Petroleum resource assessment of the East Greenland Basin

LI Bin[1,2], LIU Chenglin[1,2*,] ZHAO Yue[3], HONG Weiyu[1,2], PING Yingqi[1,2] & LIANG Dexiu[1,2]

[1] State Key Laboratory of Petroleum Resource and Prospecting, China University of Petroleum, Beijing 102249, China;

[2] College of Geosciences, China University of Petroleum, Beijing 102249, China;

[3] Institute of Geomechanics, Chinese Academy of Geological Sciences, Beijing 100081, China

Abstract   The onshore and offshore parts of the East Greenland Basin are important areas for petroleum exploration at the North Pole. Although assessments by the US Geological Survey suggest a substantial petroleum potential in this area, their estimates carry a high risk because of uncertainties in the exploration data. This paper compares the reservoir-forming conditions based on data from the East Greenland Basin and the North Sea Basin. The petroleum resources of the East Greenland Basin were assessed by geochemical and analogy methods. The East Greenland Basin was a rift basin in the late Paleozoic–Mesozoic. Its basement is metamorphic rock formed by the Caledonian Orogeny in the Archean to Late Ordovician. In the basin, Devonian–Paleogene strata were deposited on the basement. Lacustrine source rock formed in the late Paleozoic and marine source rocks in the Late Jurassic. Shallow-marine sandstone reservoirs formed in the Middle Jurassic and deep-marine turbiditic sandstone reservoirs formed in the Cretaceous. The trap types are structure traps, horst and fault-block traps, salt structure traps, and stratigraphic traps. The East Greenland Basin possesses superior reservoir-forming conditions, favorable petroleum potential and preferable exploration prospects. Because of the lack of exploration data, further evaluation of the favorable types of traps, essential amount of source rock, petroleum-generation conditions and appropriate burial histories in the East Greenland Basin are required.

Keywords   East Greenland Basin, North Sea Basin, stratigraphy, analogy method, resource assessment

1   Introduction

In 2007, the US Geological Survey (USGS) released the results of North Pole petroleum resources evaluation, covering a total of 33 basins. Estimates of the undiscovered resources in the North Pole region amount to 9×10^{10} barrels of oil, 1.669×10^{15} cubic feet of gas and 4.4×10^{10} barrels of condensate gas; 84% of these petroleum resources are in marine areas. The East Greenland Basin is very rich in petroleum resources, accounting for 10%, 5% and 18% of the total oil, gas and condensate gas of the North Pole petroleum resources, respectively (Zhao et al., 2014; Gautier, 2007). In the northeastern part of Greenland, resin-rich, high-sulfur coal was found, which confirmed the hydrogen index of up to 700 units of high-quality source rock (Bojesen-Koefoed et al., 1999). However, the East Greenland Basin has not been thoroughly explored, with only a few wells providing exploration data. The degree of exploration has a great influence on resource assessment; therefore, it is important to study the petroleum resource potential of the poorly explored East Greenland Basin.

Resource assessment methods have developed rapidly since the 1950s, because of the increased demand for petroleum products worldwide. From statistical forecasting in the 1950s to basin modeling in the 1980s, to the development of expert systems and decision analysis in the 1990s, petroleum resource assessment has become an established research field with advanced assessment theories and many assessment methods. In this study, the petroleum resources of the East Greenland Basin were analyzed by reviewing the geological characteristics of the basin presented in previous studies and using petroleum geology analysis methods. The petroleum resources in the East Greenland Basin were evaluated by using the North Sea Basin as an analogy scaled area, and the petroleum potential was analyzed to determine the relevant geological background of the East Greenland Basin.

2   Structural background

Greenland, the largest island in the world, belongs to Denmark. The island is located in the Arctic Circle, close to the northeastern coast of North America, the Arctic Ocean and the Atlantic Ocean. Greenland has an area of about 2.16×10^6 km^2, most of it covered by inland ice, ice sheets and glaciers. The East Greenland Basin is located between 60°N and 80°N, with an area of about 3×10^5 km^2, accounting for 13.9% of Greenland's total area (Figure 1). The USGS divides the East Greenland Basin into seven tectonic units: the North Danmarkshavn Salt Basin, the South Danmarkshavn Basin, the Thetis Basin, the Jameson Land Basin, the Liverpool Land Basin, the Jameson Land Basin Subvolcanic Extension and the Northeast Greenland Volcanic Province (Figure 2).

The tectonic pattern of the East Greenland Basin is dominated by the evolution of the North Atlantic (Feng et al., 2013). The dominant tectonic feature in East Greenland is the Caledonian orogen, part of the 6000-km-long Caledonian–Appalachian orogenic belt, the original width of which is estimated to have been 700–800 km in the North Atlantic region (Schiffer et al., 2014). The opening of the North Atlantic region was one of the most important geodynamic events that shaped the present-day passive margins of Europe, Greenland and North America (Schiffer et al., 2017). The initiation of the Atlantic rift system between Greenland and Norway that run eastwards through the Nordkapp basin in the Barents Sea, and the Arctic rift systems that extended westwards between North Greenland and Spitsbergen to the Sverdrup Basin, took place during the latest Devonian and earliest Carboniferous (Stemmerik et al., 1991). This latest Devonian–early Carboniferous rift pulse was characterized by non-marine sedimentation in narrow, isolated half-grabens. The rifting is well documented in East Greenland, Spitsbergen and Bjørnøya, where sedimentation started during the latest Devonian, and in eastern North Greenland, where sedimentation began in

the Visean (Stemmerik, 2000; Stemmerik et al., 1991).

In the North Sea and Norwegian Sea, crustal movements that had begun in the late Permian continued into the Early Triassic (Ziegler et al., 1982). During the Triassic, Pangea started to fragment, and the Tethys Ocean opened in a westerly direction from the present-day Middle East and separated the new Europe from Africa (Nøttvedt et al., 2008). During Early and Middle Jurassic times, the rift axis propagated progressively northwards, with formation of the central Atlantic Ocean. In the Late Jurassic, seafloor spreading in the Mid-Atlantic progressed northeastwards, leading to major rifting between East Greenland and Norway, with a branch extending southwards into the North Sea (Peace et al., 2016). Following the earliest Cretaceous South Atlantic opening, break-up and seafloor spreading progressed into the North Atlantic between Europe and North America in the Late Cretaceous, and culminated with continental separation and formation of the Norwegian and Greenland seas in the early Cenozoic.

In the Paleogene, breakup of the Greenland region occurred in three stages: (1) Paleocene separation between North America and Greenland, which was still attached to Eurasia; (2) continued separation between Greenland and North America during the Eocene, at the same time as separation between Eurasia and Greenland (with Greenland moving as a separate plate); and (3) continued separation between Eurasia and Greenland since the Oligocene, with the latter attached to North America (Peace et al., 2017; Mjelde et al., 2008). Cenozoic compressional structures constitute potential hydrocarbon traps, either as four-way dip closures or closure along-strike of pre-existing fault blocks and terraces, which are potential targets for petroleum exploration (Dore et al., 1996).

3   Stratigraphy

The post-Caledonian geology of East Greenland comprises a nearly complete succession of Devonian to Upper Cretaceous strata deposited in continental to deep-marine environments. These strata are unconformably overlain by Paleocene–Eocene sediments (Larsen et al., 2014; Nøhr-Hansen et al., 2011; Jolley and Whitham, 2004), which are more regionally overlain by Eocene tholeiitic plateau basalts (Pedersen et al., 1997; Hald, 1996; Upton et al., 1980). Figure 3 shows the distribution of stratigraphic units in East Greenland between latitudes 71°N and 74°N.

Devonian strata in the Traill Ø (Traill Island) region are exposed at the western end of Traill Ø and Geographical Society Ø. These strata belong to the Kap Kolthoff and Celsius Bjerg Groups (Olsen et al., 1993). They have a minimum thickness of 2700 m and were deposited in a fluvial–lacustrine environment. This unit comprises sandstone and conglomerate, siltstone, shale and volcanic rock. The base of the unit is not exposed (Larsen et al., 2008; Clack and Neininger, 2000; Olsen et al., 1993; Surlyk, 1990).
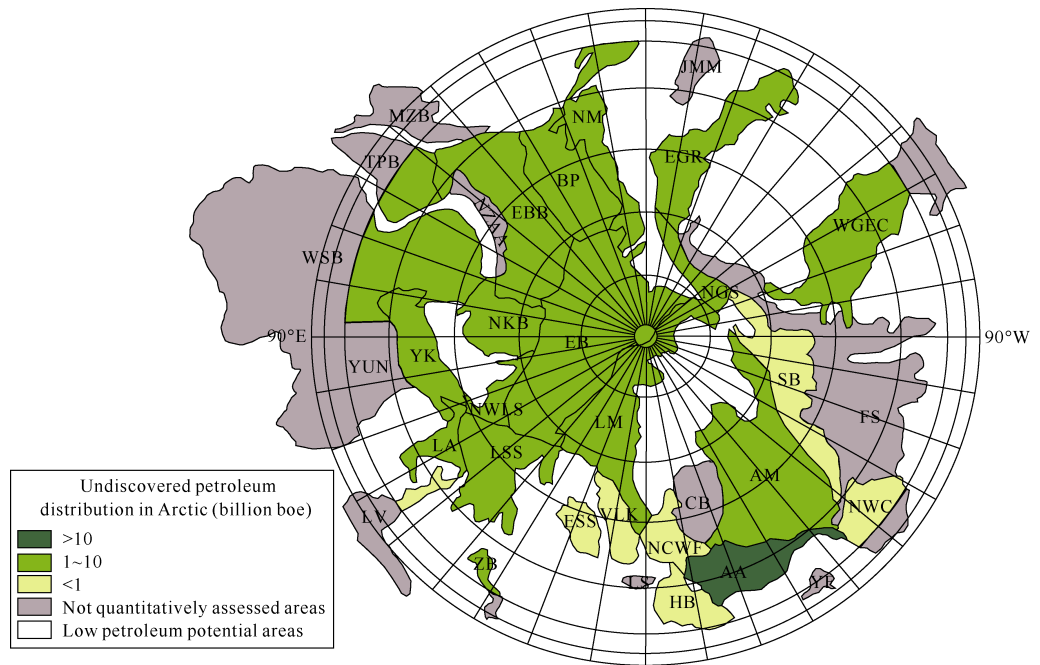
Figure 1 Geographical position of the East Greenland Basin (Bai et al., 2011). WSB: West Siberian Basin; AA: Arctic Alaska Basin; EBB: East Barents Sea Basin; EGR: East Greenland Basin; YK: Yenisey–Khatanga Basin; AM: Amerasia Basin; WGEC: West Greenland–East Canada; LSS: Laptev Sea Shelf; NM: Norway Margin; BP: Barents Basin; EB: Eurasian Basin; NKB: North Kara Sea Basin; TPB: Timan–Pechora Basin; NGS: North Greenland Shear Zone; LM: Lomonosov Makarov; SB: Sverdrup Basin; LA: Lena–Anabar Basin; NCWF: North Chukchi–Wrangel Foreland Basin; VLK: Vilkitsky Basin; NWLS: Northwest Laptev Sea Shelf; LV: Lena–Velayi Basin; ZB: Zyryanka Basin; ESS: East Siberian Basin; HB: Hope Basin; NWC: Northwest Canada Basin.
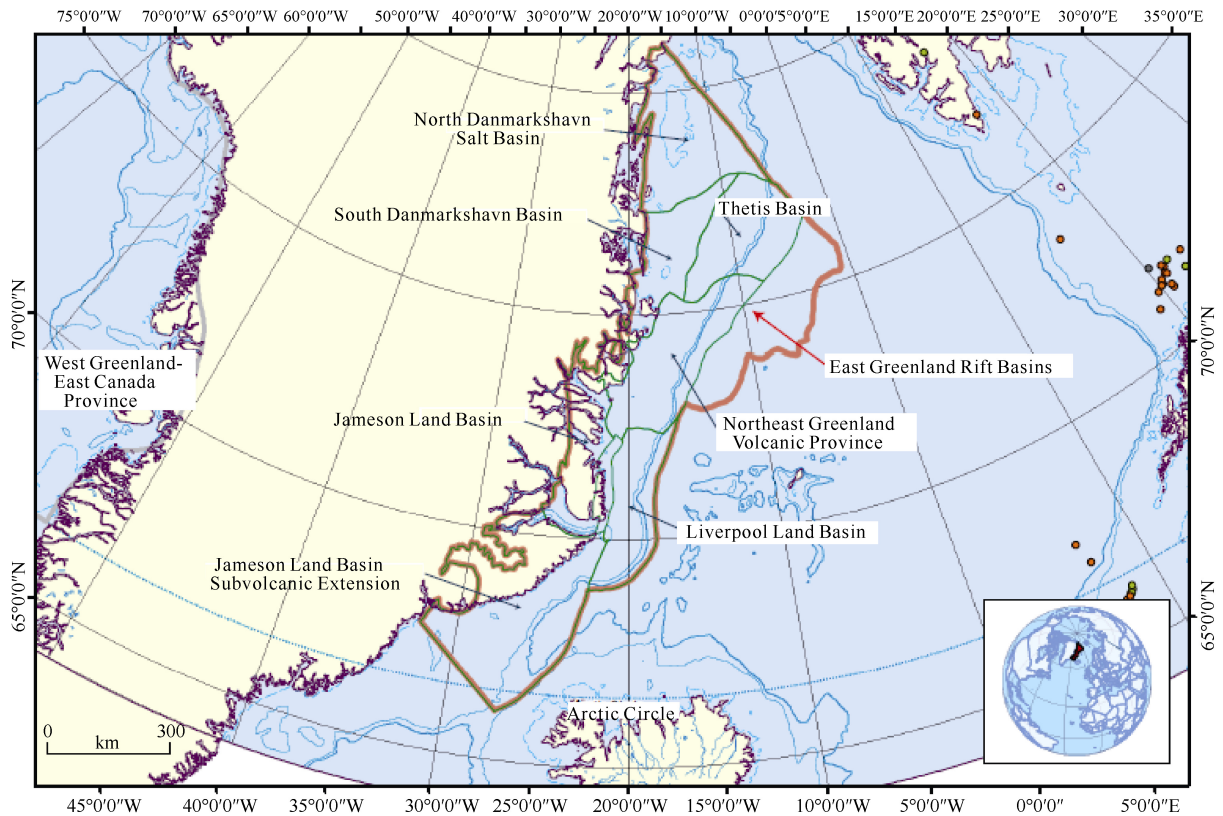

Figure 2 Tectonic units of the East Greenland Basin. The solid brown line outlines the East Greenland Basin; the green lines indicate unit boundaries (Gautier, 2007).

Carboniferous strata exposed in the western parts of Traill Ø and Geographical Society Ø belong to the Traill Ø Group (Vigran et al., 1999). They have a minimum thickness of 3000 m and were deposited in alluvial-fan, fluvial, alluvial-plain and lacustrine environments. The unit consists largely of sandstone and mudstone, coal, and conglomerate. The basal contact is an angular unconformity with the Devonian strata (Surlyk, 1990; Surlyk et al., 1986).

Permian strata of the Foldvik Creek Group (Christiansen, 1990), with a thickness of 90–125 m, are exposed on central Traill Ø. Deposited in a marine environment, this unit consists of conglomerate, sandstone, mudstone, carbonates and evaporites. The basal contact has a 4°–12° angle with the underlying Carboniferous strata (Stemmerik et al., 2001; Christiansen, 1990; Surlyk, 1990; Clemmensen, 1980).

Triassic strata are found across central Traill Ø and in Tværdal and around Laplace Bjerg on Geographical Society Ø (Parsons et al., 2017). This unit has a thickness of $\geqslant$ 1800 m; this is a minimum estimate because a complete section of the entire group has not been observed (Bjerager et al., 2006). This unit consists of mudstone and sandstone overlain by gypsiferous mudstone and sandstone. The basal contact is observed on Traill Ø and is conformable with the underlying Permian strata (Parsons et al., 2017; Decou et al., 2016; Andrews et al., 2014; Stemmerik et al., 2001; Surlyk, 1977).

The Jurassic strata in this region consist of the Jameson Land Group overlain by the Hall Bredning Group. The Jameson Land Group is found across Traill Ø and Geographical Society Ø (Therkelsen and Surlyk, 2004; Engkilde and Surlyk, 2003; Price and Whitham, 1997). This group has a combined maximum thickness of between 990 m (Bjerager et al., 2006) and 1790 m (Birkelund and Callomon, 1985) and consists of sandstone, mudstone, subordinate conglomerate, shale and coal. The Jameson Land Group was deposited in fluvial and shallow-marine environments. The Hall Bredning Group is exposed in eastern Traill Ø, the exposed sections have a maximum thickness of 300 m. This unit consists of black, micaceous, organic-rich shale with subordinate sandstone. The basal contact is conformable with the Jameson Land Group (Vosgerau et al., 2004; Engkilde and Surlyk, 2003; Whitham et al., 1999; Birkelund and Callomon, 1985; Donovan, 1957).

Cretaceous strata are found in the northern part of the Traill Ø region, in Hold with Hope. This unit has a minimum thickness of 2400 m. The strata were deposited in a continental–marine environment. This unit consists of black mudstone with subordinate sandstone and conglomerates. The basal contact is conformable with the Jurassic strata (Engkilde and Surlyk, 2003; Donovan, 1957).
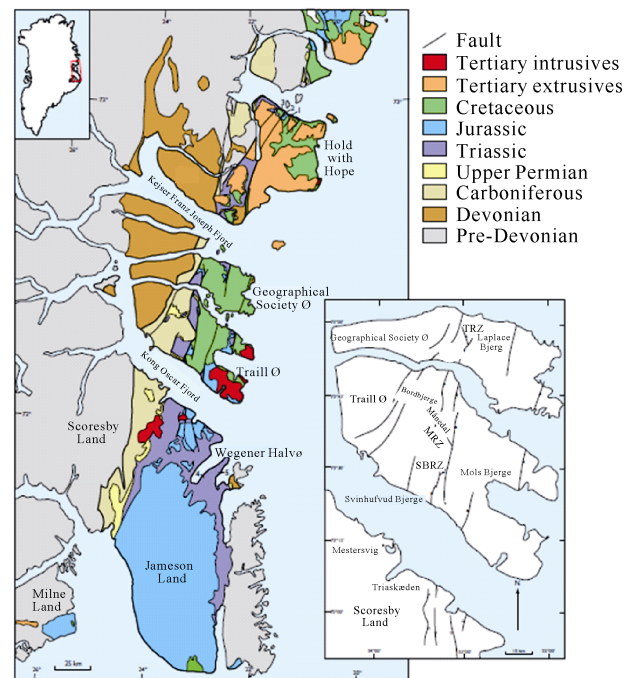

Figure 3 Geological map of the area between Jameson Land and Clavering Ø. The inset map shows major structural elements in the Traill Ø area. TRZ: Tværdal relay zone; MRZ: Månedal relay zone; SBRZ: Svinhufvud Bjerge relay zone (Stemmerik et al., 1997).

4 Assessment methods and processes

Analogy, genetic and statistical methods are the most commonly used petroleum resource assessment methods (Zhang et al., 2014). The analogy method is often used in less-explored areas such as the East Greenland Basin. The analogy method is carried out as follows: statistical analysis of the geological parameters of mature oil and gas exploration areas analogous to the prospective areas is conducted; the analogy factor is determined through various scores; and the petroleum resources are estimated. In this study, the analogy method was used to calculate the amount of petroleum resources in the East Greenland Basin.

When using the analogy method, we must first understand the geological conditions in the assessment area to select an analogous scaled area. The scaled area can be used as an assessment area analogy standard for the evaluation of the basic geological unit when we evaluate the petroleum resources (Guo et al., 2006; Hu et al., 2005). The selection of the scaled area is an important step that directly affects the outcome of the assessment. The scaled area should be well-explored with extensive geological data and contain large amounts of confirmed petroleum resources. After selecting the scaled area, a comprehensive investigation is performed to determine the oil geology conditions, the correlation coefficients of the resources and the amount of resources in the scaled area. Based on this information, the petroleum conditions in the assessment

area are investigated and studied. The geological parameters and petroleum conditions of the assessment area and the scaled area are summarized and categorized, then the parameters are scored according to the unified analogy standard, and the analogy coefficient between the scaled area and the assessment area is obtained. The amount of resources in the assessment area is calculated using the resource abundance and other correlation coefficients of the scaled area. Finally, the data are summarized, and the results are obtained (Liu et al., 2012; Zhao et al., 2005; Zhou et al., 2005). The formula is as follows (Liu et al., 2012):

$$Q = S \times \sum_{i=1}^{n} \left(\frac{K_i \times a_i}{n} \right)$$

Q: amount of resources of the assessment area (unit: 10^8 boe),

S: area of the assessment area (unit: 10^4 km^2),

K_i: resource abundance of the scaled area (unit: 10^4 boe·km^{-2}),

a_i: analogy coefficient,

$$a_i = \frac{analogy\ total\ scores\ of\ the\ assessment\ area}{analogy\ total\ scores\ of\ the\ scaled\ area}$$

5 Establishing the scaled area

Based on the selection criteria mentioned above and the tectonic evolution characteristics, we selected the North Sea Basin as the scaled area in this analogy assessment.

5.1 Geological location

The North Sea Basin is on the western side of Europe, with the Norwegian Sea to the north, the Strait of Dover to the south, and the Shetland Islands to the northwest. The North Sea Basin is surrounded by the United Kingdom, Denmark, Norway, Holland, Germany, France and Belgium, and covers an area of about 57.5×10^4 km^2. Based on global tectonics, the early North Sea Basin is a late Paleozoic rift basin that evolved into a Paleogene–Neogene basin after a prolonged geological process (Ye and Yi, 2004). The basin is situated on the northwest Europe Craton, and can be divided into multiple tectonic units (Figure 4).

5.2 Hydrocarbon distribution characteristics

At the end of 2009 there were 1731 petroleum fields in the North Sea Basin (Stemmerik et al., 1997). The proven reserves of petroleum are about 1504.26×10^8 boe; of these, 994.17×10^8 boe are in the northern North Sea Basin and 510.09×10^8 boe are in the southern North Sea Basin, accounting for 66.1% and 33.9% of the total reserves, respectively (Table 1). Classifying reserves by the hydrocarbon type, the North Sea Basin oil reserves are 608.00×10^8 boe while the gas reserves are 851.10×10^8 boe.
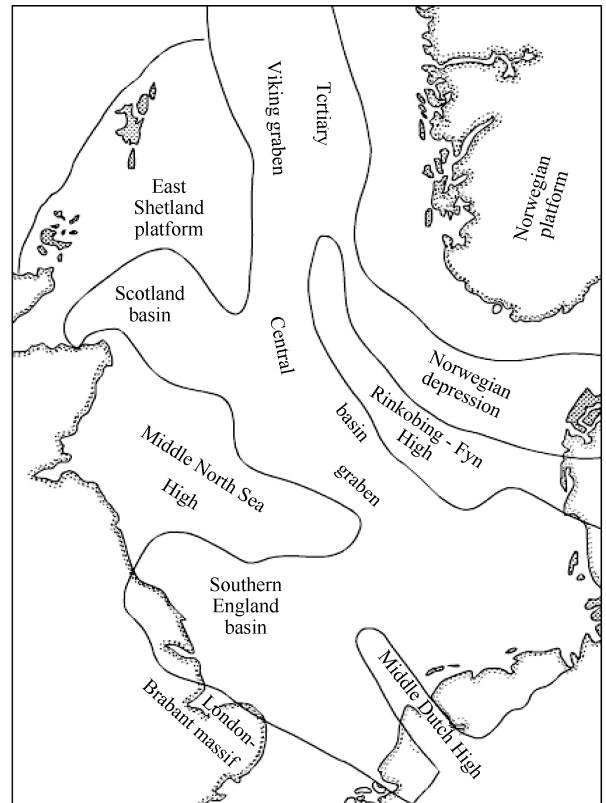

Figure 4 Schematic map of the principal geological structures of the North Sea Basin (Zabanbark, 2012).

5.3 Petroleum geological conditions

5.3.1 Source rocks

The most widely distributed source rocks in the northern North Sea Basin are the Upper Jurassic Kimmeridge Clay Formation shales, which are a set of marine source rocks that occur over the entire area (Yang et al., 2014; Yang et al., 2011; Ye and Yi, 2004; Cooper et al., 1995). The Upper Jurassic sequence contains another set of source rocks, the Heather Formation shales, with a more limited distribution than that of the Kimmeridge Clay Formation shales. The main kerogen in the Kimmeridge Clay Formation and the Heather Formation is type II and the average total organic carbon (TOC) value is 2%.

The source rocks of the southern North Sea Basin are Carboniferous Westphalian coal-bearing strata and are the most important source rocks in this area (Keym et al., 2006; Gormly et al., 1994). The TOC of the coal beds is more than 60%; the shale layers contain mainly type III kerogen and >1% TOC; the average TOC is 75% overall (Zhang et al., 2011; Li and Jin, 2005; Kubala et al., 2003; Leeder and Hardman, 1990). The vitrinite reflectivity (Ro) is up to 1.5% and the maturity decreases from the center of the basin to the margin (Kubala et al., 2003). Ro of the Westphalian coal-bearing source rocks in the southern North Sea Basin is generally more than 2% (Doornenbal and Stevenson, 2010). Based on the maturity of the source

rocks, the northern North Sea Basin mainly generated oil and the southern North Sea Basin mainly generated gas.

Table 1 Distribution of proven hydrocarbons in the North Sea Basin (Yang et al., 2014)

Tectonic division	Geomorphology	Number of oil and gas fields	Oil		Gas		Oil equivalent	
			Reserves /($\times 10^8$ t)	Occupancy /%	Reserves /($\times 10^8$ m^3)	Occupancy /%	Reserves /($\times 10^8$ boe)	Occupancy /%
The northern North Sea Basin	Viking Graben	offshore	254	37.86	40.8	20446	16.4	412.39	27.4
	Central Graben	offshore	242	26.58	28.7	13605	10.9	284.55	18.9
	Moray Firth Basin	offshore	101	9.33	10.1	2511	2.0	84.95	5.6
	Horda Platform	offshore	38	9.57	10.3	14844	11.9	168.08	11.2
	Other areas	offshore	53	4.08	4.4	2151	1.7	44.20	2.9
	Sum	offshore	688	87.42	92.4	53556	42.9	994.17	66.1
The southern North Sea Basin	Anglo-Dutch Basin	offshore	424	0.99	1.1	24972	19.9	171.96	11.4
		onshore	119	0.61	0.6	1024	0.1	11.21	0.8
		subtotal	543	1.60	1.7	25996	20.8	183.18	12.2
	Northwest basin of Germany	offshore	62	0.51	0.5	31546	25.3	211.91	14.1
		onshore	438	3.24	3.5	13834	11.0	115.01	7.6
		subtotal	500	3.75	4.0	45380	36.3	326.92	21.7
	Sum	offshore	486	1.50	1.6	56518	45.2	383.87	25.6
		onshore	557	3.85	4.2	14858	11.9	126.22	8.3
		subtotal	1043	5.35	5.8	71375	57.1	510.09	33.9
Total		offshore	1174	88.92	95.8	110074	88.1	1378.04	91.6
		onshore	557	3.85	4.2	14858	11.9	126.22	8.4
		subtotal	1731	92.77	100	124932	100	1504.26	100

5.3.2 Reservoirs

Several sets of reservoirs formed in the North Sea Basin from the Paleozoic to the Cenozoic. Regional reservoirs formed in the northern North Sea Basin in the Early Jurassic, Late Cretaceous, Paleocene and Eocene (Wilkinson et al., 2006; Ye et al., 2004). The main reservoirs are the Lower Jurassic Statfjord Formation and the Middle Jurassic Brent Group (Wilkinson et al., 2006).

The Middle Jurassic Brent Group sandstone reservoir of the East Shetland Basin has an average thickness of more than 150 m, an average porosity of 18% and an average permeability of about 650 mD (Ehrenberg, 1997; Beydoun et al., 1990).

The Lower Jurassic Statfjord Formation is a fluvial–delta facies sandstone reservoir with shale interlayers. The average porosity of the reservoir is 13.5% and the average permeability is 330 mD (Sun and Zhao, 2012; Ramm and Ryseth, 1996).

The main reservoir in the southern North Sea Basin is the lower Permian Rotliegende sandstone. The maximum thickness of the reservoir is more than 300 m (Nagtegal, 1979), the maximum porosity is 30% and the permeability varies from 1 to 3000 mD (Glennie and Provan, 1990).

5.3.3 Cap rocks

The main cap rocks in the northern North Sea Basin are the source rocks of this region, the Upper Jurassic Kimmeridge Clay Formation shale and Heather Formation shale, which cover the Middle Jurassic reservoirs and prevent hydrocarbon diffusion. As regional cap rocks, the two sets of cap rocks are widely distributed, and are approximately 150–1000 m thick (Yang et al., 2014).

The cap rock of the southern North Sea Basin is the salt rock of the Permian Zechstein Formation (Yang et al., 2014; Ye et al., 2004; Ramm and Ryseth, 1996). The Zechstein Formation is a set of regional cap rocks with a wide distribution and a thickness of about 200–1000 m.

5.3.4 Petroleum migration and reservoir characteristics

The source rocks of the Kimmeridge Clay Formation in the northern North Sea Basin matured in the Late Cretaceous; at the same time, the thickness of the Cretaceous strata reached 1700 m. The Kimmeridge Clay Formation shale in the Viking graben reached its peak hydrocarbon generation in the Paleogene (Grabinski, 1983). The hydrocarbon migration distance was short (2–30 m), and the migration was generally vertical (Liu et al., 2012; Isaksen and Ledje, 2011). Based on previous studies, hydrocarbons in the northern North Sea Basin were either generated in older strata and accumulated in younger strata or generated in younger strata and accumulated in older strata (Zhang et al., 2012).

Hydrocarbon generation in the source rock of the Anglo-Dutch Basin in the southern North Sea Basin reached its peak in the Late Cretaceous (Fraser and Gawthorpe, 1990). The salt rock stratum of the fracture system caused by tectonic action provided a good migration pathway for the generated petroleum, creating favorable conditions for petroleum accumulation (Liu et al., 2011). In general, hydrocarbons in the southern North Sea Basin were generated in older rocks and migrated to younger strata.

6 Petroleum geological conditions of the assessment area

6.1 Source rocks

There are four sets of source rocks in the East Greenland Basin: the Upper Permian Ravnefjeld Formation, the Upper Triassic–Lower Jurassic Kap Stewart Formation, the Middle Jurassic Fossilbjerget Formation and the Upper Jurassic Hareelv Formation (Feng et al., 2013; Stemmerik et al., 1998) (Figure 5).

The Upper Permian Ravnefjeld Formation is a set of marine shales that was deposited in a hypoxic shallow sea. In the central area of the Jameson Land basin, dark shale with rich organic matter is widely distributed. The kerogen type is mainly type II and a small amount of type III, which have good hydrocarbon generation potential (Nielsen et al., 2008). The average TOC is 4.5%, and the hydrogen index is 300–400 mg HC·g^{-1} TOC (Wignall and Twitchett, 2002; Christiansen et al., 1962). Based on previous studies of more than 20 cores, the average R_o is 1.75%, which indicates mature source rock (Karlsen et al., 1988).

The Middle Jurassic Fossilbjerget Formation is equivalent to the Heather Formation of the North Sea Basin and is a set of marine shales with about 1%–4% TOC (Feng et al., 2013; Ehrenberg et al., 1990).

The Upper Jurassic Hareelv Formation is a set of marine dark shales in the Jameson Land basin, with type II kerogen, a thickness of 200–500 m and an area of more than 4500 km^2. Based on samples analyzed in previous studies,

the TOC content is 6%–12% and R_o is 0.5%–0.7%, indicating mature source rock, and the hydrogen index is 200–300 mg HC·g^{-1} TOC (Surlyk and Noe-Nygaard, 2001; Requejo et al., 1989).

The Upper Triassic–Lower Jurassic Kap Stewart Formation shale mainly occurs in the Jameson Land Basin of the East Greenland Basin. The rock represents delta-plain facies, and extends over an area of 1.19×10^4 km^2. The organic matter includes algae and higher plant debris, with type I and type III kerogen. The total thickness of the formation is 155–400 m, and the source rock with hydrocarbon-generation capacity is about 15 m thick. The density of the source rock is 2400 kg·m^{-3} and the TOC varies from 0.5% to 10.3%. In the middle of the formation, a set of shales with a thickness of about 10–15 m has good oil-generation potential. The TOC of this shale is about 10%, the hydrogen index is up to 700 mg HC·g^{-1} TOC, and the sulfur content is very low. The average R_o is less than 1.0%, indicating low-maturity to mature source rock (Krabbe, 1996; Ehrenberg et al., 1990).

6.2 Reservoirs

Several sets of reservoirs are developed in the East Greenland Basin: the upper Permian Wegener Halvø Formation reef limestone; the Upper Triassic–Lower Jurassic Kap Stewart Formation sandstone; the Lower Jurassic Neill Klinter Formation sandstone; the Middle Jurassic Pelion Formation sandstone and the Upper Jurassic Olympen Formation.

The Upper Jurassic Olympen Formation contains a set of shallow-marine and fluvial deltaic sediments with a thickness of less than 250 m and a depth of more than 2500 m. The lithology is quartz lithic sandstone. The porosity varies from 7% to 27%, the average porosity is 20% and the maximum permeability is 622 mD (Price and Whitham, 1997).

The Upper Triassic–Lower Jurassic Kap Stewart Formation sandstone is equivalent to the Statfjord sandstone of the North Sea Basin, with similar physical properties. Some studies have shown that the porosity in the East Greenland Basin ranges from 10% to 30% (Cheatwood et al., 1986). Further research on the other reservoirs and potential reservoirs is required.

6.3 Cap rock

The cap rock in the East Greenland Basin can be categorized as inner cap rock, most of which is mudstone and shale, and occurs over the entire region; however, the thickness of the cap rock is thinner than in the North Sea Basin (Li and Tong, 2010).

6.4 Petroleum migration and reservoir characteristics

The Late Jurassic to Early Cretaceous was an important developmental period of the source rocks of the sedimentary basins in the Atlantic (Schiffer et al., 2014); it
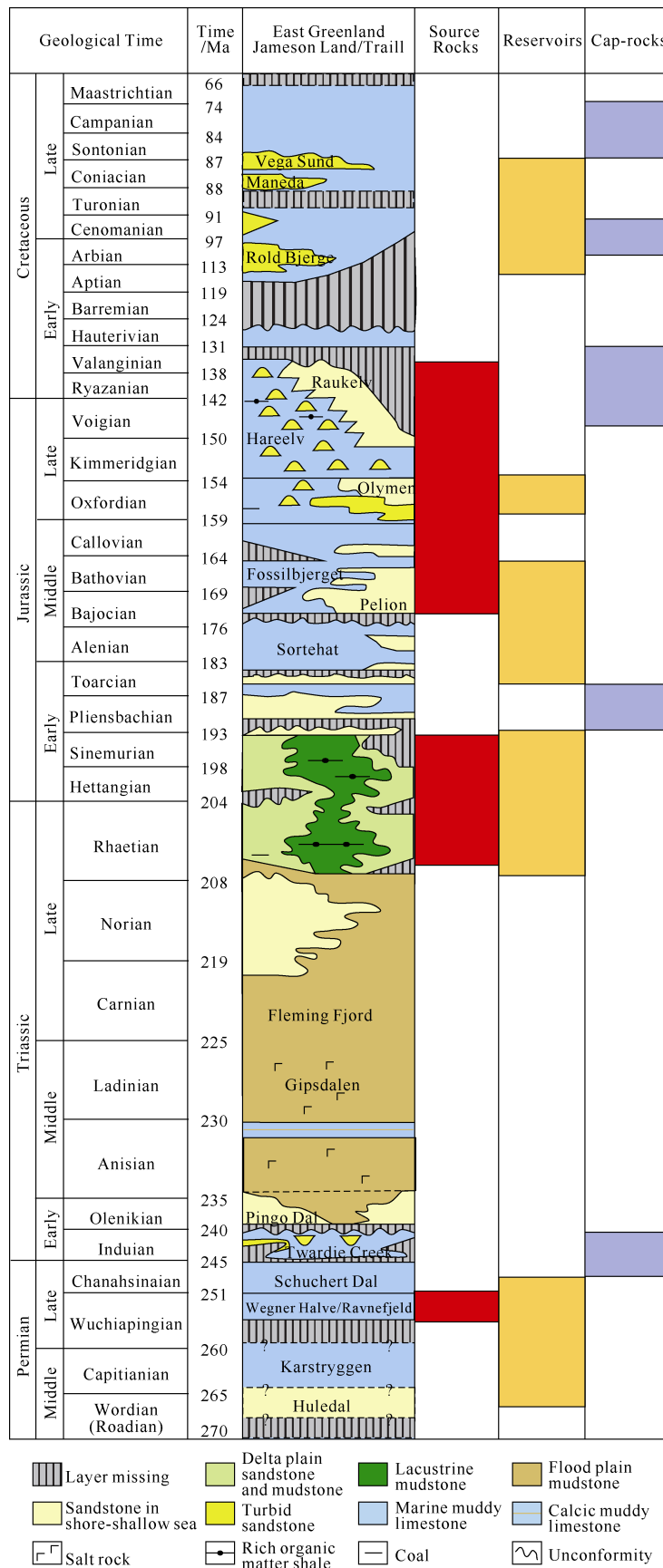
Figure 5 Stratigraphic column and petroleum plays in the East Greenland Basin (Feng et al., 2013).

is estimated that hydrocarbon generation peaked in the East Greenland Basin after the Late Cretaceous. Studies of fluid inclusions indicate that the petroleum migration pathways were microcracks, faults and unconformities. Petroleum accumulated mainly through vertical migration pathways rather than lateral migration pathways into anticline traps, fault traps and some stratigraphic traps formed by tension and salt structures; the migration distance was short (Spencer et al., 2011; Baron and Parenell, 2007; Jonk et al., 2005).

Based on the source rock, reservoirs and the development horizons of the cap rocks, hydrocarbons in the East Greenland Basin were generated in older rocks and accumulated in younger rocks.

7 Calculation and comparison of resources

7.1 Calculating petroleum resources

After determining the scaled area and analyzing the petroleum geological conditions in the assessment area, the scores were calculated based on the standard presented in Liu et al. (2012). Table 2 lists the assessment parameters for the East Greenland Basin, the northern North Sea Basin and the southern North Sea Basin.

Table 2 Geological characteristics of the assessment area and the scaled area

Basin		The East Greenland Basin	The northern North Sea Basin	The southern North Sea Basin
Trap conditions	Type	Anticline, fault and a few stratigraphic traps	Anticline, fault block, lithologic traps	Anticline, fault block, salt structure traps
Cap-rock conditions	Thickness/m	Less than the thickness of the North Sea Basin	150—1000	200—1000
	Lithology	Mudstone and shale	Mudstone and shale	Salt rock
	Area factor	Regional	Regional	Regional
	Damage degree of fracture	Small	Small	Smallest
Reservoir conditions	Sedimentary facies	Shallow sea, deep sea turbidity	Braided river, delta, fluvial facies	Delta, fluvial facies
	Average thickness	—	—	—
	Porosity	20%	16%	15%
	Permeability/mD	<622	490	<3000
	Depth/km	>4.7	>3	>3
Source rock conditions	TOC	7%	6%	75%
	Type of organic matter	Type Ⅱ, type Ⅲ	Type Ⅱ mainly, type Ⅲ less	Type Ⅲ mainly, coal
	Maturity	Low mature—mature	High mature—over mature	High mature—over mature
	Peak time of hydrocarbon generation	After the Late Cretaceous	Paleogene	Late Cretaceous
	Migration distance	Short	Short	Short
	Transportation conditions	Cracks, faults, unconformities	Faults, microcracks	Cracks, faults
Petroleum system	Play formation and hydrocarbon generation peak	Play formation was earlier	Play formation was earlier	Play formation was earlier
	Migration mode	Vertical migration mainly, lateral migration less	Vertical migration mainly, lateral migration less	Lateral migration mainly, vertical migration less
	Pattern of generation, Reservoir and cap rock	Generation in lower zone and storage in upper zone	Generation in lower zone and storage in upper zone and generation in upper zone and storage in lower zone	Generation in lower zone and storage in upper zone
Resources	Oil/(10^8 boe)	—	127.64	1.43
	Gas/(10^8 boe)	—	68.79	46.93
	Condensate gas/(10^8 boe)	—	18.07	0.64

From Table 2, the petroleum conditions of the East Greenland Basin are very similar to those of the North Sea Basin. So, analogy can be used to calculate the amount of resources in East Greenland Basin. But there are some differences, which are as follows: (1) the sedimentary facies of the East Greenland Basin are marine, but those of the North Sea Basin are terrestrial; (2) the depth of the East Greenland Basin reservoir is deeper than that of the North Sea Basin; and (3) the source rocks of the East Greenland Basin are low-maturity to mature and in the phase of oil generation, but in the North Sea Basin, the source rocks are high-maturity to over-mature and in the phase of condensate gas–gas generation.

Table 3 lists the scores of the parameters based on the scoring standard, and the resource abundance for oil, gas and condensate gas. Scoring standards without data were deleted. From the scores, we calculated the analogy coefficient:

$$\alpha_1 = \frac{S_{EGB}}{S_{NNB}} = \frac{49.5}{52.3} = 0.95$$

$$\alpha_2 = \frac{S_{EGB}}{S_{SNB}} = \frac{49.5}{54.8} = 0.90$$

α_1: analogy coefficient between the East Greenland Basin and the northern North Sea Basin

α_2: analogy coefficient between the East Greenland Basin and the southern North Sea Basin

S_{EGB}: total analogy score of the East Greenland Basin

S_{NNB}: total analogy score of the northern North Sea Basin

S_{SNB}: total analogy score of the southern North Sea Basin

Using the formula given above, the oil, gas and condensate gas resources of the East Greenland Basin can be calculated. Table 4 shows the results of the analogy calculations and the evaluation results of undiscovered petroleum resources in the northern North Sea Basin, southern North Sea Basin and East Greenland Basin, which were published by the USGS in 2007.

Table 3 Scores of geological characteristics and resource abundance in the assessment area and scaled area

	Basin	The East Greenland Basin	The northern North Sea Basin	The southern North Sea Basin
Trap conditions	Type	3.5	3	3
Cap-rock conditions	Thickness/m	2	3	3.5
	Lithology	2.5	2.5	4
	Area factor	3	3	3
	Damage degree of fracture	3	3	3.5
Reservoir conditions	Sedimentary facies	3	3.5	3.5
	Average thickness	—	—	—
	Porosity	3	2.6	2.5
	Permeability/mD	3.5	3.7	3.8
	Depth/km	1	1.5	1.5
Source rock conditions	TOC	4	4	4
	Type of organic matter	2	2.5	1
	Maturity	2	2.5	2.5
	Peak time of hydrocarbon generation	3	4	3
	Migration distance	3.5	3.5	3.5
	Transportation conditions	1.5	2	2
Petroleum system	Play formation and hydrocarbon generation peak	3	3	4
	Migration mode	2.5	2.5	3
	Pattern of generation, Reservoir and cap rock	3.5	2.5	3.5
Analogy calculation	Analogy total scores	49.5	52.3	54.8
	Analogy coefficient	—	0.94646	0.90329
Resource abundance	Area/(×10⁴ km²)	50	35	22.5
	Oil/(×10⁴ boe·km⁻²)	—	3.6468	0.0636
	Gas/(×10⁴ boe·km⁻²)	—	1.9654	2.0858
	Condensate gas /(×10⁴ boe·km⁻²)	—	0.5163	0.0284

Table 4 Undiscovered petroleum resources in the assessment area and scaled area

	The northern North Sea Basin	The southern North Sea Basin	The East Greenland Basin	
			The evaluation results of the USGS	The results of this analogy calculations
Oil/($\times 10^8$ boe)	130.99	1.47	88.99	90.01
Gas/($\times 10^8$ boe)	70.59	48.16	160.98	96.33
Condensate gas/($\times 10^8$ boe)	18.54	0.66	66.04	10.78

7.2 Comparative analysis

In general, there is good agreement between our results and those of the USGS for undiscovered oil resources; however, there is a notable difference between the estimates for undiscovered gas resources, and the largest difference is between the results for undiscovered condensate gas resources. The relative error of the three resource types is as follows:

$$\delta_{\text{oil}} = \frac{\left| Q_{oil}^* - Q_{oil} \right|}{Q_{oil}^*} \times 100\% = 1.15\%, \qquad (7\text{-}1)$$

$$\delta_{\text{gas}} = \frac{\left| Q_{gas}^* - Q_{gas} \right|}{Q_{gas}^*} \times 100\% = 40.16\%, \qquad (7\text{-}2)$$

$$\delta_{\text{con}} = \frac{\left| Q_{con}^* - Q_{con} \right|}{Q_{con}^*} \times 100\% = 83.68\%, \qquad (7\text{-}3)$$

where δ is the relative error, Q is the undiscovered petroleum resources of our analogy calculations and Q^* is the undiscovered petroleum resources of the USGS evaluation.

The large relative errors found in the results of undiscovered gas and condensate gas resources (Eqs. (7-2) and (7-3), respectively) may be explained in two ways. One is that there are some differences between the methods used by scholars in China and in other countries to determine the type of kerogen and the temperature and pressure of the reservoir; another may be that some standards of the geological characteristics we used are different from those used by the USGS.

Comparison of the petroleum geological conditions between the East Greenland Basin and the North Sea Basins reveals many differences, such as the type of kerogen. The southern North Sea Basin is dominated by type III kerogen and coal but shows a strong trend of oil generation, whereas small amounts of gas are produced in the East Greenland Basin.

In general, the analogy is based on the nature of the basin, mainly using a statistical method that largely eliminates the subjectivity of parameter selection. Our results of the resource analysis of the East Greenland Basin can serve as a guide for further research into petroleum resources in the region.

8 Conclusions

Through analogy and calculation of resources between the East Greenland Basin and the North Sea Basin, we have drawn the following conclusions.

Several sets of source rock developed in the East Greenland Basin, mainly shale that formed in lacustrine and marine environments. The superior petroleum geological conditions indicate a high resource potential in the East Greenland Basin.

(1) The analogy method was used to assess the undiscovered resources of the East Greenland Basin, using the North Sea Basin as an analogy scaled area. The calculation results show that the East Greenland Basin has an estimated 9.001×10^9 boe of undiscovered resources of oil, 9.633×10^9 boe of gas and 1.078×10^9 boe of condensate gas.

(2) A comparison of our results with those of the USGS shows differences in the undiscovered gas and condensate gas resources estimates. The main reasons for the discrepancies may be that some geological data and standards of the geological characteristics used in China differ from those used in other countries.

References

Andrews S D, Kelly S R A, Braham W, et al. 2014. Climatic and eustatic controls on the development of a Late Triassic source rock in the Jameson Land Basin, East Greenland. J Geol Soc, 171(5): 609–619

Bai Z R, Li M Y, Yang G F. 2011. Oil and gas resources potential and exploration and development tendency in the Arctic region. Petrol Petrochem Today, 19(9): 39–44 (in Chinese)

Baron M, Parnell J. 2007. Relationships between stylolites and cementation in sandstone reservoirs: examples from the North Sea, U.K. and East Greenland. Sediment Geol, 194(1–2): 17–35

Beydoun W B, Mendes M, Blanco J, et al. 1990. North Sea reservoir description: benefits of an elastic migration/ inversion applied to multicomponent vertical seismic profile data. Geophysics, 55(2): 209–217

Birkelund T, Callomon J H. 1985. The Kimmeridgian ammonite faunas of Milne Land, central East Greenland. Greenl Geol Surv Bull, 153: 1–56

Bjerager M, Seidler L, Stemmerik L, et al. 2006. Ammonoid

stratigraphy and sedimentary evolution across the Permian-Triassic boundary in East Greenland. Geol Mag, 143(5): 635–656

Bojesen-Koefoed J A, Christiansen F G, Petersen H I, et al. 1996. Resinite-rich coals of Northeast Greenland—a hitherto unrecognized, highly oil-prone Jurassic source rock. Bull Can Petrol Geol, 44(3): 458–473

Cheatwood C J, Mansfield C F. 1986. Reservoir petrology of analogous Middle Jurassic sandstones from Haltenbanken, Norway, and Jameson Land, East Greenland. AAPG Bull, 70(5): 572

Christiansen F G. 1990. Mapping of Mesozoic sediments in Svinhufvuds bjerge and Mols bjerge, Traill Ø, North-East Greenland. Grønlands Geologiske Undersøgelse Open-File Report, 10

Christiansen F G, Piasecki S, Stemmerik L, et al. 1962. Depositional environment and organic geochemistry of the Upper Permian Ravnjeld Formation source rock in East Greenland. Psychol Rep, 10(2): 174

Clack J A, Neininger S L. 2000. Fossils from the Celsius Bjerg Group, Late Devonian sequence, East Greenland; significance and sedimentological distribution// Friend P F, Williams B P J. New perspectives on the old red sandstone. Geological Society, London, Special Publication, 180: 557–566

Clemmensen L B. 1980. Triassic lithostratigraphy of East Greenland between Scoresby Sund and Kejser Franz Josephs Fjord. Greenl Geol Surv Bull, 139: 1–56

Cooper B S, Barnard P C, Telnaes N. 1995. The Kimmeridge clay formation of the North Sea// Katz B J. Petroleum source rocks. Berlin, Heidelberg: Springer, 89–110

Decou A, Andrews S D, Alderton D H M, et al. 2017. Triassic to Early Jurassic climatic trends recorded in the Jameson Land Basin, East Greenland: clay mineralogy, petrography and heavy mineralogy. Basin Res, 29(5): 658–673

Donovan D T. 1957. The Jurassic and cretaceous systems in East Greenland. Medd Grønl, 155(4): 1–214

Doornenbal H, Stevenson A. 2010. Petroleum geological atlas of the southern Permian Basin area. Houten, the Netherlands: EAGE

Doré A G, Lundin E R. 1996. Cenozoic compressional structures on the NE Atlantic margin: nature, origin and potential significance for hydrocarbon exploration. Petrol Geosci, 2(4): 299–311

Ehrenberg S N. 1997. Influence of depositional sand quality and Diagenesis on porosity and permeability: examples from Brent group reservoirs, Northern North Sea. J Sediment Res, 67(1): 197–211

Ehrenberg S N, Gjerstad H M, Hadler-Jacobson F. 1990. Geology of the Smoerbukk field−a gas-condensate fault trap//Gulf coast association of geological societies and gulf coast section of SEPM (Society of Economics, Paleontologists, and Mineralogist) meeting. Lafayette, LA, USA: AAPG Bull, 74: 9

Engkilde M, Surlyk F. 2003. Shallow marine syn-rift sedimentation: Middle Jurassic Pelion formation, Jameson land, East Greenland// Ineson J R, Surlyk F. The Jurassic of Denmark and Greenland. Geological Survey of Denmark and Greenland Bulletin, 1: 865–892

Feng Y W, Yang C Y, Qu H J, et al. 2013. Petroleum geology and exploration potential of the East Greenland margin. Mar Geol Front, 29(4): 27–32 (in Chinese)

Fraser A J, Gawthorpe R L. 1990. Tectono-stratigraphic development and hydrocarbon habitat of the Carboniferous in northern England. Geol Soc London Spec Publ, 55(1): 49–86

Gautier D L. 2007. Assessment of undiscovered oil and gas resources of the East Greenland Rift Basins Province. Gautier, D.L: U.S. Geological Survey Fact Sheet.

Glennie K W, Provan D M J. 1990. Lower Permian Rotliegend reservoir of the Southern North Sea gas province. Geol Soc London Spec Publ, 50(1): 399–416

Goff J C. 1983. Hydrocarbon generation and migration from Jurassic source rocks in the East Shetland Basin and Viking Graben of the Northern North Sea. J Geol Soc, 140(3): 445–474

Gormly J R, Buck S P, Chung H M. 1994. Oil-source rock correlation in the North Viking Graben. Org Geochem, 22(3–5): 403–413

Guo J Y, Zhang D L, Deng H W, et al. 2006. Resource assessment methodology of oil and gas in the areas of low-degree prospecting. Petrol Geol Recov Effic, 13(6): 43–45 (in Chinese)

Hald N. 1996. Early Tertiary lavas and sills on Traill Ø and Geographical Society Ø, northern East Greenland: petrography and geochemistry. Greenl Geol Surv Bull, 171: 29–43

Hu S Y, Tian K Q, Liu G D, et al. 2005. Dissection of calibrated units and key parameters for oil and gas resource assessment. Acta Petrol Sin, 26(S): 49–54 (in Chinese)

Isaksen G H, Ledje K H I. 2001. Source rock quality and hydrocarbon migration pathways within the greater Utsira high area, Viking Graben, Norwegian North Sea. AAPG Bull, 85(5): 861–883

Jolley D W, Whitham A G. 2004. A stratigraphical and palaeoenvironmental analysis of the sub-basaltic Palaeogene sediments of East Greenland. Petrol Geosci, 10(1): 53–60

Jonk R, Parnell J, Whitham A. 2005. Fluid inclusion evidence for a Cretaceous-Palaeogene petroleum system, Kangerlussuaq Basin, East Greenland. Mar Petrol Geol, 22(3): 319–330

Karlsen D A, Leythaeuser D, Schaefer R G. 1988. Light hydrocarbon redistribution in a shallow core from the Ravnefjeld formation on the Wegener Halvø, East Greenland. Org Geochem, 13(1–3): 393–398

Keym M, Dieckmann V, Horsfield B, et al. 2006. Source rock heterogeneity of the Upper Jurassic Draupne Formation, North Viking Graben, and its relevance to petroleum generation studies. Org Geochem, 37(2): 220–243

Krabbe H. 1996. Biomarker distribution in the lacustrine shales of the Upper Triassic-Lower Jurassic Kap Stewart Formation, Jameson Land, Greenland. Mar Petrol Geol, 13(7): 741–754

Kubala M, Bastow M, Thompson S, et al. 2003. Geothermal regime, petroleum generation and migration// Evans D, Graham C, Armour A, et al. The millennium atlas: petroleum geology of the central and northern North Sea. London:

Geological Society, 289–315

Larsen L M, Pedersen A K, Tegner C, et al. 2014. Eocene to Miocene igneous activity in NE Greenland: northward younging of magmatism along the East Greenland margin. J Geol Soc, 171(4): 539–553

Larsen P H, Olsen H, Clack J A. 2008. The Devonian basin in East Greenland—review of basin evolution and vertebrate assemblages// Higgins A K, Gilotti J A, Smith M P. The Greenland Caledonides: evolution of the northeast Margin of Laurentia. Boulder, Colo.: Geological Society of America, 273–292

Leeder M R, Hardman M. 1990. Carboniferous geology of the Southern North Sea Basin and controls on hydrocarbon prospectivity. Geol Soc London Spec Publ, 55(1): 87–105

Li G Y, Jin Z J. 2005. World atlas of oil and Gas Basins. Beijing: Petroleum Industry Press (in Chinese)

Li H W, Tong X G. 2010. Exploration potential analysis of oil and gas resource s in Arctic Regions. Overs Explor, 15(3): 73–82 (in Chinese)

Liu C L, Che C B, Yang H L, et al. 2012. Methods and application of conventional and unconventional oil and gas resources assessment. Beijing: Geological Publishing House (in Chinese)

Liu G D, Yu S, Sun M L. 2012. Methods and parameter systems for analog assessment of petroleum resources in marine carbonate strata: a case study of the Ordovician in Tarim Basin, China. Acta Petrol Sin, 33(S2): 125–134 (in Chinese)

Liu Z, He D F, Tong X G, et al. 2011. Formation and distribution of giant oil and gas fields in North Sea Basin. China Petrol Explor, 16(3): 31–43 (in Chinese)

Liu Z, He D F, Wen Z X, et al. 2012. Control effect of evolution of North Sea Basin on formation of giant oil-gas fields. Xinjiang Petrol Geol, 33(3): 382–386 (in Chinese)

Mjelde R, Breivik A J, Raum T, et al. 2008. Magmatic and tectonic evolution of the North Atlantic. J Geol Soc, 165(1) 31–42

Nagtegal P J C. 1979. Relationship of facies and reservoir quality in Rotliegendes desert sandstones, Southern North Sea Region. J Petrol Geol, 2(2): 145–158

Nielsen J K, Shen Y N, Nielsen J K, et al. 2008. Late Permian oxygen-deficiency in the East Greenland Basin: implications for the potential source rock formation in Northern Europe and Arctic regions//Proceedings of the 33rd international geological congress 2008. Oslo, Norway: Norwegian Academy of Science and Letters

Nøhr-Hansen H, Nielsen L H, Sheldon E, et al. 2011. Palaeogene deposits in North-East Greenland. Geol Surv Den Greenl Bull, 23: 61–64

Nøttvedt A, Johannessen E P, Surlyk F. 2008. The Mesozoic of western Scandinavia and East Greenland. Episodes, 31(1): 59–65

Olsen H, Larsen P H. 1993. Lithostratigraphy of the continental Devonian sediments in North-East Greenland. Greenland Geol Surv Bull, 165: 1–108

Parsons A J, Whitham A G, Kelly S R A, et al. 2017. Structural evolution and basin architecture of the Traill Ø region, NE Greenland: a record of polyphase rifting of the East Greenland continental margin. Geosphere, 13(3): 733–770

Peace A, McCaffrey K, Imber J, et al. 2017. The role of pre-existing structures during rifting, continental breakup and transform system development, offshore West Greenland. Basin Res, doi: 10.1111/bre.12257

Peace A, McCaffrey K, Imber J, et al. 2016. An evaluation of Mesozoic rift-related magmatism on the margins of the Labrador Sea: Implications for rifting and passive margin asymmetry. Geosphere, 12(6): 1701–1724

Pedersen A K, Watt M, Watt W S, et al. 1997. Structure and stratigraphy of the early Tertiary basalts of the Blosseville Kyst, East Greenland. J Geol Soc, 154(3): 565–570

Price S P, Whitham A G. 1997. Exhumed hydrocarbon traps in East Greenland: analogs for the Lower-Middle Jurassic play of northwest Europe. AAPG Bull, 81(2): 196–221

Ramm M, Ryseth A E. 1996. Reservoir quality and burial diagenesis in the Statfjord Formation, North Sea. Petrol Geosci, 2(4): 313–324

Requejo A G, Hollywood J, Halpern H I. 1989. Recognition and source correlation of migrated hydrocarbons in Upper Jurassic Hareelv Formation, Jameson Land, East Greenland. AAPG Bull, 73(9): 1065–1088

Schiffer C, Balling N, Jacobsen B H, et al. 2014. Seismological evidence for a fossil subduction zone in the East Greenland Caledonides. Geology, 42(4): 311–314

Schiffer C, Peace A, Phethean J, et al. 2017. The Jan Mayen microplate complex and the Wilson cycle. Geological Society, London, Special Publications, doi: 10.1144/SP470.2

Spencer A M, Embry A F, Gautier D L, et al. 2011. Arctic petroleum geology. London: Geological Society of London

Stemmerik L. 2000. Late Palaeozoic evolution of the North Atlantic margin of Pangea. Palaeogeogr Palaeoclimatol Palaeoecol, 161(1–2): 95–126

Stemmerik L, Bendix-Almgreen S E, Piasecki S. 2011. The Permian-Triassic boundary in central East Greenland: past and present views. Bull Geol Soc Den, 48: 159–167

Stemmerik L, Clausen O R, Korstgård J A, et al. 1997. Petroleum geological investigations in East Greenland: project 'Resources of the sedimentary basins of North and East Greenland'. Geol Greenl Surv Bull, 176: 29–38

Stemmerik L, Dam G, Noe-Nygaard N, et al. 1998. Sequence stratigraphy of source and reservoir rocks in the Upper Permian and Jurassic of Jameson Land, East Greenland. Geol Greenl Surv Bull, 180: 43–54

Stemmerik L, Vigran J O, Piasecki S. 1991. Dating of late Paleozoic rifting events in the North Atlantic: new biostratigraphic data from the uppermost Devonian and Carboniferous of East Greenland. Geology, 19(3): 218–221

Sun P, Zhao P F. 2012. Reservoir distribution and diagenesis in the northern North Sea Basin. Mar Geol Front, 28(2): 23–28 (in Chinese)

Surlyk F. 1990. Timing, style and sedimentary evolution of late Paleozoic–Mesozoic extensional basins of East Greenland// Hardman R P F, Brooks J. Tectonic events responsible for Britain's oil and gas reserves. Geological Society, London,

Special Publication, 55: 107–125

Surlyk F. 1977. Stratigraphy, tectonics and palaeogeography of the Jurassic sediments of the areas north of Kong Oscars Fjord, East Greenland. Bull Grønl Geol Unders, 123: 1–56

Surlyk F, Hurst J M, Piasecki S, et al. 1986. The Permian of the western margin of the Greenland Sea—a future exploration target// Halbouty M T. Future petroleum provinces of the world. Tulsa, Okla.: American Association of Petroleum Geologists Memoir, 629–659

Surlyk F, Noe-Nygaard N. 2001. Sand remobilisation and intrusion in the upper Jurassic Hareelv Formation of East Greenland. Bull Geol Soc Den, 48: 169–188

Therkelsen J, Surlyk F. 2004. The fluviatile Bristol Elv Formation, a new Middle Jurassic lithostratigraphic unit from Traill Ø, North-East Greenland // Stemmerik L, Stouge S. The Jurassic of North-East Greenland. Geol Surv Den Greenl Bull, 5: 19–30

Upton B G J, Emeleus C H, Hald N. 1980. Tertiary volcanism in northern E Greenland: Gauss Halvø and hold with hope. J Geol Soc, 137(4): 491–508

Vigran J O, Stemmerik L, Piasecki S. 1999. Stratigraphy and depositional evolution of the uppermost Devonian–Carboniferous (Tournaisian–Westphalian) non-marine deposits in North-East Greenland. Palynology, 23(1): 115–152

Vosgerau H, Alsen P, Carr I D, et al. 2004. Jurassic syn-rift sedimentation on a seawards-tilted fault block, Traill Ø, North-East Greenland// Stemmerik L, Stouge S. The Jurassic of North-East Greenland. Geol Surv Den Greenl Bull, 5: 9–18

Whitham A G, Price S P, Koraini A M, et al. 1999. Cretaceous (post-Valanginian) sedimentation and rift events in NE Greenland (71–77°N)// Fleet A, Boldy S. Petroleum geology of northwest Europe: proceedings of the 5th conference. London: The Geological Society, 5: 325–336

Wignall P B, Twitchett R J. 2002. Permian-Triassic sedimentology of Jameson Land, East Greenland: incised submarine channels in an anoxic basin. J Geol Soc, 159(6): 691–703

Wilkinson M, Haszeldine R S, Fallick A E. 2006. Jurassic and Cretaceous clays of the northern and central North Sea hydrocarbon reservoirs reviewed. Clay Miner, 41(1): 151–186

Yang J Y, Yang Y Q, Zhao Q F, et al. 2011. Oil and gas distribution pattern and petroleum geological condition of the North Sea Basin. Mar Geol Front, 27(12): 1–9 (in Chinese)

Yang Y Q, Yang J Y, Zhao Q F. 2014. Comparision and analysis of hydrocarbon accumulation conditions between the southern and northern the North Sea Basin. J East China Inst Technol, 37(1): 62–68 (in Chinese)

Ye D L, Yi D T. 2004. Petroleum geological characteristics and exploration practice in North Sea Basin. Beijing: Petroleum Industry Press (in Chinese)

Zabanbark A. 2012. Geological structure and petroleum resource potential of the North Sea Basin. Oceanology, 52(4): 513–525

Zhang F F, Yang J Y, Yang C S. 2011. Forming condition of large gas field in southern North Sea Basin. Mar Geol Front, 27(12): 27–33 (in Chinese)

Zhang L Y, Li Z, Kong Y X, et al. 2014. Study on evaluation method of petroleum resources in mature exploration area: taking Niuzhuang Sag of Bohaiwan Basin as an example. Nat Gas Geosci, 25(4): 477–489 (in Chinese)

Zhang S Y, Gong J M, Li S L, et al. 2012. Characteristics of hydrocarbon accumulation in North Sea Basin. Mar Geol Front, 28(1): 38–43 (in Chinese)

Zhao W Z, Hu S Y, Shen C X, et al. 2005. New advancements of oil and gas resource assessment methods. Acta Petrol Sin, 26(S): 25–29 (in Chinese)

Zhao Z, Liang Y B, Hu J J, et al. 2014. Arctic oil and natural gas potential and exploration and development trend. Earth Sci Front, 21(3): 47–55

Zhou Z Y, Bai S S, He H. 2005. Comparison of genetic and statistical methods for petroleum resource assessment. Petrol Geol Exp, 27(1): 67–73 (in Chinese)

Ziegler P A. 1982. Geological atlas of western and central Europe. The Hague: Shell Internationale Petroleum Maatschappij B V, 230