Project Acronym and Title:

M4ShaleGas - Measuring, monitoring, mitigating and managing the environmental impact of shale gas

IMPROVING WELL INTEGRITY IN EUROPEAN SHALE GAS WELLS

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Definitive version

Disclaimer

This report is part of a project that has received funding by the *European Union's Horizon 2020 research and innovation programme* under grant agreement number 640715.

Published December 2017 by M4ShaleGas Consortium

Public introduction

M4ShaleGas stands for *Measuring, monitoring, mitigating and managing the environmental impact of shale gas* and is funded by the *European Union's Horizon 2020 Research and Innovation Programme*. The main goal of the M4ShaleGas project is to study and evaluate potential risks and impacts of shale gas exploration and exploitation. The focus lies on four main areas of potential impact: the subsurface, the surface, the atmosphere, and social impacts.

The European Commission's Energy Roadmap 2050 identifies gas as a critical fuel for the transformation of the energy system in the direction of lower CO_2 emissions and more renewable energy. Shale gas may contribute to this transformation.

Shale gas is – by definition – a natural gas found trapped in shale, a fine grained sedimentary rock composed of mud. There are several concerns related to shale gas exploration and production, many of them being associated with hydraulic fracturing operations that are performed to stimulate gas flow in the shales. Potential risks and concerns include for example the fate of chemical compounds in the used hydraulic fracturing and drilling fluids and their potential impact on shallow ground water. The fracturing process may also induce small magnitude earthquakes. There is also an ongoing debate on greenhouse gas emissions of shale gas (CO_2 and methane) and its energy efficiency compared to other energy sources
There is a strong need for a better European knowledge base on shale gas operations and their environmental impacts particularly, if shale gas shall play a role in Europe's energy mix in the coming decennia. M4ShaleGas' main goal is to build such a knowledge base, including an inventory of best practices that minimise risks and impacts of shale gas exploration and production in Europe, as well as best practices for public engagement.

The M4ShaleGas project is carried out by 18 European research institutions and is coordinated by TNO-Netherlands Organization for Applied Scientific Research.

Executive Report Summary

This report summarizes potential well-integrity and drilling challenges that are likely to be encountered during shale-gas exploration and production in Europe. Geological factors that are likely to affect shale-gas drilling and well integrity in European shale plays are discussed for selected countries that have significant shale-gas potential and/or have begun with exploration. Based on this information, European shale plays are compared to those in the U.S. Suitable North American analogues, in terms of well-integrity and drilling hazards, are found for European shales. Significant experience gathered in the U.S. makes it possible to project well-integrity issues in European shale plays. Recommendations for improving well integrity and reducing drilling hazards in future European shale-gas exploration and development projects are provided at the end.

TABLE OF CONTENTS

Page

1 INTRODUCTION

1.1 Context of M4ShaleGas

Shale gas reservoir rocks are widely distributed around the world, and many countries have now started to investigate their shale gas potential. Some argue that shale gas has already proved to be a game changer in the U.S. energy market (EIA 2015[1]). The European Commission's Energy Roadmap 2050 identifies gas as a critical energy source for the transformation of the energy system to a system with lower CO_2 emissions that combines gas with increasing contributions of renewable energy and increasing energy efficiency. It may be argued that in Europe, natural gas replacing coal and oil will contribute to emissions reduction on the short and medium terms.

There are, however, several concerns related to shale gas exploration and production, many of them being associated with the process of hydraulic fracturing. There is also a debate on the greenhouse gas emissions of shale gas (CO_2 and methane) and its energy return on investment compared to other energy sources. Questions are raised about the specific environmental footprint of shale gas in Europe as a whole as well as in individual Member States. Shale gas basins are unevenly distributed among the European Member States and are not restricted within national borders, which makes close cooperation between the involved Member States essential. There is relatively little knowledge on the footprint in regions with a variety of geological and geopolitical settings as present in Europe. Concerns and risks are clustered in the following four areas: subsurface, surface, atmosphere and society. As the European continent is densely populated, it is most certainly of vital importance to understand public perceptions of shale gas and for the European public to be fully engaged in the debate about potential development of shale gas.

Accordingly, Europe has a strong need for a comprehensive knowledge base on potential environmental, societal and economic consequences of shale gas exploration and development. Knowledge needs to be science-based, needs to be developed by research institutes with a strong track record in shale gas studies, and needs to cover the different attitudes and approaches to shale gas exploration and exploitation in Europe. The M4ShaleGas project is seeking to provide such a scientific knowledge base, integrating the scientific outcome of 18 research institutes across Europe. It addresses the issues raised in the Horizon 2020 call LCE 16 – 2014 on *Understanding, preventing and mitigating the potential environmental risks and impacts of shale gas exploration and exploitation.*

[1] EIA (2015). Annual Energy Outlook 2015 with projections to 2040. U.S. Energy Information Administration (*www.eia.gov*).

1.2 Study objectives for this report

This report summarizes information about potential drilling and well-integrity challenges that can be expected during exploration and development of shale-gas fields in Europe. The shale gas exploration in Europe is still in its infancy, and no commercial exploitation has begun yet. There are no shale gas (production) wells in Europe apart from some exploration wells. Moreover, information about the already drilled shale gas exploration wells in Europe is, in most cases, not readily available. Thus, it is not possible, at present, to review well-integrity issues in Europe.

Another approach on the well integrity was therefore taken in this report. We address possible well-integrity issues during drilling, completion and production by comparing the most productive shale plays in the U.S. with the most prospective ones in Europe. The geological factors that are likely to affect shale-gas drilling and well integrity in Europe are discussed for selected European countries that have significant shale-gas potential and/or have begun with exploration. Information has been gathered from peer-reviewed scientific literature, websites of various research or governmental institutions and from research reports. The report is wrapped up with research-based recommendations on how to improve the long-term integrity of potential future European shale-gas wells.

All phases of a well's life can affect well integrity. We use an extended definition of well integrity, in this report which means not only to avoid leakage through/along the well but also to avoid drilling hazards during well construction.

1.3 Aims of this report

This report is a public dissemination summarizing well-integrity challenges that are likely to be encountered during future shale-gas exploration and production in Europe. The aims of the report are to:

- compare the most prospective European shale gas plays and the most productive plays in the North America with regard to geological factors that affect well integrity and drilling hazards;
- find suitable North American analogues for different European shales, in terms of the expected well-integrity and drilling challenges;
- project North American experience onto European soil and thus assess the expected well-integrity and drilling challenges in Europe;
- provide recommendations on how well integrity could be improved in future European shale-gas exploration and development projects.

1.4 Factors affecting well integrity in shale-gas wells

Well-integrity during drilling, subsequent gas production and well abandonment is essential for preventing hydraulic communication between geological horizons. Such communication, caused e.g. by damage to casing or cement sheath, may lead to groundwater contamination, buildup of fluid pressure between adjacent casing strings (so-called sustained casing pressure, SCP), leakage of hydrocarbons to surface, or blowouts (Davies et al., 2014). Essentially any factors that adversely affect the quality of primary cementing or inflict damage to casing, cement and surrounding rock during subsequent lifetime of the well, may compromise well integrity. Particularly dangerous are continuous pathways in the cement sheath. Such pathways may be e.g. due to a channel of undisplaced mud creating a conducting "chimney" between the casing and the rock (or adjacent casing). Such conducting channels may also be due to gas migration up the annulus during cement setting. Such migration is caused by the elevated pore pressure in the formation, as is often the case in shales (the so called "abnormal pressure").

Elevated pore pressure often gives rise to another trouble, namely gas influx into the well during drilling or during subsequent life of the well. During drilling, gas influx, if not kept under control, may lead to a kick, one of the potentially dangerous events when well control is lost. Influx can usually be prevented or stopped by increasing the mudweight. However, due to the notoriously narrow mudweight window in shales, higher mudweight may lead to formation fracturing higher up in the hole (typically near the last casing point), which is another type of well-integrity breach.

Fracturing the formation during drilling or well cementing leads to losses (Lavrov, 2016c, Lavrov, 2017): The drilling fluid or cement starts flowing into the fracture rather than along the annulus. In shales, this situation, often referred to as "lost circulation", is particularly common since a well-developed network of natural fractures is often present in this type of rock. Loosing cement into the fractures means that, after pumping the planned amount of cement, a shorter-than-planned cement sheath will be built in the annulus. Shorter cement sheath may result in poorer well integrity.

In addition to nearly-cylindrical channels, undisplaced mud can effect another type of damage in cement, namely a so-called microannulus. This happens when a thin mud film remains undisplaced on the surface of casing or the rock face exposed in the annulus. Another mechanism of microannulus development is cement shrinkage.

Wells drilled in sedimentary rocks are rarely circular. Anisotropic in-situ stresses may induce breakouts (approximately symmetric enlargements of the wellbore's cross—section). Action of the circulating fluid and rock heterogeneities may result in washouts and fallouts – local enlargements of the well. During subsequent cementing, it is difficult to ensure that mud is completely displaced from breakouts, washouts and fallouts (Lavrov, 2016b, Roustaei and Frigaard, 2015, Roustaei et al., 2015). The resulting mud pockets, even if they do not form a continuous channel along the well, may serve as stress concentrators after the cement has hardened (Lavrov et al., 2016). Elevated stresses around such inclusions may inflict damage in cement, e.g. cracks running from the casing towards the rock face, thus enabling hydraulic communication between the rock and the well. Maintaining high standards of drilling and cementing is therefore paramount for ensuring well integrity in shale-gas development projects.

It should be noted that, even though maintaining high standards in well construction certainly helps to minimize well-integrity risks, not everything can be predicted and

accounted for by proper well design. Rocks are inherently heterogeneous media. During drilling, problems often occur at transitions between sand layers and the surrounding shales, where the pore pressure regime and rock properties undergo a sudden (and often unpredictable) change. Washouts can occur, drilling fluid and cement can escape along sand-shale interfaces, the formation can fracture, etc. Sudden changes in the pore pressure is another source of trouble leading to influxes into the well. Such sudden pore pressure changes are common e.g. in the U.S. Haynesville shale (Zhang and Wieseneck, 2011).
Poor cementing might not create a lot of trouble during well construction, but is likely to cause problems later on. In particular, it may lead to a gradual build-up of annular pressure, commonly referred to as sustained casing pressure (SCP). Excessive annular pressure needs to be bled off regularly. Two primary factors affecting SCP are formation pore pressure (which in shales is often abnormally high) and the integrity of the cement sheath. In particular, higher pore pressure results in higher SCP, and higher cement sheath permeability (e.g. due to channels or microannuli) results in faster SCP build-up (Xu and Wojtanowicz, 2001).

Any loading of the well, be it mechanical, hydraulic or thermal, may affect well-integrity. In particular, injecting fracturing fluid into the formation during well-stimulation jobs may result in inadvertently creating cracks in the cement sheath around perforations. Whether or not such cracks jeopardize well integrity depends on their dimensions and whether they create a connected flow path along the well.

Mechanisms of well-integrity breach discussed above were largely due to poor primary cementing or some defects created in cement sheath during subsequent well life. Another source of well-integrity problems is due to casing. Even though casing is a strong, steel pipe, this pipe still can be corroded, given sufficient time and environment. Moreover, casing can be damaged mechanically if the well intersects a rock discontinuity (a weakness plane, a large fracture, or a fault), and displacement is induced on this discontinuity during gas production (Dusseault et al., 2001). Such displacements require some change of in-situ stresses. It is well known that hydrocarbon production (as well as water injection) alter in-situ stresses, which may result in fault reactivation (Fjær et al., 2008, Zoback, 2007, Lavrov, 2016a). Even though sedimentary rocks are softer than steel, of which casing is made, the total mass of the rock undergoing shear displacement may be so large that the casing will deform and/or eventually rupture.

Based on the above discussion, the following natural and technological factors are the most crucial ones:

- weak and/or heterogeneous rock resulting in irregular wellbore cross-section (washouts, breakouts);
- elevated pore pressure; sudden pore-pressure changes;
- narrow mudweight window;
- natural fractures;
- faults and fractures that can be reactivated during shale-gas production;
- elevated formation temperature;

- shale activity (this is, fortunately, usually lower in gas-bearing shales than conventional shales).

In addition, worth mentioning are poor well design, inadequate drilling and cementing practices, and poor or outdated monitoring and control routines.

Predicting well-integrity in European shale plays amounts to analysing these factors and drawing conclusions based on this analysis.

2 WELL-INTEGRITY CHALLENGES IN THE U.S. ANALOGUE SHALES

As described in the Introduction, the method of choice in this report is to draw a comparison between U.S. and European shale-gas deposits. Based on this comparison, we then project the U.S. experience onto the European soil, in terms of expected drilling and well-integrity challenges. There are about half a dozen major shale plays in the U.S. In this Chapter, these shales are briefly described in terms of their properties affecting drilling and well integrity. These properties are the basis for the comparison between European and U.S. shales we draw in Chapter 3 for different European countries. Based on these properties, we will establish, in Chapter 3, suitable U.S. "analogues" for European shales, in terms of the properties that might affect drilling and well integrity. We also describe in this Chapter the main documented drilling and well-integrity challenges in the U.S. shales. This information is used in Chapter 3 to predict drilling and well-integrity challenges in European shales. Our approach is schematically illustrated in Figure 1.

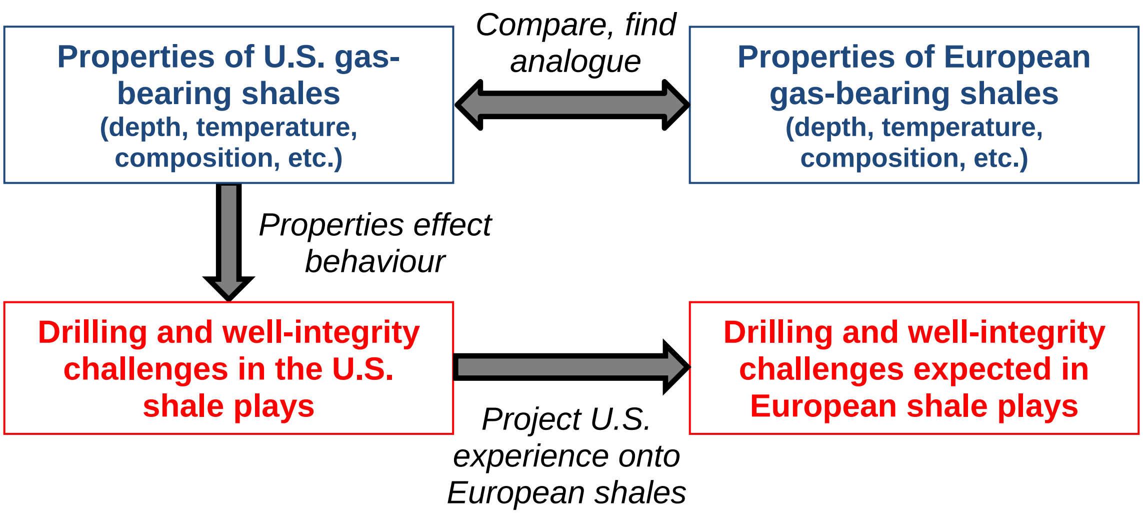

Figure 1. Methodology pursued in this report.

The following seven U.S. shales were selected into the pool of U.S. "analogue" shales: Barnett, Eagle Ford, Fayetteville, Haynesville, Mancos, Marcellus, and Utica.

Barnett shale is a Lower Carboniferous rock (mudstone) found in Texas. Its main properties are summarized in Table 1. Drilling and well-integrity challenges in Barnett are due to relatively great depth, which causes elevated temperature and pore pressure.

Table 1. Properties of Barnett shale affecting well integrity.

Property	**Value**
Geologic age	Lower Carboniferous
Depth	1800…2700 m
Thickness	90…150 m
Porosity	5 %
Total organic carbon (TOC)	3…12 %
Temperature	70…90 °C

Eagle Ford shale (Texas) is an Upper Cretaceous rock found in Texas. Its main properties are summarized in Table 2. Cap rock for Eagle Ford is Austin Chalk. Eagle Ford has relatively low TOC, high pore pressure (in excess of 14 ppg), laminated structure with fractures running along bedding planes. The shale has high calcite percentage (55 %), low clay content (8 %), low cation exchange capacity, thus low reactivity (Guo et al., 2012a). The following drilling and well-integrity challenges have been documented in Eagle Ford (Guo et al., 2012a, Ridley et al., 2013):

- In surface section (sands): seepage losses. Usually successfully cured with lost-circulation materials (LCM).
- Main mechanism of shale-fluid interaction: fracturing and delamination along bedding planes, reopening of natural fractures running along bedding planes.
- Severe losses in Austin Chalk (overburden for Eagle Ford shale); presumably due to induced fractures.
- Losses due to natural fractures in Eagle Ford.
- Losses into Olmos sand during cementing of production casing.
- No shale instabilities with oil-base mud (OBM). Instabilities, stuck pipe, packoffs, bit balling and low rate of penetration (ROP) with water-base mud (WBM).
- Well-control issues (influx) during underbalanced drilling into hydraulic fractures created from completed offset wells.

Table 2. Properties of Eagle Ford shale affecting well integrity.

Property	**Value**
Geologic age	Upper Cretaceous
Depth	1200…3000 m
Thickness	30…90 m
Porosity	9 %
Total organic carbon (TOC)	3 %
Temperature	150…160 °C

Fayetteville shale is a Lower Carboniferous rock found in Arkansas and Oklahoma. Its main properties are summarized in Table 3.

Table 3. Properties of Fayetteville shale affecting well integrity.

Property	**Value**
Geologic age	Upper Carboniferous
Depth	300…2100 m
Thickness	6…60 m
Porosity	2…8 %
Total organic carbon (TOC)	4…10 %
Temperature	80 °C

Haynesville shale is a Jurassic rock found in Arkansas, Louisiana and Texas. Its main properties are summarized in Table 4. This is a deep, hot, highly overpressured shale. Its pore pressure is even higher than Eagle Ford's and is up to 18 ppg (Zhang and Wieseneck, 2011). Percentage of clay and calcite in Haynesville shale is 25…35 % and 5…30 %, respectively (Guo et al., 2012b). Haynesville has low reactivity (cation exchange capacity of 6 meq/100 g). Drilling and well-integrity challenges in Haynesville are due to high pore pressure and great depth (thus high temperature) of this shale (Elshehabi and Bilgesu, 2016, Guo et al., 2012b):

- Shallow gas influx during drilling the surface hole section.
- Poor (poorer than in Marcellus) performance of WBM in Haynesville, due to very reduced inhibition capacity of WBM at high temperature in Haynesvill.
- High temperature and high-pressure of the reservoir.
- Washing out conductor pipe.
- Elevated pore pressure near intermediate casing point.
- Problems getting production casing to bottom. Having to cement casing off bottom on multiple occasions. This may lead to poor cement sheath quality.
- During drilling in the reservoir, pore pressure can increase to high overpressure over a short interval, leading to kicks and blowouts.
- Lost circulation when one attempts to prevent influx by increasing mudweight.
- Poor hole cleaning.
- Controllable kicks due to intersection of natural fractures.

Table 4. Properties of Haynesville shale affecting well integrity.

Property	**Value**
Geologic age	Jurassic
Depth	3200…4000 m
Thickness	20…90 m
Porosity	8…9 %
Total organic carbon (TOC)	0.5…4.0 %
Temperature	140…180 °C

Mancos shale is an Upper Cretaceous rock found in the Western United States. Its main properties are summarized in Table 5.

Table 5. Properties of Mancos shale affecting well integrity.

Property	**Value**
Geologic age	Upper Cretaceous
Depth	4500 m
Thickness	900 m
Porosity	3.5 %
Total organic carbon (TOC)	0.5…4.0 %

Marcellus shale is a Middle Devonian rock found in the eastern part of the U.S. Its main properties are summarized in Table 6. Clay content is about 30%; Marcellus is a low-reactivity shale, with cation exchange capacity of 5 meq/100 g (Guo et al., 2012b). The following drilling and well-integrity issues have been documented in Marcellus (Elshehabi and Bilgesu, 2016, McDaniel et al., 2014, Guo et al., 2012b):

- During drilling: wellbore stability, poor hole cleaning, lost circulation, torque and drag. Poor hole cleaning is due to long horizontal sections necessary to access the reservoirs in the highly populated areas (eastern part of the U.S.)
- Fracture development along bedding planes (delamination).
- Deteriorated well integrity and zonal isolation due to gas migration through cement during setting.
- Sustained casing pressure due to mechanical damage to the cement sheath after cement has set.

Table 6. Properties of Marcellus shale affecting well integrity.

Property	**Value**
Geologic age	Middle Devonian
Depth	1200…2400 m
Thickness	15…75 m
Porosity	8…10 %
Total organic carbon (TOC)	2…13 %
Temperature	55…80 °C

Utica shale is a Middle Ordovician rock found in the northeastern part of the U.S.. Its main properties are summarized in Table 7.

Table 7. Properties of Utica shale affecting well integrity.

Property	**Value**
Geologic age	Middle Ordovician
Depth	2500…3800 m
Thickness	150 m
Total organic carbon (TOC)	2…4 %

3 PROJECTED WELL-INTEGRITY CHALLENGES IN SHALE-GAS WELLS IN EUROPE

In this Chapter, potential drilling troubles and well-integrity challenges are discussed for shale plays in several European countries. Since large-scale exploration and development of shale gas in Europe has not started yet, we need to resort to analogues: Potential well-integrity and drilling issues in Europe are assessed based on comparison with U.S. analogue shales, where a considerable amount of drilling and production data has been collected over the past two decades.

3.1 Geographic overview of shale gas potential and exploration in Europe

It is difficult to identify the global resources of the shale gas at the moment, since most of the world has not yet been explored in this regard. From the rough estimate the worldwide shale resources of the unconventional gas are about ten times larger than of the conventional gas. The most information is gathered for North America; for example, in U.S. 40% of the current total gas production comes from the shale gas.

According to the U.S. Energy Information Administration and the International Energy Agency, trillions of cubic metres (Tcm) of shale gas could be located underneath Europe (US-EIA, 2013d, IEA, 2017). A report by the European Commission's Joint Research Centre (Pearson et al., 2012) presented to-date available estimates of the shale gas resources in the world, and for Europe a range of values from 2.3 Tcm to 17.6 Tcm was found in the literature. There is a large number of European countries that lie above shale basins, and many of the shale basins in Europe overlap several countries. According to a number of sources (Boros, 2014, Toelle and Maache, 2015, US-EIA, 2013d, Schulz et al., 2010), European countries that arguably have the largest shale gas reserves are Poland, France, Germany, the UK, Romania and Ukraine (note that order does not indicate the size of the reserves). But, it is still uncertain how much reserves are in place and how much is recoverable.

The European Union has given freedom of decision for shale gas exploration to each member state. The national governments thus have the right to decide whether their country is to engage in exploration, and which locations to explore. To date, different policies have been adopted by different European countries. An overview of the European countries, corresponding shale basins and plays, and the latest known status of permission for exploration is given in Table 8. Hydraulic fracturing is for example banned in the Netherlands, France and Bulgaria. On the other hand, exploration operations have already started in a number of countries (for example in Poland, the UK, Spain, Sweden, Germany, Romania, etc.). An overview of the shale gas wells in Europe by the end of 2015 was presented in the annual report by European Science and Technology Network on Unconventional Hydrocarbon Extraction (von Estorff et al., 2016). Table 9 is summarizing their findings regarding the number of shale gas exploration wells. At present, Poland has more shale gas exploration than any other European country.

However, there are no commercial drilling operations in Europe yet. Thus for the shale gas exploitation and shale gas well integrity, the most abundant source of information are still shale gas operations in the North America. Apart from the US and Canada, shale gas is commercially produced only in China and Argentina (Dong et al., 2015, Herrero et al., 2016, Kietzmann et al., 2016).

Given that there have only been drilled exploration wells in some countries, and hydraulic fracturing was tested in only a few of those wells, it is clear that there is no sufficient field experience with European shale plays that could be used as a basis for analysis of possible well integrity issues. Another approach to well integrity discussion was therefore chosen, namely, a comparison of the relevant European shales with the most productive U.S. shales. Relevant European shale gas plays and their properties will thus be discussed in the following section.

Table 8. Shale gas resources distribution over European countries. Overview of the European countries where shale gas exploitation is allowed according to (US-EIA, 2013d, IEA, 2017). In some of these countries licenses have already been issued and exploration has started. Legend: Y – yes, N – no, N/A – information not available.

Country	Shale basins and plays	Exploration permitted
Albania	N/A	N/A
Andorra	N/A	N/A
Austria	Vienna Basin (Mikulov Shale), Molasse Basin (Liassic Shale)	Y
Belarus	N/A	Y
Belgium	North Sea – German Basin (Posidonia Shale, Epen)	Y
Bosnia and Herzegovina	Ponnonian-Transylvanian	Y
Bulgaria	Carpathian Basin (Dysodile Shale, Menilite)	N
Croatia	Ponnonian-Transylvanian	Y
Cyprus	N/A	N/A
Czech Republic	N/A	N
Denmark	Alum Shale	Y
Estonia	Baltic Sea Basin	Y
Finland	N/A	N/A
France	Paris Basin (Liassic Shale, Schistes Carton, Permian-Carboniferous), France South-East Basin (L. Jurassic Liassic Shale, U. Jurassic Terres Niores)	N
FYR Macedonia	N/A	N/A
Germany	Lower Saxony (Posidonia Shale, Wealden Shale), Northeast German basin (Tournaisian, Westphalian, Visean Shale), Molasse Basin (Liassic Shale)	Y
Greece	N/A	Y
Hungary	Ponnonian-Transylvanian	Y

Country	**Shale basins and plays**	**Exploration permitted**
Iceland	N/A	N/A
Ireland	N/A	N/A
Italy	N/A	N/A
Latvia	Baltic Sea Basin	Y
Lithuania	Baltic Sea Basin (Ordovician and Silurian Shales)	Y
Luxembourg	N/A	N
Malta	N/A	N/A
Moldova	N/A	Y
Monaco	N/A	N/A
Montenegro	N/A	N/A
Netherlands	Namurian Shale, North Sea – German Basin (Posidonia Shale, Epen)	N
Norway	Alum Shale	Y
Poland	Baltic Sea Basin, Podlasie-Lublin Basin (Silurian Shale, Graptolitic Shale), Carpathian Basin (Dysodile Shale, Menilite)	Y
Portugal	Lusitanian Basin	Y
Romania	Carpathian-Balkanian Basin (Dysodile Shale, Menilite)	Y
Russia	Timan-Pechora Basin (Domanik Formation)	N/A
San Marino	N/A	N/A
Serbia	Ponnonian-Transylvanian	Y
Slovakia	N/A	Y
Slovenia	N/A	Y
Spain	Basque Cantabrian Basin (Liassic Shale)	Y
Sweden	Alum Shale	Y
Switzerland	Molasse Basin (Liassic Shale)	N/A
Turkey	Thrace Basin (Ceylan Formation, Hamitabat Shale, Mezardere Formation)	Y
Ukraine	Silurian black shales Dnieper-Donets Basin Lviv-Volyn Basin Shales in Carpathian Foreland Shales in Carpathian flysh nappes Oligocene black shales	Y
United Kingdom	Weald Basin (Kimmeridge Clay, Liassic Shale), UK Petroleum System (Liassic Shale, Oxford Clays), Bowland Shale, Pennine Basin (Namurian Shale)	Y

Table 9. Shale gas exploration wells distribution in Europe by country (von Estorff et al., 2016). The number of wells may include wells that have been drilled but not necessarily fractured, wells that are no longer active, licenses for shale gas exploitation but with no wells actually drilled.

Country	Number of wells	Hydraulically fractured
Poland	72	14 (vertical) 14 (horizontal or oblique)
The UK	20	1 (horizontal)
Spain	14	-
Sweden	5	-
Romania	4	-
Germany	4	1 (vertical)
Hungary	4	-
The Netherlands	3	-
Denmark	2	-
Austria	1	-
Lithuania	1	-
Total	**132**	**14**

3.2 Geological factors that could affect shale gas well integrity in Europe

Substantial amount of information is required in order to estimate the potential of gas-bearing shales. This includes geological, geochemical, geophysical, and geomechanical data. There are many important parameters to identify, such as depth of deposition, thickness of the reservoir, conditions in the reservoir (stresses, pressure, temperature), mineralogy, porosity, permeability, heterogeneity layers, intrusions, pre-existing fractures and microfractures), type of hydrocarbon (thermal maturity, composition, incl. total organic carbon (TOC)), fluid properties in the reservoir (e.g. salinity and type). Some of these factors are more crucial than the others, but access to as many data as possible can only improve estimates and help in drilling operations.

A brief overview of the properties of the U.S. shales was presented in Chapter 2. These shales will be compared with the European shales in the following. Not all shale plays in Europe have been characterized so far, and information given in Table 10 includes only the European shale plays where some published information is available.

As outlined in Cuss et al. (2015), there is still a need for research of the differences between the major U.S. shale gas formations and potential European shale gas formations. With regard to drilling and well integrity, the most important properties of shale plays are depth, thickness, mineralogy, tensile strength and elastic properties, degree of natural fracturing, in-situ temperature, and in-situ stress state (Cuss et al., 2015). Prior to M4ShaleGas project, there was an interdisciplinary shale gas research initiative "Gas Shales in Europe", led by German Research Centre for Geosciences (GFZ), in the period of 2009-2012 (GFZ, 2009). Within this initiative 18 multinational research projects were conducted, and the main outcome was a European black shale database based on various types of data (outcrop samples, depth thickness, TOC, maturity, logs, seismic, etc.) from at least 26 European countries. However, this database is not open access – and shale properties for this report was therefore found elsewhere (journal articles, open-access reports, books).

The European countries and their respective shales that were selected for detailed study in this report are Poland, the United Kingdom, Spain, Germany, Sweden, Denmark and Ukraine. The selection criteria were presence of recent or ongoing exploration activities, significant shale gas potential and availability of information about the exploration wells and the shale plays. Ukraine is the only country from our list that was not studied in the European Commission report by von Estorff et al. (von Estorff et al., 2016), but we included Ukraine due to its possibly significant shale gas reserves. Other European countries with suspended, ongoing or planed exploration activities, but with little available information about their shales or drilled exploration wells, are discussed briefly.

*Table 10. Basic properties of European shales, covering Denmark, Sweden, Poland, Lithuania, UK, Netherlands, Germany, France, Spain, Ukraine, Bulgaria, Romania. *Different shale plays (Aeronian, Telychian, Wenlock) are contained in the Lower Silurian succession of the Lithuanian Baltic Basin, thus there is some variation in all properties. **Three different shale plays. ***Territory de facto under Russia's control.*

European shales	**Depth (m)**	**Thickness (m)**	**TOC (%wt)**	**References**
Alum, Denmark	1500…6900	160 offshore, 20…180 onshore	10-25	(Nielsen and Schovsbo, 2006, Gautier et al., 2013, Schovsbo et al., 2011)
Alum, Denmark	3300…4500	60	7.5	(US-EIA, 2015b)
Alum, Sweden	690…840	20…100	7	(Erlström, 2014, Pool et al., 2012, Nielsen and Schovsbo, 2006)
Alum, Sweden	990…2100	60	7.5	(US-EIA, 2015b)
Baltic basin, Lower Silurian*, Lithuania	1000…2000	110…180	1.5-2.2	(Sliaupa et al., 2016)
Baltic basin, Lower Silurian, Llandovery, Lithuania	2000…3000	95	3.9	(US-EIA, 2013a)
Baltic-Podlasie-Lublin Basin Poland (Cambrian, Ordovician and Silurian)	500…4400	0…170	0.1-17.4 (typically < 9)	(Karcz and Janas, 2016) (Dyrka, 2016)

European shales	Depth (m)	Thickness (m)	TOC (%wt)	References
North UK, Carboniferous	1500…3900	120	3	(US-EIA, 2013c)
South UK, Lias L. Jurassic	1200…1800	45	3	(US-EIA, 2013c)
West Netherland Basin, Epen shale U. Carboniferous	1000…4650	135	2.4	(US-EIA, 2015b)
West Netherland Basin, Geverik member shale U. Carboniferous	1500…4900	40	4	(US-EIA, 2015b)
West Netherland Basin, Posidonia L. Jurassic	990…3750	27	6	(US-EIA, 2015b)
Posidonia, the Netherlands	3450	30	6	(Janszen et al., 2015)
Lower Saxony Basin, Posidonia, Germany	1550-2150 m	20- 50 m	2-10.5	(Andruleit et al., 2012)
Lower Saxony Basin, Wealden, Germany	1300…1660	200…830	2.0…18.7	(Andruleit et al., 2012, Ladage et al., 2016)
Midland Valey, Scotland, UK	700	Thin sequence	2.6…20	(Monaghan, 2014)
Bowland shale, UK	<2850	60…3000	1…8	(Andrews, 2013)
Weald/Wessex Basin, UK	1000…3000	20…300	Typically <2% for Lower Jurassic; up to 21.3 % for Kimmeridge Clay	(Andrews, 2014)
Paris Basin, Liassic Shale**, France	1200…3000	30	4.5	(US-EIA, 2015b)
Paris Basin, Permian-Carboniferous**, France	1800…4900	25…50	9	(US-EIA, 2015b)
South-East Basin, France	2500…4900	50	2	(US-EIA, 2015b)
Basque-Cantabrian, Jurassic, Spain	2400…4350	45	3	(US-EIA, 2013b)
Basque Cantabrian Basin, Spain.			19/24 wells <1 %, no	

European shales	Depth (m)	Thickness (m)	TOC (%wt)	References
Ordovician and Silurian			wells above 2 %	
Cantabrian-Pyrinees Basin, Spain, bituminous shale, Carboniferous		Up to 600 (gross)	Up to 51 %	(SanLeonEnergy)
Cantabrian-Pyrinees Basin, Spain, Jurassic Marino, Liassic (Jurassic) age		Max 600	Up to 8.7	(SanLeonEnergy, Quesada et al., 1997)
Cantabrian-Pyrinees Basin, Spain, Enara shale gas, Albian-Cenomanian (Cretaceous)		1950 (gross)	1, up to 3.6 locally	(SanLeonEnergy)
Silurian black shales, Ukraine	1500…5000		<1	(Sachsenhofer and Koltun, 2012)
Lower carboniferous black shales in Dniepr-Donets Basin & in the Lviv-Volyn Basin, Ukraine			2…5	
Middle Jurassic black shales beneath the Carpathian foreland, Ukraine	2500…4500		2…8, up to 12	(Sachsenhofer and Koltun, 2012)
Lower Cretaceous black shales in Carpathian flysh nappes, Ukraine			2…8	
Oligocene black shales in Carpathian flysh nappes, Ukraine	500…1500		12…17, up to 35	(Krupsky et al., 2013)
Oligocene black shales in Crimea***, Ukraine	100…5000	300…5000		(Mikhaylov et al., 2014)
Moesian Platform, L. Silurian shale, Romania, Bulgaria	2000…4900	135	3	(US-EIA, 2015a)

European shales	Depth (m)	Thickness (m)	TOC (%wt)	References
Moesian Platform, Etropole shale, L. Jurassic, Romania Bulgaria	1500…4900	80	3	(US-EIA, 2015a)

3.2.1 Poland

The following summary of Polish shale-gas formations is based on available open-source information referring to seismic profiling, analysis of archival geological data and actual exploration drilling results. Information concerns the most prospecting region of the Baltic-Podlasie-Lublin Basin that mainly consist of the Lower Palaeozoic formations i.e. Cambrian, Ordovician and Silurian.

Depth of deposition and thickness of shale gas formations

The deposition depth of the main prospective shale gas formations in Poland varies from 500 m to 1000 m in the east, and exceed 4500 m in the west (PGI, 2012).

- In the Baltic Basin the depth ranges from 1000 m (east sector) to >4500 m (west sector);
- In the Podlasie Basin depth is between 500 m (west sector) and 4000 m (in Mazovia region);
- In the Lublin Basin depth changes from 1000 m (east sector) to 3000-3500 m (Kock region) and even higher at the faults areas (> 4500 m).

The large prospective depths of shale gas formation in Poland enhance significantly the safety of fracturing operations, in terms of occurrence of unconstrued fracture propagation and induced seismicity. However, they also increase potential development costs. The thickness of prospective shale gas formations in Poland is in the range of 0 – 175 m. Thickness of Upper Ordovician increases from west to north-east as follow:

- In the Baltic Basin thickness of 3.5 – 37 m (onshore) and 26.5 – 70 m (offshore);
- In the Podlasie Basin and Mazovia thickness of 1.5 – 52 m.

Thickness of Silurian shale is typically 20 – 70 m and higher.

Composition of shale gas formations – mineralogy (incl. clay content) and TOC

Mineralogical composition of shale gas formations in Poland changes depend on the region and formation type (Dyrka, 2016):

- In the Baltic Basin the cumulative average content of quartz, feldspars and carbonates is 39.5 % (range 24.2 – 62.7 %), the average content of silica is 44.8 % (range 2.8 – 68.8 %), and the average content of clay is 49.2 % (range 36.5 - 60.0 %).
- In the Podlasie-Lublin Basins the cumulative average content of quartz, feldspars and carbonates is 48.8 % (range 34.8 – 76.1 %), the average content of silica is 42.6 %

(range 5.9 – 60.9 %), and the average content of clay is 47.8 % (range 26.4 – 59.3 %).

Gas-bearing shale formations in Poland vary significantly in terms of amount and distribution of organic matter. The TOC content is in the range of 0.1 to 17.4 wt%, but typically the maximum values reach about 9 wt% (Karcz and Janas, 2016). Ordovician and Silurian shale in Poland are only occasionally in excess of 2 wt% of TOC.

- In the Baltic Basin the TOC content vary from 0.5 to 11.0 wt%, while the highest TOC contents have been reported for Ordovician and Silurian formations focused in the Bay of Gdansk;
- In the Podlasie Basin TOC content range from low 0.6 wt% to very high values about 20 wt%;
- In the Lublin Basin the TOC values oscillate between 0.5 and 4.5 wt%.

Thermal maturity (Ro) of organic matter is also highly variable. It depends mainly on the burial history and depth. In the western slope of the East-European Craton formations show whole spectrum of thermal maturity zones, from the immature (< 0.6 % Ro) in the north-east regions, through the oil window (0.6 -1.1 % Ro), condensate and wet gas window (1.1-1.4 % Ro), dry gas window (1.4-3.5 % Ro), to over-mature (>3.5 %Ro) in the south-west regions. The maturity progression from east to south-west regions goes along with the increase of burial depth.

Four prospective zones (SP1-SP4) of shale gas formations have been distinguished in the Lower Palaeozoic formation in Poland (Podhalanska et al., 2016), (Dyrka, 2016):

- SP1 – Piasnica formation – it is restricted to offshore part of the Baltic Basin. Formation is within the Upper Cambrian and the Lowest Ordovician. The main source rock consists of black bituminous shales. The shales are rich in organic matter (3.5 – 12.0 wt% TOC on average), their maturity increases from oil window to dry gas window from north-east to south-west. The thickness ranges from 10 to 30 m. The average mineral composition of Piasnica shales is: quartz, feldspars and carbonates 25 %; clay minerals 47 %; silica 48 %. The average effective/total porosity is: 5.0/7.6 %.
- SP2 – Sasina formation – it is located in the offshore and north part of onshore Baltic Basin, Mazovia region and Podlasie Basin, while its regional analogue is present in the Lublin Basin (Udala formation). Formation is composed of Ordovician dark shales. The shales are considered as a good source rock (1.0 – 3.0 wt% TOC on average). Their maturity increases from north-east to south-west changing from oil window to dry gas window. The thickness of the formation ranges from 10 to 70 m in the Baltic Basin. The average mineral composition of Sasina shales is: quartz, feldspars and carbonates 51 % (Baltic Basin) and 46 % (Podlasie-Lublin Basins); clay minerals 47 % (Baltic Basin) and 50 % (Podlasie-Lublin Basins); silica 50 % (Baltic Basin) and 53 % (Podlasie-Lublin Basins). The average effective/total porosity is: 5.4/9.0 % (Baltic Basin) and 5.3/11.1 % (Podlasie-Lublin Basins).

- SP3 – Jantar formation – it is restricted to the north part of Baltic Basin, west from Gdansk. Analogue of the formation is present in the north-west part of the Podlasie Basin but due to insufficient thickness is not considered as prospective shale. The formation or its analogues were not found in Lublin Basins. It consists of dark-grey and black bituminous shales and massive dusty shales. The shales are rich in organic matter (2 – 5 wt% TOC on average). Their maturity increases from north-east to south-west changing from oil window to dry gas window. The thickest zone of 15.0 – 17.5 m is in the Baltic shelf. The average mineral composition of Jantar shales is: quartz, feldspars and carbonates 38 % (Baltic Basin); clay minerals 53 % (Baltic Basin); silica 45 % (Baltic Basin). The average effective/total porosity is: 4.9/9.2 % (Baltic Basin).
- SP4 – Pelplin formation – is the zone with the largest spatial range, found in all shale gas basins. Formation is within the Mid and Upper Silurian. It is dominated by black-grey mud rocks and shales with relatively consistent geological properties, aside from carbonates content, which increases towards the east direction. The organic content is highly variable (> 2 wt% TOC for protective zones), in many areas formation has relatively low hydrocarbon potential e.g. within the Baltic Basin. The thickness of shale in the Podlasie-Lublin Basins is in the range of 30 – 100 m. The maturity increases from north-east to south-west changing from oil window to dry gas window. The average mineral composition of Pelplin shales is: quartz, feldspars and carbonates 44 % (Baltic Basin) and 49 % (Podlasie-Lublin Basins); clay minerals 49 % (Baltic Basin) and 47 % (Podlasie-Lublin Basins); silica 43 % (Baltic Basin) and 40 % (Podlasie-Lublin Basins). The average effective/total porosity is: 6.5/10.4 % (Baltic Basin) and 4.9/8.4 % (Podlasie-Lublin Basins).

Structure of shale gas formations – porosity, heterogeneity, fractures and joint system

Porosity of shale gas formations in Poland varies depending on the region and depth (Dyrka, 2016). Typically, total and effective porosity decrease with depth due to compaction. With this respect, the shallower formations have better petrophysical parameters.

- In the Baltic Basin an average effective porosity is 5.5 % (range 2.2 – 10.9 %), whereas an average total porosity is 9.1 % (range 4.9 – 15.9 %).
- In the Podlasie-Lublin Basins an average effective porosity is 4.7 % (range 0.6 – 11.1 %), whereas an average total porosity is 9.2 % (range 4.5 – 17.8 %). This region has distinctly larger change of petrophysical properties than Baltic Basin.

The Baltic and Podlasie Basins have rather simple tectonic structure. In these regions, some zones have only flexural bindings. The Lublin Basin has somewhat more complex tectonic structure due to number of blocks and faults, which were uplifted and eroded (PGI, 2012). As a general rule, borehole sites are selected far from any major fault zones in order to enhance effectiveness of fracture stimulation and to minimize well integrity risk. The gas-bearing formation in Poland are covered by natural sealing complexes that have various distribution and thickness depending on the region (PGI-NRI et al., 2015).

- In the Baltic Basin (Pomerania region) the gas-bearing Ordovician and lower Silurian formations are overlain by thick impervious sealing complexes. These complexes consist of younger Silurian shale covered by Zechstein evaporates. The thickness of Silurian sealing complex changes from 3000 m in the west to 300 m in the east, whereas thickness of the Zechstein sealing complex is 280 m in the north to 500 m in the south. There is only few faults penetrating to the bottom of Silurian formation, but none passes through the entire complex. The thickness of the sealing complexes is several times higher than the throws of faults in this region, which only occasionally exceed 100 m. In addition, the natural fractures surrounding the faults are most likely inactive and mineralised with calcium carbonate. Therefore, it can be assumed that sealing in Pomerania region ensures continuity of the formation, so that the integrity of the area upon fracture stimulation would be retained.
- In the Lublin Basin the facies distribution and thickness of sealing complexes are much more complex than in Pomerania region. The sealing complexes are not continuous throughout the region, since the basin is divided by major faults zones. Therefore, each location should be considered independently. The main sealing complex in the region is the Upper Silurian formation, located above fracture stimulated Lower Silurian beds. The thickness of this formation varies depending on the location, for example 857 m at Syczyn OU-2K well (2700 m prospective depth) and 1387 m at Zwierzyniec-1 well (3100 m prospective depth). In addition, the Silurian complex is covered by local lower Palaeozoic sealing complexes – the Devonian and Carboniferous formations, which thickness of about 800 m in Syczyn well. There is no evaporate cover in the area, thus the complexes younger than Carboniferous cannot be considered as effective sealing. The Upper Silurian complex appears to have very good sealing properties, and only risk for the integrity of sealing is in disrupt continuity at faults and whether the faults zones are tight.

The prospective shale gas basins in Poland are located in seismically safe areas. Pomerania is among the least seismically active regions in Europe. The short breakouts occur occasionally and out of the fracture stimulated complexes. In the Lublin region, the downhole logging data indicate much higher differential tectonic stresses. Although the risk of earthquake in the Lublin region is somewhat higher than in Pomerania, it is still considered as minimal.

Mechanical properties of shale gas formations

Mechanical properties of shale refer to strengths and elastic moduli. These factors are primarily dependent on the mineralogy of the rock and the conditions at deposition such as tectonic stresses, pressures and temperatures.

A few selected samples from the Baltic Basin (Laura, 2015) show Young's modulus in the range of 0.69 – 13.65 GPa and Poisson's ratio of 0.14 – 0.42. With respect to pore fluid pressure no significant overpressures have been observed in Polish shale rocks at the prospective depths (down to 3.5 km), which is favourable from well-control and well-integrity perspectives.

Expected drilling and well-integrity challenges

The thickness of shale deposit in Poland is considered to be thin(in most favourable areas has about 50 m (PGI, 2012)), which necessitates directional drilling and horizontal wells. The depth of deposition is relatively large, between 2500 to 4000 m in Silurian sediments. These factors make drilling less predictable and technologically more complicated. Next unfavourable feature of Polish shale is the large amount of clay minerals, which may contribute to borehole instabilities, especially when drilling the build section and the horizontal section.

Because of wide variation in their properties, Poland's shales are difficult to relate to any particular single U.S. analogue shale. Geologic age of Poland's shales could indicate that they might be close to the Utica shale in the U.S. However, a close examination of their depth, TOC, clay content, and thickness suggests that a more suitable U.S: analogue would be Haynesville or Marcellus shale, in terms of the expected drilling and well-integrity challenges (Table 11).

Table 11. U.S. analogues to predict well-integrity challenges in Poland's shales.

Polish shale	**U.S. analogue**
Upper Ordovician & Silurian shales in the Baltic-Podlasie-Lublin Basin	Haynesville or Marcellus

The following drilling and well-integrity challenges in the Baltic-Podlasie-Lublin can be predicted, based on the comparison with the U.S. analogues:

- Borehole instabilities in the build and horizontal sections, exacerbated by great depth and high clay content in Polish shales.
- Lost circulation during drilling and cementing, due to the lack of overpressure.
- Bit balling due to high clay content, which may lead to poor hole cleaning, packoffs and buildup of bottomhole pressure. This may additionally enhance losses during drilling.
- High temperatures at great depth may adversely affect the integrity of the cement sheath during the well life.

3.2.2 The United Kingdom

There are three major shale-gas basins in the U.K.: Midland Valley, Bowland shale, and Weald Basin (Table 12).

Table 12. Shale properties of the UK basins. QFP: quartz, feltspar and pyrite.

	Geologic age	Depth, m	Thickness, m	TOC, %wt	Mineralogy
Midland Valley, Scotland	Carboniferous	700	Thin, sequence	2.6...20	Average: 59% phyllosilicates/clay mineral, 32 % QFP, 9 % carbonate minerals
Bowland shale	Carboniferous	<2850	60…3000	1...8	"medium/high" clay content
Weald/Wessex Basins	Jurassic	1000…3000	20…300	Typically <2% for Lower Jurassic; up to 21.3 % for Kimmeridge Clay	Average 33-51 % clay minerals

Midland Valley, Scotland

The Carboniferous shale is the Midland Valley in Scotland is located in four stratigraphic intervals: Limestone coal formation, Lower limestone formation, West Lothian Oil-Shale unit and Gullane unit (Monaghan, 2014). The shale is found in thin stacked layers at shallow depths (700m). The TOC values are high, from 2.6 and up to 20 %. The mineralogy is variable, on average the Midland Valley shales has a higher content of clay minerals, but a lower content of carbonate minerals compared to the US shales. Additionally, brittle sandstones, limestones and ironstones are interbedded with the shales.

Based on the above data, a suitable U.S. analogue for Midland Valley shales might be Barnett or Fayetteville. However, most drilling and cementing challenges in Barnett are due to its greater depth, thus high pore pressure and temperature. Midland valley shales in the U.K. are much shallower and therefore are unlikely to present the same challenges as their U.S. counterparts. The following drilling and well-integrity challenges are envisioned in Midland Valley shales:

- Borehole instabilities, exacerbated by high clay content.
- Shallow gas.

Bowland shale

The Carboniferous Bowland shale is found in several shale gas basins in the UK (i.e. Bowland-Hodder, Blacon, Gainsborough, Widmerpool, Edale and Cleveland basins). The depth of the shale plays varies up to 3000 m, but mostly those shallower than 1500 m are excluded. The thickness varies from 60…3000 m (Andrews, 2013). The Average TOC content is typically 1...3 %, but up to 8 % has been reported. Bowland shale may be comparable to Barnett shale of the U.S.

Greater depth than that of Midland Valley shales is likely to make borehole instabilities more severe in Bowland shale. High clay content is another factor contributing to instabilities.

Weald/Wessex Basins

The Weald/Wessex Basins include Jurassic shale from Mid & Upper Lias Clays (Lower Jurassic), Oxford Clay, Corallian Clay, and Kimmeridge Clay (Upper Jurassic). The thickness varies in the different Jurassic units from 20…300 m, with the thickest being Oxford Clay (up to 65 m) and Kimmeridge Clay (up to 300 m) (Andrews, 2014). For the lower Jurassic, the TOC content is usually below 2 %, but up to 8 % has been reported. These are thus less organic rich than their counterparts in the Paris Basin (in France). The TOC content of the Oxford clay is reported up to 7.8 % and up to 21.3 % for the Kimmeridge Clay. For the shales with TOC>2 %, an average of 31...51 % clay minerals are observed.

Based on the above data, a suitable U.S. analogue for Midland Valley shales might be Haynesville. The following drilling and well-integrity challenges are therefore expected in Weald shales:

- Shallow gas influx during drilling the surface hole section.
- Poor performance of water-base mud.
- Problems getting casing to bottom.
- Problems during well cementing; incomplete cementing.
- Influxes and lost circulation in shale.
- Poor hole cleaning.
- Sustained casing pressure.

Table 13. U.S. analogues to predict well-integrity challenges in the U.K. shales.

U.K. shale	U.S. analogue
Midland Valley, Scotlane	(Barnett or Fayetteville)
Bowland shale	Barnett
Weald/Wessex Basin	Haynesville

3.2.3 Spain

Shale resources in Spain include the Basque-Cantabrian Basin and the Ebro Basin in the north. In the Basque-Cantabrian region shales of Silurian-Ordovician, Jurassic and Cretaceous age are found. Based on analysis of outcrops, the Jurassic shale has shown the highest potential for wet gas and condensate. The potential of the Ebro Basin was evaluated from 30 older petroleum wells in the area revealing shale with possibility for both wet and dry gas. However, the average TOC was determined to be less than 1 % (US-EIA, 2013b).

Not much information regarding the properties of the shale plays in Spain has been found, but a short summary is provided below.

Table 14. Shale properties in Spain.

Property/Geologic age	**Cretaceous**	**Jurassic**	**Carboniferous**	**Ordovician and Silurian**
Depth, m	1600…4000	2400…4350	N/A	N/A
Thickness (ft)	50…2000 (gross)	85…600 (gross); 10…50 (net)	up to 600 (gross)	N/A
TOC (wt%)	av. 1% wt (3.6% wt locally)	up to 8.7 wt %	up tp 51%	80 % <1 %, none above 2 %

Based on their properties (Table 14), Spanish shales can be assigned U.S. analogues, as shown in Table 15.

Table 15. U.S. analogues to predict drilling and well-integrity challenges in Spanish shales.

Shale in Spain	**U.S. analogue**
Cretaceous shale	Eagle Ford
Jurassic shale	Haynesville
Carboniferous shale	(Barnett or Fayetteville; based on geologic age)
Ordovician and Silurian shales	(Utica; based on geologic age)

Cretaceous shale:
The Cretaceous shale is found at 1600…4000 m with a varying thickness of 50…2000 m. The average TOC content is quite low (1%), however, locally 3.6 % has been discovered. Experience from gas producing fields through these shales in the 1960's indicated that the permeability of the Cretaceous shales were low (US-EIA, 2013b, SanLeonEnergy).

Eagle Ford shale seems to be a suitable U.S. analogue for this Spanish shale. Therefore, the following drilling and well-integrity challenges can be expected: (Guo et al., 2012a, Ridley et al., 2013):

- Losses due to natural fractures in the shale reservoir (fracturing and delamination along bedding planes, reopening of natural fractures running along bedding planes).
- Borehole instabilities, stuck pipe, packoffs, bit balling and low ROP with WBM.
- If shale is overpressured, this may create well-control challenges (gas influx) during drilling and sustained casing pressure during production and well abandonment.

Jurassic shale:
The Jurassic shales is found at a depth of 2400…4350 m and with a maximum thickness of 85…600 m (10…50 m net). For these shales, the TOC content is determined to be up towards 8.7 %. The shales in the Lower Jurassic Comino are imbedded in limestones and marls, similar to the Bakken Shale of the Williston Basin in U.S. (US-EIA, 2013b).

Haynesville shale seems to be a suitable U.S. analogue for this Spanish shale. Therefore, the following drilling and well-integrity challenges can be expected:

- Shallow gas influx during drilling the surface hole section.
- Poor performance of water-base mud.
- Problems getting casing to bottom.
- Problems during well cementing; incomplete cementing.
- Influxes and lost circulation in shale.
- Poor hole cleaning.
- Sustained casing pressure.

Carboniferous shale:
The Carboniferous shale found in Spain is comparable to the Carboniferous shale play San Leon holds in Poland, which has shown great shale gas potential. The shale is quite thick, up to 2000ft with a possible high TOC content (up to 51 %) (SanLeonEnergy).

It is difficult to assign a U.S. analogue shale to this Spanish shale since little data is available. Based on geologic age, Barnett or Fayetteville shales might be considered as analogues.

Ordovician and Silurian shales:
Based on outcrops, the TOC content was determined to be less than 1% (for 80 % of the outcrops) and none of the outcrops showed a TOC content above 2%.

It is difficult to assign a U.S. analogue shale to this Spanish shale since little data is available. Based on geologic age, Utica shale might be considered as analogue.

3.2.4 Germany

Three formations are currently considered as having potential for shale-gas accumulation in Germany (Andruleit et al., 2012):

- Lower Carboniferous formations in the North ("Alaunschiefer");

- Lower Jurassic Posidonia shale in the North and South;
- Lower Cretaceous Wealden shale in the North.

Data on Germany's shales are listed in Table 16.

Table 16. Data on German shales used to assess the anticipated well-integrity issues. Based on (Ladage et al., 2016, Andruleit et al., 2012).

Property/Age	Lower Carboniferous shale "Alaunschiefer"		Lower Jurassic Posidonia shale	Lower Cretaceous Wealden shale
Depth, m	1000…5000		1550…2150	1300…1660
Thickness, m	30…340		20…50	200…830
TOC, %	2.0…2.3		2.0…10.5	2.0…18.7
Porosity, %	3…10		3…22	4…10
Density, g/cm^3	2.7		2.4	2.6

Lower Carboniferous formations in the North ("Alaunschiefer")

This formation has depth 1000…5000 m, relatively low TOC 2.0 to 2.3 %, thickness 30…340 m and porosity 3…10 % (Andruleit et al., 2012). Suitable U.S. analogues for this shale would be Lower Carboniferous U.S. shales, such as Barnett (depth 1800…2700 m, TOC 3…12 %, thickness 90…150 m, porosity 5 %) or Fayetteville (depth 1200…1600 m, TOC 7 %, thickness 300 m, porosity 5 %).

Drilling and cementing challenges in Barnett are due to its depth, thus high pore pressure and temperature. In addition, similarity in mineral composition (w.r.t. quartz, carbonate, and clay minerals) between Lower Carboniferous German shales and Barnett shale demonstrated in (Ladage et al., 2016) suggests that Barnett could be considered to be a decent analogue for these German shales. Natural fractures in "Alaunschiefer" are mostly sealed, with calcite (Ladage et al., 2016). This, again, makes this shale similar to Barnett (Gale et al., 2007). Natural fractures, mineralized with calcite, are common in Barnett (Gale et al., 2007) and may open up and contribute to losses during drilling and cementing. Similar well-integrity challenges can thus be expected during development of the German Lower Carboniferous shales.

Another suitable analogue to the German "Alaunschiefer" could be the U.S. Eagle Ford. Even though the geological age is way off (Eagle Ford is Upper Cretaceous), there are many similarities between the two: Eagle Ford has depth 1200…3000 m, relatively low TOC (3 %), thickness 30…90 m, and porosity 9 %. Moreover, Eagle Ford is overlain by Austin Chalk, while "Alaunschiefer" is overlain by "Kulm / Kohlenkalk", which is a sequence of shale, *limestone* and sandstone. Thus, drilling and completing the intermediate section of the well to access "Alaunschiefer" might encounter similar problems to those experienced in Eagle Ford fields while drilling through Austin Chalk, e.g. kicks and severe losses (Guo et al., 2012a). Most wells accessing Eagle Ford were drilled with OBM in both intermediate and production sections.

Lower Jurassic Posidonia shale

This formation has depth 1550…2150 m, relatively high TOC of 2.0 to 10.5 %, thickness 20…50 m in the North and < 30 m in the South of Germany, and porosity 3…22 % (Andruleit et al., 2012). Even though, by its geological age, Posidonia formation could be considered analogue to the Jurassic Haynesville shale in the U.S., it has much shallower depth (Haynesville's depth: 3200…4000 m). Except age, other properties of Posidonia are closer to those of Eagle Ford (depth 1200…3000 m, TOC 3 %, thickness 30…90 m, porosity 9 %) or Marcellus (depth 1200…2400 m, TOC 2…13 %, thickness 15…75 m, porosity 8 %) U.S. shales. We conjecture therefore that Eagle Ford and Marcellus might be considered as the analogue U.S. shales for Posidonia. Similarity in mineral composition (w.r.t. quartz, carbonate, and clay minerals) between Posidonia shale and Eagle Ford shale demonstrated in (Ladage et al., 2016) suggests that Eagle Ford can be considered as a decent analogue for Posidonia. Well-integrity challenges in Posidonia should therefore be fewer and milder than in Haynesville.

If we assume Eagle Ford as the U.S. analogue, the following well-integrity challenges could be projected onto the Posidonia shale (Guo et al., 2012a, Ridley et al., 2013):

- Losses due to natural fractures in the shale reservoir (fracturing and delamination along bedding planes, reopening of natural fractures running along bedding planes). The presence of extensive natural fracture networks is well-documented for the Posidonia shale (Ladage et al., 2016).
- Losses into overlaying sands during production casing cementing.
- Borehole instabilities, stuck pipe, packoffs, bit balling and low ROP with WBM.
- Overpressure in the reservoir creates well-control challenges (gas influx).
- Sustained casing pressure due to overpressure.

Lower Cretaceous Wealden shale

This formation has depth 1300…1660 m, relatively high TOC of 2.0 to 18.7 %, large thickness 200…830 m, and porosity 4…10 % (Andruleit et al., 2012). The Wealden shale contains layers of coal and sandstone, which may create challenges during drilling and cementing (losses, influxes, washouts). In particular, washouts and fallouts may prevent wells from being perfectly cemented. Poor quality of cement jobs may jeopardize well integrity at later stages in the well life.

Based on its age, depth, TOC and porosity, Wealden shale could be considered similar to the U.S. Eagle Ford (Upper Cretaceous, depth 1200…3000 m, TOC 3 %, porosity 9 %). The following well-integrity challenges could therefore be projected onto the Posidonia shale (Guo et al., 2012a, Ridley et al., 2013):

- Losses due to natural fractures inth shale reservoir (fracturing and delamination along bedding planes, reopening of natural fractures running along bedding planes). The presence of extensive natural fracture networks is well-documented for the Wealden shale (Ladage et al., 2016).
- Losses into overlaying sands during production casing cementing.

- Instabilities, stuck pipe, packoffs, bit balling and low ROP with WBM. (No instabilities with OBM.)
- Overpressure in the reservoir creates well-control challenges (gas influx, including through fractures stimulated from offset wells).
- Sustained casing pressure due to overpressure.

It should be noted that Wealden shales have high clay content (up to 100 %) (Ladage et al., 2016) while Eagle Ford has low clay content (ca. 8 %). Therefore, borehole stability problems might be more common in Wealden. On the other hand, the expected relatively high ductility of Wealden shale (due to its high clay content) might contribute to healing of near-well fractures created during drilling (or microannulus created during subsequent well life), with positive influence on the well integrity in this shale.

Table 17 below sums up the U.S. analogues that could be used to predict drilling and well-integrity challenges that are likely to be encountered during development of Germany's shale-gas fields:

Table 17. U.S. analogues to predict drilling and well-integrity challenges in Germany's shales.

German shale	U.S. analogue
Lower Carboniferous formations in the North ("Alaunschiefer")	Barnett (or Eagle Ford's Austin Chalk for the intermediate well section)
Lower Jurassic Posidonia shale	Eagle Ford
Lower Cretaceous Wealden shale	Eagle Ford

3.2.5 Sweden and Denmark

Alum shale in Sweden and Denmark

Alum shale from Mid-Cambrian to Early-Ordovician (Lower Paleozoic) period underlies most of Denmark, south-central Sweden and a portion of south-eastern Norway (US-EIA, 2015b). Alum shale contains two important source rocks: black organic rich mudstone with TOC of 5-7 % in Middle Cambrian and up to 20 % in the Upper Cambrian, and black and gray inter-bedded mudstone with TOC of about 5 %. Average TOC was estimated to 7.5 % in both Sweden and Denmark (US-EIA, 2015b), which is close to average TOC (7 %) measured from the cores extracted from the exploration wells in Skåne region (Pool et al., 2012). Outcrop samples of Alum shale from Bornholm island gave average TOC of 10 % (Schovsbo et al., 2011). Thickness also varies between the regions: about 20 m in central Sweden, 34...44 m in Höllviken (south-west tip of Sweden), 60...100 m in southern Sweden, 80...90 m in Oslo district, and 160 m in an offshore well in Denmark (Nielsen and Schovsbo, 2006, Erlström, 2014).

The Lower Paleozoic shales are much shallower in the southern Sweden (900...2602 m) (US-EIA, 2015b, Erlström, 2014, Pool et al., 2012) than in Denmark (3353...7000 m) (US-EIA, 2015b, Gautier et al., 2013, Chaîneau et al., 2016). The Alum shale is even shallower in the central Sweden (about 100 m deep in Västergötland for example) (Erlström, 2014). In the central part of the Norwegian-Danish basin the Lower Paleozoic shales reach depths of over 5000 m, whereas around the margin the depths are 2000-4000 m (Schovsbo et al., 2011). The Lower Paleozoic shales for tilted fault blocks underneath Denmark and can be found between 1500 and 7000 m of depth (Gautier et al., 2013). For example, an exploration well onshore in Denmark encountered the Alum shale at 3600 m of depth (Chaîneau et al., 2016).

Based on these sources, the average properties of Alum shale would thus be: TOC of 7.5 %, thickness of about 60 m, and depths of 900...2600 m in Sweden and 3400...7000 m in Denmark.

Based on the information given above, Marcellus shale could be considered a viable analogue for Alum shale in Sweden. The following drilling and well-integrity can thus be expected in Alum shale in Sweden:

- During drilling: wellbore stability, poor hole cleaning, lost circulation, torque and drag.
- Fracture development along bedding planes (delamination).
- Deteriorated well integrity and zonal isolation due to gas migration through cement during setting.
- Sustained casing pressure due to mechanical damage to the cement sheath after cement has set.

Haynesville shale could be considered a viable analogue for Alum shale in Denmark. The following drilling and well-integrity challenges can thus be expected in Alum shale in Denmark:

- Shallow gas influx during drilling the surface hole section.
- Poor (poorer than in Alum in Sweden) performance of WBM.
- High temperature and high-pressure of the reservoir.
- Problems getting production casing to bottom. Having to cement casing off bottom on multiple occasions. This may lead to poor cement sheath quality.
- During drilling in the reservoir, pore pressure can increase to high overpressure over a short interval, leading to kicks and blowouts.
- Lost circulation when one attempts to prevent influx by increasing mudweight.
- Poor hole cleaning.
- Controllable kicks due to intersection of natural fractures.

All in all, due to greater depth, drilling and well-integrity challenges in Alum shale in Denmark are likely to be more severe than in Alum shale in Sweden.

In Sweden, Shell was licensed in 2008 for exploration of unconventional gas resources for a period of three years in the Skåne region (Pool et al., 2012). The purpose was to explore the properties and gas content of the Cambro-Ordovician Alum shale. During previous drilling activities in this region, it was found that the Alum shale layer had a thickness up to 90 m and TOC values up to 15 %, which was promising for exploration.

Three exploration wells were drilled in 2009 to middle of 2010. The final depth of the wells was about 1000 m, and they reached the Middle Cambrian Hardeberga sandstone. Well design included an additional casing when the depth below the aquifer was reached, to prevent/reduce the risk of aquifer contamination by the fluids from the Alum shale. No further details were provided about well design and integrity during the operation in this publication (Pool et al., 2012).

The aim of the first phase of exploration was to core and analyse the Alum shale. Extensive coring was performed over the entire Alum shale formation. A number of cores were analyzed on site for gas desorption, while the remaining cores were preserved for geochemical analysis in the U.S. The obtained data was compared to available literature information on the thickness, lithology, richness and maturity. The thickness, richness and maturity of the shale were as expected, but the average total canister gas content was much smaller than the total storage capacity. Based on the drilling, seismic and shallow borehole data, the depth of the Alum shale in the Colonus Shale Trough was estimated to at most 1500 m in a small region and mostly shallower. This was significantly shallower than previous estimate. Shell concluded that the gas saturation was too low for economically viable extraction. The wells were plugged and abandoned and the site was restored. Consequently, after the initial three-year period, Shell did not renew the exploration licenses. Apart from Shell, there are four other companies which have received exploration licenses in Southern and Central Sweden (Becker and Werner, 2014).

In Denmark, the first shale gas exploration well was drilled in 2015 by Total (Chaîneau et al., 2016). The target was the Alum shale formation that was expected at a depth of about 3600 m (Gautier et al., 2013). Based on the 2D seismic surveys performed in 1984 and 1986, and on the geological interpretation that was performed in 2010-2011, a prospect area was selected. The prospect area partly covered regions of Dybvad and Østervrå. The exact location of the well was selected to meet several criteria including geological, safety, logistical, environmental and societal aspects. The well was drilled between May and September 2015. No details were provided about well design and integrity during the operation in (Chaîneau et al., 2016). Monitoring of the naturally occurring radioactive materials was performed on drill cuttings. Water-base mud was used until a depth of 3600 m was reached. At this depth, the shale formation was cored for analysis and sampling. The analysis confirmed the presence of the gas in the shale. However, it was estimated that it is not economically viable to produce the gas due to insufficient thickness of the shale layer (Chaîneau et al., 2016). The well was then plugged and abandoned, and the site was restored.

Table 18. U.S. analogues to predict drilling and well-integrity challenges in Sweden's and Denmark's shales

Shale in Sweden/Denmark	U.S. analogue
Alum shale in Sweden	Marcellus
Alum shale in Denmark	Haynesville (or Utica)

3.2.6 Ukraine

The following seven deposits may have shale-gas potential (Sachsenhofer and Koltun, 2012):

- Silurian black shales along the western margin of the East European Craton;
- Lower Carboniferous black shales accumulated along the axis of the Dniepr-Donets rift basin (DDB);
- Lower Carboniferous black shales in the Lviv-Volyn Basin;
- Middle Jurassic black shales beneath the Carpathian Foreland;
- Lower Cretaceous black shales in Carpathian flysch nappes;
- Oligocene (Menilite) black shales in Carpathian flysch nappes;
- Oligocene black shales in Crimea.

Due to the lack of information about well-integrity issues that might be encountered during future shale-gas development in these basins, a comparison with U.S. shales is made in the remainder of this Section, and the U.S. experience is then extrapolated onto the Ukrainian shales.

Silurian black shales along the western margin of the East European Craton

Based on their great depth (1500…5000 m), relatively low TOC (< 1.0%), and geologic age (Silurian) (Sachsenhofer and Koltun, 2012), Utica shale could be used as analogue for these Ukrainian shales. Due to high temperature (100…120 °C at 5000 m depth (Krupsky et al., 2013)) and high pressure, the following well-integrity issues may be expected during drilling, production and well abandonment in the Silurian black shales in Ukraine:

- Well control challenges (gas influx) and possible fracturing at casing shoe during drilling; these may happen unexpectedly due to likely heterogeneity of the reservoir (sudden changes in the pore pressure over short distance).
- Mud losses in overlaying strata during drilling and cementing, if mudweight is kept high to prevent influxes. These may lead to poor quality of cementing and, thus, poor zonal isolation.
- High reservoir pressure and temperature may lead to cement sheath deterioration during production and abandonment.
- High reservoir pressure may lead to sustained casing pressure during production.

Managed-pressure drilling (e.g. dual-density drilling) successfully used in shale plays in the U.S. (Ridley et al., 2013) could be used to mitigate well-control issues and their effect on well-integrity in these Ukrainian gas-shale fields. Another solution is to set additional casing points. Loss zones in the upper sections should be sealed by lost-circulation material (LCM) during drilling in order to prevent cement losses and poor quality of cement sheath during subsequent cementing.

Lower Carboniferous black shales accumulated along the axis of the Dniepr-Donets rift basin (DDB) & Lower Carboniferous black shales in the Lviv-Volyn Basin

Based on their age (Lower Carboniferous) and TOC (2…5 %), these shales could be compared to the U.S. Barnett shale (Lower Carboniferous, TOC = 3…12 %). Drilling and cementing challenges in Barnett are due to its great depth (1980…2600 m), thus high pore pressure and temperature. Natural fractures, mineralized with calcite, are common in Barnett (Gale et al., 2007) and may contribute to losses during drilling and cementing. Sand layers in the Ukrainian Lower Carboniferous shales (Sachsenhofer and Koltun, 2012) are likely to create washouts and contribute to losses during drilling and cementing. Washouts lead to subsequent poor cementing since drilling fluids cannot always be fully displaced from a washout (Nelson and Guillot, 2006, Roustaei et al., 2015, Lavrov and Torsæter, 2016). Poor cementing quality may jeopardize well integrity during drilling or at later stages of the well life. In addition, elevated reservoir pressure may contribute to sustained casing pressure.

Middle Jurassic black shales beneath the Carpathian Foreland

Due to their age and depth, these shales can be considered analogue to the U.S. Haynesville shale (Haynesville: Jurassic; depth: 3200…4000 m). The following well-integrity challenges are known in Haynesville and are likely to be encountered in the Ukrainian Middle Jurassic shale (Elshehabi and Bilgesu, 2016), see also Webster J. Presentation "Haynesville Shale. Presentation. Chesapeake Energy":

- Shallow gas may lead to poor well integrity in the surface section.
- Washing out the conductor pipe.
- Problems getting production casing to bottom. Having to cement casing off bottom on multiple occasions. This may lead to poor cement sheath quality.
- During drilling in the reservoir, pore pressure can increase to high overpressure over a short interval, leading to kicks and blowouts.
- Lost circulation and poor hole cleaning.
- Controllable kicks due to intersection of natural fractures.

Lower Cretaceous black shales in Carpathian flysch nappes

With regard to their age and depth, these Ukrainian shales seem to be close to Eagle Ford shale (Upper Cretaceous). However, the Ukrainian shales have carbonate content 19% (9% calcite, 10% dolomite and <1% siderite) and relatively high TOC (2…8 %), while the Eagle Ford shale has 55% calcite and relatively low TOC of 3 % (Guo et al., 2012a). Another analogue shale could be Mancos (Upper Cretaceous, TOC 0.5…4%). If we use Eagle Ford as analogue, the following well-integrity challenges could be projected onto the Ukrainian Lower Cretaceous black shales (Guo et al., 2012a, Ridley et al., 2013):

- Losses due to natural fractures in shale reservoir (fracturing and delamination along bedding planes, reopening of natural fractures running along bedding planes).
- Losses into overlaying sands during production casing cementing.

- Instabilities, stuck pipe, packoffs, bit balling and low ROP with WBM. No instabilities with OBM.
- Overpressure in the reservoir creates well-control challenges (gas influx, including through fractures stimulated from offset wells).
- Sustained casing pressure due to overpressure.

Oligocene black shales in Carpathian flysch nappes & Oligocene black shales in Crimea (Maykop formation)

Oligocene black shales in Carpathian flysch nappes (Menilite formation) have TOC of 12…17%, up to 35%; gas-bearing shales are found at 500…1500 m (Krupsky et al., 2013). Due to the lack of suitable age-wise U.S. analogue, little can be deduced about potential well-integrity challenges in these shales. However, since the formation is heavily folded and faulted, well-integrity issues may be due to (i) fractures and (ii) complex stress regime. Fluid escape into open fractures may create challenges during drilling and cementing. Reactivation of faults during subsequent production may represent a risk since it may lead to casing and cement failure (Dusseault et al., 2001).

Maykop formation in Crimea[2] is 300…5000 m thick, is located at depths 100…5000 m and has porosity 5…30% (Mikhaylov et al., 2014). Folded formation may result in complex stress paths and well integrity issues during drilling and production. Hight temperatures at great depths may create well-integrity issues due to thermal stresses and fatigue in cement.

Table 19. U.S. analogues to predict drilling and well-integrity challenges in Ukraine's shales.

Ukrainian shale	U.S. analogue
Silurian black shales along the western margin of the East European Craton	Utica
Lower Carboniferous black shales accumulated along the axis of the Dniepr-Donets rift basin (DDB)	Barnett
Lower Carboniferous black shales in the Lviv-Volyn Basin	Barnett
Middle Jurassic black shales beneath the Carpathian Foreland	Haynesville
Lower Cretaceous black shales in Carpathian flysch nappes	Eagle Ford or Mancos
Oligocene black shales	No suitable analogue could be identified

3.2.7 Other countries

European countries which have started shale gas exploration or temporary suspended exploration activities, but with little or no information available about the planned or already drilled exploration wells or shale properties on their territories, are mentioned in this section. The information about exploration operations or plans was mostly gathered

[2] Territory de facto under Russia's control.

from online news sources, and as such needs to be considered possible unreliable. Note that not all European countries which have a possibility for shale gas exploration are covered in this section.

The Netherlands

Shale gas exploration was banned in the Netherlands in 2015, for the next five years. This means the existing licenses within this period will not be renewed. Since 2013, the Dutch government has commissioned a number of studies on the environmental consequences, the social effects and the economic viability of shale gas extraction. Exploration drilling can happen only at the request from the Dutch government. Thus, it is still uncertain how much shale gas reserves are present, and whether the Dutch shale plays are promising for commercial development. This implies that the three possible shale gas wells in the Netherlands, indicated in the report by von Estroff et al. (von Estorff et al., 2016), refer to issued exploration licenses. Three companies have acquired exploration licenses before 2015 according to the report by the US Energy Information Administration (US-EIA, 2015b). However, before the exploration was banned, there were 140 wells drilled through the Posidonia shale, which provided data for resource assessment (US-EIA, 2015b).

Recently, Jahszen et al. performed a comparative analysis of the Dutch Posidonia shale and three highly productive shale gas plays in the U.S., namely Barnett, Marcellus and Woodford shales (Janszen et al., 2015). The authors reached the following conclusions:

- The Dutch Posidonia shale has high TOC, high porosity and has likely reached gas maturity, which are all necessary conditions for shale gas production.
- Simple planar fractures are predicted to form upon hydraulic fracturing.
- Due to extreme softness, viscous fracturing fluid with high proppant concentrations would be the most appropriate to keep the fractures opened.

Posidonia shale was discussed also in the section about Germany. For the scarcity of data, it is difficult to assign a definitive U.S. analogue to the Dutch Posidonia shale. We assume therefore that the same analogue shale can be used here as for the German Posidonia shale, i.e. Eagle Ford (Table 20). The following drilling and well-integrity challenges can therefore be expected in the Dutch Posidonia:

- Losses due to natural fractures in the shale reservoir (fracturing and delamination along bedding planes, reopening of natural fractures running along bedding planes). The presence of extensive natural fracture networks has been documented for the Posidonia shale in Germany (Ladage et al., 2016).
- Losses into overlaying sands during production casing cementing.
- Borehole instabilities, stuck pipe, packoffs, bit balling and low ROP with WBM.
- If the reservoir is overpressured, it may create well-control challenges (gas influx).
- Sustained casing pressure due to overpressure.

Table 20. U.S. analogues to predict drilling and well-integrity challenges in The Netherlands' shales.

Dutch shale	U.S. analogue
Lower Jurassic Posidonia shale	Eagle Ford

Lithuania

Unconventional shale plays are located in the Baltic sedimentary basin, and include Middle Cambrian shales/siltstones, Late Ordovician and Early Silurian black shales. The depth of the Lower Silurian shales is within 1000…2000 m. The thickness of the Lower Silurian shales in west Lithuania is 115…180 m (Sliaupa et al., 2016). The Lower Silurian shales are composed of two sections: Llandovery (up to 55 m thick) and Wenlock (80…130 m thick) (Sliaupa et al., 2016). Llandovery section consists of Aeronian graptolitic black shales with rare clayey limestones (1…11 m thick), and Telychian dark grey graptolitic shales (30…40 m thick). TOC above 2 wt% was measured only for the Aeronian shales which are 1…8 m thick in the western part of Lithuania. The average TOC is about 1.5…2.2 wt% in Telychian and Wenlock shales. Lithuanian part of the Baltic sedimentary basin has similar shale gas prospects as the western part of this basin which belongs to Poland. Although the depth and thickness of the shales on the Lithuanian side are more favorable than in Poland, the TOC is at the low limit. The shales in the Baltic basin are discussed in more detail in the section about Poland.

Marcellus shale may serve as an analogue for Lithuanian shales (Table 21). The following drilling and well-integrity can be expected in Lithuanian shales:

- During drilling: wellbore stability, poor hole cleaning, lost circulation, torque and drag.
- Fracture development along bedding planes (delamination).
- Deteriorated well integrity and zonal isolation due to gas migration through cement during setting.
- Sustained casing pressure due to mechanical damage to the cement sheath after cement has set.

Table 21. U.S. analogues to predict drilling and well-integrity challenges in Lithuania's shales.

Lithuania's shale	U.S. analogue
Baltic basin	Marcellus

4 IMPROVING SHALE-GAS WELL INTEGRITY IN EUROPE

Drilling and well-integrity challenges in European shale-gas wells are difficult to predict before the exploration and production activities begin. As our review in Chapter 3 suggests, in-situ conditions vary quite substantially between different basins in Europe. Accordingly, different challenges may be encountered in different countries and different shale plays as exploration and production take off.

Based on a comparison with North American shale plays, well integrity in European shale-gas wells can be improved by consistently applying several measures, and by documenting their success and failure. Openness about successes and failures will ensure continuous improvement of well-construction technologies and will also improve the acceptance of shale gas by the general public.

The following measures can be implemented to improve well integrity in future shale-gas development projects in Europe:

- **Before and during drilling**: Improved **reservoir & caprock characterization**:
  - ➢ Risk analysis and assessment of **potential leakage scenarios** at well-design stage is crucial for short-term and long-term well integrity.
  - ➢ Reservoir and overlying rocks should be thoroughly characterized in terms of **pore pressure** regime. Formation pressure tests, being part of logging-while-drilling (LWD) or wireline logging, should be used regularly. This will enable the operators to prevent well control incidents during drilling and to reduce sustained casing pressure during subsequent well life.
  - ➢ Reservoir and overlying rocks should be thoroughly characterized in terms of **shale properties**, particularly rock mechanical properties and shale activity. This will enable the operators to improve borehole stability in shales.
  - ➢ Reservoir and overlying rocks should be thoroughly characterized in terms of the current **in-situ temperature**. This will enable the operators to improve the quality of well cementing by optimizing cement composition.
  - ➢ Reservoir and overlying rocks should be thoroughly characterized in terms of **in-situ stresses and stress anisotropy**. This will enable the operators to optimize the well design (well trajectory) and to improve borehole stability.
  - ➢ Reservoir and overlying rocks should be thoroughly characterized in terms of **natural fractures and faults**. This will enable the operators to optimize well trajectory in directional drilling and to avoid mud losses and borehole failures, both during drilling and cementing. More (and more detailed) information about fracture properties (connectivity, dimensions, apertures) could be obtained by better interpretation of image logs and formation pressure tests.
  - ➢ Characterization of reservoir & caprock should be **continuously updated** as drilling and field development advance.

- During drilling and well construction:

- ➢ Implementation of **best drilling practices** to minimize damage to the borehole and thus to make the wellbore cross-section more regular. This will reduce washouts and breakouts. This will later improve the quality of the cement sheath by preventing mud channels and mud pockets that otherwise might build up in washouts and breakouts. It will also reduce problems associated with hole cleaning and running casing in hole.
- ➢ Prevention of **bit balling** and **pack-offs**.
- ➢ Optimization of **mud weight** to prevent instabilities and formation fluid influxes.
- ➢ Optimization of **mud composition** to reduce borehole instabilities. **Oil-base mud** usually performs better in shale.
- ➢ Minimization of (future) casing corrosion by properly selecting the **casing material and/or coating**.
- ➢ Minimization of (future) cement deterioration by optimizing **cement composition**.
- ➢ Cement practices must ensure **optimal cement placement** and **prevent gas migration** during primary cementing jobs.
- ➢ Post-job evaluation of the cement sheath quality (**cement logging**).

- During gas production and after well abandonment:
  - ➢ Continuous **monitoring of sustained casing pressure and gas migration** in order to evaluate the cement sheath integrity.
  - ➢ Monitoring of soil contamination.

- Data pertaining to well integrity (e.g. lithology, shale properties, in-situ temperatures and stresses, well design schematics, leakage and sustained casing pressure data, well-integrity case histories) should be **available in public domain** and should be regularly updated by the operators. This should enable examination by independent research contractors and government authorities at any time.

5 CONCLUSION

Presently, there are only shale gas exploration activities in some European countries. This makes it difficult to provide targeted advice on improving well integrity in European shale-gas wells. It is, however, possible to try and make a comparison between the U.S. shales (where production is underway and at least some information about well-integrity and drilling issues is publicly available) and European shales. This is the approach chosen in this report.

Analogue U.S. shales for shales in several selected European countries were identified in terms of shale properties and geology data relevant for well integrity. American experience was then projected onto the European shales. This comparison shows that well-integrity issues in Europe might be as diverse as they are in the U.S., depending on the reservoir depth, reservoir overpressure, clay content, etc. It also suggests that well-integrity challenges in European shale plays can be overcome by the operators, just as they have been overcome in the U.S. When shale-gas exploration and production take off in Europe, well integrity is, in fact, likely to be better than in the U.S. since

(i) American experience and technological solutions are already available, thus some trial-end-error pathways can be reduced and
(ii) technology is likely to become significantly more advanced by the time commercial shale-gas production in Europe starts.

6 ACKNOWLEDGEMENTS

We are grateful to Ivan Karpenko (Naftogaz of Ukraine) and Gennady Mishuris (Aberystwyth University) who helped us locate some references used in the preparation of this report.

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