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12. Shale-Gas, CO_2 Storage and Deep Geothermal Energy

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12. Shale-Gas, CO_2 Storage and Deep Geothermal Energy

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Swiss Geothermal Society,
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TALKS:

12.1 Abdelfettah Y., Schill E., Kuhn P.: Delimitation and characterization of geothermally relevant Permo-Carboniferious graben in the Swiss Crystalline basement

12.2 Alt-Epping P., Diamond L. W.: Numerical simulation of fluid-rock interaction upon CO_2 injection into the Muschelkalk aquifer in N-Switzerland

12.3 Aschwanden L., Diamond L.D., Ramseyer K., Mazurek M., Fallick T., Donnelly T.: Development of porosity in the Upper Muschelkalk carbonate aquifer, NE-Switzerland: relevance for geothermal energy and gas storage

12.4 Badoux V., Mégel T.: Cartographic representation of a geomechanical criterion for site-screening of sub-surface projects in the energy sector

12.5 Burri P., keynote speaker: Unconventional Hydrocarbons - The Revolution in Exploration (Chances and Risks) (Keynote)

12.6 Diamond L. W., Alt-Epping, P.: Simulation of water-rock interaction and porosity evolution in a granitoid-hosted, enhanced geothermal system (Basel, Switzerland)

12.7 Fabbri S., Zappone A., Madonna C.,Mazzotti M.: The effects of CO_2 injection in Muschelkalk: first laboratory results

12.8 Gawenda P.: Unconventional plays along the East European Craton – a review of E & P activities in Poland

12.9 Herwegh M., Baumberger R., Wehrens P., Schubert R., Mock S., Berger A., Mäder U., Spillmann T.: Internal structure of the Aar Massif: What can we learn in terms of exploration for deep geothermal energy?

12.10 Li C., Laloui L.: Hydromechanical coupling in carbon dioxide injection into a deep aquifer

12.11 Manceau Jc., Claret F., Tremosa J., Audigane P., Nussbaum C.: Field experiment in an underground rock laboratory to study the well integrity in the context of CO_2 geological storage

12.12 Moscariello A., Mondino F., Vinard P.: The geothermal site of Eclépens: new geological insights from an integrated seismic and satellite study.

12.13 Paolacci S., Gorin G., Moscariello A.: The subsurface geology of the Western Swiss Plateau and its French extension: state of the art and implications for geo-resources exploration.

12.14 Schilke S., Probert T., Bradford I., Özbek A., Robertsson J. O. A.: Use of surface patches for hydraulic fracture monitoring

12.15 Tomin P., Lunati I.: Multiphysics methods: a link between pore-scale and Darcy-scale models

12.16 Wyss R.,: Deep geothermal Energy in Switzerland – actual developments and perspectives for the future (Keynote)

POSTERS:

P 12.1 Jain C., Clauser C., Vogt C.: Optimized layout of engineered geothermal systems and potential in Germany

P 12.2 Räss L., Omlin S., Podladchikov Y. Y., Simon N. S. C.: Solving three-dimensional non-linearly coupled hydro-mechanical two-phase flow on GPUs

P 12.3 Soma L., Ambrosi C., Bernoulli D., Bonini L., Pera S. & Seno S.: Geochemical and structural data for the evaluation of the geothermal potential

12.1

Delimitation and characterization of geothermally relevant Permo-Carboniferious graben in the Swiss Crystalline basement

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We have investigated the application of 3D geology for gravity forward modeling as well as the application of Butterworth filters of different wavelength. Real application was conducted in the northern part of Switzerland under the Molasse basin in order to systematically assess the potential of the gravity data to detect and characterize the horizontal and vertical extension of the Permo-Carboniferious (PC) troughs in the Crystalline basement.

Synthetic gravity data sets were generated for these geological models using basement's homogeneous density. Gravity forward modeling is carried out using developed and unpublished finite element code. The finite element mesh allows approaching the geological geometry using tetrahedrons shape. To simulate the real conditions, the gravity stations are located on the real topography. After computing a gravity effect of the 3D geological model, we get a complete Bouguer anomaly. Since, and as expected from the geology, the Bouguer anomaly is strongly dominated by the gravity effect of the Molasse sediments, where the slightly bended Mesozoic sediments are inclined by about 2-5 ° towards the Alps and the Tertiary filling of the molasses basin is deepening following this geometry. A code using Butterworth filter was developed and so applied on the computed anomaly as well as on the observed Bouguer anomaly to eliminate this regional trend, and characterize a probable presence of PC grabens.

The result reveals high potential in the delimitation of the PC-troughs by the combination of the seismic and gravity interpretation. Assuming a similar geometry for these graben structures, gravity data post-processing traces these structures at different depth using a Butterworth filter with different wavelength, in order to calculate a residual gravity anomalies. Filtered Bouguer anomaly with different wavelengths is an essential tool to detect and characterize the horizontal and vertical extensions of the PC-troughs. The different wavelengths provide insight into different vertical levels of the trough and thus, allow describing 3D geometry of the graben structures in depth and give us a pseudo-tomography image.

Finally, the application of the filters to real measurements reveals the distribution of the PC-grabens in the northern west part of Switzerland. The results is an agreement with the informations provided in different deep boreholes exit in the studied area. Roughly speaking, the negative residual anomalies agree with the PC-trough whereas the lack of these end, agree generally with a positive residual anomalies. The geophysical and geological interpretations allow also to confirm the geological concept of intracontinental alternation of transpression and transtension resulting in wrench-faulting, which was also observed in analogue shear faulting dual-layer models, where a complex pull-apart basins as observed in the northern studied area, southern Basel.

12.2

Numerical simulation of fluid-rock interaction upon CO_2 injection into the Muschelkalk aquifer in N-Switzerland

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A recent study (Chevalier et al., 2010) has identified several deep saline aquifers in the Swiss Molasse Basin, which may potentially be useful as reservoirs to store industrial CO_2. Of these aquifers, the Trigonodus Dolomite of the Upper Muschelkalk appears to be the most promising. To further evaluate its potential of storage capacity, injectivity and the long-term isolation performance, predictive numerical simulations constrained by experimental and observational data have been carried out. These simulations assess the implications of the dynamics of the CO_2 plume and the ensuing fluid-fluid and fluid-rock reactions for the safe, long-term storage of CO_2 in the aquifer.

The numerical simulation of processes during and after the injection of CO_2 into deep saline aquifers is a challenging task because of the complexity and the coupled nature of the physical and chemical phenomena. During and shortly after injection, the immiscible CO_2 displaces the brine in a drainage-like process and migrates laterally away from the injection wells and to the top of the injection aquifer due to buoyancy forces. Once injection stops, CO_2 continues to migrate upward and displace water at the leading edge of the plume, while at the trailing edge water displaces CO_2 in an imbibition-like process. A trail of residual, immobile CO_2 is left behind the plume. The residual CO_2 and the CO_2 at the plume/brine interface slowly dissolves into the formation water, altering its chemical composition and density. Over longer time scales the fluid may then be involved in reactions with the rock and under favourable conditions dissolved CO_2 may precipitate and be permanently trapped as carbonate minerals.

Critical aquifer properties and their spatial variability are known only from core samples but for realistic simulations these properties need to be specified for regional-scale domains. The most important of these properties are the porosity and the permeability of the rock. The porosity of the rock determines the overall CO_2 storage capacity and it affects the permeability of the reservoir rock. The permeability controls the injectivity of CO_2, the dynamics of the CO_2 plume and its size and shape (Fig. 1). The porosity/permeability distribution determines the contact area between the plume and the brine and thus the dissolution rate of CO_2 into the aqueous phase. Laboratory measurements on core samples of the Trigonodus Dolomite indicate a strongly heterogeneous distribution of porosity (values in the range of 3 - 24%) and permeability (1.6e-18 m^2 – 5.6e-15 m^2).

Preliminary simulations suggest that in carbonate-hosted aquifers such as the Trigonodus Dolomite, CO_2 can be trapped as a residual phase in the pore space, by dissolution into the aqueous phase or by the physical containment of the CO_2 plume in structural traps such as anticlines. Unlike in silicate aquifers, the storage in carbonate minerals is not possible. This emphasizes the need to ensure the long-term integrity of the seal to prevent the leakage of CO_2 into overlying freshwater aquifers. Potential leakage pathways include existing faults/fractures or those created as a consequence of pressure build-up in the aquifer during injection, concrete-plugged abandoned wells or the corrosion of the seal due to the influx of CO_2 and acidity from the underlying aquifer.

We are conducting numerical simulations with the code PFLOTRAN (Hammond & Lichtner, 2010 and Hammond et al. 2011). The code permits fully coupled simulations involving multiphase fluid flow, solute transport, heat transport and chemical reactions. We present preliminary results of numerical simulations carried out for domains with heterogeneous, correlated porosity/permeability fields (Fig. 1) and for smaller-scale, simplified systems at high spatial resolution (Fig.2) to address some of the above issues.

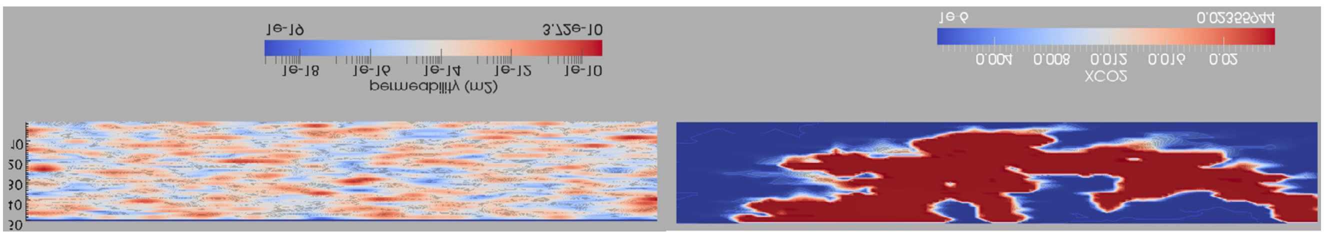

Figure 1: A generic (and extreme) example of how the extent and shape of the CO_2 plume is controlled by the permeability distribution. Correlated random permeability field and the CO_2 plume after 25 years. Total injected CO_2 is 315 t.

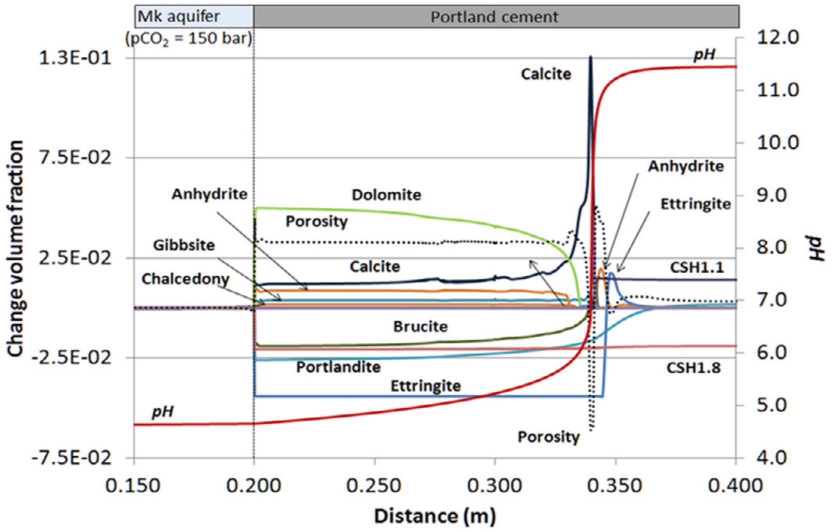

Figure 2: Reactions at the contact between the aquifer and a cement plug in a well. High pCO_2 conditions in the aquifer induce carbonatization and mechanical weakening (porosity increase) of the cement. Shown are mineral volume changes after 25 years (<0: dissolution, >0 precipitation) and pH.

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12.3

Development of porosity in the Upper Muschelkalk carbonate aquifer, NE-Switzerland: relevance for geothermal energy and gas storage

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In the Swiss Molasse Basin, deeply buried Middle Triassic carbonate rocks of the Upper Muschelkalk aquifer show potential for geothermal energy exploitation and for geological storage of gas – whether permanent storage of waste CO_2 or seasonal storage of imported methane (Chevalier et al., 2010). Particularly the Trigonodus Dolomite, the top of the Upper Muschelkalk aquifer, regionally shows elevated porosities and permeabilities. However, owing to the low spatial density of wells with available core in the region of interest, there is currently only a rudimentary understanding of the 3D distribution of porosity and permeability throughout the basin. One way to better characterize the reservoir is to develop a genetic understanding of how porosity and permeability developed over time. This understanding could then be used to interpolate the distribution and magnitudes of the rock properties between boreholes and to extrapolate their values outside the region sampled by wells.

This study takes a first step in this direction by focusing on the genesis of porosity in the Trigonodus Dolomite at one specific drill site, Benken, which is situated 5 km south of Schaffhausen at the northeastern margin of the Swiss Molasse Basin. The investigated drill core was extracted by the Swiss National Cooperative for the Disposal of Radioactive Waste (Nagra). This study presents a detailed reconstruction of the formation, diagenesis, burial history and water-rock interactions of the Trigonodus Dolomite at Benken with emphasis on processes that generated or clogged porosity. The reconstruction is based on new petrographic observations by standard optical, UV-fluorescence and scanning-electron microscopy, and on analyses of stable and radiogenic isotopes (i.e. δD, $\delta^{13}C$, $\delta^{18}O$, $\delta^{34}S$ and $^{87}Sr/^{86}Sr$) in bulk samples of rock-forming and pore-filling minerals. Literature data on fluid inclusions and on the regional geological and hydrological evolution are integrated into the interpretations. No new insight is provided on porosity provided by fracture networks, as no evidence for these was found in the drill core.

The results show that the present-day 2-22% bulk porosity (Chevalier et al., 2010) in the Trigonodus Dolomite is the combination of (1) micropores (< 10 µm diam.) formed during dolomitzation of the precursor calcareous sediment, (2) intergrain pores formed during its deposition, (3) moldic pores formed by the selective dissolution of bivalve shell fragments and (4) cavernous pores formed by the dissolution of anhydrite nodules. The formation of intergrain pores is closely associated with the deposition of shore-parallel oolite shoal bodies in the in the back-bank environment of the Upper Muschelkalk carbonate ramp. Following deposition of the initially calcareous sediment, eogenetic dolomitization affected the still unlithified sediment. The dolomitization process is characterized by three different stages. The earliest corresponds to an evaporation-related, replacement dolomitization entailing formation of microporosity between the individual dolomite crystals, the selective dissolution of bivalve shell fragments (formation of moldic porosity) and the precipitation of anhydrite as nodules. The two later stages correspond to burial related precipitation of primary dolomite cement in the available pore space, thereby reducing porosity. The latest stages of dolomite cementation are at least partially contemporaneous with the early stages of dissolution of the anhydrite nodules and thus the formation of cavernous porosity. The dissolution of the anhydrite nodules was accompanied by the replacement of the anhydrite by quartz, which co-precipitated with pyrite and probably sphalerite from diagenetically modified pore waters. Most likely the dissolution was caused by an event of pervasive infiltration of highly saline water into the Mesozoic sediment stack of the Zürcher Weinland. Neither the timing of infiltration nor the origin of the brine is exactly known but the appearance of primary, high-salinity fluid inclusions in the Dogger β limits its maximum age to late Dogger/Malm (Bläsi et al., 2002), whereas its minimum age is the Eocene. Later pore space reduction by the precipitation of pore-filling kaolinite and calcite is related to the Paleocene–late Neogene doming of the Schwarzwald area and associated infiltration of meteoric water into crystalline rocks, which recharged into the Upper Muschelkalk aquifer. The exact timing of mineral formation cannot be determined but it must have occurred before the recent ground water infiltrated the rock during the last glacial period at around 12–14 ka.

This study shows that the porosity of the Trigonodus Dolomite at Benken is highly influenced by the depositional environment and by early diagenetic processes. It has been shown that the volumetrically dominant cavernous porosity formed before the late Neogene establishment of the current hydrogeological system at Benken. Consequently, there is presently no reason to rule out the presence of similar porosity in the central and southern parts of the Swiss Molasse Basin. In contrast, porosity reduction by precipitation of pore-filling calcite and kaolinite was clearly related to the doming of the Schwarzwald area and to the establishment of the Recent hydrogeological system. Therefore, these pore-filling minerals are likely restricted to the northern margin of the basin. Overall, these findings are a positive indication for the potential of the Trignodus Dolomite aquifer in other parts of the basin for geothermal energy and gas storage.

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12.4

Cartographic representation of a geomechanical criterion for site-screening of sub-surface projects in the energy sector

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The knowledge of the geomechanical behaviour of the deep underground is of prior importance for sub-surface projects related to the energy sector (shale-gas, CO_2 storage and EGS or hydrothermal projects,…). Experience from past and present projects has shown that a modification of the stress conditions in the reservoir could induce seismicity. The understanding of the geomechanical conditions of the underground should be addressed in an early phase of any sub-surface project in order to reduce collateral risk in a later phase of the project such as induced seismicity or groundwater pollution, for instance.

A new methodology is presented here to allow using a criterion derived from the classical geomechanical theory for site screening of sub-surface project. The proposed methodology consists in a cartographic representation of this criterion at the depth of a target horizon. Depending on the project, the target horizon could be a geological layer or an isotherm surface. The resulting map could then be used for site-screening of sub-surface projects complementary to other site screening criteria. A generic example of the cartographic representation of the geomechanical criterion is presented in Figure 2.

The geomechanical criterion is derived from the classical Mohr-Coulomb rock-failure approach, which allows estimating the additional fluid pressure required in the reservoir to reach the failure. Prerequisite is the knowledge of the stress-field magnitudes, the geomechanical properties of the rocks and the depth of the target horizons (Figure 1). The resulting geomechanical criterion in MPa is presented in Figure 2.

For reservoirs where the productivity is known to be naturally good enough to make the project economically viable (e.g. hydrothermal projects), no hydraulic stimulation is required. The site of such projects should thus be located in areas where the geomechanical criterion is high. This would reduce the risk of induced seismicity while testing the well or while reinjecting the water in the reservoir during the exploitation phase. In contrary, for reservoirs where the natural productivity is expected to be too low to make the project economically viable, engineering techniques are then required to increase artificially the reservoir productivity (EGS or petrothermal projects). The site of these projects would thus be located in areas where the geomechanical criterion is low enough to make the engineering techniques applicable (overpressure reachable by normal injection pumps). The map could also be used to delineate areas where the stress-field is subcritical.

The presented methodology has been developed using generic case datasets. The methodology is ready to be applied with real datasets as an additional criterion for site selection of sub-surface projects in the energy sector.

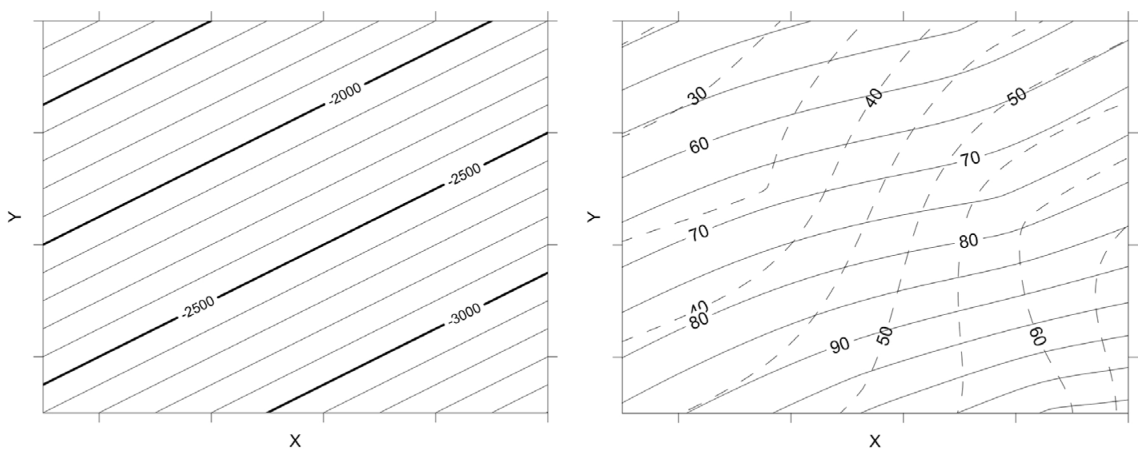

Figure 1. (left) Depth of the target horizon (m BGL) and (right) principal stress field components in MPa along the target horizon (S1 in plain lines; S3 in dashed lines).

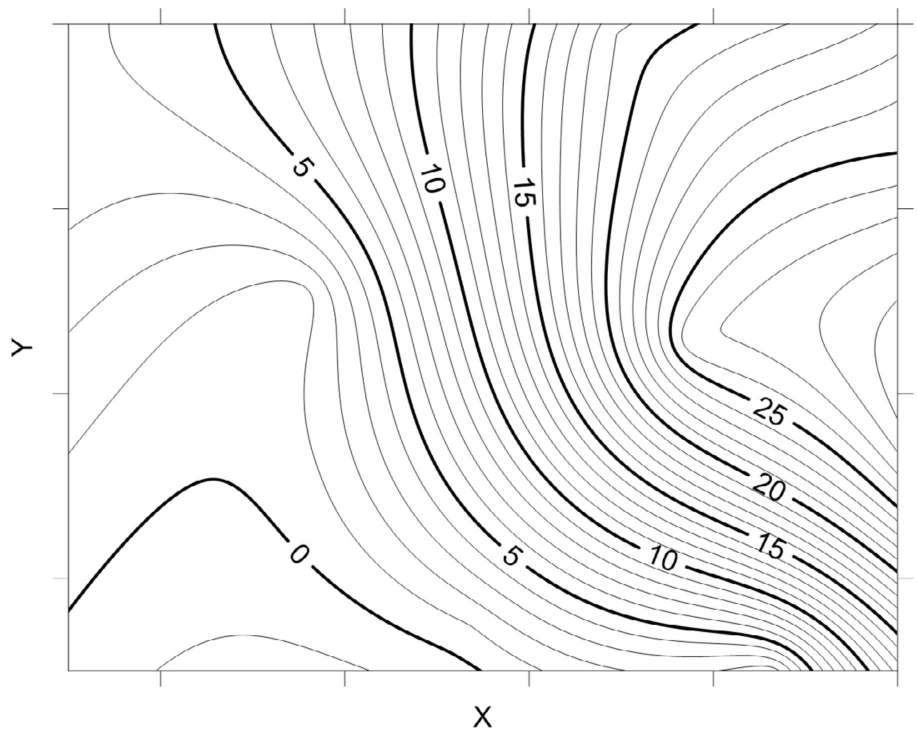

Figure 2. Cartographic representation of the geomechanical criteria (MPa) along a target horizon.

12.5
Unconventional Hydrocarbons - The Revolution in Exploration (Chances and Risks)

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Contrary to common belief the recent, dramatic development in the unconventional hydrocarbon exploration is not primarily a question of operational technology but has its roots much more in revolutionary new insights into the geological and geochemical aspects of hydrocarbon generation, migration and accumulation. Key new insights are: that probably the larger part of the generated hydrocarbons remain in the source rocks and that the porosity of the source rocks is created by the hydrocarbon generation itself. The latter is the explanation for the phenomenon that even nano-porosity can be economically produced, something considered impossible only a few years ago.

The methods of hydraulic fracturing and horizontal drilling are routine technologies that have been used in the industry safely for many decades. Nevertheless unconventional hydrocarbon production has led in the US locally to inacceptable cases of water and surface pollution. This is mainly due to human error, poor execution of wells and unprofessional operating practices. The methods have, however, evolved very considerably. Best practice examples show that safe and environmentally responsible operations (through cluster drilling, recycling of fluids and the use of only non-toxic additives) are today not only possible but also economic.

Unconventional gas has fundamentally changed the energy outlook of the world, and the scenarios that were used until the last decade have no longer any validity. The very large new gas reserves give the world the possibility to replace coal, the fastest growing and by far dirtiest fossil energy and partially diesel and can thus help to significantly curtail the output of CO_2 and of air pollutants. In this role natural gas can provide an ideal bridge to a predominantly renewable energy future.

12.6

Simulation of water-rock interaction and porosity evolution in a granitoid-hosted, enhanced geothermal system (Basel, Switzerland)

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From 2003 to 2006 a 5 km well was drilled into basement granitoids below the city of Basel as a step towards establishing a geothermal doublet circulation system to produce electricity and space heating. To enhance the permeability of the granitoids, river water was injected into the base of the well. Unfortunately, this hydraulic stimulation induced seismic events strong enough to be felt at the surface, leading to the project being permanently abandoned. Nevertheless, there is still interest in Switzerland to pursue this approach to geothermal energy exploitation. To aid planning of future projects, the present study uses numerical simulations based on the specifications of the Basel project to address some of the open geochemical questions associated with such deep enhanced geothermal systems (EGS).

The important geochemical issues regarding the sustainability of EGS are (1) whether mineral precipitation due to water–rock reactions will eventually lead to clogging of flow paths in the reservoir, wells and surface installations and thereby reduce or even completely block fluid throughput; and (2) whether the well casing will be significantly corroded by the production fluid. Using the computer code FLOTRAN (Hammond et al., 2011), we have constructed a reactive transport model that allows the main chemical reactions to be predicted and the resulting evolution of porosity to be tracked over the expected 30-year operational lifetime of the system.

The simulations show that injection of surface water to stimulate fracture permeability in the monzogranite reservoir at 190 °C and 5000 m depth induces redox reactions between the oxidized surface water and the reduced wall rock. Although new calcite, chlorite, hematite and other minerals precipitate near the injection well, their volumes are low and more than compensated by those of the dissolving wall-rock minerals. Thus, during stimulation, reduction of injectivity by mineral precipitation is unlikely.

During the simulated long-term, closed-system operation of the system (Fig. 1), the main mineral reactions are the hydration and albitization of plagioclase, the alteration of hornblende to an assemblage of smectites and chlorites and of primary K-feldspar to muscovite and microcline. Within a closed-system doublet, the composition of the circulated fluid changes only slightly during its repeated passage through the reservoir, as the wall rock essentially undergoes isochemical recrystallization. Even after 30 years of circulation, the calculations show that porosity is reduced by only ~0.2%, well below the expected fracture porosity induced by stimulation. This result suggests that permeability reduction owing to water–rock interaction is unlikely to jeopardize the long-term operation of deep, granitoid-hosted EGS systems.

A peculiarity at Basel is the presence of anhydrite as fracture coatings at ~5000 m depth. Simulated exposure of the circulating fluid to anhydrite induces a stronger redox disequilibrium in the reservoir, driving dissolution of ferrous minerals and precipitation of ferric smectites, hematite and pyrite. However, even in this scenario the porosity reduction is at most 0.5%, a value which is unproblematic for sustainable fluid circulation through the reservoir.

Owing to the low ligand content of the circulating fluid in the closed-system doublet, mass transfer and scaling in the wells and surface installations is predicted to be very limited. While this closed-system simulation represents an interesting end-member case, in reality the inevitable loss of water at depth would require the circulation to be periodically topped-up with fresh river water. This could result in slightly higher levels of scaling. Assuming kinetic inhibition of quartz and chalcedony precipitation (as observed in comparable natural geothermal systems), the model shows that scaling due to precipitation of amorphous silica can be avoided completely by keeping the reinjection temperature of the fluid above 58 °C.

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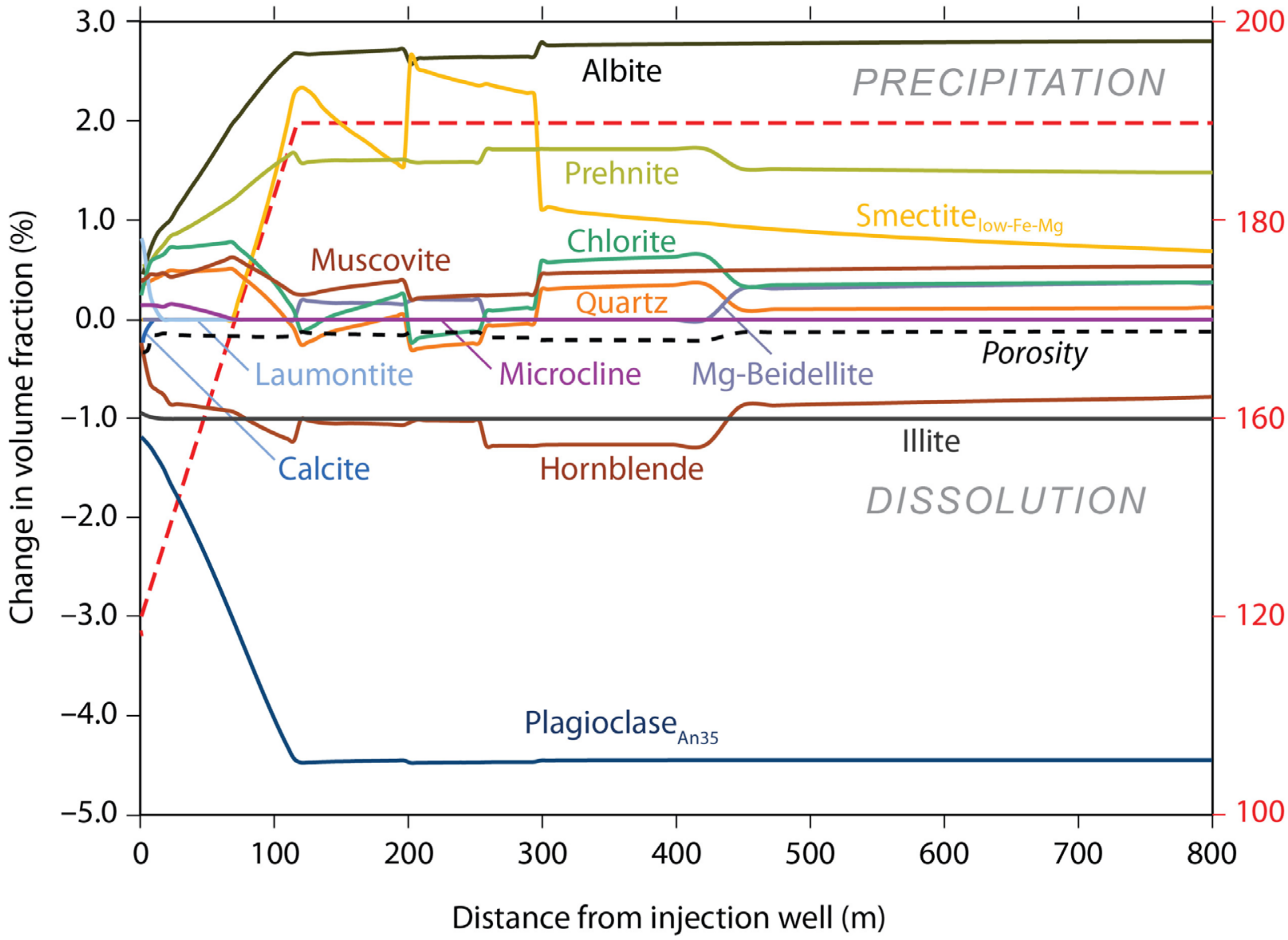

Figure 1. Changes in reservoir mineralogy during the first 15 years of closed-system doublet operation. Red dashed line: temperature profile. Time-integrated changes in volume fractions of minerals are plotted as a function of distance from the base of the injection well. Positive volume fractions indicate mineral precipitation; negative fractions indicate dissolution or porosity decrease (dashed curve). Minerals with very low changes in volume (e.g. biotite, and the ferric oxides and hydroxides formed during initial stimulation) are not shown.

12.7
The effects of CO_2 injection in Muschelkalk: first laboratory results

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Anthropogenic emissions of Carbon Dioxide (CO2) are one of the key drivers regarding global climate change (IPCC, 2007). Carbon Dioxide Capture and Storage (CCS) is one valuable technology to mitigate current climate change with an immediate impact. Switzerland has started to investigate its potential for CO2 storage and is currently performing research on the characterization of the most promising reservoir rocks for CO2 sequestration. One aquifer of considerable large extent in the Swiss Molasse Basin is the Muschelkalk, a carbonate sequence of shallow marine limestones, with an estimated storage potential of 706 MtCO2 (Chevalier et al., 2010). The uppermost part of the Muschelkalk unit, reveals favorable storage properties. The Gipskeuper, a thinly bedded alternation of clay-stones, anhydrite, gypsum and marls, overlies the Muschelkalk and acts as tight seal.

A series of laboratory measurements were carried out at the Rock Deformation Laboratory of ETH Zurich, on dolomite core samples recovered from a drill core from Benken, in the northeast of Switzerland (courtesy of Nagra). The transient step method (Brace et al., 1968) was used to measure the permeability, using argon and dry carbon dioxide, and employing an experimental setup developed in house (Pini et al., 2009). The rig is capable to simulate in situ pressure and temperatures conditions, and thus it allows an accurate evaluation of the reservoir's capacities for CO2 sequestration. Recent implementations of the rig enable to perform permeability measurements and acoustic velocity measurements simultaneously (Fig. 1).

The minimal injection depth considered for CO_2 sequestration is 800 m, corresponding to a lithostatic pressure of 20 MPa and a temperature of 50°C (Chevalier et al., 2010; Nagra report, 2001). At such PT conditions, CO_2 changes its state of aggregation to supercritical and is significantly denser than in gaseous state. The experiments were performed under confining pressure of 6 MPa, 10 MPa, 14 MPa, 18 MPa and 20 MPa. The samples were heated in steps, together with the injected gas to temperatures of 23 °C, 35 °C and 50 °C. The two gas pressure reservoirs (see Fig. 1) were set to 2 MPa and 2.5 MPa. After the reservoirs equilibrated, a pore pressure of around 2.3 MPa was set and acoustic velocities were measured. Then the two reservoirs were set to 8 MPa and 8.5 MPa with a final pore pressure of 8.3 MPa after equilibration.

Our result indicate that the permeability crucially depends on confining pressure, temperature and pore pressure conditions of the sample. Especially at in situ conditions with CO2 being at supercritical state, a substantial loss in permeability have to be taken into consideration when it comes to the calculation of potential injection rates.
These results are part of an on-going study and are very preliminary, up to now only cores perpendicular to bedding have been investigated, and we expect different physical properties behaviour in samples cut at different angles to bedding. Further investigations of more rock samples and in wet conditions, are required to support the results shown in this study.

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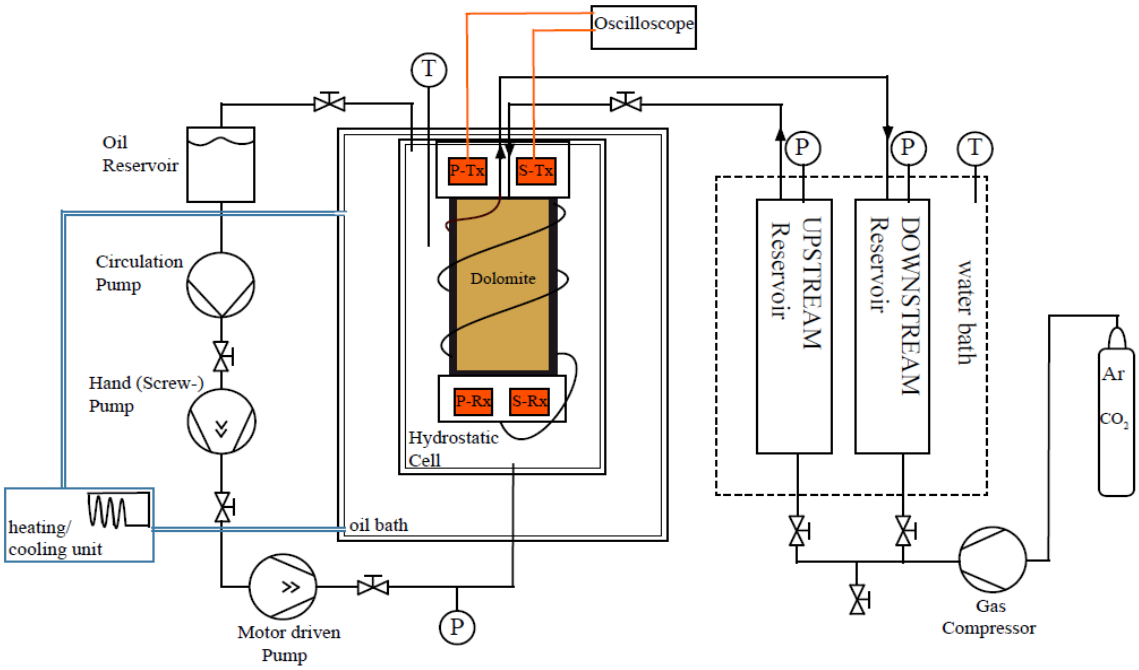

Figure 1. Setup of the modified Pini rig (redrawn from Pini et al., 2009 and updated) for permeability/velocities measurements. The transducers in the new sample holder emit at 0.5 MHz ultrasonic waves and enable the user to record acoustic wave velocities without any change on the set-up. Confining pressures up to 100 MPa and temperatures up to 100°C can be reached.

12.8

Unconventional plays along the East European Craton – a review of E & P activities in Poland

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The western limit of the Precambrian East European Craton (EEC) in Poland (Fig. 1) is being intensely explored for unconventional resource potential since a few years. The key tectonic units of interest are the Baltic Syneclise, Danish-Polish Marginal Trough and Volhyno-Podolian Monocline, all within the EEC, as well as the Pomeranian and Kujawy highs, elements of the Northeast German-Polish Basin.

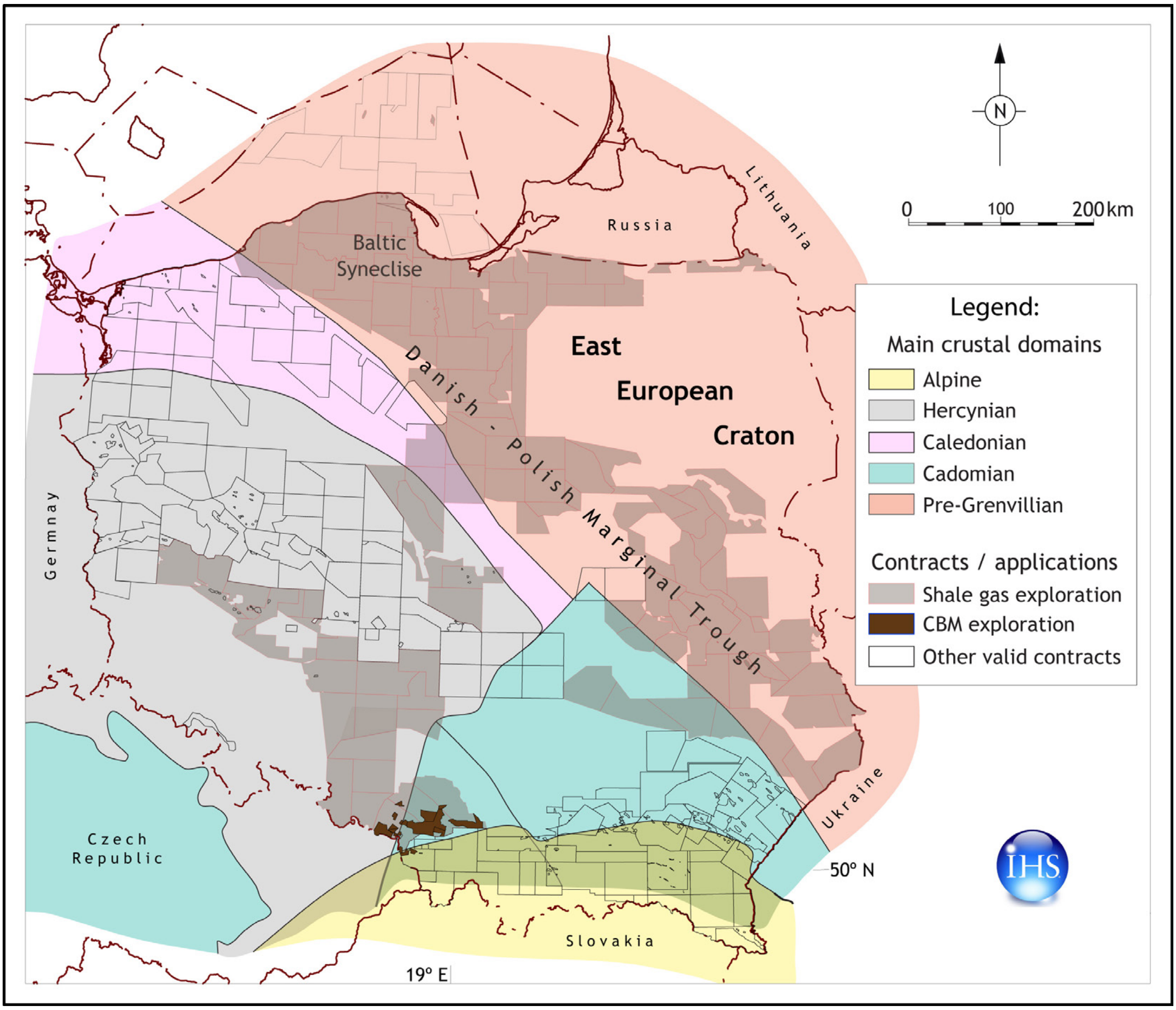

Figure 1. Map of Poland with location of the permits for unconventional exploration on the background of crustal terrains (after Karnkowski 2008).

The prime targets of exploration are found within the Upper Cambrian-Ordovician-Lower Silurian organic-rich sequences (Carboniferous series are also seen as a potential exploration target in places). The available seismic and well data indicate that the top of the Carboniferous series within the EEC limit can be traced at depths of 500-5,500 m, with the depth increasing to the west and southwest, towards the Teisseyre-Tornquist fault zone. Subsidence history reconstructed from well data shows that the Lower Palaeozoic formations in Poland were subject to rapid burial initiated during the Early Silurian and that the series attained hydrocarbon-generating maturity as early as in the Late Silurian/Ordovician, with the major pulse of thermal maturation associated with the Variscan orogeny.

Some 100 valid exploration contracts awarded in the sector since 2007 cover almost the entire acreage deemed prospective for hydrocarbon exploration. Following the initial period of land-grabbing, when operators of diverse sizes secured a significant acreage position, the late 2012/ 2013 period was epitomised by the withdrawal of a few players.

Over 40 shale wells have been drilled since mid-2010 to attest the potential of the area - majority of the wells is located within the Baltic basin (Fig. 2) – with some dozen of them flow-tested. The results of to-date drilling operations show that prospective series are gas-bearing over a few dozen metre-thick intervals. Tests conducted in the wells in northern Poland have proven that gas can be brought to surface, albeit not always at commercial rates.

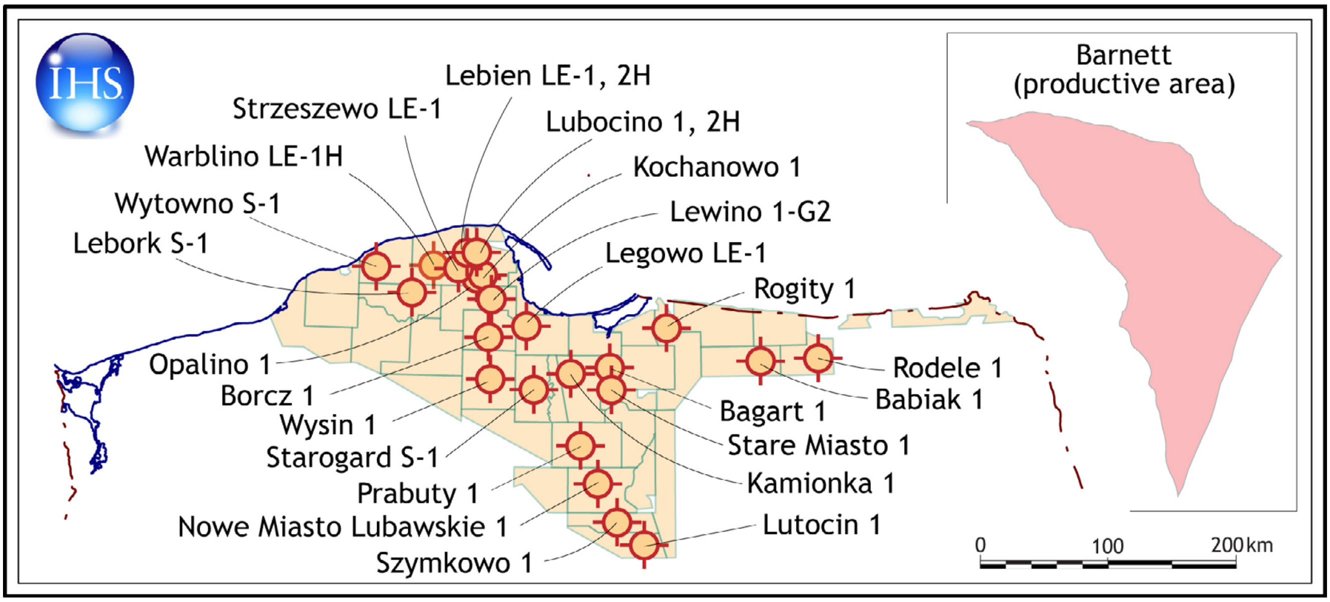

Figure 2. Map of northern Poland showing the wells drilled to-date for unconventional resources. Barnett (US) productive area is given for scale.

In spite of the initial exploration successes, unconventional exploration in Poland is still in its very early stage. The geological and technical features of the tested plays need further addressing; it has yet to be unequivocally determined if, and to what extent, a commercial production of hydrocarbons from the Palaeozoic series is feasible. The process requires more wells/tests than initially anticipated, consequently more time and investment to arrive at comprehensive conclusions.

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12.9

Internal structure of the Aar Massif: What can we learn in terms of exploration for deep geothermal energy?

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The successful use of deep geothermal energy requires 3D flow paths, which allow an efficient heat exchange between the surrounding host rocks and the circulating fluids. Recent attempts to exploit this energy resource clearly demonstrate that the new technology is facing sever problems. Some major problems are related to the prediction of permeability, the 3D structure of the flow paths and the mechanical responses during elevated fluid pressures at depths of several kilometers. Although seemingly new in a technical perspective, nature is facing and solving similar problems since the beginning of the Alpine orogeny.

Based on detailed studies in the Hasli Valley (Aar Massif) we can demonstrate that deformation and fluid flow are strongly localized along mechanical anisotropies (e.g. lithological variations, brittle and ductile faults). Some of them already evolved during Variscan and post-Variscan times. Interestingly, these inherited structures are reactivated over and over again during the Alpine orogeny. Their reactivation occurred at depths of ~13-15 km with elevated temperatures (400-475°C) and involved both ductile and brittle deformation processes. Brittle deformation in form of hydrofracking was always present due to the circulating fluids. It is this process, which was and still is responsible for seismic activity. With progressive uplift and exhumation of the Aar Massif, ductile deformation structures became replaced by brittle cataclasites and fault gouges during fault activity at shallower crustal levels. Existing hydrotest data from the Grimsel Test Site (Nagra's underground research laboratory) indicate that these brittle successors of the ductile shear zones are domains of enhanced recent fluid percolation. Note that although being exposed today, the continuation of these fault structures are still active at depth in both brittle and ductile deformation modes, a fact that can be inferred from recent uplift rates and the active seismicity.

On the scale of the Aar Massif, the aforementioned deformation sequence induced a complex and dense network of large-scale fault zones. The 3D structure of this network and the associated spacing between the individual faults strongly depends on the type of host rock, intensity of background strain and the location (kinematics) within the massif. Similar effects have to be expected in the crystalline rocks underneath the sedimentary cover in Northern Switzerland. However, based on the aforementioned findings, several facts might be in favor for future exploration of deep geothermal energy in the Aar Massif: (i) enhanced permeability in brittle fault rocks, (ii) dense 3D network auf brittle faults, (iii) weak vegetation allows a reliable projection of the structures to depth as well as tracking of their lateral continuation (crucial for estimates on seismic potential) and last but not least the existence of an elevated geothermal gradient.

12.10
Hydromechanical coupling in carbon dioxide injection into a deep aquifer

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CO_2 storage in deep aquifer is considered as a compromising technology to reduce the impact of CO_2 on the greenhouse effect. Practically, large-volume (>1Mt/year) of CO_2 could be injected into a system which consists of a highly porous host aquifer covered by a very low permeable sealing caprock. High rate injection could result in an abrupt fluid pressures build-up, deforming the aquifer and compromising the integrity of caprock. The interaction between fluid flow and mechanical reaction of geomaterials gives rise to a complexly coupled system. It is crucial to understand such hydromechanical processes in order to secure the injection.

We investigate numerically the multiphase hydromechanical effects induced by CO_2 injection on the aquifer and the related interactions with the caprock. The proposed simulator incorporates real physical properties of supercritical CO_2 such as the density, the viscosity and the fugacity. A conceptual deep aquifer is modelled to investigate the state of stress and strain during the injection of CO_2. Simulation responses show that significant geomechanical variations occur during the early period of injection where fluid pressures are increasing sharply (see Figure. 1). Overpressure leads to a decrease in the effective stress, which leads to volumetric expansion around the injection well. Because of this porosity and permeability increase via the hydromechanical coupling, which allows fluid flow more easily. As injection continues, the stress path moves away from the failure line and geomaterials return back to the elastic state. In this study, the safety of carbon dioxide injection is assessed mainly from a geomechanical point of view. Most influential parameters in the injection-induced responses are highlighted with the aid of a predefined security factor, which can be employed in the design of an industrial CO_2 storage project.

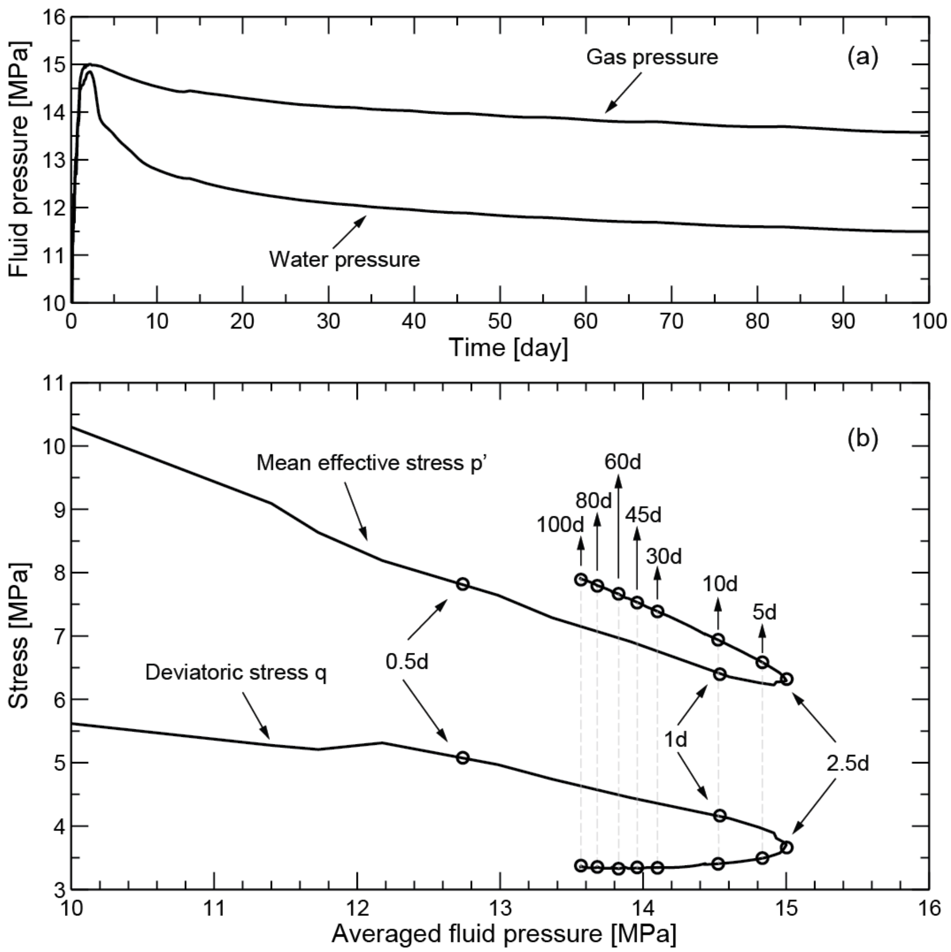

Figure 1. Temporal evolution of the water pressure and CO_2 pressure, (b) Temporal evolution of relationship between stress and fluid pressure on the top of the aquifer and next to the injection well.

12.11

Field experiment in an underground rock laboratory to study the well integrity in the context of CO_2 geological storage

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Wells drilled through low-permeable caprock are potential connections between the CO_2 storage reservoir and overlying sensitive targets like aquifers and the surface environment. The long term well integrity is therefore essential for fluids confinement (brine with or without dissolved CO_2 or buoyant gaseous CO_2). This integrity can be first affected by *in situ* operations (Zhang & Bachu, 2011): during the drilling, the caprock can be damaged leading to the formation of an excavation damaged zone; the quality and placement of the cement during the completion is also essential for a suitable bonding; the pressure and temperature changes during the life of the well as well as the conditions of its abandonment are additional factors that may impact the isolation capacity of the well. The well integrity can also be modified by geochemical reactions occurring between well compartments (cement, caprock, casing) and fluids (CO_2-saturated water as well as wet CO_2). Cement reactivity is of first concern and a significant amount of studies have already been carried out to characterize these interactions (for instance Kutchko et al., 2007; Duguid and Scherer, 2010).

Given the buoyant character of CO_2 associated with a potential overpressure due to the leakage (driving force), the hydraulic properties of the wellbore environment and their evolution over time appear to be the more influent variables for assessing the long term risks related to the wells. Some field studies have assessed the consequences of the contact between wellbores and CO_2 in an EOR field and in a natural CO_2 reservoir (Carey et al., 2007; Crow et al., 2010). They highlighted in particular the lack of integrity that may occur at the interfaces rather than through the cement matrix. Understanding the near well sealing integrity then requires studying the potential pathways and associated migration via altered well compartments but also along interfaces with deficient bonding: it implies the study of the well environment as a whole.
To go beyond the state of the art, we present a new experiment, implemented in the Underground Rock Laboratory of Mont Terri (St-Ursanne, Switzerland), at an intermediate scale between the laboratory experiments (which offer the opportunity to assess specific phenomena over time) and field observations (which allow an assessment of the entire system in subsurface at a specific time). Our purpose is to follow the integrity evolution of the whole well system due to changes in well conditions (e.g. changes in temperature and in the geochemical environment with and without CO_2).

To meet this purpose, the following steps are contemplated: 1/ the building of classical well elements to reproduce a part of the barrier system constituted of the low permeable formation, the cemented annulus, the casing and the cement plug; 2/ the characterization of the initial geochemical and hydraulic properties of the system; 3/ the increase in temperature of the system and the characterization of the potential geochemical and hydraulic changes; 4/ the injection of CO_2-rich fluid in the experimental apparatus and the characterization of the potential geochemical and hydraulic changes; 5/ the retrieval of solid samples from the experimental apparatus for further analyses in laboratory.

The concept of the experiment is as follows: the system is divided in two parts, an internal part consisting of the casing and the cement plug inside the casing, and an external part consisting of the formation rock, the cemented annulus and the casing. A first interval, where fluids are injected, is located below the well elements. Over the cement plug, a second interval allows measuring the flow inside the casing. A third interval allows measuring the flow outside the casing.

The drilling of the borehole and well completion were performed in autumn 2012. The system was then saturated with synthetic pore water and relaxed. Some pulse and constant head tests have been run at the beginning of 2013 with the purpose of characterizing the initial hydraulic properties of the system (well and surrounding caprock). In addition to the constant head tests, the experimental set-up allows a continuous monitoring of the effective well permeability over time at steady state. The system was relaxed again to observe the evolution of the hydraulic properties under initial conditions. No major changes were observed in one month. The temperature was then increased in the system up to 50°C. The system was let at this temperature during several months in order to equilibrate the temperatures and then to characterize the changes in terms of hydraulic properties. Significant modifications in the hydraulic behavior of the system have been observed, showing clearly an increase of the well integrity. The next steps of the experiment plan are the injection of CO_2-saturated water associated with tracers and the monitoring of the well hydraulic properties and fluids composition evolution over time.

In addition to that experiment, modeling work has been performed. The caprock and wellbore hydraulic properties have been retrieved from the hydro-tests using analytical and numerical modeling. In terms of geochemical modeling, predictive models have been built to understand the potential behavior of the well system in contact with CO_2. These predictive modeling are used to calibrate the experimental conditions. Predictive modeling also makes possible to link the measured changes in chemistry during the experiment to the interaction processes occurring at the casing/cement/clay interface.

Acknowledgements
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12.12

The geothermal site of Eclépens: new geological insights from an integrated seismic and satellite study.

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In response to the ever-increasing demand of energy supply in Switzerland, over the last 10 years a concerted effort to identify technically and economically viable deep geothermal projects has been promoted both by the public and private sector.

One of the most promising projects currently in the phase of the feasibility study is the EGS project of Eclépens (Canton of Vaud, Western Switzerland) promoted primarily by BKW and a group of industry partners.
The targeted site was discovered in 1981 by the hydrocarbon exploratory well Eclépens -1 which encountered the known stratigraphy of the region (from top to bottom Tertiary Molasse, Lower Cretaceous and Jurassic series) and reached the top of the Triassic at around 2200 m below surface where a temperature of ca.110°C was recorded.

This paper aims to present the preliminary results of the recent study carried out based on both he newly acquired and the reprocessed vintage 2D seismic lines (Fig. 1) integrated with the satellite image analysis of the area.

The Eclépens area has been investigated since mid 70s for hydrocarbon resulting on a relatively large number of cross cutting 2D seismic lines and the presence of few hydrocarbon exploration wells. The latter allow a good calibration of the stratigraphy imaged by seismic data. The newly reprocessed 2D seismic lines from the 70s (SAdH survey) using DMT's CRS technology (signal/noise improvement), have brought a remarkable improvement in the imaging. In particular, much sharper contrast between stacked reflectors with different amplitude and better definition and vertical extension of faulted/damage zones have been achieved.

The reprocessed data have been integrated with few newly acquired seismic lines (survey Geo2X in 2012) around the well Eclépens-1 and few others vintage lines re-examined by the recent comprehensive regional work carried by Paolacci (2013). The Eclépens area and its immediate western neighbouring Jura relief have been also examined using aerial photographs and satellite images with the aim to identify major structural lineaments which could be linked to subsurface features.

The examination of 2D lines seismic highlighted the occurrence of 0.5 to 2.5 km wide deformation zones interrupting the stratigraphical continuity of the subsurface. These deformation zones are predominantly vertical and sub vertical (5-15°) and often appear to have little or not associated vertical displacement.
Inverse faulting has been observed often associated with convex bending of stratigraphical seismic reflectors (Fig. 1). The latter are often deformed also in correspondence of vertical fault zones forming convex deformation interpreted as drag folds. Overall, the deformation style observed on seismic data, suggest a strike-slip system with transpressive component.

Moreover, the detailed seismic interpretation carried out in a 3D environment (Petrel software by Schlumberger) has allowed the identification of several discontinuous and segmented faults which can be grouped in 2 main clusters intersecting each other at an angle of ca 80°. These two systems have been interpreted as a Riedel/Anti-Riedel conjugate set likely associated with a NNW-SSE left-lateral strike slip system.

The identification of a Riedel and Anti Riedel conjugate set is key to understand better the influence of structural features and the working mechanisms of the Eclépens geothermal system.
These fault systems appear to be deeply rooted within the Permo-Carboniferous strata suggesting a possible link with original basement lineations. Moreover, considerable changes in stratigraphic thickness of Jurassic sequences across some of these fault zones, suggest that the latter may represent possibly vertical reactivation of Mesozoic lineaments during the subsequent Alpine deformation phases.
This proposed structural model will be used to build a realistic range of discrete fault and fracture network models for characterisation and quantification of water discharge and heath flow associated with a potential EGS development.

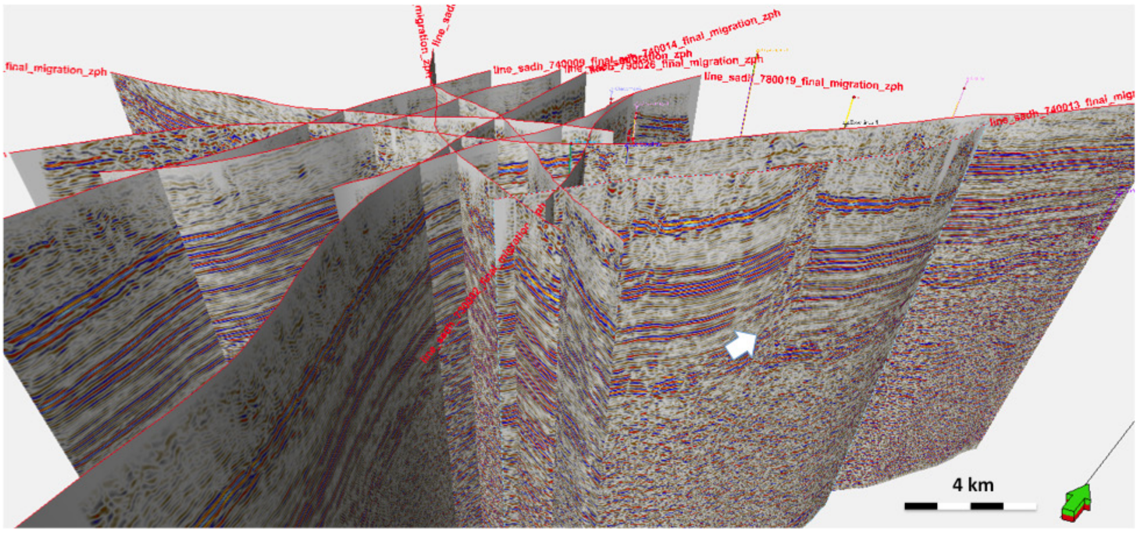

Figure 1. Three dimensional view of the newly reprocessed 2D seismic lines in the Eclépens area. Subvertical fault damage zone indicated with white arrow is ca. 1.2 km wide.

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12.13

The subsurface geology of the Western Swiss Plateau and its French extension: state of the art and implications for geo-resources exploration.

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A large comprehensive study of the subsurface geology of the western part of the Swiss Molasse Basin, from its western-most part in France up to the border between cantons Fribourg and Bern has been recently completed (Paolacci, 2012). This work is based on more than 1700 kilometers of vintage 2D seismic lines (early 70s through 90s) and some 27 wells with penetration ranging from the Tertiary down to the Palaeozoic, obtained during both hydrocarbon and geothermal exploration activities over the last 50 years.

Subsurface data from seismic, integrated with published outcrop data indicate that the Molasse Basin is affected by numerous strike-slip faults which cut the Jura arch in a radial way, and by SSW-NNE trending thrust faults. These structures have been analyzed at Mesozoic level, focusing on their possible interaction with underlying tectonic features affecting the Palaeozoic and basement.

Above the crystalline basement, the Intra-Permo-Carboniferous (IPC) seismic unit is defined by a group of high amplitude continuous reflections underlying a more transparent seismic facies, corresponding to the more homogeneous Permian siliciclastics. The IPC reflections are interpreted as coal rich sequences, possibly containing primary hydrocarbons as indicated by the frequent occurrence of amplitude anomalies (bright spots) likely associated both with stratigraphic and structural traps. Source rocks also may be contained in Early Permian shales overlaying the Carboniferous coal-bearing sequence.

In the Greater Geneva region, the detailed mapping of the IPC reflective sequence suggests the presence of basins with asymmetric geometry (i.e. half-grabens) and structural features mostly oriented NE-SW. These half-grabens extend below the Bornes Plateau Basin, at the front of the Salève ridge s.l. and close to the Jura Mountain. In the Vaud-Fribourg region, these basins have more variable orientations, varying between NW-SE (below the Pontarlier fault zone and at the front of the Prealps), E-W (in the Chamblon region) and NE-SW south of the Cuarny Anticline.

The thickness of the Triassic varies within the study region, partly for tectonic but also for depositional reasons. The Keuper evaporites represent the main ductile level in the major part of the study region, whereas the Anhydrite Group (Middle Muschelkalk) constitutes the detachment horizon in the eastern half of the Vaud-Fribourg region. Both these units may represent sealing intervals although their integrity may have been jeopardised by subsequent tectonic movements.

In the Greater Geneva area, the SSW-NNE trending Salève ridge s.l. is crosscut by numerous WNW-ESE trending left-lateral strike-slip fault zones. The basal detachment plane of these thrusted anticlinal structures flattens within the Liassic marls and Keuper anhydrites, thereby determining characteristic flat-ramp geometry. Moreover, they all seem to have formed above a basement high delimited to the NW by a Permo-Carboniferous half-graben.

Compressive tectonics date back to the Late Cretaceous-Early Tertiary which in some cases reactivated Late Hercynian lineaments (Salève ridge s.l.). Possible structural traps such as anticlines and fault traps may have formed during this time. The majority of the NW-SE trending strike slip faults in the studied region affect the underlying Permo-Carboniferous at depth. Several of them (e.g. Vuache, Pontarlier, etc.) have been active at least from Triassic times, during Lower and Upper Jurassic and Lower Tertiary times. Considerable differences of thicknesses in the Mesozoic sequence (e.g. Vuache and Eclepens area) may suggest an active structuration during time of deposition. This will implies likely lateral facies changes and higher variability, especially during Triassic and Jurassic time of reservoir development (Keuper sandstone, Malm carbonates) and potential source rock represented by the Posidonia shales Formation.

The entire studied area is disseminated by both left-lateral and conjugate right-lateral strike-slip faults, forming complex-shaped, often transpressive, fault systems. Many of these (e.g Pontarlier, Fribourg lineamets, etc.) are deeply rooted in Palaeozoic strata, and could be likely target for deep geothermal projects (e.g. la Côte, Eclépens) as suggested by some boreholes data (Eclépens-1, Moscariello et al., 2013).

Overall, this study (Paolacci, 2012) represents the first complete overview of the Western Switzerland subsurface based on almost all available data. However, further investigations are required to quantify the geo-resource potential of this large region. Seismic reprocessing, for instance, has been key to obtain better images although new 3D seismic will be necessary in order to map accurately complex structural features (see Moscariello et al., 2013) and thus generate predictive reservoir models (e.g. fracture network). Detailed petrophysical log evaluation, rock typing studies and seismic facies analysis are currently being carried out, to characterise the subsurface and assess quantitatively the possibility of geo-resources occurrence.

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12.14
Use of surface patches for hydraulic fracture monitoring

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In the last decade the exploration of unconventional reservoirs has increased significantly. To produce a conductive pathway to the producing well, additional stimulation referred to as hydraulic fracturing is necessary. One method of monitoring the fracturing process is the observation of microseismic events.

In 2011 Schlumberger and an independent operator (who are required to be anonymous) jointly acquired a comprehensive dataset of hydraulic fracturing operations which stimulated the Fayetteville shale in Arkansas in order to track signal and noise from the reservoir to the earth surface and then across the surface. The performance of alternative monitoring technologies such as surface and shallow borehole seismic arrays as well as a downhole seismic array are analyzed.

The level of noise on different seismic arrays is characterized and appropriate attenuation techniques are applied. Furthermore linear and non-linear stacking methods are successfully utilized to increase the signal-to-noise ratio (SNR). The application of the Source- Scanning-Algorithm (SSA) to locate microseismic events conclude that an accurate source location requires an accurate velocity model together with consistent and aligned signal. Coherent noise, insufficient signal or noise discrimination are key factors influencing location uncertainty.

Although surface line segments benefit from larger receiver apertures, SNRs of stacks were usually only slightly higher than from stacks of surface patches using linear stacking methods. However, source localization is more accurate using surface lines. Nevertheless, surface patches are easily deployable so provided sufficient signal is recorded and noise attenuation methods are applied prior to stacking and source scanning, they may ultimately become the preferred surface monitoring configuration.

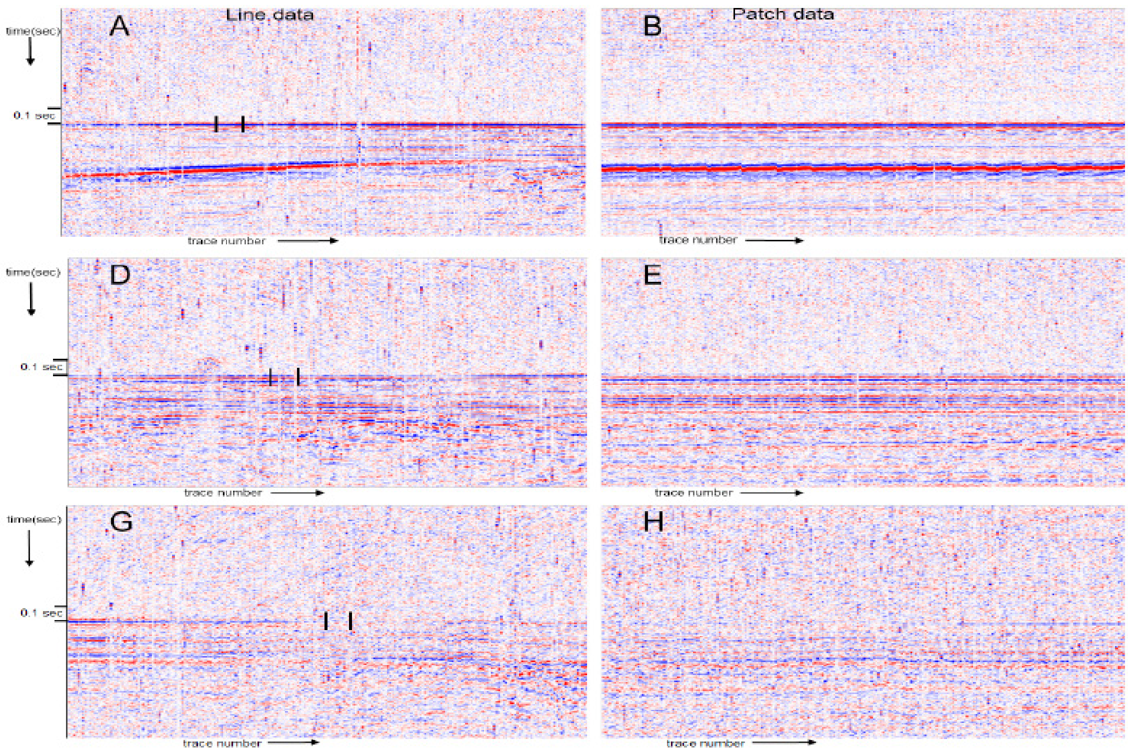

Figure 1. Comparison of static corrected surface line segment and surface patch data. The position of the surface patch on the line segment is indicated by vertical black lines.

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12.15

Multiphysics methods: a link between pore-scale and Darcy-scale models

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Modern energy-related applications require an increasing complexity in the physical processes that have to be considered in geological formations. In hydrocarbon recovery, Carbon Capture and Storage, or deep geothermal energy one has to deal with multiphase multicomponent flow, reactive transport, thermal and geomechanical coupling. Under these circumstances, traditional macroscopic models might be inadequate and new approaches are required that allow a more accurate description of pore-scale processes.

The Darcian approximation of momentum transfer, for instance, is well justified for simple linear problems (e.g., single-phase flow), but is not always applicable to nonlinear flow regimes, leading to a breakdown of Darcy's law and to a macroscopic solution that depends on the pore-scale details. However, the failure of Darcy's law is often local in space, such that a detailed, pore-scale description is required only in regions characterized by specific flow conditions, whereas Darcy's law remains sufficiently accurate in the rest of the domain. Multiphysics (or hybrid) numerical algorithms that couple different scales of description offer an effective tool to investigate this problem.

We present a multiphysics model that couples a Darcy coarse-scale description with a pore-scale description in which full Navier-Stokes equations are solved and the Volume Of Fluid (VOF) method is used to model the evolution of the fluid-fluid interface in presence of wetting and surface-tension effects. The Darcy coarse-scale description is constructed by using the Multiscale Finite Volume (MsFV) method as numerical volume averaging procedure and assuming that pressure is the only relevant degree of freedom at the coarse scale.

This framework allows great flexibility in the adaptive strategies that can be used to resolve the details of the flow process only where and when needed. Also, it offers a tool to numerically investigate the limits of validity of the Darcy assumption, as well as to test alternative models.

12.16

Deep geothermal Energy in Switzerland – actual developments and perspectives for the future

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In the last decades, several geothermal projects for district heating or balneological use were realized in Switzerland. In contrast, «deep geothermal power» has not been produced yet. Through the enacted nuclear phaseout in 2011, the perspectives of deep geothermal energy have been distinctively improved and the development has accelerated. The expectations related to deep geothermal energy increased but the general acceptance is currently ambivalent. Deep geothermal energy is of high potential in Switzerland and could play an important role in Swiss energy supply in the future. However to achieve this goal, challenges of the most different kind must be tackled. One of the most important barriers in Switzerland is the still poorly known deep underground, as its unexpected response in St.Gallen illustrates.

P 12.1

Optimized layout of engineered geothermal systems and potential in Germany

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The forward modelling code SHEMAT can simulate operated Engineered Geothermal System (EGS) reservoirs by solving coupled partial differential equations governing fluid flow and heat transport. Building on EGS's strengths of inherent modularity and storage capability, it is possible to implement multiple wells in the reservoir to extend the rock volume accessible for circulating water in order to increase the heat yield. By varying parameters like flow rates and well-separations in the subsurface, we analyse their long-term impacts on the reservoir's development in time. This allows us to experiment with different placements of the engineered fractures and different EGS layouts for achieving optimized heat extraction. Considering the available crystalline area and accounting for competing land uses, we evaluate the overall EGS potential in Germany and compare it with those of other popular renewables: The area available in Germany suffices to support 13450 EGS plants each consisting of six reversed-triplets (18 wells), providing an average electric power of 35.3 MW_e corresponding to a total capacity of 475 GW_e. When operated at full capacity, these systems can collectively supply 4155 TW h of electric energy in one year, more than six times the electric energy produced in Germany in 2011. We conclude that Engineered Geothermal Systems make a compelling case for contributing towards national power production in a future powered by a sustainable and decentralized energy system, provided that suitable fracture systems can be engineered at depths.

P 12.2

Solving three-dimensional non-linearly coupled hydro-mechanical two-phase flow on GPUs

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Computational geodynamics benefit from the fast-growing computer industry, allowing to solve real-world complex problems at higher resolution and faster rates than in the past. An actual problem that requires codes that efficiently solve complex non-linear problems in three-dimensions (3D) is CO_2 underground storage. All over the world, large amounts of CO_2 and other waste fluids are being injected into reservoirs. One example is the injection of about one million tons of CO_2 per year since 1996 into the Utsira formation at Sleipner in the Norwegian North Sea. Conventional reservoir simulations fail to predict the formation of flow channels or chimneys, and the fast lateral and directional spreading of CO_2 underneath the caprock.

We developed a fully three-dimensional, non-linear mechanical model, utilizing the latest computing technologies, such as graphical processing units (GPU), high-performance computing parallel implementations with message passing interface (MPI), on our in-house mid-sized cluster (Räss 2013). A speed-up of more than 700 times was reached with the C-CUDA GPU implementation in comparison to the Matlab® CPU code.

In the mechanical part, Stokes equations with non-linear viscosity (Figure 1) are solved focusing on the vertical motion that results from non-linear coupling of gravitational and tectonic forces. A new vertical velocity analytical solution for non-linear and non-zero far-field stresses is proposed to fill the gap between the two existing analytical solutions.

The newly developed fully coupled two-phase flow code takes solid velocities obtained from the mechanical solver. We then study coupled deformation and fluid flow in large pre-stressed reservoirs, based on the porosity waves concept (Connolly & Podladchikov 1998, Simon et al. 2011, Simon et al. 2013), without prescribing pre-exiting fractures.

The results of the mechanical part of our model set up a benchmark for future development. The fully coupled two-phase flow helps to understand and explain under which conditions localization of fluid will occur and is also applicable to the injection of other fluids (e.g. waste water).

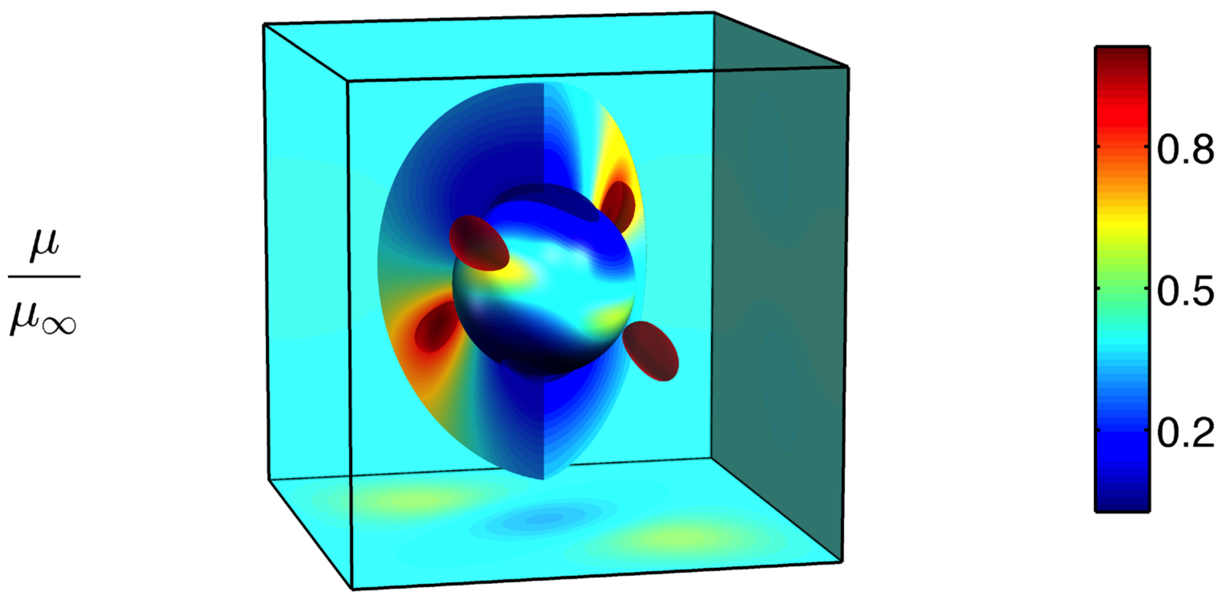

Figure 1. 3D surface plot of the viscosity reduction (viscous softening) of the surrounding media due to non-linear coupling in power-law rheology.

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P 12.3

Geochemical and structural data for the evaluation of the geothermal potential

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The aim of the research is to identify suitable areas for high-enthalpy geothermal exploitation in Tessin, Switzerland. The research is focused on the test site of Stabio, located in the southern part of the country, close to the border with Italy. The site is characterized by the presence of springs, with a different geochemistry and temperature from those in nearby areas. These waters could be related to existing geological structures like the Gonfolite backthrust. A coupled structural and hydrogeological model has been developed to check the feasibility for geothermal exploration.

The geological-structural model is based on all the available data: surface data (lithological information, dip data, maps), drillings and seismic reflection lines from the Swiss National Research Programme NRP-20. Detailed surveys were conducted to derive geological cross-sections. Moreover, these data, in association with the chemistry of waters (basic chemistry, isotopes and noble gases), allow the team to formulate hypothesis about the origin and the preferred flowpath of the springs, to understand whether these springs could have a deep origin.

To better constrain the geological-structural model it is necessary to know the precise depth of the bedrock top. Where this information is lacking, a passive seismic method (3D geophone) has been applied to improve information about the depth of bedrock. This permits to produce a geophysical monodimensional model of the subsoil. At the first stage, in the areas where there are stratigraphic data available, this method will be applied to understand the changes in the geophysical models in different points of the area, then it will applied in the nearby areas, where the depth of bedrock is lacking.

Geological and geochemical data are integrated in a 3D data base through the use of Move™ software.

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