Shale gas as seen

by Polish Geological Survey

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INTRODUCTION

author: Jerzy Nawrocki


PAŃSTWOWY INSTYTUT GEOLOGICZNY
MENTE ET MALLEO
MUZEUM GEOLOGICZNE PIG

We are pleased to present you a brief comprehensive compilation of a body of knowledge mainly dealing with gas-bearing shale rock in Poland. Recent years witnessed rapid growth in the number of studies, technical reports, research papers and media reports on gas from non-conventional resources. Therefore, you may wonder why the Polish Geological Survey decided to revert to these issues once again and in such form? The answer lies in the mission of national geological surveys that began to be established almost 200 years ago (the oldest of them, the British Geological Survey, was founded in 1835). Their mission was to act as knowledgeable scientific institutions conducting professional research as well as providing fully objective expert and consulting services and support for state administration, local governmental bodies and individual citizens in the form of objective information on the state of abiotic environment, especially mineral resources. An objective approach here means information based on hard scientific evidence and free of any influence of business or political lobbies. In order to achieve this goal, we introduced certain practices starting with the principle that our experts involved in environmental impact assessments of shale gas prospecting and exploration and estimation of its resources are not involved in any services for commercial entities.

Another reason for this compilation is the increasing and perceptible scope of activity on the part of some organisations and institutions, which, although undocumented, may lead to poor decisions affecting the future and security of our life. An example of ideologically tainted information can be the heated debate on climate warming. It has been ongoing for about 20 years and has led to very costly countermeasures to reduce the emission of greenhouse gases, especially in Europe. It is surely not my purpose to contest a proper trend in our civilization to reduce the use of non-renewable fossil fuels. This also concerns a decrease in the overly high and still growing emission of greenhouse gases into the atmosphere, whereby these gases are gradually trapped by plants – the main parent material for non-renewable fuels. I only wonder why attention is mainly focused in this heated debate on all possible negative effects of climate warming such as floods and droughts in various distant parts of the world. Absent in this debate is a fact quite obvious to inhabitants of our part of Europe, namely the cyclical nature of the Earth's climate. In accordance with these cycles, northern and central Europe should once again be covered by an ice sheet from Scandinavia in the next millennia. Therefore, the empirically probable shift in the natural Quaternary cycle of climate change even if partly caused by human activity, may protect large parts of Europe and North America for some time from the effects of an inevitable act of nature, that is, the next glaciation.

All mining operations, including prospecting, exploration and exploitation of mineral resources inevitably have some impact on the environment. However, monitoring of shale gas prospecting by our national geological and hydrogeological surveys until now did not reveal any environmental impact that is different from prospecting for classic hydrocarbon resources. These studies will be continued along with further developments in prospecting for shale gas resources and results will be made available on-line to all interested parties.

Each chapter of this book provides very concise summaries of various aspects of knowledge surrounding shale gas, including a history of use of this energy source and its role in an energy mix. The main issue is what we actually know about Polish shale gas resources after three years of prospecting. Generally, we know more about shale gas resources in concession blocks awarded to commercial companies, but even in these cases information is rather limited due to the still slow pace of prospecting. Data occasionally released by these companies suggests that in some parts of Poland shale gas may appear in amounts comparable to those recorded in resources currently exploited in the United States. However, initial production tests until now were still rather limited in number and failed to confirm expected productivity. Such low productivity may be due to the still rather limited number or technical errors in production tests or natural properties of gas-bearing shale that render them more resistant to the effects of hydraulic fracturing. To answer these questions, we must collect more data, especially on how gas is trapped in this rock. Some gas amounts may be entrapped in such tiny pores that cannot be freed by presently applied hydro-fracking. If so, we can only hope that these amounts will be minor in comparison with those that appear possible to extract with these techniques. Otherwise it will be necessary to intensify prospecting and employ different shale gas extraction technology. In any event, it appears that Poland and other European countries are still at the start of the "shale gas" road.

Prof. Jerzy Nawrocki
Director of the Polish Geological Institute – NRI*
EuroGeoSurveys Executive Committee Member

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* Polish Geological Institute – National Research Institute has been entrusted with the task of Polish Geological Survey under the Geological and Mining Law of 9 June 2011

CHAPTER 1

ON NATURAL GAS IN ENERGY SECTOR AND BEYOND...

author: Magdalena Sidorczuk

DICTIONARY

Energy mix *– the range of energy sources of a region, both renewable or non-renewable, used in in total production of power, heat and mechanical energy*

Primary energy *– energy contained in energy carriers renewable and nonrenewable resources such as oil, coal, natural gas and biomass, not subjected to any conversion or transformation process*

Natural gas *– a fossil fuel of organic origin, consisting of a mixture of volatile hydrocarbons, primarily methane and ethane, with admixtures of other chemical compounds. Depending on chemical composition, there are differentiated high methane gas with methane and ethane content of about 95% and nitrogen-rich natural gas, yielding methane and ethane as well as up to 30% of heavy hydrocarbons. Natural gas may also contain nitrogen, carbon dioxide, hydrogen sulfide and subordinate amounts of helium*

The demand for energy has been steadily growing along with the development of our civilization intensively from the beginning of the Industrial Revolution to rise sharply after World War II. In the last 20 years world electricity consumption per capita has risen 40%, ranging from as much as 150% in China and 90% in India to 20% in the United States and 7% in member states of the European Union. According to the International Energy Agency (IEA), in the year 2035 the world demand for electric energy will rise by more than 35% compared to 2010. This growth will be the highest in China and other large emerging economies such as India, Brazil and Russia. Significant growth in demand is also expected in Africa, Central America, Indonesia, Pakistan and some other countries where 1.3 billion people have practically no access to power.

ENERGY SOURCES

Oil is the main energy carrier in the global **energy mix**, covering over 30% of demand for **primary energy**. The second place goes to coal, a very controversial energy source as its combustion leads to high emission of CO_2 and other greenhouse gases. Natural gas is the third main carrier in the mix, with share exceeding 20% and rapidly growing. Some long-term forecasts show that share of gas may soon outclass both those of coal and oil. According to the IEA analyses, demand for natural gas will continue to grow 1.6% annually. The remaining components of the energy mix include nuclear power

Global and Poland's energy mix, including forecasts until 2030 (% per annum, approximate figures)

World	1990 y.	2010 y.	2015 y.	2020 y.	2030 y.
Lignite and hard coal	25.4	27.3	28.2	27.3	25.5
Oil	36.8	32.3	31.1	29.9	27.9
Natural gas	19.0	21.5	21.4	21.9	23.3
Nuclear fuel	6.0	5.6	5.4	6.0	6.5
Renewable energy and other energy	12.8	13.3	13.9	14.9	16.8

Based on: MAE, World Energy Outlook 2012

Poland	1990 y.	2010 y.	2015 y.	2020 y.	2030 y.
Lignite	14.0	12.0	12.5	10.0	8.5
Hard coal	62.0	41.0	37.0	34.0	31.0
Oil	14.0	27.0	28.0	27.0	26.5
Natural gas	9.0	13.0	13.5	14.0	14.5
Nuclear fuel	0.0	0.0	0.0	3.0	7.0
Renewable energy and other energy	1.0	7.0	9.0	12.0	12.5

Based on: Polish Ministery of Economy, Polityka energetyczna Polski do 2030 roku, 2009 and renewable energy sources – hydropower, wind power, solar and geothermal energy and biomass.

Poland's energy mix is characterized by somewhat different proportions. Coal (hard coal and lignite) constitutes about 50% of primary energy supply. The second place goes to oil with its 27% share. Similarly as in the world energy mix, gas holds the third place but its share is markedly smaller, equal about 13%.

At present it would be difficult to find someone who can imagine life without electricity in our country. However, energy experts warn that the risk of power cuts due to chronic shortages of electricity and large power outages, so-called blackouts, keep growing year by year. As admitted by the Polish Energy Regulatory Office, that risk will become a reality from the year 2015 onwards. One of main reasons of that risk may be the loss of capabilities to cover the growth in demand in electric power despite of the fact that Poland is the second among EU countries with most secure supply in energy carriers. This is thanks to domestic reserves of coal, the fuel criticized by ecologists and politicians, but which generates 88% of electricity in our country.

The growth in demand for primary energy in the years 2010–2030 in Poland is estimated at over 20% whereas the share of coal in electricity production is expected to drop down to about 60%.

CONCERNS OVER FUTURE OF THE EARTH AND INTERNATIONAL COMMITMENTS

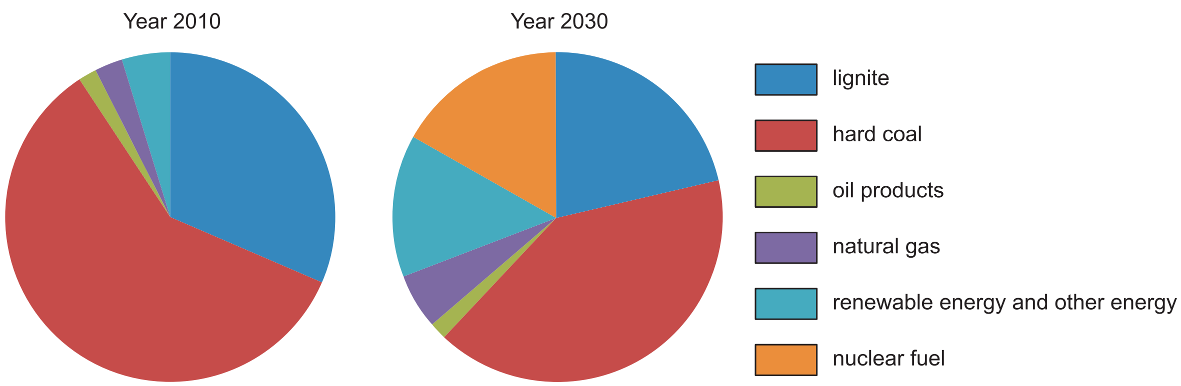
Attempts to reduce the use of fossil fuels in everyday life of the Man are related to concerns that their resources will be soon exhausted and the civilization will regress to its beginnings, that is more or less to the Early Stone Age, as well as potential influence of fuel combustion on climate.

Although research on influence of combustion of fossil fuels on climate have been going on for years, opinions of scientists are still fairly diverse. Regardless of whether we are adherents or opponents of the theory of anthropogenic climate change, we are all obliged to protect the natural environment, control emissions of greenhouse gases to the atmosphere and support sustainable use of natural resources. Concerns over potential negative influence of the Man on climate change extends beyond the scientific communities and

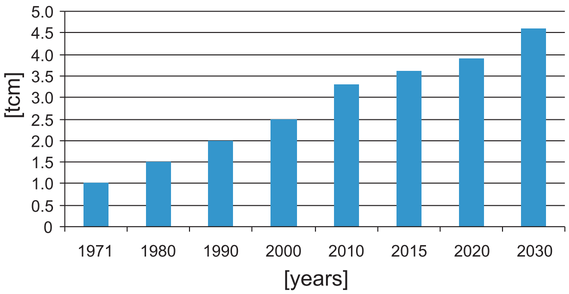
DICTIONARY

IAE *– International Energy Agency, is an autonomous body which was established in November 1974 within the framework of the Organization for Economic Co-operation and Development (OECD) to implement an international energy programme. The IEA conducts a broad programme of energy co-operation among 28 OECD member states of OECD. Poland joined the IEA in 2008*

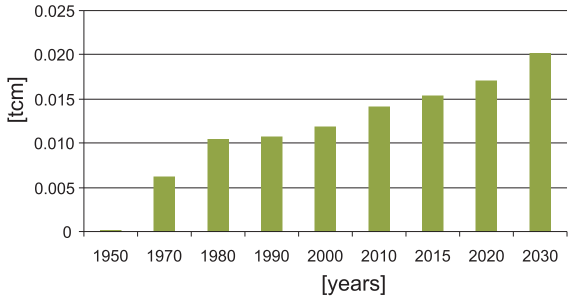
RES *– renewable energy sources such as hydropower, wind, solar and geothermal energy and biomass*



Electricity generation by source in Poland (including the combined heat and power production – CHP)



Global natural gas consumption (source: MAE, EIA)



Natural gas consumption in Poland (source: Polish Ministry of Economy, CIRE, ARE, Eurostat)

DICTIONARY

***OECD** – Organisation for Economic Cooperation and Development congregates is an international economic organization of 34 countries founded in 1960 to stimulate economic progress and world trade. 34 countries with highly developed economies and democratic governments. Poland jointed the OECD in 1996*

ecological movements, being also reflected by political decisions. The 1992 Earth Summit in Rio de Janeiro led to the signing of the United Nations Framework Convention on Climate Change (UNFCCC), aimed at stabilization of greenhouse gas concentrations in the atmosphere. In 1997 an international agreement to reduce the greenhouse emissions causing climate change has been adopted in Kyoto. This agreement, known as the Kyoto Protocol, is a legally binding international agreement to reduce the greenhouse gas emissions by 5.2% below the emission levels of 1990 by 2012. The Kyoto Protocol was ratified or accepted by 141 countries representing over 60% of the world greenhouse gas producers. Poland committed to reduce its emissions by 6% below the emission level of 1988 to overpass this commitment by 2012. However, global emissions of greenhouse gases rose by 50% in the years 1990–2011. The share of Poland in the global emission is equal to about 1%. On a per capita basis, Poland emits 10 tonnes CO_2, per year, United States – 20 tonnes and India 2 tonnes.

The **OECD**+ countries (OECD countries and EU Member States not belonging to the OECD) prefer 450 Scenario, which assumes limiting the concentration of greenhouse gases in the atmosphere to around 450 parts per million of CO_2. This requires a revolution in the power sector, connected with an increase in the share of renewable energy at the expense of coal. EU plays active role in the world policy resulting from high concern about global warming by favoring low-emission economy. The EU 3x20 Climate-and Energy Package sets the following targets for the Member States: 20% emissions reduction by 2020 in relation to the year 1990, 20% increase in energy efficiency by 2020 and 20% increase of renewable energy (here Poland negotiated 15%). There arises a new proposal of curbing greenhouse gas emissions, known as Energy Roadmap 2050. This proposal, aimed at reductions in EU domestic emissions by 80% by 2050 compared to 1990, is blocked by Poland.

In order to work out a model for zero-energy economic growth, that is economic growth not connected with any rise in demand for primary energy, there were analyzed several scenarios matching requirements of international agreements on climate. Besides omnipresent recommendations to increase the role of renewable energy sources, the majority of these scenarios supported wider use of energy of only one fossil fuel, that is natural gas.

NATURAL GAS BOOM ERA

The last years witnesses dazzling career of natural gas from both from conventional resources and new unconventional ones in the world economy. Natural gas was initially regarded as an almost useless component creating problems in exploitation of more valuable resources, to reach the status of one of three main sources of energy in the 20^{th} century. This was accompanied by high increase of its importance for chemical industry, transport and municipal economy.

High energy potential of natural gas has been known for centuries but there were problems with its effective use. Already Ancient Greeks were interested in natural gas, carrying out some experiments (as for example Philo of Byzantium and Heron of Alexandria) and trying to use for cooking, heating, in lime kilns and illuminate shrines. However, before we learned how to use gas on an industrial scale, its huge amounts were emitted to the atmosphere or fired out as useless waste from oil production. The origin of the world gas industry required solving several key problems. These included working out effective technology for prospecting and exploring gas reserves and safe methods of their exploitation, construction of gas transportation infrastructure and establishing technology for gas processing to meet product requirements. This has taken some time but was finally accomplished. The first long distance wooden gas pipeline, 40 km in length, was completed in 1872 in New York State. In our region, the first pipeline was laid from Borysław to Drohobycz in the East Galician Oil Region in 1912. The breakthrough in geological knowledge and technology has taken place in the second half of 20^{th} century, making possible to lay down extensive networks of pipelines and, in this way, facilitating access to gas supply for households. This gave a boost for mass production of gas powered household appliances.

At present, construction of gas-fired peak looping and back-up power plants became one of the most effective large-scale solutions recommended for attempts to introduce low-emission and zero-energy economic growth policies. Such gas fueled power plants can be fired up rapidly and are therefore often utilized at peak demand times or when conditions are unfavorable for power systems based on renewable energy sources. Still more advantageous solution is based on gas-steam energy generation systems of the Combined Cycle Gas Turbine (CCGT) type. Such power plants are characterized by average efficiency over 50%, much higher than coal-fired plants with efficiency of about 30%, which means much lower consumption of primary energy. Further development of gas-based economy is strongly supported by developments of liquefaction technology for the production of Liquefied Natural Gas (LNG) which makes it possible to

CO_2 emissions and efficiency of different types of power plants – subdivision based on sources of primary energy

Type of power plant	CO_2 emission associated with producing 1 MWh	Efficiency
Coal-fired (lignite)	Over 1000 kg	25–36% at the average in existing power plants to 45% in new designs
Coal-fired (hard coal)	800–900 kg	
Gas-fired	550 kg	50–60%

Subjectively selected advantages of natural gas

- **Versatility of usage.** Natural gas is used in power and heat plants as well as chemical industry, metallurgy, food industry, transportation sector, agriculture, several other sectors of industry and services and in residential sector.
- **High calorific value.** Natural gas is the best fuel from both economic and ecological points as its burning generates the largest amount of heat for 1 kg – 50.2 MJ/kg, whereas burning of black coal generates only 20.9 MJ/kg.
- **Low emission.** When combusted, natural gas releases lower levels of harmful emissions than any other fossil fuel. It releases lower levels of carbon dioxide, carbon monoxide, and other reactive hydrocarbons, very small amounts of sulfur dioxide and nitrogen oxides and virtually no ash or particulate matter, and low levels of reactive hydrocarbons. Therefore, it is the cleanest of the fossil fuels and can be used to help reduce the emissions of greenhouse gases into the atmosphere.
- **Advantages of gas-fired power plants.** Such power plants are characterized by high operational flexibility and, therefore, they may provide backup in peak demand hours, breakdown in other power plant or temporary loss of supply of power from wind farms. Their high efficiency serve can't be overestimated. Gas-fired power plants are more environmentally friendly than the coal-fired ones. Moreover, they are cheaper and quicker to assemble.
- **Transportation.** Natural gas may be easily transported by land (pipelines and road tankers) and via sea (cryogenic sea vessels – LNG carriers) which markedly contributes to energy security.
- **Public opinion supports natural gas.** Public opinion polls show that natural gas has much greater acceptance than oil, coal and nuclear energy. The polls also show that Europeans are well aware of environmental benefits of natural gas.
- **Gas is the only fossil fuel accepted by ecologists but under certain conditions.** These conditions include simultaneous retreat from economy based on coal, transfer of a part of profits to subsidize development of renewable energy sources and efficient control of natural gas production.
- **Chances for reducing natural gas price for consumers in Poland.** Domestic production of natural gas gives a chance for price reduction for consumers. At present price of gas are one of the highest in Europe (in relation to purchasing power) although domestic production covers 30% of demand for that fuel. In the United States, production from non-conventional resources led to over a three-fold cut in price of natural gas.
- **Discoveries of new resources, developments in science and energy safety.** Discoveries of conventional and non-conventional natural gas resources in the world and introduction and continuous improvement of new technologies of natural gas production and processing are highly advantageous for economic growth of individual countries and improves their energy security.

transport gas over long distances where pipelines do not exist, and technology of Compressed Natural Gas (CNG), making possible the use of gas in combustion engines. LNG is natural gas cleaned and condensed into a liquid by cooling it to −160°C. LNG takes up about 1/600th the volume of natural gas in the gaseous state. Seaborne transport of liquefied gases began in the late 1950s to develop in the end of the 20th c. and began to bloom in the last decade. In 2011 the world fleet of LNG-transporting tankers was over 360, making over 4,000 trips to handle altogether over 240 million tonnes of that fuel. The LNG market increased as much as 65-times during the last 40 years. Natural gas becomes also very popular among individual customers along with increase in usage of appliances for households and water heating supplied with that fuel by pipeline networks. Economic side of such solutions is also important.

Natural gas becomes an important energy carrier worldwide and markets of that fuel belong to the most dynamic segments in the world trade of fossil fuels.

A careful analysis of all the pros and cons should accompany continuation of prospecting and exploration of conventional or in other words "familiar" natural gas resources as well as gas entrapped in already famous shales. As stated briefly above, there is growing evidence that natural gas is the cleanest of all the fossil fuels and at the same time the most efficient of those hitherto discovered and available for rational use.

We are fully aware that quite a lot of energy has been spent to write this book for you. Too much of that energy was generated from combustion of coal and too little from combustion of natural gas and use of wind and solar energy than we would wish. Therefore, let's look for gas, preferably our own high-quality gas. Otherwise one winter evening when wind goes down and frost becomes really hard, we may find ourselves sitting in a room lit with ecological candles in cold as the central heating radiators are staying stone cold because of drastic legal regulations limiting possibilities to use coal energy. Then we may regret the chances we have lost for at least checking how much natural gas is actually hidden in Paleozoic shales in Poland.

A FEW WORDS ABOUT AUTHOR

Magdalena Sidorczuk

A geologist, PhD, an academic teacher at the Faculty of Geology, Warsaw University until 2011, when she joined Polish Geological Institute-NRI. Ms. Sidorczuk completed post-graduate management studies at Warsaw University and research project management studies at Koźmiński University. She holds an IPMA certificate. At Polish Geological Institute-NRI Ms. Sidorczuk coordinates Polish Geological Survey shale gas awareness project.

SHALE GAS – A BRIEF HISTORY OF PROSPECTING IN THE WORLD AND POLAND

author: Mirosław Rutkowski

CHAPTER 2

Development of unconventional hydrocarbon resources is sometimes called the main energy revolution of the 21st century. This may truly sound like an exaggeration, but not entirely. When that fascinating process began still remains a question but it is generally assumed that the impetus here was the economic success in 1998 of the first modern shale gas well drilled in the Barnett shale of the Fort Worth basin, North Texas. Successful development of the Barnett play is now regarded as a turning point spurring entrepreneurs to start prospecting in other areas in the United States with-bearing shale series previously considered unsuitable for gas extraction.

BEGINNINGS

In my opinion the whole history began much earlier. It is necessary to go back to 1973, the time of a successive Arab-Israeli conflict known as the Yom Kippur War. During that conflict the Arab-dominated Organization of the Petroleum Exporting Countries (OPEC) proclaimed an oil embargo. The decision to cut oil exports to countries that provided military aid to Israel prompted a serious energy crisis in the United States, Western European, Japan and other nations dependent on foreign oil. As a result, between October 1973 and January 1974 world oil price went up quadrupled.

The effects of the embargo were immediate, causing an economic crisis over the winter of 1973–74. The United States experienced an additional problem resulting from a drop in domestic production of natural gas, which until that time was sufficient to cover domestic demand. The crisis demonstrated the scale of dependence of industrialized countries on insecure sources of supply of raw materials, thus making it necessary to introduce deep changes in the global economy. The reaction was swift and wide-ranging. Countries affected by this crisis took several steps to eliminate the risk of a repetition of the situation from the early 1970s. These steps included increased production from known hydrocarbon resources as well as a search for new classic and unconventional ones. Intense research and development soon began to bring results. Special attention should be paid to results in the United States, the leader in drilling mining technologies since the oil boom of the 19^{th} century. In 1976 the Gas Research Institute, supported by subsidies of the federal government, began research on extraction of natural gas from clay shale rich in organic matter. The shale was widely known to yield natural gas, but the rather few wells drilled thus far not numerous, failed to provide output with any economic importance. The first known commercial shale gas well was dug by William Hart, a skilled tinsmith and gunsmith, in the village of Fredonia, NY, in 1821. Hart dug out a well 8 meters deep at the shore of Erie Lake to reach a layer of fractured shale from which natural gas began to escape slowly. This made it possible for Hart to pipe the gas through wooden pipes to Fredonia where it was used to light several houses, two shops and a mill over a long period of time.

From the start of the 20^{th} century, several dozen wells produced gas from shale rock of the Appalachian and Illinois basins. The soft point of these undertakings were production volumes, which were highly variable but usually low. They were actually so low that investors were on the brink of bankruptcy most of the time. Compact shale rock is characterized by very low permeability and therefore it is quite difficult to free gas locked up in such rock to escape and flow upwards into exploitation wells.

FIRST HYDRAULIC FRACTURING

Researchers from the Gas Research Institute decided to combine several well-known technologies to achieve higher productivity of shale gas wells. One of these methods was hydraulic fracturing used to enhance oil recovery since 1947. In 1977, the U.S. Department of Energy (DOE) began to demonstrate massive hydraulic fracturing in shale to promote a new approach. These demonstrations did not convince major players as the promoted technical solutions still required some improvements to be feasible at on an industrial scale. However, the idea was pursued by more ambitious entrepreneurs and small businesses looking for a niche market. Among them was George P. Mitchell, Chairman of Mitchell Energy & Development Corp., a petroleum engineering graduate of Texas A&M University. He was not a novice in this business, as he led a Fortune 500 company listed on the New York Stock Exchange and participated in over 10,000 drilling operations. In 1981 he acquired licenses to drill for and produce oil and gas in the Fort Worth area in Texas where dark Lower Carboniferous shale known as the Barnett Shale is found at depths of about 2,300 m. Numerous signs of gas presence noted when drilling showed potential, but all attempts at economic production failed. At first Mitchell used the method proposed by the Gas Research Institute – powerful injections of water with sand to vertical wells. However, effects proved unsatisfactory and costs enormous. This strong-willed entrepreneur did not give up, however, and for 18 years continually improve technology. These efforts received financial support from the DOE and the IRS qualified his corporation for a federal non-conventional fuel tax credit under the Internal Revenue Code (IRC). These efforts also gained support of the Jackson School of Geosciences and the University of Texas at Austin as well as of approximately a dozen of other research centers.

Studies on the effects of hydrofracking were conducted with the use of supermodern microseismic methods. Shale series most susceptible to fracturing were also identified by 3D seismic tomography. Hydrofracking of horizontal wells in shale gas formations turned out to be the key to success. It is very costly but allows drainage of larger volumes of rock than in classic vertical wells. The long-awaited success came in 1998 when Mitchell's corporation applied an innovative technique of hydrofracking to achieve commercial shale gas extraction. This is widely considered a milestone that pushed shale gas into full commercial competitiveness.

George P. Mitchell (1919–2013) – celebrated father of the American shale gas revolution (source: The Cynthia and George Mitchell Foundation)

In 2002 Mitchell's corporation (with knowledge and know-how as main assets) was bought by Devon Energy for $3.5 billion. It was one of the largest takeovers in history of that market until 2009 when ExxonMobil bought XTO Energy, a similar pioneer firm, for $40.0 billion.

It is worth noting the scale of these financial operations. It clearly shows how large capital is involved in the gas shale business. Much money must be spent on R&D as well as to drill a 3 km vertical well with a horizontal section 1 km long. The drilling and full hydrofracking process mean expenditures in the range of $10 million in the United States and even twice as much in Europe. Moreover, several dozen to several hundred wells have to be drilled to drain an entire shale gas play.

This may be the reason why it took some time for the shale gas revolution to spread. About eight years had to pass before Mitchell's idea began to be clearly visible in graphs showing shale gas production increases in the U.S. Graphs show an increase of that production from 10 billion m^3 in 1998 to over 150 billion m^3 in 2011.

Methods employed at the Fort Worth play gradually began to be implemented in the Fayetteville, Haynesville, Antrim, Marcellus and other shale gas basins in the United States. At present they are used in twenty basins. Two of these basins, Marcellus and Haynesville, have shale gas resources exceeding 7 billion m^3, which makes them the richest gas deposits in the world.

Some modifications in technology appeared necessary. Although all American shale formations are genetically close, it soon appeared that there is no single key to their resources. Even small differences in geology or mineralogy may require additional costly R&D activities and experiments.

Thanks to exploitation of the country's shale gas reserves the Unites States regained its position in 2009 as the world's largest natural gas producer and LNG import terminals lost importance.

COSTS OF THE SHALE GAS RUSH

Besides prestige for the United States, this success has definite economic value. A steadily growing supply of natural gas has resulted in a five-fold decrease in the price of that commodity. According to the World Economic Forum, oil and gas companies created 37,000 direct jobs thanks to developments in exploitation of unconventional plays and contributed to the creation of an additional 111,000 indirect jobs in 2011.

The pioneer stage in development of these new types of plays has also led to some negative social costs. Intense activities conducted not always in accordance with the law and drilling principles have raised the concerns of those living in a hitherto quiet countryside. Rural tranquility has become disturbed by heavy truck traffic to gas drilling sites. Moreover, in some places hydraulic fracturing waste fluids were illegally discharged into streams, ponds and surrounding woods. Voices of discontent were soon raised by environmental organizations as well as large corporations affected by the shale gas boom and disturbed foundations of business through a drastic decrease in the cost of gas. This has led to anti-fracking hysteria, the effects of which the new oil and gas industry may have to deal with even for decades. "Gasland," a documentary by Josh Fox, a New York avant-garde theater talent, was a forerunner of that hysteria. This documentary, first screened at the Sundance Film Festival in 2010, still remains the source of knowledge for environmental and political activists throughout the world, even though science has failed to provide reasonable evidence to support its message.

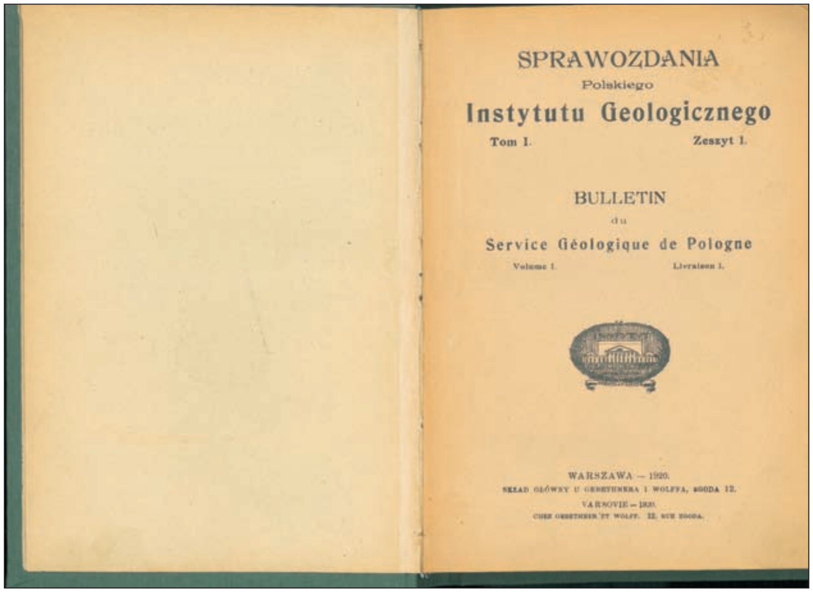
MEANWHILE IN THE REST OF THE WORLD...

This new technology was soon noted by other countries. Canada was the first country to develop a shale gas industry. The task appeared to be fairly easy as some formations already exploited with the use of most modern technology in the U.S. (Antrim Shale and Utica Shale) crossed over into Canadian provinces. Similarly as in the United States, several years had to pass before production reached levels clearly traceable in graphs showing shale gas production increases in that country in 2011. At present the United States and Canada still remain the only countries that have achieved commercial production of shale gas.

Soon, research extended to the entire world and often appeared limited to "undusting" of old maps and reports. Shale formations rich in organic matter have been well known to national geological surveys for several decades, but a practical demonstration of the possibilities of shale gas extraction was needed to alter their status to something more than an interesting trace in the Earth's history. Global potential of shale rock was first noted by the U.S. Energy Information Administration (EIA) and other agencies specializing in the energy monitoring market. In the last ten years this led to publication of several reports providing initial and very general estimates of shale gas resources throughout the world. In addition to the United States and Canada, these estimates indicate a high potential for large-scale shale gas production in China, Argentina, Mexico, South Africa, Australia, Libya, Algeria, Brazil, and in Europe – in France, Poland, Ukraine and Germany.

POLISH SHALE

The above estimates were not a surprise to Polish geologists. Occurrences of dark lower Paleozoic shale in our country were very well known as these rocks crop out at the surface in the Holy Cross Mountains. One of first references to that formation can be found in an article by Jan Samsonowicz published in "Sprawozdania Polskiego Instytutu Geologicznego" (*Reports of the State Geological Institute*) in 1920. Along with developments in studies on the geological structure of the country, in particular, very extensive drilling programs carried out since the 1960s, geology and tectonics and lithology of these formations have become very well known. The obtained results made it possible to compile maps of extent and depth of occurrence of partly eroded belts of shale formations in individual basins. Special attention should be paid to numerous hydrocarbons observed while drilling through these formations: gas bubbles escaping from fresh core material, an oily smell of rocks of sandstone intercalations



SPRAWOZDANIA
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Tom I. Zeszyt 1.

BULLETIN
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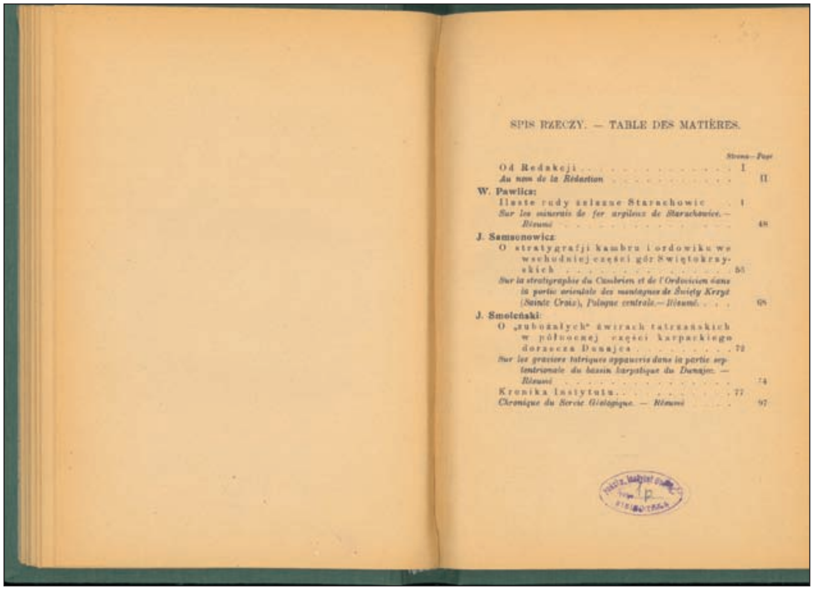
Volume I. Livraison 1.

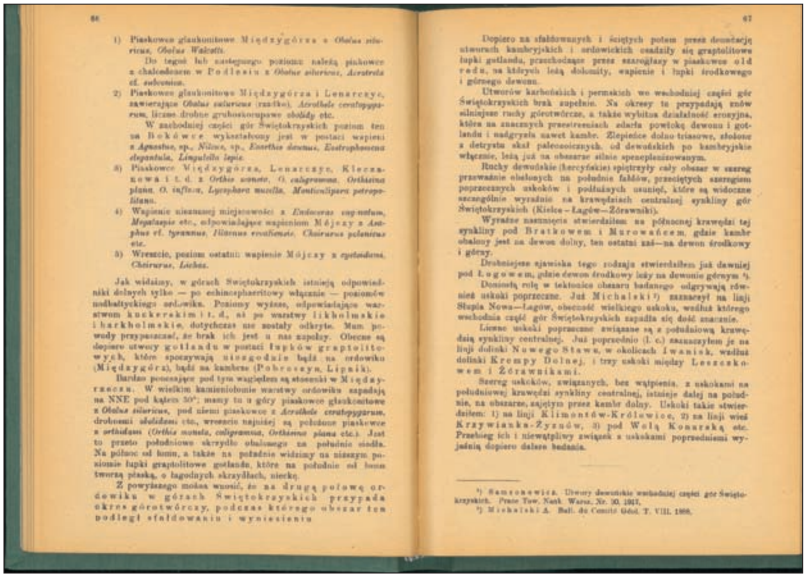
WARSZAWA — 1920.
SKŁAD GŁÓWNY U GEBETHNERA I WOLFFA, SGODA 12.
VARSOVIE — 1920.
CHEZ GEBETHNER ET WOLFF. 12, RUE SGODA.



SPIS RZECZY. — TABLE DES MATIÈRES.

Reports of the Polish Geological Institute of 1920 with one of the first information on geology of the lower Paleozoic Shale (source: the PGI-NRI Geological Library)

or increases in drilling mud pressure. Already in 1964 Stanisław Depowski and Jadwiga Królicka published an article on hydrocarbon shows in the Polish Lowlands in the Geological Quarterly. However, in line with the state of art at this time,



Reports of the Polish Geological Institute of 1920 with one of the first information on geology of the lower Paleozoic Shale (source: the PGI-NRI Geological Library)

prospecting was mainly focused on classic hydrocarbon traps in which oil and gas migrating from parent shale formations could have accumulated. Shale formations were regarded as unproductive due to the prohibitive cost of extraction.

In turn, the wealth of fossil remains of marine animals and plants made this dark shale rock that was several hundred million years old very attractive to paleontologists. The most interesting fossils are those of extinct graptolites – small invertebrates resembling grass leaves with jagged edges or a spiral coil. They were so abundant in certain time intervals in the history of the Paleozoic ocean that seafloor sediment was full of their remains. Therefore, rocks formed from these sediments were called graptolite shale.

In the last decade, Polish shale began to draw much attention in connection with news from across the ocean. After half of a century, borehole core samples resting quietly in core repositories of the PGI-NRI Central Geological Archive were dusted off and studied again. Polish and foreign geologists re-analyzed total organic content, thermal maturity and mechanical properties of these rocks. Despite the passage of time, core samples appeared fully usable for studies. Analysis of the thermal history of these rocks showed that most went through a heating phase optimal for generation of gaseous hydrocarbons in the western part of the shale belt and for generation of liquid hydrocarbons in the eastern part of that belt.

At the same time the first companies holding licenses for prospecting and exploration of shale gas hired Polish geophysical firms to carry out seismic surveys, including very expensive 3D surveys. Obtained geophysical data made it possible to update geological maps to select the best locations of first exploration wells. Drilling rigs first appeared in Pomerania (northern Poland) and later in the Lublin and Podlasie regions (eastern Poland).

Initial hydrofracking in Poland was carried out in August 2011 by Lane Energy from the 3Legs Resources group at the Łebień LE 2H well in Pomerania. Results of flow tests performed in October 2012 did not appear promising as the recorded flow of 20,000 m^3 per day corresponded to lower values obtained from American shale gas wells. Subsequent flow tests carried out by other operators also failed to give fully satisfactory results. This may be one of the reasons why some foreign companies withdrew from the Polish market. Their license blocks were taken over by other companies, including Polish firms.

At present (1st June 2013) 108 licences issued by the Polish Ministry of the Environment remains in force. The largest number of these licenses (16) went to the Polish Oil & Gas Company. License holders are obligated to drill two and sometimes even three wells as well as pass documentation and geological samples collected during prospecting to the Ministry of the Environment within three years from the date of license issue. Holders are planning to drill 333 exploration wells (123 obligatory plus 210 as an option depending on results of prospecting works). By 1 June 2013, 46 drillings were completed and four were in progress. However, full hydrofracking treatment in long horizontal well sections, most important for flow tests and confirmation of resources and their economic viability, was carried out at six wells only.

At present it is still impossible to state whether shale gas production will revolutionise the Polish economy to such a degree as in the United States. This will greatly depend on the commercial recoverability of shale gas resources. First estimates of foreign rating agencies looked quite promising. According to estimates published in 2009-2010, Polish recoverable shale gas resources may range from 1 to 3 billion m^3. An estimate made by the U.S. Energy Information Agency created a true sensation as it raised resources up to 5.3 billion m^3. The first report based on scientific premises was presented afterwards by the Polish Geological Institute – NRI in March 2012. The PGI-NRI team estimated recoverable shale gas resources in Poland at 0.35 to 0.77 billion m^3, which was a large retreat. However, it should be stressed that the method used by Polish geologists in their cooperation with the U.S Geological Survey was based on statistical analogies with American basins with known productivity. Therefore, results obtained with the use of that method can be characterised by a wide margin of error. A more accurate estimate of resources will be possible when most planned exploration wells are completed and, more importantly, appropriate long-term flow tests are made. It is not excluded that some change in technology will be also necessary as Polish gas-bearing shale may markedly differ from its American counterpart.

Outcrop of Silurian shale in the Prągowiec ravine, the Holy Cross Mts (source: W. Trela, the Holy Cross Mts Branch of the PGI-NRI)

A FEW WORDS ABOUT AUTHOR

Mirosław Rutkowski

Graduated from the Faculty of Geology, University of Warsaw in 1974, he worked as raw material geologist in large public and private companies while publishing popular science articles, mainly in Wiedza i Życie and Polityka. Since 2002 spokesman for the Polish Geological Institute – NRI.

CHAPTER 3

GEOLOGICAL ENVIRONMENT OF GAS-BEARING SHALES

scientific editor: Hubert Kiersnowski

GAS-BEARING SHALES IN POLAND

Hubert Kiersnowski

WHAT ARE THE GAS-BEARING SHALE ROCKS

The black-coloured shale rocks that contain natural gas of which exploration and production is expected to give Poland a new source of energy, had been formed in the ancient Ordovician and Silurian sea, i.e. at the time interval of 485 to 420 million years. Mostly clayey-mud

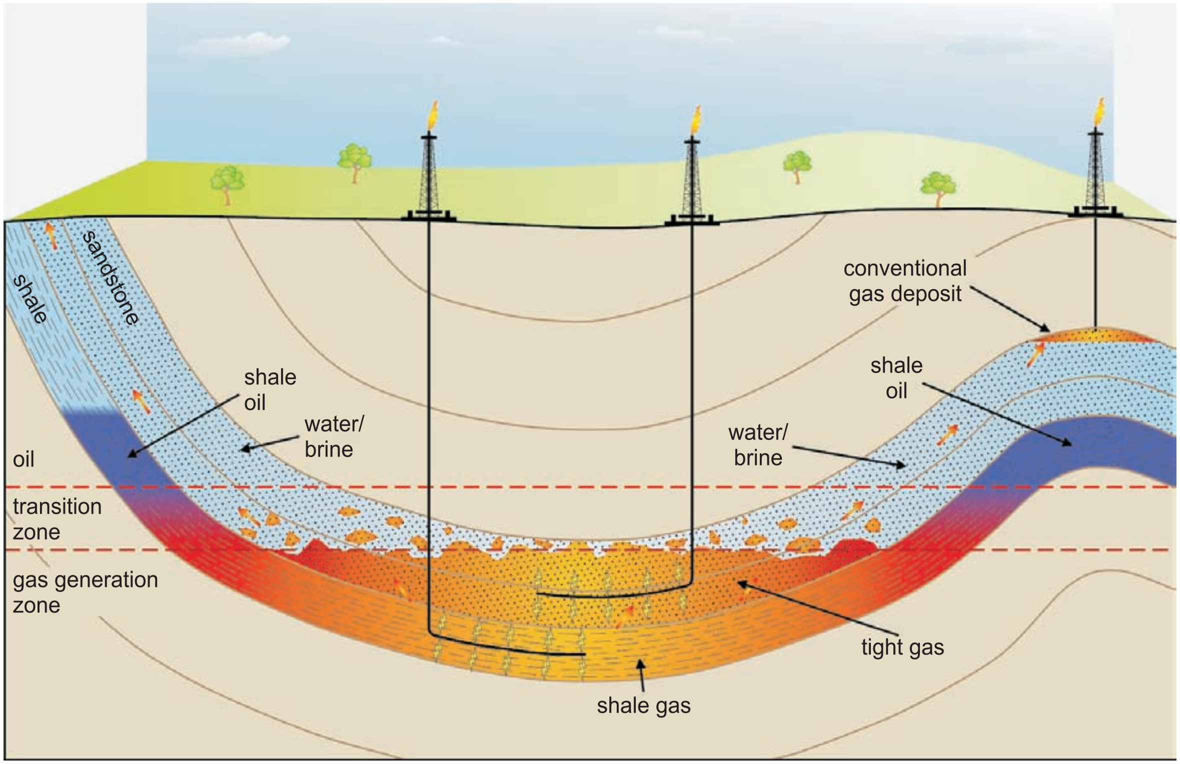
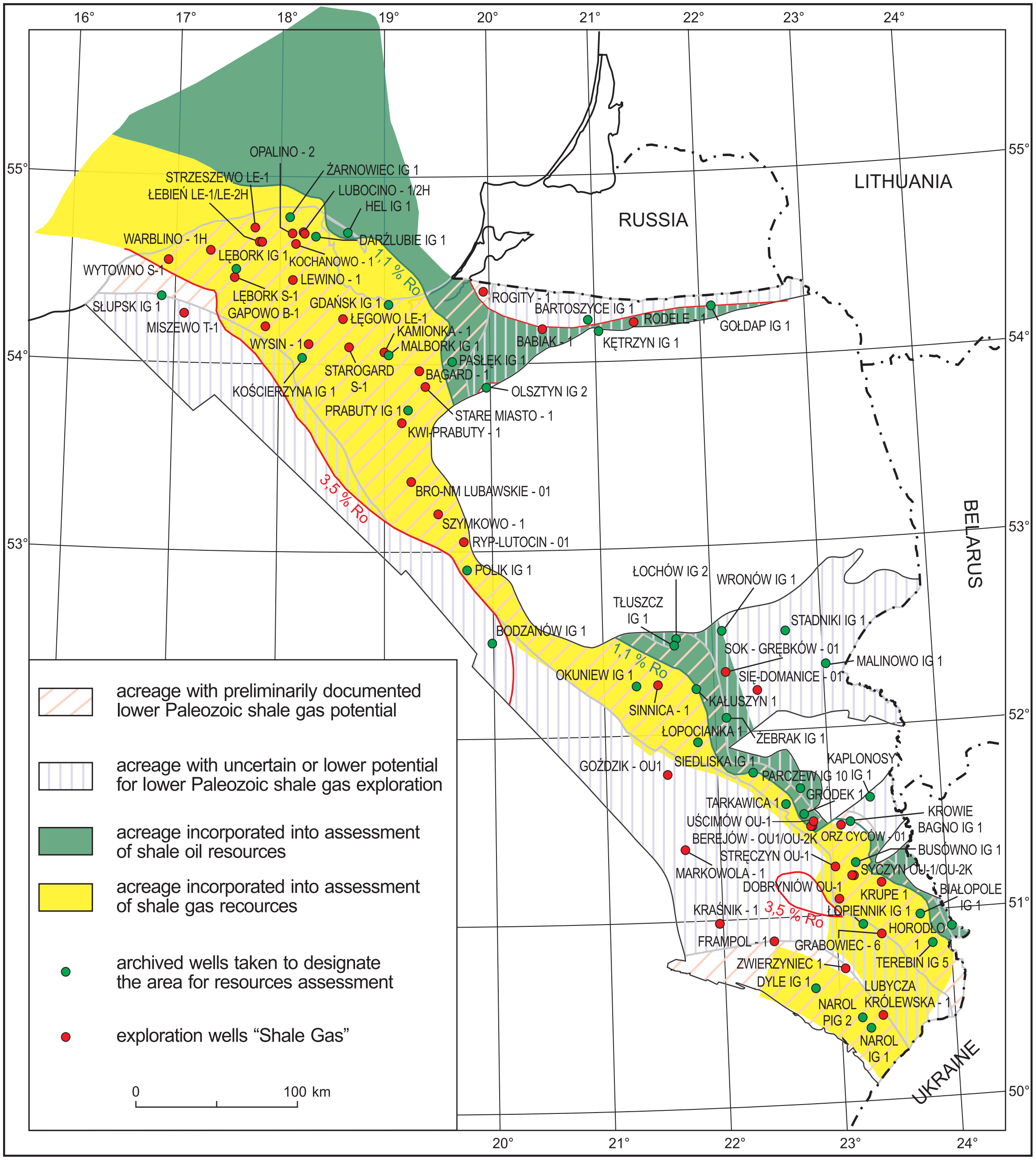


Diagram explaining the key differences between conventional and unconventional petroleum systems
Right: a conventional gas reservoir contained in a structural anticlinal trap. Shale and tight gas accumulations are present in the central part of the basin. Unlike conventional petroleum reservoirs, these accumulations are not underlain by reservoir water. Horizontal wells and fracturing procedures are required in order to produce natural gas from these accumulations (after: Pollastro *et al.*, 2003, with modifications, based on Kiersnowski, Poprawa, 2010)



Occurrence of lower Paleozoic shale rocks with potential unconventional gas accumulations, including areas considered in the calculation of gas and oil reserves (marked yellow and green, respectively) in the variant of maximum thickness of shale rocks with TOC content >2% w/w; based on data from 39 wells drilled out in the years 1950 to 1990 (based on Dyrka after Poprawa, 2010)

sediments with an admixture of organic matter were deposited at the sea bottom. With time, the sediments were transformed into shale rocks as a result of burial and compaction processes (Chapter by Joanna Roszkowska-Remin & Teresa Podhalańska and chapter by Marek Jasionowski). Organic matter contained in the deposits was preserved in bottom sediments, as they were accumulated in an anoxic environment. Subsequently, following the burial and related increase in pressure and temperature, organic matter was transformed into organic substance called **kerogen** and coloured the sediment (shale) black (Chapter by Przemysław Karcz). Organic matter was composed mainly of **phytoplankton**, or algae blooming in the sunlight, of which huge production is today the key source of natural gas and/or crude oil.

In the Ordovician and Silurian Basin, under specific temperature and pressure conditions, organic matter contained in deeply buried shale rocks was transformed first into oil and then into natural gas (Chapter by Izabella Grotek & Marcin Janas). The process of formation and accumulation of **hydrocarbons** versus shale rock burial depth is shown on the diagram. Since oil and gas generated within shale rocks do not migrate, a closed-end system is formed wherein the shale rocks are both source and reservoir rock at the same time.

The content of gas or oil in shale rocks is investigated to determine the feasibility of production and potential recoverable resources (Chapter by Adam Wójcicki).

Poland's Shale Basin is just one of several European basins. However, it is often compared to the US basins which have been developed for shale gas or oil production. These comparisons may provide a hint as to the prospective gas resources of Poland's basin, as well as to the methods and volume of potential shale gas production (Chapter by Marcin Janas & Ireneusz Dyrka).

The subdivision into gas and oil sections of the Ordovician/Silurian Basin is presented in Figure. So far, a majority of boreholes has been drilled out in the gas section, with only a few of them located in the oil section. The occurrence of condensate, which is typical to the zone of gas-to-oil transition, was reported from some of the wells. A significant part of this area is located in Poland's offshore economic area where conventional oil and gas are produced from Cambrian reservoirs. Offshore shale gas and oil exploration is still considered as economically non-viable.

In addition to subdividing the area in question into gas and oil sections, facies analyzes are carried out to determine the distribution of and interrelations between fine clastic sedimentary and carbonate rocks, stratigraphy (Chapter by Joanna Roszkowska-Remin & Teresa Podhalańska), geochemistry (Chapter by Przemysław Karcz), petrophysical (Chapter by Ireneusz Dyrka) and petrological properties (Chapter by Marek Jasionowski) that are geared towards identification of the most prospective areas.

Shale gas and oil exploration/production methodology and techniques are described in the Downhole Logging (by Michał Roman) and Seismic (by Andrzej Głuszyński and Sylwia Kijewska) Chapters. Moreover, geomechanical and micro/macrostructural studies of shale rocks are important for the determination of the most prospective areas (Chapter by Marek Jarosiński).

DICTIONARY

Kerogen *– a waxy organic substance dispersed in rocks which resists organic solvents; produces oil and natural gas under high pressure and temperature conditions (diagenesis and metamorphic processes) and therefore is sometimes called "immature oil"*

Phytoplankton *– microscopic plant organisms (algae) floating in euphotic bodies of water*

Hydrocarbons *– chemical compounds structure of which is composed solely of carbon and hydrogen atoms. Basic components of crude oil and natural gas.*

Hubert Kiersnowski

A geologist, graduated from the Faculty of Geology, Warsaw University, specializing in sedimentology and stratigraphy of clastic sediments, in particular Permian Rotliegend sandstones, as well as in analysis of conventional and unconventional reservoir rock, including tight gas accumulations. His responsibilities at Polish Geological Institute-NRI include studies on lower Paleozoic shale rocks in the context of shale oil and gas exploration and assessment of petroleum resources.

GEOLOGY OF ORDOVICIAN AND SILURIAN SHALES

Joanna Roszkowska-Remin, Teresa Podhalańska

AGE OF POLAND'S SHALE ROCKS

Unconventional gas and oil exploration efforts in Poland focused on the investigation of the prospective shale gas production areas that are located along a belt stretching through the Central and Eastern Poland. Petroleum geologists' attention is drawn especially by Ordovician and Silurian dark and rich in organic substance shale rocks. This is particularly true for the lowest and Upper Ordovician and the lower Silurian – Llandovery and Wenlock (from approx. 485 to approx. 427 million years BP). Other potential prospects are upper Cambrian alum shales occurring in the northern Gdansk Pomerania.

Graptolites, Caradoc, Ordovician

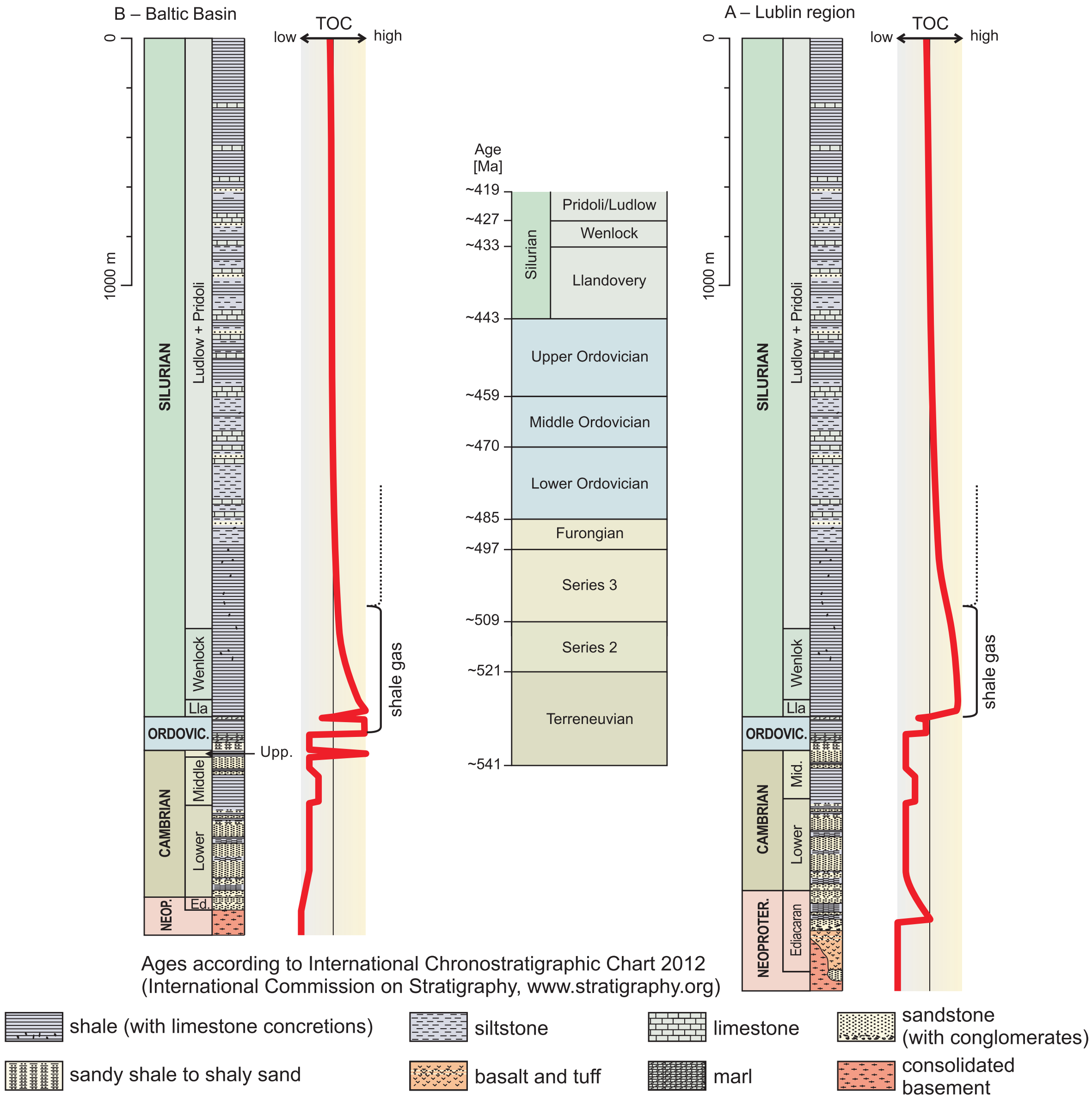
Graptolites, Landover, Silurian

Graptolites on the shale layer, Łeba Elevation, coll. T. Podhalańska

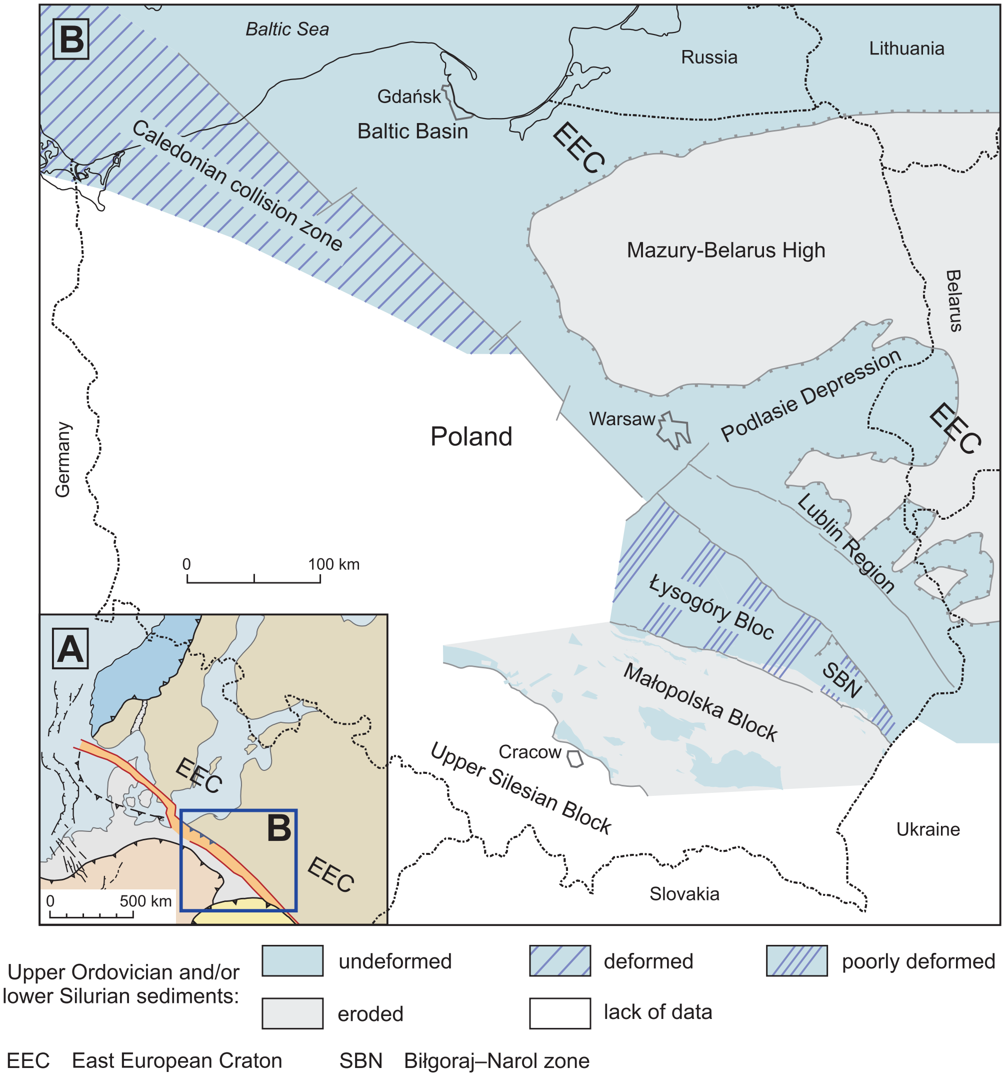
The presence of fossils, including in particular the graptolites, an extremely fast evolving group of plankton organisms, enables relative dating of the Ordovician and Silurian formations that are considered as the most prospective rocks in terms of unconventional petroleum exploration. Graptolites are common in Ordovician and Silurian dark claystones and mudstones. Biostratigraphic classification based on these fossils is the key and the best tool of stratigraphic correlation. Graptolites make it possible to determine the relative age of the prospective formations and enable the dating of stratigraphic sequences, their boundaries and of anoxic strata rich in organic matter that are the source of hydrocarbons present in the rock. By tracking the range of particular species, the points of their first and last appearance datum considered as biostratigraphic benchmarks, scientists are able to correlate prospective formations at a regional scale. Graptolites are often accompanies by other fossil fauna species: brachiopods, nautiloids, bivalves, as well as by micro-fossils: ostracods, acritarchs and Chitinozoa, but none of them compares to graptolites in terms of dating and correlation of mudstone/claystone successions. Composition and variability of fossil communities that are present in the Ordovician and Silurian black shale rocks reflect to a high extent the initial composition of the plant and animal communities that occurred in the primary depositional environment of these sediments. The state of fossil preservation, including that of graptolites, frequency of their occurrence and diversity in the shale rocks may indicate the depositional and early **diagenesis** environment, including oxygen conditions prevailing at the bottom of the sedimentary basin, and help identify aerobic and anaerobic periods which are of key importance to the accumulation and preservation of organic

DICTIONARY

Diagenesis *– a set of physical and chemical processes by which loose sediments are transformed into a solid rock*



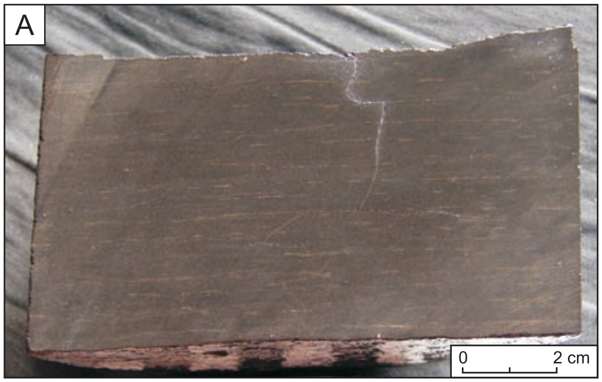
Simplified lower Paleozoic Profile in (A) Lublin Region and (B) Baltic Basin, including the location of shale rocks with enhanced organic substance content that are the potential gas/oil prospects (Poprawa, 2010, slightly modified)

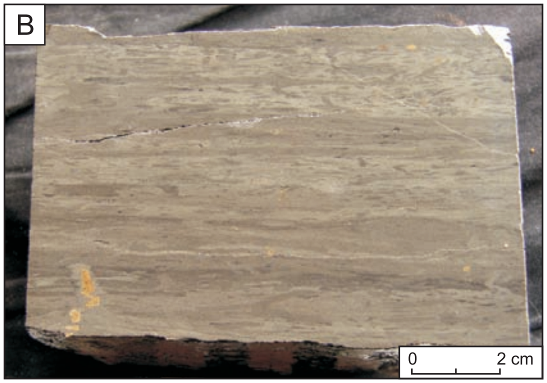


Schematic map of Upper Ordovician and lower Silurian formations in the basin at the slope of the East European Platform (Poprawa, 2010, slightly modified)

matter in the sediment. Therefore, graptolites and other fossils that occur in shale rocks are a useful tool in the investigation of the potential source rocks of hydrocarbons, including the shale gas.

Lower Paleozoic shale rocks were formed in a single marine basin at the western edge of the Baltica paleo-continent (a geological structure called the East European Platform is today a vestige of that paleo-continent). Sediments rich in organic matter were deposited in the basin which had been formed as a result of Earth crust bending, as the continents of Baltica and Avalonia progressively collided with each other. In la-





Illustrative specimens of A – blackish-brown laminated mudstone with distributed pyritic concretions, formed in an anoxic environment; B – greyish-green mudstone formed in a well oxygenated environment, as indicated by abundant traces of animal activity (photo by J. Roszkowska-Remin)

ter geologic history, lower Paleozoic formations had been erosionally stripped in some regions of Poland as a result of tectonic activity. Consequently, following a local erosion-induced segmentation there are today three main areas of Ordovician/Silurian shale occurrence: Baltic Basin (the Peribaltic Syneclize) in the north, Podlasie Depression in the east and the Lublin Basin.

SHALE ROCK FORMATION ENVIRONMENTS

Core logging and sampling is geologists' primary responsibility during shale gas exploration. Normally, this is the only opportunity to "touch" the rocks, insofar as in the real environment they are buried in the ground, sometimes as deep as 3 to 4 km. Paleozoic shale outcrops are seldom seen in Poland, they occur only in the Świętokrzyskie (Holy Cross) Mountains and the Sudetes.

The first thing to be done following the retrieval of core samples is to perform a thorough sedimentological analysis so as to reinterpret the environment in which the fine grained sediments, preserved to this day as shale rock, were deposited.

Sedimentologists describe in detail the lithology of core samples, sedimentary structures, their texture (grain size and grading) traces of animal activity and even the colour. Based on this information they distinguish **lithofacies**, i.e. rocks that display a specific set of features which indicate that they have been deposited in a single **depositional process**. This makes it possible to determine, even at an early stage of investigation, the rocks with a high content of silica, clay minerals and of organic matter, that were formed in a tranquil depositional environment with a limited access to oxygen, and those having more silica but less organic matter.

Any distinguished lithofacies can be combined into distinct **sets of lithofacies**, and the latter into **depositional systems**, which in turn reflect time and space interrelations of the accumulation processes. The entire environment of sediment deposition within the basin is reconstructed in order to get an insight into the depth of deposition, sedimentation processes involved and subsequent transformations of the sediment. Dark shale rocks are normally referred to as marine sediments deposited on

DICTIONARY

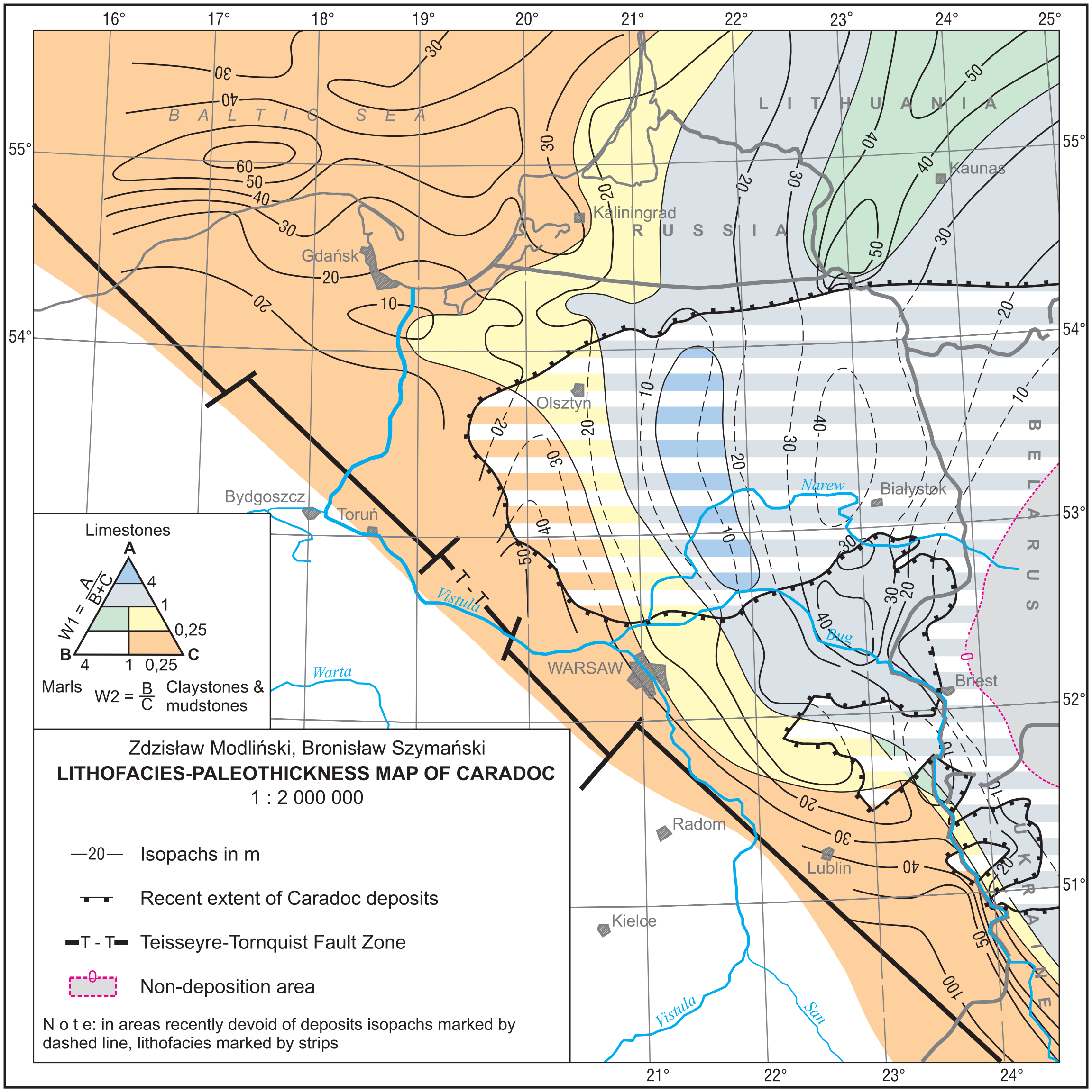
Lithofacies *– a set of sedimentary rocks that share the same specific lithology patterns (mineral composition, grain size, structure, texture and fossils) that have been formed as a result of a specific depositional process, e.g. sandstones formed by the action of storm waves*

Deposition process *– a process during which rock materials are deposited (e.g. water transport, wave action, wind transport)*

Lithofacies sets *– genetically interrelated lithofacies formed in a single sedimentary environment but as a result of different depositional process, e.g. lithfacies set formed in a sandy coastal environment will include dune, beach and shallow coastal sediments*

Depositional system *– geologic/sedimentary environment with specific lithofacies sets, for example lacustrine, fluvial or abyssal depositional systems*

Plate 9



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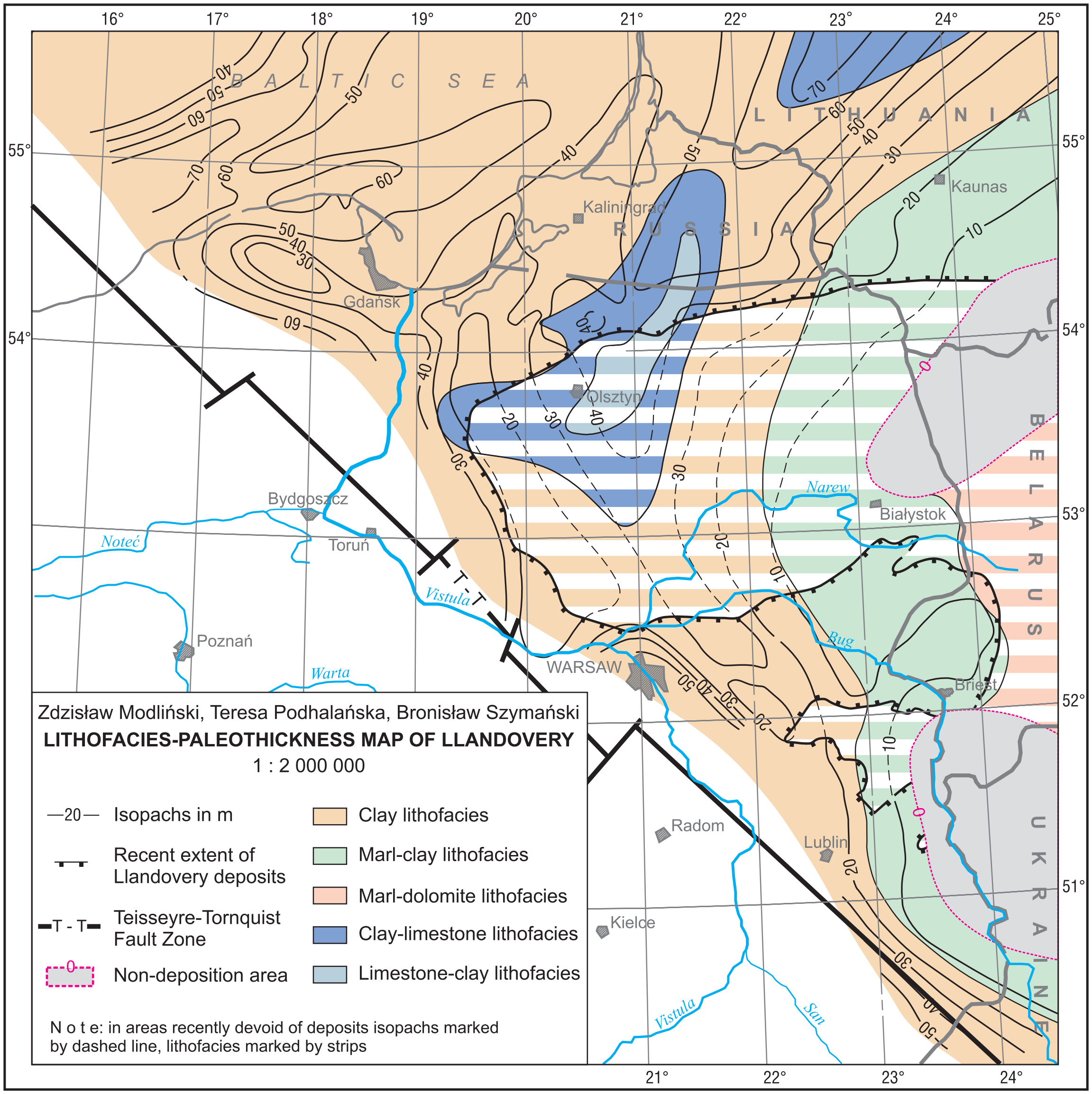
Lithofacies and paleothickness map of the Caradoc (Ordovician) (approx. 458–449 million years ago) (Modliński, Szymański, 2010)

the shelf, the continental slope or in abyssal plains. They are commonly deposited as a result of particulate falling out from the water column or the action of currents (particle rolling along the bottom). Considering shale gas and oil exploration aspects, it is important for

Plate 11



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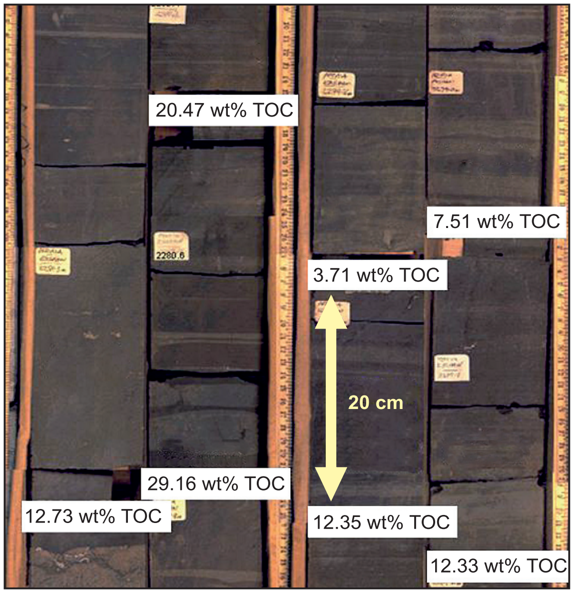
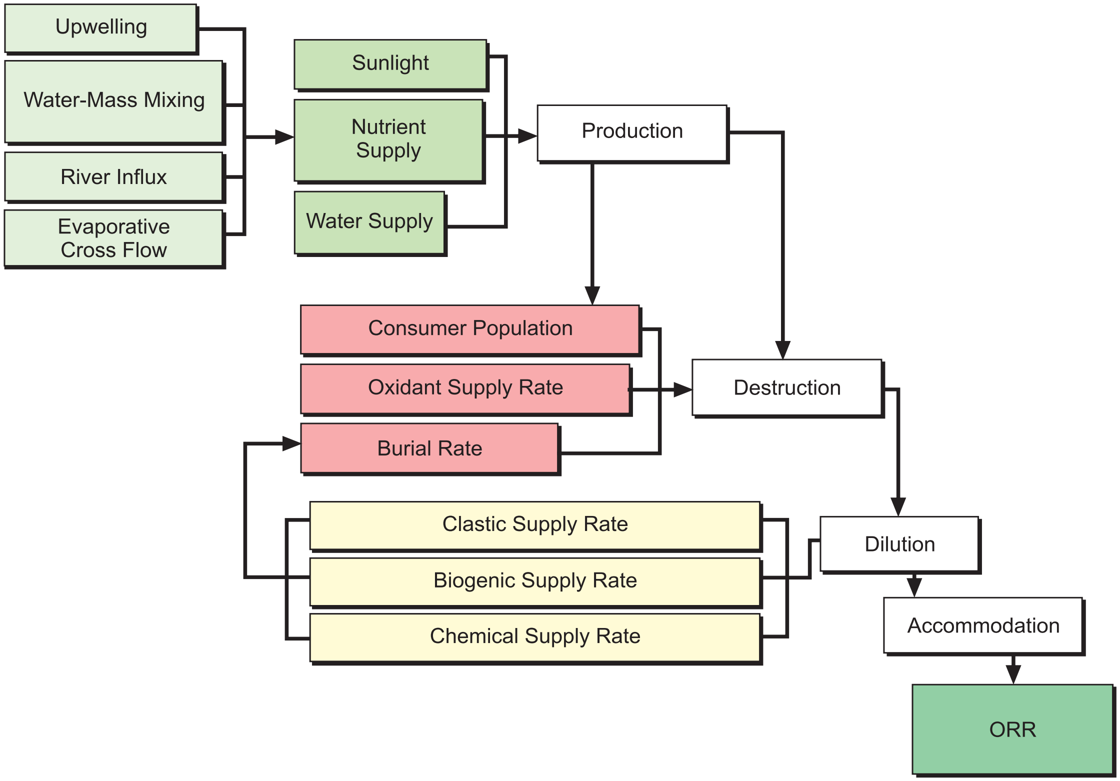
Lithofacies and paleothickness map of the Llandovery (Silurian) (approx. 443–433 million years ago) (Modliński, Podhalańska, Szymański, 2010)

the organic matter to be preserved in the sediment. This may happen only if oxygen deficient or anoxic conditions prevail at the bottom. In fact, non-oxidated sulfides and organic matter are behind the dark or sometimes even black colour of the rocks.

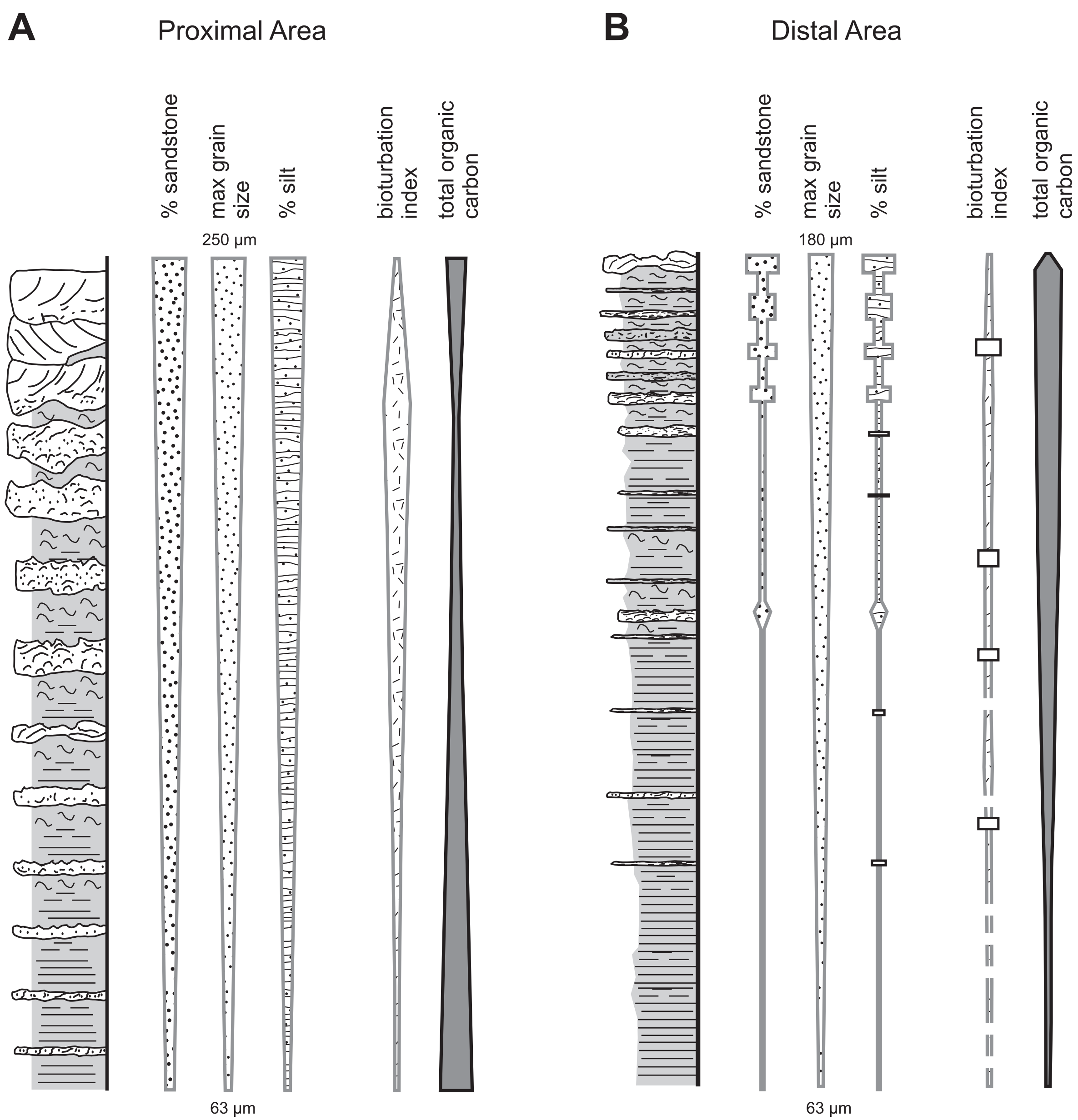


Changes in percentage content of organic carbon (TOC) along an interval which is several tens centimetres thick. An example from the US basins (Passey *et al.*, 2010)

Tabulated data from several drilling wells and other investigations (downhole logging, seismic surveys) enable the interpretation of both horizontal and vertical variability of rock lithology and characteristics. These interpretations are also made for the entire basin, for example in the form of lithofacies-paleothickness maps which depict the distribution of particular facies and changes that have occurred in the entire basin throughout its history.



Schematic representation of factors that have an effect on the production, destruction and dispersion of organic matter and lead to the formation of rocks with enhanced organic substance content (Passey *et al.*, 2010)



Illustrative variations in rock characteristics (the share of particular grain sizes, intensity of fauna activities, organic carbon content, etc. in schematic profiles A – nearshore, B – deepwater (Bohacs *et al.*, 2005)

DICTIONARY

Sweet spot *– an area within a reservoir where production characteristics are more favorable*

It is also important to know the distribution of facies at a local scale, especially in the context of locating the so called **"sweet spots"**, i.e. places that are the best petroleum prospects. Some intervals rich in organic matter are very thick and extensive but often they display a high vertical

variability, especially in terms of total organic carbon (TOC) content, a key parameter for petroleum exploration.
This vertical variability is associated with the diversity of the processes and conditions that are involved in shale rock formation. At the rock formation stage, organic matter content is controlled by three processes: production, destruction and dispersion.
The intensity of particular processes vary depending on the place of deposition. For example, organic matter production is relatively high near the shore, but at the same time the rate of dispersion is equally high due to supply of material from land and so is the rate of destruction by animals living in the well oxygenated bottom of the basin. Deeper in the sea, organic matter is produced at a much slower rate, but the processes that disturb production are less intense. As a consequence, today there might be more preserved organic matter in deep sea areas comparing to shallower ones. Locating the zone of optimal co-occurrence of organic matter production, destruction and dispersion processes is tantamount to finding rocks that today have the highest TOC content and, therefore, are the best prospects in terms of exploration for oil and gas, including unconventional hydrocarbons.

A FEW WORDS ABOUT AUTHORS

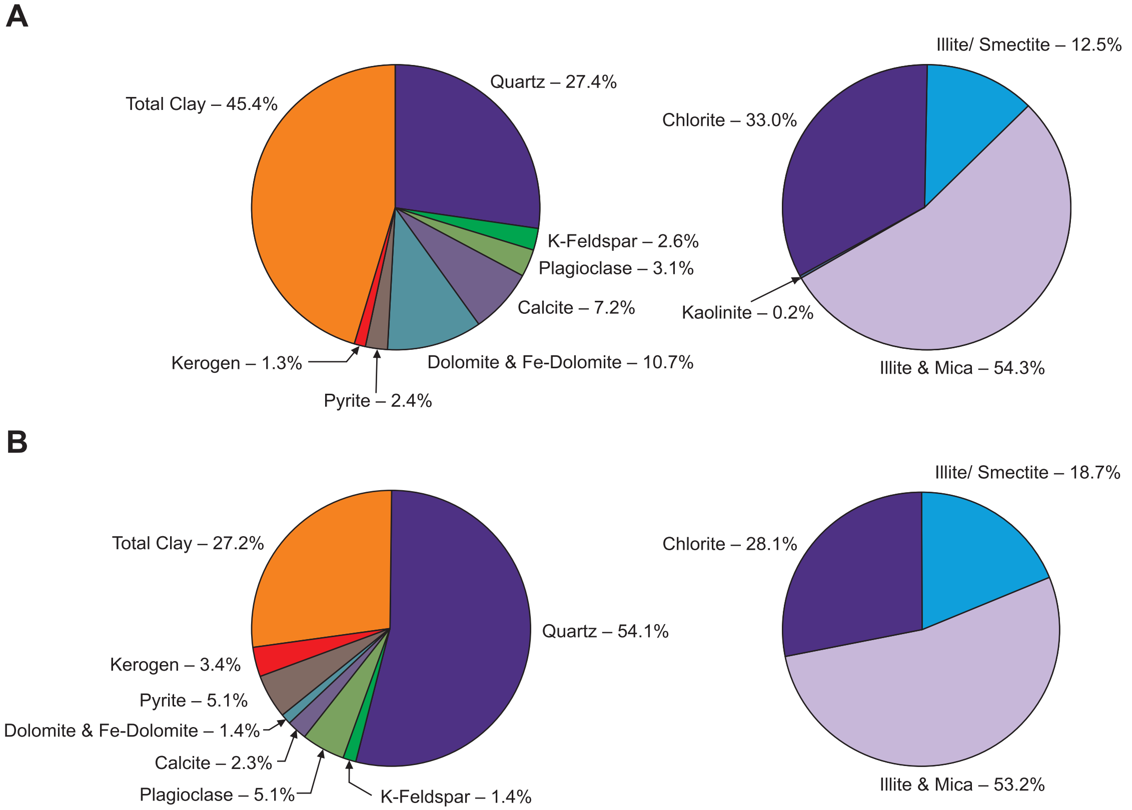
Joanna Roszkowska-Remin
Graduated from the Faculty of Geology, Warsaw University, majoring in stratigraphy and exploration. She completed post-graduate studies in Petroleum Geology at AGH University of Science and Technology in Cracow, as well as an intensive course of clastic sedimentology at Tromso University in Spitsbergen. She is about to complete at Warsaw University her PhD thesis on the Miocene of the Carpathian Foredeep. Her responsibilities at Polish Geological Institute-NRI include sedimentology of clastic sediments and paleomagnetic studies.

Teresa Podhalańska
A geologist, she graduated from the Faculty of Geology, Warsaw University. Currently on proffesor position in PGI-NRI. Her responsibilities at Polish Geological Institute-NRI include in-depth studies on regional geology of Poland, as well as on lower Paleozoic, mainly Ordovician and Silurian, stratigraphy. Her studies are extensively used in exploration and proving of unconventional hydrocarbon resources.

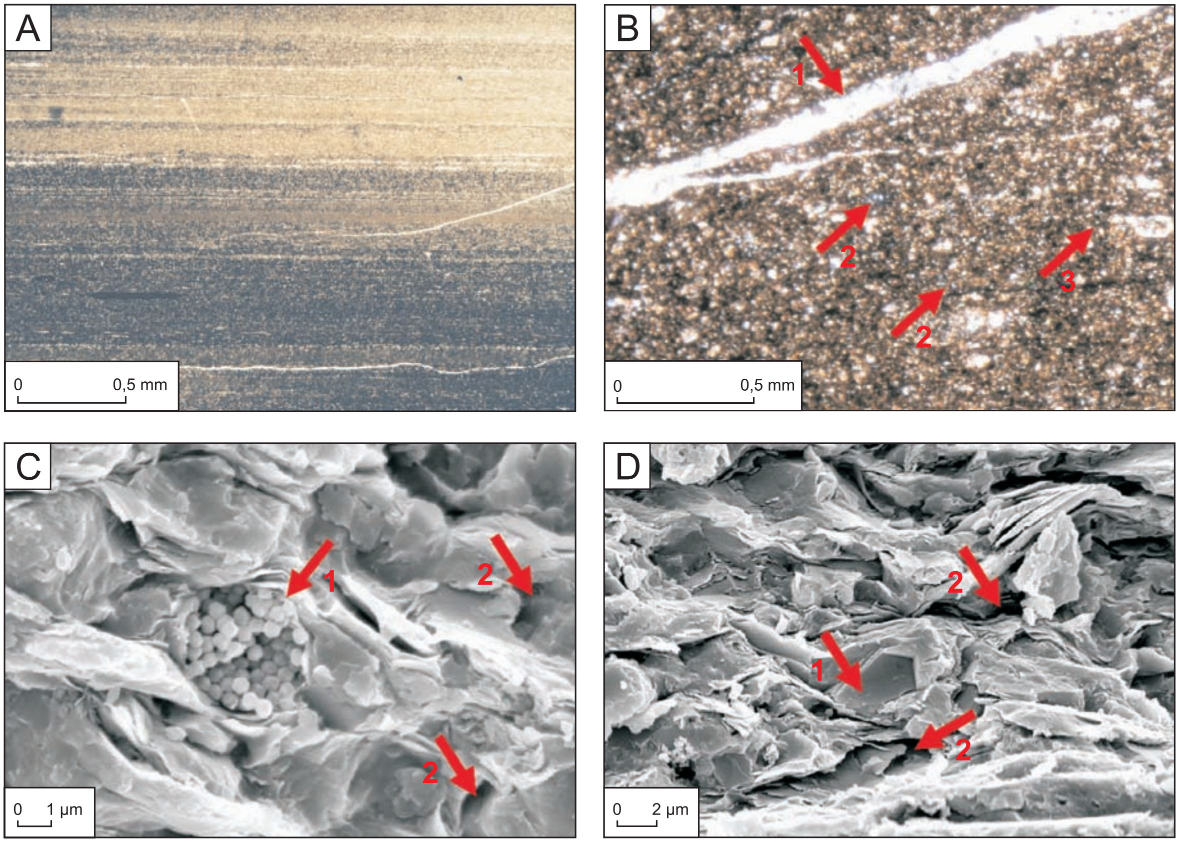
MINERALOGY AND PETROGRAPHY OF ORDOVICIAN AND SILURIAN SHALES

Marek Jasionowski

Lithologically, source and reservoir rocks of unconventional gas accumulations, commonly called "shales", are mostly mudstones and claystones. They are built of predominant clay minerals and quartz (silica) and of accessory minerals that are found in various proportions: carbona-



Mineral composition of lower Paleozoic shale rocks from the Baltic Basin A – Upper Ordovician, B – Wenlock (Poprawa, 2012)



Petrography of shale rocks (source: PGI, B - Paweł Lis, other – Teresa Podhalańska)
A – Laminated mudstone; alternating laminae richer and poorer in organic matter, Llandovery, Silurian, depth 4393 m, photomicrograph, crossed polars
B – Mudstone cut by calcite vein (1). In clay matrix (dark areas) are visible carbonate grains (white), in part probably bioclasts (large oval), grains of quartz (grayish, 2) and glauconite (green, 3), and crystals of pyrite (black), Wenlock of Lublin Basin, photomicrograph, crossed polars
C – Shale in scanning electron photomicrograph (SEM); 1) Pyrite grains between illite flakes; 2) Pores between illite flakes, Llandovery, Silurian, depth 2971 m
D – Shale in scanning electron photomicrograph (SEM); Continuous and parallel lamination of illite flakes; 1) Calcite grain between illite flakes, 2) Pores between illite flakes, Llandovery, Silurian, depth 2968 m

tes (calcite, dolomite), feldspars, pyrite, phosphates and other minerals. Shale rocks' constituent minerals may be both allo- and authigenic. The former are brought into sedimentary basins from external sources (predominantly as detritic terrigenous material derived from older rocks weathering on land and subsequently delivered to the sedimentary basin and deposited therein), while the latter minerals are the products of changes occurring in deposited sediments and rocks (diagenesis – e.g. cementation, recrystallisation). Moreover, shale rocks may contain calcareous, silicious or phosphatic skeletons of organisms.

Standard examinations of shale rocks include the determination of the mineral composition using XRD (X-ray diffraction), petrographic thin section studies (using both transmitted light and cathodoe luminescence – CL) and SEM (scanning electron microscope) analyses.

XRD analyses of mineral composition are intended to establish the presence of specific minerals (a qualitative analysis) or their percentage share (a quantitative analysis). In some of the samples detailed quantitative XRD studies of clay minerals are made. It is important to know the mineral composition because it affects mechanical properties of the rock and, consequently, its susceptibility for fracturing. XRD studies are supplemented by geochemical analyses, including the determination of the percentage share of main elements (such as Si, Al, Fe, Ca), trace elements (e.g. Mo, Ni, Pb, V) and rare earth metals (lanthanides).

The key purpose of the petrographic analysis is to determine the mineral composition of the studied rocks, their texture (arrangement and distribution of grains) and structure (grain size and shape). Shale rocks are often very heterogeneous at a small scale. Therefore, petrographic analysis is intended to provide an image of the spatial distribution of minerals in the rock (which is not feasible using XRD), to establish its origin (allogenic or biogenic grains versus authigenic cement) and, eventually, to determine the pore space characteristics (sizes, types and interconnections of the pores and micro-fractures).

Since shale rocks are composed of very fine grained mineral fractions, traditional petrographic thin section studies have inherent limitations due to achievable levels of magnification. Scanning electron microscope (SEM), the most useful complementary tool, offers very high levels of magnification. The SEM allows for imaging the distribution of individual minerals in the rock (back scattered electrons [BSE] images of polished thin sections), the determination of the chemical and (consequently) mineral compositions in a micro-area (analysis of selected grains or crystals), as well as for mapping the distribution of particular elements using X-ray detectors or electron microprobe. FIB (focused ion beam) SEM, a further development of traditional SEM, offers very high magnifications (at nanometric resolution) that enable of micro-textures and micro-structure, including detailed imaging of micro- and nano-porosity, a vital factor for natural gas retention in the shale rocks.

A FEW WORDS ABOUT AUTHOR

Marek Jasionowski

A geologist, PhD, he graduated from the Faculty of Geology, Warsaw University. His responsibilities at Polish Geological Institute-NRI include sedimentology, petrography and geochemistry of sedimentary, primarily carbonate, rocks. He is currently involved in studies on the Miocene in Poland and Ukraine, as well as on the Zechstein formations.

PETROPHYSICAL PROPERTIES OF SHALE ROCKS

Ireneusz Dyrka

DICTIONARY

Source rock *– petroleum play's lithological unit with petrographic composition that contains a sufficient quantity of fossil organic matter that enabled generation and expulsion of hydrocarbons as a result of thermocatalytic processes*

Reservoir rock *– petroleum play's lithological unit of which natural characteristics (porosity, fracturability, cavernosity and sorption properties) enable accumulation of hydrocarbons*

Cap rock *– petroleum play's lithological unit of which petrographic composition and structural characteristics make the rock impermeable for hydrocarbons*

The main feature of natural gas presence in clay-mud shale is that the gas occurs directly in the source rock. Quite a challenge for the petrophysicists who have to use more advanced techniques of research, especially in micro- and nano-scale. In order to characterize the petrophysical properties of the rock, i.e rock capability to accumulate and transport reservoir fluids, it is necessary to determine the values of two key parameters: porosity and permeability. In addition, the characterization of the reservoir fluid (oil, gas, water) present in the rock is an important aspect. An illustrative petrophysical model of an organic-rich shale rock is presented below.

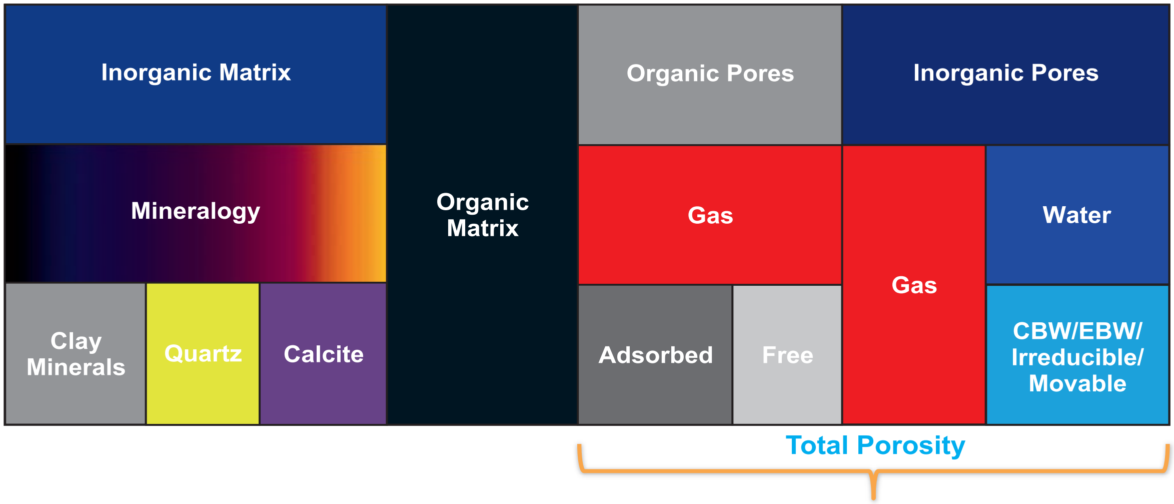
POROSITY

Porosity means the volume of void space in the rock (expressed as percentage) which can be filled with a reservoir fluid (oil, gas or water). Therefore, porosity determines the volume of reservoir fluids accumulated by the rock.

Two types of porosity are distinguished: total and effective porosity. The total porosity is calculated as the total pore volume divided by bulk volume of the rock, while in the case of effective porosity the volume of interconnected (permeable) pores is divided by bulk volume of the rock. As shale permeability is minimal, its effective porosity occurs upon fracturing procedures.

Shale rock is built of micro and nano pores with a varying degree of water saturation and partly of residual organic matter having a density which is absolutely different from that of rock grains. So far, in the case of conventional reservoir rocks (sandstone, carbonate rocks), porosity was defined as the void space between rock grains (inorganic pores and micro-pores). Free gas was accumulated in that space, laminae enriched in silica and in the system of natural fractures and micro-fractures.

In addition to the aforementioned various accumulation spaces, free gas is present in clay- and mudstone complexes also within laminae enriched in organic matter. However, a significant amount of shale gas is present in organic pores located within insoluble organic matter which is called kerogen. The gas occurs in the form of free gas and a large portion thereof is adsorbed by kerogen and some clay minerals. Considering that the gas is generated *in situ*, shale rocks form an exceptional petroleum system wherein the same rock formation is simultaneously source, reservoir, sealing rock and trap, while gas migration occurs at a micro scale or is absent.



Petrophysical model of reservoir shale rock (after Bust *et al.*, 2013, modified), CBW – capillary-bound water, EBW – electrochemically-bound water

DICTIONARY

Reservoir trap *– a spot in petroleum play which form, structurally or stratigraphically, a barrier (trap) for hydrocarbons that prevents their migration*

Hydrocarbon migration *– process linking the reservoir rock with a trap for generated hydrocarbons as a result of processes associated with the flow of water through the rocks or by way of convection or diffusion*

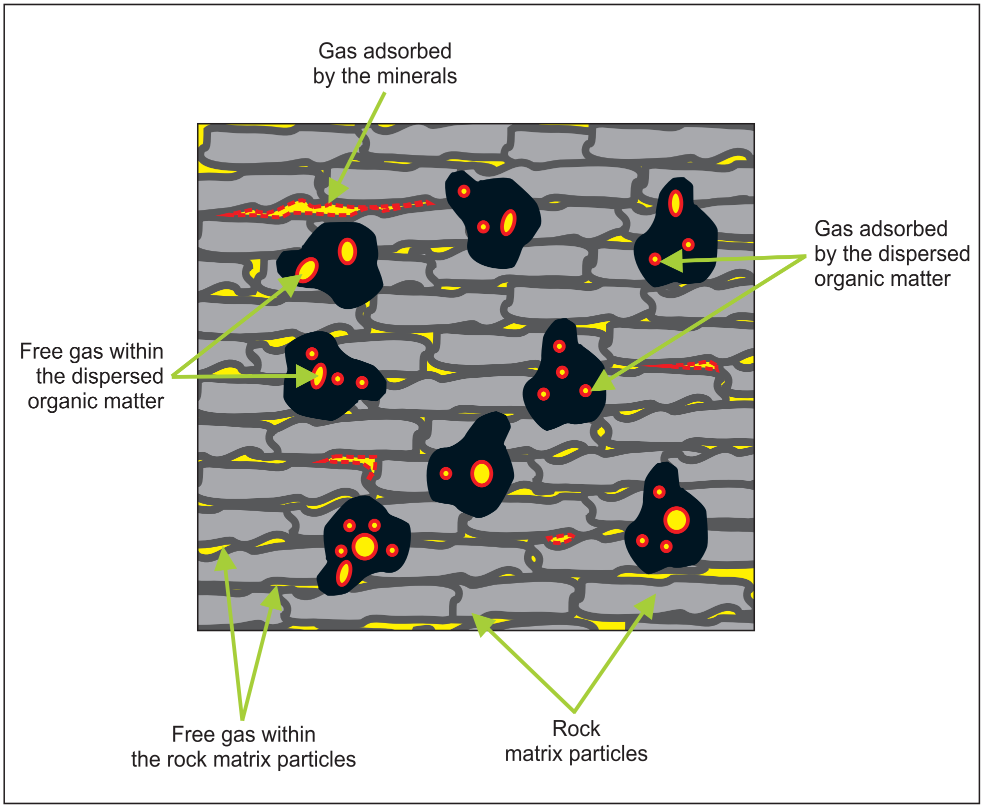
PERMEABILITY AND FRACTURABILITY

Permeability is associated with the presence of natural cracks/fractures in the rock which enable the flow of reservoir fluids between pore spaces (flow rate is expressed by Darcy equation or Knudsen's diffusion equation).

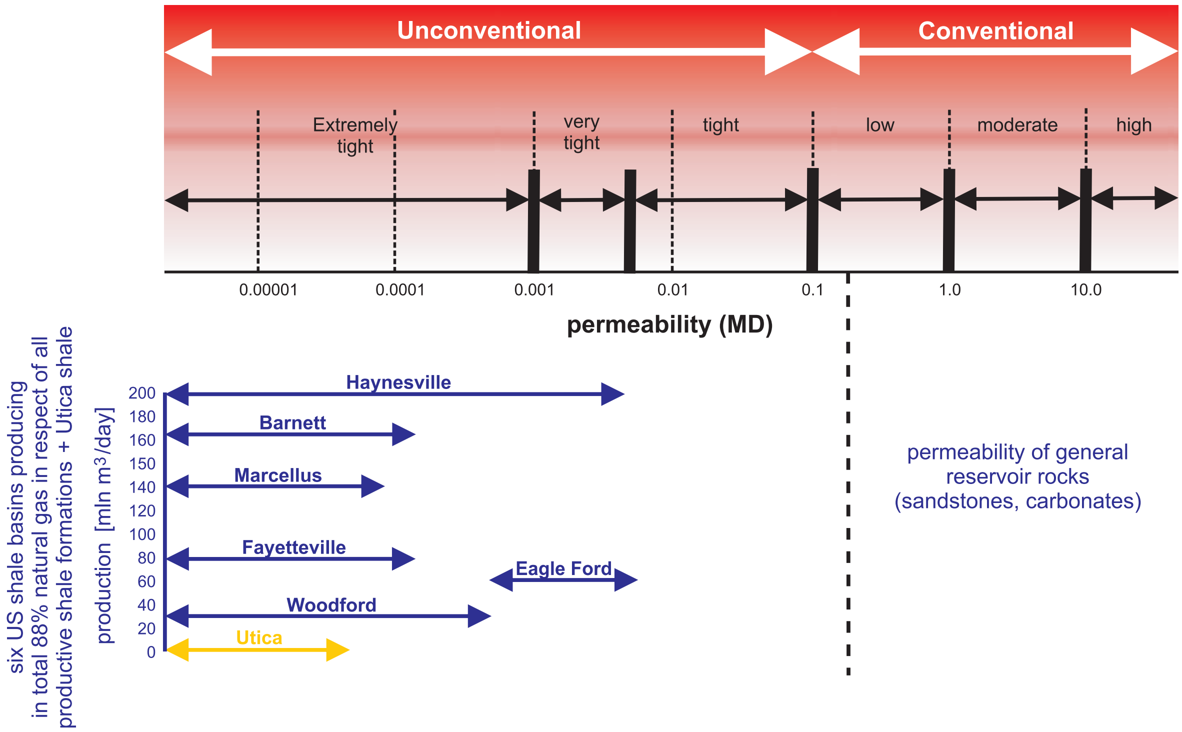
Permeability enables the flow of natural gas or oil into the borehole and its production. Permeability coefficient is dependent on the size of the pores, their relative configuration, rock grain layout, grain grading and cementation, as well as on the rock fracturing patterns. In the case of shale rocks, both permeability and porosity are highly dependent on mineral composition, organic matter distribution, their quantitative content (%) and thermal maturity.

A low permeability of shale rocks basically prevents any unrestrained flow of hydrocarbons.

Accordingly, several rock fracturing operations must be performed in order to connect the pores to the borehole and allow for an unrestrained flow of reservoir fluids.



Accumulation spaces for natural gas in the shale rock



Permeability diagram of conventional and unconventional reservoirs. Permeabilities of 6 most productive US shale formations, accounting jointly for 88% of the total production from all US shale formations, are presented on the graph. The Utica Formation, considered as the most similar to Polish lower Paleozoic shale rocks, is marked yellow (based on: Faraj, 2012; Hughes, 2013; Jarvie, 2012)

DICTIONARY

Hydraulic fracturing *– technological process intended to enhance well productivity. The process involves injection of a highly pressurized fracturing fluid (a mix of water, chemical additives and sand) in order to induce, maintain or expand fractures in the rock*

Inorganic pores *– free space between rock grains*

Organic pores *– free space within insoluble organic matter called kerogen*

Considering production aspects, shale rocks should preferably contain a high silica content which improves rock susceptibility to fracturing and, subsequently, enhances its permeability. A high content of clay minerals does not help fracturing as these minerals tend to swell in contact with water and reduce filtration capacity of shale rocks. Special chemical agents have to be applied in that case to minimize unwanted effects of water on clay minerals.

WATER SATURATION

Water saturation in shale rocks is an important factor for the flow of gas in a porous medium and for maintaining the flow of fracturing fluids. Furthermore, an assessment of gas resources in place is not limited to the volume of free gas and adsorbed gas. Water contained in the pores should be considered, too. In shale rocks that are rich in organic matter, the water occurs solely in inorganic pores.

PHYSICAL PROPERTIES THAT DEFINE SWEET SPOTS

Having obtained the results of petrographic tests we are able to determine technically recoverable gas sweet spotst which display the following characteristics:

- a low water saturation,
- a high content of organic matter with a high content of kerogen,

Gas contained in **organic pores** is free of water as kerogen is hydrophobic, i.e. it repels water particles. As a result, a low water saturation coefficient correlates with a high content of organic matter in the rock. The situation is just the opposite in the pores of inorganic origin, wherein the water is attracted by hydrophilic clay minerals. The volume of the water contained in the inorganic pores tends to decrease during compaction of sediments, their diagenesis and as a result of void filling with the migrating hydrocarbons.

Two types of bound water are distinguished depending on the amount of clay minerals present in the rock: capillary-bound water and electrochemically-bound water. The former prevails at a high content of clay minerals, while the latter is predominant if the content of clay minerals is low.

DICTIONARY

Capillary-bound water *– water held in inorganic pores, fractures and caverns regardless of gravitation.*

Electrochemically-bound water *– water present in minerals as OH^- hydroxide groups*

– a low content of clay minerals,
– a high porosity, voids preferably filled with free gas,
– a high permeability and/or rock fracturability,
– the presence of natural fractures increases the efficiency of hydraulic fracturing.

A FEW WORDS ABOUT AUTHOR

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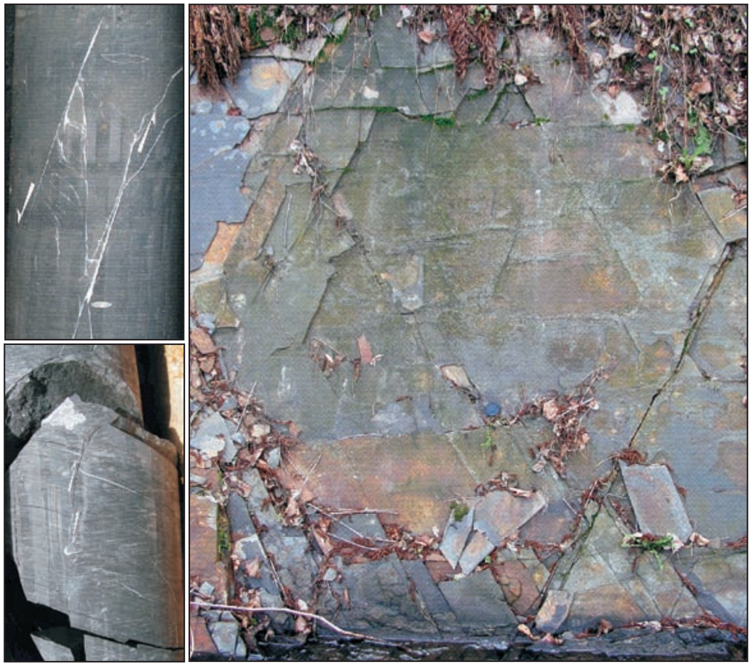
GEOMECHANICAL CHARACTERIZATION OF SHALE COMPLEXES

Marek Jarosiński

Comparing with conventional reservoir development, more refined geomechanical studies are required for the production of hydrocarbons from shale gas and oil accumulations, due to the application of hydraulic fracturing treatmentd that are intended to enhance flow of hydrocarbons from hardly permeable rocks. The key constituent elements of the geomechanical model of shale complexes are: (1) mechanical properties of the shale rocks and of the adjacent complexes, (2) tectonic structure, joint system in particular, and (3) present-day state of tectonic stress.



Tectonic fractures accompanying normal faulting (borehole core) and regular joint system in Silurian shale (outcrop in the Holy Cross Mts.) (photo by S. Salwa, PGI-NRI)

Mechanical properties of the shale rock fabric, which include mainly elasticity coefficients, compressive and extensional strength, are primarily dependent on the mineral composition which follows the distribution of facies within the sedimentary basin. The content of clay fraction is a key decisive factor behind shale properties. A large share of clay weakens the rock fabric by enhancing plastic deformation, which leads to a lower brittleness of the shale rock. Clay substance accounting for more than 40% is considered as a process problem in fracturing procedures, while a high content of silica and diagenetic carbonates enhances brittleness and helps fracturing. Shale properties can be defined at different scales of observation: from mineral grains (nano- and micro scale), through packages of lithologically homogenous laminae (mili- and centimetre scale) to higher order sedimentary complexes with their internal lithological diversification and primary patterns of depositional structure (metric scale).

Shale tectonics is another significant constituent of the geomechanical mode. Horizontally

Shale rocks are inherently mechanically anisotropic. Anisotropy is stronger vertically, mainly due to the lithological separation and orientation of clay mineral flakes (lamination). Measured in situ, horizontal anisotropy is weaker, but it is more important for the selection of an optimal trajectory of a horizontal well. The anisotropy is controlled by regular fractures of the shale complex and differential horizontal stress. Mechanical parameters of shale rock are determined using static laboratory tests or on the basis of ultrasound velocity and energy propagation in laboratory tests, acoustic wave used in downhole logging and seismic wave in 3D seismic tests and multi-directional vertical seismic profiling. Longitudinal and transverse wave propagation patterns define the dynamic parameters of the rock that depend on the direction of their recording. Accordingly, mechanical parameters of the shale rocks are dependent on the scale of observation, rate of strain, propagating wave length and the direction of wave recording. Therefore, selecting the scale of measurement that is suitable for the task (for example, hydrofracturing planning or permeability assessment) and the determination of anisotropy directions and level are the key problems that are faced when defining mechanical characteristics of shale rocks.

Moreover, geomechanical properties of shale rocks are highly dependent on the pressure of reservoir fluids which, by counteracting the lithostratigraphic and tectonic loads, govern the effective stress that is applied to the rock fabric. Pore pressure often occurs in shale rocks due to mechanical compaction that reduces pore space, as well as by directional layout of mineral flakes that reduces vertical permeability and hinders pressure release from the upward flow of fluids. Another reason behind pressure increase in shale rocks is the release of fluids and gasses from rock-forming minerals under increasing temperature and pressure, for example during hydrocarbon generation or mineral phase changes. Rock pressure may increase to the point of rock fabric's minimum stress increased by its cracking strength which is not noticeable due to the initial micro-damages of the rock. As the pressure grows above the lowest stress in the rock fabric, the rock bursts naturally and the cracks are filled with minerals precipitated from the brine water (mostly carbonates and silica). A higher pressure enhances rock brittleness and helps to push hydrocarbons towards the production well. Any significant overpressures do not occur in Polish shale rocks at the prospective depths (down to 3.5 km), which is unfavourable in terms of reservoir engineering.

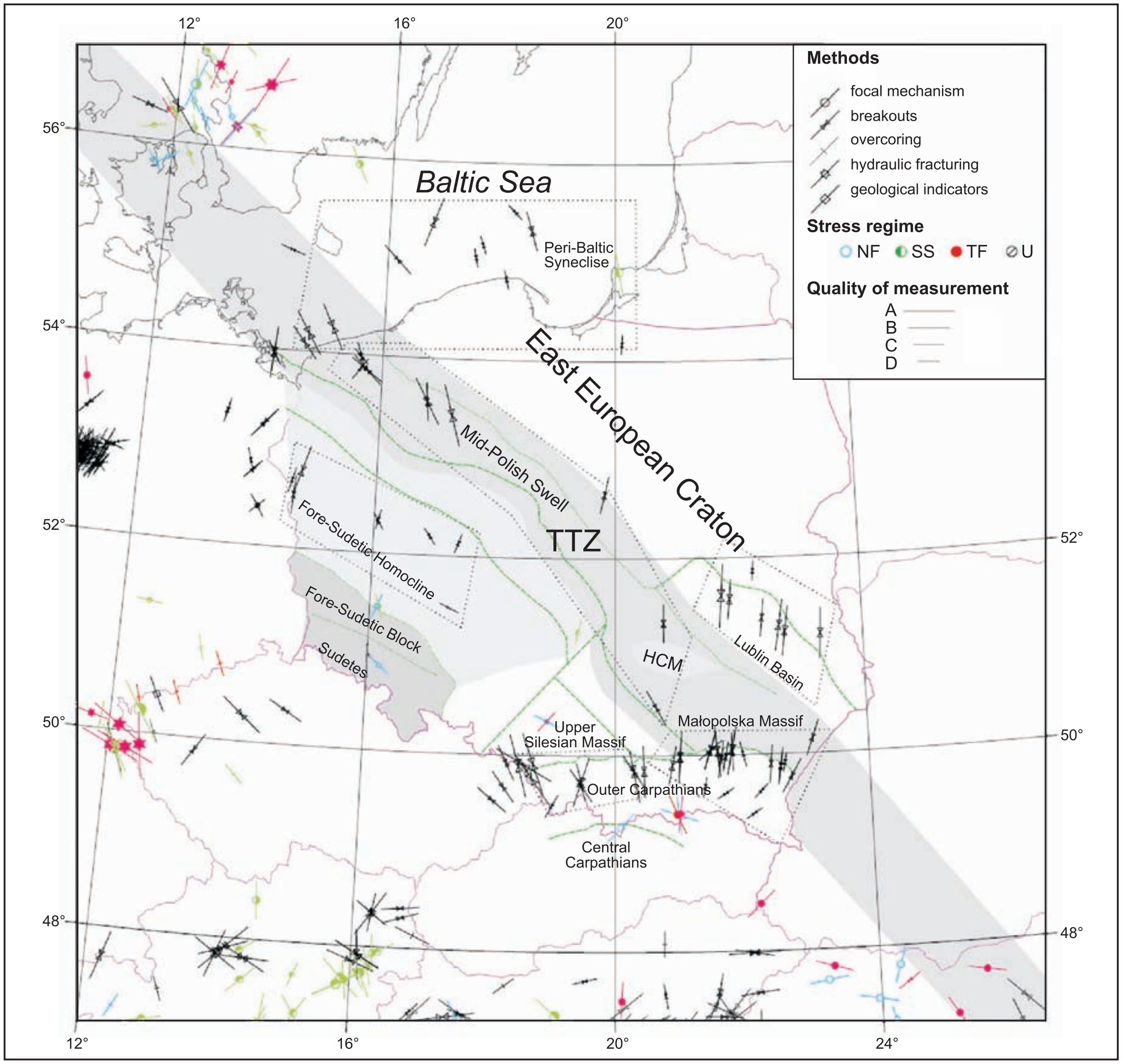
bedded formations, ideally suited for horizontal drilling and free of any major fault zones that are likely to compromise the effects of fracturing by acting as sinks of fracturing fluid, are the best candidates for the development of unconventional accumulations. An optimal drilling location is established on the basis of seismic survey results, preferably of a 3D test which, in addition to an image of the shale formation structure, provides an insight into its elasticity and mechanical anisotropy properties.

Lower-order tectonic structures, revealed by downhole logs or drilling core examination, are present in a shale rock complex in which seismic tests have not identified any noticeable deformations. Investigation of these structures and of serially occurring small faults is of a key importance to the optimization of fracturing tests and hydrocarbon flow to the wellbore through hydraulically induced or tectonic fractures.

Contemporary tectonic stresses represent boundary conditions of the geomechanical model of shale complexes. Thanks to the knowledge of contemporary stresses the horizontal section of an exploratory or production well can be directed so as to ensure that the fractures induced by fracturing jobs, which normally propagate towards the largest horizontal stress, are perpendicular to the wellbore. In the case of normally horizontally occurring shale complexes, one of the principal stress axes is oriented perpendicularly with regard to the ground surface. Horizontal stresses can be assessed on the basis of borehole **breakout** or hydrau-

DICTIONARY

Breakout *– a compressive failure of borehole walls*



Recent maximum horizontal stress directions, most of them determined by mean of borehole breakout analysis (according to Jarosiński, 2006; off-Poland data are taken from the World Stress Map Database Heidbach *et al.*, 2008)
Different symbols stand for methods of stress direction determination, their colors represent stress regimes:
NF – normal fault, SS – strike-slip, TF – thrust fault. Symbol length stands for quality according to WSMDB

lic fracture induced by highly pressurized heavy mud. Comparing these data with rock strength allows for an assessment of the stress regime (spatial relationships between ground surface and stress axes), and sometimes of the stress magnitude. Borehole wall mini-fracturing tests, which are made before the large-scale industrial fracturing jobs, are commonly used to determine the least stress value. The distribution of contemporary tectonic stresses in

Poland has been established by scientific research studies made by State Geological Institute over the past several years.

At a regional scale, the status of stress can be defined by analyzing the seismic focal solution mechanisms or using satellite geodesy data. These approaches, however, are of secondary importance in Poland where natural seismic activity is low and deformations occur at a slow rate. An in-depth mechanical characterization based on laboratory and logging measurements is required for the building of a precise model of stress distribution within specific lithological complexes. The determination of the stress distribution patterns in geomechanical complexes allows for forecasting the expected range of the induced hydraulic fractures.

The synthesis of information on shale geomechanics is presented in the form of one- or three-dimensional mathematical models considering all of the aforementioned mechanical, hydrodynamic, structural and stress components. The model makes it possible to forecast hydraulic fracturing effects and, more importantly, to design optimum fracturing sequences in several horizontal wells and to interpret the results of fracturing procedures.

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A FEW WORDS ABOUT AUTHOR

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Graduated from the Faculty of Geology, Warsaw University. He has studied for twenty years contemporary stresses and tectonic structures in sedimentary complexes on the basis of drilling core analyses, outcrops, geophysical data and numerical models. Currently he holds at Polish Geological Institute-NRI the position of professor in the Energy Security Programme.

CHAPTER 4


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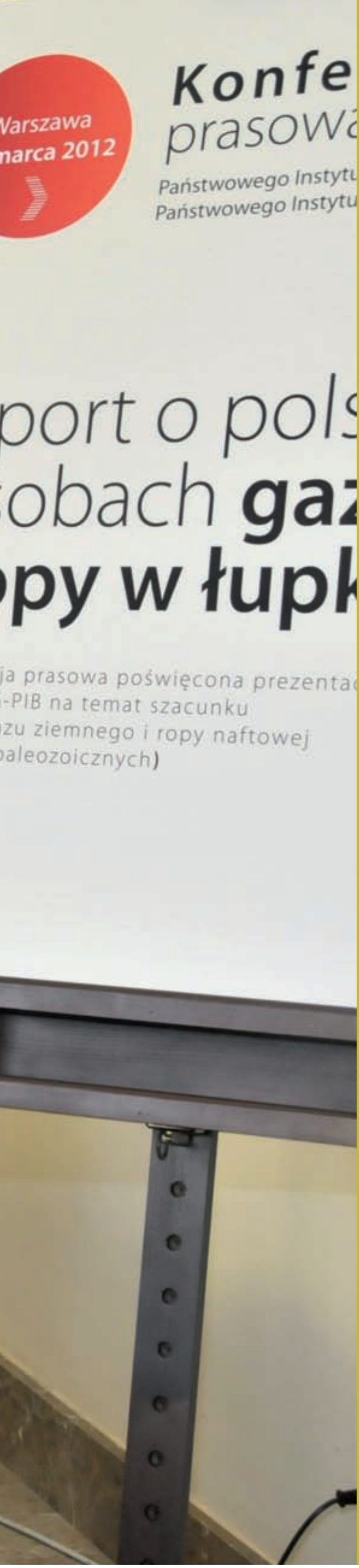


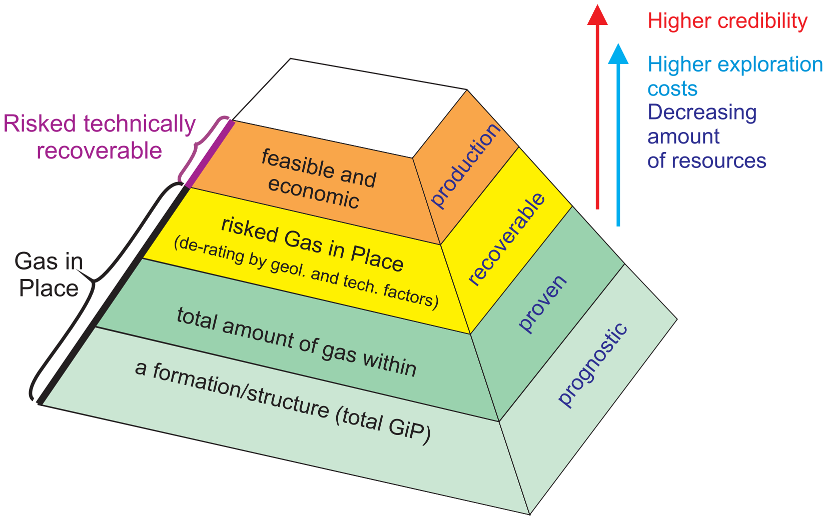
GAS RESOURCES IN SHALE FORMATIONS

scientific editor: Hubert Kiersnowski

SHALE GAS RESOURCES IN POLAND

Adam Wójcicki

The term of gas (or other mineable) resources carries several meanings that are frequently confused with each other or misunderstood. The meaning is different to a (petroleum) geologist comparing with a journalist or politician. The following drawing explains the reasons behind misunderstanding. From geologist's point of view, it is extremely important to make a distinction between different tiers of the pyramid that reflect successive progressively expensive exploration and appraisal stages, while a journalist or a politician does not care about subtleties and just wants to know field production figures (the top tier).



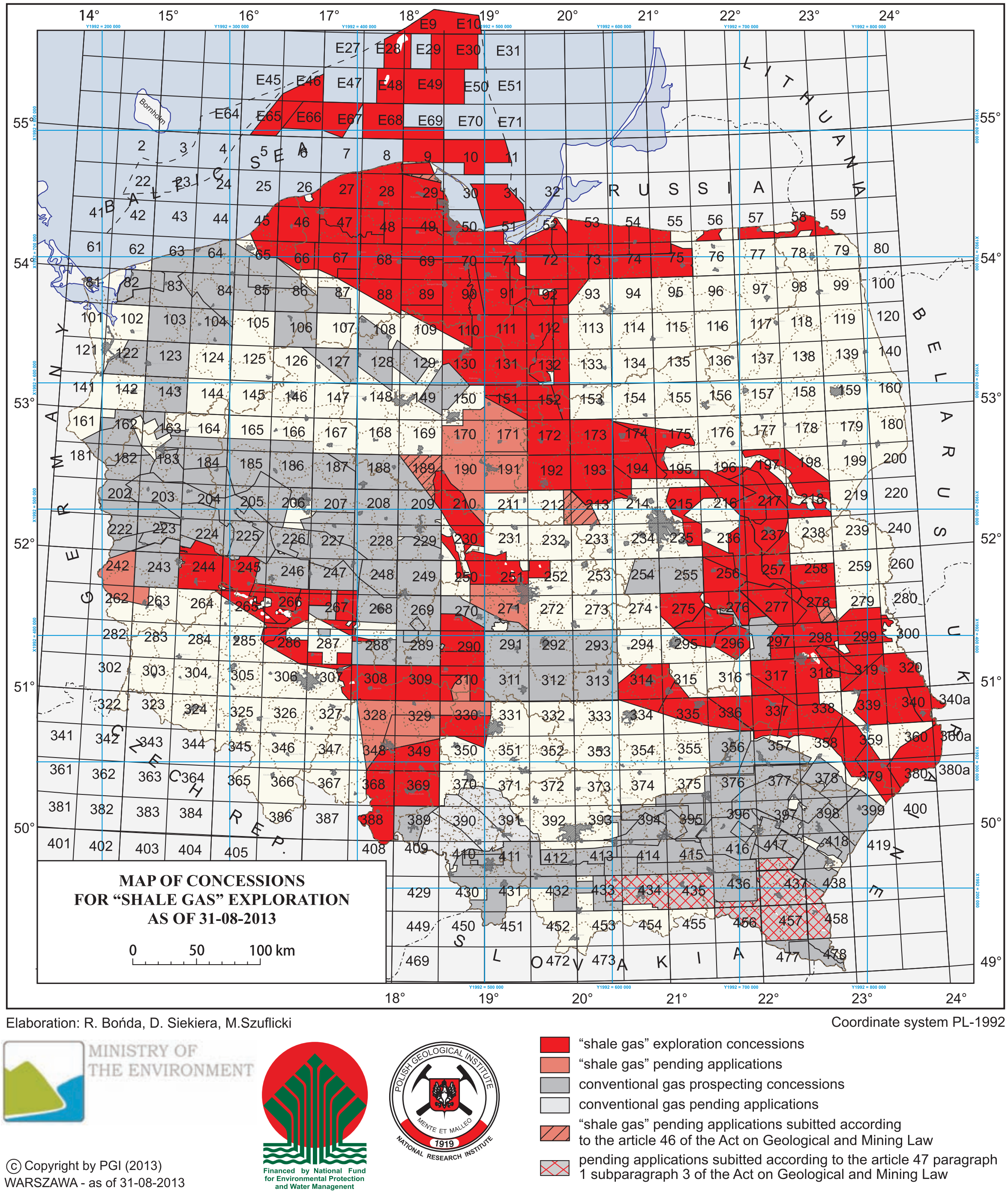
Gas resource assessment concept

Estimation of prospective resources, usually based on scarce data, is the first step of geological studies. The analyzes of Poland's shale gas resources have hardly progressed beyond that stage. They are based on the conclusion that Poland's rock formations are similar to those formations in the USA which contain (shale) gas accumulations (see the following chapter). Laboratory tests have confirmed the presence of gas in these rocks. Detailed laboratory tests of gas-bearing rock samples enabled geologists to estimate the quantity of gas per unit of volume in the rock located around the cored well. This, combined with preliminary assessment of both area and thickness of shale formations, made it possible to estimate gas in place (GIP), i.e. the volume of gas contained in the geological formations. As drilling data are scarce and drilling cores available from a few wells, the assessment of Poland's shale gas resources is still at a hypothesis stage (the resources are "potential" rather than "proven").

Subsequently, once the parameters of prospective shale formations (such as ranges, thicknesses, thermal maturity, organic matter and clay mineral contents, reservoir pressure, etc.) are known to a sufficient degree of accuracy, we may provide an initial approximation of technically recoverable resources. In practice, parameters that are comparable to those reported from productive North American shale basins are adopted. Considering differences in geology, this

allows a significant margin of error. In fact, technically recoverable resources and related shale basin surface areas are indicated by both US and Polish reports on Poland's shale gas resources.
Contrary to conventional gas reservoirs, only a small portion of the total gas in place is technically recoverable from shale gas accumulations in prospective geological formations that meet the reservoir criteria. In the case of shale gas accumulations, the transition from GIP to technically recoverable resources is a very difficult and non-obvious task. This is the reason behind huge discrepancies between technically recoverable resource figures reported by various institutions which, in addition, apply different assessment methodologies.
Potential resources of the prospective lower Paleozoic shale formations in the belt stretching from Gdansk Pomerania (including the adjacent Baltic area) to the Lublin Region were assessed by PGI-NRI in its report of 2012. Total most probable recoverable gas resources were estimated at 0.35–0.77 tcm, while according to the USGS report of the same year the resources are lower by an order of magnitude. Interestingly enough, the two reports use the same methodology which is based on estimated ultimate recovery (EUR) from a well that drains a particular area of the prospective shale formation. A much smaller area of prospective shale formations and more conservative estimates of ultimate recovery per well were assumed in the report by USGS.
On the other hand, EIA/ARI reports of 2011 and 2013 are based on a totally different methodology. Instead of EUR per well, coefficients of resource recovery (e.g. 20% of the total technically recoverable resources), contingent on basin geology and reservoir conditions were applied. According to these reports, gas resources are higher by an order of magnitude (5.3 and 4.0 tcm, respectively) comparing to the PGI-NRI report. Nevertheless, the coefficients seem to be slightly too high, considering the geology of Poland. This, in addition to a much wider area taken into account (including basins in south and west Poland, which were not considered by PGI-NRI and USGS), may well explain these significant disparities.
Considering the above, the assessments of Poland's technically recoverable resources are still hypothetical, while the estimates of the PGI-NRI

Poland's shale basins considered in recoverable resource assessments by PGI-NRI in its report of 2012



Map of conventional and unconventional gas exploration and appraisal concessions (as of 1 October 2013, source: Ministry of the Environment)

report of 2012 seem to be the most credible and best documented ones.

Commercial reserves that can be recovered in a technically and economically viable way, in compliance with the laws and regulations including environmental requirements, are the top tiers of the pyramid. As of today, there is no reliable information on Poland's potential commercial shale gas reserves. Production tests delivered in hundred or more planned wells will be required to establish the areas in Poland's shale basins that are suitable for economically viable gas production. In addition, data coming from new wells will help to firm up the estimates of recoverable resources and GIP.

Concessions for exploration and appraisal of unconventional gas (and other hydrocarbon resources) cover today large expanses of the country. A comparison of the above concession map with the map of Poland's prospective shale basins, as assumed by PGI-NRI's report of 2012 for the purposes of recoverable resource assessment, reveals that the exploration area is much wider and includes potential shale oil occurrence areas (eastern Poland's offshore economic zone of the Baltic Sea, the area bordering on Russia, eastern Masovia and the Lublin Region close to the border with Ukraine), areas wherein lower Paleozoic formations probably fail to meet reservoir criteria, at least in light of available existing data (e.g. due to insufficient content and inadequate maturity of organic matter – PGI-NRI report of 2012, areas along both sides of the "golden" belt, as shown on Figure), as well as areas which have been little investigated so far for potential presence of unconventional gas accumulations (e.g. south and west Poland).

Accordingly, the map of concessions reflects the plans and expectations of those operators who have undertaken the risk of unconventional petroleum exploration. Only the results of exploration efforts will provide a clue to the prospectiveness of the areas under investigation.

Issues concerning present and future assessments of recoverable shale gas resources are discussed in paper by Kiersnowski, Dyrka, 2013.

A FEW WORDS ABOUT AUTHOR

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US AND EUROPEAN SHALE PLAYS

Marcin Janas, Ireneusz Dyrka

DICTIONARY

Sedimentary basin *– a natural earth crust depression in which the sediments are deposited*

Subsidence *– the process of sedimentary basin sinking (deepening)*

Shales are formed from fine clastic sediments deposited at the bottom of sedimentary basins (natural earth crust depressions). Throughout their geological history, individual basins had been located at different latitudes and longitudes, while shale-forming sediments were deposited in different geological periods under various climate conditions over millions of years. Sedimentary basins were formed by various mechanisms and differ in terms of subsidence rate and subsequent tectonic deformations.

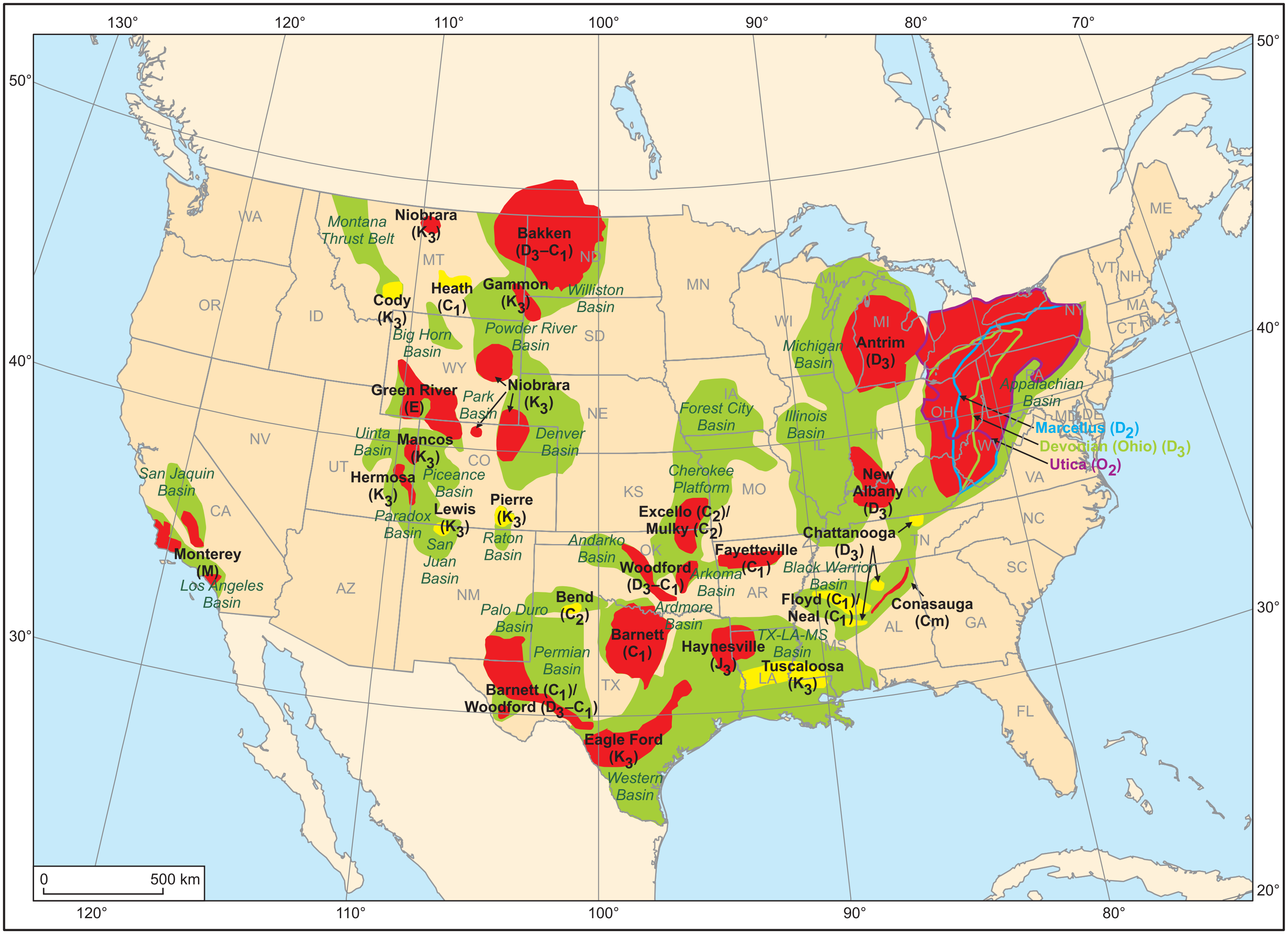
SHALE PLAYS IN THE UNITED STATES

The United States was the first country to start commercial shale gas production. Today, shale gas accounts for approximately 20% of the total gas production in the United States. According to estimates, the share of shale gas in total gas production will rise to approx. 50% by 2040. There are several tens of prospective shale formations located in various US sedimentary basins, of which six account for 88% of daily shale gas production. Haynessville, the most productive of them, is followed by Barnett, Marcellus, Fayettville, Eagle Ford and Woodford. The remaining formations account for 12% of the total shale gas production.

Fort Worth in Texas with its Barnett Formation is the best understood basin and the first one to produce shale gas. The Barnett Formation is represented by Lower Carboniferous shales rocks that occur at relatively small depths of 1980 to 2600 m. Their average thickness is in the order of 90 m, but increases to 200 m in the northeastern section of the basin. Organic matter content ranges from 3 to 12% TOC at an average thermal maturity of 1.6% *Ro* (vitrinite reflectance scale). The geological characteristics of the Barnett Formation are considered as model ones and are often used as benchmarks for other shale formations worldwide.

Recently, Upper Jurassic shales of the East Texas Basin's Haynesville Formation saw a rapid development of gas production which has increased dramatically over the past six years. Located at depths ranging from 3200 to 4100 m, this is one of the deepest US shale gas formations in the USA, but at the same time the most productive in the United States. Its average thickness is approximately 80 m, while organic matter content and thermal maturity are similar to those of Barnett Formation.

Middle Devonian Marcellus Formation of the Appalachian Basin is the third biggest shale play in the USA. At the same time, it is one of the shallowest formations as its depth ranges from 1200 to approximately 2400 in the eastern part of the basin. Marcellus beds are on average about 45 m thick. The formation is rich in organic matter: average TOC content is 4%



currently exploited shale formations

shale gas perspective area

sedimentary basins

Major sedimentary basins in the United States holding shale gas potential (after EIA, 2011b, modified)

Marcellus organic rich shale outcrop (Finck quarry near Elimsport, Pensylvania State, USA) (photo by I. Dyrka)

and ranges from 2 to 13%, at thermal maturity in the order of 1.5 *Ro*. Marcellus Formation in the Appalachian Basin is underlain by Utica, another prospective shale formation. The latter is considered as the most similar to the Polish Ordovician/Silurian shale formation. Utica is today the only US shale gas producing formation which, like its Polish counterparts, is of lower Paleozoic age. However, some Utica parameters diverge from those of Polish formations. Prospective dry gas-bearing complexes (on average about 150 m thick) occur at depths ranging from 2500 to 3800 m. Like Polish shale formation, Utica has a low content of organic matter: its average content is 1,3% TOC and thermal maturity does not exceed 1.6% *Ro*.

The Upper Cretaceous Eagle Ford Formation in South Texas is one of the youngest shale formations. The thickness of shale packages which occur at depths ranging from 1200 to 3050 m is between 30 and approx. 90 m, with maximum thicknesses reached in deeper central portions of the basin. Comparing to other "big six" plays, Eagle Ford is the lowest in organic matter (in the order of 2.7%). Thermal maturity is approx. 1.2% *Ro*. Like in the case of Poland's lower Paleozoic shale formations, there is a transition with increasing depth from the oil generation window to wet gas and finally to the dry gas window.

Devonian Woodford Formation in the Arkoma Basin (Southeast Oklahoma) is the sixth most productive shale gas play in the USA. Formation's depths range from 1820 to 3960 m and its average thickness is approx. 45 m. Its organic matter content is the highest among all US plays (about 5% on average) and thermal maturity is in the order of 1.5% *Ro*.

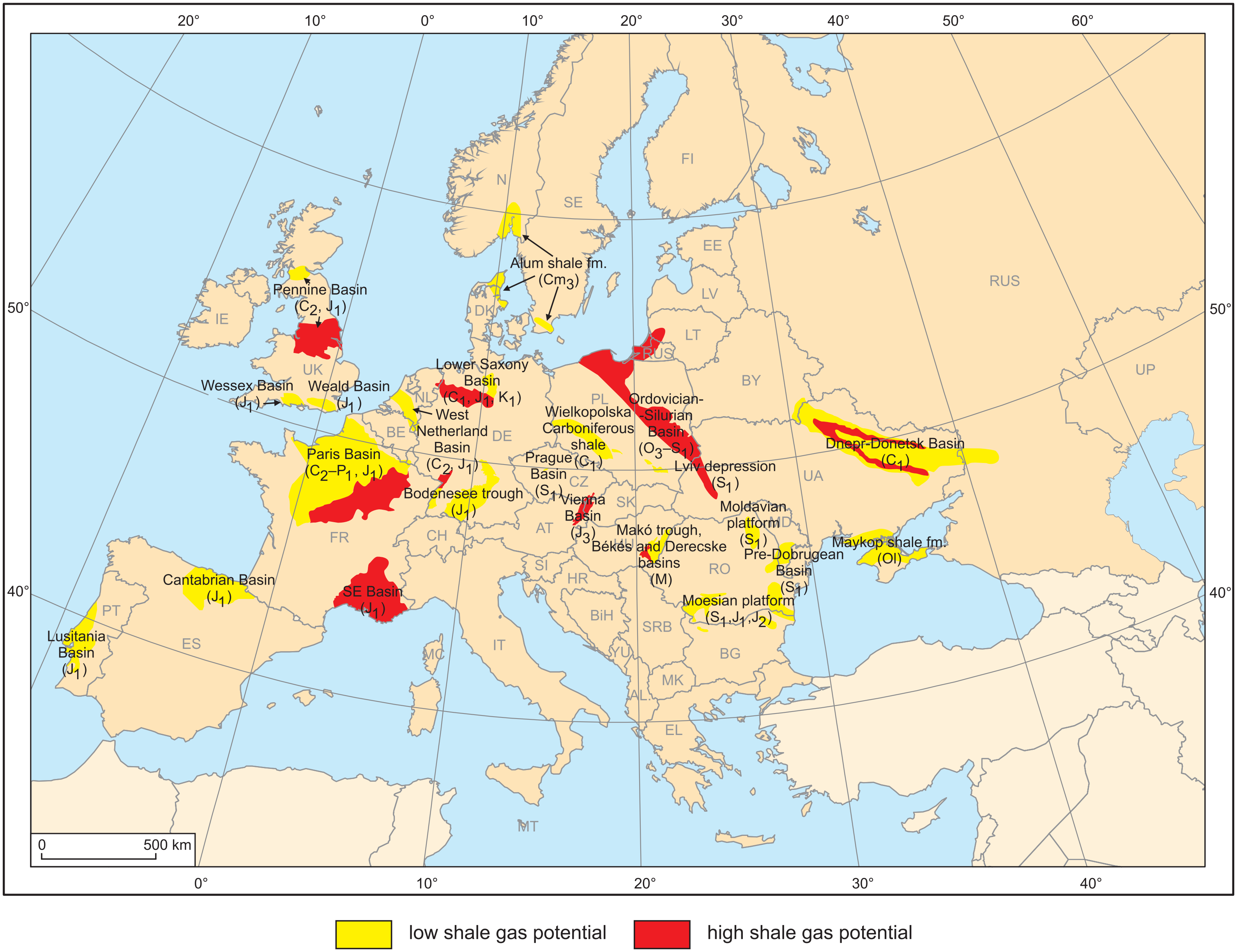
Extensive exploration works with rapidly increasing production are underway in shale formations other than the "big six" plays, for example in Bakken (shale oil), Antrim, Lewis and Utica. Low gas prices in the United States are an incentive to the drilling operations and help make the country independent of gas imports. This is just the opposite of Poland's current situation.

SHALE PLAYS IN EUROPE

Following the US gas production success story, geologists have identified within European basins a number of dark shale formations with a potential for shale gas accumulations.

The oldest European shales which have potentional for unconventional oil and gas exploration are the so-called alum shale rocks (Upper Cambrian–Lower Ordovician). They are found in Sweden, Denmark, Norway and, to a limited extent, in Poland and Estonia. In South Sweden, alum shales occur at relatively low depths (down to 1500 m) and their thickness is in the order of 100 m. Due to a very high content of organic matter (up to 20% TOC) and thermal maturities indicating a late gas window they were until recently considered excellent exploration prospects. Unfortunately, a too low shale saturation with gas was found in three wells drilled out in the region of Scania. Despite the unsuccessful exploration in Sweden it is still planned to investigate prospectiveness of the alum shales in Denmark's North Jutland and North Zealand where these rocks are found much deeper.

Like in Poland, lower Paleozoic shales of the Silurian Basin at the western slope of the East European Craton are exploration targets in South Lithuania, West Ukraine, Romania, North Bulgaria and South Moldova. In Lithuania, Silurian shales, which are though to be in oil window, occur at depths to 1000 m. They are believed to be source rocks for small oil deposits discovered in Central Lithuania. In Ukraine, Silurian shales occur at depths ranging from 1000 to 5000 m in the Lviv Depression, an extension of the structures found in the Lublin Region (Poland). Moreover, potential unconventional hydrocarbon accumulations are being explored in the Dnieper-Donetsk Carboniferous Basin (East Ukraine) and in the Maykop Oligocene Shale Formation in the south. In Romania, exploration efforts focus on the Moesian and Moldavian Platforms where the Silurian Tandarei and Jurassic Bals shale formations are considered as potential targets. In Bulgaria, the prospective Silurian and Jurassic shale



Major sedimentary basins in Europe holding shale gas potential (Compilation based on: Szalay & Koncz, 1993; Poprawa, 2010; Schulz *et al.*, 2010; EIA, 2011a; BGR, 2012; Krezsk *et al.*, 2012; Kurovets & Koltun, 2012; Sachsenhofer & Koltun, 2012; Velicu & Popescu, 2012)

formations are present in the southern part of Moesian Platform, while in Moldova prospective Silurian shales occur within the so-called Pre-Dobrogean Basin.

Lower Paleozoic (Ordovician/Silurian) shales of the Prague Basin (Czech Republic) are believed to hold gas potential. They are thick and contain a lot of dispersed organic matter, but the lack of adequate thermal maturity, as required for triggering the gas generation processes, is a potential limitation.

In Northwest Germany, potential unconventional hydrocarbon accumulations are located in Carboniferous, Jurassic and Cretaceous formations of the Lower Saxony Basin which also stretches across Belgium and the Netherlands. Lower Jurassic Posidonia shales which occur at a depth of approx. 3000 m and are 15 to 30 m thick, seem to be the best exploration prospects. *Posidonia* shales contains on average 8% TOC which over an extensive area is in the oil window. Moreover, prospective *Posidonia* shales are found in the Bodensee Trough (Southwest Germany). Equally important though less prospective are Wealden (Lower Cretaceous) shales. They are rich in organic matter and up to 700 m thick in the central portion of the basin.

A complex geology of the West Netherlands Basin includes Geverik and Epen (Carboniferous), as well as Posidonia (Lower Jurassic) shale formations which are considered as potential prospects for the production of unconventional hydrocarbons. The depth of the Geverik shale formation ranges from 1500 to 5000 m and its thermal maturity indicate that they are entirely in the gas window (1.0–1.3% *Ro*), while the younger Epen shale formation is found at depths ranging from 1000 to 5000 m and its thermal maturity ranges from 0.7 to 1.0% *Ro*. On average, organic matter content in Geverik and Epen shales is not in excess of 4% TOC. *Posidonia* shales that cover the Carboniferous rocks in the West Netherlands Basin contain on average 6% TOC and occur at depths ranging from approx. 1000 to 3600 m. Over an extensive area the shales are in the oil window (0.7–1.0% *Ro*), but locally they reach the gas window (1.0-1.3% *Ro*).

There are two shale gas and oil exploration regions in the United Kingdom: the northern region with Carboniferous shale of the Pennine Basin as exploration target, and the southern regions with Lower Jurassic shale of the Wessex and Weald Basins. In the Pennine Basin, shales are thickest in structural depressions, while intervals rich in gas generating organic matter are sometimes several hundred meter thick. Average organic matter content is approx. 2–5% TOC and its thermal maturity is equal to approx. 1.2% *Ro*. Wessex and Weald shales occur at depths ranging from 1000 to 2100 m. They are rich in oil-prone organic matter with thermal maturity of approx. 0.8% *Ro* and considered as a source of the local conventional oil deposits. A complicated geology of shale basins in the UK adds to the difficulty and risk of exploration.

The Paris Basin and the Southeast Basin in France are likely to contain significant shale oil and gas resources. Permian/Carboniferous shale, sands and coals are the potential gas- and oil-bearing rocks in the Paris Basin, along with Lower Jurassic shales. Paris Basin's rocks are most probably in the oil window and it is reasonable to assume that they are saturated with shale oil. In the Southeast Basin, Lower Jurassic shales that occur at depths ranging from 1000 to 4900 m are the richest in organic matter (TOC content approx. 2% on average). Since their thermal maturity is high and ranges from 1.3 to over 1.7% *Ro*, they are expected to contain the shale gas.

In Austria, unconventional gas resources are likely to occur in the Vienna Basin. The Upper Jurassic rocks of the Mikulov Formation, from which numerous oil and gas shows have been reported, are the most prospective formation. They have a high content of organic matter (from 0.2 to 10% TOC) and thermal maturity is in the gas window (1.6% *Ro* on average). Unfortunately, the Mikulov Formation occurs at depths ranging from 7000 to 8000 m, which makes it a tough exploration target.

In Hungary, exploration for unconventional resources focuses on the Pannonian Basin or more precisely on the Makó Trough along with Békés and Derecske Basins. Endrőd Formation, hitherto believed to be the source of oil and gas supply to conventional deposits, is considered to be the most prospective one. Nevertheless, tight gas reservoirs, such as the Miocene sandstone/claystone Szolnok Formation, are now considered as even more prospective exploration targets.

In the Iberian Peninsula, shale gas exploration is still at an initial stage. The region of Cantabria in the north of Spain is a potential exploration target where gas is expected to occur in interbedding shale, marl and Jurassic limestone beds. In Portugal, unconventional hydrocarbons may occur in the Lower Jurassic shales of the Lusitanian Basin which are counted among the most important source rocks of that basin.

A brief overview of specific US and European basins clearly reveals more differences than similarities between each other. Therefore, comparative studies are an extremely difficult task. Finding two basins that share similar characteristics does not necessarily mean that both of them will produce shale gas or shale oil.

Marcin Janas

A petroleum geologist, graduated from AGH University of Science and Technology in Cracow. At Polish Geological Institute-NRI he is involved in studies on petroleum geochemistry. His responsibilities include petroleum system analysis, petrology of dispersed organic matter and the determination of prospective shale gas and oil areas.

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A petroleum geologist, he graduated from AGH University of Science and Technology in Cracow. At Polish Geological Institute-NRI he specializes in petroleum system and processes characterization, as well as in seismic data interpretation. Currently involved in projects related to the assessment of resources and the determination of prospective shale gas zones in Poland and on analysis of geological data from the areas that are covered by the concessions for exploration and appraisal of unconventional hydrocarbon resources.

ORGANIC MATTER IN GAS-BEARING SHALES

scientific editor: Hubert Kiersnowski

CHAPTER

5

CONTENT AND ORIGIN OF ORGANIC MATTER IN BLACK SHALES

Przemysław Karcz

Since shale rocks may be simultaneously source and reservoir rock for the hydrocarbons, it is important to determine petroleum characteristics of shale rocks, i.e. their capacity to generate, retain or expulsion of hydrocarbons or, in other words, to investigate the properties of petroleum systems.

Investigations of oil- and gas-bearing shale rocks fall into three groups of analytical attitudes: 1 – investigation of depositional environment where organic matter-rich sediments accumulate; 2 – investigation of organic matter origin with the determination its thermal maturity; and 3 – the determination of the time and space of hydrocarbon generation and expulsion, as well as of the volume and type of generated hydrocarbons.

Investigation of oxygen conditions prevailing at the sea bottom during deposition is the key objective of studies on the origin of shale rocks. Other important topics are: investigation of organic matter accumulation zone and of the degree of organic matter transformation; the determination of the relative share of marine and terrigenous organic matter; and studies on the contribution of upwelling currents to the formation of shale rocks. Tools for the determination of these environmental characteristics include sulphur isotopes and the studies of biomarkers, i.e. organic compounds, of which organic compounds found in living organisms are the precursors, that have preserved an unchanged or only slightly modified carbon skeleton of its biological precursor. Moreover, the analysis of the relationship between TOC and pyritic sulphur may also be helpful.

In addition to standard Rock Eval pyrolysis, optical microscope and biomarker examination methods, a study of the origin and thermal maturity of organic matter should include an analysis of stable organic carbon and nitrogen isotopes, organic matter studies for its chemical composition and the content of extractable organic matter.

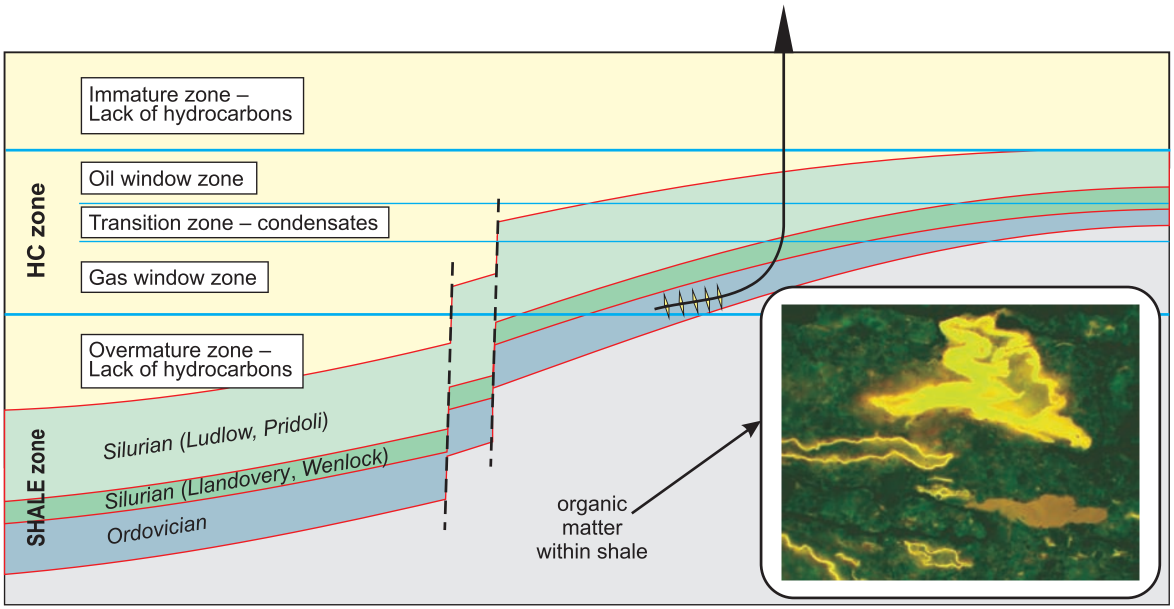
Combined techniques, such as for example Rock Eval combined with fluorescence, pyritic sulphur or extractable organic matter, are applied to establish space and time of hydrocarbon generation. Oil and source rocks can be correlated by the studies on stable carbon isotopes contained in saturated and aromatic hydrocarbons, while Lopatin diagram enables an interpretation of the source rock burial history, as well as of the time and depth of hydrocarbon generation.

ORGANIC MATTER CONTENT IN SHALE ROCKS

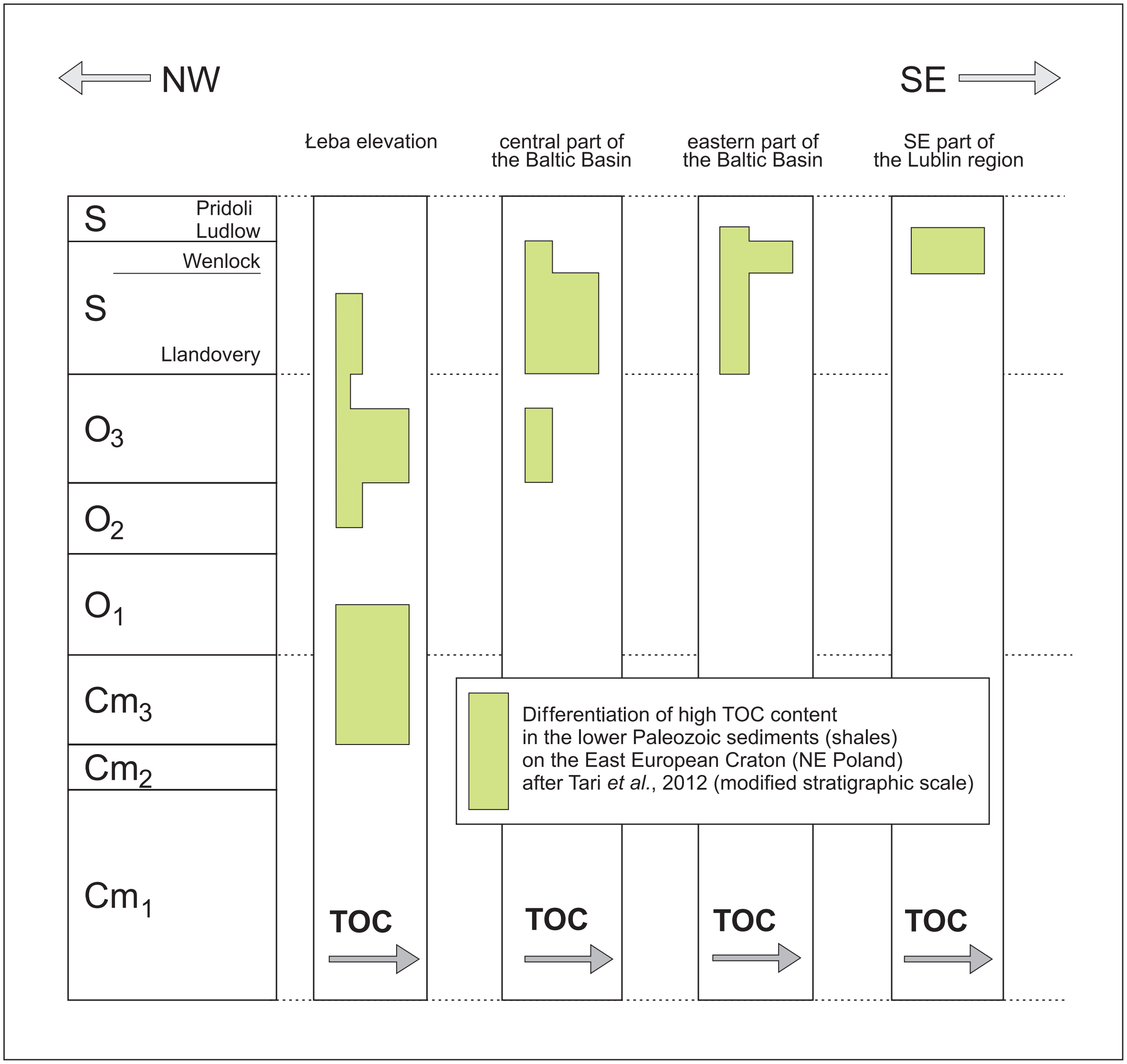
Organic matter and organic carbon are the key terms that are used to describe the shale rock characteristics.

Organic matter is primarily defined as organic compounds that are directly or indirectly derived from cells or tissues of living organisms. In the case of shale rocks, these are mostly phytoplankton organisms, while in the case of other energy resources, such as coal, organic matter is composed predominantly of terrigenous material derived from trees, shrubs, ferns or leaves. Mineral skeleton parts, like bone fragments or shells, are not attributed to organic matter. The content of organic matter is expressed as percentage share of the Total Organic Carbon (TOC) in the rock. It is generally assumed that in order for a shale rock to be the target of basic tests made by petroleum geologists, its TOC content should be higher than 1 wt% and preferably in the order of 2% or higher, like Devonian/Carboniferous New Albany Shale rocks of South Indiana (USA) or Lower Jurassic Yorkshire shales (UK). TOC content in Polish Ordovician/Silurian shale rocks are only occasionally in excess of 2%.

Organic matter present in the shale rocks has been locally (autochtonously) produced as a result of massive algae blooms that occur in surface waters of the seas and oceans in which the autotrophs (such as bacteria and algae) rely on the process of photosynthesis. During that process, autotrophic organisms transform the dissolved inorganic carbon and nutrients into organic matter. Any phytoplankton bloom is contingent on the supply of nutrients, of which distribution across the oceanic environment is very uneven and dependent mostly on the course of sea currents and the presence of river mouths that are the main sources of organic run--off from land. Accordingly, shale rocks having the highest organic matter content are formed in shallow shelf seas in the proximity of extensive river delta systems.



Scheme showing particular zones of hydrocarbon occurrence depending on the burial of shale rocks



Variability of the high TOC content in lower Paleozoic sediments (shales) of the East European Craton (NE Poland), modified stratigraphic scale. PGI-NRI Report, 2012

Once organic matter settles at the sea bottom, it enters the benthic food chain as its main component. Organic matter consumption occurs mostly on the top of sediments where the organisms that feed on organic matter dwell. There is an evidence that even beneath relatively productive waters as much as 98% of the organic matter contained in surficial sediments is decomposed as a result of burrowing organisms and their feeding activity. The activity of such organisms is controlled by the availability of oxygen in the sea bottom environment. As soon as the bottom is getting depleted in oxygen, benthic organisms move to a better oxygenated environment. A further decrease in oxygen content at the bottom is increasing the chance for preservation of organic matter accumulated in bottom sediments in the absence of benthic fauna and aerobic decomposing organisms. A small portion of organic matter that has survived destruction has a chance for preservation in deeper parts of the sediment column and may enter the geological carbon cycle. It may, under specific conditions, contribute to the generation of hydrocarbons and formation of oil or gas deposits.

As already mentioned above, the evaluation of organic matter content is a key stage of shale rock studies. Fairly sophisticated investigation tools are used to determine the TOC content. Rock Eval pyrolysis is the most frequently used method which provides information about the content, origin and maturity of organic matter in the rock. In short, the method involves thermal decomposition of a fragmented rock sample (~100 milligrams) in a furnace in the atmosphere of nitrogen gas. The sample is progressively heated to 850°C using a programmable temperature controller. During the pyrolysis, the volume of the so-called volatile hydrocarbons, released at temperatures below 350°C, is expressed as S1 parameter. A further thermal decomposition of the sample at temperatures up to 650°C involves pyrolysis of more durable organic matter fractions and again releases hydrocarbons along with carbon dioxide and oxide from the decomposition of organic and mineral matter, as well as of non-pyrolisable organic matter. The results are expressed as parameters S2, S3 and S4, respectively. Carbon dioxide is released from carbonates at 850°C (S5 parameter). The results are recalculated and expressed as the contents of pyrolisable, non-pyrolisable and total organic carbon (TOC), as well as mineral carbon content. In addition to TOC, pyrolytic analysis allows for the determination of other parameters that help to assess the type of organic matter, its thermal maturity and origin, alongside the properties that are used in oil and gas exploration. The so-called maximum temperature, which indicates the stage of maturation of the organic matter, is an important parameter, along with hydrogen and oxygen indexes that characterize the type and origin of organic matter contained in the rock.

Rock Eval pyrolysis apparatus located in Geochemistry Lab, Polish Geological Institute in Warsaw (photo by P. Karcz)

Potentially the most prospective oil and gas shale formations are located in Poland within three sedimentary basins: Baltic, Podlasie and Lublin Basin. All of them represent Ordovician/Silurian stratigraphic intervals. TOC contents are highly variable in the Baltic Basin and range from 0.5 to 11.0 wt%, which indicates co-occurrence of organic-rich and -poor shale rocks.

The highest TOC contents have been reported from Ordovician and Silurian formations focused in the Bay of Gdansk. In the Podlasie Basin organic matter content range from low (0.6%) to very high values (20.0%), whilst in the southeasternmost part of Poland i.e. in the Lublin Basin the TOC values oscillate between 0.5 and 4.5 wt%.

A FEW WORDS ABOUT AUTHOR

Przemysław Karcz

A geologist, he received his PhD degree in geochemistry of the black shales from the Institute of Geological Sciences, Polish Academy of Sciences. His research interests at Polish Geological Institute-NRI include reservoir characterization with particular emphasis on geochemistry and petrophysics. Currently, his focus is on the study of shale-gas mudrocks.

THERMAL MATURITY OF ORGANIC MATTER

Izabella Grotek, Marcin Janas

Crude oil and natural gas are formed out of the so-called source rocks which contain a required quantity of organic matter. Shale rock is the best example of a source rock. In order for crude oil, biogenic or thermogenic gas to be generated, the organic matter contained in the shale rock must be first processed by specific groups of bacteria or buried deep enough and heated so as to reach thermal maturity that is required for generation of crude oil and thermogenic gas.

First of all, thermal maturity denotes diagenetic changes of organic matter that is contained in source rocks which generate crude oil and natural gas – from the immature phase through the main phase of oil and gas generation to the post-maturity phase.

Temperature, time and pressure are the drivers of organic matter transformation. As a result of their action, mobile products (gasses and liquid hydrocarbons) are released from the biomass at an increasing concentration of stable organic components. In subsequent maturing (diagenesis) phases the aforementioned components loose their functional groups with oxygen, sulfur and nitrogen, while being enriched in carbon. These processes change the optical properties of organic matter.

The degree of thermal maturity depends primarily on the top paleotemperature, as applied to the rocks in their geological history, and on the time of exposure to that temperature. Maturity increases with burial depth due to higher temperatures that prevail in deeper parts of the earth's crust. The increase is closely related to the geothermal gradient which is usually expressed as °C/km. The effect of pressure on thermal maturity of organic matter is small, as pressure retards the chemical reactions that are involved in maturation processes, albeit it obviously affects the physical properties, such as porosity and structural layout of particles.

Diagenetic processes that have occurred in the lower Paleozoic organic matter can be recreated using different methods, including CAI (Conodont Colour Alteration Index), characterization of volatile organic compounds, elemental analysis of carbon, Rock Eval pyrolysis, chromatography, isotopic method or smectite to illite transformation. Nevertheless, white or UV light reflection microscopy is still one of the simplest and most accurate methods.

A sample examined under reflected UV light microscope reveals a decreasing intensity of fluorescent colours of primary macerals belonging to the liptinite group (e.g. alginite, bitumenite), up to the colour disappearance point. The primary material is transformed into secondary non-fluorescent components (e.g. stable bitumens). These diagenetic changes in organic matter normally occur at a depth of approximately 3000 m. In reflected white light, they are revealed by a higher reflectance (a brighter colour) of organic macerals, up to the point of bireflectance (anisotropy) of vitrinite macerals

DICTIONARY

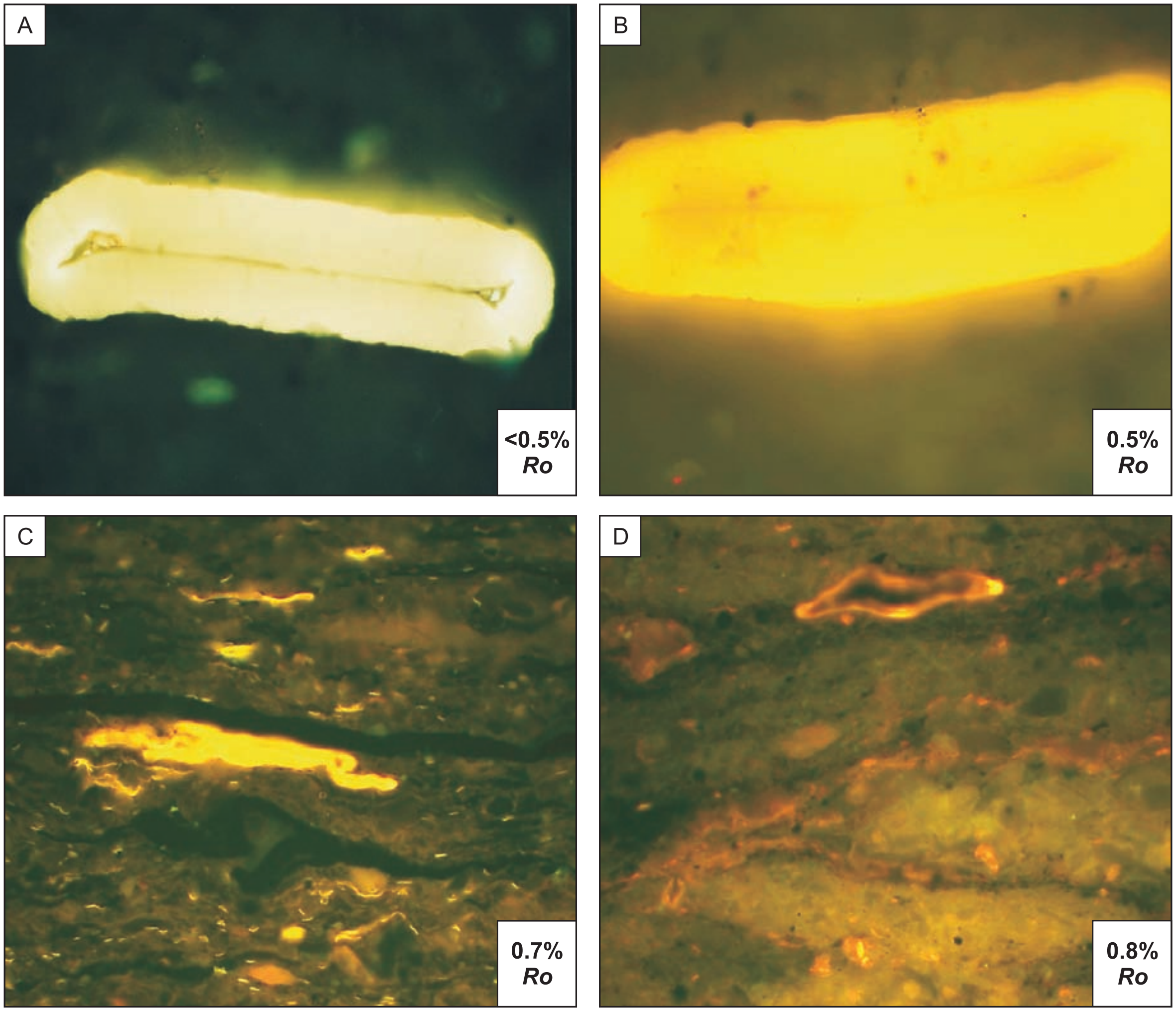
Organic matter *– organic compounds that are directly or indirectly derived from the cells and tissues of living plant and animal organisms*

TOC *(Total Organic Carbon) – total content of organic carbon expressed as percentage by weight*

Conodonts *– an extinct Chordata phylum. Built of calcium phosphate conodont fossils are found in the form of tiny tooth-like skeleton structures*

Smectite illitization *– the process of diagenetic transformation of smectite into illite, another clay mineral, with increasing depth. Changes in illite to smectite ratio are used to determine the degree of organic matter thermal maturity.*

Maceral *– an elementary non-crystalline component of fossil coals, formed as a result of plant material carbonization. In reference to coal, maceral is analogous to minerals in rocks. Macerals broadly fall into vitrinite, liptinite and inertinite groups*



Lower Paleozoic organic matter at different thermal alteration stages, as seen in UV light (photo by I. Grotek)
A – immature phase, **B** – early oil window phase, **C** – oil window phase, **D** – oil window phase

DICTIONARY

Bitumen – *mineral substances of organic origin found in various sedimentary rocks, composed predominantly of hydrocarbons*

Immersion – *filling of the space between specimen and the first lens of the microscope with a translucent fluid in order to enhance image brightness and resolution of the microscope*

Autigenic components – *basic components of sedimentary rocks and of the clastic rock cement, formed at or beyond the rock formation stage*

and vitrinite-like components (e.g. stable bitumens).

Different plant parts or other organic remains vary in terms of susceptibility to the action of physical or chemical agents. Lignin and cellulose are the most stable biomass constituents and initial components of the vitrinite group.

Reflectance of the vitrinite or, in its absence (as for example in the lower Paleozoic sediments), of a vitrinite-like material (such as stable bitumens) is a measurable microscopic parameter that defines the degree of diagenetic alteration. Vitrinite maceral reflectance is increasing with thermal maturity. Reflectance values determine the different stages of diagenetic alteration and hydrocarbon generation phases.

Reflectance of autigenic vitrinite or of an optically vitrinite-like material is measured using oil-immersion lenses obejctives and polished thin sections of the rock. Reflectance of these components increases linearly with increasing thermal maturity and the measured reflectance index value (expressed as % *Ro*) reflects a specific range of temperatures the sediments had been exposed to in their geological history.

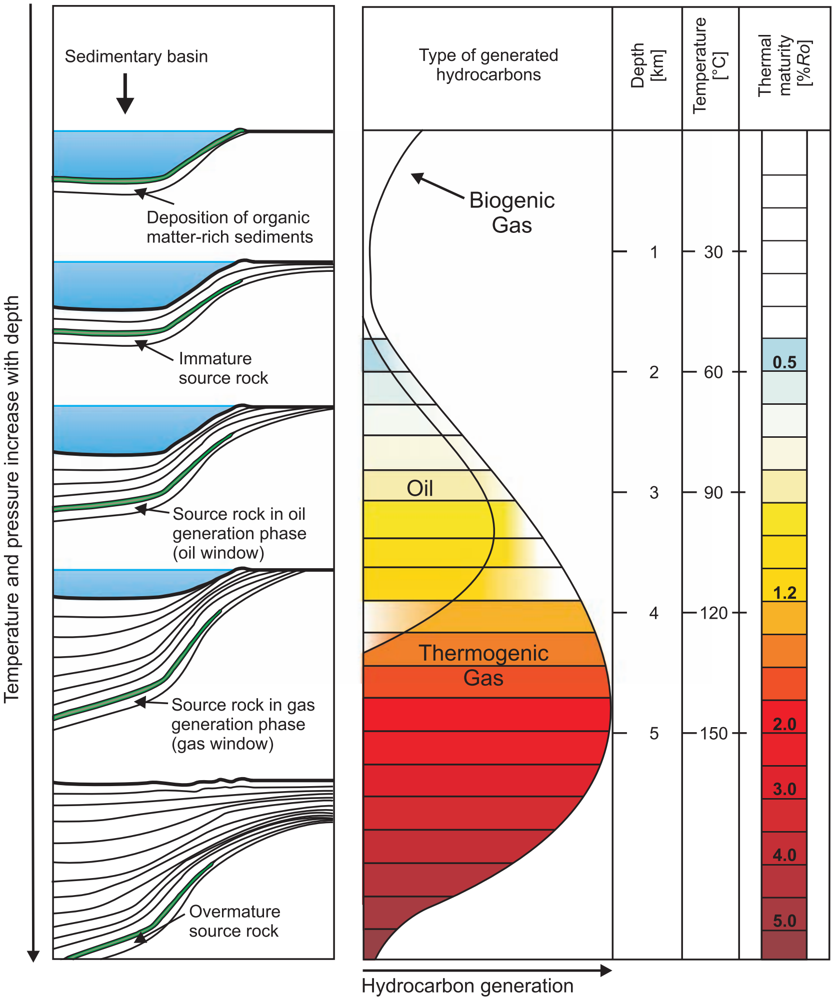
HOW THERMAL MATURITY OF ORGANIC MATTER AFFECTS SHALE OIL AND GAS EXPLORATION?

Based on thermal maturity values, source rocks are categorized as thermally immature, mature or post-mature rocks in terms of capability to generate hydrocarbons.

Immature (i.e. thermally unaltered) source rocks, that are still at relatively low depths, may generate (biogenic) natural gas which is formed by certain bacteria species as a result of their metabolic activity. Normally, these processes occur at temperatures below 50°C, and the degree of organic matter alteration, as expressed by reflectance index, is not in excess of 0.5% *Ro*. Conventional biogenic gas fields have been exploited for many years in the Carpathian Foredeep (Southeastern Poland).

As the source rock is buried, for example under an increasingly thicker overburden, the processes of bacterial organic matter alteration subside, while temperatures and pressures of the rock increase and gradually trigger chemical changes that lead to the generation of oil and smaller quantities of natural gas. A rock which had been heated so as to generate crude oil is called mature rock in the oil generation phase or in the so-called "oil window", and its alteration degree, expressed as vitrinite reflectance index, ranges from 0.5 to 1.2% *Ro*. If buried deeper, the source rock will generate mostly (thermogenic) natural gas. Accordingly, a mix of the previously generated oil and of the "newly generated" natural gas (the so-called condensate) is expected to occur in the rock.

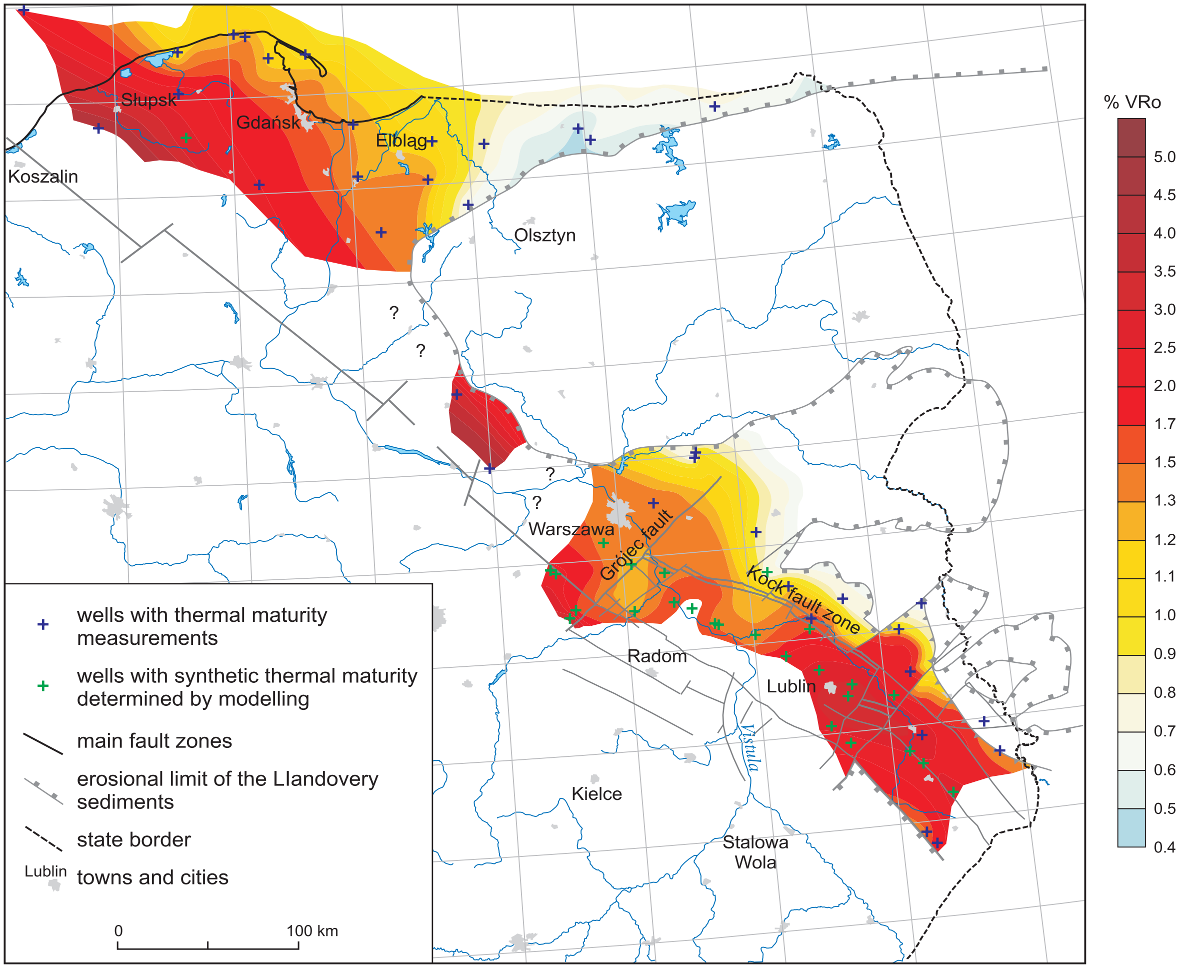
If the rock medium is even deeper buried, organic matter will generate (thermogenic) natural gas only. Moreover, any oil previously accumulated in the rock will be transformed into (thermogenic) natural gas. This degree of thermal alteration called the "gas window" occurs at temperatures



A simplified diagram illustrating hydrocarbon generative phases versus increasing burial depth and temperature (after Bjørlykke (1989), modified)

DICTIONARY

Biogenic (bacterial) natural gas *– natural gas generated at a low depth and temperature as a result of organic matter decomposition with a bacterial involvement*



Map of thermal maturity expressed as vitrinite reflectance index. Llandovery (Silurian) rocks from the western slope of the East European Craton

DICTIONARY

Thermogenic natural gas *– natural gas generated at very big depths under high temperature and pressure conditions*

in the order of 120–150°C and is expressed by reflectance index values ranging from approx. 1.2 to 2.0% *Ro*. The process will continue until alteration processes reach the degree at which the source rock becomes overmature and its hydrocarbon generative potential is exhausted (>3.0% *Ro*). This occurs at temperatures in excess of 200°C.

It should be noted that the oil and gas generation cycle, as presented above, is much simplified, and petroleum basins vary in terms of hydrocarbon generation conditions. In fact, each basin has its specific thermodynamical conditions, different type of organic matter distributed within the rocks, different rock-building minerals, different burial rates and several other factors.

Thermal maturity is a key parameter for the determination of potentially prospective shale oil and gas accumulations at initial stages of exploration.

ARE POLISH SHALE ROCKS MATURE?

Organic matter contained in lower Paleozoic rocks of the East European Craton is highly variable in terms of thermal maturity which encompasses a full range of hydrocarbon generation conditions.

Shale sediments of the eastern Baltic Syneclize (NE Poland) are the least altered rocks. They contain immature organic matter which is at an early liquid hydrocarbon generation stage. Thermal maturities of lower Paleozoic sediments markedly increase towards the marginal zone of the East European Craton. In top Silurian intervals of NE Poland they reach the main and late oil generation phases. In the central and marginal SE zone of the Craton, top Silurian formations are in the main gas window. Moreover, thermal maturities of the shale rocks tend to increase with burial depth. Bottom Silurian beds in the marginal portion of the Craton in NW Poland and the lowest penetrated Silurian beds in SE marginal area of the Craton contain organic matter in the main gas window or, locally, at the post-maturity stage.

It should be noted at this point that local positive thermal anomalies have been reported from NW and SE Poland'.

A FEW WORDS ABOUT AUTHORS

Izabella Grotek

A geologist, PhD, graduated from the Faculty of Geology, Warsaw University, with mineralogy and mineralogy as majors. Her responsibilities at Polish Geological Institute-NRI include microscopy studies on organic matter from Neogene sedimentary rocks to determine its thermal maturity and origin. The results of her studies will be used in exploration of potential oil and gas source rocks.

Marcin Janas

A petroleum geologist, graduated from AGH University of Science and Technology in Cracow. At Polish Geological Institute-NRI he is involved in studies on petroleum geochemistry. His responsibilities include petroleum system analysis, petrology of dispersed organic matter and the determination of prospective shale gas and oil areas.

SHALE GAS EXPLORATION AND EXTRACTION METHODS

scientific editor: Hubert Kiersnowski

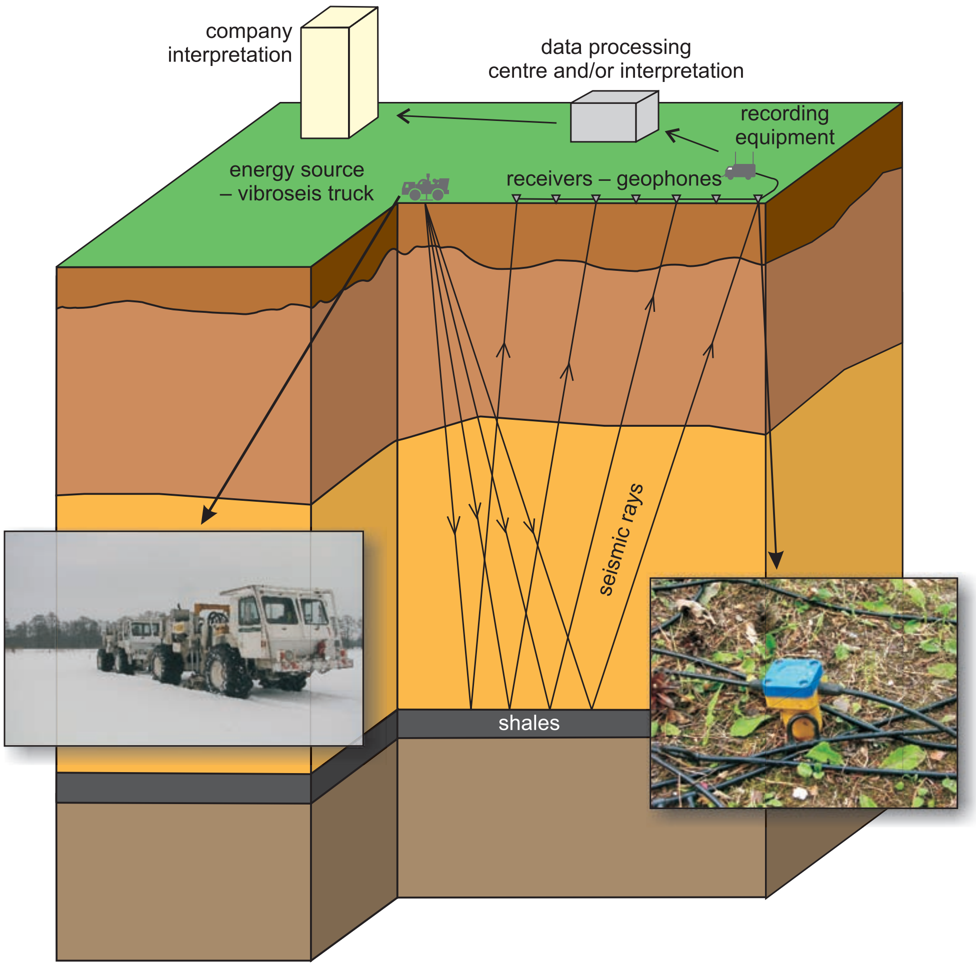
Photo by Geofizyka Toruń

CHAPTER 6

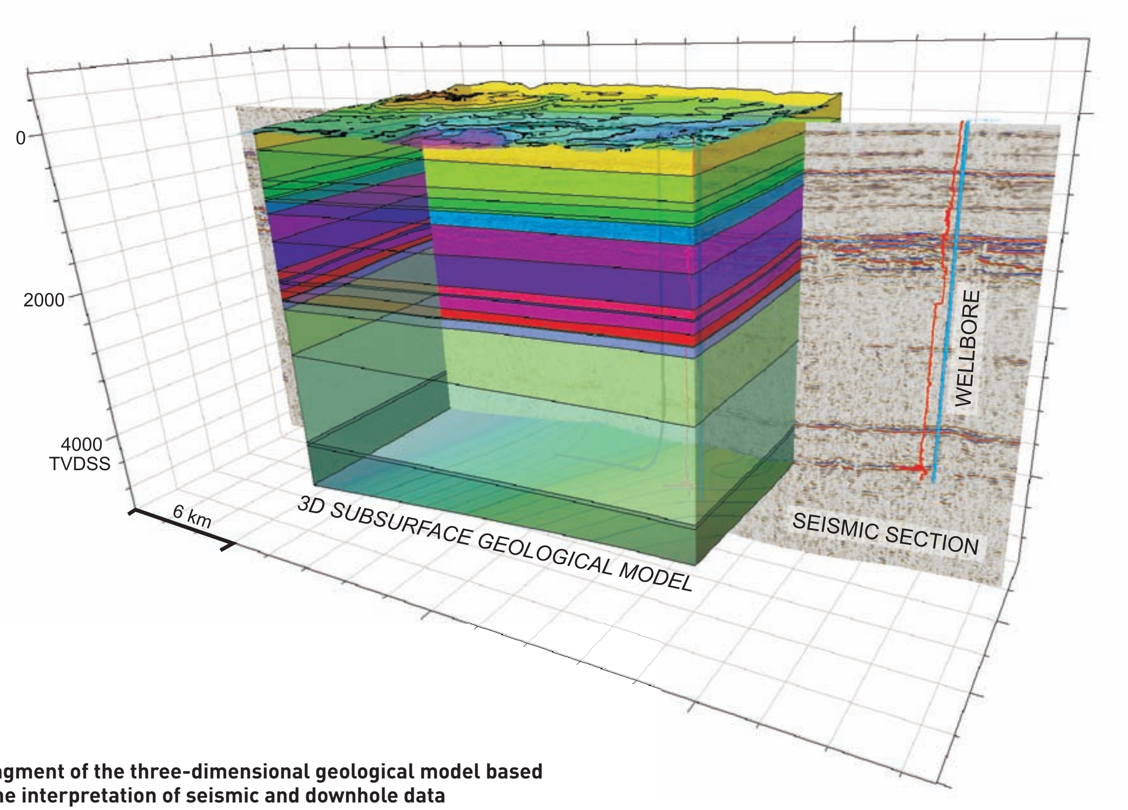
SEISMIC ANALYSIS

Andrzej Głuszyński, Sylwia Kijewska

Recent IT developments have also found their way to the upstream industry. Computer software used in the studies of deep geologic structures offers a number of capabilities, including integration and interpretation of geological and geophysical data (logging, seismic, micro-seismic data, laboratory tests/measurements of core samples, etc.) and their incorporation into three-dimensional models of geologic structure Digital models are built of a network of small



Seismic measurements and the flow of acquired data (photo by S. Kijewska and A. Głuszyński)



A fragment of the three-dimensional geological model based on the interpretation of seismic and downhole data

three-dimensional cells. Each of them contains information on specific rock properties, such as rock type, porosity, permeability, gas content, fracturability, etc. Moreover, structural data such as faults or joints are presented in digital three-dimensional space.

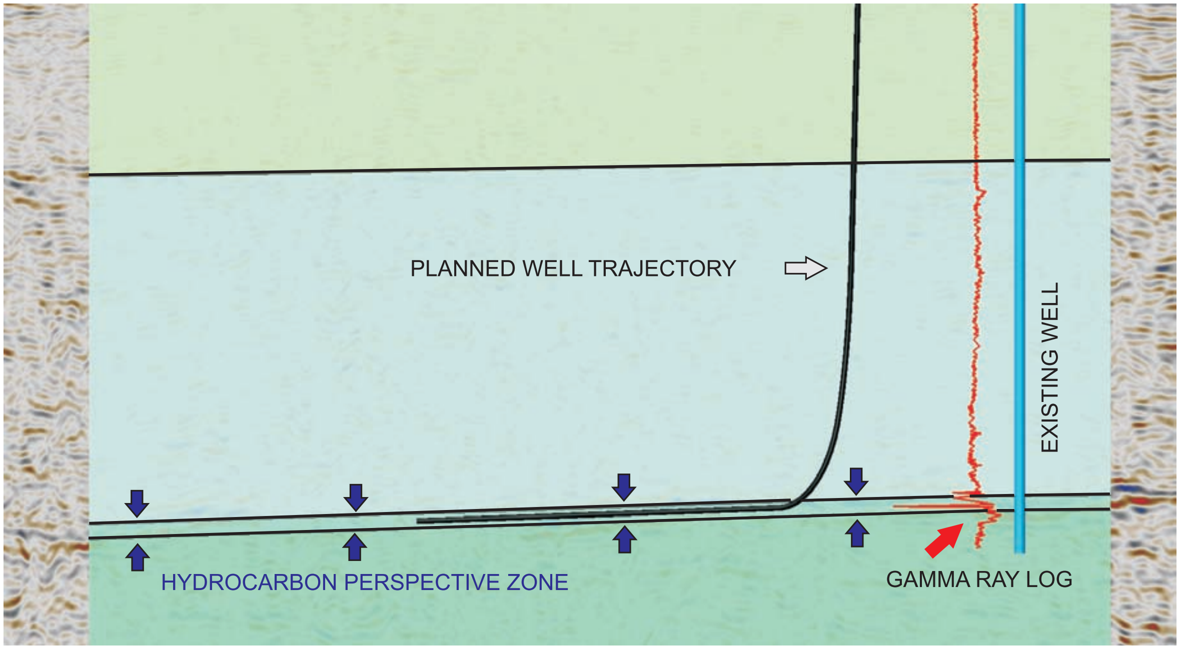
Representation of geological structure in the form of geological models is helpful in choosing economically prospective drilling locations assessment of resources or production planning, etc. As new information is available (from new wells or seismic tests) digital geological models are updated and firmed up so as to enable a more efficient exploration for hydrocarbon accumulations.

Seismic tests are essential for understanding the geology of sedimentary basins, including the shale formations. The tests involve generation of seismic (elastic) waves which propagate into the ground and recording their return to the surface Seismic waves are today generated usually by special vehicle-mounted mechanical devices (called vibrators) which generate small vibrations in the ground. Throughout its travel into the ground, a seismic wave is reflected by rock boundaries that are of a different density and elastic wave propagation velocity. The wave, deflected and partly reflected at these boundaries, returns to the ground surface. Special sensors that are called geophones receive the signal and transmit it to the registration unit. Seismic tests allow for imaging the deep geologic structure and for correlation of individual boreholes. At the same time they are almost neutral to the environment.

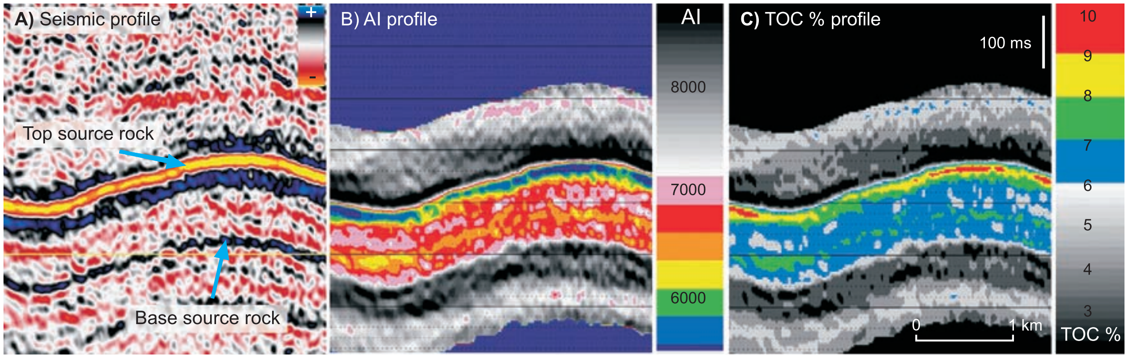
2D and 3D seismic surveys are most often used in shale gas exploration. A 2D seismic profile represents a "slice" of the earth and provides an image of the structure solely along the seismic line, while 3D seismic provides a three-dimensional set of seismic data. The advent of 3D seismic transformed the exploration industry by enabling a much more detailed image of the geological structure comparing with 2D surveys. On the other hand, shooting and interpretation of 3D seismic are more costly and time consuming projects.

In addition to three-dimensional geological models, also four-dimensional ones are built with time as the fourth dimension. The latter models provide a better insight into the processes of hydrocarbon reservoir formation. Four-dimensional models recreate the development of geological structure from the point of sediment deposition to the present day. In the case of Poland's prospective shale formations, the timeline of the model may cover more than 400 million years. Other 4D models cover a much shorter span of time, for example the period of a few years. Usually, they cover the period that follows the commencement of production: by comparing seismic and borehole data collected before the commencement of production with those measured after a certain period of production, 4D models provide an insight into the changes that have occurred in the rock formation.

Integration of information provided by other methods is required in order to perform a detailed analysis of seismic data. This makes it possible to assess a number of critical formation parameters, such as the type and thickness of the rocks, depth to reservoir, presence of faults, etc. Moreover, it helps to assess rock fractur-



Geological model-derived cross-section made for the purposes of horizontal well trajectory planning



A – seismic section
B – acoustic impedance inverted seismic section
C – inverted seismic section, where source rock interval is converted to TOC %

Seismic surveys (Løseth *et al*., 2011)

ability, estimate the directions and extension of induced fractures, assess TOC contents, etc.
Correlation of time-scale seismic data with depth-scale borehole data is the first step of the interpretation. This is done using a synthetic seismogram or vertical seismic profiling (VSP).
The next steps of interpretation include:

- **structural interpretation**: image analysis for the detection of structures such as anticlines or faults, based on the layout of seismic boundaries,
- **seismostratigraphy**: seismic data are used to assess interrelations between seismic image and lithology in the context of geometric layout so as to determine the depositional system,
- **reservoir interpretation**: intended to identify petroleum reservoirs.

Subsequently, unconventional accumulations are identified and characterized using the following parameters and advanced methods:

- Integration of data derived from seismic attributes, borehole data and AVO (amplitude versus offset) analysis, which provides an insight into the physical parameters of the rock, such as Young's modulus, Poisson's coefficient, P and S wave impedance, etc. The values of Poisson's coefficient and of the Young's modulus help to assess brittleness of shale rocks.
- Amplitude versus angle and azimuth (AVA(Az)) analysis and velocity versus azimuth (VVAz) analysis enable an assessment of stresses in the rock mass and their orientation. Significant measured changes in the recorded 3D seismic data may reflect existing fractures in the rock medium. These changes are called seismic azimuthal anisotropy. Wide-angle and multicomponent seismic (3C) data are useful in the assessment of existing fractures and their orientation.
- Seismic inversion, which results in reestablishment of acoustic pseudo-impedance curves based on seismic data, following more processing allows for estimation of TOC %, which can be incorporated into basin modeling software in order to assess the hydrocarbon generative potential of the basin.

Seismic surveying is on the rise since the inception of unconventional hydrocarbon exploration in Poland. Concession areas are now covered with numerous new 2D and 3D seismic lines that provide a much better insight into the geology of these areas, so that new reservoirs, both conventional and unconventional ones, may be discovered.

A FEW WORDS ABOUT AUTHORS

Andrzej Głuszyński

Graduated from the Faculty of Earth Sciences and Environmental Management, Wrocław University, where he is currently preparing his PhD thesis on structural geology of the Carpathian Front in the Tarnow-Pilzno Region, based on structural interpretation of 2D and 3D seismic data. His responsibilities at Polish Geological Institute-NRI include structural geology and seismic data interpretation.

Sylwia Kijewska

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GEOPHYSICAL WELL LOGGING

Michał Roman

Geophysical well logging (borehole logging,) is a set of borehole investigation methods that are based on special logging tools. First developed in the beginning of the 20th century, well logging comprises today several tens of methods that involve measurements of natural or induced physical fields in the borehole. Extreme conditions prevail in a majority of drilling wells: rocks that are penetrated several kilometres below the ground surface have temperatures in the order of hundreds degrees centigrade[1]. Moreover, throughout drilling operations the borehole is normally filled with a mix of water and clay, called drilling mud. A several kilometres high mud column exerts a pressure that is several hundred MPa high at the bottom of the well. Delicate and sensitive detectors or other instruments require special protection, while the measurements have to be corrected accordingly (considering, for example, that drilling mud infiltrating into the sandstones changes their characteristics, the temperatures affect detector sensitivity, etc.).

In addition to mud logging and core sample tests, geophysical well logs provide a wide array of information on penetrated rocks. They are relatively inexpensive to perform and allow for continuous data logging over long intervals of formation rocks that are in their natural position. Nevertheless, logging data are slightly diffuse (especially if the thickness of formation beds is lower than tool resolution). Moreover, logging data should be correlated with the results of laboratory tests of core samples, especially in early stages of exploration.

Coring operations are time consuming and laboratory test results are not readily available. On the other hand, laboratory data are very accurate and the range of available tests is in practice infinite. Since cores are sampled in specific points only (over a few of several centimetres out of a several kilometres deep boreholes), laboratory data have to be correlated with respective logging curves. For example, TOC determinations in core samples are correlated with resistivity and acoustic logs.

An appropriate correlation of all tests and measurements made allows for the determination of such important elements as, for example, full lithostratigraphic profile of the well, sedimentary rock depositional environment, the oil-water conact, percentage share of particular minerals, modulus of strength, porosity, permeability or hydrocarbon content in prospective zones. Basic traditionally used in petroleum exploration logging methods are: resistivity logs (measured at various distances from the wellbore axis and at different resolutions), natural gamma log (frequently spectrometric, which enables estimation of thorium, uranium and potassium contents in the rock), neutron porosity log, bulk density log

[1] Controlled by geothermal gradient; in Poland, the temperature is equal to approx. 150°C at the depth of 5 km

DICTIONARY

Quadcombo *– a set of measurements commonly made today in exploratory wells. The measurements include natural gamma log, resistivity log, neutron log, bulk density and sonic logs*

Triple Combo *– a set of measurements commonly made today in exploratory wells. The measurements include natural gamma, resistivity, neutron and bulk density logs*

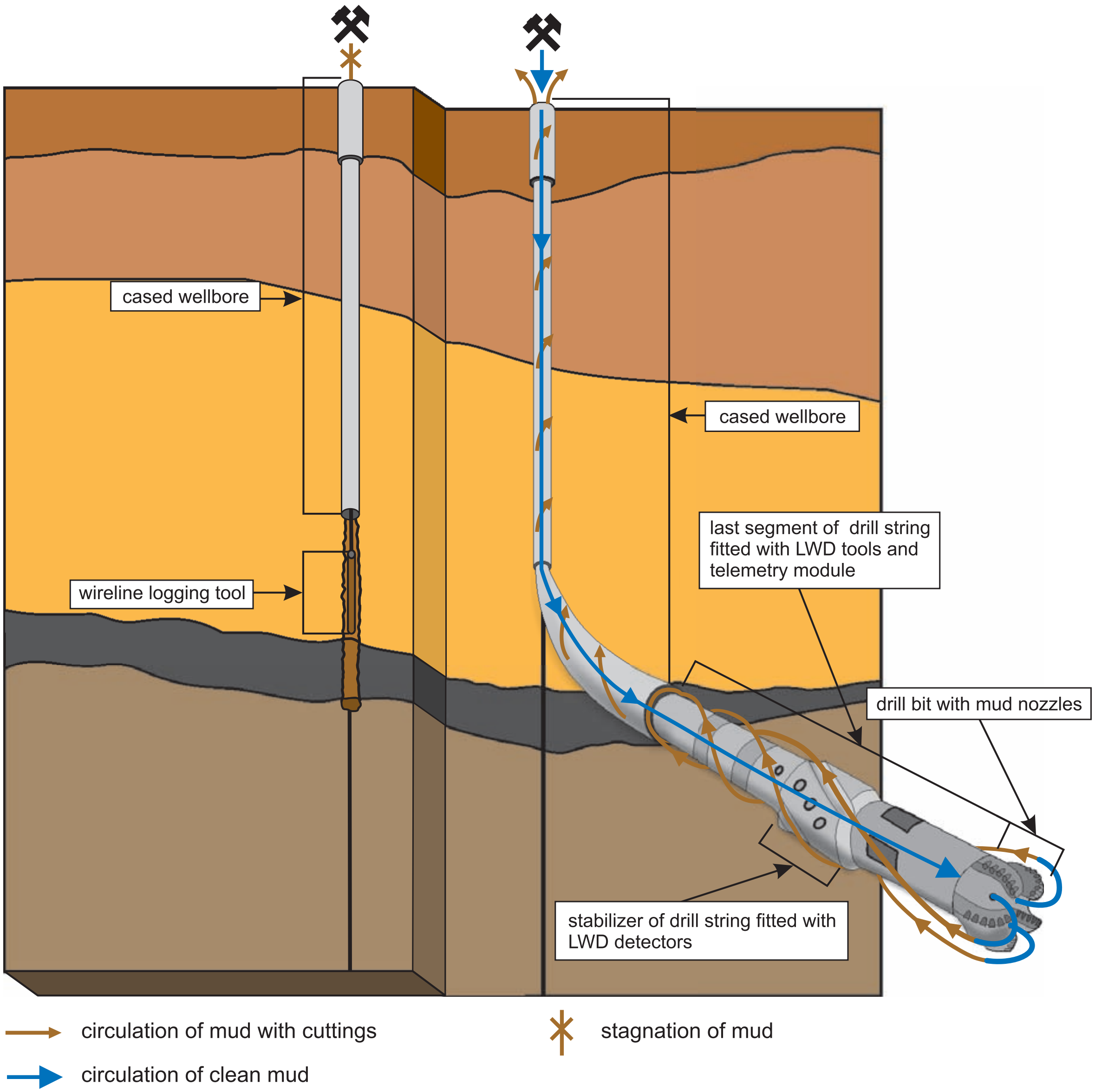
Downhole logging curve *– logs made versus depth. Temperature logging is a good example: temperatures measured by the logging tool are recorded against depth*

DICTIONARY

Logging:
electrical resistivity log (EL)
– a broad group of logs that are intended to determine the electrical resistivity of rocks so as to estimate, among other things, petroleum content of rocks – oil and brine water share in the rock

neutron porosity log (NPL) –
a type of nuclear logging based on recording of neutrons dispersed by the tool in order to determine porosity, chemistry, etc. Hydrogen significantly reduces velocity of neutrons, while trace elements present in the rock absorb the neutrons

natural gamma radiation log (GL) *– measurement of the natural radioactivity of rocks that emit a very small radiation from the decay of radioactive isotopes (potassium and radioactive series of thorium and uranium) present in the rock*



Wireline logging (WL) measurements consist of lowering the logging into usually open wellbore on a wireline. Measurements are usually conducted on the way out of the wellbore. The signal is transmitted through multiple conductor wireline to the surface and recorded. The logging while drilling (LWD) measurement techniques have been developed since 1980's. Logging tools are integrated into the rotating bottom assembly. Some basic data are transmitted to the surface using telemetry, the other data are recorded in the tool memory and logged upon gauge retrieval

New methods that have been developed since late 1980's provide useful information for shale hydrocarbon exploration and appraisal:

1. Neutron gamma spectrometry log (geochemical log) – measures the energy of gamma quanta derived from interactions between neutrons and nuclei of atoms that build the rock. The neutrons are emitted by a source encapsulated in the tool. As a result of interaction with neutrons, each element emits gamma radiation with a specific spectrum that enables its identification. Concentration of a particular element in the rock can be derived from the intensity of radiation with a specific energy. Mineral composition of penetrated rocks, including organic carbon content estimates, is derived from data calculation[1].
2. Nuclear magnetic resonance – magnetic spin of hydrogen atoms present in the rock is arranged along a magnetic field generated by the tool and then the time of the arrangement disappearance is measured. The distribution provides information on rock porosity and on the size of the pores in which water or hydrocarbons are present (the sources of hydrogen in rocks).
3. Full wave sonic log – the amplitude of acoustic vibrations is recorded versus time (rather than the time of longitudinal acoustic wave appearance which is used for calculation of its velocity). Vibrations emitted by the tool-mounted directional and radial sources propagate in the rock and then are recorded by receivers located at some distance from the sources. The measurements provide information on, among other things, porosity and permeability or – in combination with density log – on mechanical parameters (modulus of strength) of the rocks. Vibrations emitted in different directions enable the determination of rock anisotropy arising from fractures that are associated with stresses present in the rock mass.
4. Borehole wall imaging – electric or acoustic logging at a very high resolution (that allows for detecting centimetric non-uniformities) which make it possible to interpret, among other things, dip and thicknesses of laminae, fracture orientation and the so-called breakouts (vertical belts at the borehole wall at which rocks tend to get loose). Breakout orientation indicates the direction of the highest stress in the rock mass, which is a valuable information at planning the direction of production wells and the hydraulic fracturing procedures.

[1] Some probes count the dispersed neutrons and the emitted gamma quanta in relation to time. This enables an accurate direct determination of organic carbon content without reference to core samples

DICTIONARY

Logging:
bulk density log (BDL) *– measurement of gamma quanta dispersed in the rock to estimate average atomic number of the medium for subsequent calculation of rock densities, including total porosity of rocks*

sonic log (SL) *– measurement of acoustic wave velocity in the drilling well. A tool-generated wave travels through the rocks and then returns to the receivers that aree mounted in the tool. Its applications include rock porosity assessments*

(often with photoelectric absorption index capability which provides lithology data) and sonic (acoustic wave velocity) log (besides porosity assessment, sonic logs are used in seismic data interpretation).

The parameters of key importance in shale gas exploration that are determinable by geophysical well logging include:

– organic matter content estimated from the total organic carbon (TOC) parameter,
– mineral composition of shale rocks,
– porosity and pore size distribution,
– mechanical parameters of shale rocks,
– stress field in the rock mass.

The logs of a shale rich in organic matter display a higher level of radioactivity (uranium has an affinity for organic matter), a higher electrical resistivity and porosity (as indicated by lower velocity of acoustic waves, lower volumetric density or a higher neutron porosity). By appropriate correlation of resistivity and porosity sensitive logs, and having calibrated them against core samples, we are able to establish the profile of TOC percentage content in the well.

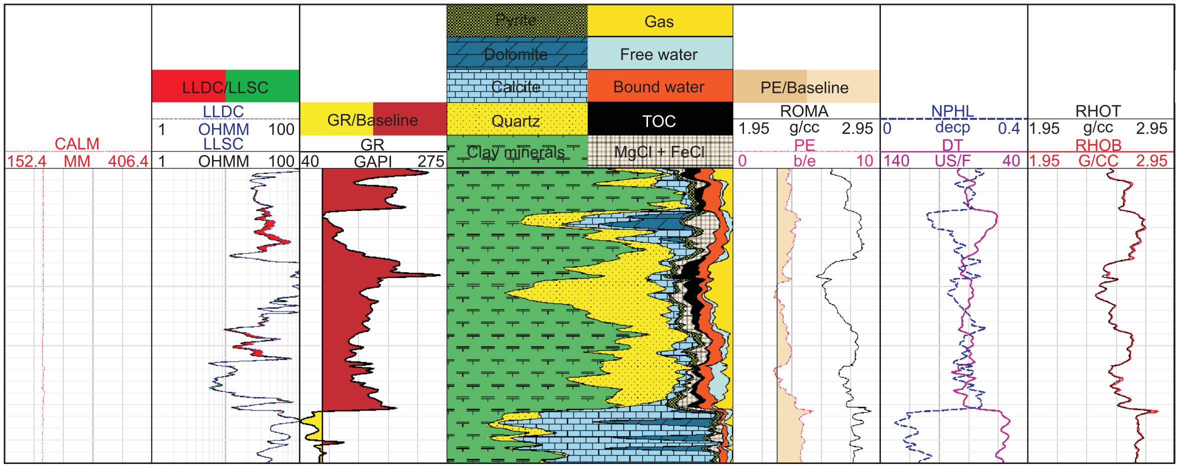
DICTIONARY

LWD *(Logging While Drilling) – downhole logs made during drilling operations by special drillstem-mounted tools*

WL *(Wireline Logging) – downhole logging with wireline-mounted probes made upon drillstem retrieval from the well*

Mud logging *– analysis of cuttings that are carried to the surface with the mud during drilling operations*

Telemetry *– a method of transmitting data from LWD tools to the surface using mud pressure pulses*



Layout of well logging curves from a Polish exploratory well
Central lithological column was created using geochemical log. Correlation between TOC and gas is noticeable. CALM – borehole diameter log, LLDC and LLSC – resistivity curves, GR – gamma ray log, PE – photoelectric absorption log, ROMA – density of rock matrix curve, NPHL – neutron porosity log, DT – sonic log (correlation between DT and NPHL indicates a good quality of the estimation of porosity), RHOT – bulk density curve theoretically calculated, RHOB – measured bulk density curve (worth of noting is a highly similar layout of the two density curves. This indicates that a proper rock composition model has been adopted and testifies to good quality of the geochemical log)

Interpreted logging data are the inputs to dynamic three-dimensional models of petroleum systems as parameters of the sub-divided rock intervals and (along with vertical seismic profiling) are used in time-depth conversion of seismic data.

A FEW WORDS ABOUT AUTHOR

Michał Roman
Graduated from the Faculty of Geology, Geophysics and Environmental Protection, AGH University of Science and Technology in Cracow. His responsibilities at Polish Geological Institute-NRI include analysis of geophysical well logging data, also for the purposes of unconventional hydrocarbon exploration.

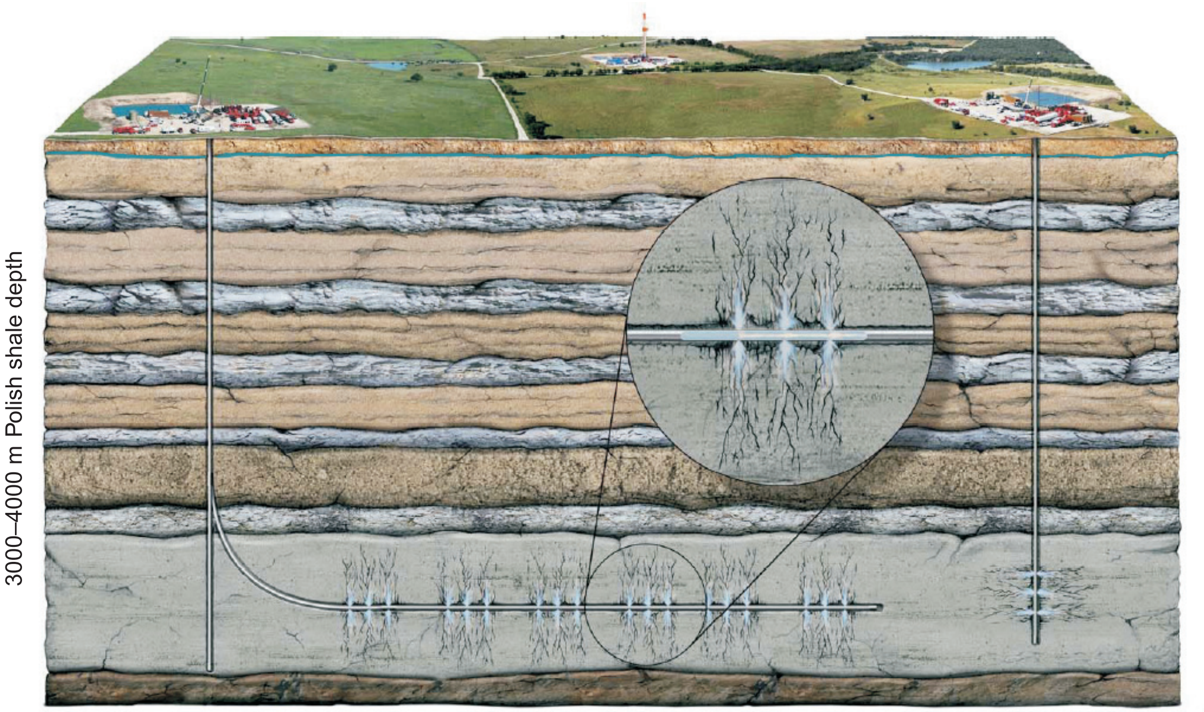
SHALE GAS EXTRACTION METHODS

Marek Jarosiński, Hubert Kiersnowski

Natural gas is stored under pressure in pores and open fractures of the shale rock (free gas), is dissolved in brine or adsorbed at the surfaces of organic fragments and mineral particles (associated gas).

Hydraulic fracturing is the key method used in shale gas production. It involves injections of highly pressurized water that contains chemical additives or another medium (e.g. carbon dioxide) or proppant. Hydraulic fracturing procedures are performed in vertical or horizontal sections of boreholes.

By establishing a network of induced fractures, hydraulic fracturing enables interconnections between small gas-filled voids and, by the same, production of some of the gas accumulated in the hydraulically fractured rock. In addition, gas flowing out of the rock decreases formation



Hydraulic fracturing in vertical and horizontal well sections (by courtesy of Pennsylvania Independent Oil & Gas Association, 2013)

A number of pumps and huge amounts of equipment and fracturing fluids are required at the drill site to produce a pressure surge that is high enough to break the rock. Hydraulic fracturing involves injection of fracturing fluid into a sealed section of the borehole with perforated casing. The rock breaks and the fracture begins to propagate in the gas-bearing shale as pressure increases beyond the minimum stress tangential to the wellbore wall. The hydraulically induced fracture always propagates in a direction that is approximate to the horizontal stress axis, at fracture pressure being higher than the minimum contemporary stress. Proppant is injected with fracturing fluid into the network of induced fractures so as to prevent fracture closure while pressure drops after completion of the procedure. On wellhead valve opening, a portion of fracturing fluid that has not been absorbed by the shale rock and the induced fractures is flowing back to the surface. Micro-seismic monitoring records any subtle shocks from shale rock deformations that are triggered by the fracturing fluid. Recorded data are used to determine the range of the fractured zone. It is worth of noting that normally micro-seismic shocks induced by fracturing operations are billion times weaker than earthquakes that are noticeable to a man standing on the ground surface. Exceptionally, a stronger seismic shock is generated, if the fracturing fluid activates a pre-existing critically stressed tectonic zone.

Alternatively, the flow of gas can be stimulated by flushing the borehole with liquid nitrogen or carbon dioxide to enhance the flow of gas under decreasing hydrostatic pressure of the fluid present in the wellbore. Unlike water, these fluids do not cause clay minerals to swell and actively displace methane gas from brine water and adsorption films. However, their use escalates the costs of the operation and of the well construction.

pressure so that the process of associated gas desorption (release) may be initiated. In order to hold the new fractures open, proppant (predominantly sand) is injected in final stages of the hydrofracturing operation.

In order for the fracturing procedure to be successful, the fracture network must be as dense as possible with fractures piercing many of the local microscopic gas migration paths within the shale rock, which include fissures of any size and laminae that are enriched in sand. A majority of tests performed in reservoir formations is focused on investigation of mechanical parameters and stress of the shale rocks so as to enable careful planning of hydraulic fracturing procedures that are required for reservoir development. In an effort to optimize the procedures, various fluid formulations are prepared with different viscosity, compressibility, surface tension parameters, different additives reacting with the rock and having different proppant, i.e. slurry that prevents the fractures from collapsing, carrying capacity. Moreover, fracturing effects can be optimized by choosing the best pressure increase rate or pressure modulation, as well by selecting an appropriate sequence of periodic fracturing fluid changes, if multiple wells are drilled from a single pad. Considering in advance the presence of any geomechanical barriers that prevent fracture propagation beyond reservoir formations is an important aspect of frac planning.

Marek Jarosiński

A geologist, he graduated from the Faculty of Geology, Warsaw University. His responsibilities at Polish Geological Institute-NRI include sedimentology, petrography and geochemistry of sedimentary, primarily carbonate, rocks. He is currently involved in studies on the Miocene in Poland and Ukraine, as well as on the Zechstein formations.

Hubert Kiersnowski

A geologist, graduated from the Faculty of Geology, Warsaw University, specializing in sedimentology and stratigraphy of clastic sediments, in particular Permian Roliegend sandstones, as well as in analysis of conventional and unconventional reservoir rock, including tight gas accumulations. His responsibilities at Polish Geological Institute-NRI include studies on lower Paleozoic shale rocks in the context of shale oil and gas exploration and assessment of petroleum resources.

CHAPTER

7

SHALE GAS PRODUCTION AND THE NATURAL ENVIRONMENT

authors: Małgorzata Woźnicka, Monika Konieczyńska

The possibility of production of energy raw materials from new sources has always aroused a lot of expectations, mainly with a view to financial and economic advantages, but also in the 21st century some questions are raised about how much we are going to pay while reaching for subsequent resources created by the nature. One could say that the contemporary civilization is always in the state of limbo between a **hope and anxiety** – a hope of economic development, first of all by a reduction of energy prices and an anxiety about the environmental impact of an investment project. There is no need to convince anybody of benefits stemming from new gas resources and one can confidently put forward a thesis that with the launch of resource production the gas market in Europe will be completely different. However, let us give some thought to the fears that are embedded in this early stage of prospecting for and exploration of unconventional gas resources in Europe. Where does the dread of shale gas production stem from? Does the extraction of hydrocarbons from unconventional resources actually differ so much from the conventional resource production which is commonly accepted throughout the world. The raw material, that is the gas, is after all the same. Therefore, what is the underlying cause of the difference and what is the reason of the anxiety which is so profound that it can blockade the process of resource exploration?

At the beginning of our deliberations, it must be clearly ascertained that just as in case of any other production, the shale gas extraction is a process which affects natural environment. Elements that are potentially threatened include water, both groundwater and surface water, soil and ground as well as atmosphere. Moreover, one should not forget about changes in landscape, increased traffic of heavy trucks and noise that adversely affect the quality of life of people and animals. Most of the above mentioned potential impacts is of short duration and they can be easily minimized by, e.g. noise barriers or low-emission equipment or/and land surface insulation. A proper well construction, and first of all, adequate insulation of water-bearing horizons, can effectively prevent groundwater from contamination caused by a well screen adjacent zone and proper post-mining area rehabilitation enables the land to be restored to its original function. There exist a lot of commonly applied solutions that can effectively minimize the threats to natural environment which result from the process of extraction of mineral raw materials. Given the many years of experience in deep drilling in Poland (more than 7,000 boreholes) and the production of hydrocarbons from conventional resources, it can be said that such work may be carried out safely, however, the specificity of unconventional hydrocarbon resources needs a more complex look at the environmental aspects of the extraction of this kind deposits. This is caused, first of all, by the necessity of **drilling much more boreholes** than in case of conventional resources and carrying out **stimulation processes** in each well.

POTENTIAL IMPACT ON NATURAL ENVIRONMENT AT EACH STAGE OF WORK

Both the character and intensity of the impact of a shale gas production process on individual elements of environment result directly from technologies applied and they are different at each stage of work. The process of shale gas production is broken down into the following stages:

- Preparatory Work;
- Well Drilling;

– Resource Stimulation Process (hydraulic fracturing);
– Preparation for Production;
– Production (extraction of the gas from wells);
– Well Liquidation and Area Rehabilitation.

With each of the above mentioned stages, different type and range of potential impacts on natural environment is carried, and for each of them separate procedures of assessment and minimization are applied. In addition, along with the progress of work certain impacts can cumulate and continue to exist even when the production is over.

The **Preparatory Work** stage comprises activities aimed at the construction of a mining plant. At an early stage of technological advancement in the United States (in the last decade of the 21st century), the necessity for a dense borehole network was considered to be one of the greatest environmental challenges. That was due to the fact that a vast area of land had to be excluded from use and also that there were impacts resulting from intense road transport among individual areas of production. In Europe, where the average population density is twice as much as that in the United States (in Poland almost four times bigger), the problem might be even more serious. Nowadays, an area in which the activity is carried out on the ground level usually covers from 2 up to 4 hectares, and due to the directional drilling technology it is possible to exploit gas from an area 500 times larger than the land occupied (around 16,000 hectares). The directional drilling techniques are becoming increasingly effective and they make it possible to obtain operating segments which are above 3 kilometers long, while opening out resources in many directions, without having to cover an analogical surface area. This way, much of arduousness connected with shale gas extraction is limited which is known from the previous American experiences.

The Preparatory Work stage, during which the infrastructure of a mining plant is built, is essential from the point of view of a safe production. The most important elements of this stage include: the protection of organic soil layer, insulation of surface area, constructing a rain water

Preliminaries – drill site leveling and sealing (photo by M. Konieczyńska, left – with the explicit consent of the owner, right – with the explicit consent of the Polish Oil and Gas Company)

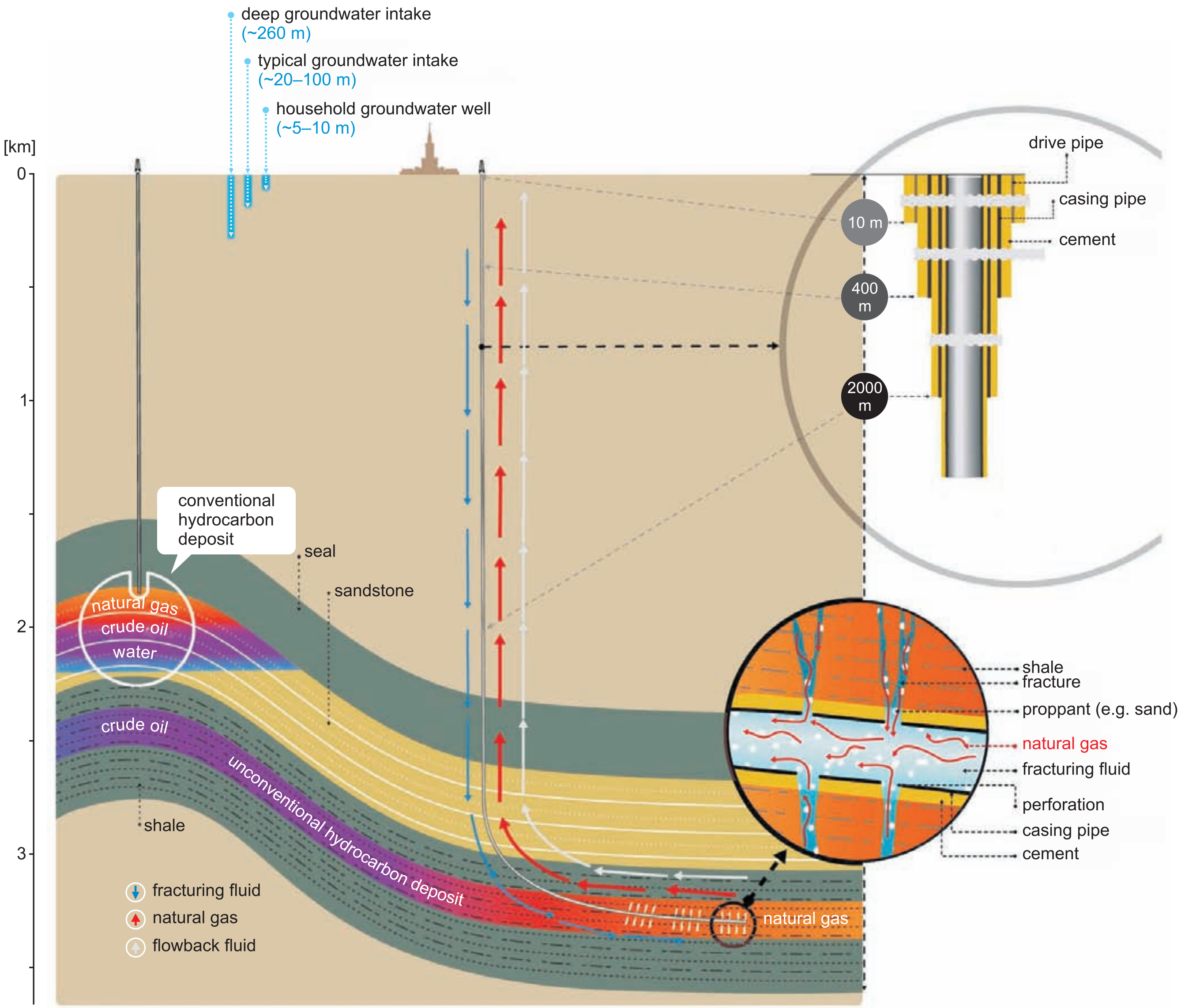
drainage system and a rain and process water tank, building water intakes and connections as well as designing future waste collection installations and a gas collection and transmission system. At present, it is a common practice to cover the surface area with impermeable foil and concrete slabs. An organic soil layer is generally removed and dumped around the mining plant which additionally forms a protective barrier. The need to transport a significant amount of equipment to carry on the production often requires access roads to be built.

The stage of **Well Drilling** usually takes a few months and, at the same time, during the Production stage in a single location usually over a dozen wells are drilled in two rows, in a network, which are a few meters apart from one another. Each well, together with its horizontal sections in different directions, is drilled with the use of the same drilling rig which is moved around the well surface installation. The work is carried out on a continual basis which in case the localization is close to a residential development may be of some nuisance to the inhabitants (lighting, noise). These nuisances can be effectively reduced by, first of all, locating well surface installations possibly far away from any buildings, taking advantage of natural barriers and using acoustic baffles.

In Poland, the drillings aimed at obtaining shale gas are made to the depth of 3.0 to above 5.0 kilometers. These depths are larger than the

Drill site view at the borehole drilling stage (photo the Archive the Polish Oil and Gas Company)

average drilling depths in the United States and Canada: Barnett Shale: 2.1–2.7 km, Marcellus Shale: 1.8–2.1 km (Modern Shale Gas Development in the United States: A Primer, U.S. Department of Energy, April 2009). On the one hand, the significant depths of the occurrence of resource formations raise the costs of work and extend its duration, but on the other hand, they constitute a factor that increases the gas production safety and can guarantee a better insulation between the formation being exploited and potable water horizons as well as the



Scheduling of drilling operations during production for conventional and unconventional hydrocarbon deposits

Drill site view at the hydraulic fracturing stage, force pumps and water containers can be seen (photo the Archive the Polish Oil and Gas Company)

surface area. Nonetheless, irrespective of the depth and purpose of drilling, the fundamental thing from the point of view of minimizing the impact on natural environment is that wells should be to high standards of construction and workmanship which should effectively eliminate any possible penetration of technological fluids and gas to the rock mass, including first of all aquifers. This is why during the drilling process the water-bearing horizons are insulated by a casing pipes columns which are cemented along the whole passage. When a well construction is proper, which can be proved by cementing leaktightness tests, the risk of groundwater contamination by technological fluids or gas migration along the vertical section of a well is practically eliminated.

The basic stage of the undertaking, thanks to which it is possible to exploit shale gas, is to carry out the **Resource Stimulation Process**.

Water tanks used in the process of technological fluid preparation (photo by M. Nidental with the explicit consent of the owner)

With the existing technology, a hydraulic fracturing technique is commonly applied which consists in sequential injecting technological fluid (so called fracturing fluid) together with proppant (hydraulic filling) under high pressure into a horizontal section. The fluid injected causes that in the rock a net of microfractures is formed which due to the filling material used (adequately selected sand or ceramic granulated product) do not close and create routes for gas migration The fracturing fluid is composed on the basis of water (about 99.5%) to which some amount of chemical additives are put with the purpose of optimizing the fracturing process, including first of all the reduction of the fluid flow resistance, decreasing its viscosity and preventing the hydrophilic clay minerals from swelling. On the list of the substances added also antibacterial agents are included that can be injected to the well during the process of its drilling and protect the pipes against corrosion. Gelling substances are applied as well, owing to which the proppant can be transported together with the fluid without falling down to the well bottom and thus preventing it from being clogged. When a fracturing process is over, at the well head a part of fracturing fluid, called flowback fluid, is recovered and then the gas that is released from the shale formation escapes through the well.

Multi-stage hydraulic fracturing, which is carried out subsequently in each drilled well at a mining plant and which is a technologically complicated and advanced process, brings about a number of potential risks for natural environment. Noise, gas and dust emissions to the atmosphere which result from the operation of high-duty power generating sets, engines and force pumps are a short-term nuisance which can be minimized the same way as in case of the Drilling stage. The risk of possible pollutants penetration to the ground and groundwater lying near the land surface is effectively lessened by the above mentioned sealing of the well adjacent zone by the foil and concrete slabs, where the work of preparation and injection of the fracturing fluid is carried out as well as fuels, chemical substances and waste materials stored. Moreover, a system of rain water drainage from the well surface installation is adopted (drainage, drainage ditch, drainage tanks).

In an analysis of the risk of groundwater contamination due to hydraulic fracturing processes being applied, one must not rule out the possibility that fracturing fluid or gas can penetrate through the horizontal section of a well. Such a situation might arise in case of an out-of-control reaction of the rock mass, as e.g. clearing of dislocation zones of a wide range. However, when one takes into consideration the significant depth at which the shale formations occur (at least 3 kms), with the average propagation range of fractures formed of some 100 meters, and the presence of impermeable deposits of a considerable thickness in the overburden that consist an effective insulation, it does not seem practically possible for pollutants to penetrate this way to the aquifers that occur at the depth up to 300 meters from the land surface.

Theoretically, an intervention into rock mass that consists in injecting a lot of fluid, might trigger a reaction in the form of a relocation of the rock mass, especially in the zones that are predisposed to this, such as earlier dislocations and tectonic zones. Such movements on the surface area might manifest themselves by perceptible vibrations or seismic impacts. It is possible that injecting fracturing fluid can lead to seismic vibrations. Such a case took place in Blackpool, the UK, where after hydraulic fracturing quakes

Wellhead protected by a blowout preventer (photo by M. Konieczyńska with the explicit consent of the owner)

of 1.5 and 2.3 magnitude were recorded. However, it should be noted that seismic impacts resulting from hydraulic fracturing take place less often than in case of other human activities such as say mining, geothermal operations or oil and ored.

The **Preparation for Production** stage comprises a demobilization of the equipment used for the resource stimulation processes, management of waste materials and construction of an installation for gas collection and transmission. This is a transitional phase between opening up the resources for production and their management. Gas tests are made in the wells that enable it to determine a predicted gas inflow at the production stage. Heads are installed which are used to collect gas from the well and a transmission infrastructure built. At this stage, the water tanks are liquidated as well as other components of the well surface installation that are not to be used at the production phase. As it is necessary to remove a lot of equipment, at this stage the road transport becomes very much intense which may be a nuisance to the local society.

The **Production of Gas** from unconventional resources which are opened up by more than a dozen wells may be carried out for a period of several dozen years. This stage does not differ at all from an analogous stage of gas production from conventional resources (at present, 199 out of 285 documented conventional gas resources are managed in Poland – *The Report on Mineral Resources in Poland, 2012*). The area which is necessary for production is much less than at the previous stages and it is usually limited to the direct surrounding of the production wellheads. There must be present production fluid tanks there which fluids may escape from the well together with gas and, in some instances, collectors that accumulate the gas before it is sent to a transmission system. The other area may be restored to its original usage. Simultaneously with the gas collecting during the production also formation water is received. Production fluids which escape from the resources must be stored and managed in a proper way. Potential gas emission which migrates in the well screen adjacent zone is an important issue often raised by ecological organizations, especially when the pipes and cement that protect the well become unsealed over time. As it can be a serious natural environment hazard, the quality of well protection should be monitored throughout the whole production period.

When the production is over, the last stage takes place: **Well Liquidation and Area Rehabilitation.** Its purpose it to restore the original function of the area. The work is carried out the same way as in case any other extraction activities. Of great importance is the evaluation of possible geochemical changes in the ground geochemical properties, soil degradation due to the loss of organic matter and subsoil compaction resulting from a long-lasting loading by the infrastructure of the mining plant.

WATER AND WASTES IN THE SHALE GAS PRODUCTION PROCESS

While making an analysis of pressures and impacts of the work related to shale gas production on environment, one can easily propose a thesis that **water management and waste & wastewater management,** in the broad sense of the term, in the process of shale gas production is the key element in terms of natural environment safety. This is owing to the fact that, on the one hand water is indispensable at each stage of the work, and on the other hand, there is a risk of water (surface water and groundwater) contamination in the area where the work is carried out. Significant amount of water used in the process of the first driving of resources results in generating a large amount of waste materials of a fluid or

Land reclamation – site restored to its original function (photo the Archive the Polish Oil and Gas Company)

Potential impacts on environment at individual stages of work

Work Stage	Type of Work	Potential Impact on Natural Environment
Preparatory Work	Construction work, including earthwork, transport and drilling rig assembly	Noise, emissions, increased heavy vehicles traffic, soil contamination, land surface transformation
Well Drilling	Drilling, drilling fluid and waste collection	Noise, emissions from drilling rigs, ground contamination, groundwater contamination also in other locations when waste material management is improper
Resource Stimulation Processes (hydraulic fracturing)	Preparing and injecting the fracturing fluid, return fluid collecting	Noise and equipment emissions to the atmosphere, contamination of surface water and groundwater, soil contamination (also in other locations when waste material management is improper), excitation of seismic activity, resource gas emissions
Preparation for Production	Production tests, equipment disassembly and transport, construction work	Resource gas emissions, increased heavy vehicles traffic, landscape transformation
Production (extraction of gas from the wells)	Collecting the gas and production water	Shale formation gas emissions from the wellhead and transmission systems, groundwater contaminated by shale gas, improper waste material management
Well Liquidation and Area Rehabilitation	Construction work	Shale formation gas emissions, groundwater contaminated by shale gas

semi-fluid consistency that need to be managed appropriately.

During the fracturing process in a horizontal well, about 1 kilometer long, on the average over a dozen thousand cubic meters of water is used, a part of which amount comes back to the land surface as return fluid. The American experiences show that at the production phase from 10,000 up to 30,000 cubic meters of water is used per each well, which, when one takes into consideration the concentration of wells, might mean the need for so called cumulative water abstraction. However, at this early stage of the prospecting and exploration of resources one cannot indicate the regions and areas of future production. In spite of a vast prospective zone that was designated in Poland, a possible production of shale gas will take place only in areas showing the best resource parameters, so called *sweet spots*. These can be small areas that, after a decision about launching production has been taken, will be intensely developed. To this end, a network of directional boreholes is designed which wells enable it to drain shale gas from the whole area. The localization of production plants will depend on the technological possibilities of reaching an adequate length of a well directional sections and the propagation range of fractures that are formed by the stimulation processes; however, a big technological advancement can be observed in this respect.

Another issue, which results from the necessity for collecting the full amount of water in a mining plant before the fracturing process has started, is the need for abstraction of a big qu-

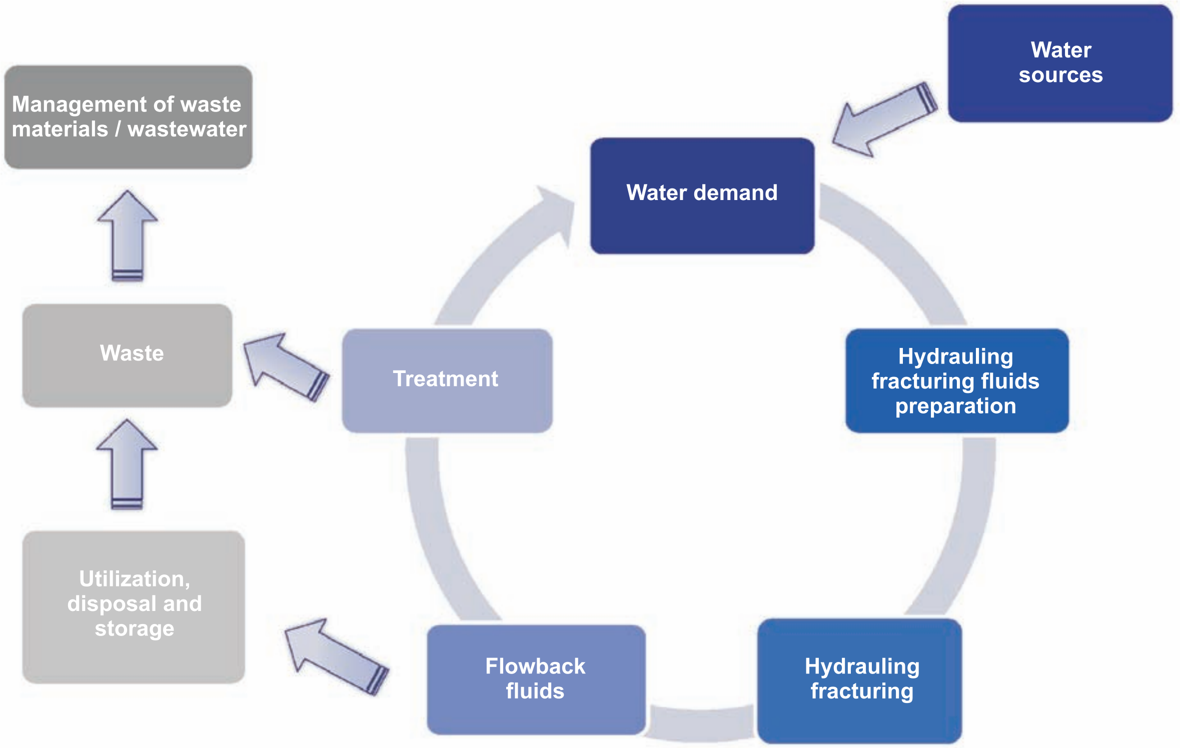


Diagram of water circulation cycle in the process of shale gas production

antity of water within a relatively short period of time. In case given resources are to be exploited, the hydraulic fracturing process is carried out in a few or over a dozen wells, directly one after the other, and this is why some sources of providing required amount of water within a relatively short time must be indicated. For the purpose of drilling and fracturing, from the technological point of view, water from various sources can be used, and in particular:

- surface water;
- shallow groundwater – first aquifer;
- groundwater from deeper levels – useful aquifers, including the main useful aquifer;
- post-production water (technological and refrigerating water);
- mining drainage system water;
- municipal water (from a storm water drainage);
- treated wastewater;
- sea water;
- brines; and
- cleaned flowback fluid.

The total quantity of groundwater resources available to development (renewable resources) in Poland, according to the state of exploration as at 31 December 2012, is about 36 million cubic meters per day, including 18.7 million cubic meters per day determined as disposable resources in compliance with the procedure of the hydrogeological documentation for the area representing 56% of the Poland's territory. The annual registered groundwater abstraction for municipal and industrial purposes is going for 1.58 billion cubic meters, and water consumption for mining drainage system is running at about 900 million cubic meters. At present, the consumption level of the manageable groundwater is about 19%, and thus there is a significant reserve. The amount of manageable groundwater reserves in a balance area constitutes basic information that is indispensible for a water economy balance to be created was well as for setting out the conditions for the use of drainage area, and for a water-legal permit for the water abstraction to be granted. Therefore, it is a tool which can guarantee that groundwater is not excessively depleted which might have serious ecological effects and lead to conflicts among the water consumers.

Therefore, the knowledge of manageable groundwater reserves is indispensible for rational and safe management of the groundwater in this country, also in terms of using it for extractive industry purposes. However, a question arises which is often brought up by ecological organizations and local communities: should we let the groundwater be used for the purpose of shale gas production, even if we have considerable reserves of the water? The groundwater, as being characterized by the best quality, is the basic potable water supply for the population, and in large areas of the country it is the only source of water provision to the inhabitants. Thus, one should not be surprised by the anxiety caused by the information about possible use of the water for other purposes. While considering this issue, it should be distinctly mentioned that the groundwater should not be the only source of water supply for the purpose of carrying out the resource stimulation processes (hydraulic fracturing). Knowing the fact that water used for preparing the fracturing fluid does not have to meet excessive quality standards, a few possible ways of obtaining it can be suggested. It seems that the most appropriate procedure would be to clean the fluid which returns to the borehole and use it again in the next fracturing process in another well. With such a solution, the needs for water in the process is reduced and the amount of waste materials limited. Technological water of various types may be applied successfully, e.g. refrigerating water, water from biogas production plants, etc. Possible use of treated wastewater or so called municipal water, that is the water from a stormwater drainage should be taken into consideration as well. In case of a favourable location, also water from mining excavation drainage systems can be used, whereas in a coastal zone a possible use of salt water is being considered. In addition, brines which are common in Jurassic levels are very much promising.

Therefore, it seems that there are a lot of alternative water supply sources to serve the needs of shale gas production, but their possible use will require legal regulations to be adopted and taking into consideration technological and regional conditioning every single time, since it is not advisable to transport water for long distances. At the stage when a decision about the localization of extraction work is to be taken, it is recommended that a study on the possibility of obtaining water be carried out to serve the needs of the activities planned and determine possible diversification of the sources of water.

Significant amount of water used in the whole process is inextricably linked with the issue of the big quantity of waste materials generated. The majority of waste materials that are generated at various stages of the process of opening up and production of shale gas resources is drilling wastes – drill cuttings and used up drilling fluid, at the stage of drilling the wells, and return fluid with a small amount of returning proppant as a result of the hydraulic fracturing processes. One borehole which opens up resources in gas-bearing shales means a few thousand tons of drill cuttings and used up drilling fluid as well as another several thousand tons of return fluid only in the initial period of production. These wastes materials are of a fluid or semi-fluid consistency and distinguished by significant diversification with respect to their chemical constitution which additionally can be subject to changes over time, as well as to their physical and mechanical properties and potential harmfulness to environment. It may turn out that a part of those waste materials will have to be qualified as dangerous wastes due to the content of crude oil or hazardous substances and (in a particular case) increased radioactivity.

So all of this makes one understand that management of such waste materials must be well thought out and responsible. Rock drill cuttings and drilling fluid that come from the drilling stage, unless they comprise hazardous substances, which is to be documented by appropriate tests, may be processed in proper installations and used for the purpose of, e.g. building materials production. A suitable treatment of return fluid is a more serious problem. It seems to be the most rational solution to use it again as long as possible in the fracturing processes in subsequent wells, at the same or at the nearby mining plants. The process may require the return fluid to be slightly cleaned, e.g. in mobile installations. If it is impossible to use the return fluid again for subsequent processes, it must be sent to utilization that can guarantee it is brought to such a chemical state that it can be discharged to environment, i.e. it must meet the standards required for the discharge of wastewater to surface water or to ground. Here, it should be noted that in the course of such utilization, the return fluid changes its category from liquid drilling waste to wastewater and as such one it must not be used, with the currently binding regulations, for technological processes. Other method of the return fluid utilization in Polish conditions does not seem to be possible. Storing it in drilling waste facilities would be both uneconomical and potentially dangerous in case of a breakdown of any kind, due to its big amount and fluid consistency. Theoretically, if return fluid is not classified as hazardous waste, it can be injected underground, e.g. to exploited conventional hydrocarbon resources. However, such a solution requires a concession for underground storage of wastes that belong to the group of drilling wastes, but in view of expected social protests it does not seem to be a commonly used utilization method both in Poland and across Europe.

ENVIRONMENTAL RISK MANAGEMENT

It is possible to exploit shale gas in a form which is safe for natural environment, when an assumption is made that it will be carried out in compliance with the recommendations resulting from the pressure analysis. In order to determine the real range and degree of the impact of the shale gas production process on natural environment, it is necessary to carry on further studies that will make it possible to monitor the work progress and evaluate the impact of processes performed in a specific location on environment, on the one hand, and to draw general conclusions related to the applied technologies backed up by experiences and test results on the other hand.

Specially adapted **monitoring of environment** is an effective tool which not only provide data about the impact on natural environment of work being carried out and makes it possible to safely plan new undertakings, but also which enables it to verify programs and taking corrective measures in case any adverse events are reported. Management of environmental risk is aimed at the maximal reduction of the risk with the use of manageable resources and accessible technologies, and this includes as follows:

- hazard identification;
- risk characteristics;
- work planning with a view to risk reduction actions;
- work progress control;
- environmental monitoring (environmental assessment before the work gets started as a referential level and long-term monitoring in the course of production and after it has been finished); and
- emergency actions.

At present, to develop an effective and comparable scheme of long-term environmental monitoring in the areas which run the most risk of being potentially affected by work related to the opening up and production of resources presents a special challenge. Such a monitoring should comprise the following:

- soil air – within the scope of testing for geogenic hydrocarbons, in particular methane and in certain cases other gases that have been found in the resources;
- surface water – within the scope of testing for concentration of some selected indicators;
- groundwater – within the scope of testing for concentration of some selected indicators at points fixed on the basis of a flow pattern and a quantitative analysis;
- management/storage of wastes – within the scope of proper management or storage, with allowance made for their properties that may change over time;
- seismic phenomena – within the scope of observation of the effects of rock mass decompression as a result of production;
- area rehabilitation – control of the effectiveness of the process of restoring an area to its original function.

Pursuing production activities in compliance with the above mentioned principles and methods will form a basis for proper decisions to be taken in the event the risk is on an unacceptable level. Such a course of action makes it possible to implement procedures that can be modified depending on the results obtained. This also leads to transparency and enables it to avoid any social conflicts. Advanced, multi-option studies help to orient further development of technology as well so that shale gas can be exploited in a safe way, with social approval. And this is the greatest challenge Poland is facing now.

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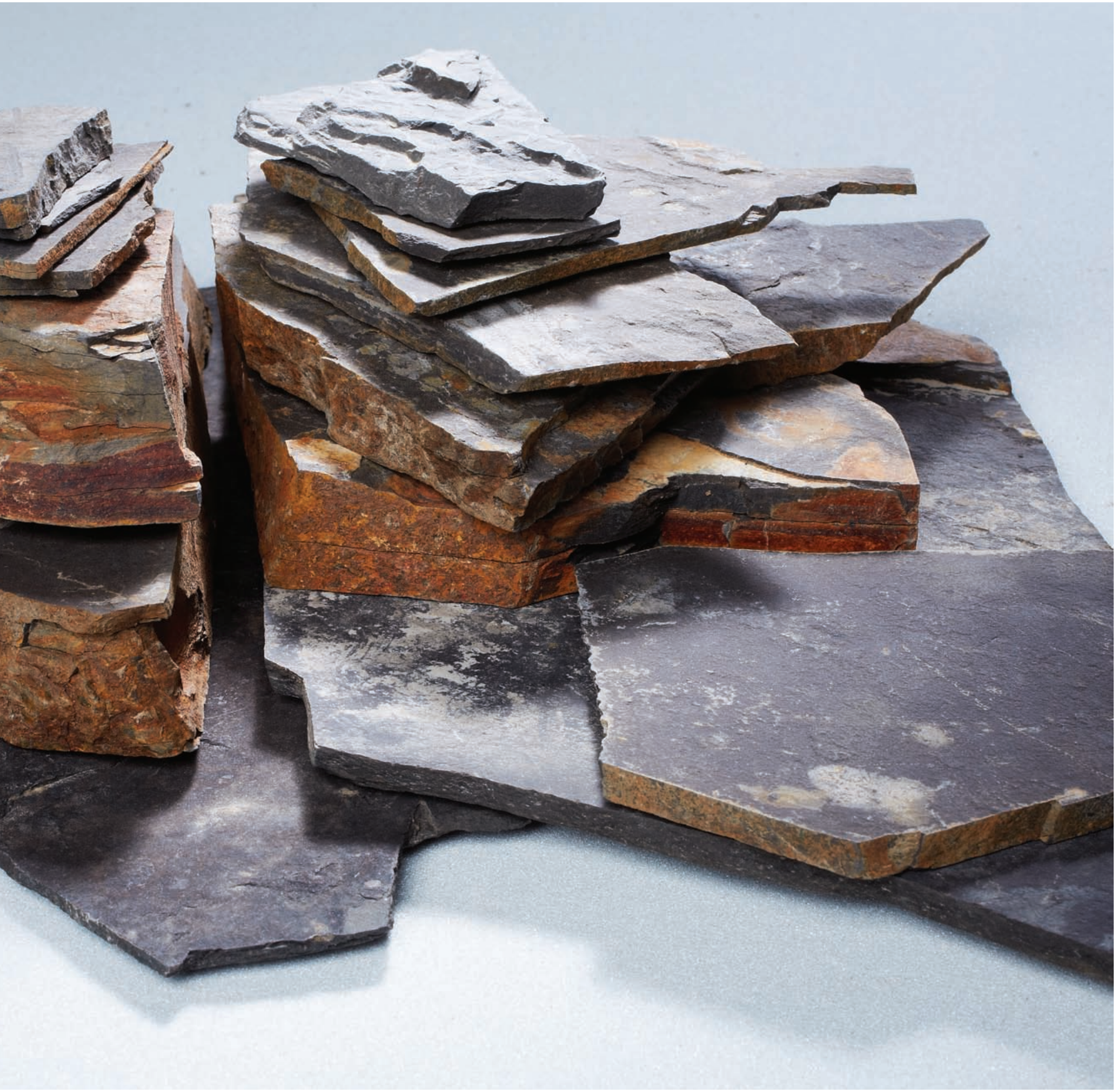
REFERENCES



APLIN A.C., MACQUAKER J.H.S., 2011. Mudstone diversity: Origin and implications for source, seal, and reservoir properties in petroleum systems. *AAPG Bulletin*, **95**: 2031–2059.

ASSESSMENT OF SHALE GAS and shale oil resources of the Lower Paleozoic Baltic-Podlasie-Lublin basin in Poland. First Report, 2012. Polish Geological Institute – National Research Institute.

BAI B., ELGMATI M., ZHANG H., WEI M., 2013. Rock characterization of Fayettville shale gas plays. *Fuel*, **105**: 645–652.

BGR, 2012. Abschätzung des Erdgaspotenzials aus dichten Tongesteinen (Schiefergas) in Deutschland. Hannover, Mai.

BJØRLYKKE K., 1989. Sedimentology and Petroleum Geology. Springer-Verlag, Berlin–Heidelberg.

BOHACS K., GRABOWSKI G., CARROLL A., MANKIEWICZ P.J., MISKELL-GERHARDT K., SCHWALBACH J.R., WEGNER M.B., SIMO J.A., 2005. Production, destruction, and dilution the many paths to source--rock development. *SEMP Special Publication*, **82**.

BREYER J.A., ed., Shale reservoirs – Giant resources for the 21st century: *AAPG Memoir*, **97**: 69–87.

BUST K.V., MAJID A.A., OLETU J.U., WOTHINGTON P.P., 2013. The petrophysics of shale gas reservoirs: Technical challenges and pragmatic solutions. *Petroleum Geosciences*, **19**: 91–103.

CURTIS M.E., SONDERGELD C.H., AMBROSE R.J., RAI C.S., 2012. Microstructural investigation of gas shales in two and three dimensions using nanometer-scale resolution imaging. *AAPG Bulletin*, **96**, 665–677.

EIA, 2011a. World shale gas resources: an initial assessment of 14 regions outside the United States. U.S. Energy Information Administration & U.S. DOE, Washington.

EIA, 2011b. Review of Emerging Resources: U.S. Shale Gas and Shale Oil Plays. U.S. EIA & U.S. DOE, Washington.

ENGELDER T., GOLD D.P., 2008. Geological conundrums involving joints, layer-parallel shortening strain, and the contemporary tectonic stress field. Pittsburgh Association of Petroleum Geologists Field Trip & AAPG-SEG Eastern Section Meeting Field Trip: 1–85, (http://www3.geosc.psu.edu/~jte2/references/link151.pdf)

FARAJ B., 2012. Shale Gas Advancement Its Significance and Global Implications. Shale Gas World Europe 2012 Conference, Warsaw, 27–29 November.

HEIDBACH O., TINGAY M., BARTH A., REINECKER J., KURFESS D., MÜLLER B., 2008. The World Stress Map database release 2008 doi:10.1594/GFZ.WSM.Rel2008, 2008.

HUGHES D., 2013. Drill, Baby, Drill: Can Unconventional Fuels Usher in a New Era of Energy Abundance? Post Carbon Institute. Santa Rosa, California, USA.

JAROSIŃSKI M., 1999. Badania współczesnych naprężeń skorupy ziemskiej w głębokich otworach wiertniczych w Polsce metodą analizy zniszczeń ścian otworów wiertniczych breakouts. *Instrukcje i Metody Badań Geologicznych*, **56**: 1–144.

JAROSIŃSKI M., 2006. Recent tectonic stress field investigations in Poland: a state of the art. *Geol. Quarterly*, **50**: 303–321.

JARVIE D.M., 2012. Shale resource systems for oil and gas: Part 1 – shale-gas resource systems, *in* Breyer J. A., ed., Shale reservoirs – Giant resources for the 21st century: *AAPG Memoir*, **97**: 69–87.

JAVADPOUR F., FISCHER D., UNSWORTH M., 2007. Nanoscale gas flow in shale gas sediments. *Journ. Canadian Petrol. Technol.*, **46**, 10.

KAPROŃ H., WASILEWSKI A., 2012. Gaz ziemny paliwem XXI wieku; Wyd. KAPRINT, Lublin.

KIERSNOWSKI H., DYRKA I., 2013. Ordovician--Silurian shale gas resources potential in Poland: evaluation of Gas Resources Assessment Reports published to date and expected improvements for 2014 forthcoming Assessment. *Prz. Geol.*, **61**, 11/1: 606–623.

KIERSNOWSKI H., POPRAWA P. (eds.), 2010. Rozpoznanie basenów węglowodorowych polski pod kątem możliwości występowania i zasobów oraz możliwości koncesjonowania poszukiwań niekonwencjonalnych złóż gazu ziemnego – etap I. Zbiorowe opracowanie archiwalne. Nar. Arch. PIG-PIB, Warszawa.

KLIMUSZKO E., 2002. Silurian sediments from SE Poland as a potiential source rocks for devonian oils [in Polish, Engl. sum.]. *Biul. Państw. Inst. Geol.*, **402**: 75–100.

KREZSEK C., LANGE S., OLARU R., UNGUREANU C., NAMAZ P., DUDUS R. & TURI V., 2012. Non-conventional plays in Romania: the experience of OMV Petrom. *In*: SPE/EAGE European Unconventional Resources Conference and Exhibition, Vienna, Austria, March 20–22, 2012. Conference paper. Soc. Petrol. Eng., USA, SPE 153028.

KUROVETS I.M., KOLTUN Y.V. 2012. Depositional environments of prospective for shale gas Silurian deposits of the East European Platform, Ukraine. *In*: 74th EAGE Conference & Exhibition, Copenhagen, June 4, 2012 [http://www.earthdoc.org/publication/publicationdetails/?publication=59368].

LIS P., 2010. Upper Ordovician-Lower Silurian fine-grained sediments in the Podlasie-Lublin Basin. *Prz. Geol.*, **58**, 3: 259–262.

LOUCKS R.G., REED R.M., RUPPEL S.C., JARVIE D.M. 2009. Morphology, Genesis, and Distribution of Nanometer-Scale Pores in Siliceous Mudstones of the Mississippian Barnett Shale. *J. Sediment. Res.*, **79**: 848–861.

LOUCKS R.G., REED R.M., RUPPEL S.C., HAMMES U., 2010. Spectrum of Pore Types in Siliceous Mudstones in Shale-Gas Systems. AAPG Hedberg Conference, 5–10 December, Austin, Texas.

LOUCKS, R.G., REED, R.M., RUPPEL, S.C., HAMMES, U. 2012. Spectrum of pore types and networks in mudrocks and a descriptive classification for matrix-related mudrock pores. *AAPG Bulletin*, **96**: 1071–1098.

LØSETH H., WENSAAS L., FADING M., DUFFAUT K., SPRINGER M., 2011. Can hydrocarbon source rocks be identified on seismic data? *Geology*, **39**, 12: 1167–1170.

ŁUCKI Z., MISIAK W., 2012. Energetyka a społeczeństwo, aspekty socjologiczne. PWN, Warszawa.

MODLIŃSKI Z., SZYMAŃSKI B., 2010. Lithofacies-paleothickness map of Caradoc. *In*: Paleogeological Atlas of the sub-Permian Paleozoic of the East-European Craton in Poland and neighbouring areas (ed. Z. Modliński). Państwowy Instytrut Geologiczny – PIB, Warszawa.

MODLIŃSKI Z., PODHALAŃSKA T., SZYMAŃSKI B., 2010. Lithofacies-paleothickness map of Llandovery. *In*: Paleogeological Atlas of the sub-Permian Paleozoic of the East-European Craton in Poland and neighbouring areas (ed. Z. Modliński). Państwowy Instytrut Geologiczny – PIB, Warszawa.

MOHAGHEGH S.D., 2013. A Critical View of Current State of Reservoir Modeling of Shale Assets. Society of Petroleum Engineers, 165713: 1–23, (http://shahab.pe.wvu.edu/Publications/Pdfs/SPE165713.pdf).

PASSEY Q.R., BOHACS K.M., ESCH W.L., KLIMENTIDIS R., SINHA S., 2010. From Oil--Prone Source Rock to Gas-Producing Shale Reservoir – Geologic and Petrophysical Characterization of Unconventional Shale-Gas Reservoirs. Conference paper: CPS/SPE International Oil&Gas Conference and Exhibition in Beijing, China 8–10. June 2010.

POLITYKA ENERGETYCZNA POLSKI DO 2030, Załącznik do uchwały nr 202/2009 Rady Ministrów z dnia 10 listopada 2009 r., Ministerstwo Gospodarki, Warszawa 10.11.2009.

POLLASTRO R.M., HILL R.J., JARVIE D.M., HENRY M.E., 2003. Assessing Undiscovered Resources of the Barnett-Paleozoic Total Petroleum System, Bend Arch–Fort Worth Basin Province, Texas. Online adaptation of presentation at AAPG Southwest Section Meeting (www.southwestsection.org), march 2003, Fort Worth, Texas, USA

POPRAWA P., 2010. Shale gas potential of the Lower Palaeozoic complex in the Baltic and Lublin-Podlasie basins (Poland). *Prz. Geol.*, **58**, 3: 226–249.

POPRAWA P., 2012. The impact of shale gas on the availability of feedstock – potential role of Europe. 3nd Annual Global Petrochemicals Technology Conference Doha, 1–3.10.

POPRAWA P., KIERSNOWSKI H., 2008. Potential for shale gas and tight gas exploretion in Poland. *Biul. Państw. Inst. Geol.*, **429**: 145–152.

PORTAL gazlupkowy.pl/technologia

RZECZPOSPOLITA ŁUPKOWA: studium wiedzy o gazie z formacji łupkowych (praca zbiorowa). 2012. *Praca Naukowa INiG*, nr 183, Kraków.

SACHSENHOFER R.F., KOLTUN Y.V., 2012. Black shales in Ukraine – a review. *Mar. Petrol. Geol.,* **31**: 125–136.

SCHIEBER J., ZIMMERLE W., 1998. Petrography of shales: A survey of Techniques. *In*: Shales and Mudstones (vol. 2): Petrography, Petrophysics, Geochemistry, and Economic Geology (eds. J. Schieber, W. Zimmerle, P. Sethi): 3–12. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart.

SCHULZ H.-M., HORSFIELD B., SACHSENHOFER R.F., 2010. Shale gas in Europe: a regional overview and current research activities. *Geol. Soc. London, Petrol. Geol. Conf. Ser.*, **7**: 1079–1085.

SLATT R.M., PHILP P.R., ABOUSLEIMAN Y., SINGH P., PEREZ R., PORTAS R., MARFURT K.J., MADRID-ARROYO S., O'BRIEN N., ESLINGER E.V., BARUCH E.T., 2012. Extended abstract – Pore-to-regional-scale integrated characterization workflow for unconventional gas shales. *In*: Shale reservoirs – Giant resources for the 21st century (ed. J.A. Breyer). *AAPG Memoir*, **97**: 5–9.

SLATT R.M., PHILIP P. R., ABOUSLEIMAN Y., PRERNE S., PEREZ R., PORTAS R., MARFURT K.J., MADRID-ARROYO S., O'BRIEN N., ESLINGER E.V., BARUCH E.T., 2011. Pore-to--regional-scale integrated characterization workflow for unconventional gas shales. *In:* Shale reservoirs – Giant resources for the 21st century (ed. J.A. Breyer). *AAPG Memoir*, **97**: 1–24.

SONDERGELD C.H., AMBROSE R.J., RAI C.S., MONCRIEFF J., 2010. Micro-structural studies of gas shales. *In*: SPE 131771 presented at the unconventional gas conference. Pittsburgh, PA, USA, 23–25 February.

SUCH P., LEŚNIAK G., 2012. Porowatość przepuszczalność i parametry przestrzeni porowej. *In*: Rzeczpospolita łupkowa – studium wiedzy o gazie z formacji łupkowych: 159–170. *Praca Naukowa INiG*, nr 183, Kraków.

SYTUACJA ENERGETYCZNA w Polsce, Krajowy Bilans Energii, Energy Situation in Poland; Agencja Rynku Energii S.A. *Biuletyn kwartalny*, nr 1 (91), I kwartał 2013.

SZALAY A., KONCZ I., 1993. Migration and accumulation of oil and natural gas generated from Neogene source rocks In the Hungarian part of the Panonian Basin. *In*: Generation, accumulation and production of Europe's hydrocarbons III (ed. A.M. Spencer). *Spec. Publ. EAGE*, **3**: 303–309.

TARI G., POPRAWA P., KRZYWIEC P., 2012. Silurian Lithofacies and Paleogeography in Central and Eastern Europe: Implications for Shale Gas Exploration. Society of Petroleum Engineers – SPE 151606.

VELICIU S., POPESCU B., 2012. Paleozoic shale gas plays of the Eastern Europe: Romania case study. *In*: Romania Oil & Gas Conference, Bucharest, December, 4–5, 2012 [http://www.romania-og.com/RomaniaOG/media/Site_Images/ContentPhotos/Intercontinental/4-Bogdan-Popescu_Zeta.pdf].

WANG F.P., REED R.M., 2009. Pore networks and fluid flow in gas shales. *In*: SPE 124253 presented at the annual technical conference and exhibition. New Orleans, LA, 4–7 October.

WATERS G.A., LEWIS R., BENTLEY D., 2011. The Effect of Mechanical Properties Anisotropy in the Generation of Hydraulic Fractures in Organic Shales. SPE (Society of Petroleum Engineers) Annual Technical Conference, 30 October–2 November, Denver, CO.

WORLD ENERGY OUTLOOK 2012. International Energy Agency, 2012.

www.weatherford.com

ZOBACK M.D., 2007. Reservoir geomechanics. Cambridge University Press, UK: 1–449.