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Autor(en): **Leu, Werner / Gautschi, Andreas**

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# The Shale Gas Potential of the Opalinus Clay and Posidonia Shale in Switzerland – A First Assessment

Werner Leu[1], Andreas Gautschi[2]

**Keywords:** Shale gas, Opalinus Clay, Posidonia Shale, Switzerland, Molasse Basin, organic richness, thermal maturity, recoverable gas resources

**Abstract**
There has been recent interest in the shale gas potential of the Opalinus Clay and Posidonia Shale (Middle and Lower Jurassic) below the Swiss Molasse Basin in the light of the future role of domestic gas production within the expected future energy shift of Switzerland and possible conflicts in underground use. The Opalinus Clay of northern Switzerland is a potential host rock for repositories of both high-level and low-to-intermediate level radioactive waste and the exploitation of shale gas resources within or below this formation would represent a serious conflict of use.

Well data from northern Switzerland shows that these two formations are unsuitable for future shale gas recovery. They never reached the gas window during their burial history (maturity values are ≤ 0.6% $R_0$) and as a consequence never generated significant quantities of thermogenic gas. Geochemical data further shows that the average TOC values are in the range of 0.7%, i.e. clearly below accepted values of more than 1.5% for prospective shales.

A review of available exploration data for the Opalinus Clay and Posidonia Shale in the deeper and western part of the Swiss Molasse Basin indicate that their shale gas potential may be substantial. The gross Posidonia Shale thickness increases from central Switzerland from less than 10 m to over 100 m in the Yverdon-Geneva area and is characterised by numerous bituminous intervals. A simplified shale gas resource calculation results for a geologically likely scenario in a technically recoverable gas volume of ~120 Mrd. $m^3$. The current database for such estimates is small and as a consequence, the uncertainties are large. However, these first encouraging results support a more detailed exploration phase with specific geochemical and petrophysical analysis of existing rock and well log data.

## 1 Introduction

Recently, the Opalinus Clay (Middle Jurassic, Aalenian) and the underlying Posidonia Shale (Lower Jurassic, Toarcian) of the Swiss Molasse Basin have been mentioned in connection with the search for shale gas (Chew 2010, Leu 2014a). Also the *European Shale Gas Map* (JPT 2012) shows two potential resource plays in Switzerland: Jurassic Shales (probably the Opalinus Clay and the Posidonia Shale) to the north of Lake Geneva and Permian Shales in the eastern part of the Molasse Basin.

The shale gas potential of these formations is currently being discussed in Switzerland because of two reasons: a] domestic natural gas resources, if present, could play an important role in the envisaged energy transition and b] conflicting interests in the future use of the deep underground (natural resources, storage, water, geothermal energy etc.).

In particular, the Opalinus Clay in northern Switzerland is a potential host rock for repositories for both high-level and low- to intermediate-level radioactive waste (Nagra 2008). The conceptual part of the *Sectoral Plan for Deep Geological Repositories* sets out the procedure and criteria for selecting sites for repositories for all waste categories in Switzerland (SFOE 2008). One of the criteria to be evaluated (criterion 2.4) relates to conflicts of use. Within and beneath the host rock, there must be no natural resources that would be worth exploiting in the fore-

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[1] Geoform Ltd., 1844 Villeneuve, Switzerland
[2] Nagra, 5430 Wettingen, Switzerland

seeable future with the potential for conflict of use. Exploiting such resources within or beneath the host rock formation of a radioactive waste repository could compromise the long-term stability of the barrier system, either by damaging the geological barrier or by drilling directly into disposal caverns. The shale gas potential of the Opalinus Clay and the Posidonia Shale [corresponds to Rietheim Member of the Staffelegg Formation (Reisdorf et al. 2011)], as one possible conflicting natural resource, has been evaluated as part of stage 2 of the Sectoral Plan process (Leu 2014b, Leu & Gautschi 2012).

The objective of this paper is to provide a first assessment of the shale gas potential of these Jurassic formations and its distribution within the entire Swiss Molasse Basin. The analysis differentiates between northern Switzerland (wider area surrounding the potential siting areas for radioactive waste repositories) and the more southern parts of the Molasse Basin (Central/Western Switzerland).

## 2 Shale gas: origin, recovery technology and rock parameters

### 2.1 Origin of shale gas

Besides coal bed methane and oil shales, gas shales are part of the group of unconventional resource plays (EIA 2011).

Shale gas consists principally of methane stored in micropores and in fractures within an organic rich shale formation (bituminous shale). Part of the gas is further adsorbed on organic components and clay minerals within fine-grained sediments (Passey et al. 2010, Jarvie et al. 2007, Curtis 2002, Canadian National Energy Board 2009). The gas is generated by biogenic (early diagenetic and recent; see below) and thermogenic processes during geological burial and in situ heating within the source rock.

The term *shale gas* originates from the common use of the term *shale* to describe the group of extremely fine-grained sedimentary rocks like clay- and mudstones composed of particles like clay, quartz, feldspars, organic matter and heavy minerals (Passey et al. 2010). The particle size is generally in the range of < 2 microns up to 62.5 microns (clay and silt fraction).

Part of the hydrocarbon gases that are generated within the organic particles escapes from the source rock rock (primary migration) and migrates into more porous, generally overlying reservoir layers that are sealed at the top with a tight barrier (classical or conventional gas plays). Shale gas is the gas component that remains trapped in the tight, fine-grained rock and cannot normally escape without artificial stimulation by fracturing technology and preferably drilling of horizontal wells. These reservoir rocks have permeability's in the micro- to nanodarcy range (BGR 2012). A gas shale is therefore a source rock, a reservoir and a seal in one and the same formation (*resource play*). Today it is well known that often the greater part of generated gases remains trapped within the source rock (Burri et al. 2011, Burri 2010).

It has only been recognised in recent years that biogenetically generated methane can form economically viable gas deposits in argillaceous rocks. Examples of this are the New Albany Shale (Tab. 1; Devonian, Illinois Basin, USA) and the Antrim Shale (Devonian, Michigan Basin USA; Martini et al. 1996 and 1998). Two types of biogenic methane formation are distinguished: a) early diagenetic biogenic processes related to alteration and decomposition of organic material that begins shortly after deposition of the sediment and b) relatively recent (last 1 to 2 million years) methanogenesis related to bacterial activity associated with the infiltration of meteoric waters into near-surface decompaction and fracture zones. Theoretically it is possible to distinguish between the two biogenic and the thermogenic gas fractions, using carbon and hydrogen isotopes of methane, ethane, propane and $CO_2$. Complex mixing processes, however, often make the distinction not very straight forward (Shurr & Ridgley 2002, Martini et al. 2003, Curtis 2002 and 2010).

### 2.2 Typical rock characteristics of proven shale gas resource plays

Successful shale gas formations that have been proven to be capable of producing gas at commercial rates can be characterised using typical values for specific rock parameters. However, experience over the last ten years has also shown that economic recovery is often dependent on a combination of these rock parameters that are very specific for one region. This clearly indicates that there is no unique «recipe» for exploration of shale gas resources and each basin and stratigraphic unit has its own learning curve. Several tens of specifically designed exploration wells are normally necessary to assess the technical and economic potential. As part of a broad based comparative study, Gilman & Robinson (2011) showed that the minimum values that are generally published for typical rock parameters are often too pessimistic and that other factors such as stimulation technology, reservoir temperature or natural fracture intensity also play an important role.

The following key rock parameters have to be investigated when exploring shale gas plays:

- *Organic richness* (TOC, total organic carbon): Determines the amount of hydrocarbons that can be formed by the transformation of kerogen. TOC has also a positive correlation with the total gas filled porosity in shales (micro pores and adsorption in organic particles, Passey et al. 2010).
- *Thermal maturity*: Measure for the degree of transformation of kerogen into hydrocarbons (Fig. 1; early biogenic or thermogenic formation during burial; oil window, gas window).
- *Rock mineralogy*: The fractions of clay minerals, quartz and carbonate and organic matter determine the microporosity, and hence the possible total storage volume of free gases. The mineralogy also influences the brittleness of the rock for hydraulic stimulation (Fig. 2).
- *Thickness* of the shale formation: Determines the overall gas in place per unit area.

Examples of typical rock characteristics for historical shale gas formations with economic production in the USA are summarised in Table 1 (Curtis 2010, see also EIA 2011).

Formation depth is only a relevant factor for economic consideration because it influences the necessary drilling costs to reach the target formation. Prospective areas should have shale resources in the depth range of 1.000 m to 5.000 m (EIA-ARI 2013). Porosity, permeability and the density and type of the natural fracture network are also important, but are secondary parameters that determine the production rate and recovery factor. Regions with intense and deep reaching fault tectonics are normally avoided because of the increased risk of triggered earthquakes and possible inflow of formation waters from over or underlying formations.

The depositional environment determines the kerogen type (I-II-III) in sedimentary rock. Valid shale gas formations could have been deposited either in a marine, a lacustrine or a terrigenous (swamp) environment, as long as the organic richness is high (Fig. 2). Marine and lacustrine shales have a greater potential to produce also oil before the gas. But marine shales tend to have a lower clay content with a higher proportion of brittle minerals such as quartz, feldspar or carbonates (EIA-ARI 2013).

The key rock parameters organic richness, thermal maturity, hardness and formation thickness (discussed above) should generally lie at least within the ranges compiled in Table 2.

If reference wells are available in an exploration area, various parameters like TOC, mineralogy or porosity can be estimated or calculated using geophysical measurements from wireline logs (e.g. Passey et al. 2010). To optimise the hydraulic stimulation parameters, geomechanical properties and local stress states are increasingly being determined from well data (borehole wall breakouts, analysis of dipole sonic and image logs).

## 3 The shale gas potential of the Opalinus Clay and the Posidonia Shale in Northern Switzerland

### 3.1 Key shale rock properties (Northern Switzerland)

The Opalinus Clay, together with the directly underlying Posidonia Shale (Toarcian) has been considered in the context of the conventional hydrocarbon exploration as a potential source and cap rock (Brink et al.

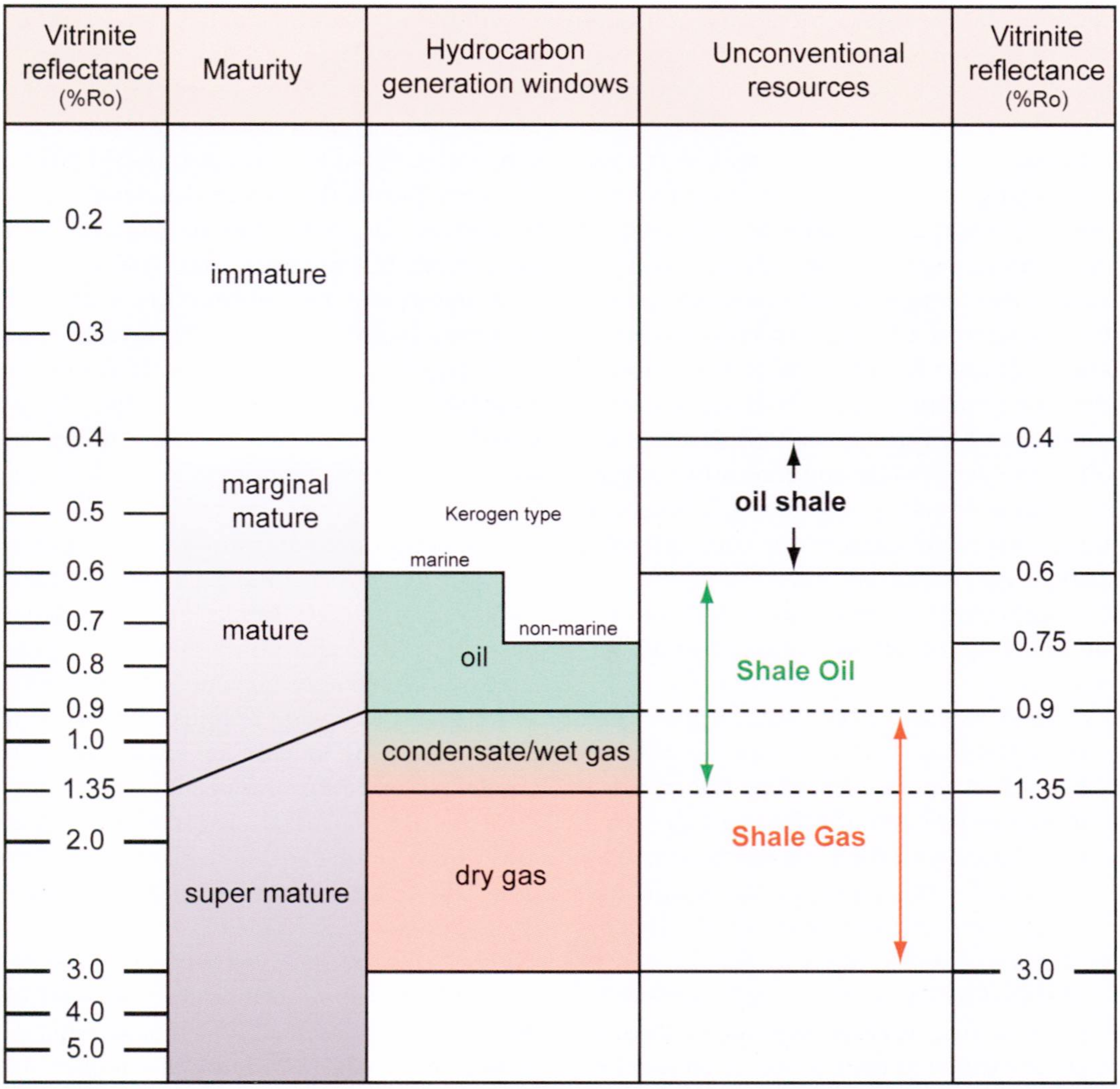

Fig. 1: Thermal maturation scale (vitrinite reflectance) with typical values for oil shale, shale oil and shale gas rocks (modified after EIA-ARI 2013, BGR 2012).

1992, Greber et al. 1997, Schegg et al 1999). Boyer et al. 2011 include also the Swiss/German Molasse Basin in their global shale gas review and Chew (2010) mentions explicitly the Jurassic shale formations in Switzerland in connection with the shale gas exploration activities of the company Schuepbach Energy LLC in Cantons Fribourg and Vaud. Although the Toarcian Posidonia Shale in northern Switzerland may reach up to 10 wt.% TOC (Todorov et al. 1993, Bitterli 1960) its overall thickness remains less than 10 m in the potential siting areas of Northern Switzerland (Kiefer et al. 2014) and any assessment of the shale gas potential has to concentrate in this area on the Opalinus Clay. Related to its shaly lithology with elevated organic contents (grey to brownish/black colours) this Middle Jurassic unit has some similarities to known historic shale gas formations (Tab. 1) but also very distinct differences.

A detailed compilation of key rock parameters of the Opalinus Clay for northern Switzerland based on ten Nagra exploration wells and further data from the Mont Terri underground rock laboratory (Mazurek 2011, Nagra 2002) have been summarized in Table 3.

Very low organic richness values of ~0.7 wt.% TOC indicate that the Opalinus Clay is a rather lean source rock in this area and stays clearly below accepted minimum values of ~1.5 wt.%. Other formations that are also being investigated by Nagra as potential host rocks (e.g. «Brauner Dogger» and Effingen Member) have even lower values for TOC

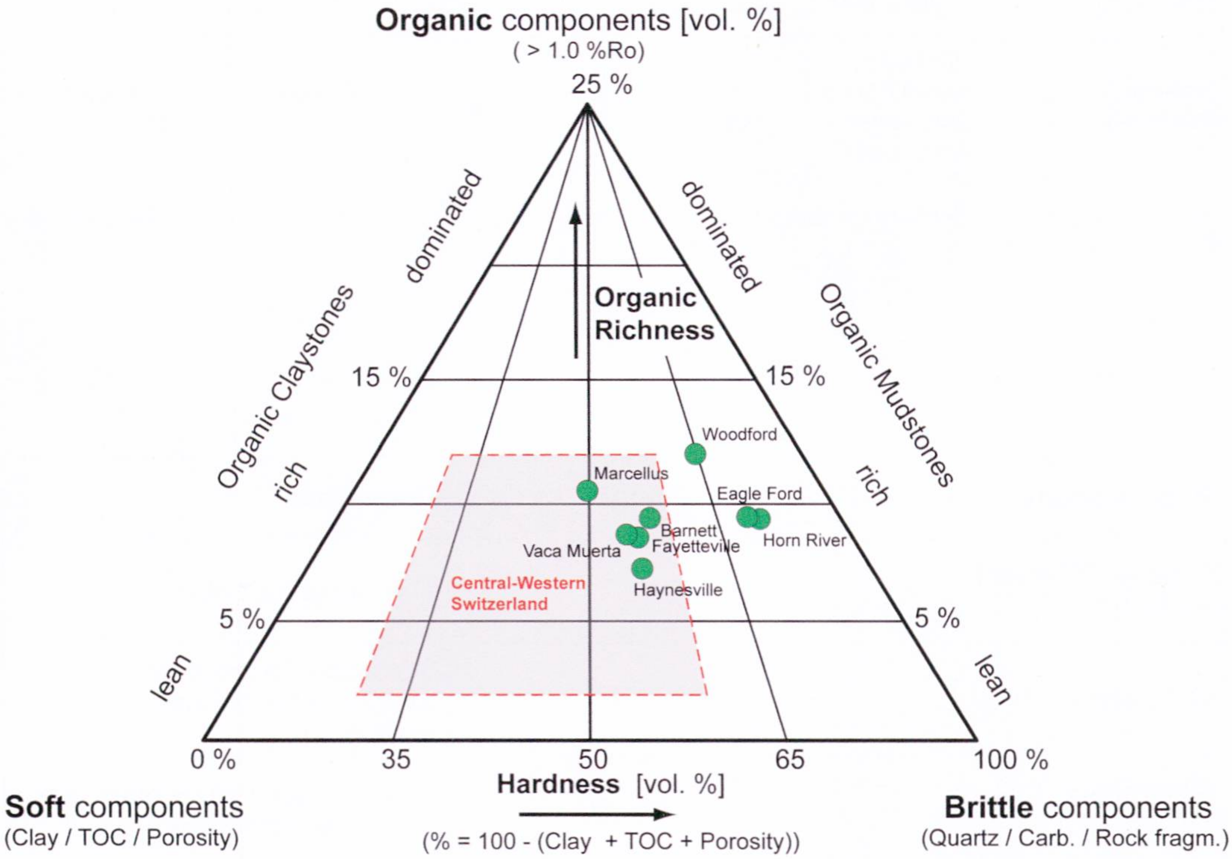

Fig. 2: Characterization by compositional properties of shale reservoirs (modified from Ottmann & Bohacs 2014). The horizontal axis is a measure of the rock hardness, differentiating between soft and more brittle components. The vertical axis describes the organic richness (total organic content). Note that all units are in volume percent. Successful US shale reservoir rocks are indicated with green circles and potential shale gas reservoirs (Opalinus Clay and Posidonia Shale) of Western-Central Switzerland plot within the stippled outline.

| **Property** | **Barnett Shale** | **Ohio Shale** | **Lewis Shale** | **Antrim Shale** | **New Albany Shale** |
|---|---|---|---|---|---|
| **Basin** | Fort Worth | Appalachian | San Juan | Michigan | Illinois |
| **Age** | Mississipian | Devonian | Cretaceous | Devonian | Devonian |
| **Lithology** | Black/grey shale | Black/grey shale | Siltstone | Black shale | Black shale |
| **Kerogen transformation** | Thermogenic | Thermogenic | Thermogenic | Biogenic | Thermogenic /biogenic |
| **Maturation** [VR%] | 1.1–1.4 | 0.6–1.9 | 1.6–1.9 | 0.6–0.7 | 0.6–1.2 |
| **Richness** [wt.% TOC] | 2–5 | 2–6 | 0.5–1.75 | 5–15 | 5–20 |
| **Porosity** [%] | 3–7 | 2–6 | 2–5 | 5–12 | 5–12 |
| **Mineralogy** [% non-clay] | 45–70 | 4–60 | 50–75 | 55–70 | 50–70 |
| **Thickness** [m] | 60–120 | 90–300 | 150–580 | 50 | 55 |
| **Depth** [m] | 2.100–2.600 | 760–1.830 | 1.370–1.830 | 150–760 | 300–760 |
| **Natural fractures** | Critical to product./faults into lower water beds | Critical to productivity | Important | Critical to productivity | Critical to productivity |

Tab. 1: Examples of rock characteristics of historic shale gas plays exploited economically in the USA today (Curtis 2010, modified).

| **Rock property** | **Range** | **Comments** |
|---|---|---|
| **Organic Richness** [wt.% TOC] | > 1.5 | The higher the better |
| **Maturation** [VR%] | (0.6) – 1.2 – 3.0 | Secondary for biogenic transformation (oil/gas window see Fig. 1) |
| **Mineralogy** [% non-clay] | > 30 – 50 | Quartz + carbonate + other rock fragments, brittleness |
| **Thickness** [m] | > 20 – 50 | |

Tab. 2: Key shale rock properties and their minimal requirements for potentially economic shale gas plays (compiled after Jarvie et al. 2007, Gilman & Robinson 2011, Curtis 2010).

and maturity than the Opalinus Clay (Mazurek 2011).

The relatively low maturity values (immature to lower boundary for the oil window, Tab. 3, Fig. 1) of the Opalinus Clay in northern Switzerland is well documented with data from detailed analysis in wells Benken, Weiach, Herdern-1 and the Mont Terri rock laboratory (Fig. 3).These values are in good agreement with the regional coalification trend of increasing maturity values of this stratigraphic interval towards the Alpine front (Fig. 4).

### 3.2 Observed gas occurrences in the Opalinus Clay in northern Switzerland

In Nagra's deep boreholes in northern Switzerland, continuous gas measurements were carried out as part of the drilling fluid monitoring programme (Hinze et al. 1989, Jäggi & Steffen 1999). The measured gas concentrations were always very low when drilling through the Opalinus Clay, with methane concentrations < 100 ppm (< 0.01 vol.%). No trip gas peaks were observed, with the exception of a small peak (< 100 ppm) in the lowermost clayey facies in the Riniken borehole. In comparison, the methane concentrations in the Muschelkalk and the Permo-Carboniferous were several orders of magnitude higher and marked trip gas peaks were observed regularly.

In connection with stress measurements, two multiphase hydro-fracturing tests with repeated cycles were carried out in the Opalinus Clay in the Benken borehole (Nagra 2001). Well stimulation of this type generates fractures with surfaces in the order of one to a few square meters. None of these tests indicated the presence of a free gas phase. This is further confirmed by investigations on numerous core samples, where combined porosity/water content and hydrochemical analysis resulted in 100% water saturation in the Opalinus Clay. It can be concluded that the mud gases observed during drilling are dissolved in pore water under in situ downhole conditions.

Similar observations were made in the Mont Terri underground rock laboratory: during tunnel excavation gas measurements in the tunnel atmosphere showed only very low methane concentrations (i.e. below the detection limit of 0.05 vol.%; written communication, Dr. Paul Bossart, swisstopo). Methane influx into sealed test boreholes monitored over longer times under high hydraulic gradients was also very low (methane flux 1.7 × $10^{-5}$ mol/day/$m^2$; written

| **Rock property** | **Opalinus Clay**<br>(Northern Switzerland) | **Accepted minimum values**<br>(see Tab. 2) |
|---|---|---|
| **Organic Richness**<br>[wt.% TOC or $C_{org}$] | **0.7** ± 0.4 | > 1.5 |
| **Maturation** [VR%] | 0.5 – **0.6** | (0.6) – 1.2 – 3.0 |
| **Mineralogy** [% non-clay] | **35** ± 10 | > 30 – 50 |
| **Thickness** [m] | **80 – 140** | > 20 – 50 |

Tab. 3: Average rock property values for the Opalinus Clay in Northern Switzerland (Mazurek 2011, Nagra 2002) compared to accepted minimum values (Tab. 2).

communication Dr. Agnès Vinsot, Andra). Also gas migration experiments, including numerous hydro-fracturing tests gave no indication of a free gas phase (Bossart & Thury 2008).

The isotopic ratios of methane, ethane, propane and carbon dioxide of the head-space gases in boreholes in the Opalinus Clay at the Mont Terri further indicate that the formation of gases is complex. Thermogenic gases generated at temperatures above 60 °C are subsequently altered by bacterial processes. In addition diffusive migration from underlying layers cannot be ruled out (Eichinger et al. 2011). None of the known economic shale gas plays indicate gas migration from underlying, more mature source rocks.

## 4 The shale gas potential of the Opalinus Clay and the Posidonia Shale in Central and Western Switzerland

### 4.1 Formation thickness, organic richness and thermal maturity

The question remains if the Opalinus Clay and the Posidonia Shale in the central and western part of the Swiss Molasse Basin could have some relevant shale gas potential. Data remain scare with only a few deep wells that indicate that the Liassic in general is thickening towards the west with a basin centre in the Besançon-Geneva area (e.g. Röhl & Schmidt-Röhl 2005, Bitterli 1972, Büchi et al. 1965, Sommaruga 1996, Sommaruga et al. 2012). In well Essertines-1 (Schegg et al. 1997) in the north-western part of the Molasse Basin the Opalinus Clay has a thickness of over 150 m and the Toarcian Shales 93 m, respectively.

The organic richness (TOC) is likely to increase towards viable levels in the range of 1-4 (max. 10) wt.% in the Posidonia shale along the basin axis towards the southwest, as indicated by some data in wells Essertines-1 and Treycovagnes-1 (see also Schegg et al. 1999 and Todorov et al. 1993). The organic content in the overlying Opalinus Clay is expected to remain below 1.0 wt.%, related to a lithological transition from shale dominated to more carbonate rich platform facies towards the west (Nagra 2008).

Despite these large uncertainties a comparison with successful shale formations of the US in a rock hardness/organic richness triangular plot (Fig. 2) indicates that some of the characteristics could overlap. The available data for the Molasse Basin (not including northern Switzerland) plot in a hardness range of 20-60% and an organic richness range of 2-12 vol.%.

The maturity of the Opalinus Clay to Posidonia Shale interval (Fig. 4) is clearly increasing from oil window levels (0.6-0.9% $R_0$) into the gas window (> 0.9% $R_0$) towards the Alpine front. The iso-reflectance lines run slightly oblique to the Molasse Basin axis with generally higher maturities further north and at shallower depth towards the western part of the basin. Hence, an interesting corridor for potential shale gas resources (maturity range of 0.9 to 1.35% $R_0$, condensate/wet gas, Fig. 1) with a width of 15-30 km extends from Lake Constance over Lucerne-Berne towards Lausanne and across Lake Geneva below the Molasse Basin (see also Leu 2014b). The potential clearly increases from central to western Switzerland related to more favourable rock characteristics (see above) and generally shallower depth. The northern edge of the potential trends lies in depths of at least 2.000 to 2.500 m, whereas the southern limit reaches ~5.000 m (economic floor) in the east and 3.500-4.000 m in the west. The depths are extrapolated from the available deep well information and depth maps based on seismic data (e.g. Sommaruga et al. 2012).

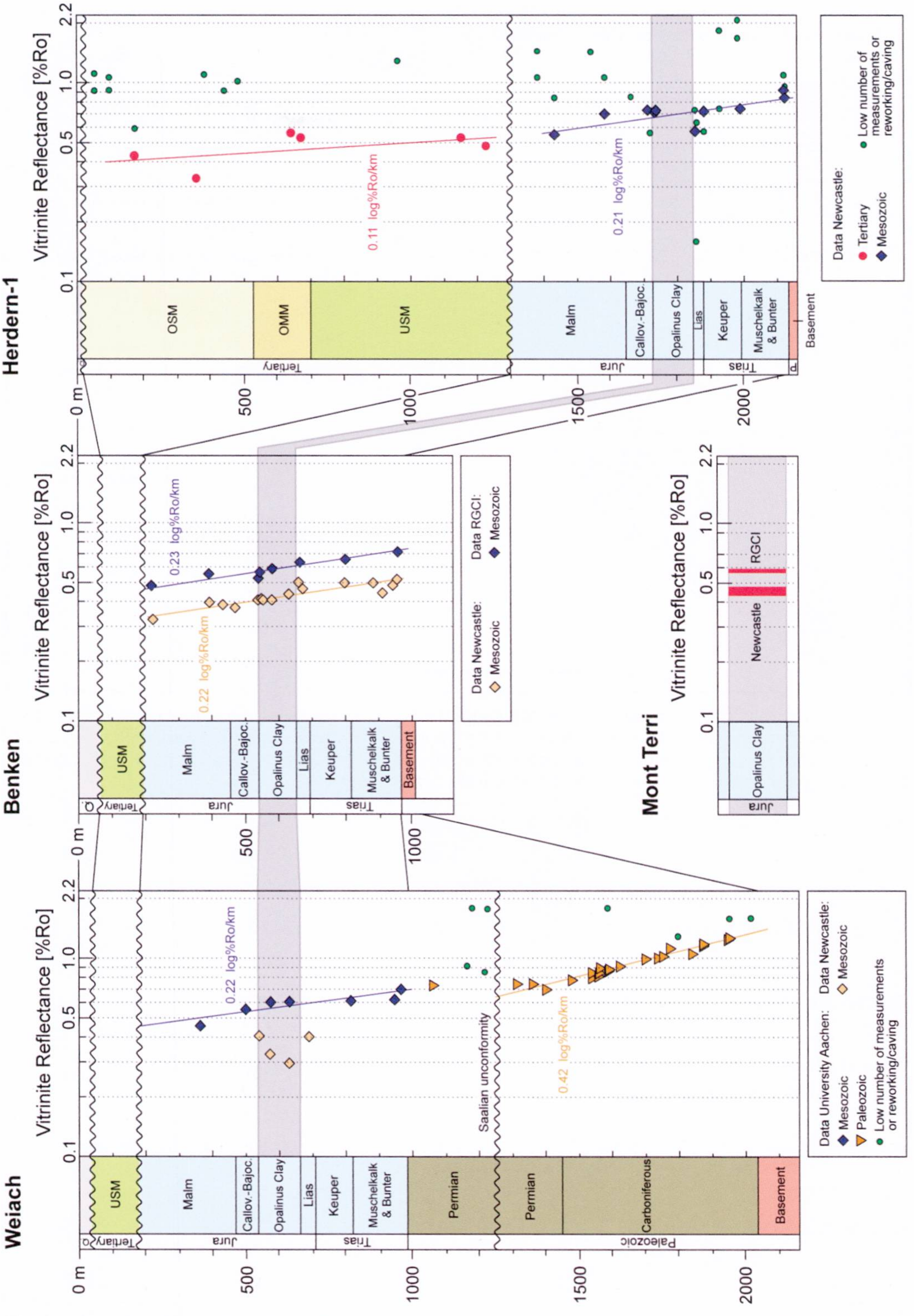

Fig. 3: Maturity profiles in Northern Switzerland based on cores and cuttings from wells Benken, Weiach and Herdern-1. For comparison also data of the Mont Terri underground rock laboratory are shown (Nagra 2002).

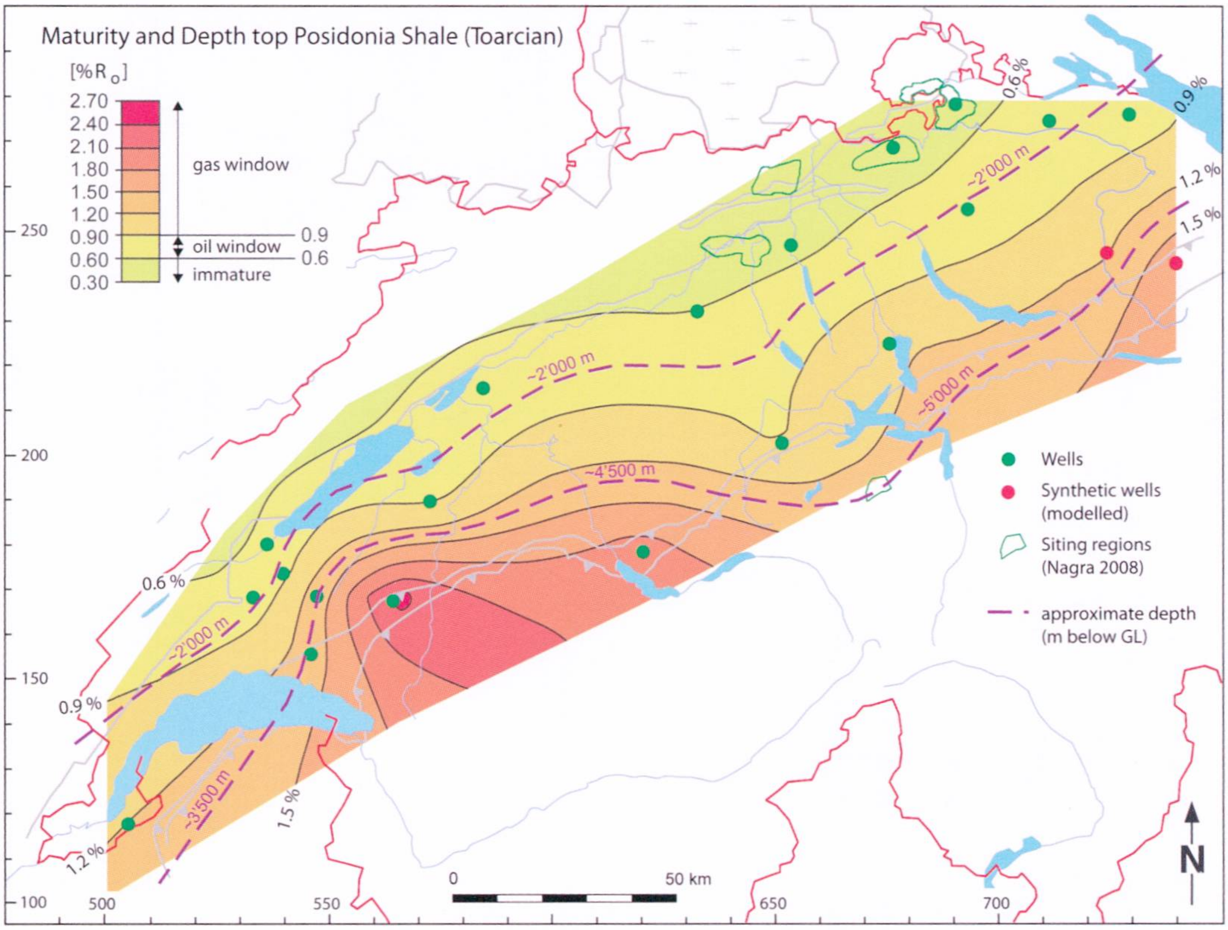

Fig. 4: Maturity map of the transition Base Opalinus Clay/Top Toarcian (Posidonia Shale) with approximate depths below ground level. Map constructed using borehole data and synthetic basin modelling points (after Greber et al. 1997, modified). The geological siting regions in northern Switzerland (Nagra 2008) are outlined in green and the depths were estimated from Sommaruga et al. (2012).

| | | Low | Likely | High |
|---|---|---|---|---|
| **Gas in place GIP/unit rock** | [m$^3$/m$^3$] | 7 | **10** | 30 |
| **Thickness shale** | [m] | 20 | **40** | 100 |
| **Area shale play**<br>(depth ~2.000 – 4.500 m) | [km$^2$] | 1.000 | **3.000** | 5.000 |
| **Recovery factor** | [%] | 5 | **10** | 20 |
| **Recoverable shale gas** | [Mrd. m$^3$] | 7 | **120** | 3.000 |
| | [TCF] | 0.2 | **4.2** | 106 |

Tab. 4: Estimate of technically recoverable shale gas volume of the compound Opalinus Clay/Posidonia Shale interval in Central and Western Switzerland. Gas volumes are given for standard temperature and pressure conditions. See text for explanations for the three scenarios.

## 4.2 Estimate of technically recoverable gas volumes

Keeping in mind the above discussed uncertainties, it is possible to estimate the technically recoverable shale gas potential for the Swiss Molasse Basin for the Opalinus Clay and the underlying Posidonia Shale (Tab. 4). Detailed procedures for the calculation of recoverable shale gas reserves are described in BGR (2012) or EIA-ARI (2013). As no specific data are currently available for several parameters used in the Molasse Basin we have chosen the following simplified approach:

$$\text{Recoverable gas } [m^3] = \text{GIP/unit rock } [m^3/m^3] \times \text{thickness } [m] \times \text{area } [m^2] \times \text{recovery factor } [\%]$$

Three individual scenarios were calculated: a] «Low» case, where all four parameters are unfavorable, b] «Likely» case representing median values ($P_{50}$) and c] «High» case, where all four parameters would be very favorable.

For the GIP (gas in place per rock unit) norm values we took the assumptions for the Posidonia Shale as proposed by BGR (2012). A likely value of 10 $m^3/m^3$ is conservative compared to their range of 7 to 38 $m^3/m^3$ ($P_{05}$ to $P_{95}$). Productive shale gas plays in the US have values in the range of 5 to 25 $m^3/m^3$ (e.g. Curtis 2002).

For the net prospective shale thickness a likely value of 40 m and for the likely prospective region an area of roughly 20 × 150 km is assumed. Depending on the lithological characteristics of the shale formation and assuming today's state-of-the-art production technology (drilling and stimulation) only a fraction of the GIP volume can be produced. In the US such recovery factors are in the range of 5 to 25% with some exceptionally high values of up to 60% in the Antrim Shale of Michigan (Tab. 1, Curtis 2002, EIA-ARI 2013). For the Posidonia Shale assessment of Germany a likely value of 10% was assumed (BGR 2012).

In the likely scenario a technically recoverable shale gas volume of 120 Mrd. $m^3$ results (Tab. 4). In comparison, the current annual gas consumption of Switzerland is 3.5 Mrd. $m^3$ and 100 Mrd. $m^3$ for Germany. The wide range between the low scenario (7 Mrd. $m^3$) and the high scenario (3.000 Mrd. $m^3$) reflects the uncertainties at this early stage of exploration in the Swiss Molasse Basin.

# 5 Conclusions

The Opalinus of Clay and Posidonia Shale of northern Switzerland are characterised by two parameters that are unsuitable in terms of future shale gas recovery: TOC and maturity. These formations did not reach the gas window during their burial history (maturity values are ≤ 0.6% $R_0$) and as a consequence significant thermogenic gas generation never occurred.

Geochemical data for northern Switzerland further show that the average TOC values are in the range of 0.7%, i.e. clearly below an accepted value (> 1.5%) for prospective shales.

A review of available exploration data for the Opalinus Clay and Posidonia Shale in the deeper and western part of the Swiss Molasse Basin indicate that their shale gas potential may be substantial. Especially, the gross Posidonia Shale thickness increases from central Switzerland to over 100 m in the Yverdon-Geneva area.

A simplified calculation of the technically recoverable shale gas indicates that for a geologically likely scenario a volume of around 120 Mrd. $m^3$ is possible. The current data base for such estimates is small and as a consequence the uncertainties large. However, these first encouraging results support a more detailed exploration phase with specific geochemical and petrophysical analysis of existing rock and well log data.

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