Chapter 1

An overview of the petroleum geology of the Arctic

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Abstract: Nine main petroleum provinces containing recoverable resources totalling 61 Bbbl liquids + 269 Bbbl of gas are known in the Arctic. The three best known major provinces are: West Siberia–South Kara, Arctic Alaska and Timan–Pechora. They have been sourced principally from, respectively, Upper Jurassic, Triassic and Devonian marine source rocks and their hydrocarbons are reservoired principally in Cretaceous sandstones, Triassic sandstones and Palaeozoic carbonates. The remaining six provinces except for the Upper Cretaceous–Palaeogene petroleum system in the Mackenzie Delta have predominantly Mesoazoic source rocks and Jurassic reservoirs. There are discoveries in 15% of the total area of sedimentary basins (<8 × 1013 km2), dry wells in 10% of the area, seismic but no wells in 50% and no seismic in 25%. The United States Geological Survey estimate yet-to-find resources to total 90 Bbbl liquids + 279 Bbbl gas, with four regions – South Kara Sea, Alaska, East Barents Sea, East Greenland – dominating. Russian estimates of South Kara Sea and East Barents Sea are equally positive. The large potential reflects primarily the large undrilled areas, thick basins and widespread source rocks.

This book is mainly a product of the 33rd International Geological Congress (IGC) which took place in Norway, a country with strong Arctic interests. As the Arctic becomes more accessible, interest in its potential resources is increasing, as is public concern for the environmental consequences of petroleum exploration and possible production. Additional public awareness has been created by the ongoing activities of Arctic coastal states as they respond to the United Nations Convention on the Law of the Sea, which has been ratified by all Arctic nations except the United States. The Convention stipulates conditions for granting coastal states sovereign rights seaward of the Exclusive Economic Zone (see Marcusen & Macnab). Text references in bold type and lacking year of publication refer to papers appearing in the present volume.

An additional contributing element to this volume is the assessment of the petroleum potential of the 4.2% of the Earth’s surface that lies north of the Arctic Circle by the United States Geological Survey (USGS). The initial results of this study, the Circum-Arctic Resource Appraisal (CARA; Gautier et al. 2009), became available at the International Geological Congress in Oslo in 2008. A number of papers from studies performed as a part of CARA (Charpentier & Gautier) are included in this volume, as are a number of studies of the Russian Arctic, in particular its shelf areas (Grigorenko et al.; Kaminsky et al.; Kontorovich et al.). As a result, this book can present a relatively complete view of Arctic petroleum geology.

Previous compilations on Arctic geology

Symposia dedicated to charting the state of knowledge of Arctic geology, especially from the point of view of petroleum, were held in North America at 10 year intervals from 1960 to 1981. The resulting volumes (Rausch 1961; Pitcher 1973; Embry & Balkwill 1982) contain a wealth of articles describing the lands and shores bordering the Arctic Ocean and the oceanic area itself. Review articles summarized the earlier history of geological thought (Eardley 1961) and the knowledge of mineral and petroleum resources (Meyerhoff & Meyerhoff 1973) and hydrocarbon resources (Meyerhoff 1982). Two special volumes described the oceanic regions and the surrounding continental margins: Nairn et al. (1981) and Grantz et al. (1990), with the latter including reviews of the history of investigation and of the resources. The 27th IGC published a report on arctic geology (Gramberg et al. 1984). The last Arctic-wide, petroleum-focused symposium volume was from Norway (Verren et al. 1993).


Geological knowledge of the Arctic is built upon studies in the islands and continents surrounding the Arctic Ocean, many of which have spectacularly well exposed bedrock – vegetation-free, ice-soured and exposed in mountains and fjord walls. These regions have recently been the subject of many, comprehensive, finely illustrated summaries of their geology. The following is a listing of some of these: Iceland – Sigmundsson et al. (2008); Greenland – Escher & Watt (1976), Henriksen et al. (2009), Henriksen (2008); Arctic Canada – Trettin (1991), Dixon (1996); Alaska – Plafker & Berg (1994), Miller et al. (2002); North Pacific realms – Nokleberg et al. (2001); Wrangel Island – Kosko et al. (1993); Franz Josef Land – Dibner (1998); Timan–Pechora – Nikonov et al. (2000); Svalbard – Harland (1997), Dallmann (1999); Norway – Spencer et al. (1984), Ramberg et al. (2008), Smelror et al. (2009).

Advancement of the geological knowledge of the Arctic calls for international cooperation. Examples of this are the production of comprehensive maps of the Arctic, notably by the Geological
Survey of Canada, which issued a 1:6 million geological map (Okulitch et al. 1989) and then a 1:5 million geological map (Harrison et al. 2008). Most recently, the USGS CARA work has been based on another multi-institute compilation, the 1:6.7 million map of sedimentary successions in the sedimentary basins of the Arctic (Grantz et al. 2009; Grantz, Scott et al.). The new Arctic bathymetric map (Jakobsson et al. 2008) is the basis for the map inside the front cover of this book. It is obvious from these maps that, despite difficult accessibility, the onshore geology of the Arctic is now well known, having been furthered by a century of work by government agencies and by the fascination of the region to the exploratory mind, in what might be termed the ‘Nansen tradition’ (see Kristoffersen). In contrast, only select parts of the Arctic marine realm are well known. Much of the Arctic remains beyond drilling or can be drilled only at extreme cost, as demonstrated by the three-icebreaker ACEX expedition to the Lomonosov Ridge in the summer of 2006 (Moran et al. 2006), but there are now plans for a dedicated Arctic Ocean drilling vessel (Thiede et al.).

How the book is organized

The memoir starts with several contributions having the Arctic in its entirety as their subject matter. These include the map of Grantz, Scott et al. of Arctic sedimentary successions and their tectonostratigraphic content, followed by two reconstructions: Lawver et al. of Palaeozoic palaeogeography and Golonka of the palaeoenvironments of the present day Arctic land masses and their borders through Phanerozoic time. Two papers are based on new Arctic maps of gravimetric and magnetic data resulting from international collaborative efforts: Gaina et al. and Saltus et al. The latter discusses a topic which will be recurring in papers to follow: the tectonic interpretation of the Amerasia Basin and its shelves which together with the areas covered by the major polar ice sheets remain our planet’s ‘white spots’. Arctic resources that have already been found are dealt with by Chew & Arbouille. The methods used in evaluating undiscovered resources in CARA by the USGS are described by Charpentier & Gautier and the results are summarized by Gautier, Bird et al. Despite considerable uncertainty, there is a consensus that the majority of resources yet to be found (on an oil equivalent basis) occur within the Russian Exclusive Economic Zone. This becomes evident from comparison of the USGS CARA assessment with that of the resource potential of the Russian Arctic described by Kaminsky et al. and by Kontorovich et al. (see Table 1.1). The remaining articles are grouped in relation to four geographical regions (Fig. 1.1): Baltica, Siberia and its borders, Laurentia and the Arctic Ocean Basin. The locations of the areas described in these articles are shown on the map inside the front cover of the book.

The Baltica-related contributions are concerned with the Barents Sea and the Timan–Pechora Basin. The latter’s economic significance derives from the Devonian ‘Domanik facies’, the oldest Phanerozoic petroleum system of the Arctic. The carbonate strata containing both source rocks and reservoirs are described by Bagrintseva et al. and by Klimenko et al. and the resource

<table>
<thead>
<tr>
<th>Region</th>
<th>Area (10^6 km²)</th>
<th>Wildcat wells</th>
<th>Discoveries</th>
<th>Total discovered recoverable resources (x 10^9 bbloe)</th>
<th>Estimates of mean, unrisked, yet-to-find recoverable resources of all of the Assessment Units in the region (x 10^9 bbloe)</th>
<th>Estimates of most probable yet-to-find recoverable resources in the basins in the region (x 10^9 bbloe)</th>
</tr>
</thead>
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<tr>
<td>Norwegian Sea</td>
<td>0.1</td>
<td>38</td>
<td>12</td>
<td>0.7</td>
<td>0.7</td>
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</tr>
<tr>
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<td>1.4</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>West (Norway)</td>
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<td>80</td>
<td>25</td>
<td>0.5</td>
<td>1.5</td>
<td>5; 3; 1</td>
</tr>
<tr>
<td>East (Russia)</td>
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<td>13</td>
<td>5</td>
<td>0.2</td>
<td>22.5</td>
<td>10; 126</td>
</tr>
<tr>
<td>Svalbard</td>
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<td>15</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>15</td>
</tr>
<tr>
<td>Timan–Pechora</td>
<td>0.2</td>
<td>646</td>
<td>142</td>
<td>12.4</td>
<td>3.6</td>
<td>5; 3; 1</td>
</tr>
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<td>West Siberia and South Kara Sea</td>
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<td>426</td>
<td>92</td>
<td>22.0</td>
<td>226.3</td>
<td>100</td>
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<tr>
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<td>–</td>
<td>–</td>
<td>–</td>
<td>9</td>
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<td>Yenisey–Khatanga</td>
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<td>16</td>
<td>0.1</td>
<td>3.4</td>
<td>24; 1</td>
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<tr>
<td>Lena–Anabar</td>
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<td>13</td>
<td>4</td>
<td>Negl</td>
<td>Negl</td>
<td>5</td>
</tr>
<tr>
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<td>–</td>
<td>–</td>
<td>–</td>
<td>15; 9; 3</td>
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<tr>
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<td>1; 4</td>
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<tr>
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<td>–</td>
<td>–</td>
<td>–</td>
<td>5</td>
</tr>
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<td>–</td>
<td>–</td>
<td>–</td>
<td>14; 59; 4</td>
</tr>
<tr>
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<td>317</td>
<td>61</td>
<td>23.1</td>
<td>6.8</td>
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<tr>
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<td>196</td>
<td>59</td>
<td>1.4</td>
<td>1.8</td>
<td>13</td>
</tr>
<tr>
<td>Eagle Plain + Northern Interior Platform</td>
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<td>114</td>
<td>8</td>
<td>Negl</td>
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<td>Sverdrup Basin</td>
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<td>20</td>
<td>0.5</td>
<td>2.5</td>
<td>1; 5</td>
</tr>
<tr>
<td>Canada Passive Margin</td>
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<td>–</td>
<td>9</td>
<td>–</td>
<td>9</td>
</tr>
<tr>
<td>North Greenland</td>
<td>0.1</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>4; 5</td>
</tr>
<tr>
<td>West Greenland and Baffin Bay</td>
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<td>12</td>
<td>–</td>
<td>–</td>
<td>11; 22; 14; 14; 6</td>
<td>21; 19; 4; 6; 2</td>
</tr>
<tr>
<td>East Greenland</td>
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<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>20</td>
</tr>
<tr>
<td>Totals</td>
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<td>2006</td>
<td>444</td>
<td>60.9</td>
<td>269.2</td>
<td>8</td>
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</table>

Sources for the information in Table 1.1: wells and discoveries from Chew & Arbouille (table 1); discovered resources from IHS (courtesy of K. Chew); yet-to-find estimates from Gautier, Bird et al. (table 1) and Kontorovich et al. (table 2, converted to recoverable values using assumed recovery factors of 35% for oil and 70% for gas). The probabilities associated with each of the estimates by Gautier, Bird et al. are shown on Figure 1.7. Note that each of the three data sources employs different geographical areas for regions that they discuss. The wells, discoveries and discovered resources are north of 66°N, but some of the yet-to-find estimates are for areas that extend somewhat south of the Arctic Circle. Negl, negligible.
potential of the Timan–Pechora Basin is covered by Schenk. Regional, deep reflection, seismic lines covering the eastern Barents Sea, the Kara Sea and the intervening Novaya Zemlya fold belt are described by Ivanova et al. and these regions are also assessed geologically by Stoupakova et al. A contribution by Werner et al. similarly deals with the crustal structure across the Arctic parts of both Baltica and West Siberia. The petroleum systems of the Barents Sea region are comprehensively described by Henriksen, Ryseth et al. Potential Triassic reservoir successions in the NW of the Barents Sea are discussed by Hoy & Lundschien who present good quality seismic sections illustrating the increasing uplift of these strata towards the Svalbard–Franz Josef Land. Uplift in the Barents Sea is also the subject of another paper by Henriksen, Bjørnseth et al. Exploration has inspired substantial optimism about petroleum potential of the eastern Barents Sea as indicated in the contributions by Kontorovich et al. and Khlebnikov et al. A summary of the USGS assessment of undiscovered resources in the east of the Barents Sea is presented by Klett & Pitman.

Arctic Siberia covers large areas in which knowledge of the subsurface geology is meagre: no offshore exploratory wells have been drilled between the Laptev Sea and Wrangel Island and seismic data are sparse, as noted by Kaminsky et al. The geological character of the islands in this region are therefore of particular importance, as illustrated in the paper by Drachev, who uses the geology of Wrangel Island and the New Siberian Islands, together with that of the adjacent mainland areas, to paint a picture of the offshore geology and likely petroleum systems in this little-known region. Supplementary views concerning this part of Russia are to be found in Stoupokava et al. and in Grigorenko et al. The petroleum potential of the Laptev Sea region, with its impressive, active rift system, is the subject of the contribution by Kirilova-Pokrovskaya et al. while the chapter by Klett et al. presents the USGS appraisal of the arctic parts of the onshore north and east borders of the Siberian craton. Ivanova et al. deal with the geological structure of the southern Kara Sea and northern end of the West Siberia Basin, an area with a huge perceived potential. The lack of data over large areas of Arctic Siberia leaves substantial gaps in understanding the regional tectonics of the eastern Arctic. Papers on this subject and wider problems of interpreting the tectonics of the Arctic Ocean region are authored by Pease and Lebedeva-Ivanova et al.

A section of Laurentia-related papers begins with contributions by Creaney & Sullivan, who deal with the Phanerozoic evolution in relation to petroleum, and Colpron & Nelson, who describe the Palaeozoic evolution of Laurentia. Kumar et al. present new deep seismic lines from the Chukchi Sea and Bird & Houseknecht deal with the most thoroughly studied sector of Arctic petroleum geology: Northern Alaska. These are followed by two chapters on the Beaufort passive margin by Houseknecht & Bird and Helwig et al. – with the latter paper including new deep seismic lines. The Sverdrup Basin is the subject of papers by Embry, by Omma et al. by Chen & Osadetz and by Dewing & Obermajer. Harrison et al. describe the Baffin fan which constitutes the third largest Cenozoic delta of the Arctic after the Mackenzie Delta, which built into the southeastern part of the Canada Basin, and the Lena Delta, which built into the Eurasia Basin. The petroleum potential of the entire region between Canada and Greenland has been assessed by Schenk as part of the CARA work and the petroleum exploration history of Greenland is described by Christiansen. The final Laurentian papers cover the most inaccessible parts of offshore Greenland: the NE Greenland shelf as discussed by Gautier, Stemmerik et al. and the Lincoln Sea by Sorensen et al.

The last group of papers addresses the Arctic Ocean basin. Historical views of the scientific exploration of the Arctic Ocean are presented by Kristoffersen and by Thiede et al., Marcussen & Macnab review current work by coastal states to extend their
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(a) Stratigraphic columns on Figure 4

A. US Chukchi Sea
B. Alaska North Slope
C. Mackenzie Delta
D. Sverdrup Basin
E. Wandel Sea Basin
F. Onshore East Greenland
G. West Greenland

Fig. 1.2. A simplified map of the tectonic provinces of the Arctic. Compiled mostly following Grantz et al. (2009) and Harrison et al. (2008). The outline of the oceanic crust in the Canada Basin follows Alvey et al. (2008, fig. 6b). Sedimentary thicknesses in Siberia are from Petrov et al. (2008) and Milanovsky (2007).
Fig. 1.2. Continued.
offshore boundaries. Moore et al. assess the petroleum geology and resource potential of the Lomonosov Ridge, a sliver of continental crust that was split from Baltica and Siberia by the Cenozoic seafloor spreading that led to the formation of the Eurasia Basin. Moore & Pitman contemplate the petroleum potential of the Amundsen Basin itself. The last paper of the book, like the first, has Arthur Grontz, whose scientific endeavours in the Arctic span more than four decades, as the first author. It is concerned with the evolution of the Amerasia Basin. This basin and its bordering shelves remain the main challenge to our understanding of Arctic tectonics and geology.

Structure of the Arctic

The structure of the Arctic may be portrayed, as shown in Figures 1.1 and 1.2, in terms of four elements:

- North Pacific accretionary terrane collage and its successor basins;
- oceanic basins and sedimentary prisms prograding onto these basins;
- long-lived sedimentary basins established on Phanerozoic sutures;
- continental cores with mainly neoProterozoic and Lower Palaeozoic platform cover and their sutured margins.

A main theme of Arctic geology is the assembly and disassembly of the Pangea supercontinent through Caledonian–Hercynian–Uralian suturing events and subsequent rifting and seafloor spreading in the Arctic and Atlantic beginning about 200 Ma (Fig. 1.3). One might term this the Atlantic theme of Arctic geology. A second theme is the long-lasting tectonic activity, going back at least to the late Palaeozoic, in the areas bordering the northern Pacific rim, which have brought about the accretion to present day northeastern Siberia and northwestern North America of a multitude of terranes with interleaved sedimentary and magmatic rocks. Nokleberg et al. (2001) described this as a ‘collage of accreted terranes’; their complexity is illustrated by Colpron & Nelson. While accretion is mainly a destructive process in relation to petroleum geology, the processes involved in the dismembering of Pangea are mainly constructive in relation to the formation of hydrocarbon deposits. In other words, from a petroleum geology point of view, the main dividing lines in the structure of the Arctic are not the present day plate boundaries but the distinction between the North Pacific accretionary collage (NPAC) and the rifted parts of the North American and Eurasian plates.

The Caledonian, Ellesmerian and Uralian orogenies sutured the Laurentian, Baltic and Siberian shields in Silurian through late Palaeozoic time but the three shields persist as the cratonic cores of the Arctic continents to the present day. Basins bordering these continental cores are, in general, prospective for hydrocarbons.

By contrast, in the NPAC region, compressional tectonics led to the formation of later orogenic belts: thus the Brooks Ranges in Alaska and the Verkhoyansk Fold Belt in NE Siberia formed due to accretion of Chukotka and the Kolyma–Omolon superterrane in Jurassic–Early Cretaceous times (Lawver et al. & Grontz). Young sedimentary basins occur in the NPAC region but are considered relatively unprospective (Haimila et al. 1990). The uncertainty (Fig. 1.1) about the position of the boundary of the NPAC region between the Laptev Sea and Wrangel Island is a key reason for uncertainty about the petroleum potential of the East Siberian offshore.

Ocean-floor formation is well dated as spanning most of the Cenozoic in the North Atlantic and the Eurasian part of the Arctic Ocean. In the Amerasian part of the Arctic, rifting as a precursor to ocean-floor spreading is inferred to have occurred during the earliest Jurassic, followed by ocean-floor spreading in the mid-Early Cretaceous (Grantz, Hart & Childers). Bordering the oceanic basins are progradational sedimentary wedges, which overlie long-lived basins on their continental side and oceanic crust on the other and thus represent a transition zone between the prospective shelf and the less prospective oceanic basin. Three thick Cenozoic deltas – from the Lena and Mackenzie rivers and in northern Baffin Bay – are in this zone. Other basins in the zone can be glimpsed from the thickness contours on Figure 1.2 – north of Alaska and Siberia and west of the Barents Sea; these are the passive margin basins of Grantz et al. (2009).

Stratigraphy and geological history of the sedimentary basins

The continental blocks projecting north of today’s Arctic Circle travelled far during the Phanerozoic under the names of Laurentia, Baltica and Siberia, as detailed by Lawver et al. and Grontz (Fig. 1.3). At the start of Phanerozoic time all lay south of the equator and all travelled northward throughout the Phanerozoic. The suturing of these initially independent blocks led first to the merging of Laurentia and Baltica during Silurian continent–continent collision in the Caledonian Orogeny, lasting into the Devonian. The Ellesmerian Orogeny is currently interpreted to reflect tectonic collision on northern Laurentia from Late Silurian to earliest Carboniferous (Lawver et al.; Colpron & Nelson), although the origin and nature of the colliding terranes is still

Fig. 1.3. Maps of palaeogeography of the Arctic based on Golonka’s maps for the Late Devonian, the Middle Triassic, the Late Jurassic and the Middle Palaeogene, representing the times of deposition of some of the major Arctic source rocks, and inspired by the work of Ulmishek & Klemme (1990). Jan Golonka kindly supplied extended versions of some of the maps appearing in Golonka.
speculative. During the Permian Siberia and Kazakhstan collided with Baltica, completing the assembly of Pangea. An outpouring of vast volumes of basalt (the Tunguska flood basalts) took place near the Permian to Triassic boundary, covering the northern Siberian shield (Tunguska flood basalts) and areas now beneath adjacent basins (Nikishin et al. 2002).

Large sedimentary basins, of prime significance to petroleum exploration, developed on these intercontinental suturets through extension and collapse of the former orogenic highlands that had developed within the suturets. Thus, economic basement beneath these basins is of Caledonian, Ellesmerian and Uralian ‘ages’. Simplified stratigraphies of the basins, where drilled, appear in Figures 1.4 and 1.5. From these sedimentary columns, a first conclusion must be their general similarity. The Upper Palaeozoic successions consist of intermixed carbonates and siliciclastics with sporadic occurrences of evaporites. In contrast, the Mesozoic and Cenozoic successions consist almost entirely of siliciclastics, which locally include intervals of coal-bearing strata. Although not shown on Figures 1.4 and 1.5, the Lower Palaeozoic successions in Laurentia, Baltica and Siberia (Golonka) are also quite similar. We consider this similarity surprising, since the Phanerozoic drift of Laurentia, Baltica and Siberia away from the Permian and Mesozoic basins were receiving deltaic to basinal siliciclastics from Santonian age onwards (Beauchamp & Baud 2002).

The transition from carbonate to clastic deposition, caused by the Phanerozoic drift of Laurentia, Baltica and Siberia away from equatorial to high latitudes, occurred during the Permian. Passage through intermediate latitudes is witnessed by the deposition of thick and widespread evaporites on the margins of both Laurentia and Baltica during the Carboniferous and Permian. Deposition of warm-water carbonates with stacked organic build-ups in Late Carboniferous–Early Permian was replaced by more extensive siliciclastic sedimentation in both shallow- and deep-marine depositional environments on extensive marine ramps during the Mid and Late Permian and Triassic. This effect was pronounced in the areas surrounding the Uralian suture, which became a major source of siliciclastics to northern Siberia and Baltica. Conditions shifted towards a cold temperate climate during the Mid–Late Permian and Triassic. This was caused by the widespread development of phosphatic, organic-rich shales and mudstones. Organic-rich facies were restricted to many areas in the Late Triassic and the organic-rich facies became much more limited in geographic extent (mainly western Sverdrup and northern Alaska).

The extensional basins established during Late Palaeozoic and the Triassic continued to receive variable amounts of siliciclastics throughout the Jurassic and alternating sandstone-dominated and shale-siltstone sequences characterize the stratigraphy in all basins across the Arctic. Organic-rich facies were restricted to times and areas of low sediment input and occur mainly in Alaska and Siberia. Major transgressions occurred during the early Toarcian, early Bajocian, early Oxfordian and early Tithonian and shale units of these ages are present in all Arctic basins (Embry) and are often organic-rich and petroleum source rocks. Also during the Jurassic, as the continental blocks migrated further north, a distinct boreal fauna developed which had little in common with the faunas of the Triassic and later. One of the more notable tectonic developments of the Jurassic was the initiation and subsequent development of the Amerasia Rift Basin between what is now northern Alaska and Chukotka (Arctic Alaska plate) and the Canadian Arctic Archipelago (Lawver et al.). Little is known about these rift basins because they now lie beneath the thick continental terrace wedges on the shelves and slopes of the Amerasia ocean basin. Current data indicates that rifting began possibly as early as Sinemurian and no later than latest Aalenian, and continued until the start of seafloor spreading during the Hauterivian (Embry & Dixon 1994; Mickey et al. 2002).

During the Cretaceous siliciclastic sediment delivery to the Arctic basins intensified and was highest during the Early Cretaceous. New basins were formed in both extensional and compressional regimes. Foreland basins developed in front of rising orogenic mountain ranges in the North Pacific accretionary region (e.g. the Colville Trough in front of the Brooks Range of northern Alaska) and rift and ocean basins formed and/or continued to develop in the Amerasia region as well as in Baffin Bay between Canada and Greenland. Significant transgressions which followed widespread uplift events occurred in the early Valanginian, early Barremian, late Aptian and in earliest Late Cretaceous. Early Cretaceous deltaic deposits dominate most of the Amerasia basins and alternations of sand-rich delta plain and delta front deposits and shale-dominant prodelta and shelf strata are widespread.

The second phase of seafloor spreading in the Amerasia Basin, which followed the creation of continent–ocean transitional crust during the Jurassic and Early Cretaceous, was the intrusion of a northerly trending belt of mid-ocean ridge basalts (MORB) into the central part of the Amerasia Basin in mid-Early Cretaceous (Hauterivian and Barremian) time (Grantz et al.). Intrusion of the MORB was followed by a huge outpouring of basalt related to the Alpha Plume and resulted in the formation of the 30 km thick Alpha and Mendeleev ridges of the Amerasia Basin, as well as widespread diabase dyke and sill emplacement in adjacent continental areas (eastern Sverdrup Basin and northern Barents Sea, Buchan & Ernst 2006). A brief interval of widespread uplift occurred at the Early to Late Cretaceous juncture and, following this tectonic episode, sediment supply was greatly reduced to both the extensional and foreland basins that surround the Arctic Basin. By Turonian time the sea covered most of the Arctic and bituminous muds were deposited in starved basins from Alaska to Siberia (Golonka). Sedimentation rates gradually recovered and most basins were receiving deltaic to basinal siliciclastics from Santonian through Maastrichtian time. Widespread uplift and associated
prominent regression brought the Mesozoic era to a close throughout the Arctic.

The Cenozoic saw a new tectonic regime over most of the Arctic. Rifting and subsequent seafloor spreading took place in the North Atlantic and extended into the Arctic, where it created both the Eurasian and Baffin Bay basins. Sedimentation rates became high and large volumes of siliciclastic sediments were funnelled into these Cenozoic extensional basins and also into the Amerasia Basin. Exceptional thicknesses, perhaps exceeding 15 km, are associated with the Mackenzie and Lena Deltas and thicknesses up to 10 km are common along the margins of most of the oceanic basins (Grantz, Scott et al.). Compression and deformation continued in the north-vergent North Pacific accretionary collage region. Mountainous uplift and associated foreland basins developed in the Canadian Arctic Archipelago (Eurekan Orogeny) and in the western Barents Sea (West Spitsbergen) areas in the Palaeogene due to compression and transpression related to seafloor spreading in nearby areas (Fig. 1.2). These areas became uplifted by a kilometre or more in latest Palaeogene to early Neogene time as compression continued (Henriksen, Bjørnseth et al.).

Major transgressions occurred in early Paleocene, early Eocene, late Eocene, earliest Oligocene, late Oligocene and earliest Pliocene in the Beaufort–Mackenzie Basin in the SE corner of the Canada Basin (Dixon 1996). Most of these events followed episodes of tectonic uplift and in some cases folding and faulting and they probably reflect tectonic extension and collapse of the basin floors. The climate remained warm during much of the Paleocene and Eocene but started to cool in Oligocene times and continued to deteriorate throughout the Neogene, leading to the alternating glacial/inter-glacial conditions which now characterize the Arctic.

**Petroleum geology**

**Exploration**

The first exploratory drilling in the Arctic was government-sponsored and carried out for strategic reasons – on the south shore of the Laptev Sea in the 1930s and in northern Alaska in 1944 (Chew & Arbouille). The first significant petroleum discoveries in onshore Arctic basins were made in the decade from 1960 to 1970: in the Eagle Plain, Sverdrup Basin and Mackenzie Delta regions of Canada, in West Siberia, in Timan–Pechora and in Arctic Alaska. The finds in West Siberia and Timan–Pechora extended existing prolific provinces northwards, but in Alaska the 1968 discovery of the supergiant Prudhoe Bay field opened a major new petroleum province.

Offshore drilling started later: in the Beaufort Sea in 1973, West Greenland in 1976, the Barents Sea in 1980, the Pechora Sea in 1982 and the Kara Sea in 1987. Discoveries in the Beaufort, Pechora and Kara seas extended proven petroleum provinces to the north. In the Barents Sea new petroleum provinces were discovered: in the Norwegian sector, in the SW, in 1981 and in the Russian sector, where the super-giant Shtokman gas field was found in 1988. As a result of this exploration, there are now nine main petroleum provinces containing a total of 444 discoveries in the Arctic with total discovered recoverable resources of 61 Bbbl of liquids and 269 Bbbloe of gas. Four provinces

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**Fig. 1.4.** Stratigraphy of the well-known basins of the western Arctic. Principal sources: (a) Sherwood et al. (2002); (b) Moore et al. (1994) and Magoon et al. (2003); (c) Norris & Hughes (1997) and Dixon (1982); (d) papers in Trettin (1991); (e) Stemmerik & Håkansson (1991) and Håkansson et al. (1991); (f) Birkeland & Perch-Nielsen (1976); (g) Gregersen et al. (2007). For locations see Figure 1.2. The arrows on the left of some columns link source rocks to reservoirs to indicate proposed petroleum systems.
dominate the resource picture: West Siberia – South Kara (22 Bbbl + 226 Bbbloe), arctic Alaska (23 Bbbl + 7 Bbbloe), Barents Sea East (0.2 Bbbl + 23 Bbbloe), and Timan–Pechora (12 Bbbl + 4 Bbbloe) (Table 1.1).

Source rocks

Although a wide variety of potential source rocks, ranging in age from Proterozoic to Cenozoic, have been identified in the Arctic, most of the petroleum discovered to date – the proven petroleum systems – is derived from a few narrowly defined stratigraphic intervals in the Devonian, Triassic and, especially, Jurassic.

On the Siberian craton, south of the Arctic Circle, giant oil fields have been sourced from Proterozoic strata. Chemometric analysis of biomarker and isotopic data (Peters et al. 2007) suggests that at least four genetic families of oils are present; Upper Riphean source rocks, particularly those of the Iremken Formation account for most of the known oil (Ulmishek 2001), including accumulations on the Baykit High.

Organic-rich, marine rocks of Devonian age were deposited on the east margin of Baltica and the west margin of Laurentia, where they have sourced important oil-prone basins in front of the west side of the Urals and in western Canada. Oils in the Timan–Pechora Basin were probably sourced from the Late Devonian to Early Carboniferous marine Domanik Formation (Ulmishek 1982). In northern Laurentia the Ellesmerian orogeny has probably destroyed most Devonian sources. Lacustrine shales with high TOC occur in Devonian strata onshore in northeastern Greenland (Christiansen et al. 1990) and the Upper Carboniferous strata in central East Greenland and the Sverdrup Basin contains organic-rich lacustrine shales (Christiansen et al. 1990; Piasecki et al. 1990). In eastern North Greenland, the Upper Carboniferous and Permian succession is fully marine with the older units consisting of carbonates and evaporites (Stemmerik 2000). During the later Permian, however, marine shales accumulated widely in East Greenland (Surlyk et al. 1986; Christiansen et al. 1993) and may serve as source rocks in the adjacent basins offshore. Late Permian marine black shales occur in several wells in the western Barents Sea (Henriksen et al., 1993).

Triassic source rocks are the most widespread in the Arctic. Middle and Late Triassic (Anisian–Carnian) marine shales with good to excellent source potential and proven productivity occur along the northern rim of Laurussia from Alaska to the Barents Sea (Leith et al. 1993). They were deposited at intermediate latitudes within a huge back-arc embayment (Fig. 1.3), located between the landmasses of North America and Eurasia. The Triassic Shublik formation has generated most of the discovered oil in northern Alaska (Peters et al. 2006), including most of the oil in the geochemically mixed, supergiant, Prudhoe Bay Field, the largest oil field north of the Arctic Circle. In the Sverdrup Basin, most if not all of the known petroleum accumulations are believed to be sourced from Middle to Late Triassic strata (Schei Point Group), with lesser sources in rocks of Early and Late Jurassic age (Brooks et al. 1992). In the Barents Sea region, the TOC-rich, phosphatic, Middle Triassic Botneheia Formation crops out on Spitsbergen and is believed to have sourced at least some oils in the Norwegian sector of the Barents Sea. In the Russian sector, equivalent rocks have been buried to great depths, which may explain the gas-prone quality of most discovered hydrocarbons in that area, outstanding among which is the supergiant Shтокман gas field.

Upper Jurassic source rocks were deposited at higher latitudes than the Triassic source rocks and in shallow basins far removed from their source. As the Arctic Ocean basin opened, coarse clastic sediments were transported along the Polar Arc and filled the basins and embayments of the shelf. These sediments were eventually redistributed into the deeper basins by tectonic, eustatic, and mass-flow processes controlled by the opening of the Arctic Ocean. In the area adjacent to the게리로바 shine (e.g., the Sverdrup Basin), deposition of pelagic sediments occurred, and organic-rich shales and mudstones of Lower to Middle Jurassic age currently serve as the source rocks for the major Jurassic accumulations in this region. In the Barents Sea region, the TOC-rich, phosphatic, Middle Triassic Botneheia Formation crops out on Spitsbergen and is believed to have sourced at least some oils in the Norwegian sector of the Barents Sea. In the Russian sector, equivalent rocks have been buried to great depths, which may explain the gas-prone quality of most discovered hydrocarbons in that area, outstanding among which is the supergiant Shтокман gas field.
from the North America/Eurasia embayment (Fig. 1.3). Upper Jurassic marine shales are the principal source rocks for most of the oil and much gas in the main West Siberian Basin (Kontorovich et al. 1997). Seven oil families have been identified in these deposits on the basis of geochemical signatures. More than 80% of the identified oil was sourced from the Bazhenov Formation, an organic-rich, siliceous and calcareous shale of Volgian to Berriasian age, but the Middle Jurassic Tyumen Formation also contributed (Kontorovich et al. 1991; Peters et al. 1993, 1994; Petrov 1994). Upper Jurassic strata may also have been the source for hydrocarbons in other Siberian Basins, including the Yenisey–Khatanga Basin and as far east as the Laptev Sea. Significant oil and gas volumes in northern Alaska, including part of the mixed petroleum deposits in the Prudhoe Bay Field were derived from Upper Jurassic marine strata of the Kingak Shale (Peters et al. 2006).

Marine shales of Upper Jurassic age are also thought to have sourced most of the known petroleum in the Norwegian Sea. TOC-rich Upper Jurassic strata are also present throughout much of the Barents Shelf, although they are only mature in restricted areas. These beds sourced some of the oil and gas in the Hammerfest Basin. Source rocks occurring in Upper Jurassic marine shales in the Kimeridgian-clay equivalent Hareely Formation of northeastern Greenland, are postulated to extend offshore and could provide a world-class source interval on the continental shelf.

Cretaceous and Cenozoic marine shales are known to have sourced petroleum systems in northern Alaska (Peters et al. 2006) and source rocks of Palaeogene and Cretaceous ages generated the oil and gas accumulations in the Mackenzie Delta. Marine strata of Cretaceous age are postulated to be important, but as yet untested, source rocks in the Alaskan Chukchi Sea. In Baffin Bay, Davis Strait and West Greenland, several potential petroleum source rocks, including Palaeogene, Lower and Upper Cretaceous and Ordovician, have been suggested from geochemical data and geological evidence. Oil seeps described from onshore west Greenland provide evidence that a petroleum system is or was active in that area (Christiansen & Pulvertaft 1994; Christiansen et al. 1996; Bojesen-Koefoed et al. 1999; Gregersen & Bidstrup 2008). An oil seep offshore of Scott Inlet on Baffin Island (Balkwill et al. 1990) has been interpreted as most likely having a marine shale source (Fowler et al. 2005) and the oil is interpreted to have been sourced from shales similar to the TOC-rich Upper Cretaceous Kanguk Formation exposed on Ellesmere Island. In the western Barents Sea, Barremian organic-rich shales have been drilled (Henriksen, Ryseth et al.).

Finally we should mention the Azolla event. Drilling near the North Pole on the Lomonosov Ridge near the North Pole has demonstrated the existence of an organic-rich interval (Moran et al. 2006) within the Eocene section. The interval was created by freshwater algal blooms during the warmest part of the Eocene period (Embry 2008). Some oil seeps have been documented on the Lomonosov Ridge, but there is no evidence that these seeps are related to the Eocene event.

Discovered petroleum systems

Nine main petroleum provinces are now known in the Arctic: the West Siberia–South Kara, Arctic Alaska, the East Barents Sea, Timan–Pechora, Yenisey–Khatanga, the Mackenzie Delta, Sverdup Basin, the West Barents Sea and the Norwegian Sea (Table 1.1). Together these contain 432 discoveries with recoverable resources totalling 61 Bbbl oils + 269 Bbbl gas. Four of these provinces dominate: West Siberia–South Kara, Arctic Alaska, East Barents Sea and Timan–Pechora. The following paragraphs summarize the petroleum systems, reservoirs and plays of these nine provinces. According to Magoon & Dow (1994), petroleum systems should be linked to and named from their source rock. In the Arctic, however, source rocks occur in abundance, being present in almost all systems from the Proterozoic to the Palaeogene, which often creates uncertainty in determining the petroleum system responsible for specific oil and gas deposits.

A Proterozoic petroleum system has resulted in giant oil and gas finds in the Tunguska region of east Siberia (Klett et al.), but these lie about 1000 km south of the Arctic Circle. Major bitumen belts, however, probably from the same source rocks, also occur north of the Arctic Circle. These lie in Proterozoic and Palaeozoic rocks on the margins of the Anabar Shield (Meyerhoff & Meyer 1987; Fig. 2).

The oldest petroleum system with conventional fields in the Arctic, both in terms of the age of the sources and the timing of generation, is in the Timan–Pechora province. There, 16 Bbbl resources – principally oil – occur in 142 finds that include nine giant fields (>0.5 Bbbl). Reservoirs are Silurian to Permian shallow marine carbonates, sometimes reeal, and often fractured (Bagrintseva et al.) and Devonian and Permian sandstones. The fields occur in belts of gentle anticlines and commonly consist of multiple, stacked hydrocarbon pools at depths ranging from 1 to 5 km. The principal reservoir is in Lower Silurian strata but other source rocks range from the Ordovician to the Permian. Maturity was achieved by Carboniferous time (Klimenko et al., Fig. 13.12). The anticlinal traps formed in the Permio-Triassic in response to Uralian orogeny to the east. The stacked hydrocarbon pools indicate kilometre-scale vertical migration, allowing the mixing of hydrocarbons from different sources.

Arctic Alaska with resources of 30 Bbbl is the most prolific province sourced from Triassic rocks, but it also had important source rocks of Jurassic and Cretaceous age (Bird & Houseknecht, Fig. 34.4). The resources occur in 61 discoveries; the largest is the supergiant Prudhoe Bay oil field (16 Bbbl) but there are also seven other giant fields. The principal reservoirs are sandstones in the Triassic (200 m thick in the Prudhoe Bay Field) and the Lower Cretaceous. The fields occur in truncated anticlines with gently sloping limbs on the Barrow Arch at depths from 1 to 3 km. The arch is part of the Beaufort Rift Shoulder, formed in Jurassic to early Cretaceous times in response to the opening of the Canada Basin. Maturity of the Mesozoic sources was achieved in the foreland trough of the Brooks Range orogen as a result of sedimentary loading in Cretaceous to Palaeogene times. Long-distance northward migration of as much as 200 km filled the traps on the Barrow Arch and allowed the mixing of oils from the different sources.

The Sverdup Basin in the Canadian Arctic archipelago contains 20 discoveries concentrated in the western part of the basin, with resources totalling 3 Bbbl, predominantly gas. The sandstone reservoirs range from the Lower Triassic to the Cretaceous with the most important being Upper Triassic to Lower Jurassic (Embry). Some fields have stacked pools (e.g. Hecla, with depths that range from 500 to 1000 m and Whitefish with depths that range from 900 to 2000 m). The fields occur in anticlines with gently dipping limbs which were present by Eocene times. Maximum burial was in Paleocene times, after which there has been kilometer scale uplift. Middle to Upper Triassic strata are commonly considered the main source rock, but an analysis by Dewing & Obermajer suggests they are not gas-mature in the area of the gas fields, implying a deeper source rock.

In the East Barents Sea five discoveries have total resources of 23 Bbbl, almost all gas. There is one supergiant field (Shotkmanovskoye, 21 Bbbl) and two giant fields. The sandstone reservoirs are mainly Upper to Middle Jurassic, but gas also occurs in Triassic reservoirs. The traps are gentle domes with a field area of 1200 km² at Shotkmanovskoye, where the approximately 50 m-thick Middle Jurassic main reservoir contains a gas column of approximately 150 m at a depth of 2100 m. This field is in the centre of the basin where the total sedimentary column is 15 km thick. Presumed Triassic marine source rocks have achieved gas.
maturity over wide areas and are the most likely sourcing candidate. Neogene uplift in the east Barents Sea amounted to 0.5–1 km (Henriksen, Bjørnseth et al., Fig. 17.10). In the West Barents Sea, the Goliat Field has some oil in a Triassic sandstone reservoir that is considered to have been sourced from Triassic marine strata (Ohm et al. 2008) and a Triassic-sourced petroleum system may be widespread there also (Henriksen, Ryseth et al. Fig. 10.30).

In the West Barents Sea the total discovered resources amount to 2 Bbloc, mostly as gas in the Hammerfest Basin, probably sourced from both Upper Jurassic and Middle Triassic marine shales. The largest gas field in the basin, Snøhvit (0.7 Bbloc), is reservoired in Lower–Middle Jurassic sandstones at a depth of 2300 m, but porosities are low (12–18%). The trap is a late Jurassic fault block and oil staining extends for 100 m below the thin oil leg. The widespread Neogene uplift of the western Barents Sea region, amounting to 1–2 km has had an important effect upon the petroleum geology (Henriksen et al.) by giving low reservoir porosities at shallow depths, terminating generation from source rocks and leading to the re-distribution of hydrocarbons, as evidenced by the numerous residual oil columns encountered.

The Norwegian Sea north of 66°N contains 12 discoveries with resources totalling 1.4 Bbloc. The one giant field – the Njord oilfield (0.7 Bbloc) – is reservoired in Lower and Middle Jurassic sandstones in a Late Jurassic fault trap at 2500 m depth and was sourced from the Upper Jurassic marine shale. This shale is the predominant source rock for this mid-Norwegian petroleum province. To the west and NW scattered gas finds in Cretaceous reservoirs occur in a region where the Upper Jurassic source is so deep that either re-migration or a shallower source rock is implied.

In West Siberia and the South Kara Sea, north of 66°N, nine supergiant fields, 31 giants and 52 other discoveries contain total resources of almost 250 Bbloc, 90% of which is gas. Sourcing of these vast amounts of gas remains a matter of dispute (Fjellanger et al. 2010). Contributions from different sources are likely: especially from coaly Cretaceous strata and coaly Lower–Middle Jurassic strata; possibly from Upper Jurassic marine shales; and some gas may be of biogenic origin. The traps are anticlines with gently dipping limbs and huge extent. The largest field (Urengoy, 68 Bbloc) extends over 2400 km². Also, the fields contain many stacked pools from depths of 1000 to 4000 m, in sandstone reservoirs ranging from Turonian to Lower Jurassic. The most important reservoirs are thick fluvial–deltaic sandstones of the Albian–Cenomanian Pokur Formation. The combination of multiple sources with multiple, thick reservoirs and anticlines with extensive, gentle closures created the most prolific hydrocarbon province in the Arctic (Table 1.1).

The youngest proven petroleum system in the Arctic occurs in the Mackenzie Delta. In the south, onshore, hydrocarbons occur in Cretaceous and Jurassic sandstones that were sourced from Jurassic strata (Parsons Lake Field). Off-shore, to the north most fields are reservoired in Upper Cretaceous or Palaeogene sandstones and their hydrocarbons were sourced in Upper Cretaceous or Palaeogene rocks. The total discovered resources in the 59 discoveries amount to 3.2 Bbloc, a little more than half of which is gas. There are no giant fields in the Mackenzie Delta. The largest is the Taglu gas field with resources of 0.4 Bbloc. Fields have stacked pools and occur in closures associated with growth faults.

Future petroleum provinces

The area of the Arctic north of the Polar Circle totals c. 21 × 10⁶ km² and sedimentary basins underlie almost 40% of this area (Fig. 1.1). Of the total area of sedimentary basins (c. 8 × 10⁶ km²) there are discoveries in 15%, dry wells in 10%,

Fig. 1.6. An outline of the intensity of petroleum exploration in the Arctic.
seismic coverage but no wells in 50% and no seismic data in 25% (Fig. 1.6). Much of the Arctic is unexplored.

The USGS CARA project (Gautier, Bird et al.) estimated that for the Arctic as a whole the yet-to-find resources (mean, risked, recoverable) in the 48 (of 69) evaluated assessment units (AU) will total 90 Bbl oil + 279 Bblbloc gas. Eleven regions, containing 30 AUs, have large mean, risked resources (Bblbloe): West Siberia−South Kara, 136; Arctic Alaska, 73; East Barents Sea, c. 61; East Greenland, c. 34; Yenisei−Khatanga, 25; West Greenland, c. 25; Laptev Sea, c. 15; Mackenzie Delta, 13; Timan−Pechora, c. 8; West Barents Sea, c. 8; and the Norwegian Sea, 6 (Fig. 1.7). Note that eight of these 11 regions are proven hydrocarbon provinces; the three ‘new’ provinces are East and West Greenland and the Laptev Sea. The remaining 18 evaluated AUs are almost all ‘new’ provinces and all of them have mean risked yet-to-find resources smaller than 5 Bblbloe. The least understood of the 48 evaluated AU’s in the Arctic are the six prograded continental margin wedges that lie west and north of the Barents Sea and north of Siberia, Alaska and Canada.

The estimates by Kontorovich et al. are similar in ranking the yet-to-find resources of the South Kara Sea and East Barents Sea high, but they are more optimistic about the offshore regions north of Siberia than the USGS CARA estimates (Fig. 1.7).

The thick and complete sedimentary columns present in many basins in the Arctic, plus widespread presence of Palaeozoic and multiple Mesozoic source rocks suggest that numerous petroleum systems remain undiscovered. Figure 1.8 attempts to portray this in stratigraphic form. Proven Triassic- and Jurassic-sourced petroleum systems are the most prolific, but several areas may have new potential. Undiscovered Cretaceous and Cenozoic petroleum systems could be present in many areas.

**State of knowledge**

When in 2004 the three-icebreaker expedition ACEX set out to drill the Lomonosov Ridge near the North Pole, it had a strong scientific rationale, as expressed in the mission proposal (Backman et al. 2002) abstract:

The ridge was rifted from the Kara/Barents shelves during early Palaeogene time and subsequently subsided to its present water depth. Since that time sediments of biogenic origin, eolian and ice-rafted origin have accumulated on the ridge crest. In our primary target area between 87 N and 88°N these sediments are about 450 m thick, indicating an average rate of sedimentation of c. 10 m/m.y. throughout the course of the Cenozoic.

Disappointingly, for reasons yet to be understood, the sequence turned out to lack sediments of Middle Eocene to Early Miocene age representing a lacuna of c. 25 Ma, thus illustrating lucidly what is the main challenge to the bringing forward understanding of the petroleum geology of the Arctic, namely insufficient stratigraphic information.

Further adventure into the Arctic along the track pioneered by the ACEX expedition (Moran et al. 2006) might be realization of the vision of Thiede et al. of a dedicated Arctic drillship and innovative geophysical exploration techniques, as described for example by Kristoffersen. Exploration by energy companies beyond the shore and near-shore Arctic environment is not likely to expand our basic knowledge of Arctic geology at an appreciable
rate because much of the data thus obtained may not be shared with the scientific community. Energy companies and the Arctic nations should therefore consider joining efforts with the scientific community in exploring the Arctic and extending basic data acquisition into areas of which we presently know very little. As demonstrated by the ACEX expedition, seismic acquisition cannot stand alone: stratigraphic information is needed to ground-truth seismic data.

This introduction benefited from reviews by A. Grantz, G. Ulimshek, K. Chew, E. Henriksen, G. B. Larsen, E. Johannessen, E. Bjørkliebak and C. Cooper. The drawings were prepared by A. Hanssen, N. Ringset and E. Tjeltand in Statoil and by E. Melskens, H. K. Petersen and W. Weng in GEUS. Spencer wishes to thank Statoil for permission to publish. Sørensen publishes with permission by the Geological Survey of Canada. We all thank our host institutions for their support of this work.

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Map. The Arctic Ocean and surrounding land masses.