20
<i>Chapter 3</i>	Biological Productivity of Modern Aquatic Environments	21
3.1	Primary Producers of Organic Matter	21
3.2	Factors Influencing Primary Productivity	23
3.3	Present Primary Production of the Oceans	28
	Summary and Conclusion	30
<i>Chapter 4</i>	Chemical Composition of the Biomass: Bacteria, Phytoplankton, Zooplankton, Higher Plants	31
4.1	Proteins and Carbohydrates	31
4.2	Lipids	34
4.3	Lignin and Tannin	44
4.4	Qualitative and Quantitative Occurrence of Important Chemical Constituents in Bacteria, Phytoplankton, Zooplankton and Higher Plants	45

4.5	Natural Associations and Their Effects on Biomass Composition	50
	Summary and Conclusion	53
<i>Chapter 5</i> Sedimentary Processes and the Accumulation of Organic Matter 55		
5.1	Fossil and Modern Sediments Rich in Organic Matter, and Their Geological Implication	55
5.2	The Role of Dissolved and Particulate Organic Matter	57
5.3	Accumulation Mechanisms for Sedimentary Organic Matter	59
	Summary and Conclusion	61
References to Part I		63
 <i>Part II The Fate of Organic Matter in Sedimentary Basins: Generation of Oil and Gas</i>		
<hr/>		
<i>Chapter 1</i> Diagenesis, Catagenesis and Metagenesis of Organic Matter 69		
1.1	Diagenesis	69
1.2	Catagenesis	71
1.3	Metagenesis and Metamorphism	72
	Summary and Conclusion	73
 <i>Chapter 2</i> Early Transformation of Organic Matter: The Diagenetic Pathway from Organisms to Geochemical Fossils and Kerogen 74		
2.1	Significance and Main Steps of Early Transformations	74
2.2	Biochemical Degradation	75
2.3	Polycondensation	81
2.4	Insolubilization	85
2.5	Isotopic Composition of Organic Matter in Young Sediments	89
2.6	Result and Balance of Diagenesis	90
	Summary and Conclusion	92
 <i>Chapter 3</i> Geochemical Fossils and Their Significance in Petroleum Formation 93		
3.1	Diagenesis Versus Catagenesis: Two Different Sources of Hydrocarbons in the Subsurface	93

3.2	Hydrocarbons Inherited from Living Organisms, Directly or Through an Early Diagenesis: Geochemical Fossils (Biological Markers)	98
3.3	<i>n</i> -Alkanes and <i>n</i> -Fatty Acids	100
3.4	Iso- and Anteiso-Alkanes	110
3.5	C ₁₀ -branched Alkanes	110
3.6	Acyclic Isoprenoids	111
3.7	Tricyclic Diterpenoids	116
3.8	Steroids and Pentacyclic Triterpenoids: Occurrence in Recent and Ancient Sediments	117
3.9	Fate of Steroids and Triterpenoids During Diagenesis and Catagenesis	121
3.10	Other Polyterpenes	126
3.11	Aromatics	126
3.12	Oxygen and Nitrogen Compounds	127
3.13	Kerogen, the Polar Fraction of Sediments, and Asphaltenes of Crude Oils as Possible Sources of Fossil Molecules	129
	Summary and Conclusion	130
 <i>Chapter 4</i> Kerogen: Composition and Classification		131
4.1	Definition and Importance of Kerogen	131
4.2	Isolation of Kerogen	132
4.3	Microscopic Constituents of Kerogen	133
4.4	Chemical and Physical Determination of Kerogen Structure	139
4.5	Chemical Analysis	140
4.6	Physical Analysis	142
4.7	General Structure of Kerogen	147
4.8	Depositional Environment and Composition of Kerogen: the Evolution Paths	151
4.9	Conclusion	159
	Summary and Conclusion	159
 <i>Chapter 5</i> From Kerogen to Petroleum		160
5.1	Diagenesis, Catagenesis and Metagenesis of Kerogen	160
5.2	Experimental Simulation of Kerogen Evolution	169
5.3	Structural Evolution of Kerogen	174
5.4	Formation of Hydrocarbons During Catagenesis	176
5.5	Isotope Fractionation and Kerogen Evolution	189
5.6	Experimental Generation of Hydrocarbons from Organic Material	192
	Summary and Conclusion	198

<i>Chapter 6</i>	Formation of Gas	199
6.1	Constituents and Characterization of Petroleum Gas	199
6.2	Gas Generated During Diagenesis of Organic Matter	201
6.3	Gas Generated During Catagenesis and Metagenesis of Organic Matter	204
6.4	Gas Originating from Inorganic Sources	207
6.5	Occurrence and Composition of Gas in Sedimentary Basins: Example of Western Europe	208
6.6	Distribution of Gases in Sedimentary Basins	213
	Summary and Conclusion	214
<i>Chapter 7</i>	Formation of Petroleum in Relation to Geological Processes. Timing of Oil and Gas Generation	215
7.1	General Scheme of Petroleum Formation	215
7.2	Genetic Potential and Transformation Ratio	218
7.3	Nature of the Organic Matter. Gas Provinces Versus Oil Provinces	219
7.4	Temperature, Time and Pressure	222
7.5	Timing of Oil and Gas Generation	223
7.6	Comparison Between the Time of Source Rock Deposition and the Time of Petroleum Generation	225
	Summary and Conclusion	228
<i>Chapter 8</i>	Coal and Its Relation to Oil and Gas	229
8.1	General Aspects of Coal Formation	229
8.2	The Formation of Peat	230
8.3	Coalification Process	234
8.4	Coal Petrography	241
8.5	Petroleum Generation	245
	Summary and Conclusion	253
<i>Chapter 9</i>	Oil Shales: A Kerogen-Rich Sediment with Potential Economic Value	254
9.1	Historical	254
9.2	Definition of Oil Shales. Oil Shale Versus Petroleum Source Rock	254
9.3	Composition of Organic Matter	256
9.4	Conditions of Deposition	258
9.5	Oil Shale Density	259
9.6	Pyrolysis of Oil Shales	259
9.7	Oil Yield; Composition of Shale Oil	260
9.8	Oil Shale Distributions and Reserves	261
	Summary and Conclusion	266
	References to Part II	267

Part III The Migration and Accumulation of Oil and Gas

<i>Chapter 1</i>	An Introduction to Migration and Accumulation of Oil and Gas	293
	Summary and Conclusion	295
<i>Chapter 2</i>	Physicochemical Aspects of Primary Migration	296
2.1	Temperature and Pressure	296
2.2	Compaction	301
2.3	Fluids	307
2.4	Possible Modes of Primary Migration	309
	Summary and Conclusion	323
<i>Chapter 3</i>	Geological and Geochemical Aspects of Primary Migration	325
3.1	Time and Depth of Primary Migration	325
3.2	Changes in Composition of Source Rock Bitumen Versus Crude Oil	330
3.3	Evaluation of Geological and Geochemical Aspects of Primary Migration	333
3.4	Conclusions and Suggestions on Primary Migration	338
	Summary and Conclusion	340
<i>Chapter 4</i>	Secondary Migration and Accumulation	341
4.1	The Buoyant Rise of Oil and Gas Versus Capillary Pressures	342
4.2	Hydrodynamics and Secondary Migration	344
4.3	Geological and Geochemical Implications of Secondary Migration	347
4.4	Termination of Secondary Migration and Accumulation of Oil and Gas	351
4.5	Distances of Secondary Migration	354
	Summary and Conclusion	356
<i>Chapter 5</i>	Reservoir Rocks and Traps, the Sites of Oil and Gas Pools	357
5.1	Reservoir Rocks	358
5.2	Traps	360
	Summary and Conclusion	365
	References to Part III	366

*Part IV The Composition and Classification of Crude Oils
and the Influence of Geological Factors*

<i>Chapter 1</i>	Composition of Crude Oils	375
1.1	Petroleum Versus Source Rock Bitumen	375
1.2	Analytical Procedures for Crude Oil Characterization	375
1.3	Main Groups of Compounds in Crude Oils	379
1.4	Principal Types of Hydrocarbons in Crude Oils	382
1.5	Sulfur Compounds	398
1.6	Nitrogen Compounds	401
1.7	Oxygen Compounds	403
1.8	High Molecular Weight N, S, O Compounds: Resins and Asphaltenes	403
1.9	Organometallic Compounds	408
1.10	Covariance Analysis of Main Crude Oil Constituents Summary and Conclusion	411 414
<i>Chapter 2</i>	Classification of Crude Oils	415
2.1	General	415
2.2	Historical	416
2.3	Basis of Proposed Classification of Crude Oils	416
2.4	Classification of Crude Oils	417
2.5	Characteristics of the Principal Classes of Crude Oils	419
2.6	Concluding Remarks	422
	Summary and Conclusion	423
<i>Chapter 3</i>	Geochemical Fossils in Crude Oils and Sediments as Indicators of Depositional Environment and Geological History	424
3.1	Significance of Fossil Molecules	424
3.2	Geochemical Fossils as Indicators of Geological Environments	426
3.3	Geochemical Fossils as Indicators of Early Diagenesis	432
3.4	Geochemical Fossils as Indicators of Thermal Maturation	433
3.5	Present and Future Development in the Use of Geochemical Fossils	436
	Summary and Conclusion	437

<i>Chapter 4</i>	Geological Control of Petroleum Type	439
4.1	General and Geochemical Regularities of Composition	439
4.2	Geochemical Regularities Related to the Environment of Deposition	440
4.3	Geochemical Regularities in Relation to Thermal Evolution	450
4.4	Concluding Remarks on Crude Oil Regularities Summary and Conclusion	457
<i>Chapter 5</i>	Petroleum Alteration	459
5.1	Thermal Alteration	460
5.2	Deasphalting	461
5.3	Biodegradation and Water Washing Summary and Conclusion	463
<i>Chapter 6</i>	Heavy Oils and Tar Sands	470
6.1	Definitions	470
6.2	Composition of Heavy Oils	472
6.3	Specific Gravity and Viscosity	475
6.4	Origin and Occurrence of Heavy Oils	477
6.5	World Reserves and Geological Setting	480
6.6	Valorization of Heavy Oils Summary and Conclusion	482
References	484
 <i>Part V Oil and Gas Exploration: Application of the Principles of Petroleum Generation and Migration</i>		
<i>Chapter 1</i>	Identification of Source Rocks	495
1.1	Amount of Organic Matter	495
1.2	Type of Organic Matter	497
1.3	Maturation of the Organic Matter	515
1.4	Conclusions on Characterization of Potential Source Rocks	540
	Summary and Conclusion	546
<i>Chapter 2</i>	Oil and Source Rock Correlation	548
2.1	Correlation Parameters	549
2.2	Oil–Oil Correlation Examples	551
2.3	Oil–Source Rock Correlation Examples Summary and Conclusion	561
		570

<i>Chapter 3</i>	Locating Petroleum Prospects: Application of Principle of Petroleum Generation and Migration – Geological Modeling	571
3.1	Acquisition of the Geochemical Information	573
3.2	First Conceptual Model of Petroleum Generation in a Basin	575
3.3	Numerical Simulation of the Evolution of a Sedimentary Basin – Geological Modeling	576
	Summary and Conclusion	581
<i>Chapter 4</i>	Geochemical Modeling: A Quantitative Approach to the Evaluation of Oil and Gas Prospects	583
4.1	Necessity of a Quantitative Approach to Petroleum Potential of Sedimentary Basins	583
4.2	Mathematical Model of Kerogen Degradation and Hydrocarbon Generation	585
4.3	Genetic Potential of Source Rocks. Transformation Ratio	589
4.4	Validity of the Model	590
4.5	Significance of the Activation Energies in Relation to the Type of Organic Matter	590
4.6	Application of the Mathematical Model to Petroleum Exploration	593
4.7	Reconstruction of the Ancient Geothermal Gradient	596
4.8	Migration Modeling	604
4.9	Conclusion	607
	Summary and Conclusion	608
<i>Chapter 5</i>	Habitat of Petroleum	610
5.1	Habitat of Petroleum in the Arabian Carbonate Platform	611
5.2	Habitat of Petroleum in Young Delta Areas	615
5.3	The Linyi Basin in the People's Republic of China	624
5.4	Habitat of Gas in the Deep Basin of Western Canada	628
	Summary and Conclusion	639
<i>Chapter 6</i>	The Distribution of World Oil and Gas Reserves and Geological – Geochemical Implications	641
6.1	Introduction	641
6.2	Geological Setting of Oil and Gas Reserves	642
6.3	Age Distribution of Petroleum Reserves	648

Contents	XXI
6.4 Significance of the Age and Geotectonic Distribution of Petroleum and Coal	650
6.5 Richness of Sedimentary Basins. Role of Giant Fields and Giant Provinces	656
6.6 Ultimate World Oil and Gas Resources	660
6.7 Paleogeography as a Clue to Future Oil and Gas Provinces	662
Summary and Conclusion	666
References to Part V	667
<i>Subject Index</i>	679