

Review

Investigation of Old Exploration Boreholes in the Lublin Basin with Regard to Potential Rotary-Percussion Drilling of Shale Gas Wells

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Abstract: The rotary-percussion drilling method is a prospective way to decrease drilling costs. It is obvious, based on literature analyses and finished geothermal drilling, that the Lublin Basin can be perceived as the one where rotary-percussion drilling can be used to drill an overburden of shale rocks. The paper explained the geology of the Lublin Basin, its' geological structures, and the possibility of the use of drilling with a down-the-hole hammer, which could significantly decrease the cost of the whole shale gas drilling investment. Data collected from the wells drilled in the Lublin Basin were compared and analyzed to determine the viability of rotary-percussion drilling. Provided analyses showed that using the rotary-percussion drilling method in the Lublin Basin had a greater possibility of application than in other Polish shale basins (Baltic and Podlasie).

Keywords: shale gas; rotary-percussion drilling; DTH hammer; rotary-percussion drilling method



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1. Introduction

The need for energy is constantly rising around the world, which may be described as an exponential function. According to the Minister of Economy, the need for final natural gas energy in Poland will have risen by 20% in 20 years (from 2010) [1]. Given the decreasing natural gas resources in conventional deposits, the world is facing a situation in which it is necessary to exploit this kind of hydrocarbons from less accessible reservoirs (so-called unconventional reservoirs). In Poland, there are high hopes for a natural gas extracted from the Lower Paleozoic shale. The shale belt, amounting to ca. 37,000 km², ranges from the northern parts of the country (the Baltic Basin), through the central regions (the Podlasie Basin), to the eastern reaches (Lublin Basin). The total estimated producible resources of natural gas in shale formations of the Polish land and the marine part of the Baltic-Podlasie-Lublin Basin may amount to a maximum of 1920 billion m³ [2].

Taking into consideration the parameters of the evaluation, these resources are most likely approximately 346–768 billion m³. Even the lowest amount can make an impressive influence on many branches of domestic industries. Nevertheless, exploiting this kind of hydrocarbons from the Lublin Basin using conventional technology is expensive and unprofitable. Hence, it is desirable to use technologies that are less costly and give the possibility to succeed. The old but renewed version of the rotary-percussion drilling method is supposed to be the most efficient [3].

In the case of rotary-percussion drilling, a down-the-hole hammer operation is present. The driving factor may be either compressed air or fluid (water), which is directed to the hammer through drill pipes. Air or water also cleans the borehole from cuttings acting as a scrubber.

The air is blown out of the hammer through holes in the drill. The advantages of this kind of drilling are, especially, the lower price compared to the conventional method, lower negative influence on the environment, lower noise emission, and the possibility to operate in a small area. An additional perk is the rectilinearity of the borehole, especially for down-the-hole hydraulic hammers. Furthermore, using air instead of a drilling mud can reduce the formation damage. Formation damage during drilling, completion, and workover operations is a widely known and important issue to consider, as it reduces oil and gas recovery performance. Zhu et al. [4] investigated the impact of the filtrated mud saturation and concluded that its determination could contribute to predicting the formation damage in underbalanced drilling operations. They noted that higher saturation occurred in formations with higher porosity and permeability, lower water saturation, and higher oil viscosity. Davarpanah and Nassabeh [5] found that the determination of mechanical specific energy could assist with detecting drilling instabilities and checking drilling and bit performance. It could help with the optimization of drilling parameters. Both of the abovementioned papers presented a cost-effective way to aid the drilling operation. The rotary-percussion drilling technique has been known for its economic viability combined with an increased rate of penetration. It is generally recommended for the use in hard, abrasive rock formations due to its rock-fracturing efficiency [2,5–7].

The rotary-percussion method has been widely studied in order to further enhance its benefits. It has been proven that the rate of penetration can be increased by over 30% by using the rotary-percussion drilling method in comparison to the conventional rotary drilling method [7–9]. Derdour et al. [10] presented their work on penetration rate optimization of rotary-percussion drilling in the Hadjer Soud quarry. They have taken into consideration the air pressure, the specific-advanced pressure, the rotation speed, and the bit diameter and used the Taguchi method, signal-to-noise ratio, ANOVA (analysis of variance), and RMS (root mean square) for modeling. They concluded that air pressure had the most impact on the rate of penetration, followed by the specific advance pressure, as well as proved that the analyses used were effective in practical applications. Liu et al. [7] stated that by adjusting the impulse frequency, higher drilling efficiency could be obtained. Wu and Ye [6] noted that the impulse load and the speed of bit rotation had a significant influence on the efficiency of rock fracturing, while the impact of impulse frequency was smaller in comparison. Dong and Chen [8] mentioned that drilling parameters did not have a linear relationship with the efficiency of rock fracturing. They noted that the use of the rotary-percussion drilling method in shale formation needed to be further investigated due to the mechanical properties of shale. They recommended a small lateral movement and reasonable axial vibration frequency to achieve energetically efficient rock fracturing. Xiaohua et al. [11] researched the rock-breaking mechanism and concluded that volume breaking was caused by the torsional shear stress. It was then further accelerated together with crack extension by the tensile shear stress, and the compressive stress was identified as a secondary factor for the rock breaking.

In order to further study the rotary-percussion drilling mechanisms, many scholars published the results of numerical simulations such as DEM (Discrete Element Method), FEM (Finite Element Method), and FDM (Finite Difference Method) in recent years. The models created are proven to be effective by conducting field tests. Wu and Ye [6] conducted a numerical simulation to further study the mechanism of rotary-percussive drilling, which consisted of rotary cutting and axial impact. They concluded that rotary-percussive drilling alleviated the stick–slip vibration phenomenon, stabilized the torque fluctuation at the bit, created a smoother well, and improved the rate of penetration in comparison with other drilling techniques due to the tensile stress on the rock formation. Similar findings were presented by Liu et al. [7]. They created a three-dimensional finite element model of rotary-percussive drilling by a single Polycrystalline Diamond Compact (PDC) cutter and proved that the use of such technology could reduce the stress on the PDC cutter; therefore, prolonging the bit life and improving drilling efficiency. In their article, the breaking mechanism of soft and hard rock, as well as the rock damage by the rotary-percussive

and conventional methods, are shown. A three-dimensional finite element model was also presented by Xiaohua et al. [11] and was created to investigate the rock-breaking mechanism of the rotary-percussive drilling method considering the simultaneous influence of the static pressure, the force of impact, and the bit rotation. As a result of the field tests, they concluded the usefulness of the 3D FEM model created and defined preferred angles for the bit depending on its inserts. A three-dimensional numerical simulation created by Dong and Chen [8] indicated that the damage to the rock mass occurred in the direction of maximum principal stress. They stated that the impact-static load had the most influence on the rock formation damage, followed by the static load and the impact load. They identified the lateral vibration amplitude of the drill bit as detrimental to the rock fracturing and the repetitions of the drill bit impacting one indentation point to decrease the rate of penetration.

Due to its multiple advantages, the rotary-percussive method has also been considered for extraterrestrial drillings by many scholars [12–14], either as a driving unit under the name of the rotary-percussive drilling mechanism (RPDM) [13] or as a combination with ultrasonic drills [12,14].

The novelty of the approach presented in this paper lay in proving the advantages of using the rotary-percussion method for shale gas drilling in the Lublin Basin. The rotary-percussion drilling method, commonly used for drilling borehole heat exchangers and water wells in Poland, could be a feasible solution for drilling shale gas wells with high speed and low cost; therefore, making them more economically viable for exploitation.

2. Geological Structure

The following part briefly describes the geological conditions of the Lublin Basin. The most significant lithological-stratigraphic data for the area were given.

2.1. Quaternary

In Lublin Upland, despite numerous local lithological-facies differences, sediments from that period have multiple common characteristics: thickness up to 50 m (it is less than 30 m in many areas), low share of glacial sediments, and high amount of local material, a sizeable share of river and slope residues, widely and variously developed periglacial facies (mainly loess sediments), and numerous sites of stratigraphic and chronological significance (loess, paleosol, cave sediments) [15].

2.2. Paleogene and Neogene

Sediments from those periods occur rarely. If present, they are of low thickness. In the Warsaw basin and the northern part of the Lublin region, Paleogene and Neogene sediments from the Oligocene are represented by grey and green-and-grey non-limy quartz-glauconitic sands with quartz gravel and fine phosphorites. Its thickness amounts to a 30 m maximum but generally is 10–20 m.

Eocene sediments are characterized by a thickness of 20 m (maximum—57 m in the Kock region). Paleocene sediments are 5–6 m thick [16].

2.3. Cretaceous

The Cretaceous was the last period of the Mesozoic era lasting for about 80 million years (from ca. 145 to ca. 66 million years ago). The Cretaceous is divided into two chronostratigraphic series: the Upper and the Lower Cretaceous.

2.3.1. Upper Cretaceous

Upper Cretaceous sediments of this area are characterized by carbonated facies; chalk and limestone are mainly present. No stratigraphic gaps were found. Upper Cretaceous sediments in the northern part of the described area are covered with Cenozoic sediments. In the southern part of the Lublin-Podlasie upland, the Cretaceous is showing itself on

the surface in many outcrops. Maastrichtian rocks are mainly marl, gaize, chalk, and limestone—even 450–600 m thick.

The Campanian (thickness ca. 100–120 m) is characterized by rocks similar to those of the Maastrichtian—mainly marl and marly limestone with flintstone. The Santonian is mainly marl limestone and grey marl of 20–90 m. Similar rocks may be observed in the Coniacian (thickness up to ca. 50 m) and the Turonian profile (main presence of limestone up to 162 m thick). In the Cenomanian sediments, grey organodetritic limestone locally containing singular phosphorite concretions is predominant. In the Lower Cenomanian, marly limestone is also present—with glauconite, detritic quartz, and singular phosphorite concretions. The Cenomanian sediments' thickness ranges from 1 to 15 m [17].

In Lublin Basin, the Upper Cretaceous consists of:

- the Upper Albian: sandy marl, glauconite marly sands, and sandstones with phosphorites, locally sandy spongiolite with cherts;
- the Cenomanian: marly and inoceramus limestone, in a thill sometimes sandy with glauconite and phosphorites, locally in the West—marly gaize, sandy spongiolite, and glauconitic sands with phosphorites;
- the Turonian: marly limestone with cherts and flintstone, in the West of the basins—marly and hard gaize, secondarily limestone and marl, locally chalk;
- the Coniacian: marl and marly limestone with cherts, in the North-West—sandy spongiolite, in the South-West—gaize;
- the Santonian: marly limestone, gaize with cherts, marl, in the North-West—sandy spongiolite, in the South-West—marl gaize;
- the Lower Campanian: marly limestone and marl, in the North-West—sandy spongiolite, in the South-West—gaize;
- the Upper Campanian: limestone, marly limestone, and marl, in the North-West—sandy spongiolite and gaize, in the South-West—gaize;
- the Lower Maastrichtian: marly limestone, marl, gaize, in the West—sandy spongiolite and marly gaize;
- the Upper Maastrichtian: gaize, marl, chalk, and limestone in the Northern part, marl limestone in the South;
- the Lower Paleocene: marly clay, marl, and gaize with marly limestone insert [17].

2.3.2. The Lower Cretaceous

Early Cretaceous rocks in the Lublin Basin are almost non-existent. Those are mainly rocks from the Albian stage (upper stage of the Cretaceous), which are: sandy marl, sands, and marly glauconitic sandstones with phosphorites. They may be from a few to tens of meters thick.

2.4. Jurassic

It was the second period of the second Mesozoic era, lasting from ca. 201 to ca. 145 million years ago. It is divided into three chronostratigraphic series: the Upper, Mid, and Lower Jurassic.

2.4.1. Upper Jurassic

Kimmeridgian sediments (both Lower and Upper): crystal and clayey dolomite layered with grained limestone in the West and with anhydrite in the East (0–300 m). Layers of Portland covering them have mainly grained oolitic and oncolytic limestone and politic limestone (0–162 m).

In the southern part of the Lublin basin, two regions are differentiated: Cieszanów-Tomaszów and Tyszowców-Hrubieszowa. The latter contains rocks from the Upper Oxfordian.

In the Cieszanów-Tomaszów region, Lower Oxfordian sediments include detritic limestone, dolomitic in the East, the nodular bed below (0–50 m). Mid-Oxfordian rocks are mainly detritic limestone (20–140 m). In the Cieszanów region: grey-green marl, detritic, with layers of limestone, mudstone, and claystone. In Tomaszów region—sandstones and colored mudstone, grey mudstone with flora below (0–120 m) [17].

2.4.2. Mid Jurassic

Callovian sediments lying on the level of the floor conglomerate are mainly sandy limestone or light-grey or creamy limy sandstones. Oolites are common. The thickness of this layer amounts to 0.2–1 m.

Above, one may find rocks from the nodular layer (fine-crystalline ballstone, a bit sandy, generally light, creamy or grey, sometimes marly, hard, normally full of oolites; overgrowth of xenoliths; and pebbles from rocks of the floor conglomerate are present) and organodetritic limestone, which dominates in the Lublin-Podlasie region. This is mainly fragmental, a bit sandy, light creamy crinoidal limestone. It includes an admixture of earthy limonite and limonitic oolites. The thickness of organodetritic limestone amounts to, depending on the formation, 0.35 to 5 m.

In the upper part of the Bathonian lies a 3 to 11 m thick clayey-sandy or clayey-mudstone packet. In places where there is no clayey-sandy packet, the bottom is formed by rusty or red, and in some places grey and green organodetritic limestone. Its thickness may amount to 1–4 m. The ceiling of the clayey-sandy complex is represented by a conglomerate layer, covered with organodetritic, locally dolomitic, sandy limestone. The Upper Bathonian sediments are 4.5 to 45 m thick.

Below, there is a thin layer of bottom conglomerates, whose composition may vary depending on the area. The rocks included in these layers are mainly integrated with the tilled parts of the Upper Bathonian sediments. Lithologically speaking, those are xenoliths and pebbles, sometimes sandy conglomerates. Sometimes, heavily sandy detritic limestone rests on a smooth, cut surface of Paleozoic bedrock, with no sign of a floor conglomerate [17].

2.4.3. Lower Jurassic

There are no Lower Jurassic rocks in the Lublin Basin.

2.5. Triassic

The oldest period of the Mesozoic era; it lasted from 252.2 to 201.3 million years ago. The Triassic is divided into the Lower, Mid, and Upper Triassic.

Upper Triassic

In the south-eastern part of the basin, Rhaetian sediments were best characterized based on profiles of the Magnuszew and Pionki one boreholes. The Rhaetian is represented here by sandy-marly sediments. Its floor is comprised of quartz, quartzite, and chert. The pebbles are up to 4 m in diameter. In Magnuszew, the conglomerates are 2 m thick and 6 m in Pionki. In the Pionki one borehole, over conglomerates lie slightly dolomitic, mid-, and large-grained grey sandstones with quartz gravel. The Rhaetian is 7 m thick in Magnuszew, 15 in Ursynów, and 24 in the Pionki one borehole. The Rhaetian sediments' thickness is gradually rising towards the North-Western part of the basin, with 100 m already in Płońsk.

Lithologically, the Rhaetian is formed here by limestone and marl with sandy inserts in the lower part of the profile. North-West of Płońsk, the thickness of the Rhaetian sediments probably drops to zero. Simultaneously, one may observe an increase in clayey and sandy sediments.

Sediments from the Late Triassic are mainly present in the North-West of the Lublin basin because of the lack of the Silurian sea in the Lublin Basin's area [17].

2.6. Carboniferous

It was the fifth period of the Paleozoic era, lasting from ca. 359 to ca. 299 million years ago. It is divided into the Mississippian and the Pennsylvanian.

The top is the mudstone series. The thickest segments of this kind were found in Dorohuczka, Żyrzyn, and Magnuszew: over 1200 m. Below, there lies a sand-mudstone series of 200 m maximum. In the far North-Western part of the area, the series rests on the Silurian, in other parts—on mudstone series with limestone inserts.

The lowest is the mudstone series with limestone inserts (boreholes in, e.g., Tyszowce, Dołhobyczów, Mircze, Husynne, Hrubieszów, Chełm, Michałów)—in the South-Eastern part of the area, it reaches 450 m of thickness and declines towards the North and the North-West [18].

For the Lublin-Podlasie area, these are the characteristic rocks of the Pennsylvanian:

- the Stephanian rocks are not present in the Lublin-Podlasie area;
- the Westphalian: mudstone, claystone, sandstone, coal-seams of varying thickness, siderite (1200–1800 m);
- the Namurian (younger): sandstone, conglomerates, mudstone, claystone, coal-seams (220 m);
- the Namurian (older): mudstone, claystone, limestone, sandstone, coal-seams of varying thickness (200–480 m).

When the Mississippian is considered, the Viséan sediments found in all boreholes in the eastern part of the marginal synclinorium are in the form of the limestone-clayey series and lie incongruously on colored sediments of the Turnaisian. Their thickness varies between 125 and over 230 m [18].

In some boreholes, the Turnaisian sediments are represented by dolomitic facies and in others by gangue sediments, mainly colored and lithologically variable fragmental sediments. Limestone is predominant in the lithologic profile only in Husynne. The highest Turnaisian is locally characterized by sandstone-conglomerate series. The series of sediments from the dolomitic (colored) facies is 200 m thick.

The Mississippian in the Lublin-Podlasie area is represented by:

- the Upper Viséan: claystone, mudstone, limestone, sandstone, conglomerates, coals, tuffite;
- the Lower and Mid Viséan: coals, conglomerates, sandstone, claystone, mudstone, limestone;
- the Turnaisian: conglomerates, sandstone, dolomite, mudstone, claystone, limestone.

2.7. Devonian

It is the fourth period of the Paleozoic era. It lasted for about 60 million years (from ca. 419 to ca. 359 million years ago).

In the upper part of the Devonian profile, the Famennian facies are present. Those are mainly dark-grey limestone, locally dolomitic, ca. 190 m thick. Below, there are three carbonate series (dolomitic, limestone-dolomitic, and limestone) which are included in the Frasnian.

Below, there is a limestone-dolomitic series of ca. 110 m of thickness and even lower—light-grey fine-crystallite limestone with light and dark-grey fine-crystalline dolomitic inserts of up to 100 m of thickness [18].

The Lublin Upland is characterized by:

- limestone—for the Famennian,
- limestone and dolomite—for the Frasnian,
- marl, limestone, and dolomite—for the Mid Devonian (the Eifelian, the Givetian),
- mudstone and sandy clayey shale—for the whole Lower Devonian (the Gedinnian, the Siegenian, the Emsian).

2.8. Silurian

In the Lublin Upland area, the Silurian is mostly observed around the Tomaszów, Lubelski, and Kock areas. In the former, the lithology thickness of the boreholes is around 500 m. One may generally encounter series of clayey shale with no graptolitic fauna.

The Kock area is characterized by the presence of the Silurian layer on 810 m of depth. Characteristic rocks include grey claystone with a slightly greenish tone; in the upper part of the profile, there is a rich fauna of brachiopods and trilobites. No graptolitic fauna was found.

When the less prospective Lubaczów region is considered, the Silurian was found in Uszkowice and Doliny (outside Cieszanów). It was mainly claystone and black clayey-siliceous shale. In Uszkowice, only the Wenlock shale layers of 8 m of thickness were found [18].

Figures 1 and 2 show geological cross-sections marked on the map in Figure 3.

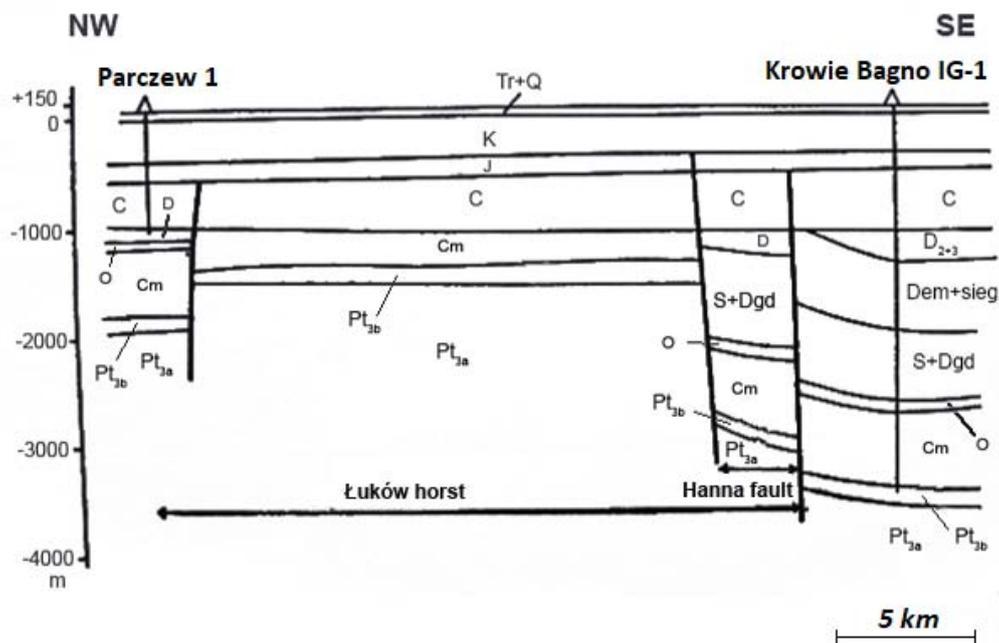


Figure 1. Geological cross-section (AA' on Figure 3) of the Hanna fault (according to [19]); Pt_{3a}—Upper Proterozoic (crystalline rocks); Pt_{3b}—Lower Proterozoic; Cm—Cambrian; O—Ordovician; S—Silurian; D—Devonian; Dgd—Lower Devonian, marine facies of Gedinnian and Siegenian; sieg—Siegenian; Dem + sieg—Lower Devonian, old red facies of Siegenian and Emsian; D₂₊₃—Mid and Upper Devonian; C—Carboniferous; Tr + Q—Triassic and tertiary; J—Jurassic; K—Cretaceous.

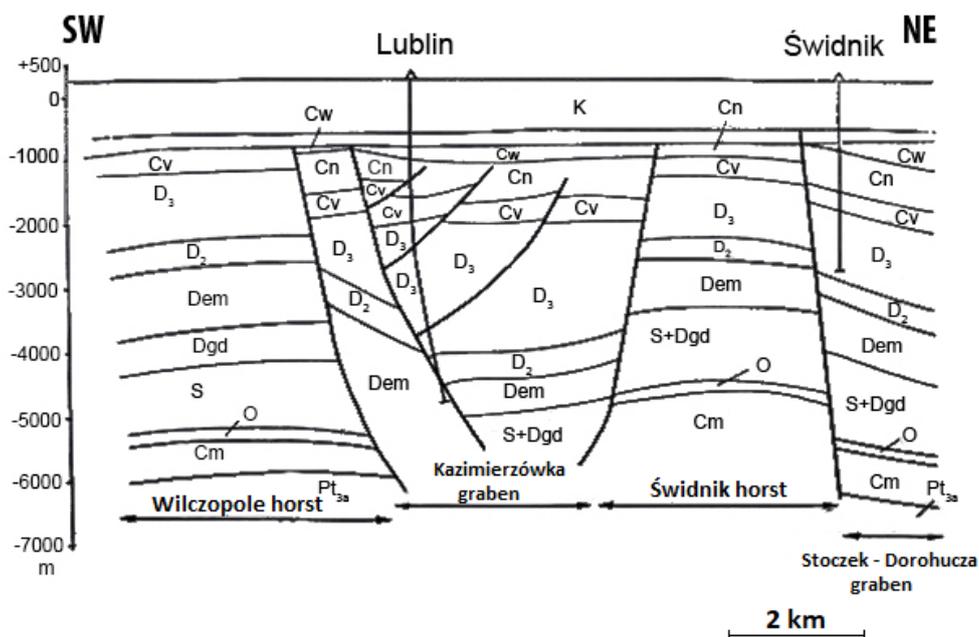


Figure 2. Geological cross-section (BB' on Figure 3) of the Kazimierzówka graben [19]; Pt_{3a}—Upper Proterozoic (crystalline rocks); Cm—Cambrian; O—Ordovician; S—Silurian; Dgd—Lower Devonian, marine facies of Gedinnian and Siegenian; Dem—Lower Devonian, old red facies of Emsian; D₂—Middle Devonian; D₃—Upper Devonian; Cv—Carboniferous-Viséan; Cn—Carboniferous-Namurian; Cw—Carboniferous-Westphalian; K—Cretaceous.

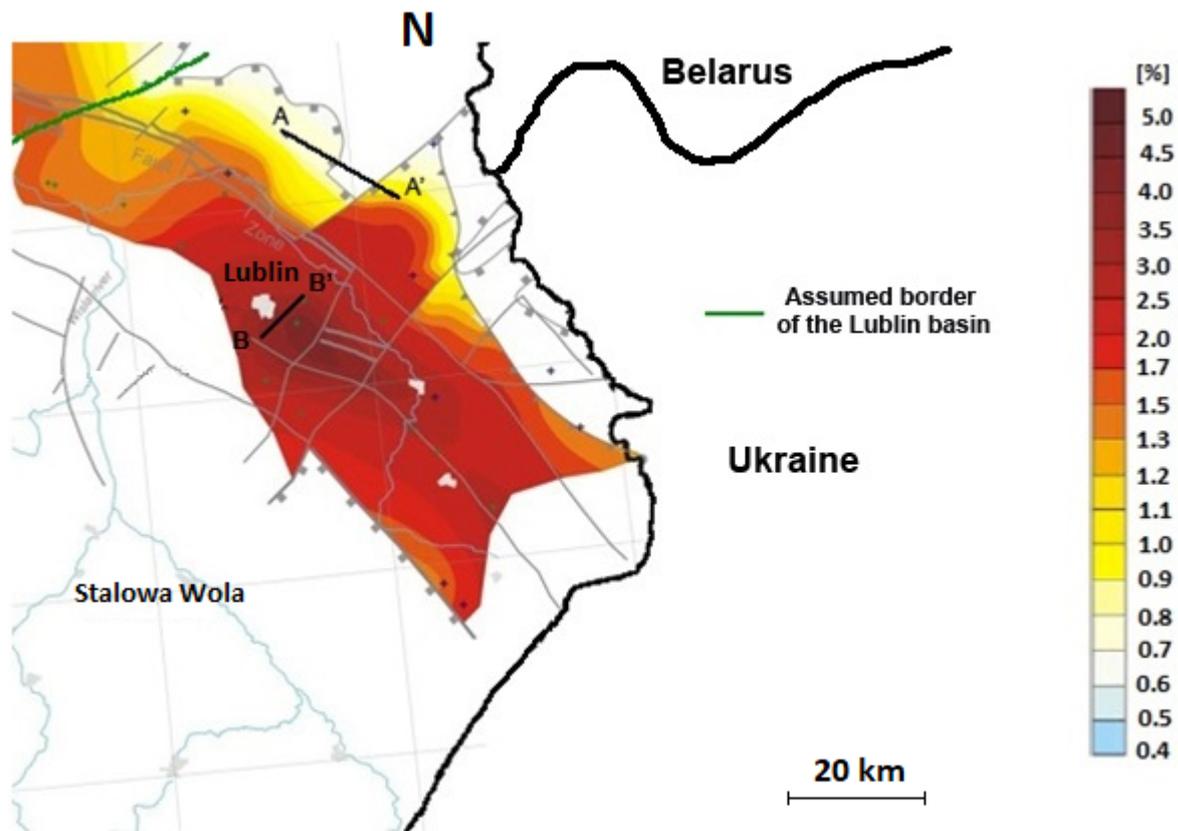


Figure 3. The level of transformation of the organic matter in Lublin Basin (based on [20]).

3. Gas Reservoirs from Shale Rocks

In the Lublin Basin, as in the entire Baltic-Podlasie-Lublin Basin, gas-bearing shale is located in the Lower Paleozoic rocks, in the Silurian period, in its lower epochs (the Llandovery and the Wenlock) and, to a smaller extent, in the epoch of the Lower Ludlow.

A potential gas-bearing rock should be tested for the thermal maturity of the organic matter within it. Thermal maturity may be described by the parameter called the vitrinite reflectance R_o (Figure 3).

For gas, the parameter's value R_o should range from ca. 1.7 to ca. 2.7%. If the value of the vitrinite reflectance is over 2.7%, then the organic matter becomes a graphite residuum. On the other hand, if the value is lower than 1.7%, then the organic matter enters the petroleum range, where an increasing amount of petroleum is present along with natural gas. It was assumed that below 1.0%, the amount of gas from the organic matter is scarce, and there is a sizeable amount of petroleum. Between 1.0% and ca. 1.7%, the ratio of gas to petroleum increases up to a threshold (ca. 1.7%), where petroleum disappears [21].

It is assumed that natural gas may be present in shale rocks of 3.5% vitrinite reflectance (Report of the National Geological Institute, Warszawa, March 2012). The described dependence is presented in Figure 4.

In a major part of Poland, natural gas may be present in the shale of the Lower Paleozoic, in rocks of the Silurian period, mainly its lower epochs (Llandovery, Wenlock, Lower Ludlow). Lithologically, rocks containing this gas are mainly solid claystone, of shale texture and, to a smaller extent, black shale.

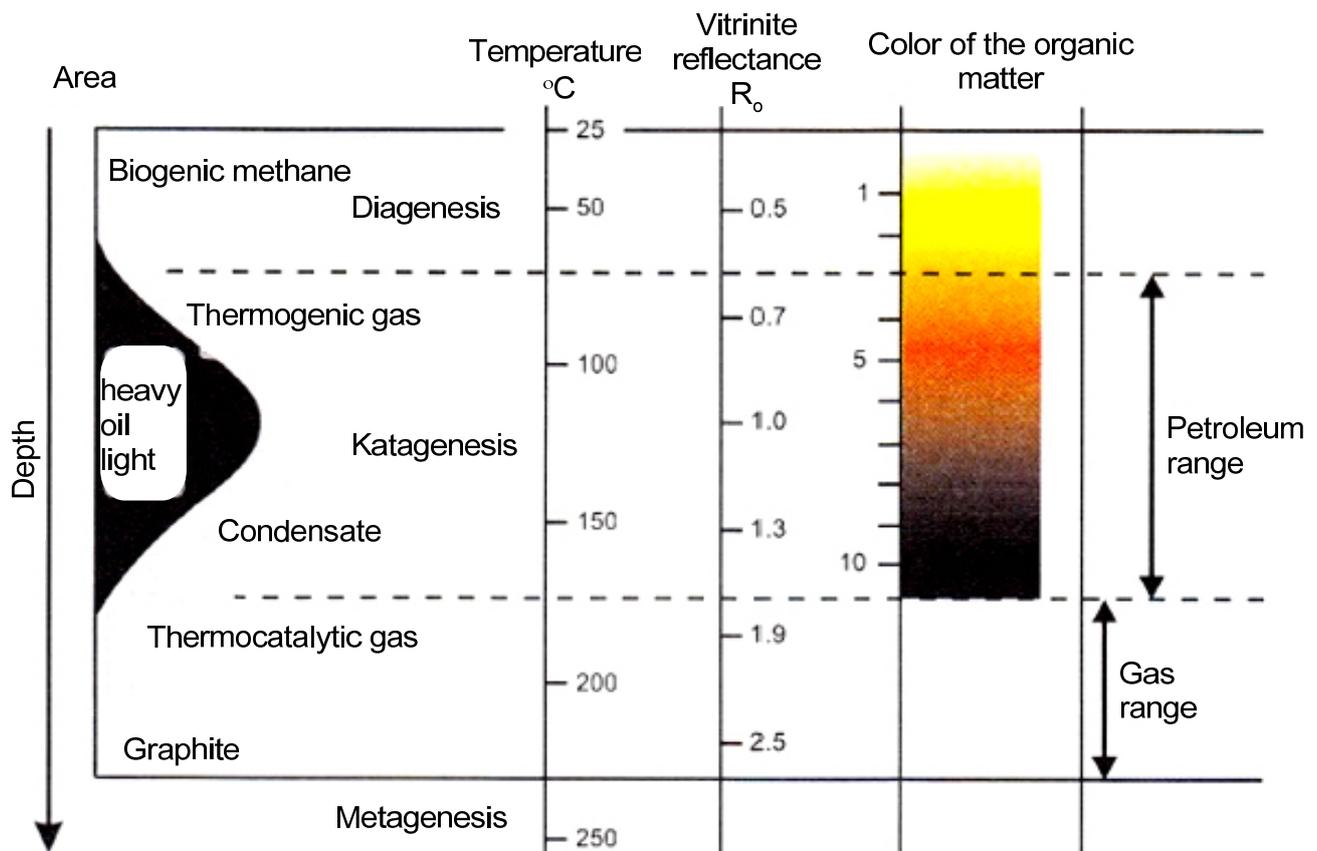


Figure 4. Correlation of organic diagenesis with temperature and thermal maturity indicators [21].

4. Data from Boreholes

To verify the possible use of the rotary-percussion method, one needs to check the lowest parts of the rocks in the prospective area. The deeper solid rocks exist, the more possible it is to use a down-the-hole hammer.

To evaluate the possibility of using the rotary-percussion method for drilling gas deposits in shale, the following boreholes were tested: Magnuszew IG1 [22], Bąkowa IG1 [23], Ciepeliów IG1 [24], Opole Lubelskie IG1 [25], Niedrzwica IG1 [26], Piotrków XX [27], Bychawa SW3 [27], Trawniki SW2 [27], Krowie Bagno IG1 [28], Tomaszów Lubelski IG1 [29], Jarczów IG2 [29], Ruszów IG1 [30], Tarnawatka IG1 [30], Lublin IG1 [31], Busówno IG1 [32], Kock IG1 [33], Kaplonosy IG1 [34], Strzelce IG1 [35], Strzelce IG2 [35], Białopole IG1 [36], Parczew IG1 [37] (Figure 5).

However, it was assumed that the Magnuszew IG1 borehole is located on the boundary of the Lublin and Warszawa basins.

Subsurface layers for particular boreholes are described below (order according to Figure 5). A detailed description of the geological structures of every borehole is presented in Appendix A.

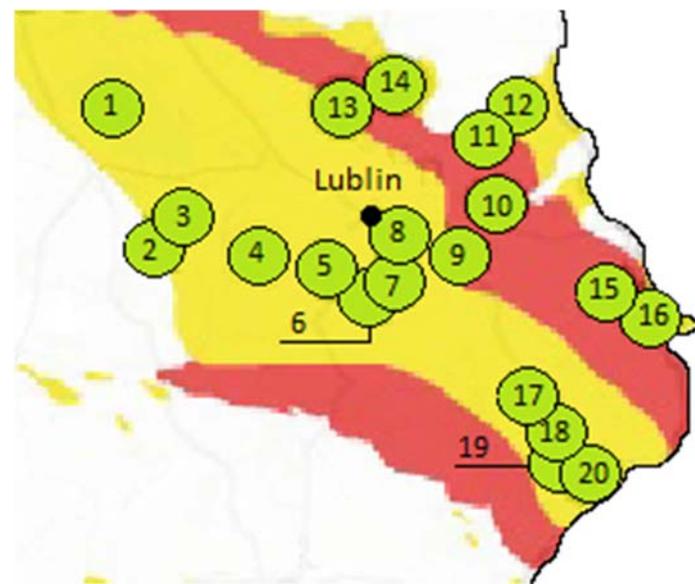


Figure 5. Locations of the abovementioned boreholes in the Lublin Basin: the yellow area signifies areas of lower or undefined gas-bearing potential in shale, the red area signifies areas of initially documented gas-bearing potential in shale of the Lower Paleozoic. 1—Magnuszew IG1; 2—Bąkowa IG1; 3—Ciepielów IG1; 4—Opole Lubelskie IG1; 5—Niedrzwica IG1; 6—Bychawa SW3; 7—Piotrków XX; 8—Lublin IG1; 9—Trawniki SW2; 10—Busówno IG1; 11—Krowie Bagno IG1; 12—Kaplonosy IG1; 13—Kock IG1; 14—Parczew IG1; 15—Białopole IG1; 16—Strzelce IG1 i Strzelce IG2; 17—Ruszów IG1; 18—Tarnawatka IG1; 19—Tomaszów Lubelski IG1; 20—Jarczów IG1 (based on geoportal.pgi.gov.pl, accessed on 20 June 2020 [38]).

5. Possibility of Rotary-Percussion Drilling

The rotary-percussion drilling method applies a hammer tool to produce percussion on a rock formation. A top hammer system transfers approximately 84% of the energy to the drill bit, while a down-the-hole (DTH) hammer is more efficient in this regard—almost 100% of the energy is being transferred [39,40]. The mechanism works as follows: rotation is caused by the head located on the top of a drilling rig. The rotation is transferred through the drill string to the hammer and further to the drill bit. As the pipes are connected by a thread, the drill string can be lengthened while drilling.

DTH may be driven by compressed air or fluid (also water), which flows via rotating the drill string to the hammer located behind the drill bit. The medium powering the DTH flows out through the holes in the drill bit's face and carries the cuttings from the bottom of a borehole to the surface [41].

Water-powered DTH works well for drilling long and straight boreholes, also in delicate areas, preventing the occurrence of doglegs. Such a tool is able to penetrate the majority of rock formations while maintaining a high penetration rate and accuracy (wassara.com, access on 20 June 2020 [42]); however, it requires a high flow rate of water. Drilling fluid recycling systems are being proposed to minimize this disadvantage [43]. An example of a water-powered 203.2 mm (8") DTH hammer example is presented in Figure 6. Figure 7 shows examples of DTH drill bits.

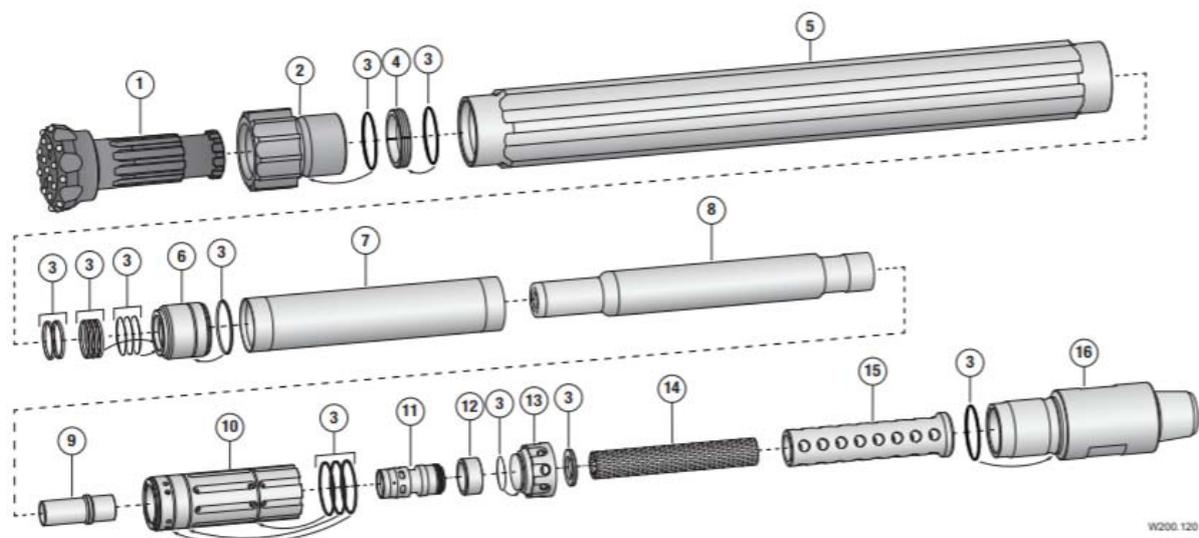


Figure 6. Wassara's W200 DTH water-powered hammer (1—drill bit; 2—chuck; 3—seal kit; 4—bit retainer; 5—hammer case; 6—piston housing; 7—inner tube; 8—piston; 9—sliding case; 10—valve house; 11—valve; 12—sleeve; 13—guided lid; 14—filter; 15—filter support; 16—backhead API 4 $\frac{1}{2}$ " IF; source: wassara.com [42]).

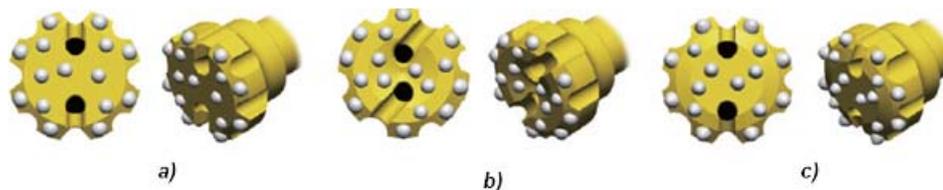


Figure 7. Heads of drill bits (a) flat—to be used in hard, medium-hard, and abrasive rocks (e.g., granite, basalt, and hard limestone); (b) concave—to be used in hard, medium-hard, and homogeneous rocks (e.g., granite, hard limestone). Good control of borehole axis deflection and washing of the bottom of the borehole; (c) convex—to be used in soft and medium-hard rocks, not in abrasive rock (e.g., shales, limestone, sandstones). Very good advance of drilling works) [44].

The selection of the drilling method, equipment, and drill string, particularly regarding the drill bit and the drilling technology parameters, is a key factor in the borehole drilling process. Among the rotary-percussion drilling methods, DTH is popular in practice, as it is more effective than drilling using top hammers. The quality of the selection is significantly dependent on the borehole design and on the available information regarding the properties of rocks to be drilled. Below is an exemplary selection of DTH drill bits for Sandvik (Sandvik Top Hammer Rock Drilling Tools—Catalog) by choosing the appropriate codes marked with letters for the rocks intended for drilling, depending on:

(a) compressive strength (hardness)

H: for very hard to hard rocks, with compressive strength above 250 MPa;

M: for medium hard rocks, with compressive strength between 150 and 250 MPa;

S: for soft rocks, with compressive strength below 150 MPa;

(b) rock homogeneity

C: for homogeneous (competent) rocks;

F: for fissured rocks;

(c) rock abrasion

V: for very abrasive rocks with a silica content above 40%;

A: for abrasive rocks with a silica content between 20 and 40%;

N: for non-abrasive rocks with a silica content below 0–20%.

A similar tool selection for rock drilling is presented by Copco Secoroc Atlas (Secoroc Rock Drilling Tools, Product catalog—DTH equipment). The selection is limited to the bit profile, hard and abrasive formations, and shows rock examples.

Another criterion for the drilling method selection is the system for cleaning the bottom of the borehole and carrying drill cuttings to the surface. In practice, both the water-to-power down-the-hole (DTH) percussion hammer and the air-powered DTH hammer are applied. Compared to conventional air-powered DTH hammers and water-powered DTH hammers, we can say that DTH offers a wide range of advantages, including low energy consumption, minimal hole deviation, a cleaner environment, deeper drilling capabilities, and a minimal impact on the surrounding ground. Water-powered DTHs do not create dust and using water as a flushing medium also better cleans the borehole.

The rotary-percussion drilling method with the DTH tool may be divided into two types: with a single and a double drill string. The single drill string method is used mainly in solid rocks, with a low risk of crumbling walls. In case loose rock layers precede the solid rock layer, to prevent the crumbling of borehole walls, the initial drilling is done by a casing string with a drill bit. The mechanism of the rotary-percussion drilling method with a single drill string is based on a DTH being controlled remotely by an air compressor. The double drill string method is used mainly in loose or less concise rocks. Drilling is done by simultaneous operation of two strings: a casing string equipped with a drill bit, being rotated counter-clockwise by the lower head, and a drill string equipped with a hammer or saw tooth type of drill bits are rotated clockwise by the upper head [41].

Various types of drill bits are used in the rotary-percussion drilling method [44]: A flat type is used for hard, medium-hard, and abrasive rocks. A concave drill bit is used for hard, medium-hard, and homogenous rocks, making deviation control and borehole scrubbing less difficult than other drill types. A convex drill bit is used for soft and medium-hard rocks with an advantage of an increased rate of penetration.

The drilling progress is also influenced by the shape of the drill bit inserts. Spherically shaped cemented carbides are resistant to cracking but do not guarantee high penetration rates. Semi-ballistic cemented carbide inserts have lower resistance to cracking in comparison to the spherically shaped ones but provide much better penetration rates. Ballistic cemented carbide inserts have lower resistance to cracking than both spherical and semi-ballistic inserts but guarantee a high drilling speed. Cylinder cemented carbide inserts are highly prone to cracking but guarantee very good drilling progress.

Drilling fluids used with the rotary-percussion drilling method are mainly air, water, or foam. They can be run through a pressure booster when drilling deep boreholes for more efficient removal of cuttings to the surface and pressure loss reduction.

Air pressure may be increased by a pressure booster up to 20 MPa at once and up to 170 MPa gradually over a few cycles. For water, with the use of a pressure booster, the borehole can reach a depth of approximately 3500 m. The rule of thumb is to increase the water pressure by 0.1 MPa for every 10 m drilled and add 0.7 MPa on a drill bit. With the use of foam, an additional 30% of the originally assumed borehole depth can be reached, cuttings and formation fluids removal are more efficient, and if the water influx is high, the returning pressure on the hammer is decreased [41].

6. Possibility of Rotary-Percussion Drilling in the Lublin Basin

The rotary-percussion method in the petroleum industry has been tested in American deposits, such as the Berea region (on the border of Kentucky, Virginia, Western Virginia). From mid-2009 to the end of September 2010, 44 horizontal sections of 3000 to 3700 feet (914–1128 m) were drilled in this region. In the Berea region, until mid-2010, 3000–4000 feet (914–1220 m) deep boreholes were being drilled using the rotary-percussion method. The use of the drilling method was a major success since the total cost dropped by one-third, and the drilling time decreased by half in comparison to the conventional method [45].

In the process of creating boreholes, the obtained techno-economic indicators, such as the unitary drilling cost and drilling speed, are very important. They depend on the

properties of the drilled rocks, the quality of the drilling tools selection, and the drilling technology parameters. The latter include pressure on the drill bit, rotational speed, and air or water flow rate when drilling using hammers. Among them, the best researched in both laboratory and field conditions is the influence of axial pressure on drilling speed. The research showed that in the initial phase of drilling at low values of axial pressure, the so-called fatigue and surface drilling occurred, which was classified as ineffective drilling. In such a case, a significant part of the mechanical energy was converted into thermal energy, which adversely affected the drill bit condition and might lead to its accelerated wear. Only at higher pressure values did the so-called volumetric drilling occur, and a significant increase in drilling speed could be observed. A further increase in the pressure on the rock with unchanged parameters of cleaning the well bottom from drill cuttings led to achieving the maximum and, further, to a decrease in the drilling speed. If such a case occurred, the effectiveness of cleaning the well bottom from drill cuttings and carrying them to the surface should be improved, or the axial pressure on the drill bit should be reduced. For example, Atlas Copco's 6" COP64 STD hammers have a recommended working pressure of 6 to 25 bar. The research on the influence of rotational speed on drilling speed showed a smaller influence than the axial pressure on the drill bit. This influence depends mainly on rock hardness. The harder the drilled rock is, the less influence this dependence has. The main range of rotational speed changes is from 20 to 60 rpm. With rational drilling parameters, such as pressure and rotational speed, the influence of the air or water flow rate on the drilling speed decreases with the increase in the drilled rock's hardness. In practice, the drill test can be used to select the optimal drilling technology parameters.

In Poland, this method was used, e.g., in the drilling of a borehole near Lublin [46]. The drilling began with the use of a $\varnothing 140$ mm drill bit at the hammer, a $\varnothing 168.3$ mm bit at the casing pipes to 60 m of depth. In this way, the Quaternary sediments were drilled through (to 26 m), including soil (0.4 m), loess (from 0.4 to 14 m), clay (to 24 m; however, sandy clay was present between 16 and 20 m), and coarse sand (24 to 26 m). Consequently, the drilling continued through the Paleogene sediments (gaize and sandy spongiolite), which remained in this borehole up to 36 m of depth. The till of the Paleogene sediments overlapped with the depth of the water table.

Below, there were the Upper Cretaceous rocks (from 36 to 82 m), which mainly included marl and gaize (to 42 m also sandy spongiolite), with the exception of a 54–56 m interval where rubble was found. Four meters below the rubble, the drilling equipment was replaced—from that moment onward, it was a $\varnothing 140$ mm bit at the air-driven hammer until the end of the operation (to 110 m). The stratigraphy of the borehole did not change (the Upper Cretaceous formations were present), while the lithology did—from 82 m to the final stage of drilling, gaize was not found anymore, while limestone inserts were found in marl. The area of the drilling was located at 212 m above sea level.

It is noticeable that the upper part of the profile is brittle or loose, whereas, from 26 m of depth, siliceous rocks were found (sandy spongiolite, gaize), which are significantly harder.

Though the above-mentioned rotary-percussion drilling in the Lublin Basin was done up to 114 m, it was clearly possible to apply this type of drilling in lower (older) structures. The following figure (Figure 8) presents the lithological structure of the well used for the borehole heat exchanger. Like it is presented, marls, limestones, gaizes, and other formations were easily drilled. There are two possible scenarios:

1. Only the younger formations are drilled; nevertheless, the speed of drilling is increased by 30% [6–8]. In this case, the rotary-percussion drilling method is used together with the standard rotary drilling type.
2. The down-the-hole hammer is used as long as it is possible. In this case, drilling bits have to be changed; nevertheless, there is a big profit in higher drilling speed. This method is going to be promising, especially in the areas with lower depths of Silurian layers (2000–2500 m below ground level).

Both scenarios seem to be promising in the further exploitation of shale gas. Every way to reduce drilling time, which has a positive impact on the economy of the investment, is a good choice to be implemented.

To check if the drilled-through rock is hard enough to use the rotary-percussion drilling method, one may use Tables 1 and 2 referring to the hardness of rocks.

Table 1. Physicochemical properties of rocks (according to [47]).

Type of Rock	Density, g/cm ³	Uniaxial Compressive Strength, MN/cm ²
Granite	2.60–2.90	20.0–38.0
Diabase	2.90–3.30	28.0–35.0
Porphyry	2.35–2.70	9.0–49.0
Marble	2.70–2.85	8.0–37.0
Quartzite	2.50–3.00	29.0–38.5
Metamorphosed quartzite sandstone	2.50–3.00	18.0–40.0
Limestone	1.50–3.00	2.0–20.0
Dolomite	2.20–2.70	6.0–27.0
Quartzite sandstone	2.00–3.00	12.0–35.0
Rock salt	2.10–2.20	2.5–4.0
Sylvine	2.00–2.20	2.5–4.0

Table 2. Table of rock compressive strength against uniaxial stress [47].

Type of Rock	Compressive Strength under Uniaxial Loading, MPa	Shear Stress for Rock Plastic Transition, MPa	Poisson's Ratio
Loam	5.0–150	0.1–3.0	0.45–0.50
Hard coal	20.0–30.0	75.0	0.20–0.25
Rock salt	25.0–40.0	24.0–50.0	0.35–0.40
Anhydrite	40.0–50.0	17.5	0.30–0.35
Limestone	15.0–40.0	35.0	0.40–0.45
Marble	55.0–70.0	52.5	0.20–0.25
Sandy clayey shale	60.0–80.0	70.0	0.20–0.25
Clayey shale	50.0–100.0	105.0	0.25–0.30
Dolomite	180.0–200.0	70.0	0.20–0.25
Sandstone	60.0–70.0	28.0	0.10–0.20
Granite	170.0–200.0	100.0	0.15–0.25
Basalt	220.0–340.0	105.0	0.20–0.25

The rotary-percussion method is most likely to succeed when applied, especially in the Lublin Basin, taking into consideration the low thickness of the Quaternary and possibly the Tertiary layers. However, the depth at which the Silurian rocks are present might be a challenge—e.g., in the Lublin IG1 borehole, drilled to 5028 m, the formations in question were not reached; in the Tomaszów Lubelski IG1—a 3000 m deep borehole also did not drill through the Silurian layers. In other, more prospective areas, the Silurian layers are present higher in 2000–2500 m of depth. The northern part of the Lublin Basin is of particular interest.

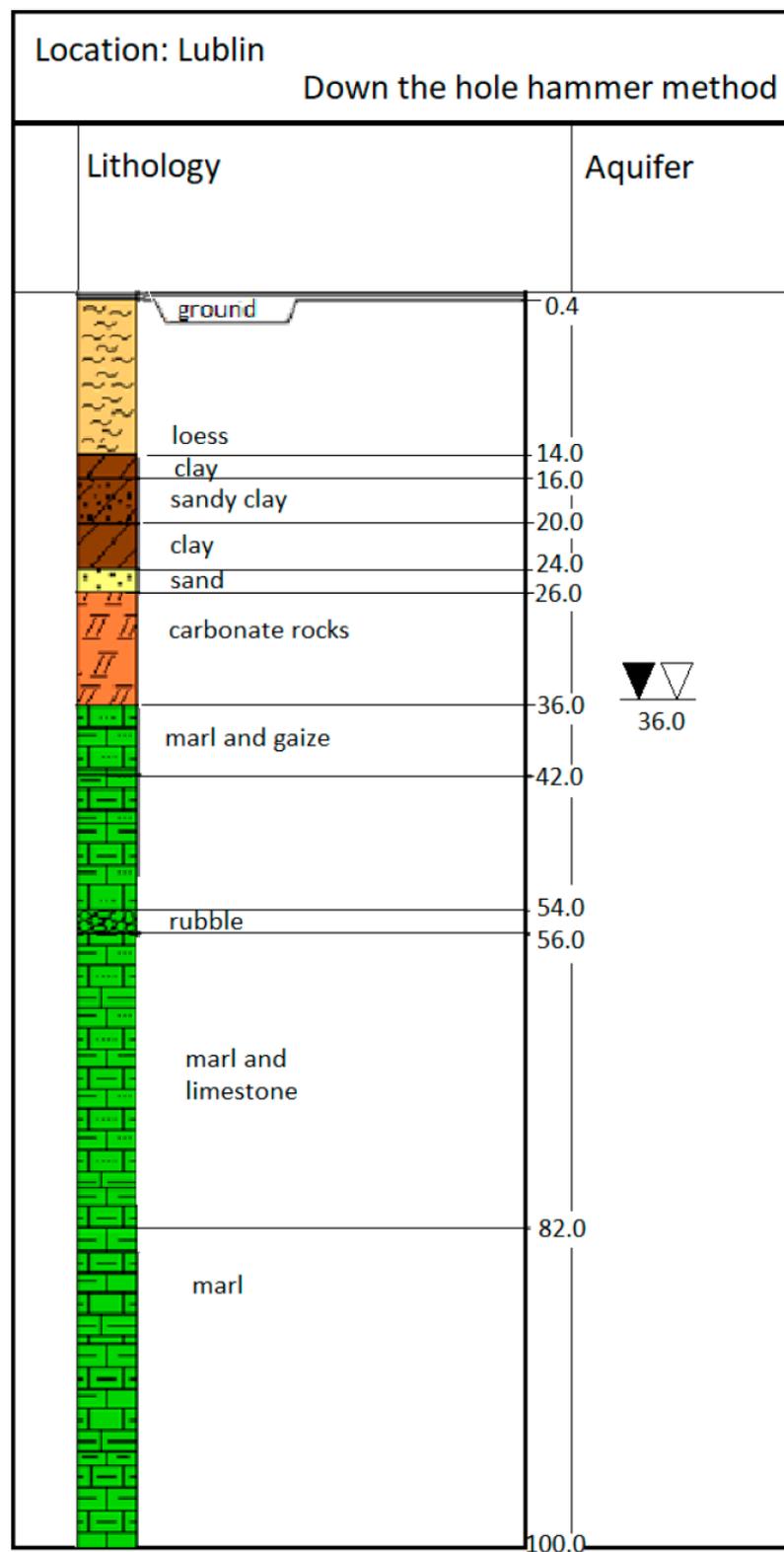


Figure 8. Geological profile and filtration schematics of the test borehole, which is common for every borehole under study [46].

7. Concluding Remarks

1. The aim of the paper was to determine the feasibility of using the rotary-percussion drilling method for shale gas drilling in the Lublin Basin. The analysis indicated that this method had a big technical and economic potential and should be considered by drilling companies for this purpose.
2. Taking into consideration the fact that Polish shale gas resources are most likely around 346–768 billion m³, and the gas consumption will rise, analysis of the possible application of the rotary-percussion drilling method in drilling the vertical section of shale gas was very reasonable.
3. Out of three shale basins in Poland, the most favorable conditions for rotary-percussion drilling were in the Lublin Basin. They resulted from the lowest thickness of loose and less concise rocks and loam. After their isolation with an initial column, further drilling might be done using a down-the-hole hammer.
4. In rotary-percussion drilling, gravity was used for the percussive force of the hammer. Therefore, it is recommended to use this method only to drill vertical sections in horizontal boreholes producing gas from the Silurian shale layers. Horizontal sections should be drilled using more standard methods.
5. In the Lublin Basin, the Silurian layers are present relatively deep. In some of the boreholes, their presence was confirmed in 2000–2500 m. However, there are boreholes that did not reach them even at 5000 m.
6. The choice of the scenario (drilling up to the Silurian layers or the possibility of drilling through upper layers and then switching to the standard rotary method) should be dependent on the region and rocks that have to be drilled.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A Data from Boreholes

- (1) Magnuszew IG1—the Quaternary rocks to 50 m (sandstone and non-uniform gravel), Pliocene to 65 m (non-uniform sandstone, loam), the Miocene (to 83 m, non-uniform sand), the Oligocene (to 143 m, non-uniform sandstone, silt), the Paleocene (to 220 m, marly clay, marl, sandy spongiolite, gize). In the Paleocene, hard rocks are already present. In the Upper Cretaceous (the Upper Maastrichtian, to 480 m), there are mainly hard marl, gize, and limestone. The borehole is located on the border of the Lublin Basin, in the South-East of the Warszawa Basin. The Silurian rocks were not drilled through; the Carboniferous was reached (the Westphalian) [22].
- (2) Bąkowa IG1—the Quaternary rocks to 10 m (the Pleistocene, different kinds of sandstone). Below are only rocks from the Upper Maastrichtian (the uppermost level of the Cretaceous), which lithologically consist of hard marly gize, except for one interval (220–270 m) made of white-and-grey marl. Rocks of this level reach 290 m. The depth of Bąkowa IG1 is too low to find the Silurian layers. The lowest layers are of the Mid Devonian (the Eifelian), lying between 2394.5 and 2433.8 m below ground level [23].
- (3) Ciepielów IG1—the Pleistocene to 20 m (sandy clay interchangeably with non-uniform sandstone, from 8 to 20 m only sand). In the Maastrichtian rocks, in the roof part, there

is mainly brittle limestone (to 58.40 m), the limestone below is harder. The Silurian layers are only in the lower part of the borehole. These are Podlasie (2598.3–2885.0 m below ground level, the so-called Upper Rzepin layer), and the Upper Ludlow (2885.0–3000.0 m below ground level, the Lower Rzepin layer). It cannot be decided whether IG1 is fit for shale gas exploitation since it is too shallow. Only after confirming the Lower Ludlow layers, one may search for organic matter transformed to a sufficient extent so gaseous hydrocarbons could be produced from shale [24].

- (4) Opole Lubelskie IG1—the Quaternary rocks to 18 m (fine and medium-grained sandstone, with an admixture of coarse sand and singular grains). Below the Quaternary, the Upper Maastrichtian interval is located (white fairly soft marly limestone to 25 m), below—the Lower Maastrichtian (to 125 m, white, fairly soft marly limestone). Opole Lubelskie IG1 borehole is located in an undefined area or one of a lower potential concerning natural gas from the Lower Paleozoic shale. The borehole was drilled only to the Lower Devonian (the Emsian). Thus, it is impossible to determine whether graptolitic fauna is present, which would enable the formation of a sufficient amount of gas [25].
- (5) Niedrzewica IG1—the Quaternary rocks to 24 m (yellow loess). Below there is the Upper Maastrichtian layer (to 280 m), which is predominantly represented by medium-hard marly limestone. The Niedrzewica IG1 borehole reached only the Upper Devonian formations [26].
- (6) Bychawa SW3—the Quaternary to 2 m (brown earth, rusty sand, sandy loess), the Upper Maastrichtian levels are below (concise gaize and marly limestone, to 278.15 m) [27].
- (7) Piotrków XX—the Quaternary rocks to 7 m (light brown and brown loess, fine and medium-grained sand), to Miocene rocks to 14 m (grey-and-yellow, and grey mudstone, brown silt, siliceous-ferrous sandstone, and sandy loam). To 62.5 m, there are the Paleocene layers (clayey-siliceous, siliceous, and limy sandy spongiolite, as well as grey marl and grey marly limestone). The Upper Maastrichtian rocks are mainly gaize and marly limestone and marl (to the bottom—150 m) [27].
- (8) Lublin IG1—a meter-deep layer of the Holocene sands, underneath which there are rocks from the Upper Maastrichtian to 321 m (gaize, limestone, and marl to 120 m, beneath is marly chalk). The borehole does not penetrate layers of the Lower Paleozoic (it ends at the Lower Devonian) [31]. In the figure (Figure 5), however, it is visible that there is a specific geological structure in the area the borehole is located in—the Silurian layers are on the side of a fault, which is why they reside lower in the rest of Lublin Basin area. The organic matter may be overripe, which may prevent the effective production of hydrocarbons.
- (9) Trawniki SW2—the Quaternary layer (to 1 m), consisting of loess-covered with 0.3 m of brown soil. Rocks of the Upper Maastrichtian (to 318 m) are mainly marl, marly gaize, and marly limestone, from 2 m being concise. From 318 m of depth to the bottom of the borehole, there are rocks of the Lower Maastrichtian (chalk to 359 m, below mainly marl) [27].
- (10) Busówno IG1—the Holocene layers to 17 m (light-grey and yellow fine and medium-grained sandstone), beneath, there are rocks of the Maastrichtian Coniacian (to 406 m), which are silt mixed with the Quaternary gravel (to 50 m) and marly chalk below. In the area, the Silurian formations (the Landower, the Wenlock, the Ludlow, the Pridoli) are present between 2008 and 2890 m. The Landower, the Wenlock, and the Ludlow formations (highest probability of gas in shale) are between 2636.5 and 2889.5 m. The uppermost layer containing a graptolitic fauna (although scarce) is the Pridoli interval between 2170 and 2176 m. In the Ordovician rocks (as in rocks of the Early Landower), the fauna is scarce; the rocks do not show the potential of containing natural gas deposits big enough for the exploitation to be profitable [32].
- (11) Krowie Bagno IG1—the Quaternary to 39 m (grey clay, sandy, and with crystalline pebbles in the upper part). The Maastrichtian rocks (to 120 m) are mainly chalk, rarely marly limestone, marl. Chalk is white, soft, and fissile. The Silurian rocks are present

between 1850.0 and 2724.0 m below ground level. The Podlasie is the uppermost layer (1850.0–2320.0 m below ground level), which is lithologically represented by grey-and-green claystone or silty claystone (sometimes with mid-layers of limestone). Not until 2213 m below ground level, one may notice a rich graptolitic fauna. Higher fauna is scarce and mostly does not include graptolites. The Upper Ludlow is below (the Siedlce layers, 2320.0–2472.0 m below ground level), which consists of dark-grey claystone and claystone with limestone inserts. A rich graptolite fauna is visible, especially in the lower part. In the Lower Ludlow (2594.0–2671.0 m below ground level, the Mielno layers), there is dark-grey claystone pure, or with layers of limestone. The Upper Pasłek, which is the Wenlock and partially the Landower (2671–2724 m below ground level), is dark-grey claystone with scarce limestone overgrowths (from 2701.5 m below ground level limestone overgrowth occur often). Rocks of the Silurian are almost only brittle, non-fissile. Lithologically, the Ashgill (2724.0–2732.5 m below ground level) consists of slightly marly limestone, as well as marly claystone. Rocks of Caradoc (2733.0–2751.8 m below ground level) are mainly grey marl, and grey limy claystone (in lower parts, it is characterized by tabular fissility), and (below 2750.7 m below ground level) limestone (grey or marly) [28].

- (12) Kaplonosy IG1—the Quaternary to 54.5 m (sandy siltstone, silty sandstone, sandy gravel, non-uniform sandstone) lying on the Lower Maastrichtian layers, which are mainly built from chalk, sometimes also clayey marl [32]. The Silurian level in the borehole is present between 445.8 and 718.5 m below ground level, and the Ordovician level between 718.5 and 774.6 m below ground level. Between 445.8 and 584.5 m, the Silurian is characterized by the Lower Siedlce layers. Below is the Ludlow between 584.5 and 676 m below ground level. Between 676 and 718.5 m below ground level, it is the Wenlock.
- (13) Kock IG1—the Quaternary to 28 m (sandy soil to 1 m, then non-uniform sandstone), the Upper Maastrichtian layers are beneath (to 178 m); mainly marly limestone (except for the interval to 45 m, where chalk is present). Given the low depth of the borehole, the Lower Paleozoic was not reached (the Lower Silurian and farther below, the Ordovician). The lowest layers reached were the Podlasie layers (845.00–1009.20 m below ground level) belonging to the Upper Silurian [33].
- (14) Parzew IG 10—the Pleistocene to 22.5 m (gravel, sandstone, and clays), the Paleocene to 26.5 m (carbonate-siliceous formations). To 122.5 m, there are rocks from the Upper Maastrichtian: chalk-like limestone, marly limestone, and from 90.5 m—marly chalk. The potentially gas-bearing Silurian rocks are present between 1071.0 m and 1471.6 m. To 1375 m, there are rocks from the Ludlow epoch, which are less prospective for hydrocarbon deposits. The more prospective layers of the Wenlock are at the interval between 1375 to 1455.2 m below ground level. Farther, to 1471.6 m below ground level, there are, also prospective, the Landower rocks [37].
- (15) Białopole IG1—the Holocene silty grey soil to 0.5 m of depth. Below are the Upper Maastrichtian rocks (to 64 m), consisting mainly of white fairly soft marly chalk. The Lower Maastrichtian (to 139 m) is mainly the same kind of rocks as in the upper part of the Maastrichtian, with limestone in the interval between 112.5 to 139 m. The Silurian rocks in the Białopole area are between 1592.5 and 2131.5 m below ground level. The uppermost rocks are from the Pridoli epoch (1592.5–1830.0 m). Below, there are rocks from the Ludlow (1830–2089.1 m). Layers from the Wenlock are at 2131.5 m below ground level. The Ordovician is present between 2126.5 and 2239.5 m. The Ashgill (to 2131.5 m) is characterized by limestone. The Caradoc (to 2191.5 m) consists of poorly fissile, rough, dark-grey claystone, and limestone in lower parts [36].
- (16) Strzelce IG1—the Quaternary to 5 m (dusty soil, and fine-grained sand); beneath, there is rock from the Lower Maastrichtian (to 8 m; white-and-grey soft carbonate rock) and the Campanian (to 124 m; marly chalk and marly limestone). Stratigraphically, the Silurian sediments lie between 1424.0 m and 1545.1 m below ground level. Thus, they are the oldest layer drilled in the borehole. Moreover, the Silurian layers in

- the borehole are of the Upper Silurian only (the Upper Podlasie layers), which are devoid of properly sizeable deposits of hydrocarbons in shale [36]. Strzelce IG2—the Quaternary rocks to 20 m (dusty soil to 1 m, then yellow-and-brown loess clay), the Lower Maastrichtian to 30 m (marly chalk), the Campanian to 152 m (marly chalk to 45 m, marly limestone to 65 m, again marly chalk to 73 m. Marly limestone also in the intervals of 73–81 m and 90–100 m, whereas chalk—from 81 to 90 m and from 100 to 152 m. Stratigraphically, the Silurian sediments are at a depth of 1732.5 m reach the bottom of the borehole, amongst which are the Upper Silurian (the Podlasie, the Upper Podlasie layers) to 1855.0 m, the Lower Podlasie (1855.0–1890.0 m), and the Upper Ludlow (the Upper Siedlce layers) to the bottom of the borehole [36].
- (17) Ruszów IG1—no Quaternary rocks in the profile The Upper Maastrichtian to 200 m (consists mainly of marl, marly limestone, and marly gaize). The borehole reaches only the Devonian layers of the Emsian (the Zwoleń formation) [30].
 - (18) Tarnawatka IG1—similar to the borehole Ruszów IG1, its profile does not include Quaternary layers. The Upper Maastrichtian, which lies within the Upper Cretaceous, is characterized by rocks such as brittle gaize and marl up to 30 m, underneath is light grey marly limestone and medium-hard rocks. Similar to the one in Ruszów, this borehole reaches only the Devonian rocks (the Upper Siegenian—the Schwarzwald formation) [30].
 - (19) Tomaszów Lubelski IG1—no Quaternary layers are present; the geological profile begins with the Maastrichtian. To 25 m, the Maastrichtian is represented by white chalk of a yellowish tinge. Below, to 100 m, there is white and light-grey marly limestone [29]. The Silurian formations were not drilled through in this borehole. The drilling was stopped at the Lower Devonian (the Emsian and the Siegenian).
 - (20) Jarczów IG2—the Quaternary to 10 m (dark-grey soil, sandy silt, non-uniform sand); below, there are rocks of the Upper Maastrichtian (to 115 m light-grey marly gaize of medium hardness, quite brittle in the upper part). The borehole, similar to the one in Tomaszów Lubelski, does not go through the Silurian layers. The lowest layer here is the Emsian layer (the Lower Devonian epoch, 1928.2–1950.3 m below ground level) [29].

In Poland, in the area of an initially documented higher potential for natural gas, there are the following boreholes: Tomaszów Lubelski IG1, Jarczów IG1 (South), Strzelce IG1, Strzelce IG2, Białopole IG1, Busówno IG1, Krowie Bagno IG1, and Kock IG1 (North).

Neither the Tomaszów Lubelski IG1 nor the Jarczów IG1 borehole did go through the Silurian layers. The former is deeper—the drilling was conducted up to 3000 m.

In the North, boreholes Strzelce IG1 and Strzelce IG2 reached only the Upper Silurian layers (the Podlasie and the Ludlow). The latter is deeper—it is 1978.8 m deep. The deep borehole Białopole IG1, reaching 3017.6 m, goes through the Wenlock at 2089.1–2131.5 m. The borehole has no sign of the Landower. The Ordovician is present between 2126.5 and 2239.5 m. The Ashgill (to 2131.5 m) is characterized by limestone. The Caradoc (to 2191.5 m) is represented by dark-grey, rough, slightly fissile claystone and limestone in lower parts.

The sample from the Wenlock has 1.23% Ro of vitrinite reflectance (at 2092.2 m). The percentage of organic matter is also the highest in the rocks from the Wenlock (ca. 0.9%).

The Ashgill rocks have ca. 1.32% Ro of vitrinite reflectance (at 2131.5 m), and the Caradoc rocks have 1.38% Ro (2178.0 m). The maturity of organic matter is, therefore, corresponding to the petroleum range.

In Busówno IG1 borehole, the Llandovery, the Wenlock, and the Ludlow formations (highest probability of gas in shale) are between 2636.55 and 2889.5 m. In the Ordovician (as well as the early Llandovery), fauna is scarce; the rocks do not show possible natural gas deposits sizeable enough for exploitation to be profitable.

Krowie Bagno IG1 borehole goes through the Silurian rocks of low fissility. The Ludlow is located here, between 2594–2671 m below ground level, the Wenlock and the Llandovery are between 2671 and 2724 m.

In Kock, the Silurian rocks were slightly drilled through.

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