Chapter 14

Lower Permian and Devonian carbonate reservoir rocks in the onshore and offshore areas of the Pechora Sea

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Abstract: In the northern part of the Varandey–Adzva zone carbonate reservoirs have developed that have porosity favourable for oil and gas accumulations. The void space in these reservoirs, besides primary porosity, is associated with fracturing, giving rise to good reservoir potential in both the onshore and offshore parts of the Varandey–Adzva zone. The similarity of today’s structure and the development during the main stages of geological history for offshore and onshore parts, the availability in the section of productive oil- and gas-bearing reservoirs, the high capacity of the reservoirs, the uniformity of lithofacial composition of the productive intervals and the uniqueness of the deposits structure – all these features contribute to the oil and gas potential of the Pechora Sea structures.

Supplementary material: Supplementary Tables 14.1–14.7 are available at http://www.geolsoc.org.uk/SUP18473.

The Pechora Sea covers the offshore part of Timan–Pechora Basin, one of the major oil-producing regions of the European part of Russia. The geographical location and the availability of substantial oil and gas reserves have led to intensive development of the oil and gas resources of its onshore part. Exploration is also important, not only within the well-known onshore area, but also in the basin’s offshore part, which is less well understood. Oil and gas prospects in the Pechora Sea occur in Palaeozoic carbonate reservoirs and in Permian–Triassic sandstones. The Peschanoe–Dolginian gas condensate–oil fields were discovered in the terrigenous Triassic and Permian reservoirs on Kolguev Island. The Pomorskoye gas condensate field in the offshore extension of Kolva Megaswell occurs in Carboniferous–Lower Permian carbonates. The major oil and gas prospects of the Pechora Sea occur in the NE. There the Pirzalzommoye, Varandey–More and Medyn–More oil fields and the Dolginskoye and Severo–Gulyaevskoye gas condensate–oil fields were discovered in the offshore extension of the Varandey–Adzva structural zone in Lower Permian–Carboniferous carbonate reservoirs. Oil prospects in Devonian carbonate strata occur in the Medyn–More, Varandey–More and Pirzalzommoye fields. Lower Permian and Devonian carbonate complexes contain substantial reserves and resources of oil and gas. Despite their reservoir complexity, they are of interest for the development of already discovered oil pools and for prospecting for new hydrocarbon accumulations.

Detailed studies of the carbonate reservoirs of the Timan–Pechora oil fields have shown the necessity of using nonstandard methods of core sample analysis, to assess the producing formations structural inhomogeneity. Also, special attention was paid to fields in the Varandey–Adzva structural zone, where the main oil prospects are associated with Devonian and Carboniferous–Permian reservoirs. This paper describes the results of integrated analyses of core samples from the fields of the Sorokin and Medynsky swells, performed in VNIGNI, and gives a forecast for the reservoir quality in the offshore part of Varandey–Adzva structural zone.

Geological structure

The Timan–Pechora Basin represents a region with heterogenic structure, where rigid blocks of the ancient platform are fragmented by zones of Early Palaeozoic, Devonian and probably Riphean continental rifting. The Pechora–Kolva and Varandey–Adzva aulacogens formed in place of rift troughs; Varandey–Adzva aulacogen is called the Varandey–Adzva structural zone (Fig. 14.1) in the literature. Late Palaeozoic (early Permian) inversion led to the formation of inversion swells within their limits (Burlin & Stoupakova 2008). The eastern structures of the Varandey–Adzva zone and depressions of the marginal troughs have been subjected to the effects of the Baikalian Pay–Khoy and Hercynian Ural folding. As a result, the Varandey–Adzva structural zone and the marginal troughs’ depressions are the most complicated tectonic elements of the Timan–Pechora Basin. They are highly fractured and tectonic activity has also affected the sedimentary fill, with multiple discontinuous faults, joining and dislocation zones.

The Varandey–Adzva structural zone is asymmetrical due to the active interference of the Polar Ural–Pay–Khoy fold zone. Along Upper Palaeozoic horizons there is a system of highly dislocated inversion uplifts and thrusts adjacent to the Pay–Khoy and Ural fold systems. In the west and east the Varandey–Adzva structural zone is limited by uplifted blocks of basement – the Bolshezemelskoye and Korotaikinskoye blocks, respectively.

Commercial oil prospects in this zone are identified within the limits of the Medynsky, Saremboysky, Sorokin and Gumburtsey swells. The main producing horizons are associated with Lower Palaeozoic, Silurian–Lower Devonian and Carboniferous–Lower Permian carbonate reservoirs. The same complexes are productive in the offshore extension of the Varandey–Adzva zone, where the offshore parts of the Sorokin and Medynsky swells are marked, along with the Gulyaevskoye and Dolginsky swells. The swells are complicated by local structures.

The Sorokin Swell is the western linear margin of the Varandey–Adzva structural zone. The swell is a horst, about 10 km wide and 150 km long. In the onshore part of the Sorokin Swell the following structures are marked from south to north: Khosolinskaya, Osoveyskaya, Syamayuskaya, Yareyaginskaya, Sedyaginskaya, Laboganskaya, Naulskaya, Yuzhno–Toraveyskaya, Toraveyskaya and Varandeyskaya. In the Pechora Sea the swell includes the Varandey–More and Pirzalzommaya structures (Fig. 14.2). The majority of the structures are narrow brachyanticlines with limbs dipping at angles from 3–6° in the NE up to 8–10° in the SW; discontinuous faults have throws from 50 to 150–200 m.

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All of the local structures trend NW and are 10–20 km long and 3–4 km wide, with amplitudes in Lower Permian strata of about 50 m. The maximum amplitude is identified in the central part of the swell, in the Sedyaginskaya structure, where in Lower Permian carbonate strata it is equal to 700 m. The amplitude is less along-strike; at Varandey onshore it is 600 m and offshore it is reduced further, from 500 m at Varandey–More to 300–350 m at Prirazlomnaya.

The producing horizons in these structures are associated with Early Permian bioherm buildups in thinly interbedded shaly-carbonate units. The total thickness of hypothetical bioherm buildups varies from 30 to 100 m.

The system of linear swells of the Varandey–Adzva zone’s eastern flank is formed along regional faults of upthrust type. From south to north these are the Saremboysko–Lekkeyaginsky, Talotinsky, Medynsky and Dolginsky swells. They extend in a

Fig. 14.1. Major structural and tectonic elements of the north of the Timan–Pechora Basin (compiled by the materials of the KOMI SO of the Russian Academy of Sciences and SMNG). 1–6, Structural elements: A, Izhma–Pechorskaya depression; B, Malozemelskaya, Kolguevskaya monocline: B1 – Udachnaya step, B-2, Naryan–Mar step; C, Pechora–Kolva aulacogen; C1, Shapkin–Yurjakha Swell; C2, Denisov Trough; C3, Laisky Swell; C4, Kolva Swell; C5, Pechora–Kozhva Megaswell; D, Bolshezemelsky Dome (Khoreyver depression); E, Varandey, Adzva structural zone; E1, Sorokin Swell; E2, Moreyusskaya depression; E3, Saremboy, Lekkyaginsky Swell; E4, Gamburtsev Swell; E5, Vorkheadvinskaya depression; E6, Talotinsky Ridge; E7, Medynskyi Swell; F, Koroitakha depression; F1, Vashutkin–Talotinskaya zone of thrusts; F2, Labogeiskaya step; F3, Odindokskoye uplift; F4, Vorkheadvinskaya zone of dislocations; F5, Pestantorskaya folding and thrust zone; F6, Sabryaginskaya folding and thrust zone; G, Chernov Ridge; L, Chernyshov Ridge; L2, Kosya-Rogovskaya Trough.

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Fig. 14.2. Geological cross-section of the Sorokin Swell (Zakharov & Timonin 1998).
NNW direction and are 50–40 km long and 4–3 km wide. Regional unconformities have ancient burial and determine the swells’ morphology as asymmetrical horsts. The amplitudes of vertical displacement decrease up the section: from 600–700 m in the Lower Carboniferous to 150–200 m in the Lower Triassic. In contrast to the faults identified onshore, the upthrusts limiting the Dolginsky Swell in the north of the Pechora Sea have small displacement amplitudes, practically constant across the whole section, 50–100 m. The upthrusts are cut by shears of NW trend: the horizontal displacement along them can achieve 3 km.

A new technique for studying fractured and vuggy carbonate reservoirs

The discovery of large and giant oil and gas accumulations in carbonate reservoir rocks of various ages and origins, with significant variation in porosity and permeability, requires a reliable evaluation method. The early lithification and proclivity to fracturing and differential solution, which are typical of carbonates, give rise to diverse morphology and the development of a wide range of reservoir rock types (Bagrintseva et al. 2007). Among the complex issues are fracturing and cavernosity, which strongly affect the permeability. The writers used cubic cores (5 × 5 × 5 cm), determined permeability in the x, y and z directions and, upon saturating the cores with luminescent material, studied the distribution of pores, vugs, and fractures on different faces of the cubic cores (Bagrintseva 1999, 2007). The technique is simple and does not require expensive equipment.

The technique involves saturating the cubic core under UV radiation. The surface fracture density (i.e. length per unit area) was determined from the photographs. The application of this technique is particularly important for qualitative and quantitative description of fractured rocks, differentiation between the cemented and open fractures, identification and evaluation of caverns and vugs and assessing the contribution of fractures and vugs to porosity and permeability.

The capillary soaking of carbonate rocks with organic liquids is analogous to a natural phenomenon of saturating reservoir rocks with hydrocarbons. After saturating the cubic core with liquid (luminophore), under the UV radiation, the pores, vugs and fractures glow bright green. There is a significant contrast between the dark background representing impermeable areas of core and the porous areas.

The best characterization of void space structure was achieved using Noriol-A mixed with kerosene and gasoline. Noriol-A has a high concentration of luminescent substances with distinct green luminescence; high brightness under UV radiation; luminescence stability over an extended time period; and high solubility in hydrocarbon solvents. Before being photographed, the film of luminophore is removed from the cube faces with a cotton wool swab liberally soaked in the solvent (gasoline). The samples must be photographed full size, in complete darkness and under a strong UV radiation source. The upper facet 1 and lower facet 6 are perpendicular to the core’s axis. The permeability to gas is determined for each core in three directions, which could vary considerably.

Fracture openness is measured at several points because it may vary due to leaching. Fracture orientation and length are important as they determine permeability. The interconnection between the fractures also must be evaluated; if fractures are interconnecting, the permeability may be about equal in all three (X, Y, Z) directions, usually a few millidarcies. The porosity of fractures in such rocks is 1.9–2.2%, whereas in the presence of vugs it may reach 3–4.5%. The openness of fractures determines capacity and permeability.

Intersecting, differently orientated fractures determine the anisotropy of permeability. Two different types of solution porosity (vugs) must be identified, that is, the ‘newly created’ and the ‘inherited’. ‘Newly created’ solution porosity occurs in dense low-porosity rocks due to movement of solutions in fractures and substantial widening of fractures until formation of vugs. The fracture openness ranges from 5 to 500 μm due to the development of vugs along the fractures. ‘Inherited’ solution porosity evolves in porous–permeable rocks where the leaching and dissolution occurs in the existing pores. The process results in the increase of radii of pore channels providing for high interconnectivity. This gives rise to high-porosity, high-permeability rocks, that is, class I or II reservoirs (Bagrintseva & Chilingar 2007).

The main benefit of this method is the opportunity to assess the development of vugs and open fractures, their morphology and interconnectivity and to evaluate the percentage of various types of voids: pores, vugs and fractures. The sample photographs demonstrate complex fracture networks, their hierarchy, vug morphology and connecting channels (Figs 14.6–14.9, 14.11, 14.12). The most important fracture characteristics are: surface density, fracture openness and orientation, morphology and connectivity.

Variations of lithological composition, secondary rocks’ alterations, types of voids and inhomogeneity of the reservoir properties are given in Supplementary Tables 14.1–14.4 and in Figures 14.4 and 14.5. Well logging data indicate the inhomogeneity of the reservoir profile and the alternation of porous–permeable and dense beds. The surface fracture density, openness, and orientation are shown on the same well log (Fig. 14.4). Supplementary Tables 14.2 and 14.4 demonstrate the variability of the reservoir properties and fracturing parameters. Data on surface density at the cube faces, fracture openness and orientation measurements are given in these tables for the Lekkeiyaginskoye and Severo–Saremboiskoye fields. Inhomogeneity of the carbonates fracturing development is clearly visible in the well 16 profile at Severo–Saremboiskoye Field (Supplementary Table 14.4, Fig. 14.4).

Lower Devonian carbonate reservoirs

The Lower Devonian carbonate reservoirs formed in a shallow-water marine basin with terrigenous–sulphate–carbonate sedimentation. Areas of high–low tidal plains with terrigenous sedimentation occurred in the west of the basin. Fuller Lower Devonian profiles are penetrated in the Varandey–Adzva structural zone wells. The profile starts 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 changes to a shaly–dolomite unit with interbeds of dolomites and argillites in the lower part and a sulphate–dolomite unit at the top, built by rhythmic interbedding of anhydrites, dolomites and argillites, accumulated under increasingly saline conditions. On the elevated basement blocks – Bolshezemelsky and Izhma-Pechorsky – sediments are partially absent due to reduction of sedimentation and subsequent erosion (Fig. 14.3).

Almost all types of traps are present within this complex, predominantly combined, often lithological, and limited stratigraphically and tectonically with multiple faults of various amplitude. Examples are represented by the fields: Severo–Saremboiskoye, Lekkeyaginskoye, Treibs, Titov and Medynskoye–More. Lower Devonian reservoirs at the Lekkeyaginskoye and Severo–Saremboiskoye fields of the Sarembly–Lekkeyaginskoye Swell are represented mainly by limy and calcareous dolomites, less often by dolomitized, sometimes shaly, limestones.

Lekkeyaginskoye Field

The Lekkeyaginskoye Field is located in the west of the Saremboiskoye Swell. At Ordovician level it is flexural uplift, elongated NW and transforming up-profile into a complex anticline fold.
The size and amplitude of the structure at the base of the Upper Silurian are 28 × 6 km and 50–400 m. At 3120–3212 m well no. 41 penetrated dark-grey porous–vugular dolomites, sometimes fractured, saturated with liquid dark-brown oil; they are the analogue of the productive bed of the Severo–Saremboiskoye Field. Integrated laboratory studies and field-geophysical surveys enabled the identification of several intervals in the Devonian section, which are substantially different in lithological composition, variability of secondary transformations and reservoir properties (Supplementary Table 14.1). The upper part of the section is represented mainly by alternating beds of secondary dolomite, dolomitized limestone, organogenic and argillite (their thickness from several centimetres to 1.5 m). The dolomite is grey and dark-grey, fine-micro-grained, low-calcareous with detritus and unbroken ostracod shells; in some areas the dolomite passes into dolomitized limestone. The porosity is low: from 2.5–6.5% up to 9.2%; permeability from 0.001 to 0.4 mD. In more porous varieties the oriented permeability varies from hundredths of millidarcies to 2.2 and 4.5 mD. Such significant anisotropy of permeability in direction indicates fracture development (Supplementary Tables 14.1 and 14.2).

The dolomites are nonuniformly fractured and vugular. The fractures are horizontally oriented, straight or sinuous, sometimes branching and echeloned, more than 5 cm long, with 16–50 μm openness (Fig. 14.6, photo 5097). In some samples vugs-fissures are observed, which were formed as a result of the fractures’ cavities leaching. Rare vugs resulting from the leaching of organic remains are observed in fractured varieties. They are arranged in the form of discontinuous chains along the dolomite and shaly dolomite stratal boundaries. In more vugular varieties short (1.5–2 cm) fractures are common; they are angular-sinuous; their openness as a rule does not exceed 15 μm; in individual cases average openness is 25–30 μm. Fractures are interconnecting vugs and are oriented mainly horizontally. Surface density of fractures at the cube faces varies: 0.32–1.16 cm cm⁻². Dolomites in well 47 are characterized by higher parameters (Supplementary Table 14.2).

A bed of porous-type reservoir rock of uniform composition and structure occurs in the studied section of well 41 (interval 3200–3207 m). These reservoir rocks are oil-saturated dolomites, nonuniformly porous and limy with relicts of algae and fragments of shells; they have a pore size of 0.08–0.24 mm, sometimes up to 1–1.5 mm. The studied calcareous dolomites have extremely low contents of nonsoluble residue – from 0.63 to 2.5%. The open porosity of the main part of the samples varies from 10.1 to 27.1%; the absolute gas permeability is up to 45.4 mD.

Porous-permeable dolomite varieties have a uniform structure of the pore space; the pore radius varies in a narrow range, 1–5 μm. The most important secondary processes affecting the pore space formation are dolomitization, recrystallization and leaching of the fractures’ cavities, leading to growth of the reservoir rocks capacity. A low content of residual water (10–20%) gives rise to high values of efficient porosity and the preservation of highly effective permeability.

Fracturing is more intense in the lower section than in the upper (Supplementary Table 14.2). Horizontal and vertical fractures are present. Filtering fractures are long (>5 cm), relatively straight, sometimes sinusuous, splitting, wider, with openness from 16 to 30 μm and higher. Vertical and inclined fractures create a system of interconnected fractures, often interconnecting with the horizontal ones; their length attains 2–4 cm and openness 16–35 μm. The surface density of fractures at the cube faces is in the range of 0.61–1.27 cm⁻².

All the rocks of Lekkeyaginskoye Field are characterized by a predominance in their organogenic remains of various ostracods – small and large, thin- and thick-walled. In the majority of cases these have been subjected to some transport, as shown by the stratification, sorting and orientation and in some cases by a lack of cement and by the presence of intraclasts. The abundance and predominance of ostracods can indicate that sediments accumulated under conditions of semi-isolated, desalinated or low-salinity basins. The presence of rocks with algal structures, combined with micro-grained and micro-nodular varieties, indicates the...
existence of bars and potholes in the basin. The presence of relict layered-ornamental algal structure is proof of the basin’s shallowness. The rocks described accumulated under conditions of extremely shallow water in a semi-isolated marine basin.

**Severo–Saremboyskoye Field**

The Severo–Saremboyskoye Field is located in the middle part of the Medynsky–Saremboysky Swell. The structural layout is an anticline fold of northwestern orientation, traced along the whole section of the sedimentary cover. The structure’s dimensions at base Upper Frasnian level are about 13 x 3 km with an amplitude of about 300 m. The oil field was discovered in June 1980 and the total sediment thickness is more than 3210 m.

Lower Devonian deposits in the interval 2660–2920 m are represented by interbedded siltstones and dolomites and form a regional cover 150–300 m thick. The top of the stratum of Lochkovian permeable dolomites horizon is at 2920 m depth. Testing of the 3002–3032 m interval gave an oil inflow at the rate of 325 m$^3$ s$^{-1}$. Further drilling to 3178 m penetrated a zone of abnormally high reservoir pressure.

![Fig. 14.4. Reservoirs types distribution variability in well 16 of the Severo–Saremboyskoye Field.](image-url)
Two oil pools were found in the Lower Devonian carbonates in well no. 15 of the Severo–Saremboiskoye Field. The lower oil pool, with an abnormal high reservoir pressure of 529 bar, occurs in the interval 3191–3201 m. The producing part of the profile is built by calcareous dolomites, organogenic and dolomitized limestones. Organic remains are represented mainly by ostracods. The upper oil pool with normal reservoir pressure occurs in the interval 3002–3032 m. The cap rock is a 70 m-thick stratum of interbedded anhydrites and dolomites.

The Lochkovian stage of the field’s productive reservoir is represented by dolomites, calcareous to various extents, and by some dolomitized limestones, according to well logging data and analysis of core from 2920 m. The upper part of the producing reservoir is a terrigenous–carbonate, about 50 m thick.

The dolomites are fine-small-grained, porous, sometimes with small vugs up to 0.6 cm across. Highly oil-saturated dolomites alternate with fine-small-grained and dense dolomites, with small vugs and fractures. Vugs (1–3 cm size) are developed in the dense matrix, filled predominantly with oil; sometimes they are developed along the fractures’ cavities. The distribution of the reservoirs of various types, lithogenetic properties and fracturing variations in the productive strata are shown in Figures 14.4 and 14.5. Porosity varies from 6 to 14% and permeability is up to 35 mD (Supplementary Table 14.3). It should be noted that

![Sample 5097. Lekkeyaginskoe, well 41, int 3207-3212 m. Rocks: Limestone organic, highly fractured. Winding fractures.](image)

![Fig. 14.6. Development sinuous fractures (luminophore capillary saturation) of Lower Devonian reservoirs.](image)
interbeds of dense, impermeable dolomites are present in well nos 15 and 16, along with porous--permeable varieties which have reservoir properties.

The porous–permeable varieties of dolomite are characterized by complex structure of their void spaces. Voids are developed selectively due to micro-grained calcite leaching between the dolomite grains. They are of irregular, rounded-angular shape, sometimes elongated and often form interconnected arrays of pores. The ultimate size is 0.08–0.5 mm, more often 0.08–0.32 mm. The vug morphology is clearly visible in the samples, saturated with luminophore (photos of samples 5394, 5417 and 5428).

Among all the secondary processes affecting development of the void space in the studied rocks, the major role was played by dolomitization, recrystallization and leaching; fracturing is also important. The post-sedimentation transformations and void characters are shown in the profile of well no. 16 (Fig. 14.4).

The fracturing intensity and characteristics are nonuniform in the section (Supplementary Table 14.4). The most densely fractured intervals in well no. 16 are 3038.0–3044.6 and 3049.3–3052.6 m, where dense dolomites with vugs are developed. Open cracks have horizontal, vertical and inclined orientation; often they form interconnected systems. The openness of the fractures is not constant, due to leaching; in some samples it attains 96–200 μm, minimum 8 μm. Owing to fracturing, the rocks are characterized by filtration properties' anisotropy. Vugs of 0.8–1 cm size in dense varieties are associated with inclined and horizontal fractures. Selective dissolution of individual fragments, shells and fracture cavities is observed. In the productive reservoir interval of the field, typical porous and vugular-fracturing reservoir types are identified.

Reservoirs of vugular-fracturing type are arranged in interbeds between the porous dolomites. Porosity values vary within 2.2–6.5%, permeability values from 0.01 to 0.8 mD. Reservoirs of vugular-fracturing type are built by fractured dolomites with a dense, practically impermeable, matrix, in which voids of isometric shape are filled with oil. Reservoirs of this type are characterized by permeability anisotropy depending on the filtration fracture orientation. Supplementary Table 14.4 shows that permeability variations are of one to two orders of magnitude due to the development of multi-oriented fractures. Horizontal, inclined or vertical fractures enable various flow routes during the cubical sample analysis.

A feature of the carbonate rocks is the development of leaching voids along the fracture cavities, which substantially increases their reservoir capacity. The value of this secondary porosity in various fields varies from 1.5 to 2.55% and due to intense vugular porosity can reach 4.5–8%.

The issue of criteria selection for identifying fractured-type reservoirs emerges permanently in the process of carbonates' studies. Individual fractures observed in low-capacity rocks have capacity equal to 0.2–0.35%. Their presence does not permit a rock to be attributed to a reservoir of fractured-type, because they do not develop a system of interconnected channels and do not provide fluids flow. The mandatory requirement for identifying rocks as fractured reservoirs is the development of a connected fracture system, providing hydrocarbon flow in the reservoir. In these cases the minimum capacity of the fractures is 0.9% at surface density 0.65 cm cm⁻² and minimum 10 μm openness of the fractures. Fulfillment of these conditions provides the cluster availability and exceeds the fluid 'flow threshold' in the reservoir.

The extensive development of fracturing and the important role of fractures in the void space structure are clearly seen on the photographs of samples saturated with luminophore (Figs 14.7–14.9, photos 5394, 5417 and 5428) and in the well sections, where the orientation is shown for variability of quantitative parameters of surface density, fractures' openness and orientation in the productive formation (Figs 14.4 & 14.5).

Fracturing occurs everywhere in the carbonate strata, but it plays different roles for porosity and permeability in porous and vugular reservoirs. The development of complex types of reservoirs is associated with fracturing and intense manifestation of dissolving and mineral particle transport, that is, with development of 'newly generated' vugular porosity. Dissolution occurs in the fracture cavities, and at individual formation components (Severo-Saremboiskoye Field). Most of the rocks have been subjected to dissolution under intense, randomly oriented fracturing, thus facilitating the development of porous zones.

Dense low-capacity reservoir rocks with a nonpermeable matrix are characterized by much higher intensity of fracturing. Also, the directional anisotropy of the fluid flow properties varies by 2–3 orders of magnitude due to the development of multi-oriented fractures. Horizontal, inclined or vertical fractures enable various flow routes during the cubical sample analysis.

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The combined effects of repeated tectonic fracturing and dissolution processes have determined the development of the complex reservoir types in the studied fields. A comparison of reservoir properties and carbonate rocks’ fracturing variations in well no. 16 is given in Figure 14.4. Multi-oriented fractures are observed and the vertical, inclined and horizontal fractures form a system of interconnected cavities. The surface density of fractures, both maximum and average, is nonuniform along the profile. On the cube faces it varies from 0.8 to 1.38 cm cm⁻², averaging
The fracture openness varies similarly—from 5–7 to 200–300 μm due to the calcite dissolution.

Similar nonuniform fractures were found during description of the carbonate reservoirs of the Lekkeyaginskoye Field (Supplementary Table 14.2), where fractures of various orientation and morphology dominate practically everywhere in the profile. Sample 5097 shows a large number of sinuous fractures (Fig. 14.6).

The method of capillary saturation of the rocks with a luminophore has shown the nonuniform geometry of the carbonate rocks void space. The photographs, taken in ultraviolet light, allow comparison of the void morphology in dense low-capacity dolomites. Sample 5394 is characterized by intense development of isolated vugs and fractures (Fig. 14.7); their capacity is significant, 4.2%.

In sample 5417 vugs are less frequent, but the fractures’ cavities are larger (Fig. 14.8). Sample 5428 is characterized by the development of flow fractures and the absence of pores and vugs (Fig. 14.9).

The substantial differences of the void space geometry in the carbonate rocks after their saturation with luminophore indicates the important role of fractures and vugs in reservoir-type assessment. The method of capillary saturation of the rocks gives additional opportunities for more reliable assessment of the complex void space. Understanding fracture orientation and openness is especially important in the planning of development wells.

**Lower Permian carbonate reservoirs**

Deposition of Upper Carboniferous–Lower Permian strata occurred on a carbonate shelf under periodic variations of sea-level (Fig. 14.10). Bioherm buildups formed, composed of grained, framework limestone, replaced by silty and vugular limestone. In the offshore part of Timan–Pechora basin these bioherm bodies are part of a unified band in the north of the basin. Most high-capacity reservoirs are associated with grained, framework limestone with vugular varieties. The oil fields discovered in the offshore part of Timan–Pechora basin are associated with them.

Lithological and physical studies have been made in wells Varandeyskaya 2 and 3, Toraveyskaya 3 and 21, Southern Toraveyskaya, Laboganskaya 71 and Sedyaginskaya 1 and 10. These show that sedimentation of the Lower Permian strata occurred under normal marine conditions varying from nearshore shallow-water to relatively deep in some depressions.
Environments of carbonate platform prevailed during the Asselian and Sakmarian, supplemented by terrigenous sedimentation in some areas during the Artinskian age (Zaets & Stoupakova 2004). The Lower Permian thickness in Varandeyskaya 2 attains 142 m. Artinskian and Asselian strata in wells Varandeyskaya 2 and 3 and Sedyaginskaya 1 are represented almost exclusively by organogenic and organogenic–clastic limestones with crinoid, bryozoan–crinoid–brachiopod and crinoid–algal associations. The limestones are low- and high-porous, oil-saturated and sometimes small-cavernous; in porous limestones an encrusted structure is observed.

A substantial portion of the limestones can be attributed to bioherm type, according to the complex of rock-forming organisms (crinoids, bryozoans, algae). They form flat bioherm bodies among indistinctly laminated limestones, without significant abnormal thickness growth in the former. Dolomitized limestones and dolomites appear in sediments of Asselian age in the Sedya-ginskaya 1–10 wells. The thickness of Asselian deposit is from 116 to 201 m.

**Sedyaginskoye Field**

The Sedyaginskaya structure is associated with the central, most uplifted part of the swell, and is present through the full section of the sedimentary cover. The structure is asymmetrical: the western limb is steep, the eastern limb more gently sloping. The structure size and amplitude at the base of the Kungurian strata are 26 × 4 km and 325 m. Two oil pools of the massive type occur in the field, in Lower Devonian and Lower Permian carbonate reservoirs.

Two layers with differing lithological composition, secondary transformations and reservoir properties (Supplementary Table 14.5) are identified in the Lower Permian strata, penetrated by the Sedyaginskaya 10 well. The upper stratum in the depth interval 1000–1112 m is represented by a wide range of lithological varieties and by various reservoir types. These are mainly dolomitized limestones interbedded with calcareous dolomites, substantially siliceous, partly shaly with subordinate interbeds of arglillites. A unit of tuffaceous sandstones occurs near the top of this interval; this tuffite at 1000–1006 m depth has a porosity of 17.7% and a permeability of 14.6 mD.

In the Artinskian section the porous reservoir type is dominant with subordinate interbeds of fractured-porous type reservoirs. The distribution of reservoir types has been analysed in the Sedyaginskaya 10 well section. The boundary values of 10% porosity and 1 mD permeability enable differentiation of intervals with porous and complex reservoir types.

The porous reservoir type is represented by several lithologies:

- Organogenic-detrital limestone – fine-micro-grained, spicular, transforming into spongolite; containing remains of Foraminifera and algae; nonuniformly oil-saturated; open porosity varying from 13 to 16%; permeability 48.8 mD.
- Dolomitized limestone – nonuniformly substituted with silica; occasionally organogenic-detrital; oil-saturated; fractured. Porosity in such limestones is higher – from 15 to 22%, permeability 1.6–78.8 mD.
- Calcareous dolomite – highly siliceous; dolomite is occasionally substituted with silica; nonuniformly oil-saturated; fractured. Porosity varies from 14 to 20%, permeability 49.7 mD.

The thickness of the porous–permeable reservoir beds averages 3 m, and is up to 9–10 m. The thickest interbed with dominantly porous type reservoirs occurs in the depth interval 1059–1112 m. Reservoirs of fractured-porous type are represented predominantly by fine-micro-grained limestones, sometimes shaly; occasionally dolomitized, siliceous and fractured. They are characterized by high porosity (11–20%), but low permeability. Intensively developed fractures in dense varieties differ in orientation: vertical and inclined fractures dominate. The fractures are filled with oil.

**Fig. 14.10.** Palaeogeography of Early Permian time.
Limestones are characterized by nonuniform, fine, porous textures of the limestones and creates the permeability anisotropy. The presence of open fractures improves the flow properties. Vertical fractures dominate; horizontal and branching fractures are less frequent. Almost all fractures are filled with oil. Limestones are less common in this lower stratum; they are fine-micro-grained, occasionally weakly dolomitized, largely substituted with silica. They are characterized by low porosity, not exceeding 6% and by permeability below 0.1 mD.

Diagenetic changes are represented by recrystallization, dolomitization and silicification. Silicification is most intense in the producing reservoirs. It occurs in limestones and dolomites, where silica is the cement and fills the organic remains. Silica plays a major role in the lower part of the section, built by siliceous–carbonate rocks. The silicification process in the Lower Permian strata is both primary and secondary and its effect upon reservoir properties is complex: important factors are silica quantity, its distribution and genesis.

**Laboganskoye Field**

The Lower Permian and Carboniferous carbonate strata of the Laboganskoye Field are characterized by substantial variability in lithology and reservoir properties. Supplementary Table 14.6 shows results of an assessment of the reservoir properties and structural parameters in the productive reservoir section. The upper unit comprises Artinskian strata 34–49 m thick represented by alternating organogenic–clastic limestones, occasionally siliceous or silty, and fine-small-grained limestone, highly silicified and fractured. The former are oil-saturated with relatively good reservoir properties: porosity up to 24%, permeability predominantly several millicidity, less often up to 10–20 mD. In the dense rocks the luminophore saturation is in the form of nonuniform impregnation of small vugs and fractures (Fig. 14.11, sample 5146). The porosity of the micro-grained varieties is high; up to 15%. Permeability is low, from fractions of a millicidity to 1 mD. The presence of open fractures improves the flow properties of the limestones and creates the permeability anisotropy. Limestones are characterized by nonuniform, fine, porous structure of the void spaces. Pore radii are 2.5–5 μm and up to 10 μm in porous varieties.

The lower unit of Asselian and Sakmarian carbonate rocks comprises organogenic–clastic and organogenic–detrital limestone, weakly dolomitized and oil-saturated, with interbeds of denser fractured limestone, with traces of oil on the fracture walls. These are mainly porous-type reservoirs with porosity 8.5–9.6%, permeability from 1 to 2.4 mD, and subordinate interbeds of reservoir rocks of fracture-porous type.

Rocks in the depth interval 1605–1628 m in the studied profile of well 141 (Severo–Sorokinskaya area) have the best reservoir properties. These are organogenic–detrital limestones, porous with small vugs, highly oil-saturated. The reservoir is predominantly of porous type, with porosity from 9 to 25% and permeability 34.5 mD. The inhomogeneity of the void space is assessed; maximum channel pore radius attains 40 μm.

In general Lower Permian–Carboniferous productive reservoirs differ in the development of porous and fracture–porous type reservoirs. Practically across the whole productive section, oil saturation of limestones is observed. It is more intense in porous varieties and in the dense limestones oil fills vugs and fractures. Oil flow was obtained from Lower Permian strata in well no. 71 at depths of 1352–1370 m; the production rate was 68 m³/day. The water–oil contact was established at a depth of 1441 m.

**Naulskoye Field**

The Naulskoye oil field, explored using wells 51, 54, 55 and 57, contains 45–50 m of Artinskian strata. Organogenic limestones predominate in the profile with bryozoans and brachiopod fragments and some interbeds with spicular limestone. Primary organogenic–detrital limestone is almost completely replaced by silica; the rocks are fractured and sometimes contain vugs (Fig. 14.12, sample 5575). Porosity varies from 12 to 28.5%; in siliceous beds it is much higher. The permeability in porous limestones attains 45.9 mD (Supplementary Table 14.7). Fractures are thin and vertical and their openness is 16 μm. Oil saturation is found practically across the whole thickness of Permian carbonates; the well production rate is 52–56 m³/day.

**Pechora Sea carbonate reservoir discoveries**

The main oil- and gas-bearing complex on the Pechora Sea shelf is represented by reefal and organogenic carbonates of Lower
Permian–Carboniferous age. The oil pools at the Prirazlomnoye, Severo-Dolginskoye, Varandey–More and Medyn–More fields occur in these deposits.

The most important is the large Prirazlomnoye Field discovered in 1989. The oil pool is of multipay common-contact type and is associated with carbonate deposits of Lower Permian–Carboniferous age, represented by organogenic and organogenic–clastic limestone. The size of the pool is 17.5 km and the height is about 180 m.

Three producing horizons (I, II, III) occur in the Prirazlomnaya structure; they contain an integrated oil pool with a height of 194 m. The maximum oil production after acid treatment is obtained from horizon I, 677 m³/day, and from horizon II, 20 m³/day. The water–oil contact is established at a depth of 2500 m.

The Varandey–More Field was discovered in 1995 on the extension of the Sorokin Swell in the Pechora Sea. The field is located 30 km SE from the Prirazlomnoye Field and 1.5–2 km from the shoreline and the onshore Varandeyskoye Field. At Varandey–More, well nos 1–2 discovered an oil pool in Lower Permian–Middle Carboniferous carbonate rocks: light-grey, organogenic, oil-saturated limestones were penetrated. The oil pool is of multipay common-contact type; the area is 19.2–4 km and the height is about 100 m. The reservoir rocks are organogenic limestones with 13–18% porosity and 100 mD permeability. Deposits of Artinskian age are absent. A 75 m thick shaly-argillite of Kungurian age serves as the cap rock.

Substantial differences are found in the productive stratum of wells 1 and 2 at Varandey–More. Well no. 1 contains Asselian–Sakmarian limestones, 81 m thick with high porosity (8 to 20%) and permeability (1–100 mD). Visean strata in well no. 1 are represented by siliceous rocks with porosity up to 10% and permeability from 5 to 80 mD. The 68 m-thick Asselian–Sakmarian limestones in well no. 2 are characterized by lower values of porosity (15%) and permeability (10 mD). Organogenic low-capacity limestones predominate in the profile. Serpukhovian strata are represented by dolomites with relatively high parameters: porosity 8–12%, permeability from 1 to 100 mD (Dzyublo 2008).

Commercial oil flows were obtained on test at Varandey–More well no. 1: 110 m³/day from 1714–1738 m interval. The water–oil contact was established at a depth of 1782 m. The geological profile along the Prirazlomnoye–Taraveyskoye line (Fig. 14.2) reflects the variability of the onshore and offshore oil pools along the Sorokin Swell. The Prirazlomnoye oil field has a much larger height and wider stratigraphic range of the oil reservoir, including Upper Carboniferous rocks. The Varandey–More Field has a lower thickness of Lower Permian strata compared with the Varandey-onshore field due to the absence of the Artinskian stage.

The Medynskoye–More Field was discovered in 1997 on the northern offshore part of the Medynsky Swell. It is located 23 km from the onshore Medynskoye oil field. Carbonate reservoirs in Lower Permian and Carboniferous strata are oil-saturated. After testing the 1185–1300 m interval, oil flowed to surface with a production rate of 39.4 m³/day (8 mm choke).

The producing reservoirs of the Medyn–More Field are represented by carbonate rocks, organogenic and chemogenic limestones. The cap rock is a shaly-argillite stratum of Kungurian age. It is in a structural trap measuring 75 × 35 km, with a height of 480 m (Vindelshtein et al. 2001).

Comparative analysis of the material from Prirazlomnoye, Varandey–More and Medyn–More fields has shown the identity of the section structure in Lower Permian–Carboniferous strata, penetrated in the offshore areas of Sorokin and Medynsky swells. The pay section contains clear reservoir beds, separated by dense interbeds. Identified oil pools are tectonic sealed multipay common-contact pools.

Conclusions

A comparison of the types and properties of the onshore and offshore reservoirs shows their strong resemblance, while the reservoir potential of carbonate rocks of the offshore fields is higher in some cases. A method of capillary saturation with luminofore has shown the wide propagation of fractures with various orientations and openness, their variability in the well profiles and the preservation of fractures at depths below 3000 m. The specific features of carbonate reservoirs include:

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

Finally it is worth emphasizing the advantage of integrated core studies using large-sized cubes and the method of capillary
impregnation with a luminofore in order to reveal the complex structure of the reservoirs’ void space and to assess the role of fractures and vugs.

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