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Upper Paleozoic Carbonate Buildups of the Timan-Pechora Basin, the Sverdrup Basin and the Barents Sea as Potential Reservoirs of the Arctic

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ABSTRACT

The main objective of this work was to study the three Arctic Provinces: the Timan-Pechora Basin, the Sverdrup Basin and the Barents Sea, and make a comparison between them with a focus on the Paleozoic sediments and their potential as reservoirs based on published literature. The Upper Paleozoic carbonate reefal structures of the Timan-Pechora Basin have been proven as good reservoirs for hydrocarbon accumulation, while similar carbonate buildups of the Sverdrup Basin and the Barents Sea are still considered to be prospective. All the three provinces were at similar latitudes in Late Paleozoic time; and they included similar paleoenvironment with similar biota that were the main constructors of the carbonate buildups. However, considering the reservoir potential, another important process must be taken into account – diagenesis. Paleozoic carbonate buildups in the selected provinces experienced prolonged or repeated periods of subaerial exposure that resulted in leaching, karstification and dolomitization, which are processes that enhance the porosity. It can be concluded that the Paleozoic carbonate reefal structures are important targets for future petroleum exploration in the Arctic.

1. INTRODUCTION

Most of the evident petroleum systems and plays have already been discovered and are being produced, however, the demand of the humankind for natural resources is only increasing, and thus, new prospects must be explored and studied for the future generations. One of such prospects could be Upper Paleozoic reef buildups in Arctic Basins. Upper Paleozoic reef carbonates form very prospective reservoirs within the Sverdrup Basin, the Barents Sea and have already been proven in the Timan-Pechora Basin. Therefore, a bibliographic research of the relevant publications has been made in order to give an overview and comparison of selected petroleum provinces in the Arctic, with emphasis on the Paleozoic carbonate reservoir geology.

The work starts with an introduction that gives a general overview about the history of exploration, geological history, stratigraphy and petroleum geology of the region. This is followed by a chapter devoted to carbonate sediments, the most important biotic elements that are the main constructors of the Upper Paleozoic buildups in the Arctic region. The subsequent chapters are devoted to the three Arctic provinces, where their geological settings, Paleozoic reef structures and reservoir quality are reviewed. As a result of this work the Timan-Pechora Basin, the Sverdrup Basin and the Barents Sea are compared, the Upper Paleozoic reefal carbonates and their reservoir potential are commented on. It has been concluded that the Upper Paleozoic buildups of these Arctic provinces have been constructed by similar biota at the similar depositional environments; however, the subsequent burial processes in the Sverdrup Basin and the Barents Sea affected the reservoir quality of these buildups. Thus, many of the buildups have experienced diagenetic processes like cementation, subaerial exposure and dolomitization. Nevertheless, there are thousands of reef buildups that show good reservoir quality and may be prospective for containing hydrocarbons.

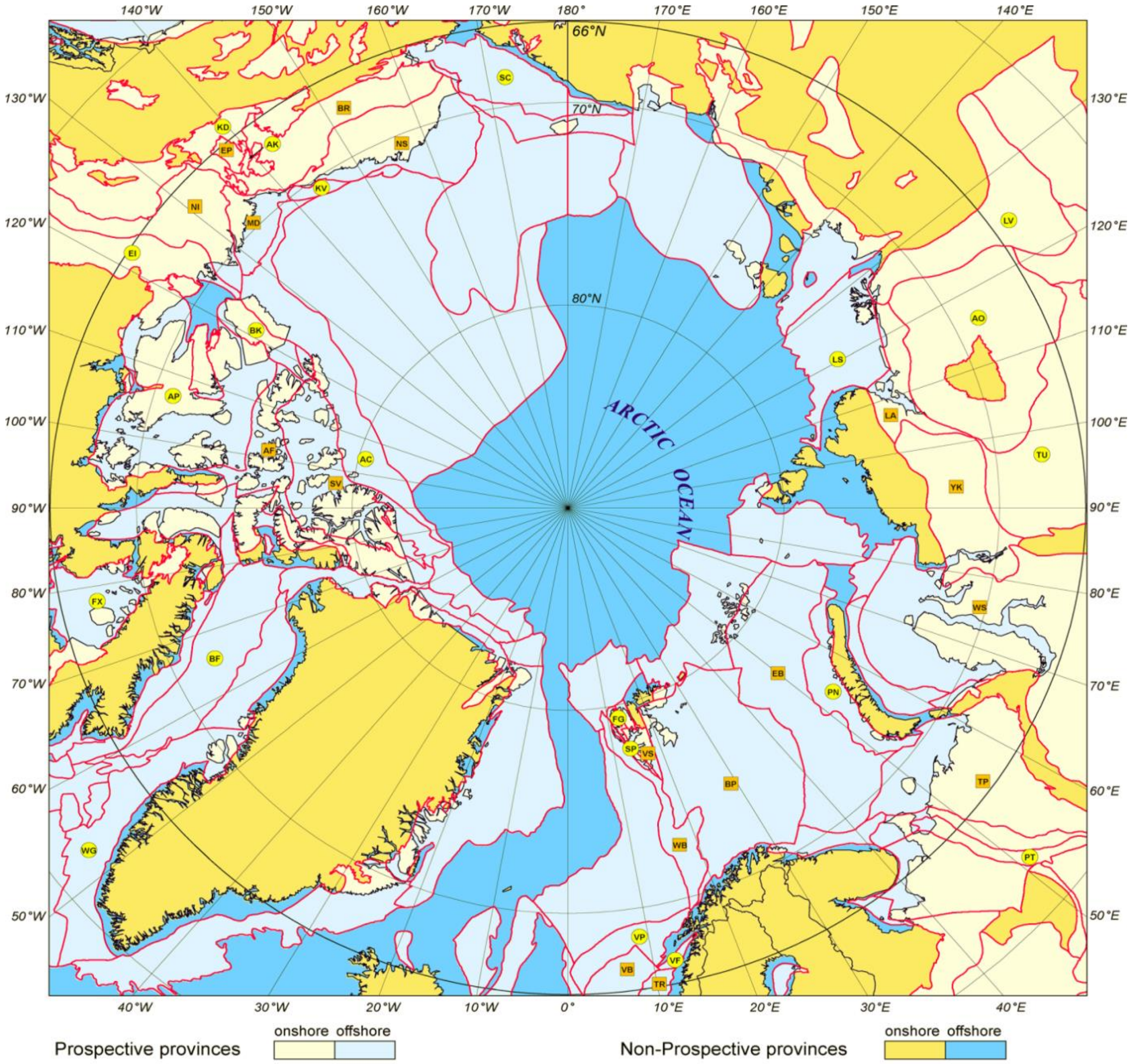
1.1 History of petroleum exploration of Arctic

Petroleum exploration of the basins north of the Arctic Circle (66^0N) began in the mid-1930s, reaching a peak in the 1970s and 1980s. Thirty eight geological provinces that are considered to be prospective for the presence of hydrocarbons have been investigated by drilling (Fig.1). More than two thousand new-field wildcat wells have been drilled in the Arctic, resulting in some 450 hydrocarbon discoveries (Chew & Arbouille, 2011).

Canada led the way in the onshore and offshore discovery in the Arctic during the 1960s (Fig.2). The first well was drilled in 1961 on the Melville Island, and in 1969 the first Arctic Island discovery (Drake Point) was made in the Sverdrup Basin on the Sabine Peninsula of the same island. The same year, the exploration of the Mackenzie Delta began, resulting in another discovery (Atkinson). In 1972, the world's northernmost discovery has been made on the Ellesmere Island at 71^0 51' N (Romulus). Exploration offshore in the Beaufort Sea commenced in 1973 with the first discoveries being made in 1976.

As for the Russian Arctic exploration, the first onshore drilling activity took place in the Nordvik Bay, Eastern Siberia during the 1930s. It resulted in discovery of some small oil/gas discoveries during 1940s, which were abandoned and have never been developed. The first offshore activity in the Russian Arctic commenced in 1982 on the shelf of the Timan-Pechora Basin and was extended into the Kara Sea by 1987, resulting in the discovery of the Rusanovskoye gas discovery. The same year was marked by the discovery of the super-giant Shtokmanovskoye field in the East Barents Sea Basin.

The history of Norwegian Arctic exploration started onshore Svalbard (Spitsbergen) in the Vestspitbergen Trough in 1977, resulting in minor shows of oil and gas. However, in 1980 the first offshore well was drilled in the Norwegian Barents Sea and in 1981 the first offshore discovery has been made (Askeladd). Since that time Norway has been dominating in the offshore Arctic exploration.



<u>PROVINCES WHICH HAVE BEEN EXPLORED BY DRILLING</u>

AK - Aklavik Arch
AO - Anabar-Olenek Basin
AC - Arctic Coastal Plain
AF - Arctic Fold Belt
AP - Arctic Stable Platform
BF - Baffin Basin
BK - Banks Basin
BP - Barents Sea Platform
BR - Brooks Range Province
EP - Eagle Plain Basin
EB - East Barents Sea Basin
EI - Eastern Interior Platform
FG - Forlandsundet Graben
FX - Foxe Basin
KV - Kaktovik Basin
KD - Kandik Basin
LS - Laptev Sea Basin
LA - Lena-Anabar Basin
LV - Lena-Vilyuy Basin
MD - Mackenzie Delta
NS - North Slope Basin
NI - Northern Interior Platform
PN - Pre-Novaya Zemlya Foredeep
PT - Pre-Timan Trough
SC - South Chukchi-Hope Basin
SP - Svalbard Paleozoic Platform
SV - Sverdrup Basin
TP - Timan-Pechora Basin
TR - Trondelag Platform
TU - Tunguska Basin
VF - Vestfjord Basin
VS - Vestspitsbergen Trough
VB - Voring Basin
VP - Voring Plateau
WB - West Barents Shelf Edge
WG - West Greenland Basin
WS - Western Siberia Basin (N of 66°)
YK - Yenisey-Khatanga Basin

Fig. 1 Prospective provinces of the Arctic Region (Chew & Arbouille, 2011)

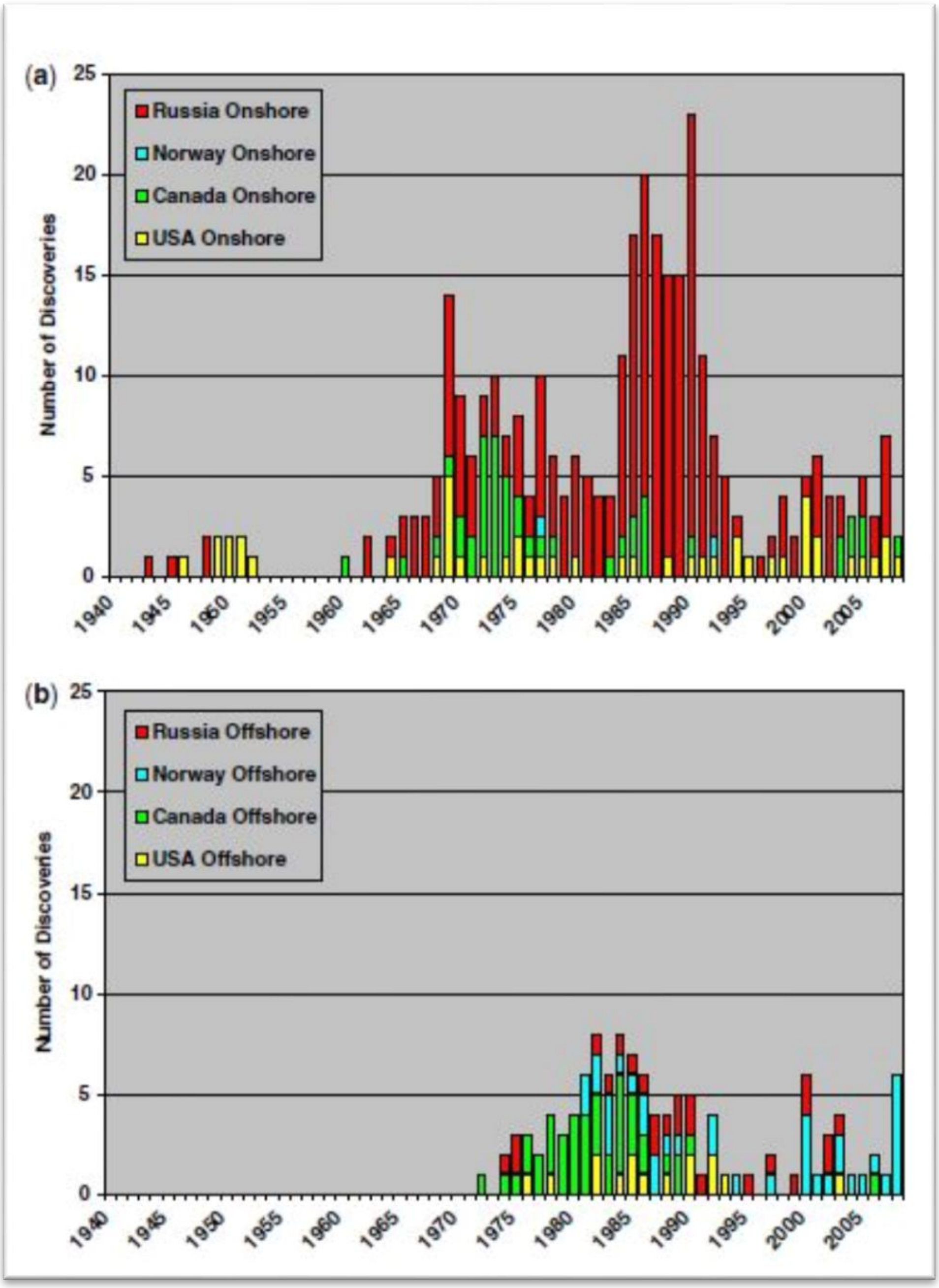


Fig. 2 (a) annual number of onshore hydrocarbon discoveries north of 66^{0}N. (b) annual number of offshore hydrocarbon discoveries north of 66^{0}N. (Chew & Arbouille, 2011)

By the end of 2000s more than 400 oil and gas discoveries have been found north of the Arctic Circle. From these fields:

- Eleven super-giant fields with estimated recoverable resources in excess of 5 billion barrels of oil equivalent (boe). Zapolyarnoe, a predominantly gas-condensate super-giant field, was discovered in 1965 in the Western Siberia. The only super-giant fields that have been discovered outside Western Siberia are Shtokmanovskoye (East Barents Sea Basin) and the Prudhoe Bay Field on Alaska's North Slope (the only super-giant oil field).

- Fifty four giant fields (500 million - 5 billion boe) have been discovered. The first giants were Usinskoye (Timan-Pechora basin) and Tavovskoye (Western Siberia basin) found in 1962. Considering giant fields, forty three have been discovered in Russia, seven in the USA, and Canada and Norway account for two each.

Hydrocarbon accumulations discovered in the Arctic region have been generated from nearly 40 different petroleum systems. However, this work mainly focuses on three of them: Timan-Pechora Sea in Russia, the Sverdrup Basin in Canada and the Barents Sea in Norway and Russia.

1.2 Geological history of the Arctic during Paleozoic

The Paleozoic plate reconstructions provide a framework to understand the changes in climate and paleoenvironment. These reconstructions are based on paleomagnetic pole values for the blocks linked to known geological events, especially the three main Arctic orogenies: the Scandian-Caledonian in the Silurian, the Ellesmerian in the Late Devonian and the Uralian in the Late Pennsylvanian. The paleoreconstruction of the Plates first of all use the Pisarevsky (2005) paleomagnetic database to confine relative Paleozoic reconstructions. The reconstruction below is summarized from Lawver et al. (2011).

1.2.1 Cambrian (541-485 Ma)

During the Paleozoic, Laurentia, Baltica and Siberia were major plates. By the beginning of Cambrian time, Laurentia and Siberia were located near the equator, with just a relatively narrow sea dividing these paleo continents (Fig.3). Thus, Siberian and northern Laurentian faunas from this period should have been very similar. The location of Baltica was far to the south, but the paleo-environment there was almost the same as in Laurentia and Siberia (Lawver et al., 2011).

After the relatively close position of these “future Arctic continents” at the beginning of the Cambrian, they began to drift apart (Fig.4), and by the end of the Cambrian, a vast Iapetus Ocean was formed between Laurentia and Baltica. As Gondwana consolidated as a supercontinent in the Southern hemisphere in the Early Paleozoic (Fig.4), Laurentia drifted just a few degrees northward from its earliest Paleozoic position.

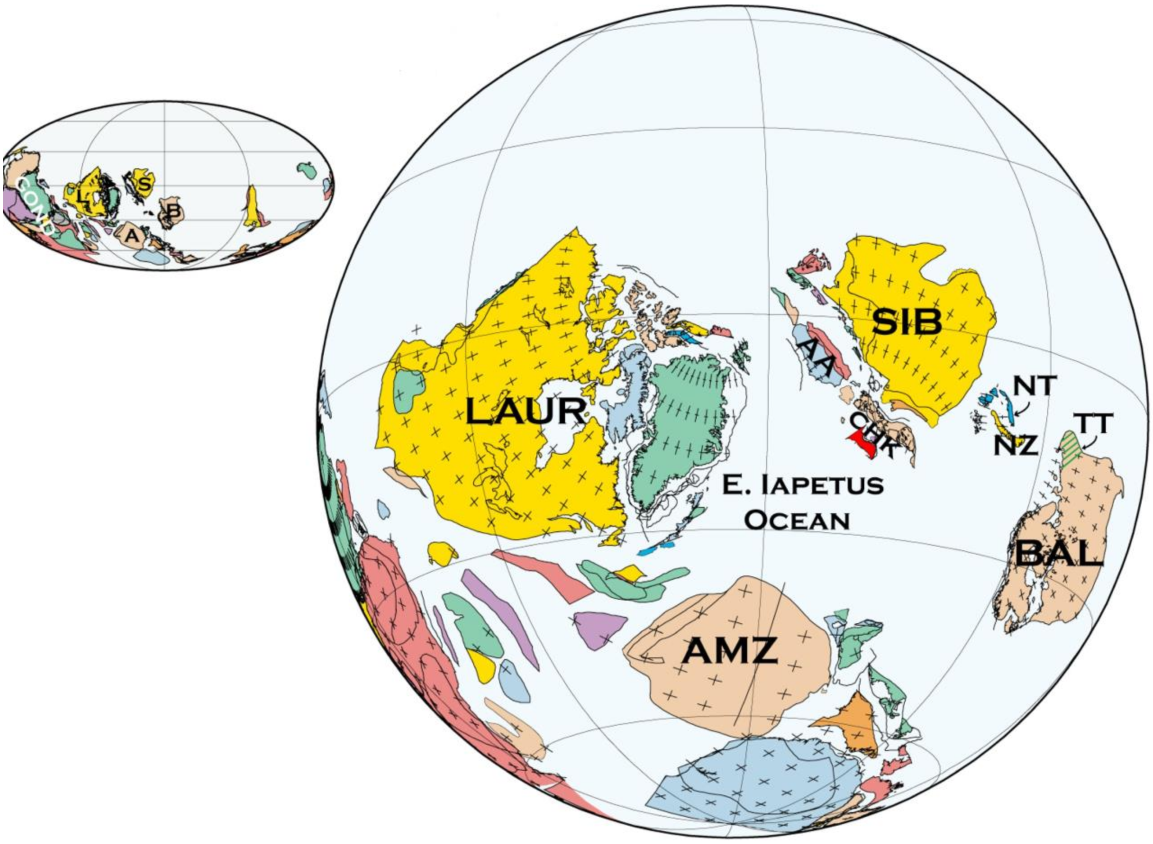


Fig. 3 Paleoreconstruction for the beginning of Paleozoic. AA, Arctic Alaska; BAL, Baltica; CHK, Chukotka; LAUR, Laurentia; NT, Northern Taimyr Block; NZ, Novaya Zemlya; SIB, Siberia; TT, Timan Terrane (Lawver et al., 2011).

1.2.2 Ordovician (485-444 Ma), Silurian (444-419 Ma)

The Eastern Iapetus Ocean was almost at its largest extent when Siberia was at its southernmost position in the Paleozoic at the beginning of the Ordovician. As for Baltica, it had rotated about 90^0 clockwise from its initial Early Paleozoic position and had changed its direction of drifting from south towards north. At the end of the Ordovician – start of the Silurian, the Iapetus Ocean started to close by movement of Baltica towards Laurentia. The collision of these two continents along the Greenland and Scandinavia margins resulted in the Caledonian Orogeny and the formation of a new continent – Laurussia (Fig.5). By the end of the Silurian, the Caledonian Orogeny was finished. As a result, Baltica was sewed with Laurentia and Pearya united with northern Ellesmere Island (Fig.5).

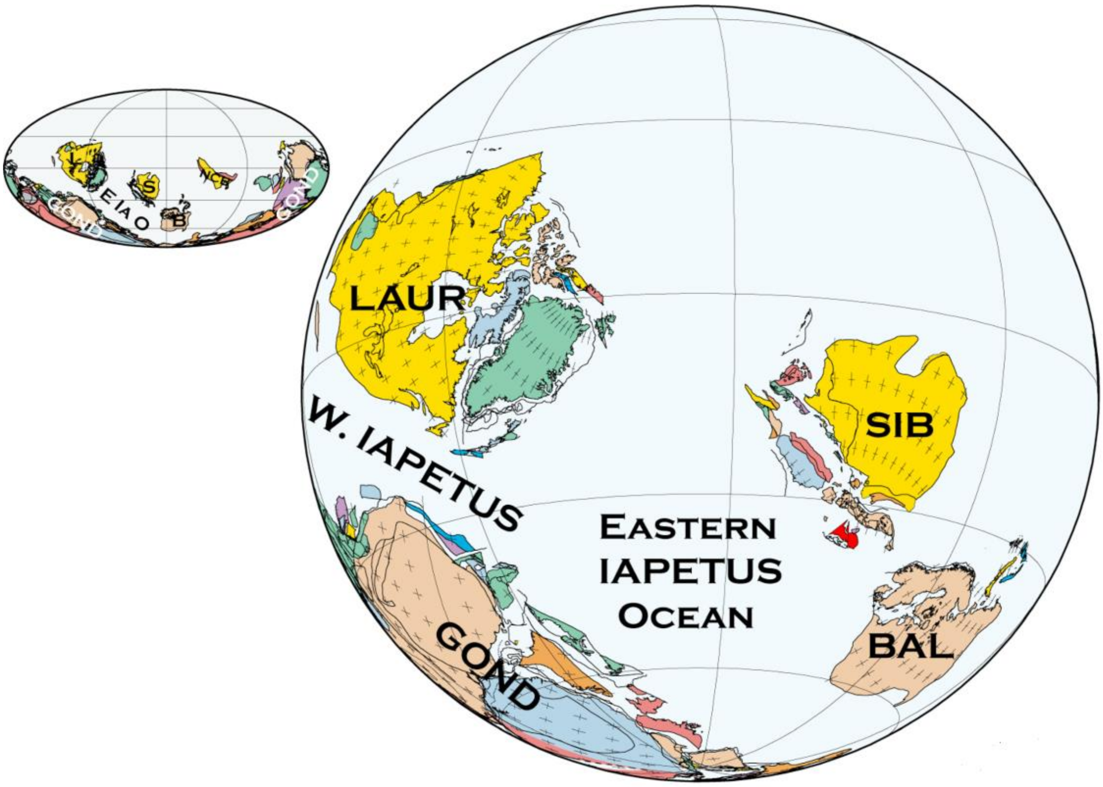


Fig. 4 Paleoreconstruction for Early Ordovician. BAL, Baltica; GOND, Gondwana; LAUR, Laurentia; SIB, Siberia (Lawver et al., 2011).

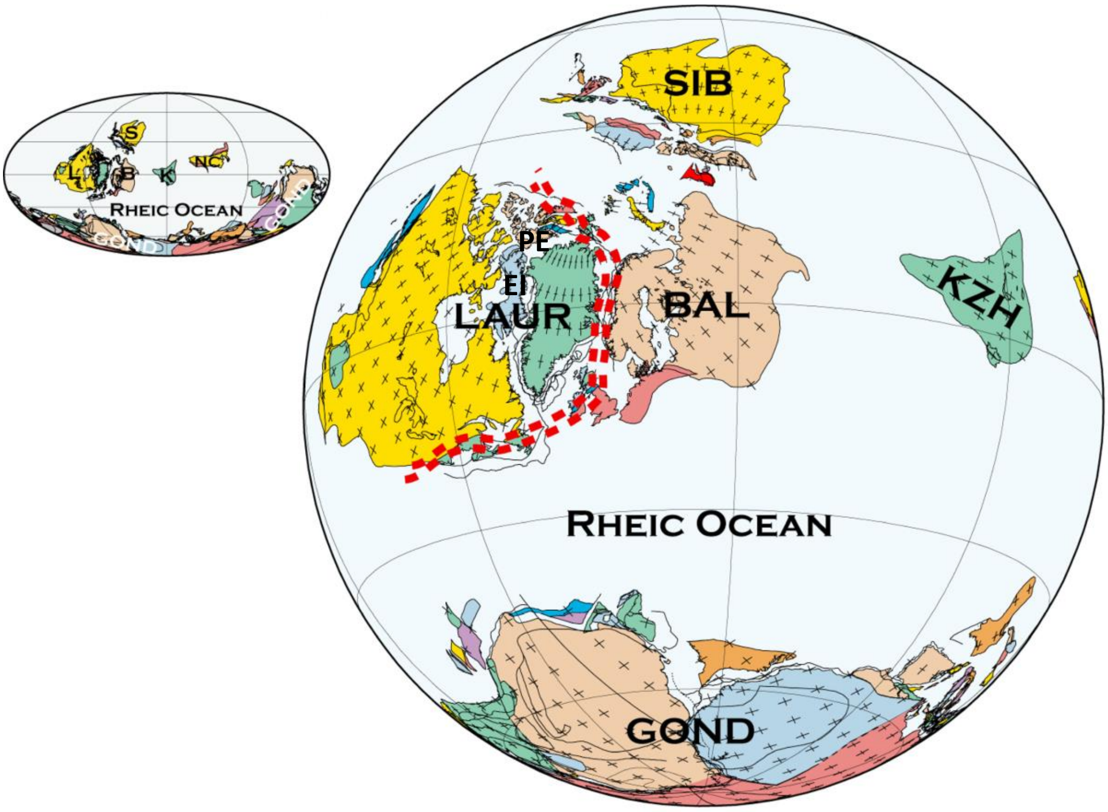


Fig. 5 Paleoreconstruction for Early Silurian. The double-dashed line show the Caledonian Orogen. BAL, Baltica; EI, Ellesmere Island; GOND, Gondwana; KZH, Kazakhstan Block; LAUR, former Laurentia; PE, Pearya; SIB, Siberia (Lawver et al., 2011).

1.2.3 Devonian (419-359 Ma)

Laurussia started southward movement, reaching its southernmost position at 406 Ma with the future east coast of North America at almost 50^0S (Fig.6). Subsequently, Laurussia changed its motion from the south direction to the north, while Siberia, with Alaska and Chukotka attached, was drifting southward at this time. Most likely, it has been driven by subduction beneath the Arctic terranes that lay along the southern margin of Siberia. The Ellesmerian Orogeny (Late Devonian to Carboniferous) most probably was a result of either collision of Siberia (SIB), with the northern margin of Laurussia or flat plate subduction along that margin (Lawver et al., 2011).

At around Middle Devonian, Laurussia and Siberia started their northward drifting. As a result, at this time, all of the future Arctic continents were partially in the northern hemisphere (Fig. 7). According to Embry (1991), one of the crucial tectonic events in the Canadian Arctic Islands took place in the Middle Devonian when the foreland basin started to subside. A widespread unconformity at the Middle to Late Devonian boundary can be explained by another important tectonic event – the rapid subsidence in the foreland and the change of the composition of molasse from mainly quartz sediments to more rock fragments and chert. The final Ellesmerian Orogeny caused a widespread unconformity in the late Frasnian, and produced folding and uplift in the Canadian Arctic Islands near the Devonian to Mississippian boundary (Lawver et al., 2011).

1.2.4 Carboniferous (359-299 Ma)

During the Early Carboniferous, Laurussia and Siberia as well as Gondwana started their relatively rapid drift to the east (Fig.8). Siberia moved slightly faster to the east, as a result, it collided with Baltica between the present day northern and central Taimyr blocks in Late Carboniferous – Early Permian (Vernikovsky, 1997).

By the end of Carboniferous the Gondwana, Laurussia, Siberia and Kazakhstan paleocontinents collided, resulting in the closure of Rheic Ocean, formation of Tethys Ocean and unification of Pangea (Fig. 9).

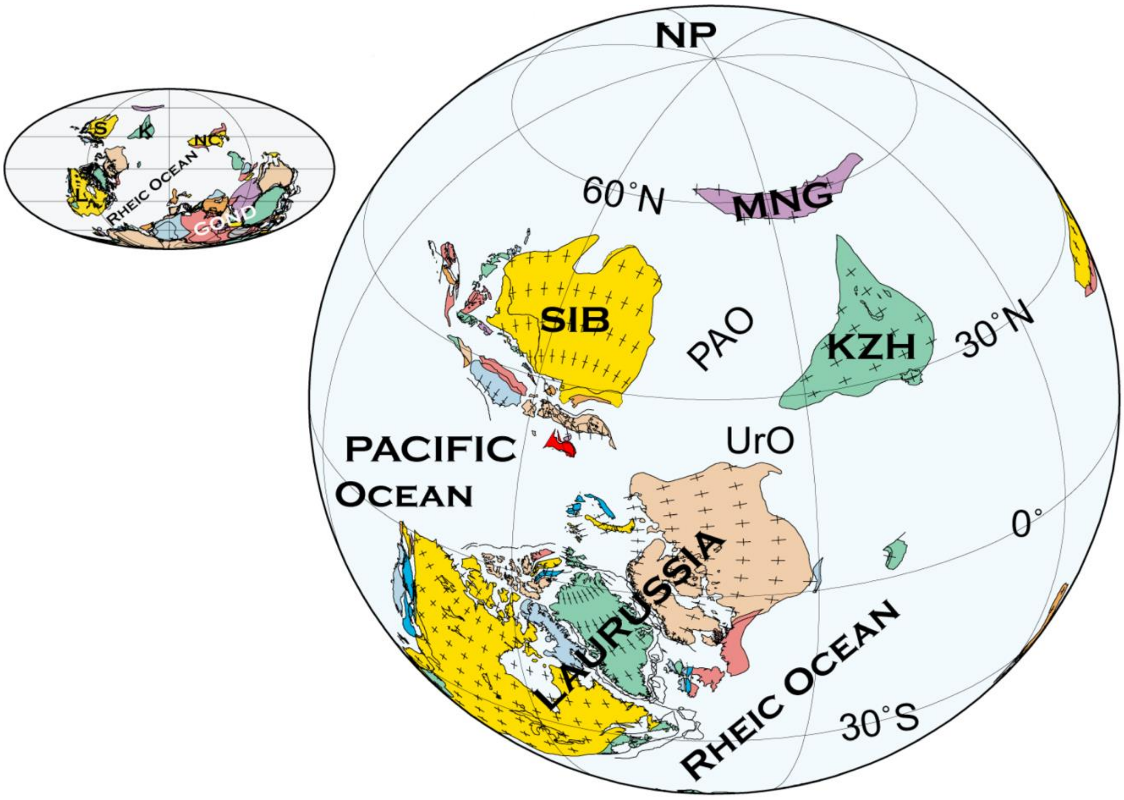


Fig. 6 Paleoreconstruction for Early Devonian. KZH, Kazakhstan; MNG, Mongolia; NP, North Pole; PAO, PaleoAsian Ocean; SIB, Siberia; UrO, Uralian Ocean (Lawver et al., 2011).

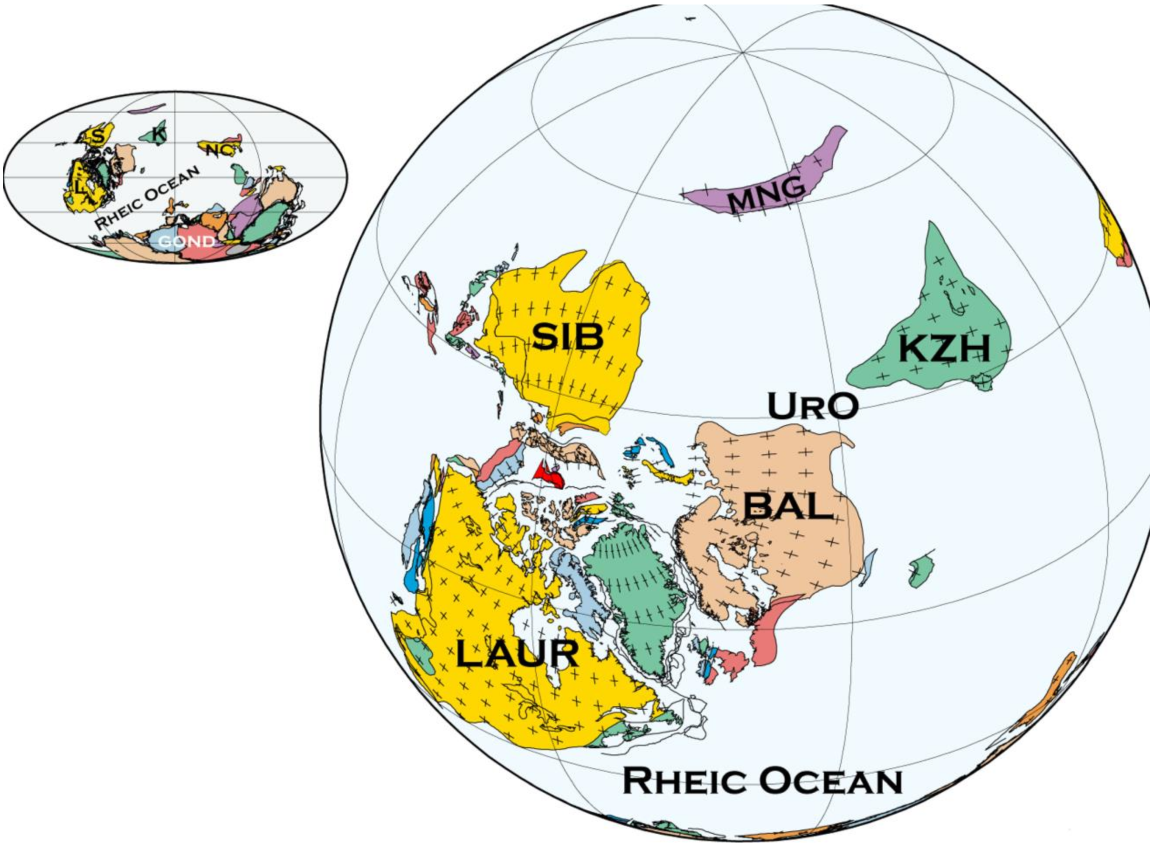


Fig. 7 Paleoreconstruction for Middle Devonian. BAL, Baltica subset of Laurussia; KZH, Kazakhstan; LAUR, Laurentia subset of Laurussia; MNG, Mongolia; SIB, Siberia; UrO, Uralian Ocean (Lawver et al., 2011).

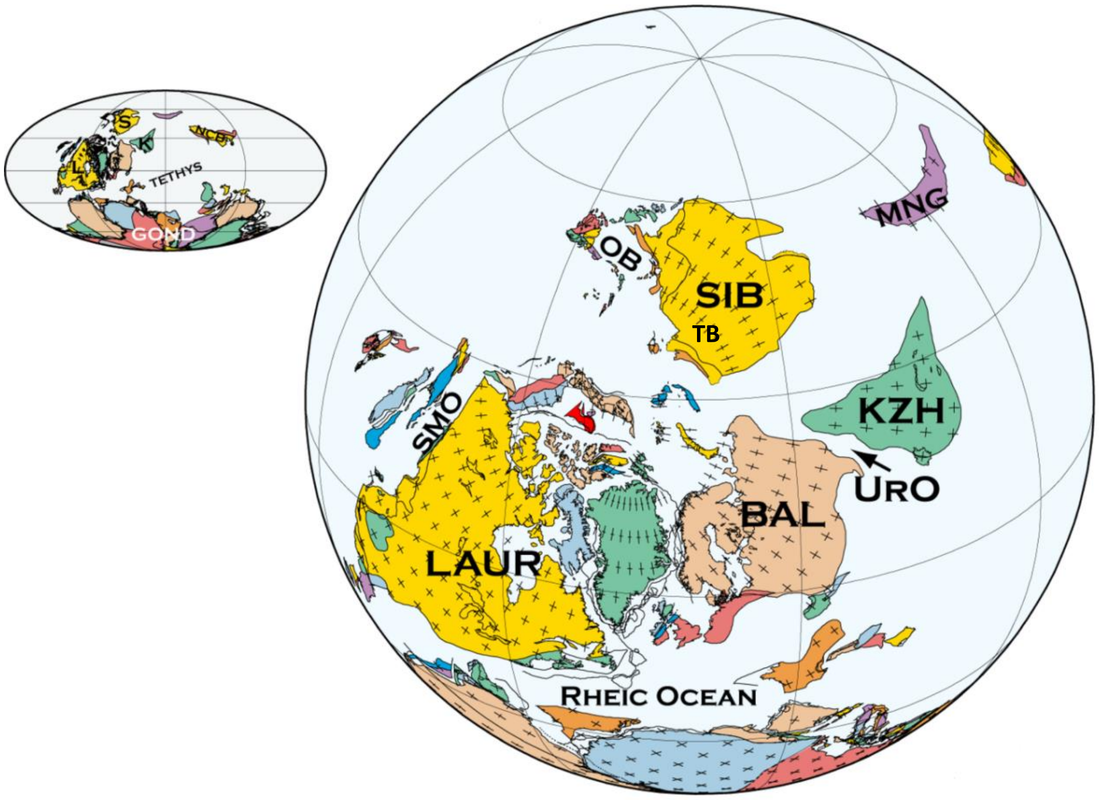


Fig. 8 Paleoreconstruction for Early Carboniferous. BAL, Baltica subset of Laurussia; SMO, Slide Mountain Ocean; KZH, Kazakhstan; LAUR, Laurentia subset of Laurussia; MNG, Mongolia; OM, Oimyalon Basin; SIB, Siberia; TB, Taimyr blocks; UrO, Uralian Ocean (Lawver et al., 2011).

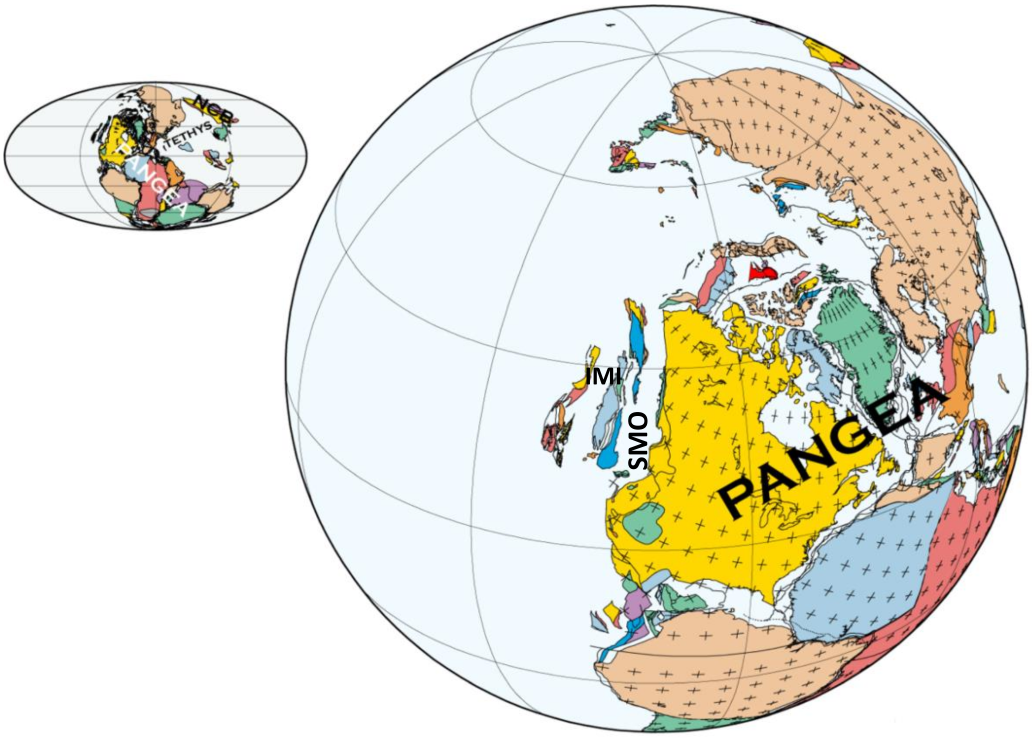


Fig. 9 Paleoreconstruction for the end of Paleozoic. IMI, Intermontane Islands; SMO, Slide Mountain Ocean (Lawver et al., 2011).

1.2.5 Permian (299 – 250 Ma)

By the beginning of the Permian, most of the future continental margins of the Arctic Ocean were located above 30^0N. The subsequent northward drift during the Permian brought the Arctic continents to roughly 40– 45^0N, with the eastern end of Eurasia being almost at the North Pole. Tectonic activity was quite low; one of the major tectonic events was the beginning of the closure of the Slide Mountain Ocean, an ancient ocean that existed between the Intermontane Islands and Laurussia until Triassic. Thus, by 251 Ma Pangea was assembled (Fig.9).

1.3 The Structural setting of the Arctic

The following four main elements can describe the structure of the Arctic : The 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 neo Proterozoic and Lower Paleozoic platform cover and their sutured margins (Fig. 10) (Spencer. et al., 2011).

The Arctic geology has been influenced by the establishment of the Pangea supercontinent through Caledonian – Hercynian – Uralian orogenies, and the following rifting and seafloor spreading in the Arctic and Atlantic which started at around 200 Ma (Fig.10). Another important influence is the continuous tectonic activity, dating back to the late Paleozoic, at the boundaries with the northern Pacific Rim, which have caused accretion to present day northeastern Siberia and northwestern North America of a multitude of terranes of interbedded sedimentary and magmatic rocks. Despite that accretion is primarily a destructive process in petroleum geology; these processes are mainly constructive for the formation of hydrocarbon deposits. A main structural feature of the Arctic is the boundary between the North Pacific accretionary collage (NPAC) and the rifted parts of the North American and Eurasian plates (Spencer et al., 2011).

The Laurentian, Baltic and Siberian shields were sutured during the Caledonian orogeny, and were later influenced by the Ellesmerian and Uralian orogenies in Paleozoic time, and these three shields form the cratonic cores of the present Arctic continents. The basins, which border these continental cores, are prospective for hydrocarbons.

In the NPAC region (North Pacific Rim at Fig. 10), some orogenic belts have been formed due to the compressional tectonics: the Brooks Ranges in Alaska and the Verkhoyansk Fold Belt in northern east Siberia formed because of the accretion of Chukotka and the Kolyma –Omolon superterrane in Jurassic–Early Cretaceous time. Some young sedimentary basins are present in the NPAC region, however they are considered to be comparatively unprospective (Haimila et al. 1990). Some uncertainty exist about the position of the boundary of the NPAC region between the Laptev Sea and Wrangel Island, which makes it difficult to predict the petroleum potential of the East Siberian offshore areas.

The formation of the ocean-floor of the North Atlantic and the Eurasian part of the Arctic Ocean took place during the Cenozoic. In the Amerasian part of the Arctic, rifting which lead to ocean-floor spreading is thought to have happened during the early Jurassic, followed by ocean-floor spreading in the mid-Early Cretaceous (Spencer et al., 2011). Progradational sedimentary wedges border the oceanic basins; they overlay longeval 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 are in this zone–the Lena (A) and Mackenzie rivers (B) and in northern Baffin Bay(C) (Fig.10).

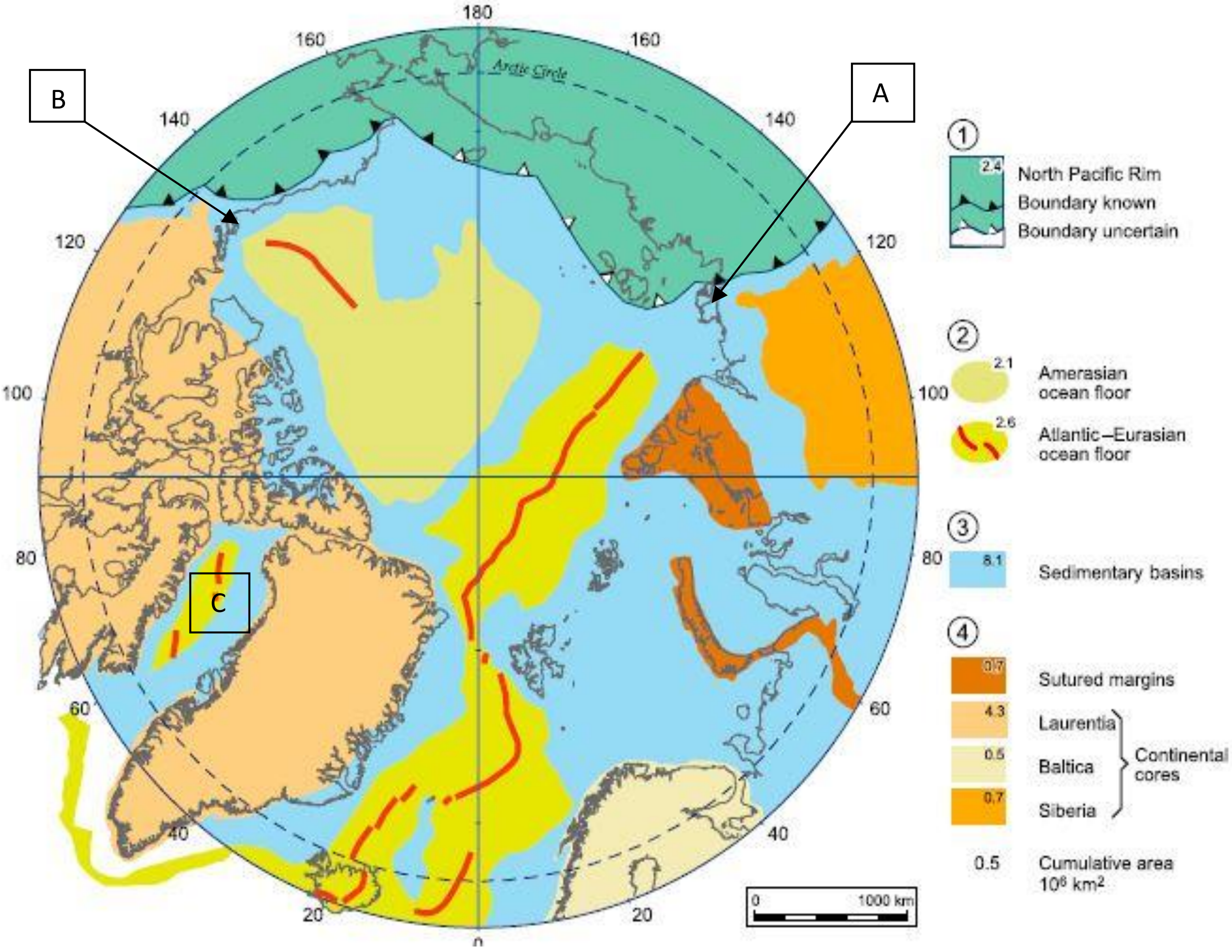


Fig. 10 The four-fold grouping of the tectonic provinces of the Arctic: continental cores, sedimentary basins, oceanic realms and the North Pacific rim. The numerical values in the legend boxes are the areas of the provinces in millions square kilometers (Spencer et al., 2011).

1.4 A stratigraphical overview of the Arctic

Simplified stratigraphic columns of the Upper Paleozoic-Paleogene successions of the Barents Sea, Timan-Pechora and Sverdrup basins, are shown on Figure 11. From these sedimentary columns, the first conclusion to be made is their actual similarity. The Upper Paleozoic sequences consist of interbedded carbonates and siliciclastics with random occurrences of evaporites and sandstones. However, the Paleozoic drift of Laurentia, Baltica and Siberia away from equatorial to high latitudes caused the transition from carbonate to clastic deposition. The interpretation of the passage through intermediate latitudes is supported by the presence of thick and widespread evaporites on the margins of both Laurentia and Baltica during the Carboniferous and Permian (Spencer et al., 2011). Thus, the Late Carboniferous – Early Permian deposition of warm-water carbonates was succeeded by more extensive siliciclastic sedimentation in both shallow- and deep-marine depositional environments during the Middle and Late Permian and Triassic. This effect was evident in the areas around the Uralian suture, which became a major source of siliciclastics to northern Siberia and Baltica (Spencer et al., 2011).

The Mesozoic and Cenozoic successions consist of interbedded siliciclastics and sandstones, which locally include intervals of coal-bearing strata.

An Early Triassic rift episode can be noticed in many parts of the Arctic and North-Atlantic regions and siliciclastic sediment supply in the Arctic was relatively high during this time. However, North Atlantic uplift and collapse at the end of the Early Triassic lead to significant reduction of siliciclastic sediment input. Thus, the Middle Triassic can be characterized by the widespread development of phosphatic, organic-rich shales from the Alaskan basins on the west to the Barents Sea area in the east (Leith et al. 1993). Nevertheless, in the Late Triassic the sedimentation rate of the siliciclastic increased in many areas, and the organic-rich facies became much more limited in geographic extent (mainly western Sverdrup and northern Alaska).

The siliciclastic infill to the extensional basins continued throughout the Jurassic. As a result, Jurassic strata in Arctic basins represent alternating sandstone-dominated and shale-siltstone sequences. Organic-rich facies were restricted to times and areas of low sediment input and occur mainly in Alaska, Siberia and the Barents Sea. Shale units of Toarcian, Bajocian, Oxfordian and Tithonian ages are present in all Arctic basins, because the major transgressions took place at that time. These units are often organic-rich petroleum source rocks for the upper reservoirs.

The siliciclastic sediment delivery to the Arctic basins even increased in the Cretaceous. Early Cretaceous sand-rich delta plain, delta front and shale-dominant prodelta and shelf deposits are widespread in most of the Amerasia basins.

Summarizing all the written above ,the main phase of carbonate sedimentation took place during the Late Paleozoic; siliciclastic deposition was established in the Arctic sedimentary basins at the Early Triassic and continued throughout the Mesozoic and Cenozoic, leading to the development of rich sources of hydrocarbons, as well as thick sandstone reservoirs to hold them.

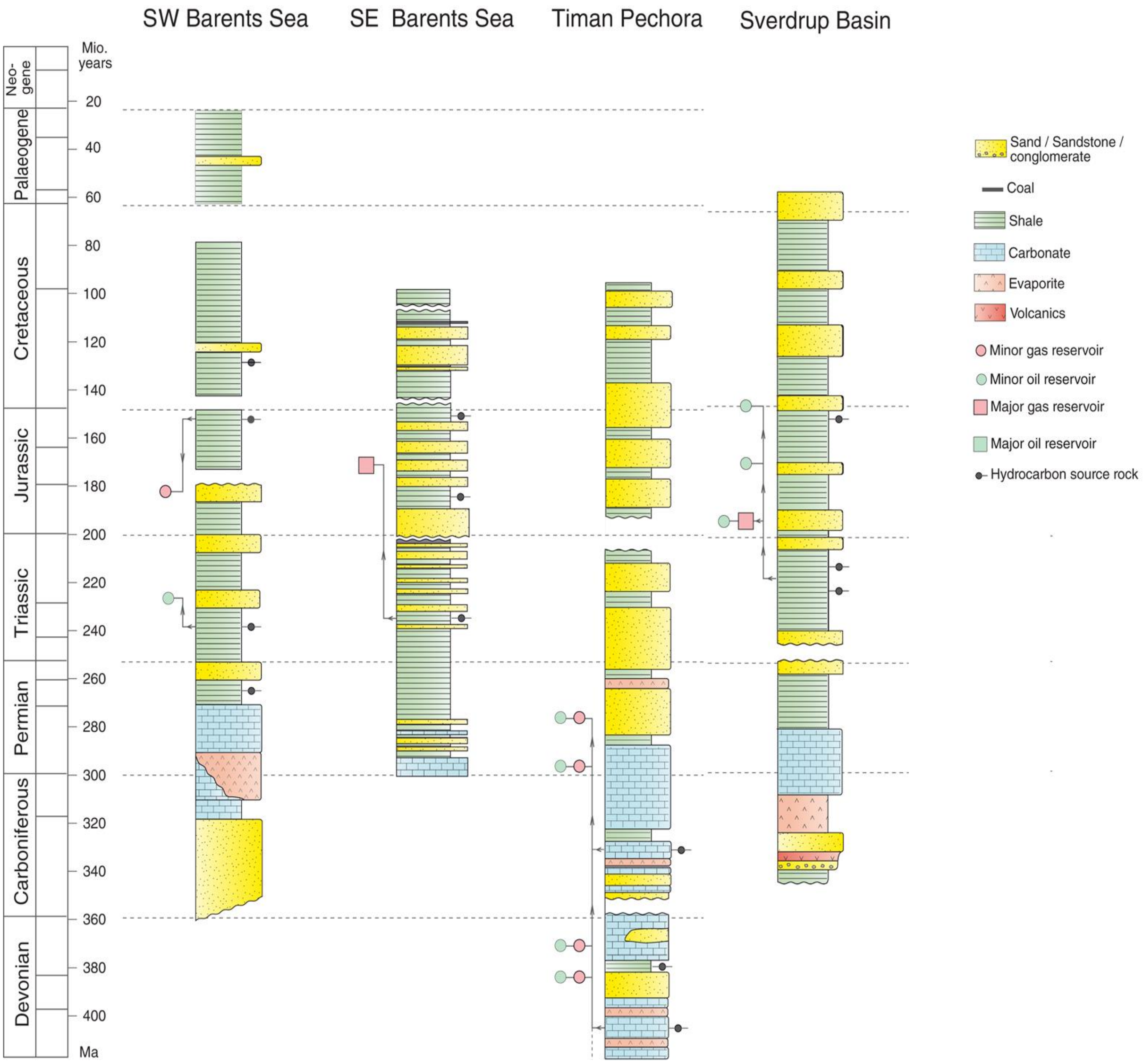


Fig. 11 Stratigraphy of the well-known basins of the Arctic, compiled from Spencer et al. (2011). The arrows on the left of some columns link source rocks to reservoirs to indicate proposed petroleum systems.

1.5 Petroleum geology

1.5.1 Source rocks

Most of the petroleum resources in the Arctic region, discovered and proven to date have been sourced from rocks of Devonian, Carboniferous, Permian Triassic and Jurassic age. However, an extensive diversity of potential source rocks from Proterozoic to Cenozoic is known. In Devonian time organic-rich, marine rocks were deposited on the margins of Baltica and Laurentia, where they sourced important oil-prone basins in Western Siberia and Western Canada. One of the best examples is, probably, the Timan–Pechora Basin, where oil is supposed to be sourced from the Late Devonian to Early Carboniferous Domanik marine formation (Spencer et al., 2011). The Sverdrup Basin contains organic-rich lacustrine shales of Late Carboniferous age, while black marine shales of Late Permian age have been found in some wells in the western Barents Sea.

1.5.2 Discovered petroleum systems

Nowadays, nine main petroleum provinces are dominated in the Arctic: the West Siberia –South Kara, Arctic Alaska, the East Barents Sea, Timan –Pechora, Yenisey –Khatanga, the Mackenzie Delta, Sverdrup Basin, the West Barents Sea and the Norwegian Sea (Fig.1). In total, these provinces contain 432 discoveries with recoverable resources of 61 billion barrels of liquids & 269 billion barrels oil equivalent of gas (Spencer et al., 2011). As the objectives of this work are restricted to the Timan-Pechora, Sverdrup and Barents Sea provinces, I will focus only on them.

The Timan-Pechora oil-field basin is the oldest petroleum system, in terms of the age of the sources and the timing of generation of hydrocarbons, with conventional fields in the Arctic. In more than one hundred and forty hydrocarbon finds around 16 billion barrels of oil equivalent (Bbbloe) resources are present. Silurian to Permian shallow marine carbonates as well as Devonian and Permian sandstones are the reservoirs in the provinces. The belts of gentle anticlinal structures, formed in the Permo-Triassic in response to the Uralian orogeny, are the main traps for hydrocarbon reservoir areas, of Ordovician to Permian age. The stacked hydrocarbon pools indicate kilometer-scale vertical migration, allowing the mixing of hydrocarbons from different sources.

In the Sverdrup Basin in the Canadian Arctic archipelago, around 3 Bbloe resources, mainly gas, occur in 20 discoveries located in the western part of the basin. The main reservoirs of the area are sandstone of Lower Triassic to Cretaceous age. The main traps for the hydrocarbons are anticlines with gently dipping limbs which have been formed in Eocene times. The main source rock is thought be of Middle to Upper Triassic age, however, a recent analysis by Dewing & Obermajer (2011) suggests they are not gas-mature in the area of the gas fields, implying a deeper source rock (Spencer et al., 2011).

Five discoveries in the East Barents Sea contain resources of 23 Bbbloe, almost all gas. The supergiant Shtokmanovskoye field (21 Bbbloe) is located in this province. The main reservoirs are the sandstones of Middle to Upper Jurassic, nevertheless gas is also found in Triassic reservoirs. The traps at Shtokmanovskoye field are gentle domes, where an extensive gas column is trapped in the Middle Jurassic reservoir, of about fifty meters thickness. The field is located in the center of the basin, where the thickness of sedimentary rocks is approximately 15 km. The source rocks are supposed to be of Triassic age.

In the West Barents Sea the total amount of discovered resources is 2 Bbbloe, predominantly as gas in the Hammerfest Basin. Marine shales of Upper Jurassic and Middle Triassic are the probable source rocks. The largest gas field in the basin is the Snøhvit field, containing 0.7 Bbbloe. The reservoirs of the Snøhvit Field are the Lower –Middle Jurassic sandstones, however they have low porosities (12 –18%). This feature can be explained by the widespread uplift of the western part of the Barents Sea in Neogene time (Henriksen et al., 2011) resulting in the relatively low reservoir porosities at shallow depths. This event was also terminating petroleum generation from source rocks, and leading to a widespread re-distribution of hydrocarbons.

1.5.3 Future petroleum provinces

Much of the Arctic remains unexplored, however almost 40% of the area north of the Arctic (around 8 million km^2) circle is underlain by sedimentary basins.

Gautier et al. (2009) estimated that for the Arctic as a whole the yet-to-find resources (mean, risked, recoverable) are 90 Bbbl oil & 279 Bbbloe gas. Eleven regions have large mean, risked resources (Bbbloe):

- 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;
- The Norwegian Sea, 6

Only three of these 11 regions are ‘new’ provinces: East and West Greenland and the Laptev Sea, the other eight are proven hydrocarbon provinces.

The presence of thick and complete sedimentary columns in many basins in the Arctic, as well as widespread presence of Paleozoic and multiple Mesozoic source rocks, proposes that numerous petroleum systems remain undiscovered. Even though, the proven Triassic- and Jurassic-sourced petroleum systems are the most prolific, some areas may have new potential – the undiscovered Cretaceous and Cenozoic petroleum systems could be present in many areas.

2. CARBONATE SEDIMENTS

Carbonates form some of the biggest petroleum reservoirs in the world. Limestones and dolomites are mostly formed within the sedimentary basins. The properties of carbonates are very important for their reservoir characteristics, like porosity and permeability. Carbonate sediments are primarily composed of calcareous organisms. The most significant floral and faunal organisms for Upper Paleozoic carbonate buildups are summarized below after Hanken et al. (2010):

Calcareous algae are represented by a various group of plants that inhabit shallow marine, clear water environments from Cambrian to Recent. The most important are red algae and green algae formed at shallow marine subtidal environments. Red algae may form primary porosity in reefs and, therefore, are usually associated with oil and gas producing reefs, while green algae are often referred as source rocks for oil. *Phylloid algae* are usually referred as of Late Paleozoic, poorly preserved, platy, calcareous algal remains that cannot be identified to generic level (Scholle & Ulmer-Scholle, 2006).

Sponges may significantly vary in size from few centimeters to more than a meter in diameter. Sponges have an internal siliceous or calcareous skeleton with a large internal cavity. Sponges mostly occur in marine clear water environment from the littoral to abyssal depths. Most sponges are benthic: calcareous are common in shallow-water, while siliceous – in deep water. The geological range for sponges is from the Cambrian to Recent, while they have been major components of some Upper Carboniferous-Jurassic buildups. Reservoir properties of sponges are quite poor. The high primary porosity is usually lost during the burial history, but may be preserved in hollow spicules, where it stays ineffective because of the low pore connectivity.

Corals are benthic marine organisms that are widespread in shallow, well-oxygenated, tropical to sub-tropical normal saline waters. Corals usually form colonies from few centimeters to several meters in diameter. However, solitary forms of corals also exist. The growth of the colonies is characterized by repeated budding from the side or top of the individual corallites. Individual corallites usually consist of horizontal partitions, radially arranged vertical elements and small partitions in the lower periphery of the corallite. The presence or absence of these structures is a basis for classifying corals into four major groups: rugosa (horn corals), tabulata and scleractinia (hexacorals), and alcyonaria (octacorals). The most important among these groups are tabulate and scleractinia corals, because they were major reef builders of

Silurian-Permian and Triassic buildups respectively. Corals may have high primary porosity in reef buildups, while scleractinian corals have high secondary moldic porosity due to dissolution of unstable primary mineralogy. Thus, corals, especially scleractinian corals, have high reservoir potential.

Bryozoans are sessile, suspension feeding organisms that form colonies from 0.5 to 60 cm in diameter. Most of bryozoans occurred in normal saline marine environments, ranging in depths from shallow to abyssal. Bryozoans were important frame builders in many Ordovician to Permian buildups. Bryozoans are characterized by relatively high primary interparticle, intragranular and framework porosity. Nevertheless, only framework and interparticle porosities have good pore connectivity and may form important reservoirs in some bryozoans buildups.

Palaeoaplysina is one more important reef building organism. It is of unknown affinity, but is probably related to the sponges or algae. Palaeoaplysina is platy in shape, 3-6 mm thick and up to one meter long. Palaeoaplysina aragonitic plates are usually filled with spar, but some plates are well preserved and have polygonal internal cells that form complex porosity (Morin et al., 1994)

2.1 Paleozoic reef buildups

The definition and use of the term reef and buildup have long been a matter of debate (Wahlman & Konovalova, 2002). A carbonate buildup, as defined by Wilson (1975), is: “A body of locally formed (laterally restricted) carbonate sediment which possesses topographic relief.” A reef, as defined by Schlumberger Oilfield Glossary, is: “A mound, ridge, or buildup of sediment or sedimentary rock most commonly produced by organisms that secrete shells.” Even though the meaning of these terms is slightly different, in most of the literature they are used as synonyms. Therefore, in order to avoid any misunderstandings, they are used as synonyms in this work as well.

In recent years a variety of studies, regarding the formation, composition and distribution of the Paleozoic reef structures took place. Many studies have been devoted to the higher tropical to temperate shallow-water buildups from the northern margin of Pangea in Arctic Canada and the Barents Sea region of Arctic Norway. These Paleozoic buildups represent potential reservoirs for hydrocarbons by the analogy of the Timan-Pechora Paleozoic reef structures that are main reservoirs in this oil- and gas-bearing province.

The main types of the Late Paleozoic bioherms, their distribution, related to temperature and latitude or depth, and main biohermal components are summarized in Figure 12 (Wahlman & Konovalova, 2002).

The tropical biohermal communities contain abundant aragonitic organisms (i.e., phylloid algae and calcisponges) and aragonitic cements (botryoidal radial fibrous cements), and are often rich in encrustations of the problematicum Archaeolithoporella (Chlorosponge association). In subtropical (more moderate) paleolatitudes, these communities are mixed with Palaeoaplysina biohermal component and grade into the Palaeoaplysina buildup community. In a temperate to boreal temperature distribution buildups become dominated fenestrate bryozan-Tubiphytes bioherms (Mg-calcite skeletal organisms) with Bryonoderm–extended to Bryonoderm associations (calcitic radiaxial cements). However, all these Bryonoderm community elements exist in the warmer-water reefs (e.g., Wahlman, 1988), but there they are minor to the tropical biota. In the conditions of cold water, the organisms with calcium carbonate skeletons are substituted by siliceous sponges dominate communities.

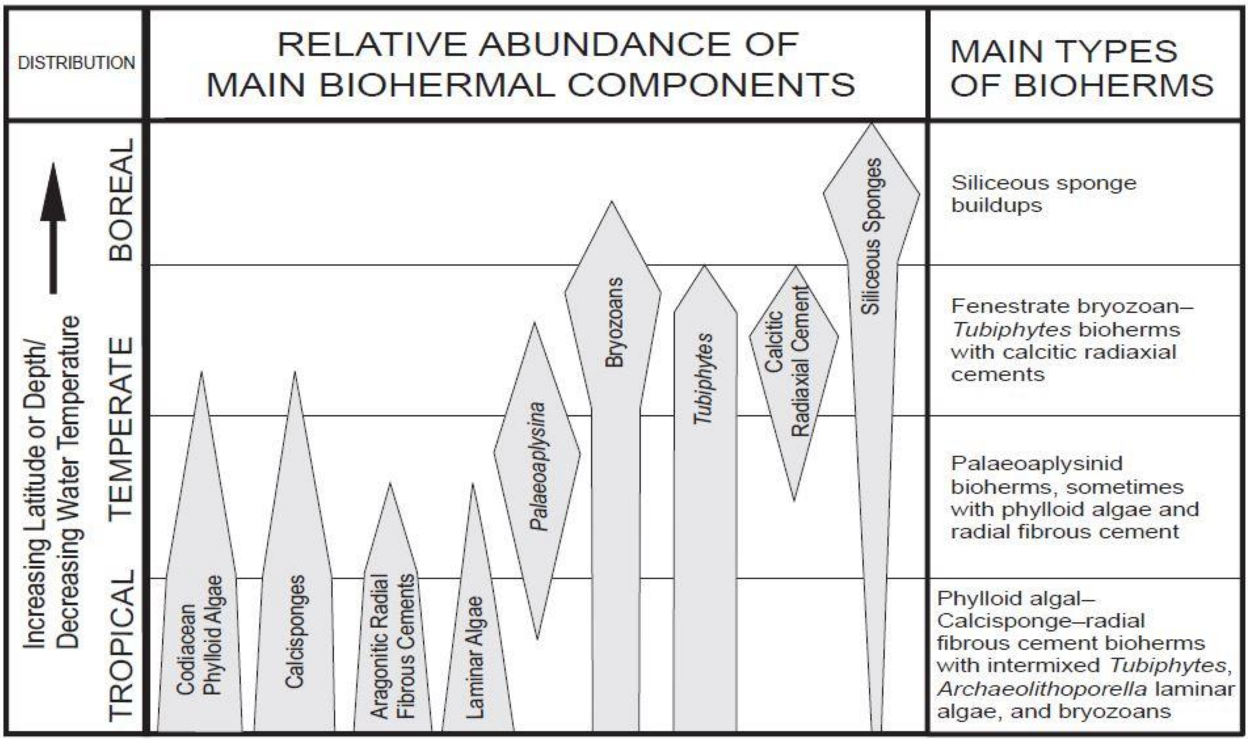


Fig. 12 Generalized distribution of major types of Late Paleozoic bioherm-building communities and their constituents relative to seawater temperature (Wahlman & Konovalova, 2002).

3. TIMAN-PECHORA BASIN

The Timan–Pechora oil- and gas-bearing Basin is a triangular shaped area of approximately 380 000 km^2 that represents the northeastern cratonic block of the European Platform (Fig.13). In its structural and tectonic position the Timan-Pechora Basin is referred to the marginal plate in front of the Urals Fold Belt and is bounded by it to the east and south-east. The western and southwestern boundaries are marked by the Timan Ridge, a north-west-south-east trending geological structure of a positive relief (Malyshev et al. 1991). To the north-east the basin is bounded by the Paikhoi High, and the northern boundary corresponds to the southern boundary of the Barents Sea Province (Fig.14).

The Timan-Pechora Basin is a heterogeneous sedimentary basin. It was formed on the fragments of the Late Precambrian Basin on the marginal part of the epi-Baikalian plate (Klimenko et al., 2011).

The proven discovered resources of the basin are estimated to be about 16 billion barrels of oil (BBO) and 40 trillion cubic feet of gas (TCFG). Simultaneously, the undiscovered resources are supposed to be 3.3 BBO, 17 TCFG and 0.3 billion barrels of natural gas liquids (BBNGL) (Schenk, 2011).

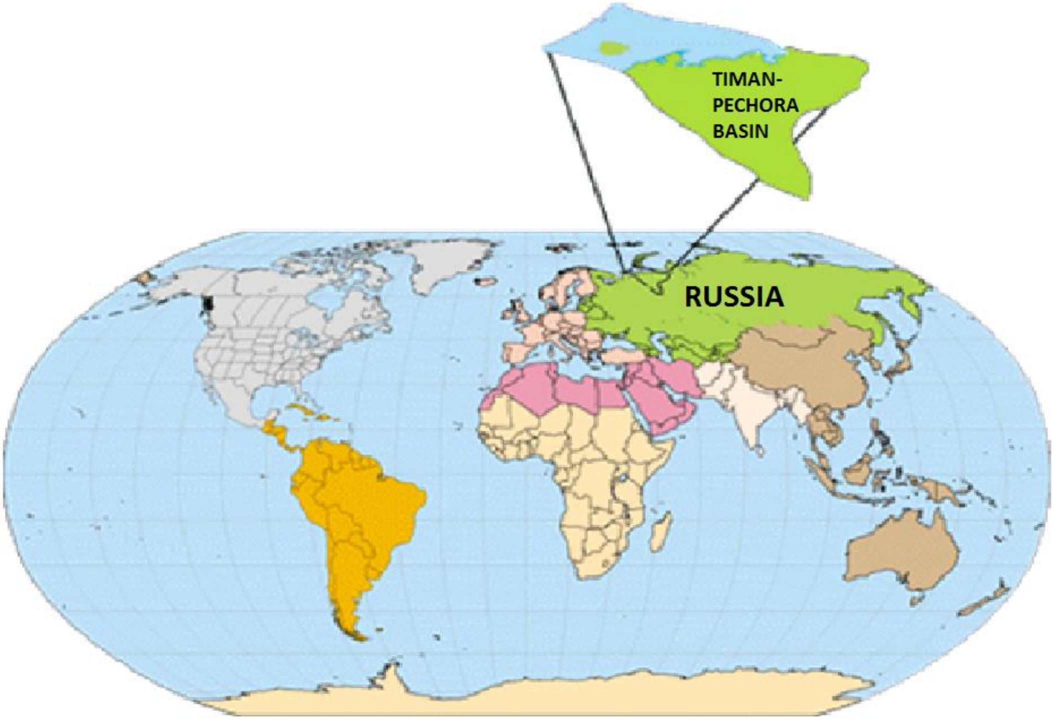


Fig. 13 Map of the Timan-Pechora Basin location (compiled after Lindquist, 1999)

3.1 Geological setting

The Timan–Pechora sedimentary basin is a submerged northeastern part of the European Platform with heterogenic structure. The geological structure of the basin consists of rift basins, inverted rifts and horsts, and a series of foreland basins along the Uralian orogenic front on the eastern margin of the province. Such complexity of the structure is due to various tectonical activities like Early Paleozoic, Devonian and Riphean continental rifting and Early Permian inversion, which resulted in formation of diverse inversion swells within the basin. The largest regional structures of the province are the Pechora Syneclise, the Timan Ridge, the Urals Fold Belt and Pre-Urals Foredeep (Fig.14).

The sedimentary cover of the Timan-Pechora Basin varies from 4-7 km in the central part of the Pechora Syneclise up to 10-14 km in the depressions of the Pre-Urals Foredeep. However, in the Kanin-Timan Ridge and the Urals, the Precambrain basement of the basin is exposed to the surface, i.e. the sedimentary cover is absent there, due to deep erosion.

The stratigraphy of the Timan–Pechora Basin is illustrated in Figure 15. It represents the tectonic and sedimentation evolution of the north-eastern part of the Eastern European Platform. Cambrian sediments are absent because of the rift shoulder erosion during Baikalian orogeny. Deep rift basins were formed during the Ordovician-Silurian rifting stages and were subsequently infilled with synrift facies sediments. A development of a passive margin with carbonate platforms and deep-basin environments took place in Ordovician-Early Devonian, where organic-rich shales were deposited. Among the Middle Devonian sediments, siliciclastic deposits are dominant, but they gradually changed to carbonate platform and basin sediments in the Upper Devonian and Carboniferous. The Early Permian started with deposition of carbonates that afterwards were overlain by siliciclastics in the foreland basin to the west of the Uralian fold and thrust belt. Siliciclastic sedimentation continued into the Triassic and Jurassic.

Main reservoir rocks in the Timan–Pechora Basin consist of Upper Ordovician carbonates, Lower Silurian carbonates, Upper Silurian to Lower Devonian platform carbonates, Middle Devonian siliciclastics, Upper Devonian reef carbonates, Carboniferous to Lower Permian platform and reef carbonates, and Upper Permian to Triassic siliciclastics (Schenk et al., 2011). Nearly all reservoirs are within structural traps, however, potential reservoirs in stratigraphic traps are practically untested, and might be future exploration targets.

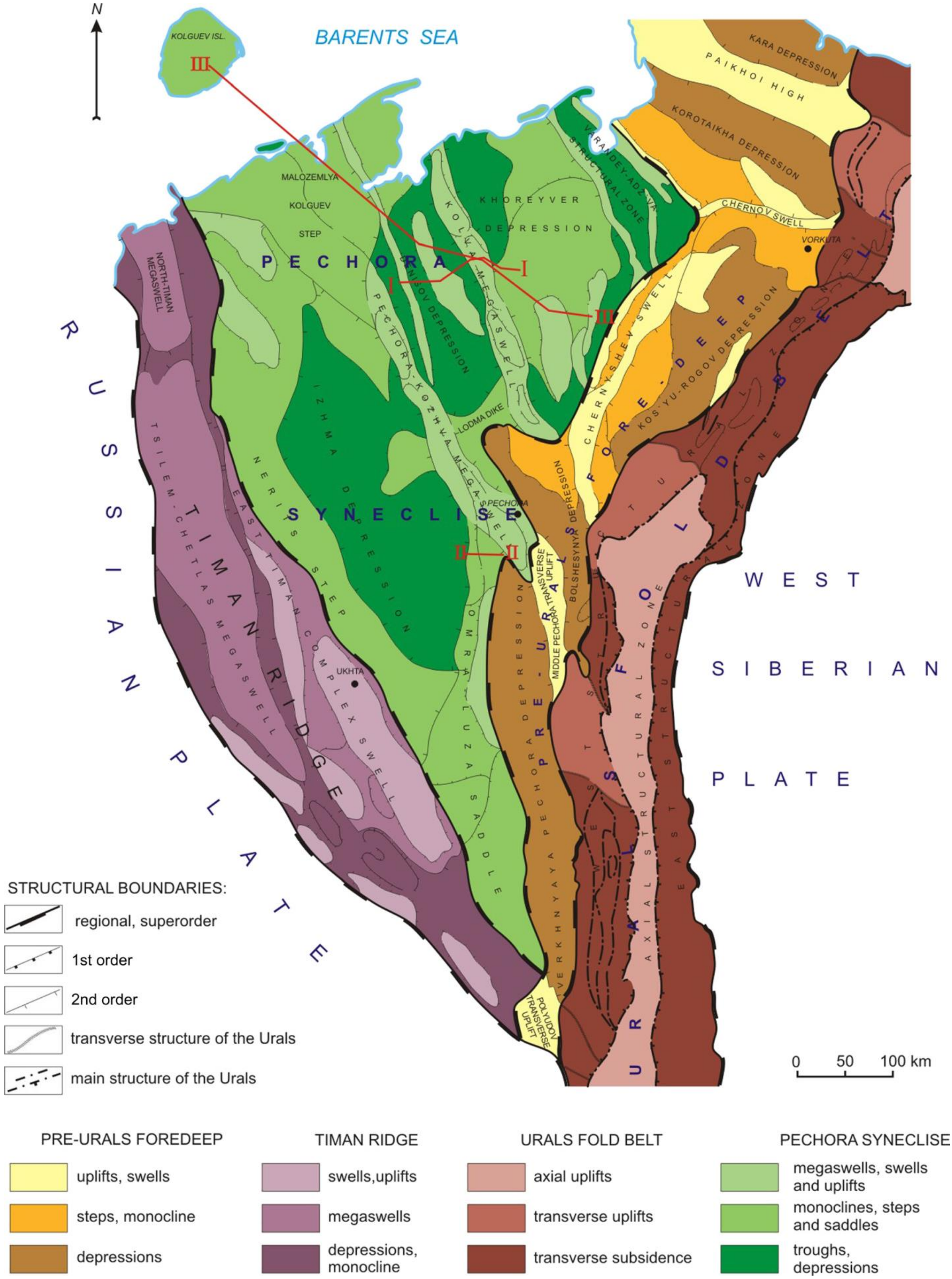


Fig. 14 Tectonic zones of the Timan-Pechora Basin (Klimenko et al., 2011)

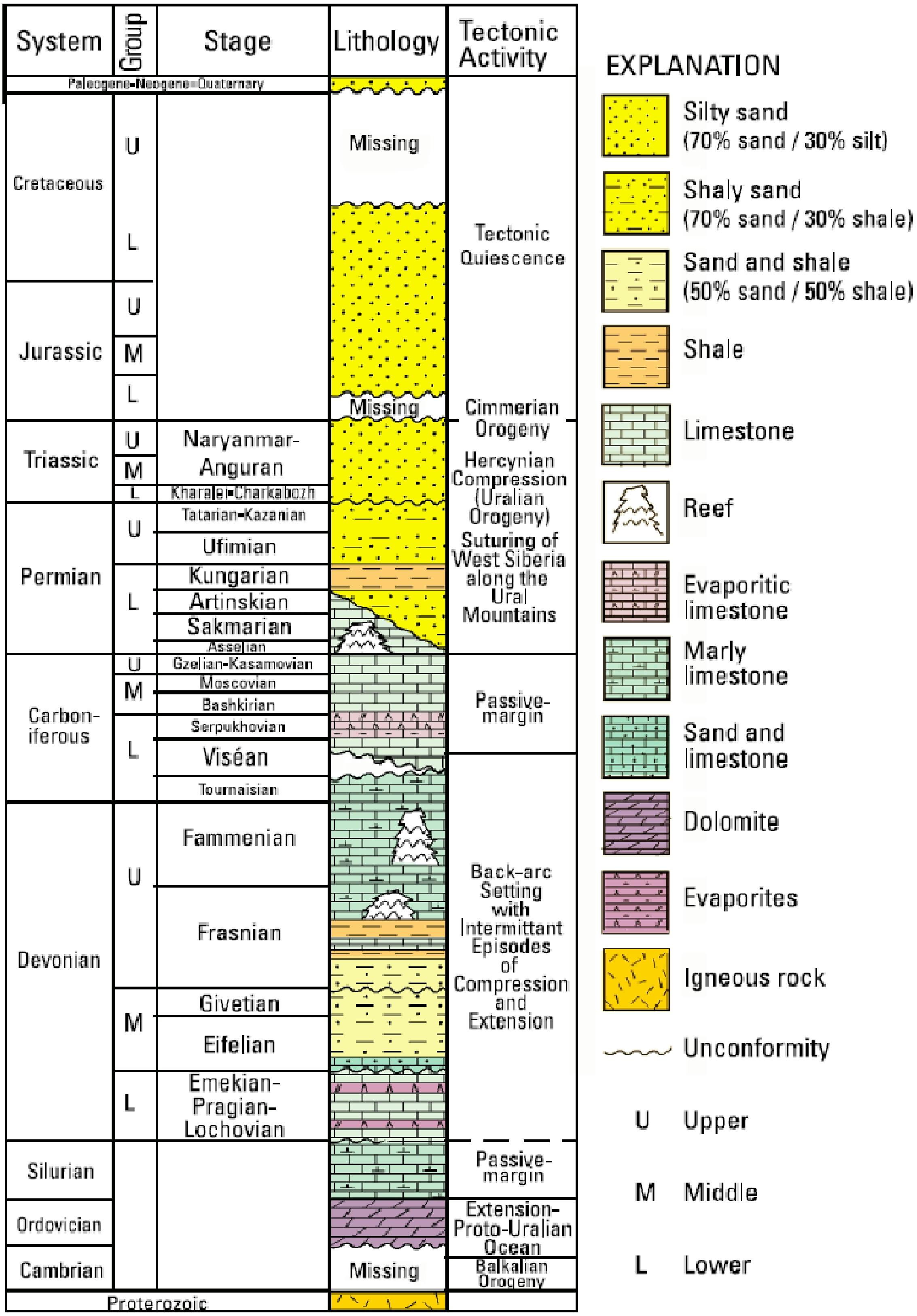


Fig. 15 Stratigraphic column for the Timan-Pechora Basin (Schenk, 2011)

There are many different types of reservoirs in the Paleozoic strata of the Timan–Pechora Basin. One of the most notable among them is Middle Ordovician-Early Permian organic build-ups, especially in the south and in areas adjacent to the Ural fold belt. Upper Devonian and Upper Carboniferous–Lower Permian reefogenic buildups within the Pechora Syneclise contain hydrocarbon fields (Klimenko et al., 2011). These carbonate buildups are very perspective potential reservoirs within areas overlain by seals.

3.2 Paleozoic reef structures in the Timan-Pechora sedimentary basin

Massive Paleozoic carbonate buildups are major petroleum reservoirs in the Timan-Pechora Basin. The Upper Paleozoic shallow-water reefs of the southern Ural Mountains of Russia and Kazakhstan are estimated to be intermediate in composition between the Tethyan and northern Pangea buildups. The southern Uralian buildups are rich in Palaeoaplysina, like the northern Pangea buildups, but they are also rich in Archaeolithoporella encrustations, like the Tethyan buildups. Also, inozoan and sphinctozoan calcisponges, which characterize many Tethyan buildups, are lacking in northern Pangea buildups, but they occur sparsely within the southern Uralian buildups (Wahlman & Konovalova, 2002).

The formation of the Paleozoic reefal structures in the Timan-Pechora sedimentary basin went through three stages of organic structures, summarized at Figure 16 (Klimenko et al.):

Caradocian – Early Emsian

This stage of the reef development is the most complex in the history of the Timan-Pechora Paleozoic reef structures and is characterized by various global abiotic and biotic events. Intra-plate rifting that took place in the Late Ordovician resulted in the first internal shelf depressions. These depressions lead to strong differentiation in sedimentation of the first Paleozoic reefs in the north of the province (Malyshev, 2002), as the first reefs were formed in the elevated blocks of the marginal part of the plate (Antoshkina, 1994).

By the end of this stage the largest barrier reefs were formed. They were located on a narrow shelf with predominant terrigenous sedimentation; therefore, these reefs had uniform faunal and sedimentary features (Antoshkina and Königshof 2008). However, in the Early Emsian, the environments of the coastal alluvial plains prograded oceanward. This movement resulted in disappearance of the Early Paleozoic reefs and intensive terrigeneous and shaly sedimentation. In the Middle Emsian time, the transgression of the sea led to termination of the reef growth and accumulation of thin carbonate-terrigeneous muds.

Middle Frasnian – Tournaisian

The second stage of the reef formation was dominated by an unstable tectonic regime, thus, the reef ecosystem had not achieved a mature stage. Primarily microbial mounds with the thickness up to 600 m were formed on the margins of the shallow water carbonate platform slopes, within the relatively deepwater anoxic depressions. Finally, the regression at the transition from the Tournaisian to Visean led to the erosion of the Tournaisian carbonate platforms and termination of the second stage of reef formation.

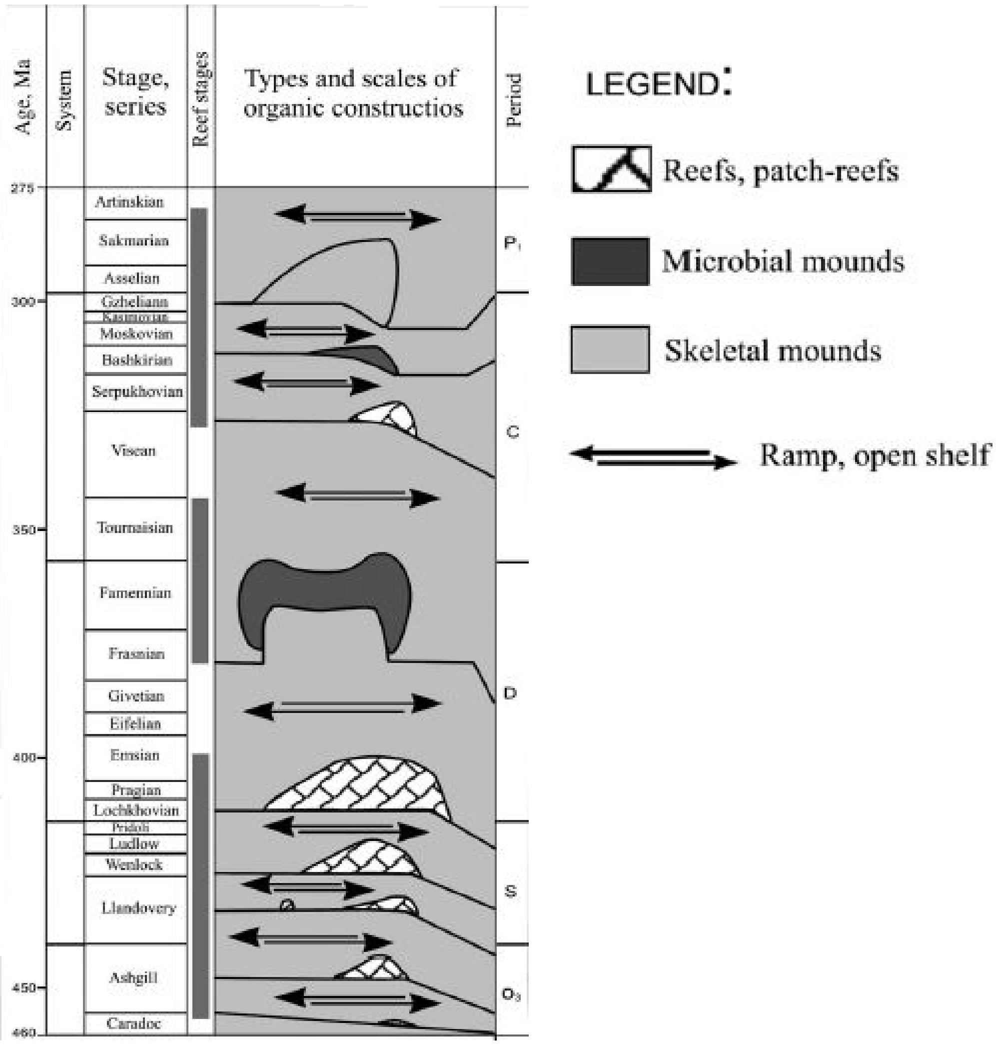


Fig. 16 Paleozoic Evolution in the NE European Platform. The Sandberg model, based on the study of ancient ooids and carbonate cements, postulated changes between times dominated by aragonite and high Mg-calcite and time dominated by calcite (Sandberg, 1983,1985).

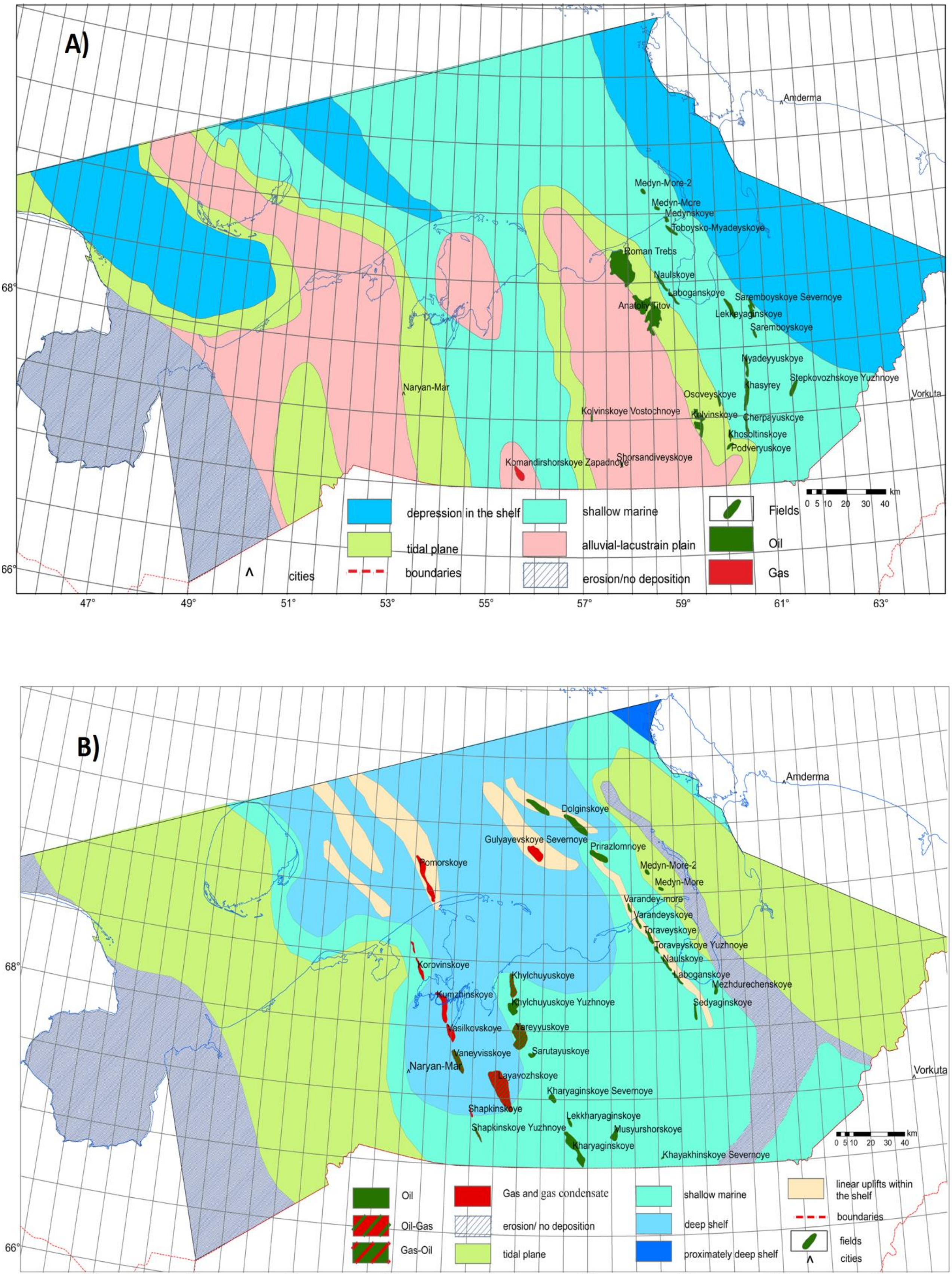


Fig. 17 Paleoenvironmental setting in the Timan Pechora Basin. A) Early Devonian time; B) Early Permian time (compiled after Bagrintseva et al., 2011).

Late Visean – Early Permian

The Paleozoic reef formation and the change of organic fabrics were completed during this final stage. Metazoan–microbial reefs and microbial bioherms reappeared on the margin between the salinized areas inside the basin and the newly developed shelf and remained up to the Middle Carboniferous regional erosion.

The composition and dimensional distribution of the diverse organogenic buildups in the Timan–Pechora basin show that the main parameters that regulated Paleozoic reef formation were the tectonic evolution of the Pechora Plate and the Uralian Ocean, the skeletal reef biota, the chemical and physical parameters of microbial carbonates and eustasy of sea-level.

3.3 Paleozoic carbonate reservoirs in the Timan-Pechora sedimentary basin

The Timan–Pechora Basin carbonate reservoirs have been formed in high energy shallow-water shelf environment and are made up from grainstone–packstone shoal deposits, with different proportions of Palaeoaplysina biohermal facies, and are often rich in fusulinid faunas. Those reservoirs are characterized by worn, sorted, encrusted, micritized and tightly packed bioclasts, showing almost no evidence of early marine cementation. The subsurface reservoir sequences usually contain numerous Microcodium horizons, indicating iterative periods of subaerial exposure (Wahlman & Konovalova, 2002).

The Lower Silurian shallow-water sediments, consisting of various facies, are supposed to be one of the most prospective Lower Paleozoic oil reservoirs. The best reservoir properties have been evaluated in the Khoreiver Depression and Denisov Depression (Fig.14), where the top of the Silurian succession was eroded during Late Silurian – Early Devonian time (Klimenko et al., 2011).

Significant amounts of oil and gas resources are trapped within microbial mounds and barrier reefs of Devonian age. Those carbonate reservoirs were formed in a shallow-water environment with terrigenous-sulphate-carbonate sedimentation (Fig.17). However, the western part of the basin is characterized by areas of high-low tidal plains with terrigenous sedimentation. The wells, drilled in the Varandey-Adzva structural zone, penetrated the Lower Devonian strata. The profiles from the wells start with a marine carbonate stratum, represented by a shaly–limestone regressive unit in the lower part, replaced by a limestone–dolomite transgressive upper unit. Upward the profile turns to a shaly–dolomite unit interbedded with dolomites and argillites in the lower part and a sulphate–dolomite unit at the top, consisting of interbedded anhydrites, dolomites and argillites, accumulated under increasingly saline conditions (Bagrintseva et. al., 2011).

Deposition of Upper Carboniferous – Lower Permian sediments occurred on a carbonate shelf during periodic fluctuations of sea-level (Fig.17). As a result, bioherm buildups, comprised of grained, framework limestone, were replaced by silty and vuggy limestone. These bioherm bodies represent a part of an integrated band in the northern, offshore part of Timan-Pechora basin. The oil fields discovered in the offshore part of Timan-Pechora basin are associated with high-capacity reservoirs, composed of grained, framework limestone with vugular varieties. Lithological and physical studies show that sedimentation of the Lower Permian strata occurred under normal marine conditions varying from near-shore shallow-water to relatively deep in some depressions (Bagrintseva et. al., 2011).

Oil and gas prospects in the Pechora Sea are attributed to Paleozoic carbonate reservoirs and Permian–Triassic sandstones. The main oil- and gas-bearing complex on the Pechora Sea shelf is represented by reefal and organogenic carbonates of Lower Permian-Carboniferous age. Those carbonate complexes contain significant reserves and resources of oil and gas. Despite complexity of the reservoirs, they are of big interest for the development of already discovered oil fields and for prospecting for new hydrocarbon accumulations. The largest field, discovered in the Pechora Sea is the Prirazlomnoye Field. It has been discovered in 1989 and has an estimated amount of 72 million tons of oil reserves (according to Gazprom) and has been recently set to production (December 2013). The oil reservoir consists of multipay common-contact type and is associated with carbonate deposits of Lower Permian – Carboniferous age, represented by organogenic and organogenic–clastic limestone.

A comparison of the types and properties of the onshore and offshore reservoirs shows their strong similarity. These specific features of carbonate reservoirs include (Bagrintseva et. al., 2011):

- considerable inhomogeneity of lithological composition and genetic properties;
- intense development of post-sedimentation transformations with prevailing processes of silicification and dolomitization;
- general occurrence of fractures with various morphology and genesis;
- intensive leaching process, which resulted in the development of vugs.

Paleozoic productive oil-bearing reservoirs, from Silurian to Permian, are located in zones of low- and medium-quality Frasnian and Carboniferous cap rocks and in the zones of active tectonic movements. The preservation and vertical migration of the hydrocarbons are dependent on the quality and thicknesses of these cap rocks and the intensity of vertical tectonic movements. Most of the traps occur within the complex lithological structures, limited stratigraphically and tectonically with multiple faults of different amplitudes.

Therefore, the occurrence of oil- and gas-bearing reservoirs is controlled by both primary (organic matter and its maturity degree) and secondary factors (regional subsidence and recent tectonic movements) (Klimenko et al. 2011).

4. SOUTHWEST BARENTS SEA

The Barents Sea comprises a vast region between Novaya Zemlya in the east and the continental slope of the Norwegian Sea in the west, and between Svalbard and Franz Josef Land in the north and the coasts of Russia and Norway in the south (Fig.18).

Geological exploration of the Norwegian Barents Shelf commenced with seismic surveys in the 1970s. In the 1985 and 1986 three wells were drilled on the southern margins of the Loppa High and one of them turned out to have a significant oil column, however there has been much debate on whether that was biodegraded oil or the carbonate reservoir was apparently tight (Larssen et al. 2002). In 1993 a small oil and gas discovery has been made on the adjacent Finnmark Platform in the Upper Permian strata. These hydrocarbon finds made Upper Paleozoic reservoirs one of the most prospective plays as well as the Finnmark Platform and the Loppa High the key exploration targets in the region.

4.1 Geological setting

In its structural and tectonic position the Barents Sea represents a pericontinental shelf, subdivided into numerous basins and highs (Fig. 18). The Upper Paleozoic to Quaternary sediments cover the area between the Norwegian coast and Svalbard, while the Lower Paleozoic basement is exposed along the Norwegian coast, on the islands of Bjørnøya, Spitsbergen and Nordaustlandet (Worsley et al., 1986; Harland, 1997).

During the Carboniferous to Permian time, the Barents Sea represented a part of a huge province of carbonate-dominated deposition (Fig. 20). Platform carbonates dominate on the Finnmark and Bjarmeland platforms and the Loppa High, however there are still untested platforms located to the north (Henriksen et al., 2011).

The Finnmark carbonate platform was developed on the south-western margin of the Barents Sea in Late Carboniferous – Early Permian time (Ehrenberg, 2004). Four main stages of depositional evolution are recognized within the Finnmark platform. First, Upper Carboniferous siliciclastic-carbonate sediments were deposited, reflecting decreasing tectonic activity. Then, they were overlain by Lower Permian warm-water carbonates including algal buildups and rich in dolomite and anhydrite. From Sakmarian to Kungurian cool-water carbonates, containing bryozoans-echinoderm grainstones to wackestones, were deposited near the Nordkapp Basin. Subsequently, Middle-Upper Permian cold-water carbonates and siliciclasts were being deposited until the deposition was terminated by massive siliciclastic influx in the Triassic (Ehrenberg et al., 1998).

The Bjarmeland Platform represents a stable area east of the Loppa High and north of the Nordkapp Basin. The Platform was formed in Late Paleozoic, and the transition from Early Carboniferous clastic to Late Carboniferous – Permian carbonate deposition represents the transition from a pre-platform to a platform development. The platform is underlain by Precambrian and Paleozoic rocks. The main structural pattern within the platform is related to salt tectonics and weak extension (Gabrielsen et al., 1990). The Bjarmeland Platform is defined as type area for the Bjarmeland Group since the offshore successions are best displayed in wells from this area.

The Loppa High represents a complex structural feature that has experienced an intricate geological history. The area had several phases of uplift and subsidence in Late Paleozoic with subsequent tectonic tilting in the Late Permian. The tectonic tilting was followed by gradual onlap of Early-Middle Triassic sediments before rapid subsidence and deposition of a significant Upper Triassic succession (Larssen et al., 2002).

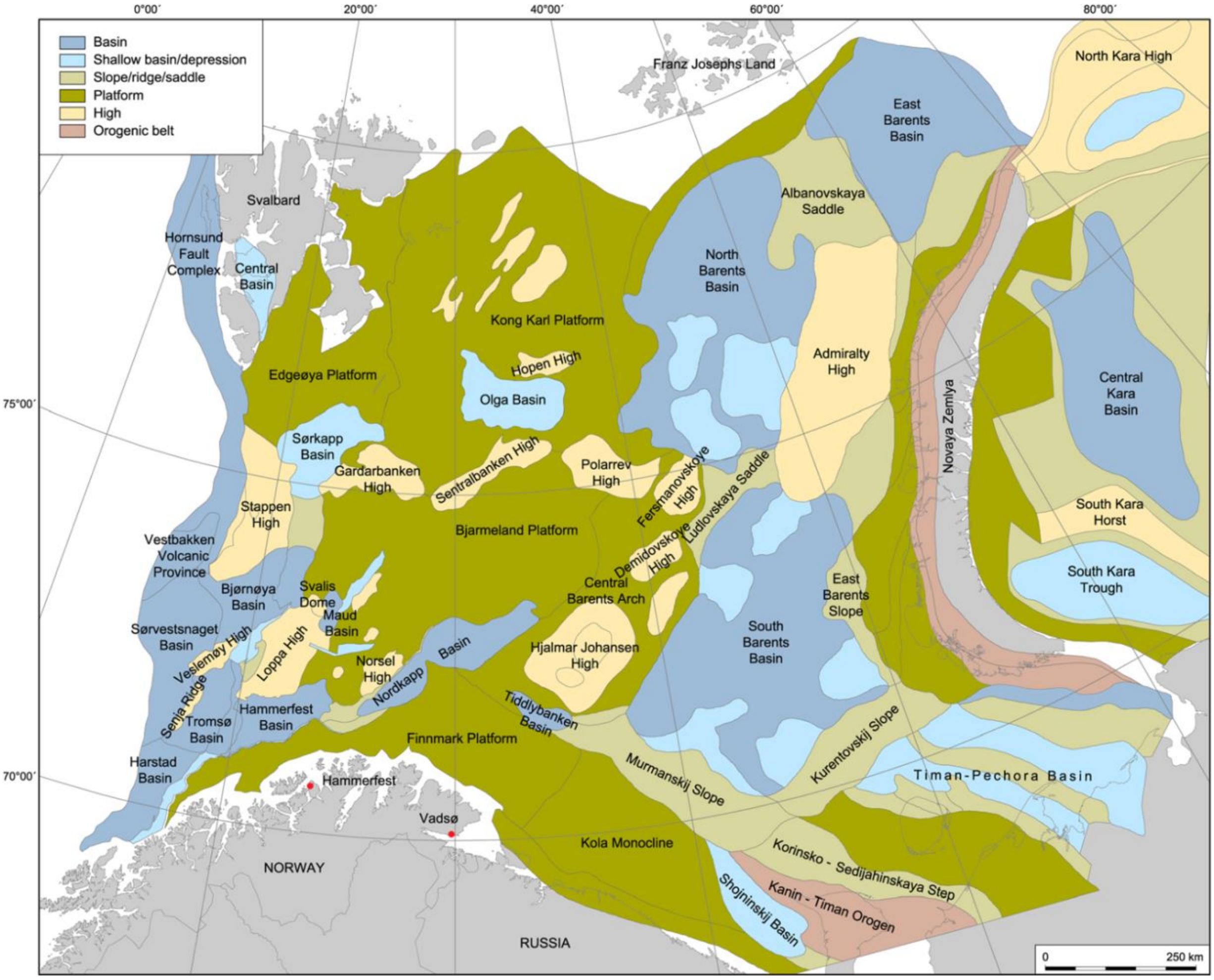


Fig. 18 Geological structural elements within the Barents Sea (Henriksen et al., 2011).

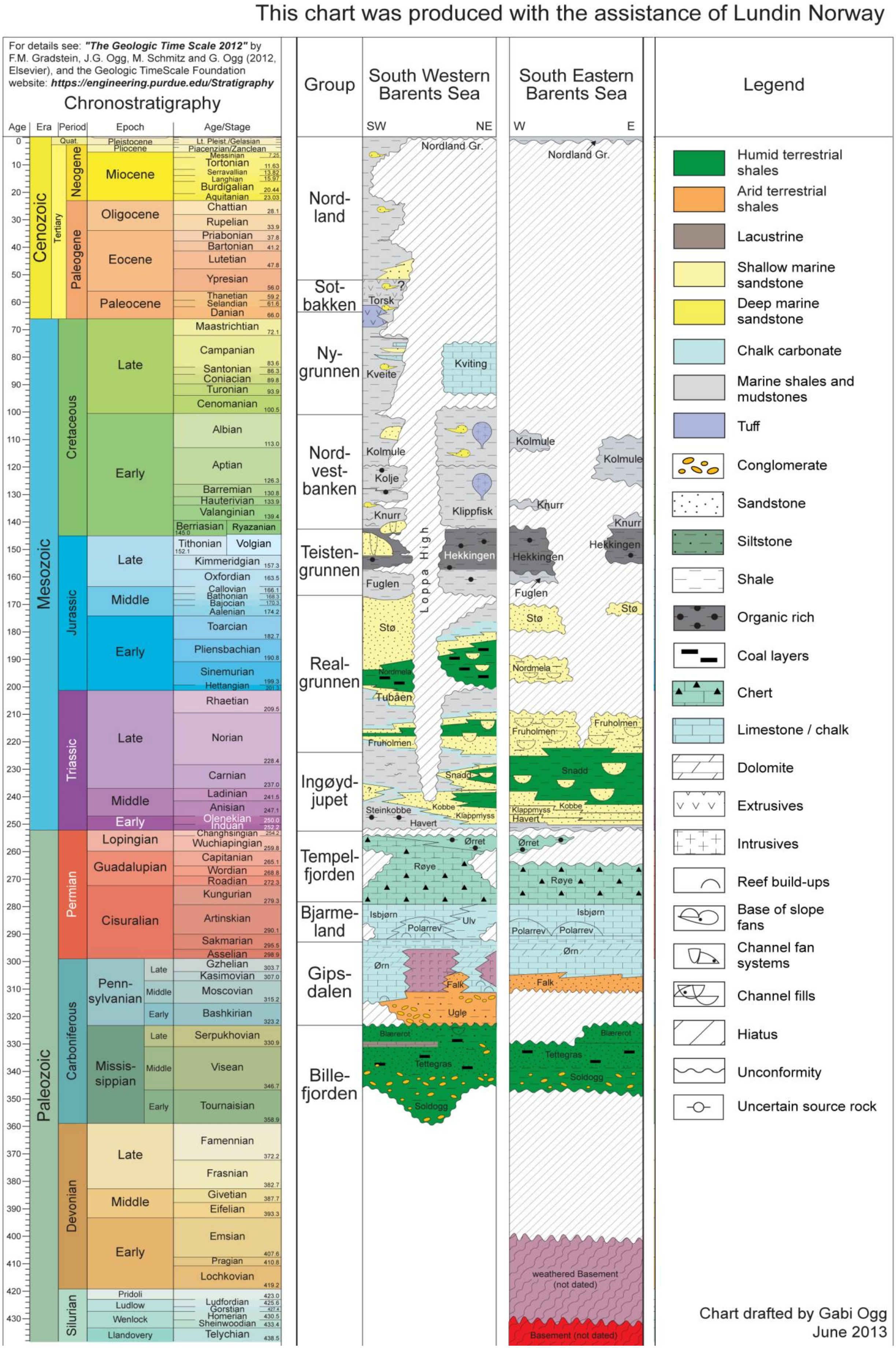


Fig. 19 Stratigraphic column for the Barents Sea (compiled after Ogg., 2013)

4.2 Paleozoic carbonates in the Southern Barents Sea

Fig 19 represents a stratigraphic column of the South Western and South Eastern parts of the Barents Sea. The main Paleozoic carbonate sediments are of Late Carboniferous – Early Permian age within the Gipsdalen and Bjarmeland Groups.

The Gipsdalen Group's sediments are spread throughout the whole Norwegian Barents Sea (Fig 20). The group formally consists of three main formations: Ugle, Falk and Ørn. Terrestrial shales and conglomerates of the Ugle Formation were deposited in arid environment, during active rifting in Late Carboniferous. They are overlain by shallow marine sediments of the Falk Formation. The uppermost part of the Gipsdalen Group is represented by shallow to deeper marine interbedded limestones and dolomites with occasional small Palaeoaplysina buildups of the Ørn Formation, which is of the most interest for petroleum exploration.

The Ørn Formation consists of shallow marine carbonates on the platforms and interbedded carbonates and evaporites in slope to basinal settings with minor occurrence of halite. The carbonates are built by warm-water foraminiferas, fusulinids, calcareous algae and fragments of Palaeoaplysina, however, crinoids, bryozoans, brachiopods and corals are present as well. The lower part of the formation is characterized by intermixed dolomitic mudstone and bryozoan wackestone with thin shales. This is overlain by Palaeoaplysina buildups and fusulinid wackestone. The uppermost part of the Ørn Formation is represented by thick layer of foraminifera and algal-rich packstones and grainstones (Larssen et al., 2002). The Ørn Formation was deposited in high frequency and high amplitude sea level fluctuation environments (Stemmerik, 1997). Siliciclastic sediments have been submerged and shallow marine carbonates deposition took place on the platforms. As a result of stacking of small buildups, large carbonate mounds were developed.

The cool-water Bjarmeland Group sediments are significantly different from the underlying warm-water Gipsdalen Group. The group consists of grey bioclastic limestones rich in crinoids, bryozans, brachiopods and siliceous sponges. Deposition occurred in different cool-water environments and range from shallow shelf bioclastic sandstones to outer shelf bryozoan buildups. The group is represented by three formations: Pollarev, Ulv and Isbjørn.

The Pollarev Formation consists of different facies that characterize isolated carbonate buildups. This stratigraphic unit is composed by bryozoan and bryozoan/Tubiphytes-dominated wackestones and cementstones with abundant marine cement. The fine-grained bioclastic limestones in the lower part of the unit indicate that the deposition started in the deep-water environment. Wackestones are characterized by cavities, which form complex interconnected pore systems that are, however, often filled with a grainstone or packstone fabric (Larssen et al., 2002).

The deposition of the Ulv Formation occurred in deep shelf environments and can be characterized by fine-grained bioclastic limestones. The formation is abundant with bryozoans-crinoidal wackestones, siliceous sponges, and brachiopods. The limestone is interbedded with thin silt laminae. Siliciclastic sediments are limited to the western margin of the Loppa High, indicating syndepositional tectonic instability (Larssen et al., 2002).

The deposition of the Isbjørn Formation occurred in inner shelf environments on cool-water carbonate platforms, which is indicated by bioclastic crinoid- and bryozan- dominated grainstones and packstones that are the dominant facies throughout the formation. Chert nodules occur sporadically throughout the section (Stemmerik, 1997).

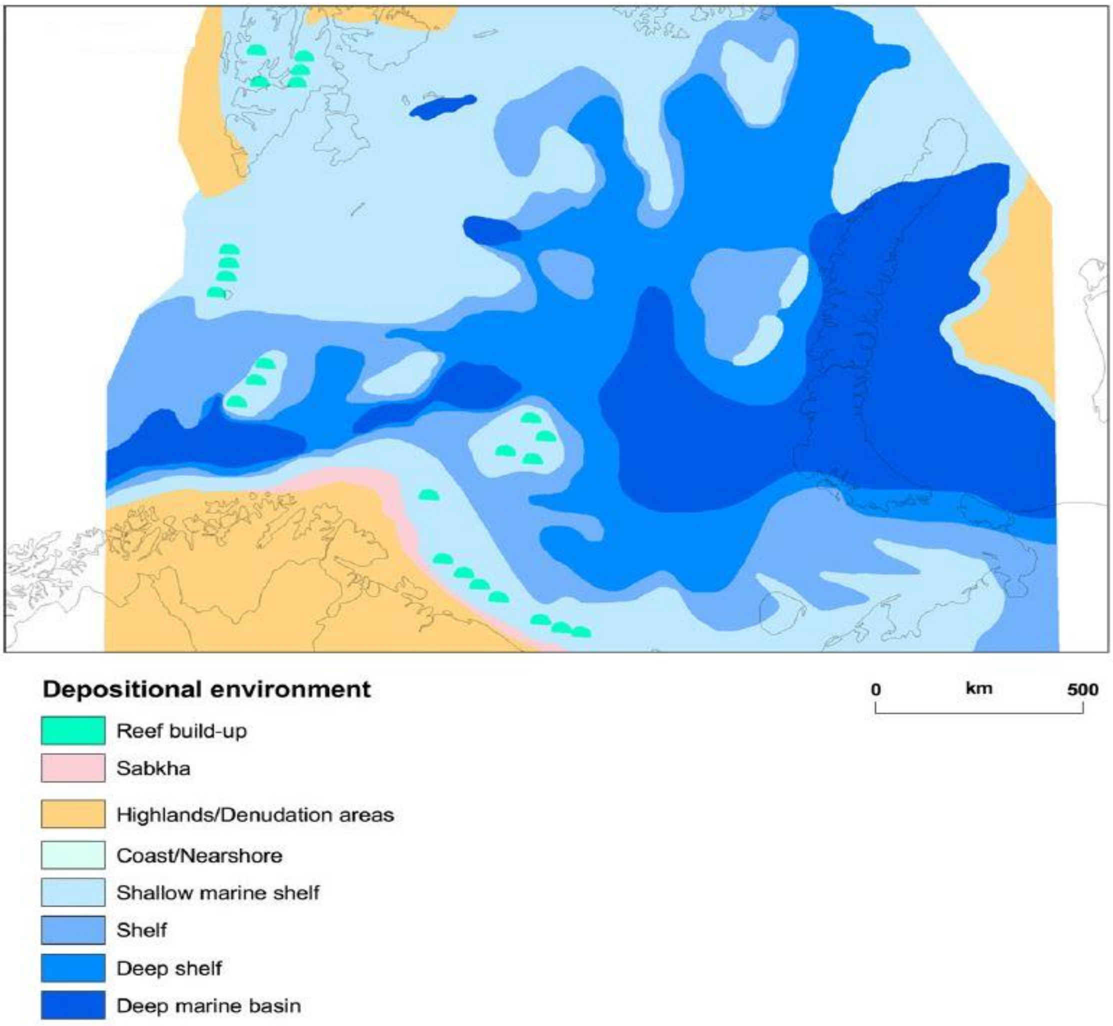


Fig. 20 Paleogeographic reconstruction of Late Carboniferous – Early Permian strata in the Barents Sea (compiled after Henriksen et al., 2011).

4.3 Reservoir quality of the Paleozoic carbonates in the Southern Barents Sea.

The Upper Paleozoic carbonates of the Barents Sea are depositionally similar and approximately age-equivalent to the carbonates that form major petroleum reservoirs in the Timan-Pechora province (Martirosyan et al., 1998), therefore, they represent important potential future hydrocarbon provinces, if source rocks are also present.

Warm-water shelf carbonates and Palaeoaplysina-phylloid algal buildups of the Gipsdalen Group (Moscovian-Asselian age) represent the best reservoir properties and, thus, are expected to be the most prospective reservoir rocks in the region. The reservoir qualities of these carbonates are strongly influenced by primary mineralogy and early diagenetic processes (Stemmerik & Worsley, 2005). A reservoir model for Moscovian-Asselian carbonates comprises extensive dolomitization and dissolution of metastable carbonate during repeated subaerial exposure. Nevertheless, this model is confirmed by drilling and is regarded as low risk. The reservoir model for the overlying cool-water carbonates of the Bjarmeland Group is characterized by either preservation of primary porosity in carbonate buildups or extensive dissolution of buildup marine cement and is regarded as high risk (Stemmerik et al., 1999).

The Late Carboniferous-Early Permian carbonate strata have multiple zones of moderate to high porosity that is either primary or created during early diagenetic processes. Figure 21 represents photomicrographs illustrating main porosity-prone facies in the Gipsdalen Group cores, which have been examined by Ehrenberg (2004) in order to determine possible effects of dolomitization on porosity.

Palaeoaplysina-phylloid-algae buildups (Fig. 21 (A)) are dominating in Upper Gzhelian-Asselian strata. These buildups are characterized by various porosities. High porosity (>10%) is present in extensively dolomitized buildups that include abundant visible porosity in forms of molds and intercrystalline matrix porosity or little dolomitized buildups but with minor presence of coarse calcite spar. Low porosity (<10%) is present in buildups that have lost their porosity due to infill of Palaeoaplysina and phylloid molds and intercrystalline pores with anhydrite, dolomite cement and calcite spar.

Fusinilid wackestone facies have >10% porosities in Asselian strata. These facies contain both intercrystalline macroporosity in dolomitized matrix areas and intrafossil macroporosity in bioclasts that have resisted dolomitization (Fig. 21 (B)). Low porosity values also appear in some fusinilid wackestone facies because of the matrix having been compacted and cemented.

Dolomitic mudstone facies occur in Gzhelian-Asselanian strata. Here porosity varies widely. High porosity trends are noted in samples with high intercrystalline matrix porosity in combination with moldic porosity (Fig.21 (C)). However, the reasons for porosity preservation and occlusion in these facies remain unknown.

Foraminifera grainstone and packstone facies are dominant in Asselian-Lower Sakmarian strata. These rocks are undolomitized or have comparatively minor evolution of microdolomite rhombs in their matrix. The high porosity in Asselian sediments is of intergranular and intrafossil genesis (Fig. 21 (D)). Many of the porous samples are represented by packstones with highly porous matrix of calcite microspar with dolomite cement. The low porosity samples have same pore types that the high porosity samples, but the pores are infilled with coarse calcite-spar cement. Therefore, calcite cementation of the pores has a major influence on the porosity in this facies.

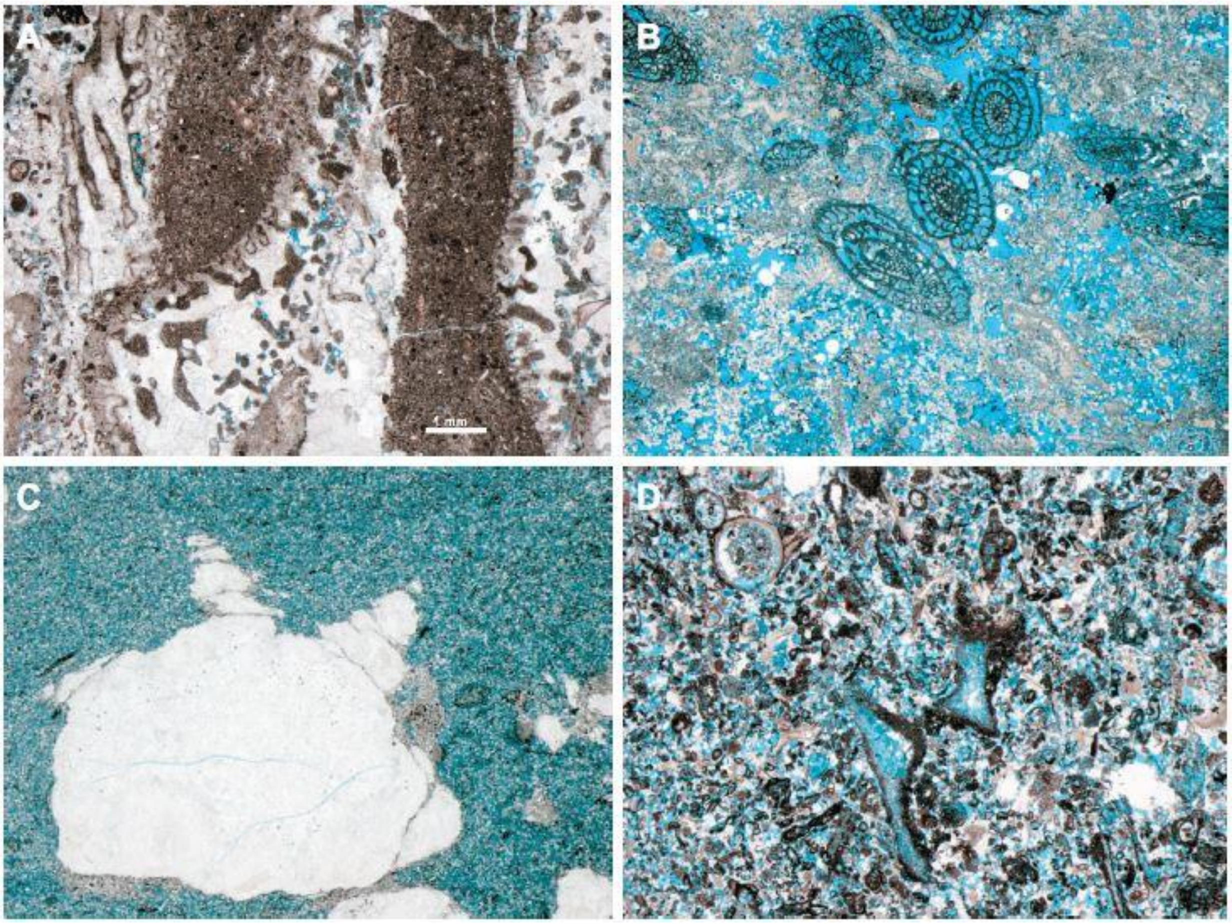


Fig. 21 Photomicrographs of main porosity-prone facies in Gipsdalen Group cores. (A) Buildup facies, brown: Palaeoaplysina molds and micropeloidal mud matrix; white: calcite cement; blue: macroporosity. (B) Fusulinid wackestone facies, composed by undolomitized fusulinids with high intrafossil macroporosity and dolomitized bioclast-rich matrix with both moldic and intercrystalline porosity. (C) Dolomitic mudstone facies, composed by microporous matrix of fine dolomite crystals with abundant quartz silt and anhydrite nodules (white areas). (D) Foraminifera grainstone and packstone facies, composed by diverse biota with high intergranular and intrafossil porosity that has been partly filled by fine calcite cement coating bioclast, coarser calcite spar (small white areas) and patchy anhydrite cement (large white areas) (Ehrenberg 2004).

In the Gipsdalen Group sediments the types of pores show a wide variation in different lithologies, but they are mainly represented by intergranular and intrafossil primary porosity or moldic and intercrystalline secondary porosity, that have been formed during early diagenesis. The porosity has been reduced by growth of cement crystals during subsequent burial diagenetic modification. Coarsely crystalline calcite has filled secondary pores in the calcite-dominated rocks and affected the porosity in these rocks (Stemmerik et al., 1999). High porosity in mudstone and wackestone facies is dependent on dolomitization, but in grain-dominated and buildup facies – on paucity of burial cements.

Main porosity destructive processes are chemical compaction, redistribution of anhydrite and cementation by coarsely crystalline calcite. These processes result in post-date hydrocarbon migration and anhydrite and calcite cementation is believed not to have significant influence on entrapment reservoir quality (Stemmerik et al., 1999).

Numerous undrilled prospects in the Norwegian sector of the Barents Sea suggest that the yet-to-find hydrocarbon resources are high and that the area remains a key target area for petroleum exploration. The main expectations are associated with Late Carboniferous-Early Permian warm-water carbonates that form the most prospective reservoirs in the southern Norwegian Barents Sea. Post-depositional fresh-water modification of the carbonates occurred during Artinskian and younger Permian uplift that resulted in subaerial exposure of these carbonate rocks. Therefore, studying of Permian karst systems is one of the major tasks for reservoir prediction (Stemmerik & Worsley, 2005).

5. SVERDRUP BASIN

The Sverdrup basin is an intracratonic rift basin, located in the Canadian Arctic Archipelago. It covers an area of 313,000 km^2 and extends for 1300 km in a northeast-southwest direction and is up to 400 km wide. The Sverdrup basin is bounded by the Sverdrup Ridge to the northwest and the Franklinian Foldbelt to the south (Fig.22).

The Sverdrup basin is composed of 13 km thick Carboniferous to Recent sedimentary strata (Embry et al., 2012). Upper Paleozoic sediments have a thickness of about 5000 m in the central parts of the Sverdrup basin. They are overlain by approximately 7000 m of Mesozoic sands and shales (Ziegler, 1987). Numerous reef buildups are known within the Carboniferous-Permian strata in the Sverdrup basin. Some of these reefs display a good reservoir potential and are likely to become major targets for petroleum exploration.

The Sverdrup basin is a proven hydrocarbon-rich province and has been a focus of intense petroleum research since 1960s. The Geological Survey of Canada estimates the potential of the Arctic Islands at 686 x 10^{6}m^3 oil and 2257 x 10^{9}m^3 gas. The Sverdrup Basin has the highest gas and oil potential, as in Mesozoic so in late Paleozoic rocks. Future exploration may target a number of untested late Paleozoic plays and margins of the basin (Northern Oil and Gas Directorate, 1995).

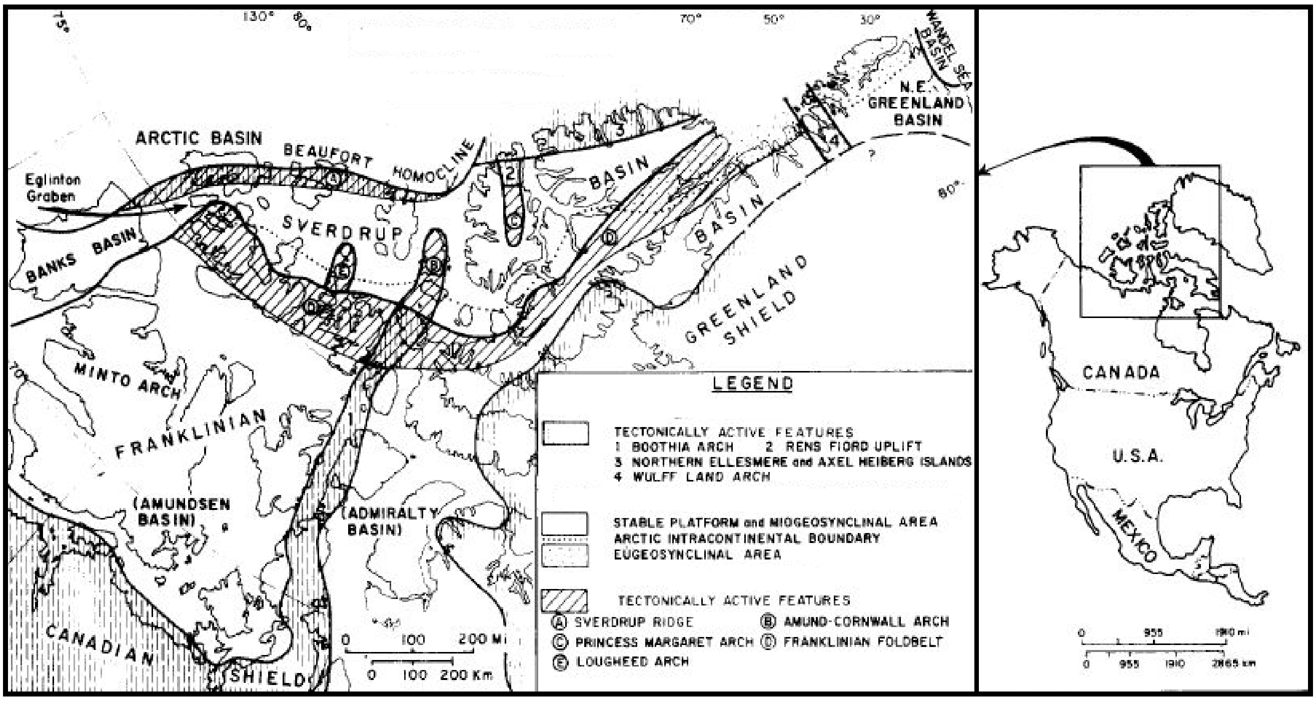


Fig. 22 Sedimentary basins and main tectonic features of the Canadian Arctic Islands(Left), Geographical position of the Canadian Arctic Islands(Right). Compiled after Smith & Wennekers, 1977

5.1 Geological Setting

The collision of the Laurentia and Baltica continents resulted in the Late Devonian-Early Carboniferous Ellesmerian Orogeny. Following the orogeny, the amalgamated continental blocks rifted leading to faulting and collapse of deformed Precambrian to Devonian rocks of the Franklinian Foldbelt, where the Sverdrup Basin has been developed. Subsequently, at the end of the active rifting extension in middle Permian time, the basin started to subside until Early Cretaceous (Bensing et al., 2008). The Late Cretaceous – Early Tertiary Eurekan Orogeny folded and uplifted eastern part of the Sverdrup basin, while the western part was experiencing subsidence due to differential loading of Carboniferous salt and the development of diaper fields (Northern Oil and Gas Directorate, 1995).

Three regions characterize the structural setting of the Sverdrup basin. A western region, extending eastward to Logheed Island, is composed of a perisyncline dipping toward the center of the basin. An eastern region is characterized by high structural deformation, where Late Cretaceous and Tertiary faults expose Triassic rocks in the cores (Fig. 23). An axial region between Lougheed Island and Ellesmere Island represents various diapric structures.

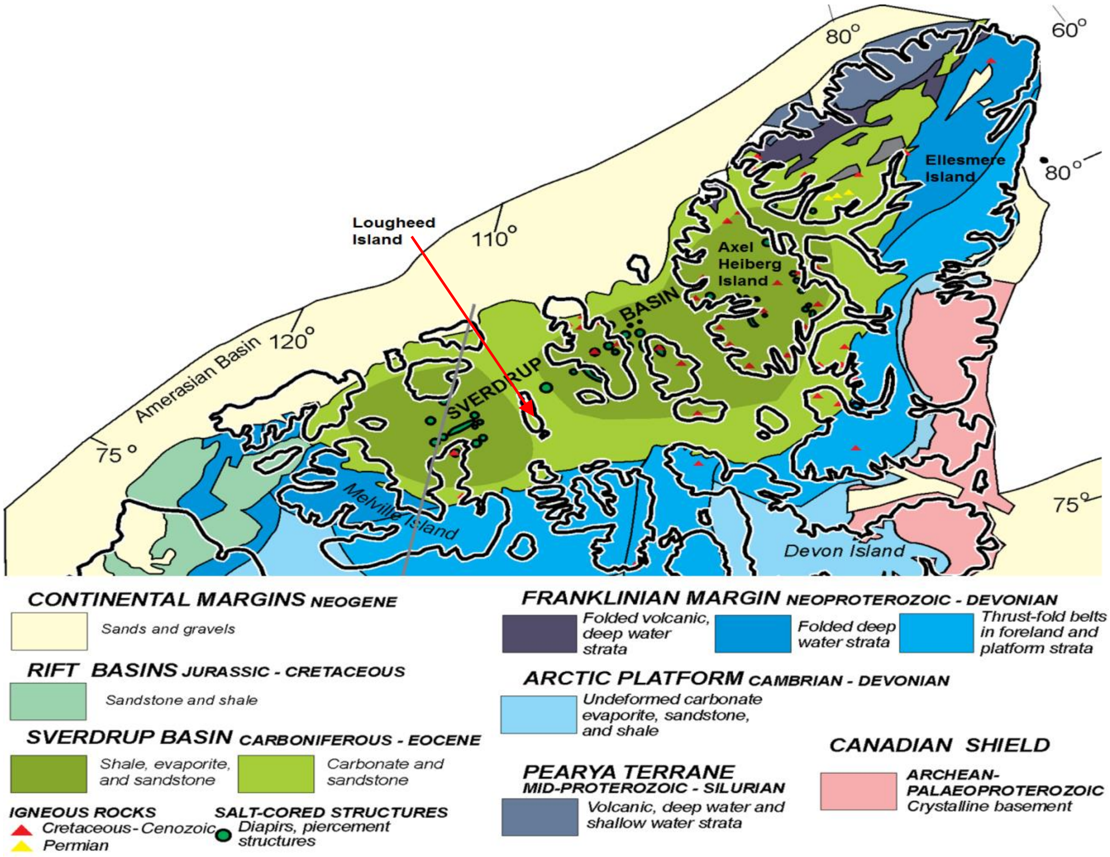


Fig. 23 Geology of the Canadian Arctic Islands. Two sub-basins of the Sverdrup Basin are shown in darker green (modified after Dewing & Obermajer, 2011)

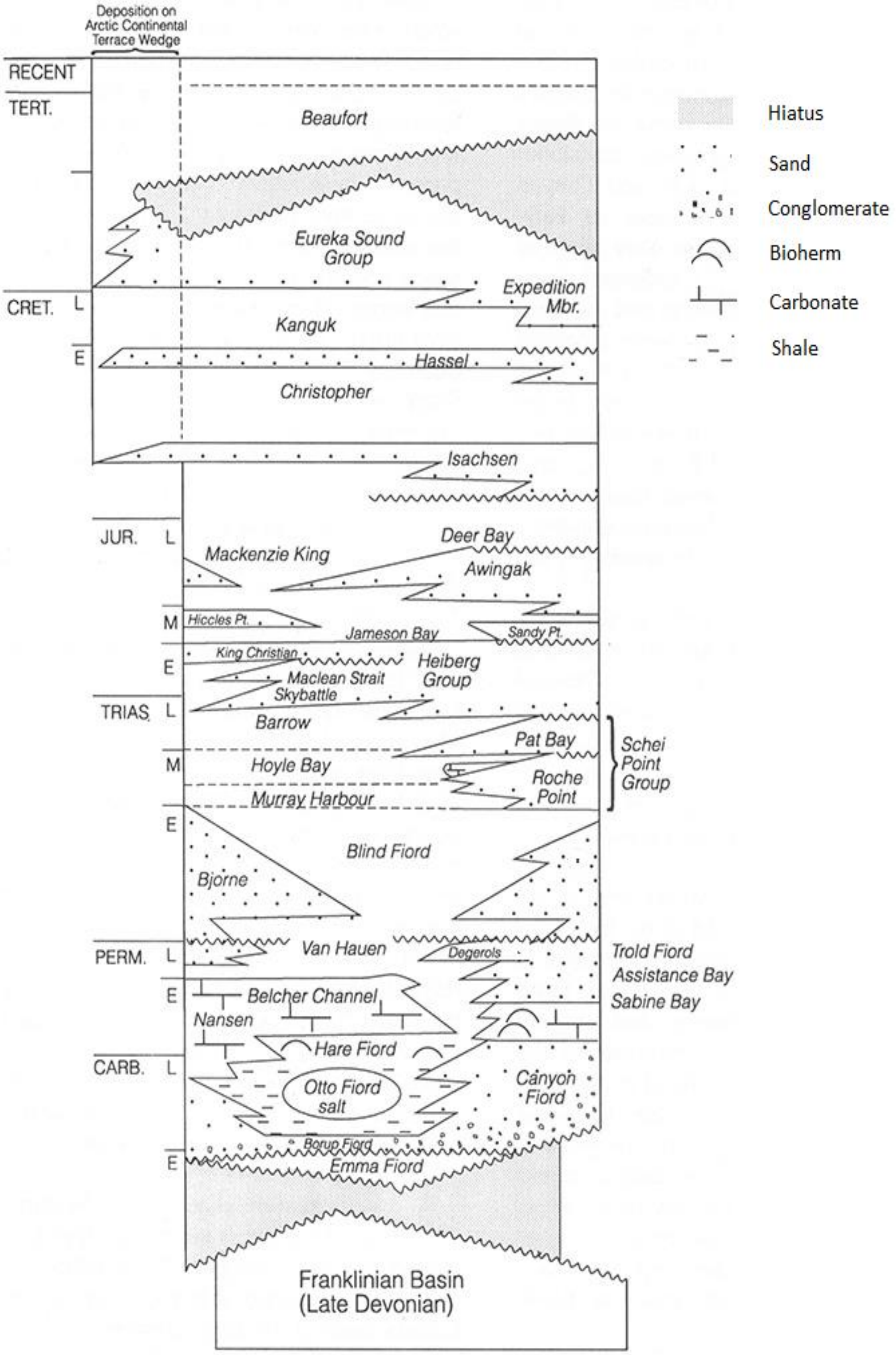


Fig. 24 Stratigraphical column of the Sverdrup Basin. Modified after Northern oil and gas directorate, 1995.

Figure 24 represents a stratigraphic column of the Sverdrup basin. The Early Carboniferous Emma Fiord lacustrine shales represent the earliest strata in the Arctic Islands, deposited after the Ellesmerian orogeny. An early phase of rapid subsidence of the Sverdrup basin is characterized by deposition of Late Carboniferous-Early Permian sandstones and conglomerates of the Borup and Canyon Fiord Formations (Northern Oil and Gas Directorate, 1995). Meanwhile, evaporites of the Otto Fiord Formation were deposited along the axis of the basin. Thick marine limestones of the Belcher Channel and Nansen Formations were deposited in the northern and eastern parts of the basin as a result of increased marine influence. Sediments of these groups are carbonate-dominated with minor occurrence of shale and local occurrence of carbonate buildups. Reef structures grew on the edges of the carbonate shelf. Evaporites of the central basin were subsequently replaced by limestones and shales of the Hare Fiord Formation. The end of the carbonate deposition is marked by shale and siltstones of the Van Hauen Formation precipitation across the basin (Northern Oil and Gas Directorate, 1995). This transition in sedimentation may be a result of the drift of the Sverdrup Basin to more northern paleolatitudes during the Late Permian. The boundary between Paleozoic and Mesozoic is marked by an unconformity at the basin margins. Mesozoic strata are mainly represented by clastic sediments (Dewing & Obermajer, 2011).

5.2 Upper Paleozoic reefs of the Sverdrup basin

During Carboniferous to Permian time extensive reefal structures have been developed by a variety of organisms within the Sverdrup Basin. These reefs are of various size, composition and shape. Upper Paleozoic reefs of the Sverdrup Basin can be divided into three main morphological categories (Fig. 25) (Beauchamp, 1993):

- Patch reefs are relatively small (less than 15 m thick and 50 m wide) bodies of lenticular shape. Sometimes patch reefs consolidate to form a larger buildup mass. However, usually they are found as isolated bodies. Patch reefs normally occur in mid- to inner-shelf settings.
- Reef mounds are sometimes referred as very large patch reefs, but unlike patch reefs, they display internal subdivision. Reef mounds are large in size (more than 150 m thick and up to 500 m wide). They can also consolidate to form much greater reefal structures. Reef mounds occur in shelf-edge and slope environments.
- Tabular banks are massive (less than 20 m thick, but some kilometers wide), structure less bodies. They are considered as buildups because they stood above the surrounding

seafloor and they consist of the same facies as patch reefs and reef mounds. Tabular banks normally occur in the outer shelf environment.

Depositional environment was the main factor controlling buildup morphology. It is supposed to reflect the availability of space for vertical and/or lateral growth of the reefs. All the types of the reefs grew on the outer shelf, shelf edge, slope or inner shelf environment below the fairweather wave base. Temperature was the major factor controlling temporal reef distribution, while water depth had a significant impact on the spatial reef distribution.

Upper Paleozoic reefs of the Sverdrup Basin were developed by the following biological components: phylloid algae, palaeoaplysinids, fenestellid bryozoans, Typiphytes, crinoids and sponges (Morin et al., 1994).

Carboniferous-Permian reefs may be grouped on the basis of main organic creators to reef or mound accumulation (Fig.26) (Davies et al., 1989):

Fenestellid Bryozoan Reefs occur in the Arctic Archipelago, Alberta, Montana and North Dakota. They are characterized by fenestellid bryozoans as main building organisms. These reefs occur on Ellesmere and Axel Heiberg Islands within the Sverdrup Basin. Fenestellid bryozoan reefs are of Moscovian age. Bryozoan reefs occupied deep water areas of the basin (middle to lower slope).

Algal Reefs are constructed by non-phylloid algae at the Late Carboniferous time and are present in the Otto Fiord Formation. They are exposed on Ellesmere Island within a cyclic limestone-anhydrite evaporitic sequence. Algal reefs occupied shallow water areas of the basin (inner and outer shelf).

Palaeoaplysinid-Phylloid Algal Reefs are composed of Palaeoaplysina and phylloid algal biota. They occur in cyclic shelf sequence of Nansen and Belcher Channel Formations on the west-central and northern parts of Ellesmere Island. These buildups are represented as patch reefs and tabular banks in outer shelf settings, while at the shelf margin and shelf slope they are of mound-like morphology.

Other Reefs and Mound Types are represented by a single occurrence of upper Sakmarian Tubiphytes-bryozoan and Artinskian sponge-bryozoan buildups within the Nansen Formation at southwestern part of Ellesmere Island. These reefs are mainly composed of fenestellid bryozoans with abundant sponge spicules.

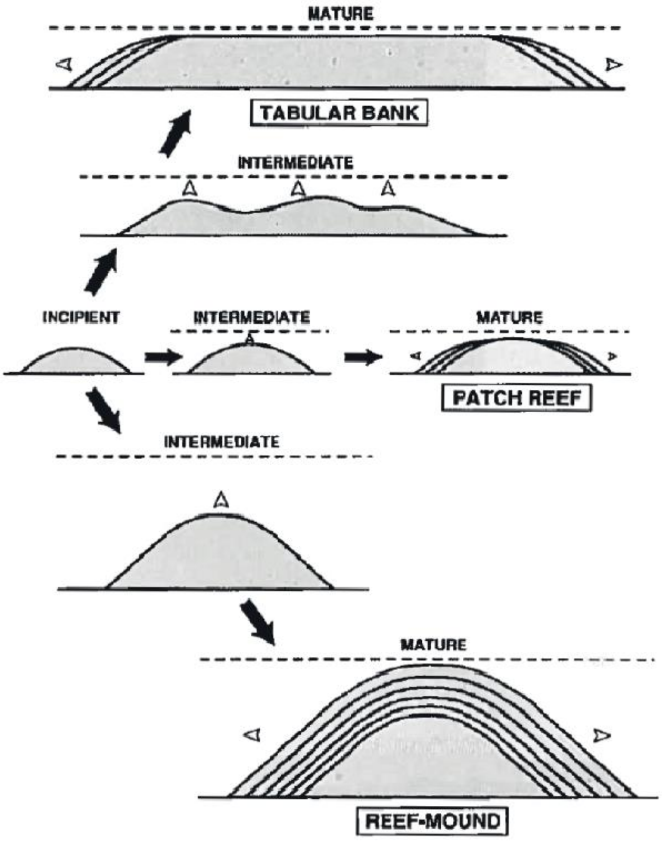


Fig. 25 Diagram showing how a mature patch reef, tabular bank and reef mound evolved from an incipient patch reef stage. The three morphological types reflect the availability of vertical and lateral space for buildup growth. Dashed line represents fair-weather base (Beauchamp, 1993).

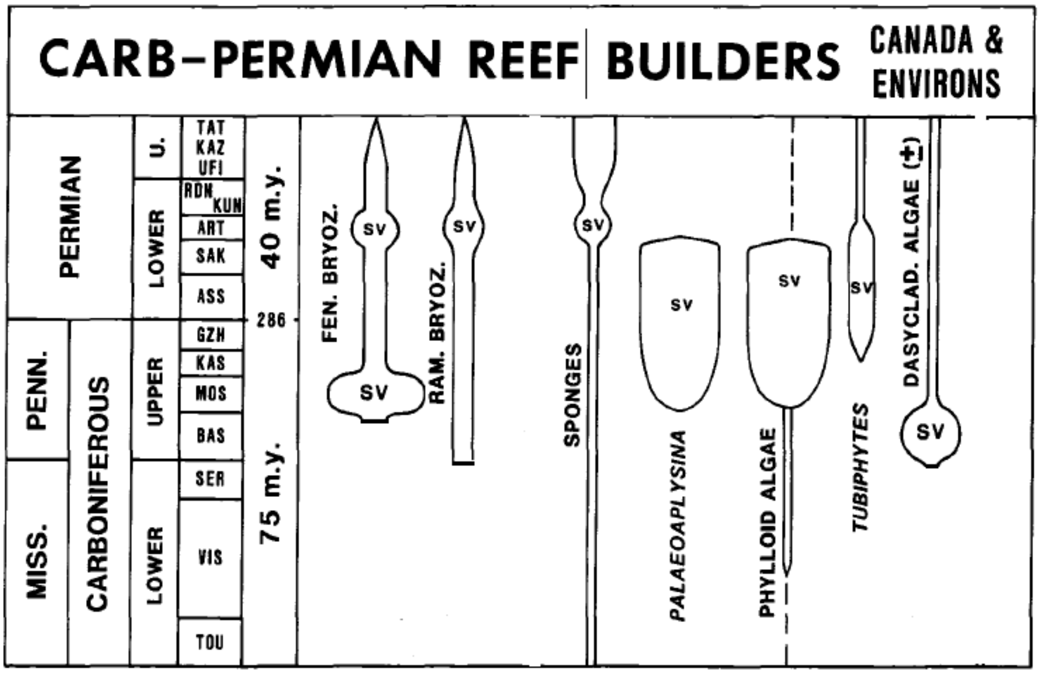


Fig. 26 Temporal distribution of Carboniferous and Permian reef builders and reef contributors in Sverdrup Basin. Overall the width of the column and its area are a subjective indication of the relative contribution of the organism to reef building. Compiled after Davies et al., 1989.

5.3 Reservoir quality of the Upper Paleozoic buildups in the Sverdrup Basin. Potential petroleum plays.

All upper Paleozoic reefal buildups of the Sverdrup Basin have their own paragenetic sequence, which to a large extent depends on the morphology, type, age and depositional and tectonic setting of the buildup. There are several diagenetic processes that effected reservoir quality of upper Paleozoic reefs in the basin: cementation, meteoric dissolution and dolomitization.

Cementation has a negative effect on reservoir properties as it is porosity reducing factor, however early marine cementation led to the preservation and stabilization of the reefal structures.

The other two processes are secondary diagenetic processes that are believed to be porosity enhancing-factors. Prolonged subaerial exposure resulted in dissolution or karstification of primary carbonates in some cases. Therefore, some primary and submarine diagenetic fabrics were dissolved to create secondary pore space. Karstification effected lime mud matrix, submarine cements and fossils, leading to development of occasionally interconnected cavities of irregular form.

Dolomitization is more of a local distribution within the Sverdrup Basin. It is apparently a later diagenetic process because its products are superimposed upon primary depositional components and submarine cements. Carbonate sediments are dolomitized either partially or completely. Completely dolomitized carbonates have a coarsely crystalline porous fabric, where only minor primary features are remnant.

Despite the fact that hundreds of upper Paleozoic reefs are present within the Sverdrup Basin, only few of them, those that underwent secondary diagenesis after cementation, have a good reservoir quality and can be considered in exploration strategy. Beauchamp (1993) has identified three most prospective reef plays within the Sverdrup Basin (Fig.27):

- Subaerially exposed tabular banks may be prospective for accumulating hydrocarbons if they have experienced a long episode of subaerial exposure that led to dissolution of the primary and diagenetic fabrics. However, another important factor is that the secondary porosity must remain unaffected by subsequent burial cementation. Nevertheless, most of the dissolved carbonates experienced this burial cementation and have a very tight fabric.
- Fault-controlled dolomitized reef-mounds that developed on the upthrown side

of growth faults may form good reservoirs. They are quite easy to identify on the seismic because of the association with extensional structures. The weakness of this play is that these fault-related dolomitized reservoirs may be of very local extent.

- Evaporite-encased dolomitized reef-mounds are the most promising prospect among the upper Paleozoic reefs in the Sverdrup Basin. Some of these reef-mounds are believed to have been subjected to subaerial exposure and erosion resulting in increased secondary porosity. This reef prospect has all the advantages of the previous two and none of their weaknesses.

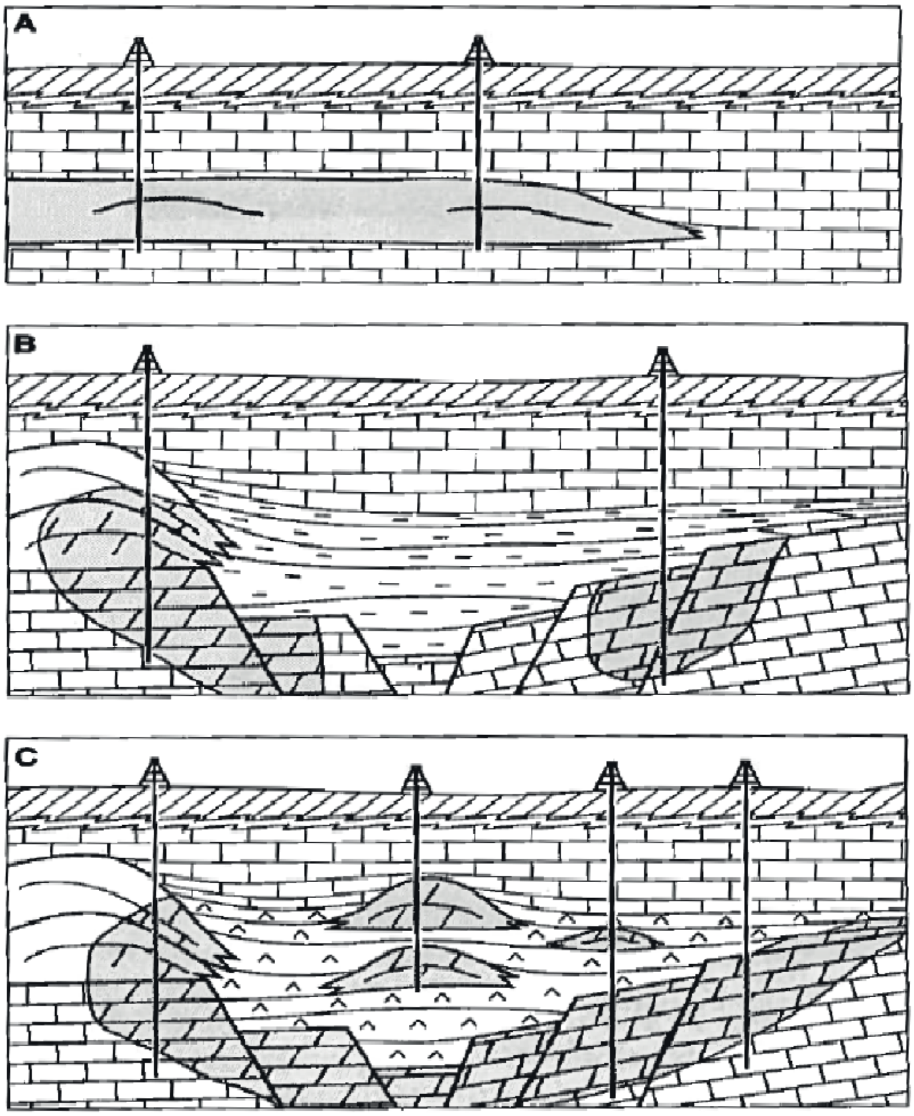


Fig. 27 Schematic representation of three potential upper Paleozoic reef hydrocarbon plays in the Sverdrup Basin. (A) Subaerially exposed, karstified, tabular bank. (B) Dolomitized, fault-controlled reef mounds. (C) Dolomitized, evaporate associated reef-mounds. (Beauchamp, 1993).

DISCUSSION

Despite the fact that petroleum exploration has been going on in the Arctic for years, it has accelerated recently. Nowadays, the significant increases in the efforts to find and develop new fossil-fuel reserves are taking place. The search for nonfuel minerals will even intensify as the technology provides improved transportation and processing methods. Thus, we are just at the starting step of the exploration phase that is supposed to result in discovery of the major resource accumulations that are present in the Arctic.

The Timan-Pechora Basin, the Sverdrup Basins and the Barents Sea represented similar carbonate-dominated basins during the Upper Carboniferous-Early Permian time as they were at approximately same latitudes (Fig.8), and having approximately same depositional environments. In the Carboniferous time all three basins were near equatorial latitudes and most of the reefs were formed by warm-water palaeoaplysinid-phylloid-algal biota. However, after the subsequent northward drift of the Arctic continents in Late Paleozoic, the depositional environment changed from tropical-temperate to temperate-boreal and warm-water biota was replaced by cool-water bryozoans-Tybiphytes biota. This facies transition can be noticed in all of the three basins, thus, similar biogenic material has formed reefal structures in the Timan-Pechora Basin, Sverdrup Basin and in the Barents Sea.

Paleozoic reef buildups have already confirmed their importance as petroleum reservoirs in the Timan-Pechora Basin and have been reviewed here to compare with Paleozoic reefs of the Barents Sea and Sverdrup Basin. Reef carbonates of Upper Devonian and Upper Carboniferous-Lower Permian age represent one of the most important reservoirs within the basin. As in the Timan-Pechora Basin, Late Paleozoic trough existed in the axial parts of the Sverdrup Basin. This trough preserved organic matter-rich sediments in anoxic to sub-oxic environment and was bounded by a belt of shelf and shelf-edge carbonate buildups identical to those that represent main reservoirs in the Timan-Pechora Basin (Beauchamp & Wahlman, 2001). Upper Paleozoic reefs of the Finnmark platform in the Barents Sea are age equivalent and have similar morphology with the reefs of the Sverdrup and Timan-Pechora Basins (Beauchamp et al., 2010).

Upper-Carboniferous-Lower Permian reefs of all three basins are mainly composed of either shallow warm-water palaeoaplysinid-phylliod or cool-water bryozoan carbonates. Thus, they could be expected to have similar reservoir characteristics, however, there is another important process that must be taken into account – diagenesis. Paleozoic carbonate reservoirs of the selected basins have experienced prolonged or repeated periods of subaerial exposure that resulted in leaching processes that lead to karstification and development of vugs, therefore enhancing the porosity within the structures. In the Timan-Pechora Basin subaerial exposure maybe a result of the tectonic evolution of the Pechora Plate and the Uralian Ocean, when the carbonate buildups were deposited in a high-energy shallow-water shelf environment during periodic fluctuations of the sea-level. Karstification and dolomitization of the Barents Sea carbonates occurred during Artinskian and younger Permian uplift that resulted in repeated subaerial exposure of these carbonate rocks. Within the Sverdrup Basin, carbonate buildups have experienced prolonged subaerial exposure that led to karstification, while dolomitization is only of local distribution. Just these carbonate buildups represent potentially good reservoirs within the Upper Paleozoic strata.

Therefore, the Sverdrup Basin and the Barents Sea Upper Paleozoic reefal structures have a good potential for containing hydrocarbons, but they need to have been sourced from the organic-rich formations and remain trapped by non-permeable rocks. The main Paleozoic reservoirs of Timan-Pechora basin are sourced from organic-rich Domanik shales of Frasnian age. Upper Paleozoic carbonate reservoirs of the Barents Sea are supposed to have been sourced from Upper Devonian-Lower Carboniferous shales and coals of the Billefjorden group and/or Upper Permian shales of the Tempelfjorden Group (NPD). Upper Paleozoic reefal reservoirs of the Sverdrup Basin may be sourced from lacustrine oil shales of the Emma Fiord Formation or a yet-unknown Carboniferous or younger source rock (Beauchamp et al., 2010).

In most cases, the carbonate sedimentation within the Arctic provinces during the Late Paleozoic time was subsequently replaced by siliciclastic-dominated sedimentation, which could have formed potential seals for trapping oil and gas inside the underlying strata.

Despite the increasing human interest to the renewable sources of energy, oil and natural gas remain the most important natural resources for all kinds of industry and are tightly connected with our everyday life. Even the most pessimistic predictions, made for the petroleum industry, acknowledge the fact that it will cover over fifty percent of the world energy demand in the nearest thirty years. However, most of the biggest hydrocarbon fields have already been discovered and there are only few places in the world that still have a potential to contain significant oil and gas reserves and Arctic is the most promising. There is no doubt that the problems of the Arctic exploration are of international character, therefore they require solutions which are also international, whether the problems are related to source exploitation, protection of the natural environment, or the development of a body of knowledge. Any decision or action of any nation, regarding to resources affect every other nation directly or indirectly; and they affect future generations as well as the present generation.

CONCLUSION

The Arctic region represents an enormous area of approximately 25 million km^2 and much of it remains unexplored because of the harsh conditions. Nevertheless, the Arctic continental shelf is one of the most prospective targets for petroleum exploration and some big discoveries have already been made there like the Prirazlomnoye oil field in the Pechora Sea or the Shtokmanovskoye natural gas field in the Barents Sea.

Upper Paleozoic carbonate buildups represent main reservoirs in the Timan Pechora Basin, but similar buildups are also present within the Sverdrup Basin and the Barents Sea. They have similar composition, morphology and have experienced same diagenetical processes during their burial history. Therefore, the Upper Paleozoic buildups of the Sverdrup Basin and the Barents Sea represent high-potential reservoirs for hydrocarbon accumulation, but they need to be sourced from the organic-rich formations and trapped by non-permeable sediments or rocks. It is obvious that these carbonate reefal structures will be one of the most important targets for future petroleum exploration in the Arctic.

The severe conditions of the Arctic have prevented human from the petroleum exploration until the technological process allowed us to do it with no harm to the environment. Since the Arctic is unique not just because of the great petroleum potential, but also because of containing significant amount of fresh water and being the habitat for variety of unique spices of fish, animals and birds, it must be treated with particular care.

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