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# **Studie zur Abschätzung des Potenzials für CO<sub>2</sub>-Sequestrierung in der Schweiz**

**Potential for geological sequestration of CO<sub>2</sub> in Switzerland**

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## Abstract

One approach to dispose of the greenhouse gas CO<sub>2</sub> is to inject it into deep, porous geological formations, where it remains safely trapped over periods of many millennia. This report evaluates the potential for this option within Switzerland, based on a literature review.

Only geological criteria for CO<sub>2</sub> sequestration are taken into account, following international best-practice principles for reservoir safety. Simultaneous consideration of nine geological attributes (including faulting and natural seismicity) allows the sequestration potential to be mapped at a resolution of a few km<sup>2</sup>, using a scale between 0 (negligible potential) and 1 (high potential).

It is concluded that the crystalline rocks of the Alps and the sediments underlying the valleys of Valais, Ticino and Grisons are unsuitable for CO<sub>2</sub> sequestration. However, the sedimentary rocks below the Central Plateau (and to lesser extent below the Jura Chain), locally show moderate to very good potential. At least four formations of porous sandstones and limestones (saline aquifers) underlie large areas of the Plateau within the technically favoured depth interval of 800–2500 m. Approximately 5000 km<sup>2</sup> of the Plateau (mostly in the sector Fribourg–Olten–Luzern) exhibits sequestration potentials above 0.6, offering a theoretical (unproven) storage capacity for approximately 2680 million tonnes of CO<sub>2</sub>.

From a purely geological point of view these results are promising. Although the high potentials do not guarantee the feasibility of CO<sub>2</sub> sequestration, they serve as guides to areas that warrant detailed investigation. If this CO<sub>2</sub> storage option is pursued in Switzerland, then more detailed geological investigations and a pilot study would be necessary to prove its feasibility. The assessed risks, leakage-monitoring procedures and non-geological criteria (proximity to CO<sub>2</sub> point-sources, economics, conflicts of use of the subsurface, etc.) would have to be taken into account.

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# Executive summary

## Potential for geological sequestration of CO<sub>2</sub> in Switzerland

Summary of report prepared for the Swiss Federal Office of Energy by L.W. Diamond (University of Bern), W. Leu (Geoform Ltd.) and G. Chevalier (University of Bern), August 2010

Reduction of anthropogenic CO<sub>2</sub> emissions is considered by the scientific community to be a necessary step towards mitigating climate change. One of the many approaches to this problem is to capture waste CO<sub>2</sub> from industrial sources and inject it into deep, porous geological formations. Under optimal geological conditions, huge amounts of CO<sub>2</sub> can be stored (sequestered) safely over periods of many millennia. This report estimates the theoretical potential for the geological sequestration option within Switzerland.

Only geological criteria for CO<sub>2</sub> sequestration have been taken into account. The conclusions are based on a review of over 150 scientific publications, on unpublished data owned by the petroleum industry, and on the expert opinions of the authors and of five reviewers. The methodology follows an existing evaluation scheme that was developed for the same purpose in Canada. Here the approach has been modified to suit the geological setting and available data in Switzerland, according to international best-practice principles for reservoir safety. Owing to the scarcity of quantitative information on the subsurface of Switzerland, the study relies on 9 qualitative and semi-quantitative attributes (including natural seismicity and the occurrence of faults) derived from analysis of deep drillholes and geological and geophysical data. The weighted combinations of these attributes have been ranked on a numerical scale between 0 (negligible potential) and 1 (high potential). Application of this scheme allows the map of Switzerland to be contoured with respect to CO<sub>2</sub> sequestra-

tion potential with a resolution of a few km<sup>2</sup> (Fig. 1).

The conclusions are as follows. The crystalline metamorphic and igneous rocks of the Alps and the sediments underlying the large valleys of Ticino, Grisons and Valais are unsuitable for CO<sub>2</sub> sequestration. In contrast, the sedimentary rocks below the Central Plateau, and to a lesser extent those below the Jura Mountain Chain, locally show moderate to very good potential. At least four layers of porous sandstones and limestones (saline aquifers) underlie very large areas of the Plateau within the technically favoured depth interval of 800–2500 m. Considering all the geological criteria simultaneously, an area of 5000 km<sup>2</sup> (mostly in the sector Fribourg–Olten–Luzern) exhibits sequestration potentials above 0.6. The theoretical (unproven) storage capacity below this area is approximately 2680 million tonnes of CO<sub>2</sub>.

From a purely geological point of view these results are promising. Although the high potentials do not guarantee the feasibility of CO<sub>2</sub> sequestration, they serve as guides to areas that warrant detailed investigation. If this CO<sub>2</sub> storage option is pursued in Switzerland, then thorough geological investigations and a pilot study would be necessary to prove its feasibility and safety. The assessed risks, leakage-monitoring procedures and non-geological criteria (proximity to CO<sub>2</sub> point-sources, economics, conflicts of use of the subsurface, etc.) would have to be taken into account.

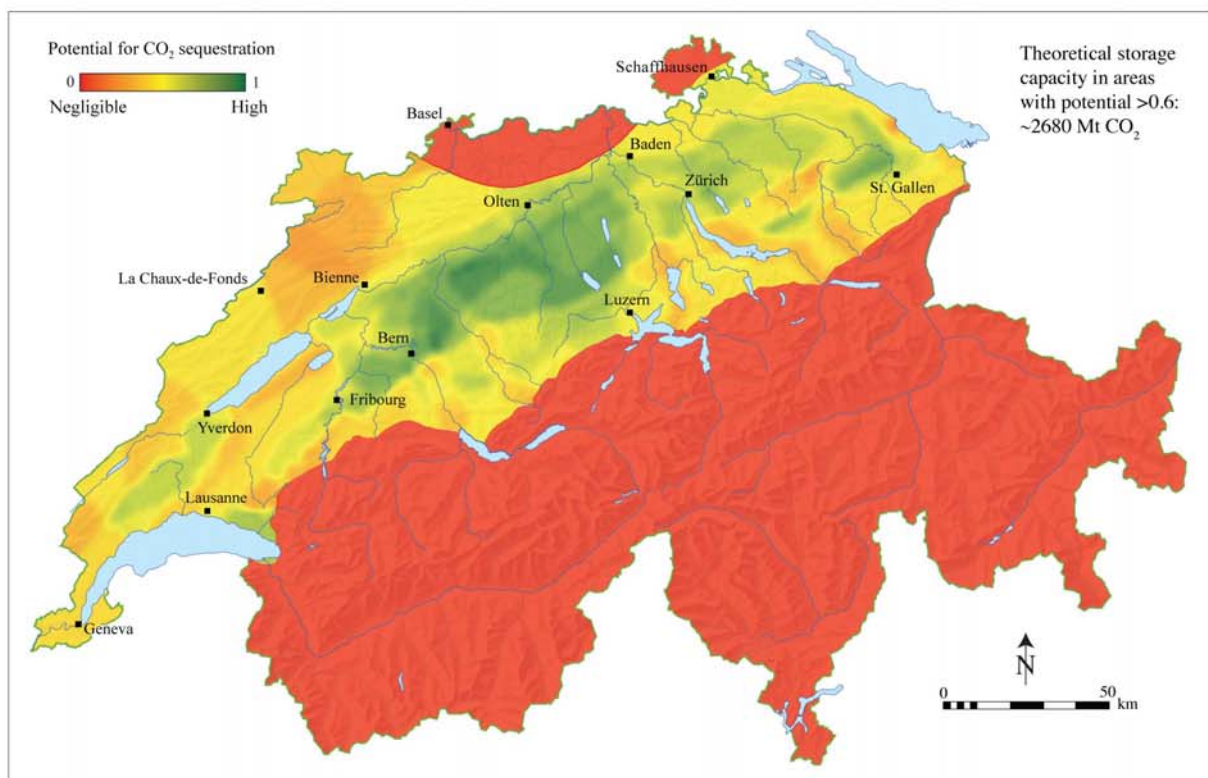


Fig. 1. Map of Switzerland showing the potential for CO<sub>2</sub> sequestration within deep saline aquifers, estimated from data in the literature. The areas of high potentials (green) do not guarantee the feasibility of CO<sub>2</sub> sequestration. Rather, they serve as guides to areas that warrant more detailed investigation. The portions of the four major aquifers with potentials above 0.6 are estimated to have a theoretical (unproven) storage capacity of approximately 2680 millions of tonnes (Mt) of CO<sub>2</sub>.

## 1. Purpose of this report

The Swiss Federal Office of Energy is responsible for long-term planning of the Confederation's energy requirements and supply. Within the context of global climate change, the Office aims to foster reduction of CO<sub>2</sub> emissions associated with energy production and consumption. No publications exist on the potential for geological sequestration of waste CO<sub>2</sub> in Switzerland. Therefore, to obtain some basic technical knowledge as a foundation for discussions on CO<sub>2</sub> sequestration, the Office has commissioned this first assessment of the potential of the deep subsurface of Switzerland, based solely on available literature.

## 2. Outline of this report

This report is intended to communicate the results of the potential study to a broad audience, including non-geologists. Accordingly, the report begins with a primer on the principles of deep geological sequestration of CO<sub>2</sub>, including issues of environmental hazards and safety assurance, and avoiding as far as possible any technical vocabulary. Knowledgeable readers may wish to skip this introduction and begin reading at Section 4. The methodology adopted to assess the sequestration potential within Switzerland is then summarised, and the results are presented in map form. The discussion of these maps emphasizes the uncertainties implicit in the term "potential". Finally, possible conflicts of use of the subsurface in Switzerland are briefly addressed as input for decision-making in the event that this option for CO<sub>2</sub> sequestration be pursued.

The scientific justification for the results presented herein is presented in detail in Appendix 1. In contrast to the main body of the report, the Appendix is written for expert geologists. It is based on a review of over 150 scientific and technical publications, on unpublished data owned by the petroleum industry, and on the experience of the authors. The Appendix has been reviewed by 5 independent experts and it will be published in parallel to this report in the *Swiss Journal of Geosciences*, a scientific peer-reviewed journal that ensures international standards of quality.

## 3. Deep geological sequestration of CO<sub>2</sub>: Principles for non-geologists

### 3.1 Occurrence of CO<sub>2</sub> in the Earth's crust

Since the early 1990s, research has been undertaken worldwide to evaluate whether anthropogenic CO<sub>2</sub> emissions can be captured and sequestered underground in deep geological formations. This approach to CO<sub>2</sub> disposal is based on a huge existing body of knowledge on the state and quantities of CO<sub>2</sub> naturally present in the Earth (this knowledge comprises part of the science of *geology*), and on the chemical and physical behaviour of gases in rocks. Much of this knowledge has been acquired by geologists and engineers in petroleum companies. Indeed, the world's vast underground reserves of natural gas, which consist mostly of methane, are proof that gases can remain trapped in rocks for many millions of years. Natural precedents for storage of pure CO<sub>2</sub> in sedimentary rocks are also known. A local example is at Montmiral, some 40 km west of Grenoble, where a natural CO<sub>2</sub> gas reservoir was discovered in 1961 during exploration drilling into sedimentary rocks at 2400–2480 m depth (LeNindre et al., 2006). The gas composition is 97–99% CO<sub>2</sub> and it is currently exploited as a commercial source of CO<sub>2</sub> for industrial applications. The CO<sub>2</sub> accumulated some 30–40 million years ago and no surface leakage is known so far. Numerous other examples are presented in the IPCC report (2005; pp. 210–211).

As well as being present in gaseous form, huge amounts of CO<sub>2</sub> are also naturally present in dissolved aqueous form in formation waters. These are the more or less saline groundwaters

or pore waters that reside in or migrate through porous rocks in the upper 10 km of the Earth's crust. Commercial bottled mineral water is essentially a sample of such formation water. When the bottle is under pressure the contained CO<sub>2</sub> is invisible, because it is completely dissolved in the water. When the pressure is released by opening the bottle, the dissolved gas separates and forms visible bubbles of free gas.

By far the largest amounts of CO<sub>2</sub> in the Earth's crust are tightly bound in solid form within the family of so-called carbonate minerals, which are the main constituents of limestone. The quantities of CO<sub>2</sub> permanently locked in limestones are truly gigantic. For example, the northernmost range of the Alps and the Jura Mountains are made up largely of limestones.

### 3.2 Options for geological sequestration

In view of this evidence from nature, several options present themselves for sequestration of anthropogenic CO<sub>2</sub>. The principle is to copy the permanent CO<sub>2</sub> storage mechanisms of nature. All of these options are being intensively researched internationally and some are already being implemented (IEA, 2010).

#### Option 1: Mineral carbonation

More than 450 CO<sub>2</sub>-bearing minerals are known to exist in nature. The most common among them, and the most stable over time and over a range of depths and temperatures in the Earth, are the family of carbonate minerals. These bind CO<sub>2</sub> to the oxides of elements such as calcium (Ca), iron (Fe) and magnesium (Mg). The main members of this family are calcite (CaO·CO<sub>2</sub>), siderite (FeO·CO<sub>2</sub>), dolomite (CaO·MgO·2(CO<sub>2</sub>)) and magnesite (MgO·CO<sub>2</sub>). Rocks that are poor in carbonate minerals but otherwise rich in the above elements are therefore candidates for reaction with anthropogenic CO<sub>2</sub>. For example, injection of CO<sub>2</sub> into Mg-rich rocks such as basalts, peridotites or serpentinites has been proposed as an option for sequestration. However, although the reactions are thermodynamically favoured, their rates are very slow at the rock temperatures easily accessible by drilling, even in the catalysing presence of formation water. Moreover, the carbonate minerals have larger volumes than their precursor minerals, so the natural porosity and permeability of the rocks become plugged as the CO<sub>2</sub>-fixation reactions proceed. To counter this problem, new permeable fractures can be created artificially by injecting high-pressure water through steel-cased boreholes, but overall the viability of in-situ mineral carbonation is still uncertain (Oelkers et al., 2008). Much research is now directed at enhancing reaction rates in ex-situ industrial settings, rather than in the geological environment. Carbonate minerals produced via an industrial process could in principle be deposited safely on the Earth's surface.

#### Option 2: Unmineable coal beds

A second option is to inject CO<sub>2</sub> into coal beds that are too deep to ever permit commercial mining. Coal beds naturally contain arrays of cleavage planes. This cleavage porosity hosts saline formation water and often methane gas – a well-known combustion hazard in coal mining. Part of the methane is physically adsorbed onto the coal surfaces, in the same way as activated charcoal adsorbs dangerous gases in the filters of car engines. A fundamental property of CO<sub>2</sub> gas is that it adsorbs more strongly than methane onto coal surfaces. Therefore, CO<sub>2</sub> injected into a coal seam displaces the existing methane and occupies its adsorption sites, thereby becoming immobilised. The amount of CO<sub>2</sub> that can be sequestered in this way depends on the volume of coal that can be accessed by the injection procedure, on the porosity of the seams, and on the rock temperature (lower temperatures are favoured). In contrast to the saline-aquifer approach described below, use of deep coal seams may provide an additional economic incentive, in that the displaced methane may be recovered commercially. This approach has thus acquired the name "enhanced coal bed methane recovery" (ECBM/R). Experience relevant to this technology has been gained mostly by the petroleum industry (White et al., 2005).

### Option 3: Natural gas reservoirs

The most obvious choice for sequestration is to pump CO<sub>2</sub> into natural gas reservoirs in which pore space has been created by commercial exploitation of the methane gas. The idea of refilling gas reservoirs is not at all new. Many countries routinely deplete then refill geological gas reservoirs in a seasonal cycle, in order to maintain large reserves and meet peaks in consumer demand. For example, the USA currently injects and then recovers more than 20 million m<sup>3</sup> of methane gas per year. There are no essential technical differences between injection of CO<sub>2</sub> and injection of methane. This option can therefore be viewed as well proven.

### Option 4: Saline aquifers

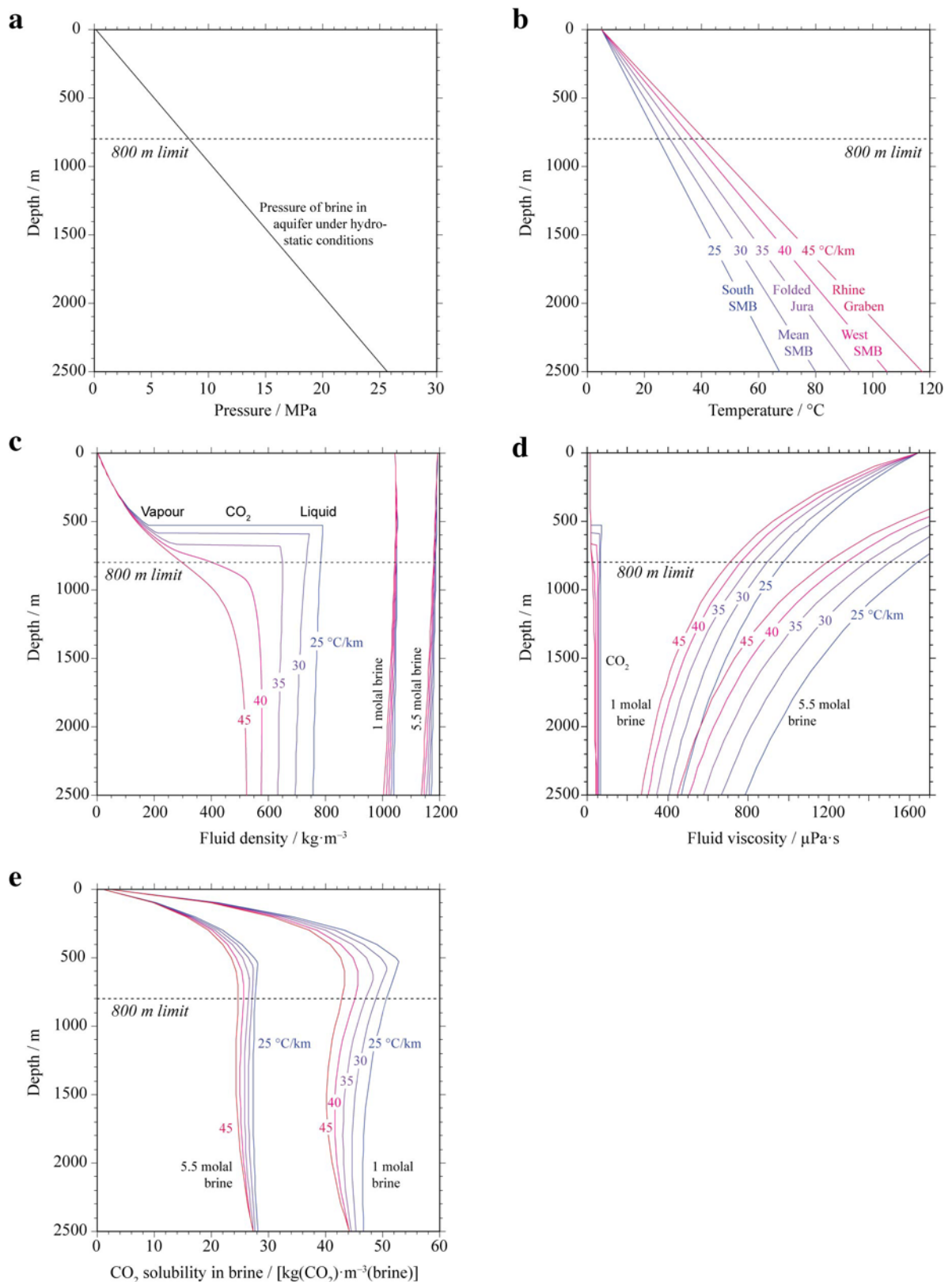
Waste CO<sub>2</sub> may be injected into deep, porous rock formations that contain slowly moving groundwater. Such rocks are termed aquifers. Here "slowly" refers to typical natural flow rates in the order of several cm per year. Like natural gas reservoirs, deep aquifers are sealed above by layers of impermeable caprock (typically mudstones or rock salt) and so water flow is normally close to horizontal. Aquifers that contain fresh water must be left undisturbed for possible future use as sources of water for drinking or for agricultural irrigation. Therefore, aquifers suitable for CO<sub>2</sub> disposal should contain saline water (brine), for which no commercial use is currently known, except perhaps in a transitory way during the production of geothermal energy.

Although a deep aquifer may behave as an open system on the scale of tens of thousands to millions of years, several trapping mechanisms combine to lock the CO<sub>2</sub> within the aquifer over comparably long periods (see below). Injection of waste CO<sub>2</sub> into a deep formation requires that the gas be artificially pressurized to a value greater than that of the in-situ brine (Fig. 2a). Thus, upon injection from a perforated or screened borehole, the compressed CO<sub>2</sub> displaces some of the brine from the rock pores. The CO<sub>2</sub> itself accumulates as an immiscible fluid plume. Its density depends on the ambient temperature (Fig. 2b) and on the pressure of the adjacent formation water (Fig. 2a). In deep aquifers at relatively low temperatures, CO<sub>2</sub> is stable in the supercritical fluid state with liquid-like density (Fig. 2c). Nevertheless, even if the pressure and temperature conditions are conducive to high density, CO<sub>2</sub> is still markedly less dense than any saline formation water (by a factor of 1.3 to 4, depending on the salinity; Fig. 2c), and it has a far lower viscosity (by a factor of 6 to 50, depending on salinity; Fig. 2d). These two attributes impart high buoyancy and mobility to the CO<sub>2</sub> plume and so it will generally migrate away from the injection point, displacing brine along the way.

The migrating plume is confined to the aquifer by the impermeable caprock and it may accumulate in traps beneath folds or beneath segments of the caprock displaced by sealed faults (termed structural trapping). As CO<sub>2</sub> does not "wet" mineral surfaces in the physicochemical sense, some of the migrating gas inevitably remains locked in the rock pores along the flow path, owing to the narrowness of their interconnecting throats (termed residual trapping). With time (decades to centuries) some or all of the CO<sub>2</sub> in the plume dissolves into the formation water (termed solubility trapping). The solubility is highest in low-salinity, high-pressure water in the temperature range 80–100 °C (solubility falls at both higher and lower temperatures).

Once dissolved, the CO<sub>2</sub> is gradually transported away from the site of the plume by the flowing formation water. During this transport the CO<sub>2</sub> chemically reacts with the aquifer rock. In sandstone aquifers the reactions may produce carbonate minerals, e.g. calcite, dolomite and siderite, that are permanently stable (termed mineral trapping), although the reaction rates may be very slow (e.g. Xu et al., 2004). In aquifers composed mostly of calcite and dolomite, the addition of aqueous CO<sub>2</sub> may acidify the formation water and cause partial dissolution of the carbonate minerals, thereby increasing the porosity of the aquifer.





**Fig. 2.** Calculated fluid properties relevant to deep geological storage of CO<sub>2</sub> in the sedimentary rocks of Northern Switzerland, plotted as a function of depth. Dashed line at 800 m marks the minimum depth recommended for CO<sub>2</sub> injection. Two examples of brines are shown: low salinity, 1 molal NaCl (5.5 mass% NaCl) and high salinity, 5.5 molal NaCl (24.3 mass% NaCl). (a) Pressure of brine in an aquifer assuming hydrostatic conditions. (b) Range of observed geothermal gradients in the Northern Switzerland. (c) Comparison of fluid densities of CO<sub>2</sub> and CO<sub>2</sub>-saturated brines over the range of observed geothermal gradients. (d) Comparison of fluid viscosities for the range of observed geothermal gradients. (e) Solubility of CO<sub>2</sub> in example NaCl brines. See Appendix 1 for sources of data.

Even under the most favourable aquifer conditions the amount of CO<sub>2</sub> that can be dissolved in a cubic metre of formation brine is small (e.g. ~25–50 kg<sub>CO2</sub>/m<sup>3</sup><sub>brine</sub>; Fig. 2e) and the capacity of many deep aquifers is already lowered by the natural presence of CO<sub>2</sub>. Therefore, aquifers with large structural traps or with very large amounts of formation water must be found to dispose of significant quantities of waste CO<sub>2</sub>. Tightly sealed structural traps are the preferred sites because storage is permanent. In the absence of structural traps, dissolved CO<sub>2</sub> may eventually degas when the brine discharges into higher-level formations or even to the Earth's surface. In this case the period over which CO<sub>2</sub> is retained underground is finite. Nevertheless, water residence times in the order of several thousand years are common and these are thought to be sufficient to mitigate global warming until future technologies solve the problem permanently (Lindeberg and Bergmo 2002; Hepple and Benson 2005; IPCC 2005).

Exactly how a given aquifer discharges is of prime interest in selecting sites for CO<sub>2</sub> injection. Faults, whether active or inactive, may possibly provide routes for leakage of CO<sub>2</sub>, especially if the injection significantly raises the fluid pressure in the formation. However, faults are often found to be sealing structures. High induced pressures may even cause the overlying caprocks to fracture and permit escape of CO<sub>2</sub> (Streit et al., 2005). Accordingly, knowledge of the occurrence and types of faults in the subsurface is an important aspect in evaluating potential storage sites.

An important demonstration of this approach to CO<sub>2</sub> sequestration is in the Sleipner gas field in the North Sea (offshore Norway). Waste CO<sub>2</sub> that is naturally present in the produced gas is separated at the wellhead and reinjected into a saline aquifer at the rate of 1 million tonnes per year (Torp and Gale, 2004). The project began in 1996 and it is still underway. Monitoring of the injected CO<sub>2</sub> plume via seismic surveys has demonstrated that the CO<sub>2</sub> is well trapped. Additional experience in injecting CO<sub>2</sub> into saline aquifers has been gained in numerous pilot projects in North America and Europe (e.g. Kharaka et al., 2006; Chadwick et al., 2008; IEA, 2010).

### 3.3 Environmental hazards and safety assurance

Any CO<sub>2</sub> sequestration project must consider the associated environmental and safety issues. A detailed treatment is beyond the scope of this study, but it must be part of any specific site investigation. The following is a brief summary of the four main issues, based on a review of international literature.

- (1) Injection of CO<sub>2</sub> entails mechanically pressing the gas into the reservoir rocks. This increases the pressure of the formation fluid. Under some circumstances the pressure increase may induce slip (displacement) on local faults and it may cause new fractures to form, whether in the reservoir or the caprock. In either case the release of pre-existing rock stress may cause perceptible seismicity. The magnitudes of the seismic shocks depend on local rock parameters and these must therefore be assessed prior to injection. An analogy is the seismicity (events up to  $M_L = 3.4$ ) produced in 2006-2007 when water was artificially injected into the Basel 1 deep geothermal borehole to induce rock fracturing (Håring et al., 2008; see also Appendix 2). Experience in induced seismicity has been gained primarily by the petroleum industry, which for several decades has been injecting both water and CO<sub>2</sub> into hydrocarbon reservoirs to enhance oil recovery (e.g. Zoback, 2007). So far this disposal has been demonstrated to be safe with risks reduced to a level as low as reasonably practicable.
- (2) Leakage of CO<sub>2</sub> may possibly pollute groundwater resources. Migrating CO<sub>2</sub> tends to acidify groundwaters by producing carbonic acid, which in turn may cause dissolution and transformation of minerals and soils along the flow paths. These chemical changes may mobilise toxic heavy metals, which could contaminate freshwater aquifers. If the storage aquifer already contains hydrocarbons, toxic BTEX components may also be mobilised,

as demonstrated in a pilot CO<sub>2</sub> sequestration study by Kharaka et al. (2006).

- (3) Dispersed leakage of CO<sub>2</sub> to the Earth's surface or into soil horizons may alter the biodiversity of ecosystems.
- (4) Because CO<sub>2</sub> gas is denser than air, large volumes of CO<sub>2</sub> that leak to focussed points on the Earth's surface may accumulate in topographic depressions. If high CO<sub>2</sub> concentrations are attained they may become hazardous to humans and other living organisms. A tragic demonstration of this phenomenon was the 1986 catastrophic release of CO<sub>2</sub> from Lake Nyos in Cameroon (Kling et al., 1987). The source of the CO<sub>2</sub> was in that case volcanic, unrelated to human activity (and in a geological setting that is entirely different from that envisaged for CO<sub>2</sub> sequestration). Evaluations of the risks of this problem in a sequestration environment are based on natural and man-made analogies of leaking storage sites (Lewicki et al., 2007).
- (5) When CO<sub>2</sub> is pressed into an aquifer, the saline formation water within its pore space is displaced. Rapid migration of the water is hampered by its relatively high density and high viscosity. However, depending on the local geological conditions, it is possible that saline water is expelled from the aquifer. If this brine enters overlying freshwater aquifers it may degrade their quality.

## Monitoring

According to the consensus reported by Chadwick et al. (2008), if precautionary measures are taken to minimise the environmental impacts, then storage of CO<sub>2</sub> can be undertaken in an acceptable way with only very minor impacts on the environment. Assurance for this is provided by:

- thorough site selection and characterisation procedures, including an assessment of the risks and potential consequences of CO<sub>2</sub> leakage;
- guidelines and standards for safe operation of the storage site;
- appropriate safety measures and monitoring during and after operation of the site. This includes sealing the wells once injection has ceased; performing long-term analyses of air and soil to detect leakage at the surface; and conducting underground geophysical imaging (using seismic, electromagnetic, gravity and density methods) to track the migration of the CO<sub>2</sub> plume and any physical changes in the rock formations.

## 4. Site-selection procedure for CO<sub>2</sub> sequestration

### 4.1 International standards for site selection

Numerous studies of the potential for deep geological sequestration of CO<sub>2</sub> have been conducted in other countries and their findings provide a methodological basis to evaluate the Swiss case. The study by Chadwick et al. (2008) is particularly broad and comprehensive. It reports on two large collaborative projects (named SACS and CO2STORE) carried out on five case studies in Europe between 1998 and 2006 by a consortium of governmental and industry partners. The publication provides a manual of guidelines for effective and safe storage of CO<sub>2</sub>, including geological, environmental and planning issues. Owing to its wide international authorship and international scope of case studies, the recommendations of Chadwick et al. (2008) carry weight as international standards. Therefore, the present evaluation of the storage potential of Switzerland is based on their guidelines.

Chadwick et al. (2008) envisage the development of a specific site for CO<sub>2</sub> storage as entailing 7 steps:

1. Statement of storage aims and benefits
2. Site screening, ranking and selection
3. Site characterisation
4. Site design and planning consent
5. Site construction
6. Site operations
7. Site closure

The task of the present report is to evaluate the geological potential at the national level. This corresponds to the initial part of step 2 above. However, such an evaluation depends in part on the statement of intentions in step 1. These include (a) the masses of CO<sub>2</sub> that need to be stored; (b) the required duration of storage, and (c) constraints of non-geological nature (e.g. conflicts of use of land above the injection site, conflicts of use of the subsurface rocks near the storage site, proximity to industrial CO<sub>2</sub> sources, etc.). As the Federal Government of Switzerland has not yet stated its intentions, the present study takes a broad regional approach. The aims are to provide a first-order scientific basis to address step 1, should this be found necessary in the future, and to provide the regional context for more detailed, site-specific investigations as envisaged in step 3, should these be found necessary in the future.

## 4.2 Geological criteria for site selection

The geological requirements of a suitable storage site are dictated by the constraints of the injection procedure and by the CO<sub>2</sub> trapping mechanisms outlined in Section 3. Thus, similar to targets for petroleum accumulations, a target site for CO<sub>2</sub> storage must consist of an aquifer–seal pair: a thick reservoir rock with sufficient permeability to permit rapid injection and sufficient porosity for high storage capacity, overlain by an extensive, low-permeability sealing caprock. The formation water must be saline and slow-moving, and the site must be distant from its ultimate discharge zone. The aquifer must be deep enough to ensure that the injected CO<sub>2</sub> is highly compressed by the formation water, thereby maximising storage capacity. Suitable CO<sub>2</sub> densities are reached at depths of 800–2500 m, depending mainly on the geothermal gradient of the basin (Bachu 2003; Chadwick et al., 2008; Fig. 2). Simple rock structures are preferred, so as to limit the scope for unpredictable escape conduits for CO<sub>2</sub>. Faults are not necessarily problematic, because many inactive faults are impermeable to fluids and they play an important role in forming structural traps (e.g. as is well known in the case of petroleum and natural gas reservoirs). However, active and permeable fault zones must to be avoided to minimise the risk of leakage, as must seismic zones in general.

Once a potential aquifer has been located, the flow regime of the formation water needs to be characterized prior to injection and the possibility of induced perturbations to this regime need to be evaluated. As CO<sub>2</sub> injection may raise the fluid pressure in the aquifer, the capillary entry pressure of the caprock has to be tested, and the existing state of rock stress needs to be known to judge the risk of hydrofracturing and hence induced seismicity. Because injected CO<sub>2</sub> will react chemically with the rocks and formation waters that it encounters, pre-injection geochemical states have to be measured or estimated in order to predict and then monitor the post-injection geochemical evolution. This requires knowledge of the three-dimensional geometry and extent of the target site, the mineralogical and hydraulic properties of both the reservoir rock and the sealing caprock, and the compositions of saline water and gas in the rock pores.

From the above considerations, 21 specific geological criteria can be identified for detailed assessment of storage-site suitability (Table 1). Limiting values for 8 of the aquifer and caprock criteria are given in Table 2.

**Table 1.** Geological criteria for detailed evaluation of CO<sub>2</sub> storage sites in aquifers

<b>Criteria related to aquifer-caprock pairs</b>	
1	Existence of an aquifer–caprock pair in the 800–2500 m depth interval
2	Geothermal gradient ( <i>P–T</i> –depth relationships)
3	Structural setting (structural traps)
4	Faults (locations and dimensions)
5	State of rock stress
6	Risk of seismicity
<b>Criteria related to aquifers</b>	
7	Depth in 800–2500 m range
8	Thickness
9	Rock type and mineralogy
10	Lateral continuity
11	Permeability (including fractures)
12	Porosity (including fractures)
13	Salinity of brine
14	Flow rate of brine
15	Distance of site from discharge zone
<b>Criteria related to caprocks</b>	
16	Thickness
17	Rock type and mineralogy
18	Lateral continuity
19	Permeability of caprock (including fractures)
20	Capillary entry pressure
21	Hydrofracturing/gas-fracturing thresholds

**Table 2.** Values of key geological indicators for storage-site suitability (Chadwick et al., 2008)

<b>Storage capacity</b>	<b>Positive indicators</b>	<b>Cautionary indicators</b>
<b>Total storage capacity</b>	Total capacity of reservoir estimated to be much larger than the total amount produced from the CO <sub>2</sub> source	Total capacity of reservoir estimated to be similar to or less than the total amount produced from the CO <sub>2</sub> source
<b>Reservoir properties</b>		
Depth (pressure)	1000–2500 m	< 800 m or > 2500 m
Thickness (net)	> 50 m	< 20 m
Porosity	> 20%	< 10%
Permeability	> 300 mD	< 10–100 mD
Salinity	> 100 g·L <sup>-1</sup>	< 30 g·L <sup>-1</sup>
<b>Caprock properties</b>		
Lateral continuity	Unfaulted	Laterally variable, faults
Thickness	> 100 m	< 20 m
Capillary entry Pressure	Much greater than buoyancy force of maximum predicted CO <sub>2</sub> column height	Similar to buoyancy force of maximum predicted CO <sub>2</sub> column height

## 5. Geological options for CO<sub>2</sub> sequestration in Switzerland

Section 3.2 has summarized the options for CO<sub>2</sub> sequestration that arise if the entire Earth's Crust would be available for this purpose. Switzerland naturally comprises only a subset of all the geological environments found in the Crust. In the following the feasibility of the various sequestration options is discussed, with reference to the restricted geological makeup of the country.

### Option 1: Mineral carbonation

The in-situ carbonation option relies on three prerequisites: (1) the presence of porous rocks with high contents of elements that readily form stable carbonate minerals (Mg, Ca, Fe); (2) rock temperatures in excess of 150 °C, which stimulate rapid reaction with injected CO<sub>2</sub>; and (3) the presence of formation water to act as a chemical catalyst. The Swiss Alps contain large quantities of basalt and serpentinite rocks that have suitable chemical compositions for this purpose. However, all these rocks are highly metamorphosed and so their intrinsic permeability is virtually nil. Most of the rocks are intensely fractured, and although these fractures could provide access for injected CO<sub>2</sub> to the reactive minerals, they are not sealed above by other impermeable rock formations. Consequently, any injected CO<sub>2</sub> would surely escape before being fixed by chemical reactions with the nearby rocks. Moreover, the necessary temperatures are encountered only at prohibitively deep levels (>4 km). In view of these facts, there appears to be no potential for in-situ mineral carbonation as the primary mechanism of CO<sub>2</sub> sequestration within Switzerland. Some carbonation is likely to occur over very long time intervals as a secondary trapping mechanism in the saline-aquifer option (no. 4 below).

### Option 2: Unmineable coal beds

Seams of coal up to 4 m thick are known from the Weiach borehole at depths (1550–1750 m) that preclude commercial exploitation. Little direct information is available on the spatial extent of the coal, but it can be deduced from the accompanying rocks that the coal was originally deposited in swamps that bordered meandering rivers. This geological setting suggests that the coal is likely to occur in only small areas. From a geological point of view it would be worthwhile conducting a pilot study in the vicinity of the Weiach well, but the outcome is unpredictable at the current state of knowledge. While this sequestration option cannot be ruled out for Switzerland, it is likely to provide only a very small capacity for CO<sub>2</sub> storage, and therefore is not discussed further in this report. Appendix 3 provides more background information on this topic.

### Option 3: Natural gas reservoirs

Exploration for oil and gas has been carried out in Switzerland since the mid-1950s, including 35 deep boreholes and over 8500 km of geophysical surveys. However, only one small gas field, situated at Entlebuch, Canton Lucerne, has ever produced gas commercially (74 million m<sup>3</sup> of natural gas, volumetrically equivalent to 1.3 million tonnes of CO<sub>2</sub>). Unfortunately, the Entlebuch gas trap lies more than 5000 m below the surface, and so the cost of refilling the liberated rock porosity with waste CO<sub>2</sub> would be extremely high. Today, exploration for gas is continuing throughout the entire Central Plateau and the Jura Chain, e.g. the Petrosvibri deep borehole at Noville, Lake Geneva; the PEOS/SEAG Hermrigen-2 well in Canton Bern; the Celtique Energy programme in Val-de-Travers, Canton Neuchâtel; and the Schuepbach Energy GmbH shale-gas project in Canton Fribourg. Despite this activity, no potential has been indicated within Switzerland so far for this approach to CO<sub>2</sub> sequestration.

### Option 4: Saline aquifers

Thick aquifers containing water of various salinities are found at several levels below the Swiss Central Plateau and the Jura Mountain Chain. Many of these aquifers are well known

to local hydrogeologists and geothermal energy firms, and a certain amount of geological information is available from boreholes and geophysical transects. Whereas most of the aquifers lie buried deep beneath the surface, in some places of northern Switzerland the rocks are exposed in surface outcrops, thanks to uplift caused by tectonic activity in the distant past. Overall, these sources of information are sufficient to reconstruct approximately the three-dimensional disposition and thickness of the aquifers down to several kilometres depth. Hydraulic testing in boreholes and in the laboratory using core samples has provided quantitative information on the intrinsic porosity and permeability of the rocks.

Evidently, saline aquifers are the most promising option for CO<sub>2</sub> sequestration in Switzerland. The remainder of this study accordingly focuses on evaluating their potential.

## **5.1 Selection of prospective saline aquifers for evaluation**

The thick sequence of sedimentary rocks underlying the Central Plateau (known as the Swiss Molasse Basin to geologists) and the adjacent Jura Chain contains numerous sealed aquifers that are worth evaluating for CO<sub>2</sub> sequestration (Table 2 and Appendix 4.2). The aquifer rocks have measured porosities between 0.5 and 22%. The Sandsteinkeuper and Arietenkalk aquifers (no. 4 in Table 3) are rather small, discontinuous layers, and their total volumes are difficult to predict. Predictability is also the problem with the sandstones in the Permo-Carboniferous troughs (no. 7 in Table 3), which sporadically underlie the sediment stack. The same applies to the fracture zones in the crystalline (non-sedimentary) basement rocks. The lack of information on their areal extents and volumes makes it impossible to evaluate their storage capacity for CO<sub>2</sub>. However, the potential of these rocks may become clearer if more wells are drilled through the base of the sediments. The remaining five aquifers (nos. 1-3 and 5-6 in Table 3) have sub-regional to regional extents, and enough is known about their volumes and properties (Appendix 5) to make a preliminary estimate of their storage capacity. These five aquifer/seal pairs are evaluated in the following pages.

## **5.2 Evaluation criteria for sequestration potential in Switzerland**

The literature data on the promising saline aquifers in Table 3 are unfortunately insufficient to evaluate quantitatively all the 21 geological criteria listed in Table 1. Some caprock parameters are lacking completely (e.g. 20 and 21), whereas data related to many of the other criteria are too sparse to provide a meaningful basis for a three-dimensional evaluation. This state of affairs simply reflects the low areal density of deep boreholes in northern Switzerland (Appendix 5), and the lack of detailed hydraulic testing within these holes. In view of this, the present assessment must be based on a subset of the criteria, and on data that are at best semiquantitative. The criteria considered are:

- 1) Existence of an aquifer–caprock pair within the 800–2500 m depth range
- 2) Thickness of aquifer in excess of 20 m minimum, sealed by ≥20 m of caprock
- 3) Geothermal gradient ( $P$ – $T$ –depth relationships)
- 4) Hydrogeology (zones of recharge versus discharge of formation water)
- 5) Exploration maturity (extent of knowledge of the subsurface)
- 6) Seismicity
- 7) Fault systems (density and dimensions)
- 8) Structural traps
- 9) Stress regime

**Table 3.** Sealed aquifers (in stratigraphic order) beneath the Central Plateau and Jura Chain, of relevance to CO<sub>2</sub> sequestration.

Aquifer / Sealing caprock	Extent of sealed aquifer	Aquifer porosity
1 Upper Marine Molasse (OMM) sandstones / <i>Upper Freshwater Molasse (OSM) marls</i>	Regionally extensive, but only a small zone within 800–2500 m depth interval.	5–20%
2 Upper Malm – Lower Cretaceous limestones / <i>Lower Freshwater Molasse (USM) marls</i>	Regionally extensive below Central Plateau.	0.5–10%
3 Hauptrogenstein limestone / <i>Effingen Member calcareous mudstone</i>	Sub-regional extent below NW Central Plateau.	≤ 16%
4 Sandsteinkeuper, Arietenkalk limestone / <i>Lias, Opalinus Clay</i>	Local-scale aquifers. Volumes are difficult to estimate.	5–15%
5 Upper Muschelkalk / <i>Gipskeuper evaporites</i>	Regionally extensive below Central Plateau.	2–22%
6 Buntsandstein and fractured crystalline (non-sedimentary) basement / <i>Anhydrite Group evaporites</i>	Sub-regional extent below NW Central Plateau. Sporadically underlain by water-conducting fractured basement (volumes are difficult to estimate).	3–18%
7 Permo-Carboniferous trough sandstones / <i>Permian shales or Anhydrite Group evaporites</i>	Locations and number of troughs and their sandstones are poorly known. Data are insufficient to estimate aquifer extents and volumes.	3–12%

The criteria concerning seismicity and stress regime of the aquifer rocks are particularly important in view of the high population density of northern Switzerland. Additional information on these topics is therefore provided in Appendix 2. The location of major faults and near-surface fold structures (potential traps) is shown in Appendix 4.1.

Not all the 9 criteria listed above carry the same weight in site selection. A numerical approach has therefore been applied (Bachu, 2003; Appendix 1), by which scores are assigned to the various attributes of the criteria, and the criteria themselves are weighted to enable their combination into a global estimate of storage potential. The resulting numerical scale of CO<sub>2</sub> storage potential ranges from 0 (negligible potential) to 1 (high potential).

## 6. Results of evaluations

### 6.1 Evaluation of sequestration potential within aquifers in northern Switzerland

As stated in the preceding paragraph, the methodology applied in this study yields numerical values of CO<sub>2</sub> storage potential. When examining the results of the following evaluations it is important to bear in mind two features of these potentials. First, although the use of numerical values may convey the impression of high accuracy, the results are based on qualitative and semiquantitative data. Therefore, the numbers cannot carry any more than qualitative or at best semiquantitative significance. Second, a high potential is not a



guarantee that CO<sub>2</sub> can be sequestered in a given area. Rather, a high potential is simply a guide for exploration companies – an indication of an area that warrants further geological investigations.

Three kinds of evaluation of sequestration potential have been performed, as explained in the following.

#### 6.1.1. Results of basin-wide evaluation

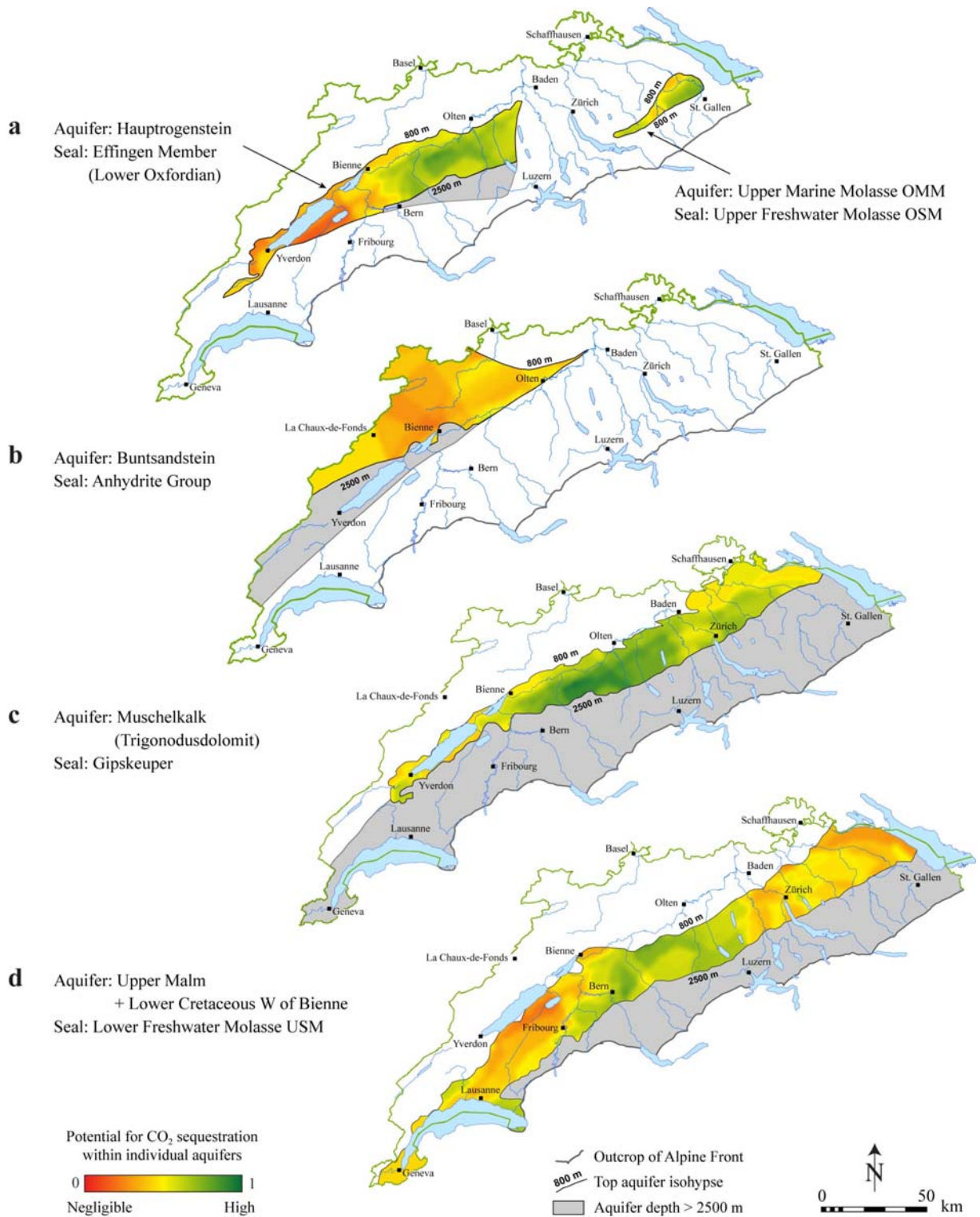
The sedimentary rocks underlying the Central Plateau and the Jura Chain have been evaluated as one coherent object, without any internal spatial differentiation. This facilitates comparison of the overall sequestration potential of Switzerland with that of other areas in the world. Application of the scoring and weighting scheme yields a potential of 0.6 for northern Switzerland. This value falls in the mid-field of sedimentary basins evaluated elsewhere (Bachu, 2003). For example, the St Lawrence Basin in Canada scores a potential of 0.31, indicating poor suitability for CO<sub>2</sub> sequestration. In contrast, the Alberta Basin in Canada scores 0.96, indicating that this stack of sedimentary rocks is predestined for the purpose. Thus, in an international context, northern Switzerland as a whole can be viewed as having moderate potential for CO<sub>2</sub> sequestration.

#### 6.1.2. Results of intrabasinal evaluation of sedimentary rock stack

A geographically differentiated, intrabasinal evaluation of northern Switzerland has been obtained by mapping the variations of the 9 evaluation criteria, then combining these maps via the scoring and weighting scheme. Thus, the potential of the entire column of sediments can be displayed on a map, with a resolution of a few km<sup>2</sup>. The result is shown in Fig. 1. The calculated potentials vary between 0.26 and 0.96, and their distribution reveals clear patterns. The highest potential for CO<sub>2</sub> storage lies beneath the green belt Fribourg–Bienne–Baden–St. Gallen. The regions immediately NW and E of Lausanne also show good potential. The total area with potentials greater than 0.6 covers 5000 km<sup>2</sup>. This presents a promising target for exploration.

#### 6.1.3. Results of intrabasinal evaluation of individual aquifers

Here the focus is on the potential of selected aquifers below each resolved area of the map, rather than on the potential of the entire column of sediments. The results for aquifers 1–3 and 5–6 in Table 3 are shown in Fig. 3. The Bundsandstein aquifer (Fig. 3b) has only moderate potential at best, and so the chances of finding a suitable sequestration site within this rock layer appear to be poor. The remaining aquifers locally exhibit good to very good potential.



**Fig. 3.** Intrabasinal evaluation of the CO<sub>2</sub>-storage potential of individual sealed aquifers beneath the Central Plateau and the adjacent Jura Chain. Inset boxes show the theoretical (unproven), effective storage capacity of the portions of each aquifer with potential greater than 0.6.

## 6.2 Estimation of CO<sub>2</sub> storage capacity within aquifers in northern Switzerland

Nominal maximum storage capacities for CO<sub>2</sub> can be calculated from the volume of the saline aquifer, the volume of its connected porosity, and the density of the CO<sub>2</sub> in equilibrium with the ambient temperature and fluid pressure. This nominal capacity can never be achieved in practice, for two main reasons. First, owing to the physical phenomenon of capillarity, not all the formation water can be expelled from the rock pores when free CO<sub>2</sub> is forced through the formation. Consequently, the space available for CO<sub>2</sub> is reduced. Second, owing to technical limitations, not all the connected porosity in an aquifer can be accessed by injection from boreholes. To account for these and other minor effects (including time-dependent aqueous solubility of CO<sub>2</sub> versus its presence as a free immiscible fluid), the nominal capacity can be multiplied by a factor (storage coefficient) to obtain the "effective" storage capacity. Generic values of such storage coefficients have been estimated from a variety of empirical and theoretical studies (IEA-GHG, 2009), and these can be used for predictive calculations in lieu of field tests at a specific site. In the case of the sedimentary rocks in Northern Switzerland, the calculated effective values nevertheless remain theoretical estimates, as the spatial density and detail of the data used in their derivation (Appendix 5) is too sparse to achieve high accuracy.

It is meaningful to calculate storage capacities only for segments of the aquifers that have at least moderately good potential. Accordingly, capacities have been calculated for those segments with potential greater than 0.6. The results, expressed in units of millions of tonnes (Mt) of CO<sub>2</sub>, are displayed in the inset boxes in Fig. 3 (see Section 8 of Appendix 1 for details of calculations). The sum of all the listed effective storage capacities is 2680 million tonnes (Mt) of CO<sub>2</sub>.

The calculated storage capacities can be put into the local context by considering that the current annual emission of CO<sub>2</sub> from industrial sources in Switzerland is approximately 11.3 Mt (Table 6 in BAFU, 2010). A 400 MWeI combined-cycle gas power station would produce approximately 0.7 Mt CO<sub>2</sub> per year (assuming 360 kg/MWh and 5000 h/year operation). Clearly, these emissions are just a tiny fraction (~0.5%) of the potential storage capacity of aquifers beneath the Central Plateau, as estimated with the semiquantitative approach in this study. However, it is worth reiterating here that the storage estimates are merely potential values. So far, no storage capacity has been proven within Switzerland.

## 7. Possible conflicts of use of the deep geological subsurface

The deep subsurface may be used for various engineering and resource-related projects, but some of these uses are mutually exclusive. Planning of future projects must therefore consider possible conflicts of use. The following summarizes the main issues that need to be considered in planning a site for CO<sub>2</sub> sequestration. Any selection programme for a specific injection site would have to address these issues, and perhaps others, in much more detail than provided here.

### 7.1 Tunnels (road, rail, hydroelectric) and gas pipelines

Engineering projects may conflict with CO<sub>2</sub> sequestration only if they are planned to be deeper than about 500 m, and to be sited within the candidate aquifers or their sealing caprocks. This appears to be very unlikely for the simple reason that the areas of the Central Plateau that are underlain by the candidate aquifers have relatively low topographic relief. Tunnels for roads, railways, hydroelectricity and gas-pipelines must be deeper than about 500 m only where topographic relief is extreme, such as in the Alps. Since the Alps pose no potential for CO<sub>2</sub> sequestration, no conflict of use is expected.

## 7.2 Disposal of radioactive waste

A search is currently underway for deep geological sites that are suitable for disposal of Switzerland's radioactive waste. The concept of Nagra (National Cooperative for the Disposal of Radioactive Waste), the organisation conducting this search, is to construct the waste repositories within impermeable clay-rich rocks at some depth between 200 and 800 m. The selected clay-rich formations must be thick enough (~100 m) to ensure long-term impermeability with respect to formation water from above and below the repository. Viewed strictly, the combination of this depth constraint and the need for more than 30 m of impermeable rock beneath the repository rules out a geological conflict with CO<sub>2</sub> injection into an underlying saline aquifer. Despite the absence of a geological conflict, it would nevertheless be unwise, for technical reasons, to inject CO<sub>2</sub> into an aquifer beneath or in the upstream vicinity of a radioactive waste repository.

Two of the formations being investigated by Nagra are also considered to be potential sealing caprocks in this study: the Opalinus Clay and the Effingen Member (nos. 3 and 4 in Table 3). Owing to the slight SE-dip of these formations, most of the areas of interest to Nagra lie to the north of, and at shallower depths than, the areas identified herein to have potential for CO<sub>2</sub> sequestration. However, some of the interesting zones for Nagra near Olten overlap geographically with the northern rim of the high-potential zone delineated in this study. Even if radioactive waste repositories are finally constructed at these sites, their planned size is relatively small (total <9 km<sup>2</sup>) and they could be easily avoided when selecting a site for CO<sub>2</sub> injection.

## 7.3 Geothermal energy resources

Active exploration is being undertaken in Switzerland for sites suitable for extraction of geothermal energy. Two strategies for exploitation are being followed, and these each have different potentials for conflict with CO<sub>2</sub> sequestration.

The first strategy involves drilling into hot crystalline rocks that do not already contain moving formation water. Fracture networks are then created artificially by injecting high-pressure water into the base of the borehole. Subsequently, water from the surface is forced to circulate down the injection hole, through the artificial fracture network (where it is heated by the surrounding rock) and then up a second production well to the surface (where the heat is extracted). To reach useful rock temperatures in Northern Switzerland, drilling must be deeper than about 4 km. This approach poses no direct geological conflict with CO<sub>2</sub> injection into saline aquifers. The target rocks and depths are quite different for the two applications. A technical issue that needs resolution would arise if the boreholes for geothermal energy perforated an aquifer that already contains waste CO<sub>2</sub>.

The second strategy involves drilling into aquifers which contain hot, upwelling water, typically situated along deep fracture- or fault zones. If pressures and flow rates are high enough, the hot water can be piped to the surface for commercial heat extraction, without reinjection. However, such high flow rates are likely to be rare in Switzerland, and so the cooled water will have to be reinjected under pressure into an upstream part of the aquifer in order to enhance flow. This strategy is directed at the same sealed aquifers and partly at the same depth range as in the case of CO<sub>2</sub> sequestration. A conflict of use is not predestined, however, as the two applications may target different sectors of a given aquifer. Geothermal energy requires sites of high fluid discharge, often associated with fault zones, and high rock temperatures. This combination of attributes is entirely unsuitable for CO<sub>2</sub> storage. Fluid discharge through fault zones would permit leakage of CO<sub>2</sub>, and the high rock temperatures would induce low density and hence low storage capacity of CO<sub>2</sub>. Instead, any sector of the aquifer suitable for CO<sub>2</sub> storage must be a zone of recharge or of very slow flow, it must be

distant from any permeable fractures or faults, and it should be as cool as possible while still sitting within the favoured 800–2500 m depth interval. In practice, proximity to potential users of geothermal energy is an important non-geological factor in geothermal site selection. Consequently, conflicts of use may indeed arise. For example, the recent deep borehole at Triemli, near Zürich City, was drilled to explore for geothermal energy at a site where the geological conditions were not optimal. According to the present study (Fig. 1), the same area shows moderate potential for CO<sub>2</sub> sequestration. In recognition of the possibility for conflict, research is now being conducted in several countries into the feasibility of simultaneously combining CO<sub>2</sub> sequestration with exploitation of geothermal energy, by using CO<sub>2</sub> rather than water as the heat-transporting medium (e.g. Pruess, 2006).

#### **7.4 Seasonal storage of hydrocarbon gas**

As mentioned for option 3 in Section 3.2, many countries hoard hydrocarbon gas for economic and supply reasons. Exhausted natural-gas reservoirs are used as seasonal caches, the gas being extracted and refilled via deep boreholes according to commercial demand. Shallow reservoirs are favoured so that costs of compressing the gas are minimized. The reservoirs themselves are usually situated in porous rocks capped by impermeable strata, in which the caprock roughly has the form of a large dome. Owing to these geological features, the reservoirs are also usually suitable for CO<sub>2</sub> sequestration. However, because CO<sub>2</sub> storage should be long-term or permanent, the two uses of the reservoirs are mutually exclusive and therefore in conflict. So far, Switzerland has no known gas reservoirs in the depth interval pertinent to CO<sub>2</sub> injection, but commercial exploration is underway and it is likely to continue in the future. Should a gas reservoir be discovered and exploited, a choice may have to be made between seasonal storage of lucrative hydrocarbon gas and long-term storage of waste CO<sub>2</sub>.

#### **7.5 Shale-gas resources**

Whereas most hydrocarbon gas is traditionally extracted from porous sandstones or limestones beneath a cupola of impermeable caprock, technological advances now permit gas to be extracted from shaly rocks (compacted claystones). The gas sits within tiny pores in the shale and/or is adsorbed in the shale matrix. As these pores are not interconnected (i.e. the rock is impermeable), the gas in a large volume of the rock cannot be pumped out through one conventional borehole. The new approach involves fracturing large volumes of the shale by injecting high-pressure water through arrays of parallel drillholes. This technology liberates the gas from the rock pores, so that it can be pumped out in the usual way.

Exploration for this type of gas resource is now being considered by the petroleum industry in Switzerland. The target reservoir rock for this alternative source of gas is quite different from the saline sandstone or limestone aquifers that could be used for CO<sub>2</sub> sequestration beneath the Central Plateau. Nevertheless, there is a clear conflict in applying these two technologies in the same area. In order to serve as a trap for injected CO<sub>2</sub>, the saline aquifers must have intact, impermeable caprocks. Moreover, where no trap structure (e.g. a dome) is present, the caprocks must be intact over very large distances downstream of the CO<sub>2</sub> injection site. For some of the potential aquifers proposed in this report, the caprocks are exactly the same compacted claystones that could also become targets for "shale gas" resources. If hydraulic fracturing of the caprock is performed to extract its hydrocarbon gas, then CO<sub>2</sub> in the underlying aquifer would leak upwards into different levels of the sedimentary layering, and perhaps even to the Earth's surface. Not only would the destruction of caprocks preclude CO<sub>2</sub> sequestration in the underlying aquifer, but also the arrays of parallel drillholes required for shale-gas extraction would create leakage paths through all the perforated rock formations overlying the shale-gas bed. If any of these overlying strata were to be used later for CO<sub>2</sub> storage, then the boreholes would have to be artificially sealed when production of the

hydrocarbon gas had ceased.

## 7.6 Mineral resources

With the exception of the fractured zones in the crystalline basement rocks, the well sealed saline aquifers beneath the Swiss Central Plateau are all limestones or sandstones. From experience in other parts of the world, both rock types may host valuable deposits of metals such as copper, lead, zinc and uranium. Where such deposits are large enough to warrant mining at depths below 800 m, a conflict of use would arise with respect to CO<sub>2</sub> sequestration. However, this situation is extremely unlikely to occur in the aquifers below the Central Plateau. None of the wide range of geological and geochemical observations amassed on this area suggests that such metal deposits exist at depth. Moreover, the geological processes that affected the rocks beneath the Central Plateau are not thought to have been conducive to the formation of such ores. Because of this evidence, no exploration for deep ore targets has ever taken place in Switzerland, and none is underway at present. Therefore, the hypothetical conflict with CO<sub>2</sub> sequestration can likely be disregarded.

Deposits of pure clays and of coal are other mineral resources that in theory may occur interstratified with the saline aquifers selected for CO<sub>2</sub> sequestration. In the case of clay deposits, mining at any more than a few hundred meters depth is not economically feasible, and so no conflict arises with CO<sub>2</sub> sequestration. Large deposits of coal can be mined to depths within the favoured interval for CO<sub>2</sub> injection, but no large deposits are known below the Swiss Central Plateau within the sediments above the Buntsandstein aquifer (Appendix 4.3). As mentioned for option 2 in Section 5, a series of coal seams is known to exist between depths of 1550 and 1750 m in a structural trough beneath Weiach. The high ash content of most of these seams renders them unusable, but two sets of seams have better properties and thicknesses up to 4 m. However, owing to their great depth these seams are unmineable, and so they do not conflict with CO<sub>2</sub> sequestration.

Two of the aquifers identified in this study, the Upper Muschelkalk and the Buntsandstein, are sealed by caprocks composed of rock salt and gypsum, which accumulated when shallow seas evaporated in the distant past. A conflict with CO<sub>2</sub> sequestration could arise if these evaporite layers were potentially interesting for mining. Both rock salt and gypsum have rather low commercial values, reflecting the abundance of mineable resources near the Earth's surface. Accordingly, the gypsum mines currently operating in the Central Plateau and the Jura Mountain Chain are all much shallower than the depth range of interest for CO<sub>2</sub> sequestration. The only active salt mines in Northern Switzerland are situated near Pratteln and Rheinfelden (Jura Chain). There the salt is extracted by dissolving it in water circulated through boreholes. This process creates porosity in the salt layer and compromises its sealing function for CO<sub>2</sub> sequestration. At present, dissolution mining is profitable down to about 450 m depth. Owing to the abundance of salt deposits at shallow levels in the Jura Chain, it seems unlikely that exploitation of significantly deeper caprocks would ever be economical. A conflict with CO<sub>2</sub> sequestration therefore appears remote.

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