Palaeozoic and Early Mesozoic evolution of the East Barents and Kara Seas sedimentary basins

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Detailed studies of the Palaeozoic and Mesozoic evolution of the East Barents and Kara sedimentary basins reveal complex tectono-stratigraphic and depositional histories. The present geodynamic and paleogeographic reconstructions are based on results from regional geological investigations, seismic surveys, stratigraphic studies of offshore and onshore sections and cores, as well as isotopic and geochemical data. The accumulated knowledge has made it possible to establish a tectonic framework for the Barents-Kara Region, and to compile a set of paleogeographic maps that illustrate the tectono-stratigraphic and depositional history for selected Palaeozoic-Early Mesozoic time intervals. The geological history of the region can be separated into the following main phases: 1) Ordovician to Early Devonian passive continental margin, 2) Early Devonian (Lochkovian to Eifelian) shelf destruction, 3) Mid to Late Devonian (Givetian to Early Frasnian) pericontinental rifting, 4) Late Devonian to Early Carboniferous development of marginal basins, 5) Carboniferous to Permian ocean closure and collision, 6) Late Permian to Triassic Uralian orogeny, followed by 7) formation of epicontinental basins from the Early Jurassic and onwards. The East Barents Basin is interpreted as the fore-deep caused by the Uralian collision and orogeny. The formation of hydrocarbon deposits is attributed to the main convergent phase of geological evolution of the Barents-Kara region.

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Introduction

The Barents-Kara Region has become a key petroleum province of the world with proven and forecasted gigantic oil and gas hydrocarbon resources recognised in different hydrocarbon plays (Gusev & Suprunenko 2004; Suprunenko et al. 2007). Consequently, this part of the Russian Arctic shelf has been a target of intensive geological and geophysical investigations during the past decades (Gramberg et al. 2004). However, many aspects of the geological history of this region have had differing or controversial interpretations (Verba 1985; Gramberg 1988; Korago et al. 1992; Gavrilov 1993; Johansen et al. 1993; Aplonov 1996; Gramberg 1997; Daragan- Suschova et al. 2000; Gramberg et al. 2004; O'Leary et al. 2004; Otto & Bailey 2005; Petrov et al. 2005; Ivanova et al. 2006; Ebbing et al. 2007; Buiter & Torsvik 2007; Petrov et al. 2007). This is particularly the case for the tectono-stratigraphic and the paleogeographic reconstructions defining the framework for depositional regimes through geological time, including those where hydrocarbon deposits have formed.

At the All-Russian Geological Research Institute (VSEGEI), integrated studies of the North Eurasian sedimentary basins are currently being undertaken as a component of a major national project. The main goal of this project is to compile models of the geological structures and geodynamics of the Eurasian sedimentary basins based on a comprehensive compilations and integrations of existing and new regional data. The geological and geophysical studies of the whole of the Barents Sea and the western part of the Kara Region are undertaken in collaboration with the Geological Survey of Norway (NGU), StatoilHydro ASA and the Norwegian Petroleum Directorate (NPD). This study will result in the publication of an an atlas presenting a fully integrated coverage of potential field maps and a series of paleogeographic maps covering the entire Norwegian and Russian sectors of the Barents Sea and extending eastwards into the Kara Sea region.

The aim of the present paper is to show the broad features of the Palaeozoic and Mesozoic evolution of the East Barents and Kara sedimentary basins within a tectono-stratigraphic and paleogeographic framework. The present geodynamic and paleogeographic reconstructions are based on results from a series of regional geological investigations, seismic surveys, stratigraphic studies of offshore and onshore sections and cores, as well as isotopic and geochemical data.

The accumulated knowledge has made it possible to compile a tectono-stratigraphic framework (Fig. 1), and

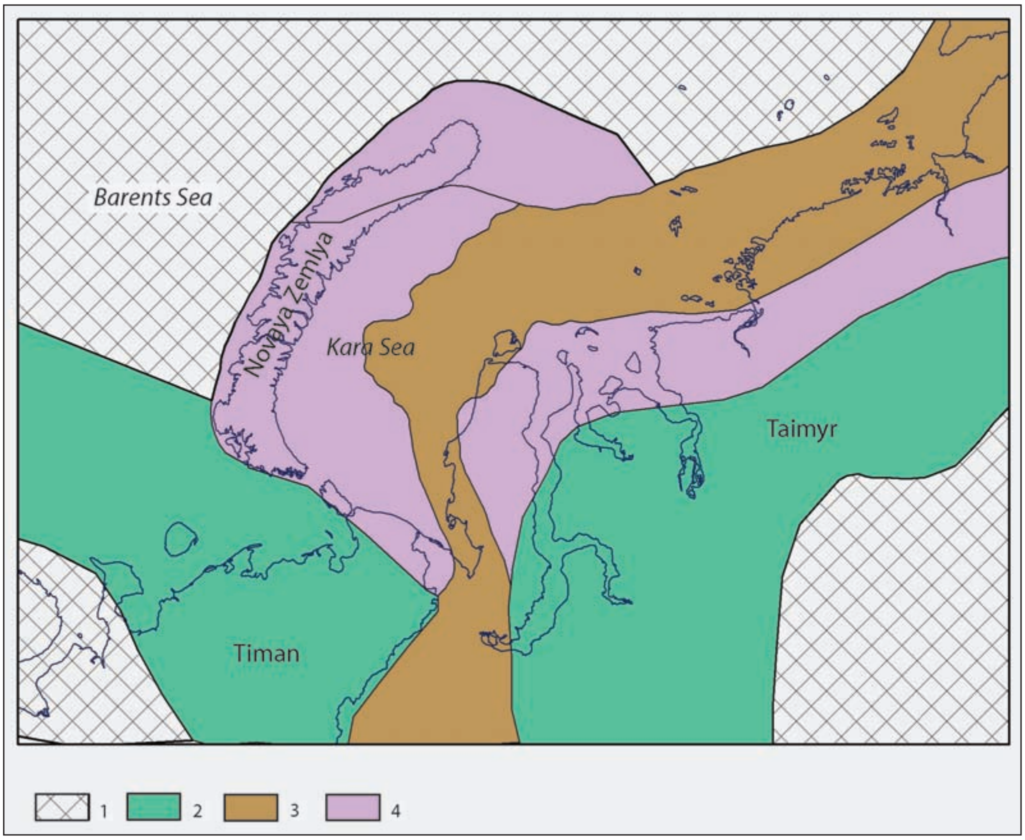

Fig. 1. Schematic map showing the main tectonic units of the Barents-Kara region basement. Legend: 1 - pre-Baikalian/Timanian cratons, 2 – Baikalian/Timanian (Late Neoproterozoic) fold belts 3 - Hercynian (Late Palaeozoic) orogenic belt, 4 –Cimmerian (Late Triassic – Early Jurassic) fold belt.

to provide a refined interpretation of the deep seismic profiles such as 2-AR and 3-AR (Petrov et al. 2005). In the eastern part of the region a fold belt is clearly distinguished. The isotopic ages of granites located in Taimyr and Severnaya Zemlya (Gramberg & Ushakov 2000) dates the folding as early Hercynian (Early Carboniferous) on North Taimyr and early Cimmerian (Late Triassic – Early Jurassic) on South Taimyr and Severnaya Zemlya. The area of the early Hercynian folding extends from North Taimyr through the South Kara Shelf to the Urals. Early Cimmerian folding is revealed on Novaya Zemlya, Pai Khoi, the western part of the South Kara Shelf, Jamal and Southern Taymir.

A set of paleogeographic and lithofacies maps was compiled for 11 time slices within the Palaeozoic to Early Mesozoic. These maps are used as a base for interpreting the geodynamic processes that led to the formation of the Taimyr-Novaya Zemlya fold belt. The maps further serve as key tools for understanding the tectonic influences on the sedimentation patterns and depositional history of the basins.

Main tectono-stratigraphic phases and paleogeographic settings

The geological evolution of the Barents-Kara Region is intimately related to the development of the Uralian Ocean; an ocean that formed along the eastern margin of Baltica by Ordovician rifting (Zonnenshain 1990). Subsequent closure of the Uralian Ocean in the Carboniferous-Permian, and continuing into Triassic time, led to continent-continent collision between Baltica and Kazakhstan and the formation of the Ural Mountains south of Pai-Khoi (Zonnenshain 1990). The paleogeographic settings and lithofacies patterns indicate seven main, tectono-stratigraphic phases within the Ordovician to Triassic time interval. These start with the Ordovician to Early Devonian, passive, continental margin phase, followed by Early-Mid Devonian

Age	Geodynamic settings
J–N	Epicontinental basins
P_2–T	Orogeny
C_1–P_2	Collision
D_3fr^2–C_1	Formation of marginal basin
D_2–D_3fr^1	Pericratonic rifting
D_1p–e – D_2	Shelf destruction
O_1 – D_1 l	Passive margin

Fig. 2. Overview of the main tectono-stratigraphic phases of the Barents-Kara Region.

shelf destruction, Mid-Late Devonian pericontinental rifting, and the development of marginal basin in the Late Devonian to Early Carboniferous. The subsequent phases are associated with the Uralian movements with an Early Carboniferous to Late Permian collision phase and a Late Permian to Triassic orogenic episode (Fig. 2). The tectono-stratigraphic development described here was terminated by the development of epicontinental basins from the beginning of the Early Jurassic, which has continued to the present day.

The passive continental margin phase

The passive continental margin phase extended from Early Ordovician to Early Devonian time. The Lochkovian map (Fig. 3) shows the paleogeographic situation near the end of this phase. The distribution of non-marine terrigenous sediments in the northwest of the Barents Region documents the existence of alluvial, lowland settings. The non-marine red beds are traced along the paleo-Barents Sea shore of Novaya Zemlya, from the Gribovaya Bay in the south to the Russkaya Gavan' in the north. They commonly contain intercalations of marine near-shore dolomites, whereas limestone layers are more rare. The red beds are replaced by carbonate deposits, which were accumulated in the extensive shallow-water basin. This shallow-water basin contained anhydrides, chemogenic and biogenic carbonates, stromatolitic limestones, mudstones and siltstones with subordinate coquina or detrital limestone layers.

The shelf destruction phase

The subsequent Pragian–Emsian phase is typified by a transgression of marine sediments to the northwest, resulting from destruction of the shelf. At this time, pre-rifting activation led to the formation of sediment-starved, deep-water troughs (Fig. 4). They were filled up by organic-rich black shale deposits whereas carbonate build-ups were formed along their margins. It is suggested that deep-water marine settings were migrating in a westerly direction during the Early Devonian.

The pericratonic rifting phase

An active phase of pericratonic rifting took place in the late Middle and early Late Devonian (Givetian to early Frasnian) (Figs. 5-6). By this time, the transition from a stable, passive continental margin to an active margin was completed, and this is expressed in the subduction of the Uralian oceanic crust beneath the southeastern part of the Barents Shelf. This process was accompanied by pericratonic rifting. By the early Frasnian, rifting was accompanied by intensive basaltic eruptions, well documented in the Novaya Zemlya and Timan-Pechora regions. Two different types of magmatic setting are recognised in Novaya Zemlya. The first one is present in the eastern and central parts of the South Island and is represented by pillow lavas with siliceous layers; the second one is exposed along the western shore and the southern part of Novaya Zemlya and includes thick volcaniclastic rocks dominated by tuffs (Timofeeva 1982; Korago & Timofeeva 2005).

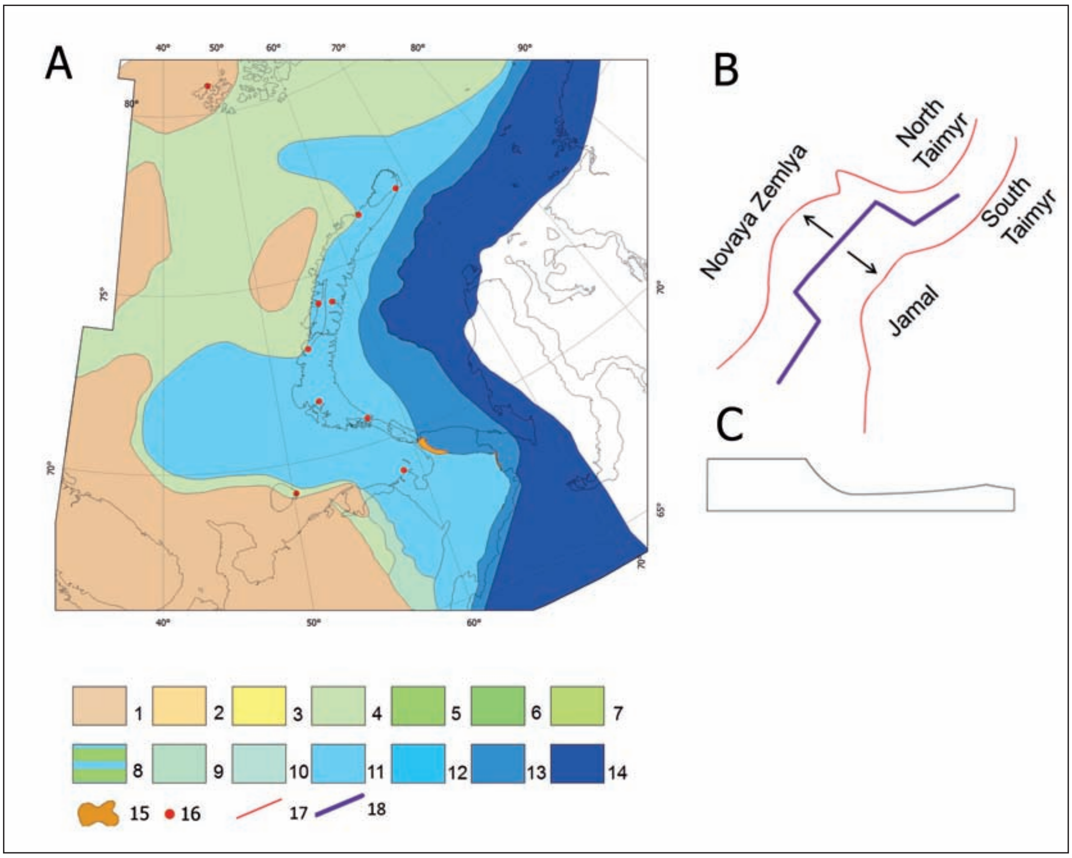

Fig. 3. The passive margin phase of the Barents-Kara Region, illustrated by the paleogeographic map for the Lochkovian (A), simplified sketch (B) and profile (C), showing paleogeographic settings. Legend: 1 - highlands, 2 - denudation plains, 3 - fans, 4 - accumulative plains, 5 - alluvial flats, 6 - lakes, 7 - deltas, 8 – periodically flooded areas, 9 - coastal zones, 10 -shallow-water shelf, 11 - shelf plains, 12 - deep-water shelf, 13 - basin and continental slope, 14 -oceanic basin, 15 - reef complexes, 16 - reference sections, 17 - continental margins, 18 - oceanic rifting.

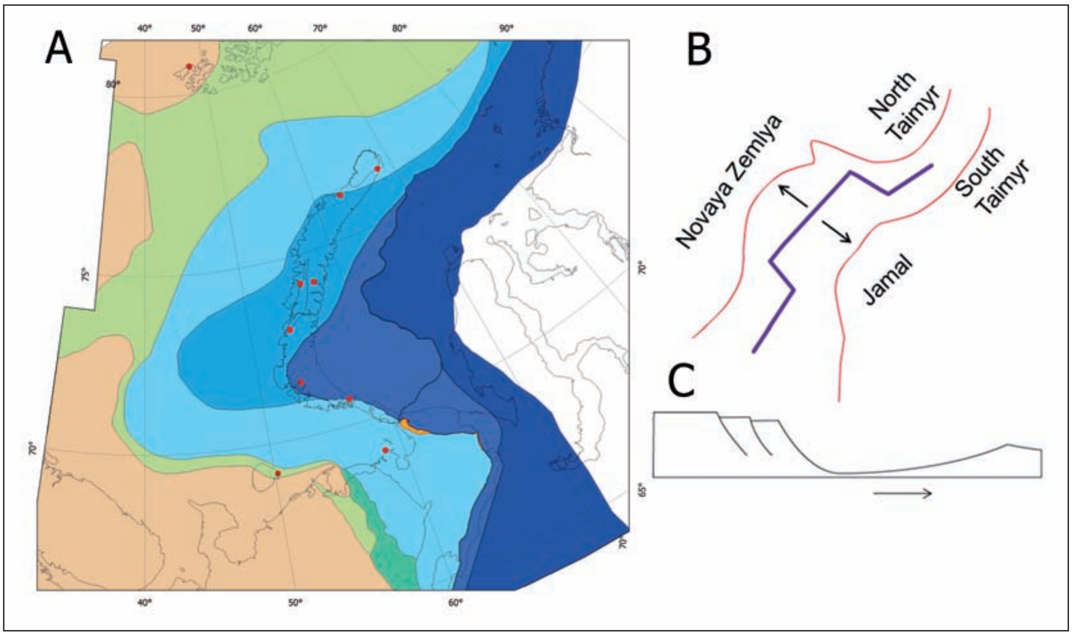

Fig. 4. The shelf destruction phase, illustrated by the paleogeographic map for the Emsian (A), simplified sketch (B) and profile (C), showing paleogeographic settings. For legend see Fig. 3.

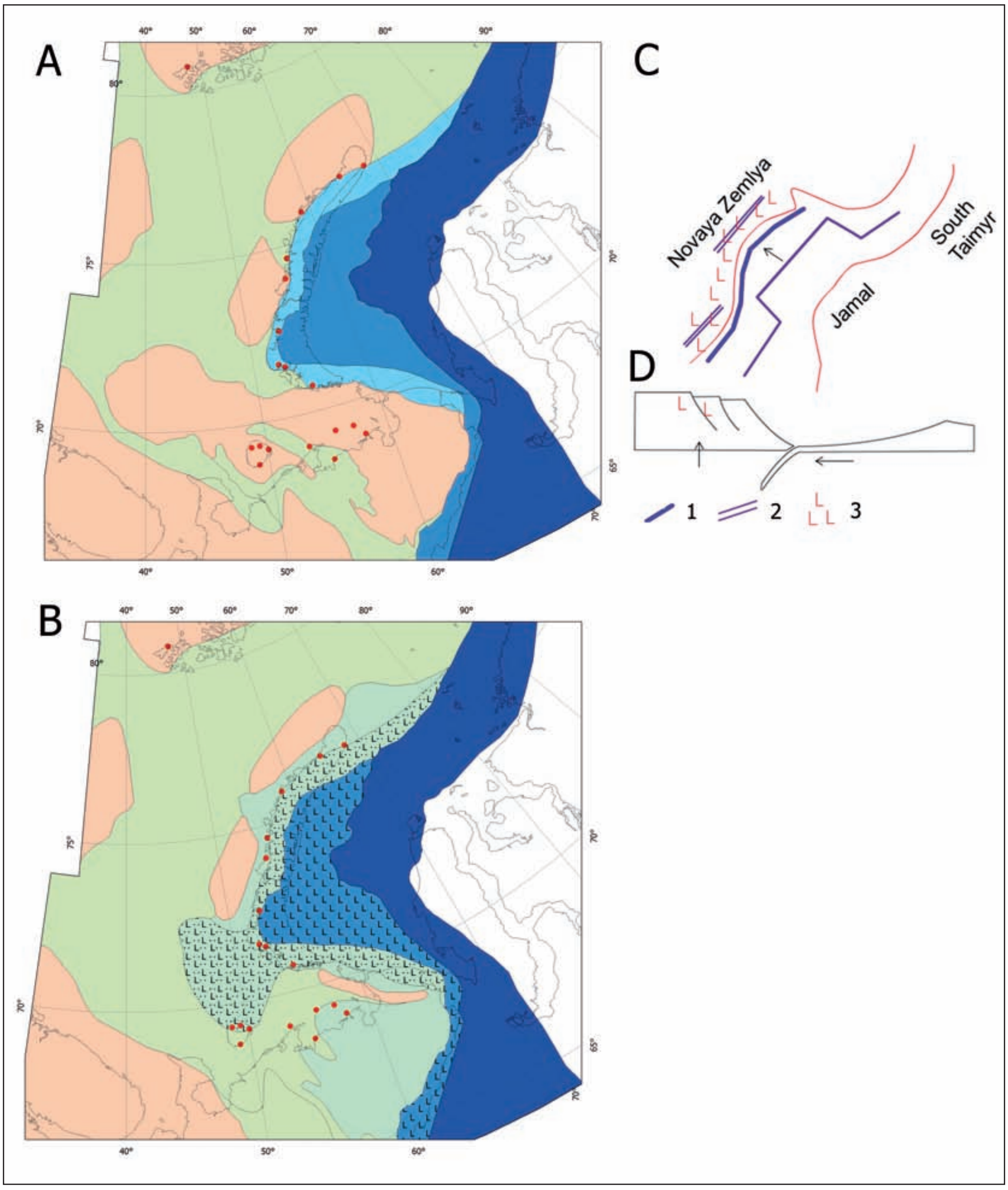

Fig. 5. The pericratonic rifting phase illustrated by the paleogeographic and lithofacies map for the Givetian (A) and for the late Frasnian (B); simplified sketch (B) and profile (C), showing paleogeodynamic settings. Legend: 1- subduction zone, 2 - pericratonic rifting, 3 - basalts; for the rest - see legend to Fig. 3.

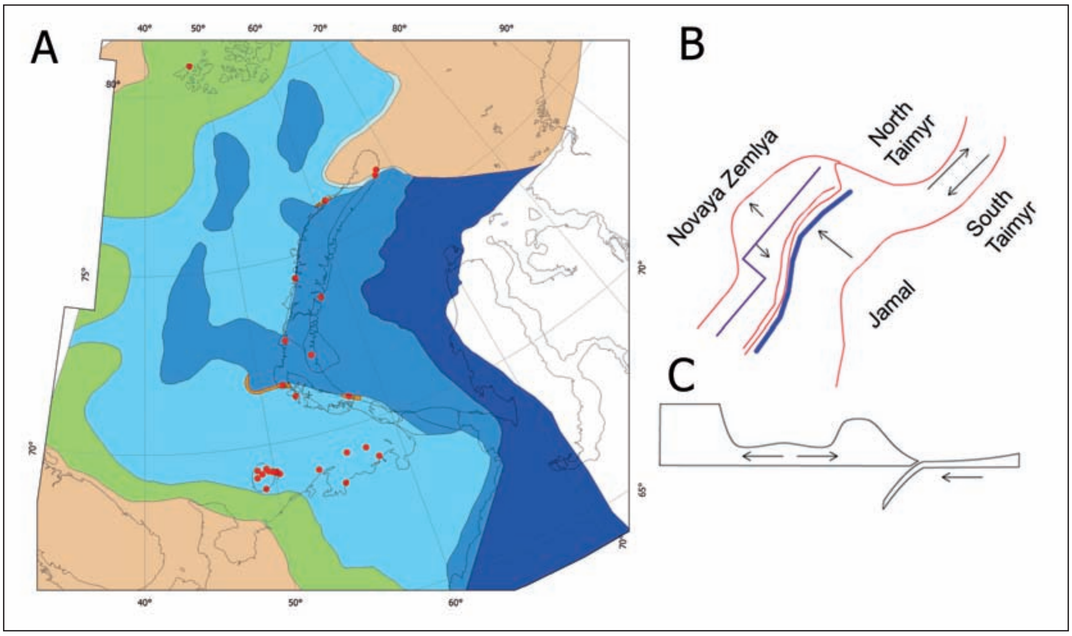

Fig. 6. The marginal basin phase illustrated by the paleogeographic map for the Late Devonian (late Frasnian) - Early Carboniferous (A), (B) – simplified sketch and profile (C), showing paleogeodynamic settings. For legend see Figs. 3 and 5.

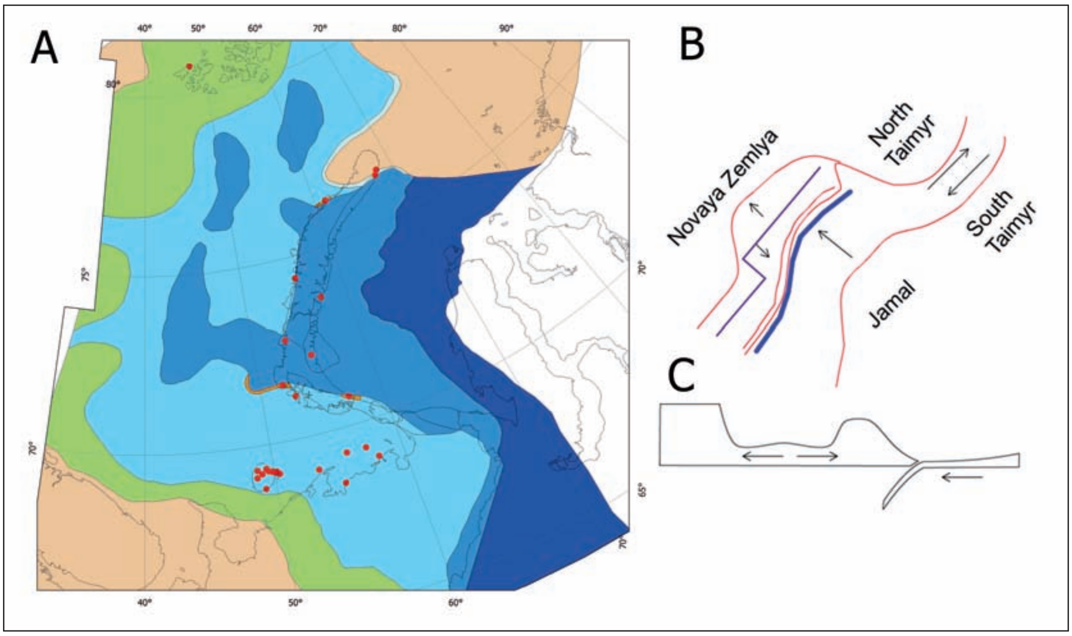

Fig. 7. The collision phase illustrated by the paleogeographic map for the Asselian (A), sketch scheme (B) and profile (C), showing paleogeodynamic settings. For legend see Figs. 3 and 5.

The formation of a marginal basin

A marginal deep-water basin caused by rifting, and bordered by a magmatic arc, was formed in Novaya Zemlya and the adjacent part of the Kara Shelf from Late Devonian through Early Carboniferous time (Fig. 7). In this deep basin, interbedded pelagic biogenic cherts and carbonates accumulated. In the central part of the East Barents Region, a carbonate platform existed at this time.

The collision phase

During early Late Carboniferous through Permian time, the paleogeographic settings in the Kara Region were influenced by collision and orogeny. By this time, the final closure of the Uralian Ocean took place as a result of an inferred collision of the Yamal-Gydan Plate and the island arc bordering the Novaya Zemlya marginal basin. This assumption is supported by seismic data that shows evidence of folding within the eastern part of the South Kara Basin during Carboniferous and Permian time (Petrov at al. 2005). Along the eastern edge of the Barents Plate, the carbonate shelf was gradually destroyed. This caused a filling of the Novaya Zemlya foredeep with terrigenous material derived from the growing Kara Orogen (Fig. 8). Seismic data suggest the existence of inter-montane troughs and depressions in the distal parts of the orogen. On Novaya Zemlya, deep-water cherts and turbidites accumulated. At the same time, numerous reefs were formed along the margins of sediment-starved, deep-water troughs within the Barents Plate.

The orogenic phase

In the Late Permian to Early Triassic, the final phase of the Hercynian deformation resulted in Uralian orogenesis building and closure of the marginal basin in Novaya

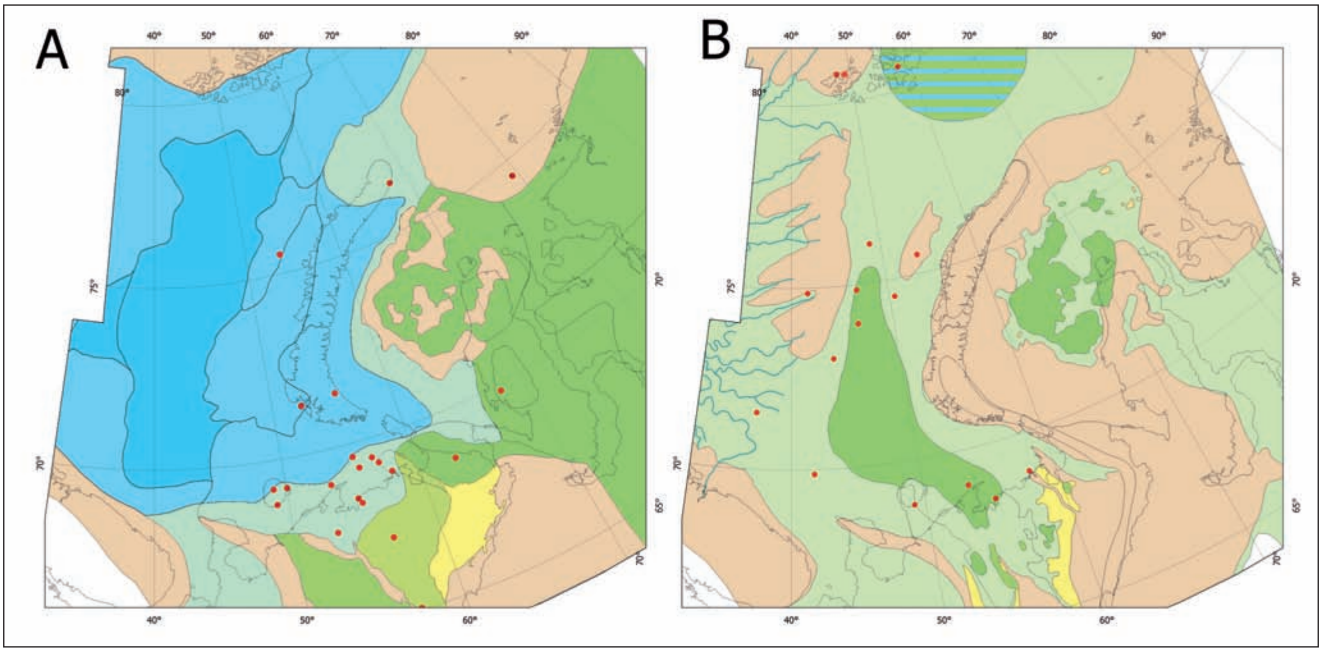

Fig. 8. The orogenic phase illustrated by the paleogeographic map for the Roadian/Wordian (A) and the Carnian (B). For legend see Fig. 3.

Zemlya. In the beginning of the Late Permian time the subsidence continued, accompanied by turbiditic sedimentation. At the same time, the remnant shallow-water basin continued to cover a vast area (Fig. 8). Most probably, the development of the Pai-Khoi – Novaya Zemlya fold structures in the Triassic resulted from thrusting of the island arc above the Barents Plate. Several models have been proposed for the westward displacement of Novaya Zemlya, including those models of Otto & Bailey (1995) and Torsvik & Andersen (2002) suggesting large convergence estimates of 500-700 km. These estimates require a scenario where Novaya Zemlya first was involved in the Uralian Orogeny (and forming a near-linear continuation of the Uralian Belt), and then subsequently thrusted into the Barents Sea to reach its more westerly position. In a more recent model, Buiter & Torsvik (2007) assumed that Novaya Zemlya was already in a more westerly position by Late Triassic-Early Jurassic times, and speculated that it may not have been aligned with Taimyr and the Uralian Belt. In this model, the westward movement occurred in the Late Triassic-Early Jurassic and was limited in magnitude to 100-200 km (Buiter & Torsvik 2007).

By the end of the Triassic the whole of the Eastern Barents Sea-Kara Sea area was covered by non-marine sediments. Istopic studies of detritial zircons from the Triassic deposits of the East Barents region have provided some ideas about their origin (Khudoley 2007). Most probably, these deposits were derived from erosion of the Hercynian fold belt and pre-extsiting island arc.

Epicontinental basins

Towards the end of the Triassic a unified Barents-Kara Megaplate had formed. As a result of subsidence, epicontinental marine basins originated in the Early Jurassic. During Early and Middle Jurassic time, continental and marine deposition was widespread in the East Barents Basin, which is interpreted as a foredeep resulting from the Uralian collision and orogeny. A major regional transgression was initiated by early Late Jurassic time (i.e. in the Middle Oxfordian) (Smelror 1994; Smelror et al. 2001), and by the end of the Jurassic period the entire Barents Shelf had been transgressed and shallow-shelf to deep-marine sedimentation prevailed over large areas (Johansen et al. 1993) (Fig. 9). During the Early Cretaceous the north-eastern Barents Sea area was uplifted and large amounts of sediment were shed from the uplifted continental areas in the northeast into deeply subsiding basins in the west (Olaussen et al. 2004). This uplift was associated with basic volcanism which occurred on Franz Josef Land and adjacent offshore areas. By Late Cretaceous time, large parts of the Barents Shelf were uplifted, a situation that continued into Cenozoic times and controlled the sedimentation pattern over most of the region.

Distribution of hydrocarbons

Several large oil and gas discoveries have been made in the Eastern Barents Sea-Kara Sea Region, including the giant Shtokmanovskoe gas field, and the Ledovoe, Ludlovskoe and Prirazlomnoe fields on the Barents Shelf, and the Rusanovskoe and Leningradskoe fields on the Kara Shelf (Fedorovsky et al. 1993; Johansen et al. 1993; Suprunenko et al. 2007). The most prolific, potential hydrocarbon source rock in the region is the Late Devonian Domanic shale (Gurari 1981; Ulmishek 1988; Alsgaard 1993). This marine shale was deposited at times of eustatic highs and basin subsidence during the

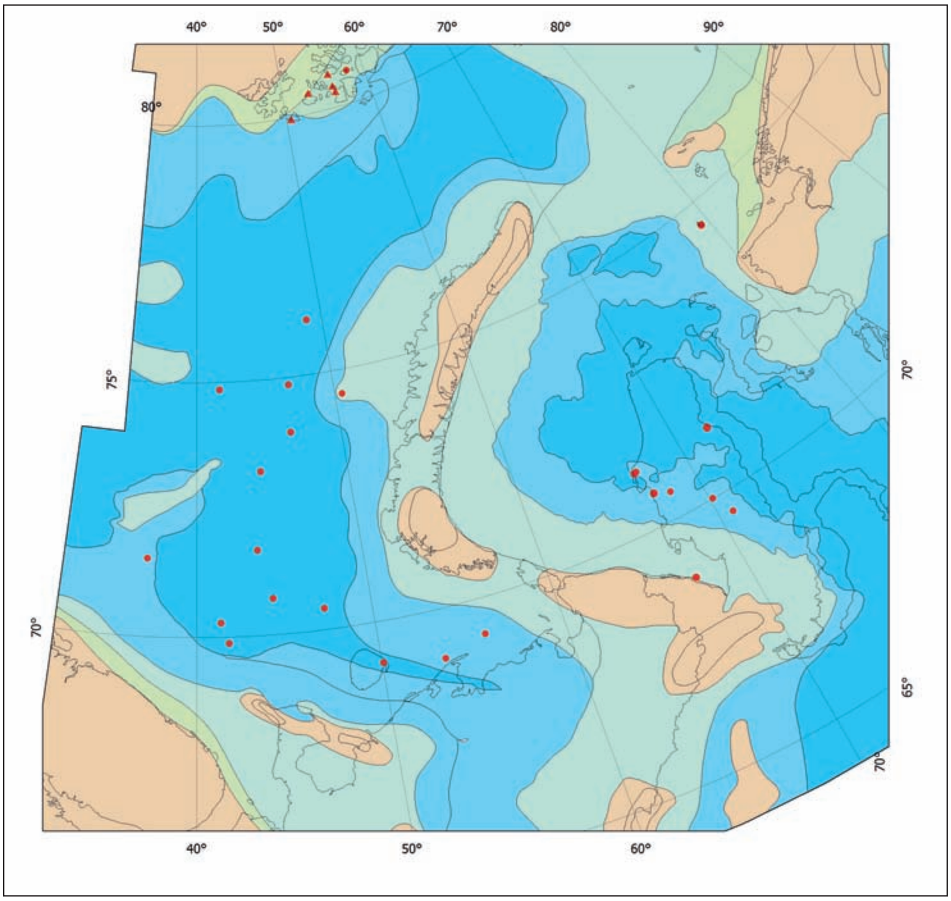

Fig. 9. The epicontinental basin phase illustrated by the paleogeographic and lithofacies map for the Tithonian. For legend see Fig. 3.

marginal basin tectono-stratigraphic phase. In the subsequent Mid Carboniferous to Permian collision phase, carbonate structures (reefs) were developed, which later became the reservoirs for hydrocarbon accumulations.

Among the main features of the Late Permian-Triassic orogenic phase are the substantial thicknesses of the succession formed during times of high sedimentation rate and by subsequent horizontal tectonic compression, which generated anomalously high intra-formation pressures and active fluid migration. Taking into account the fact that Triassic deposits comprise mostly mudstones and siltstones, it can be suggested that a vertical hydrocarbon migration prevailed over lateral migration. This possibly resulted in accumulation of hydrocarbons in the channel and deltaic sedimentary strata covering the East Barents Basin.

Conclusions

The present geodynamic and paleogeographic reconstructions document that the Palaeozoic and Mesozoic tectono-stratigraphic and paleogeographic development of the East Barents Region appear closely connected with the evolution of the Uralian paleo-Ocean. In the South Kara Region and North Siberian Arch, an influence of the Hercynian orogeny is recognised. The Novaya Zemlya sedimentary basins are interpreted as marginal basins resulting from the peri-cratonic rifting near the Middle to Late Devonian boundary. The East Barents Basin is interpreted as a foredeep caused by the collision and orogeny.

The formation of hydrocarbon is attributed to the convergent phase of the regional geological development. In the Mid Carboniferous to Lower Permian hydrocarbon reservoirs are found in the zones of the carbonate shelf destruction and reef belts, while in the Triassic they are confined to the deltaic and river-bed deposits in the East Barents Basin.

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