STRUCTURAL, PETROPHYSICAL AND GEOMECHANICAL CHARACTERIZATION OF THE BECANCOUR CO_2 STORAGE PILOT SITE (QUEBEC, CANADA)

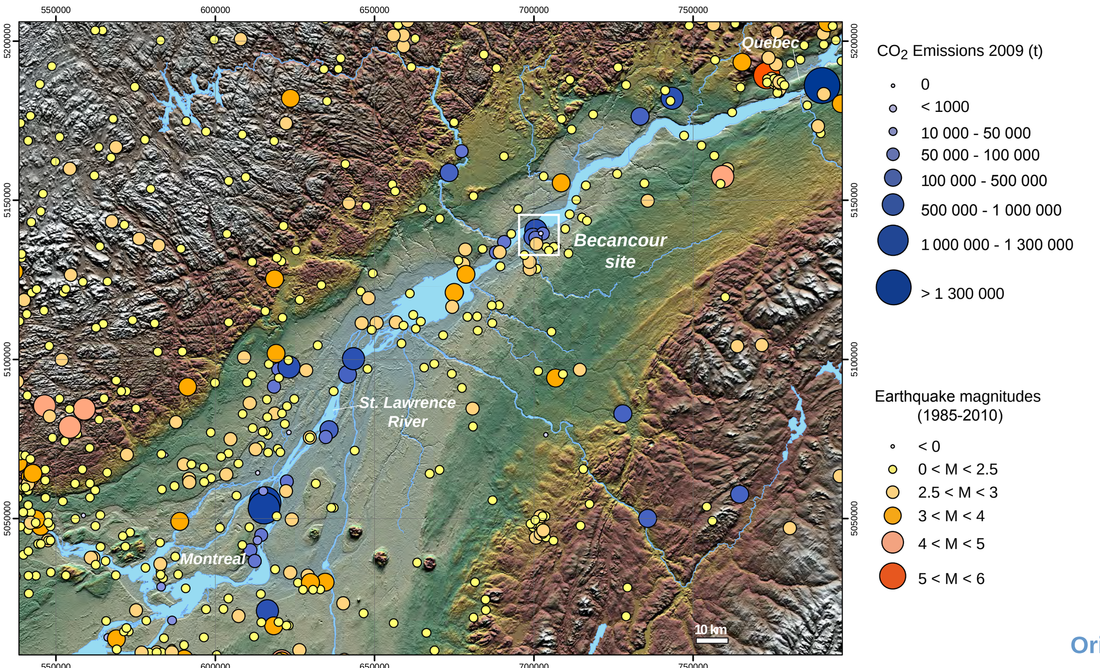
SÉQUESTRATION GÉOLOGIQUE DU CO_2
CHAIRE DE RECHERCHE
INRS

Elena Konstantinovskaya, Michel Malo, Maxime Claprood, Tien Dung Tran-Ngoc, Erwan Gloaguen, René Lefebvre

Institut National de la Recherche Scientifique, Centre Eau-Terre-Environnement (INRS-ETE), 490 de la Couronne, G1K 9A9 Quebec City (Quebec) Canada, Elena.Konstantinovskaya@ete.inrs.ca http://chaireco2.ete.inrs.ca/

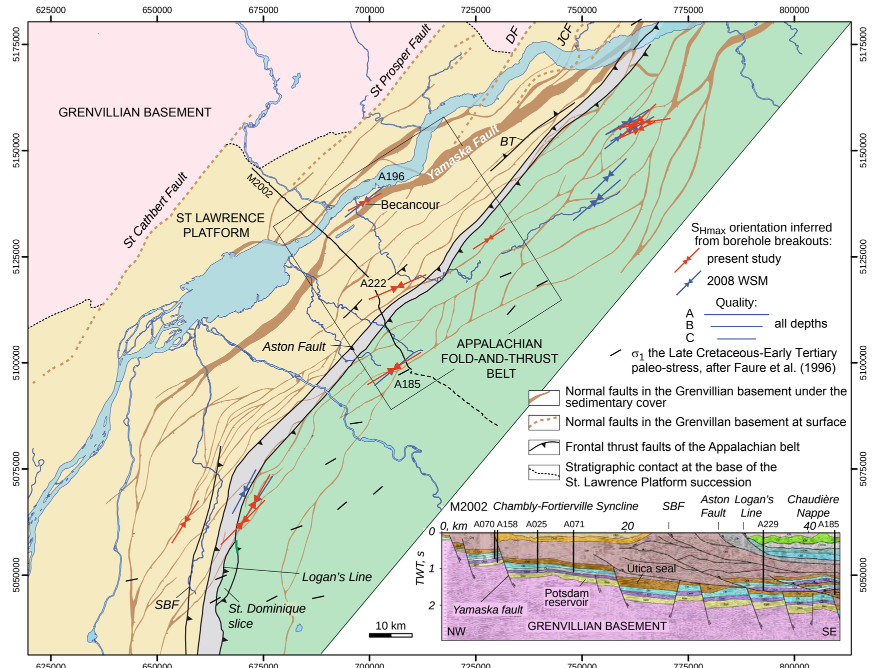
Développement durable, Environnement et Parcs
Québec

Seismicity and CO_2 emissions in the St. Lawrence Lowlands



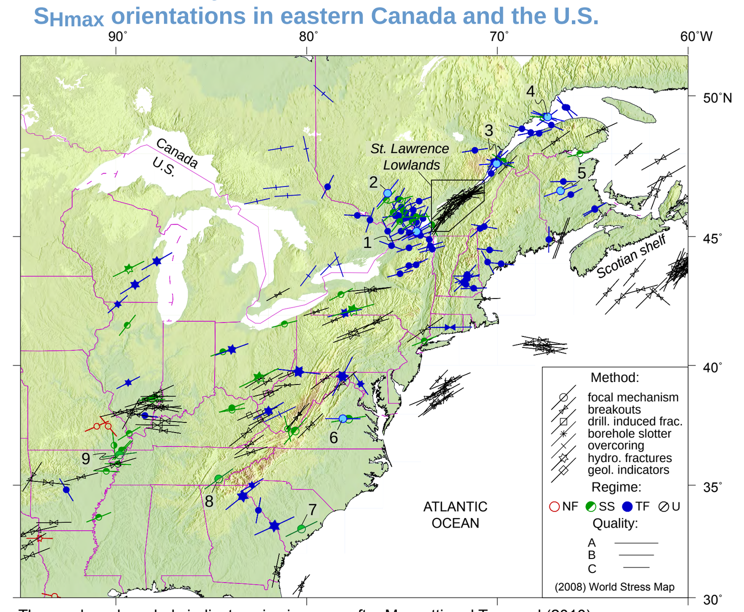
The Becancour site is located in the area of high CO_2 emissions (data after Canada Environment). The southern shore of the St. Lawrence River is characterized by relatively low seismicity (data after Geological Survey of Canada Catalog).

Regional fault patterns and the S_{Hmax} orientations in the St. Lawrence Lowlands



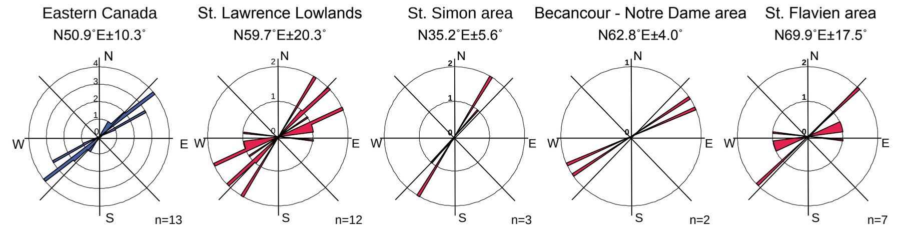
The normal faults in the Grenvillian basement are projected from the seismic map of Thériault et al. (2005). The thrust faults are shown after Clark (1964a; 1964b), Globensky (1987), Konstantinovskaya et al. (2009). The interpreted seismic line M2002 is after Castonguay et al. (2006). Abbreviations: DF, Deschambault Fault; JCF, Jacques Cartier Fault; NF, Neuville Fault; SBF, Saint-Barnabé Fault; BT, backthrust of the triangle zone. Box indicates Becancour - Notre Dame area.

Present-day maximum horizontal stress S_{Hmax} orientations in eastern Canada and the U.S.



The numbered symbols indicate seismic zones after Mazzotti and Townend (2010).

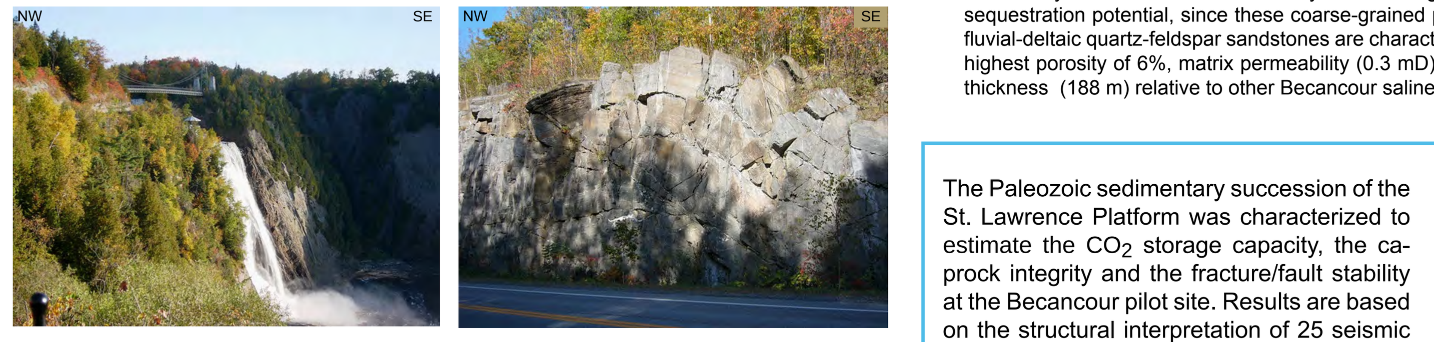
Orientations of present-day S_{Hmax} from borehole breakouts



after Plumb and Cox (1987) *after Konstantinovskaya et al. (2012)*

The average S_{Hmax} orientation is NE-SW in Eastern Canada (N51°E). The S_{Hmax} is oriented N60°E in the St. Lawrence Lowlands rotating along the Appalachian front. The S_{Hmax} orientation is N63°E in the Becancour-Notre Dame area.

NE-SW rifting related normal faults and NE-SW reverse faults and folds of the Taconic orogeny



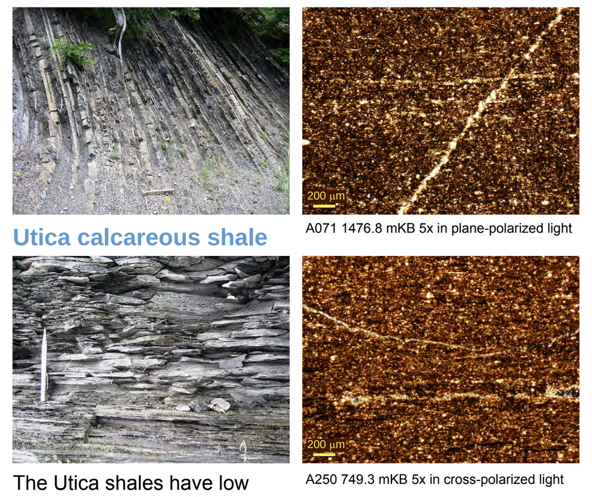
The Montmorency normal fault in Quebec City represents the surface analog of high-angle SE-dipping normal faults affecting the Grenvillian basement and the St. Lawrence Platform.

The NW-vergent thrust of the Saint-Dominique tectonic slice represent an example of low-angle frontal reverse faults of the Appalachian fold-and-thrust belt.

Reservoir and caprock lithology

Lorraine sandstones/siltstones

Utica calcareous shale

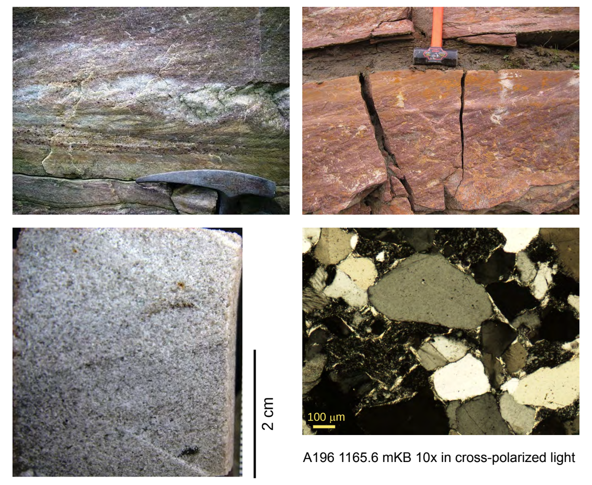


A071 1476.8 mKB 5x in plane-polarized light

A250 749.3 mKB 5x in cross-polarized light

The Utica shales have low permeability K < 10^{-3} mD.

Petrography of the Covey Hill reservoir sandstones

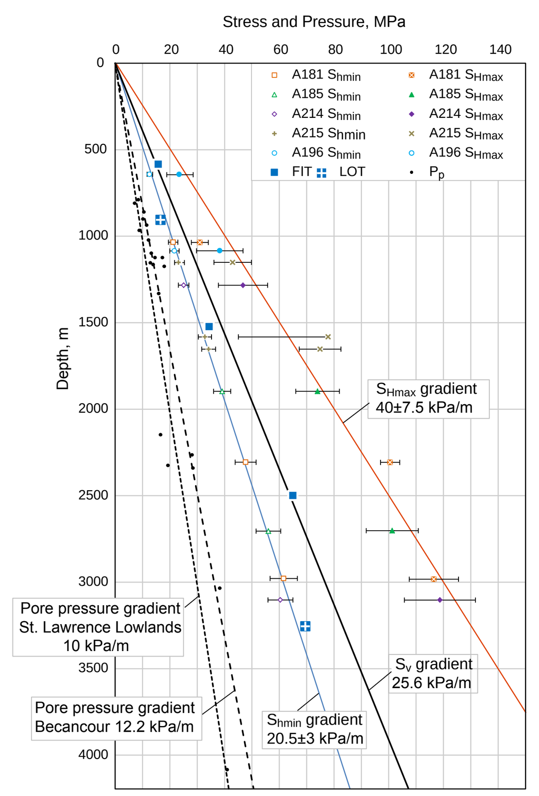


A196 1165.6 mKB 10x in cross-polarized light

The Covey Hill is found to be the only unit with significant CO_2 sequestration potential, since these coarse-grained poorly-sorted fluvial-deltaic quartz-feldspar sandstones are characterized by the highest porosity of 6%, matrix permeability (0.3 mD) and net pay thickness (188 m) relative to other Becancour saline aquifer units.

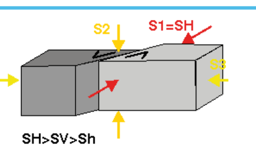
The Paleozoic sedimentary succession of the St. Lawrence Platform was characterized to estimate the CO_2 storage capacity, the caprock integrity and the fracture/fault stability at the Becancour pilot site. Results are based on the structural interpretation of 25 seismic lines and analysis of 11 well logs and petrophysical data.

Variations of pore pressures and stresses with depth determined from the stress magnitude analysis in the St. Lawrence Lowlands



To estimate maximum sustainable pore pressures necessary for the opening of vertical tensile fractures and for the shear reactivation of pre-existing optimally oriented faults and fractures

Determine :
- prevailing stresses (orientations and magnitudes)
- fault geometry and sliding tendency
- rock strengths (reservoir and caprock)



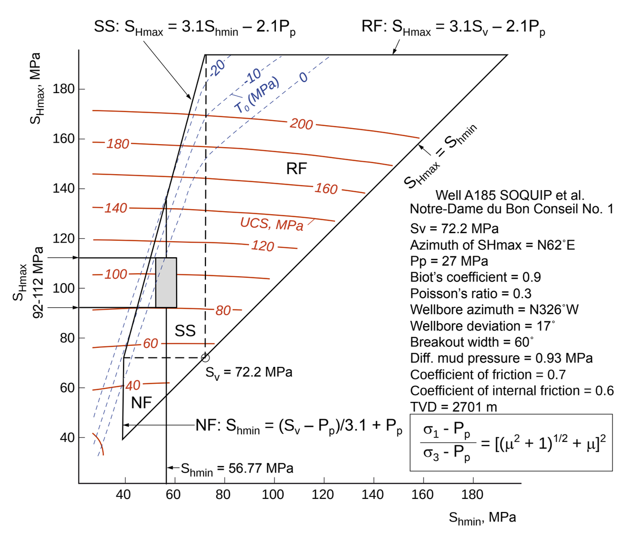
Variations of pore pressures and stresses with depth determined from the stress magnitude analysis in the St. Lawrence Lowlands are compatible with the strike-slip stress regime $S_{hmin}<S_v<S_{Hmax}$.

A geomechanical analysis of the St. Lawrence Platform sedimentary basin provides the maximum sustainable fluid pressures for CO_2 injection that will not induce tensile fracturing and shear reactivation along pre-existing fractures and faults in the caprock.

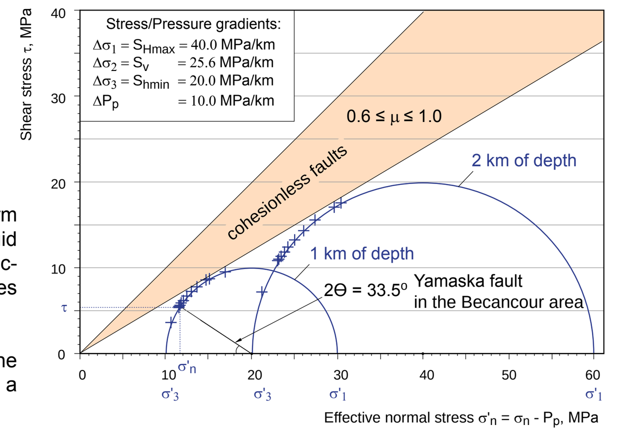
The regional stresses/pressure gradients estimated for the Paleozoic sedimentary basin (depths < 4 km) indicate a strike-slip stress regime.

The Covey Hill sandstones have the lowest static Young modulus and compressive strength relative to other sandstone units. The calcareous Utica shale of the regional seal is more brittle and has higher Young modulus and lower Poisson's ratio than the overlying Lorraine siltstones.

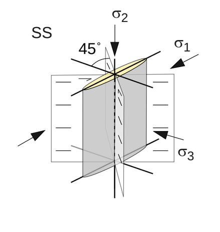
Polygon of S_{Hmax} estimation constrained by wellbore failure



Shear and effective normal stresses acting on the NE-SW high-angle normal faults in the Grenvillian basement of the St. Lawrence Lowlands

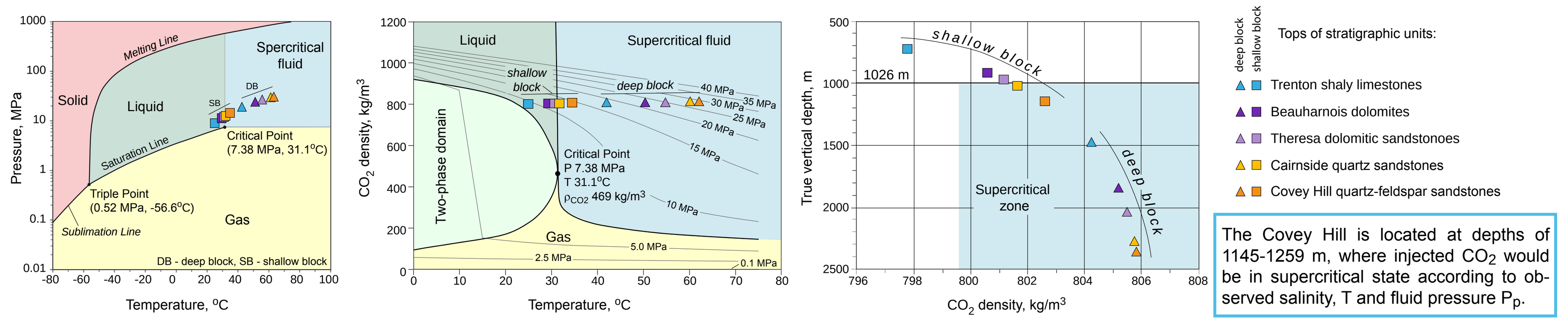


Angle Θ between fault and σ_1 in σ_1-σ_3 plan	Slip tendency τ/σ'_n
10.6° to 22°	0.30-0.47
22° to 36.6°	0.56-0.58



The high-angle NE–SW Yamaska normal fault is oriented at 16.7° to the S_{Hmax} orientation in the Becancour site. The slip tendency along the fault in this area is estimated to be 0.47 based on the stress magnitude and rock strength evaluations for the borehole breakout intervals in local wells. The regional pore pressure–stress coupling ratio under assumed parameters is about 0.5–0.65 and may contribute to reduce the risk of shear reactivation of faults and fractures. The maximum sustainable fluid pressure that would not cause opening of vertical tensile fractures during CO_2 operations is about 18.5–20 MPa at a depth of 1 km.

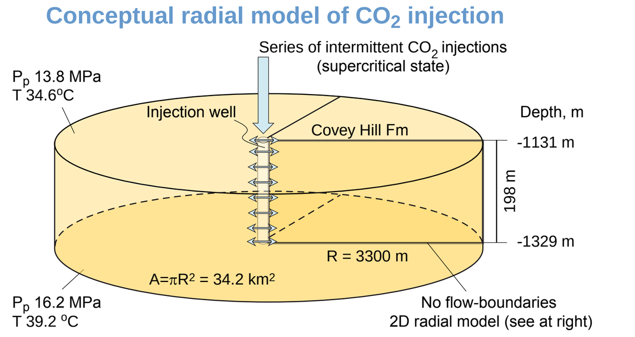
Predicted CO_2 state in the Becancour saline aquifers



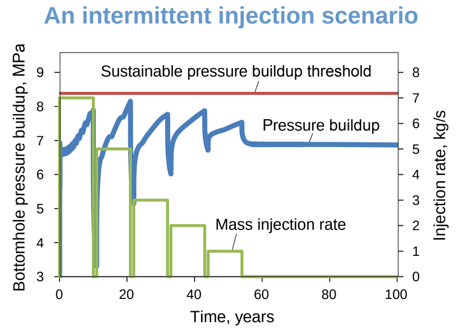
The Covey Hill is located at depths of 1145-1259 m, where injected CO_2 would be in supercritical state according to observed salinity, T and fluid pressure P_p.

The CO_2 injected in the saline aquifers of the Becancour area is predicted to behave as supercritical fluid at depths below 1026 m where observed pore pressures (P_p gradient 12.2 MPa/km), temperatures (T_0 surface 8°C, T gradient 23.5°C/km) and CO_2 density (>800 kg/m³) are above critical values. The predicted CO_2 density is calculated in the saline aquifers under the observed pressures and temperatures using the equation of Span and Wagner (1996).

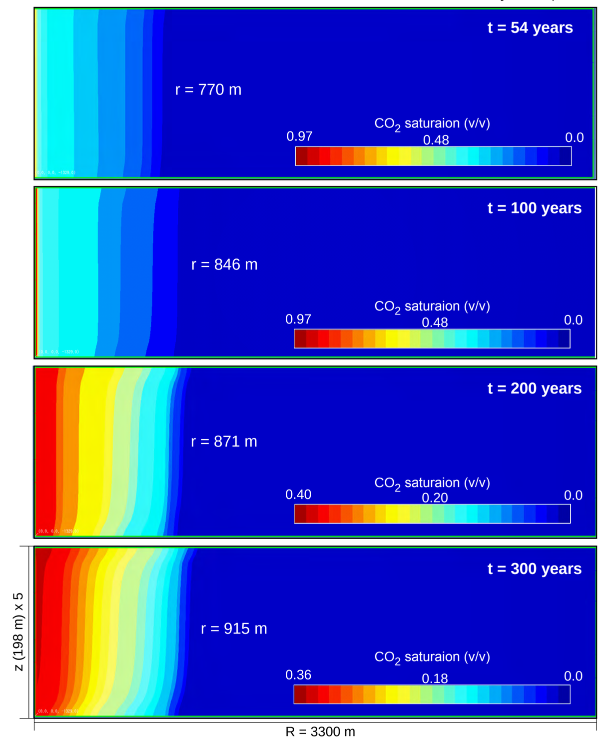
Conceptual radial model of CO_2 injection



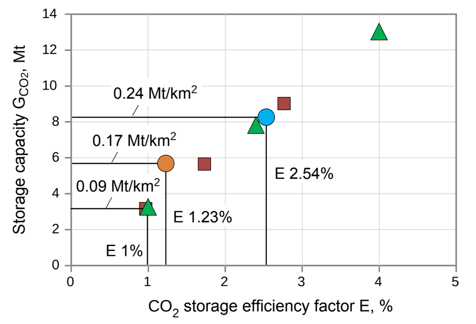
An intermittent injection scenario



Snapshots of the free-phase CO_2 plume from the injection well



Estimation of CO_2 storage capacity in the Covey Hill sandstones for the area A=34.2 km²



Volumetric method (DOE-NETL2008) $G_{CO2} = A_t h_g \phi_{tot} \rho E$: G/A=0.24 Mt/km² for E=2.54%

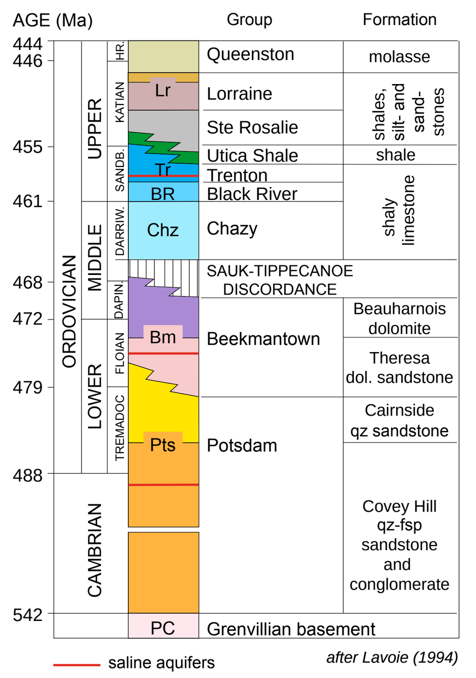
Volumetric method (Goodman et al., 2011) with E values (min, mean, max) determined statistically by the US Department of Energy (DOE)

Compressibility method (DOE-NETL2008) with varying compressibility coefficient $G_{CO2} = A_t h_g \phi_{tot} \rho (c_p+c_w)(P_c-P_o)$: G/A=0.09 Mt/km² for E=1%

Dynamic method TOUGH2 (Doughty et al., 2001): G/A=0.17 Mt/km² for E=1.23%

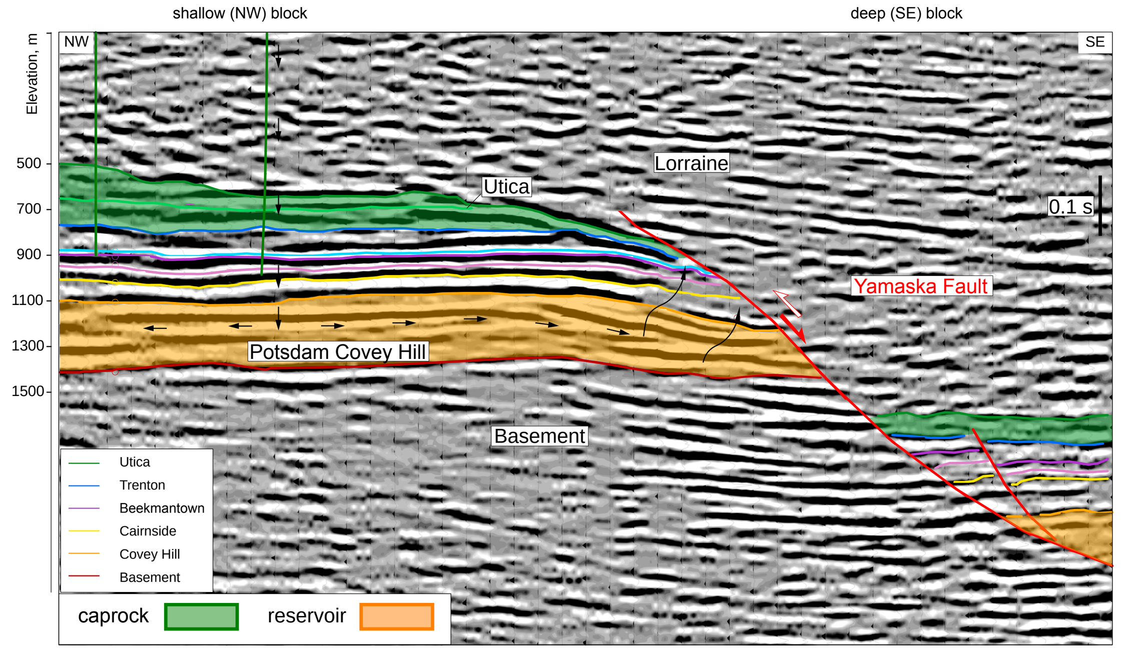
For details on the storage capacity estimation methodolgy see http://www.netl.doe.gov/technologies/carbon_seq/refshelf/methodology2008.pdf

Sedimentary succession of the St. Lawrence Platform



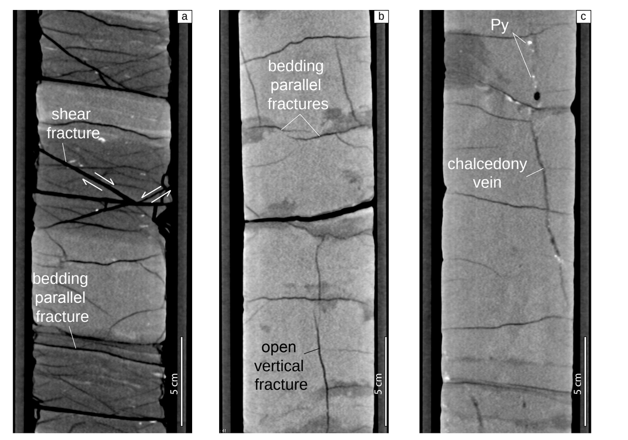
The three potential storage units of Potsdam, Beekmantown and Trenton saline aquifers are known in the St. Larence Platform succession of the Becancour area. The Potsdam reservoir rocks are overlain by a multiple caprock system of Utica shales and Lorraine siltstones and sandstones.

The Yamaska normal fault in the Becancour area



The NE-SW syn-sedimentary rifting-related Yamaska normal fault is dipping to SE at about 55°. This fault affects the subhorizontal sedimentary succession of the St. Lawrence Platform and the Grenvillian basement with 870 m of vertical separation. It was reactivated as reverse fault at the end of Taconian orogeny or during the later compressive phases. The seismic line is about 2 km of length. The ratio of vertical to horizontal scale is 1:2.

Natural fractures observed in cores of the Utica shales (a) and the Trenton limestones (b, c) in the Becancour area

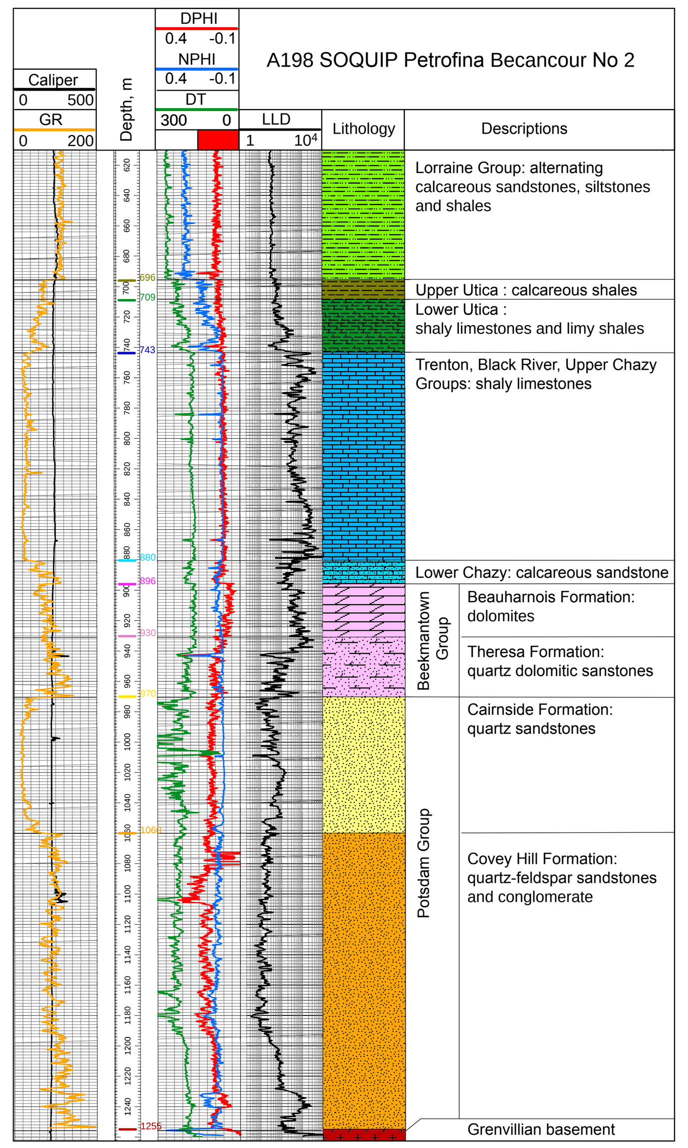


CT (computed tomography) scanner images of the longitudinal (vertical) sections of cores. Stratification is subhorizontal. Shale beds are dark gray, limestones are light gray, shaly limestones are medium gray, open fractures (filled with air) are black, the chalcedony vein is dark gray to black and sulfide mineralization (Py) is bright white spots in the vein. The bedding-parallel and inclined shear fractures are observed in Utica shales.

ACKNOWLEDGEMENTS

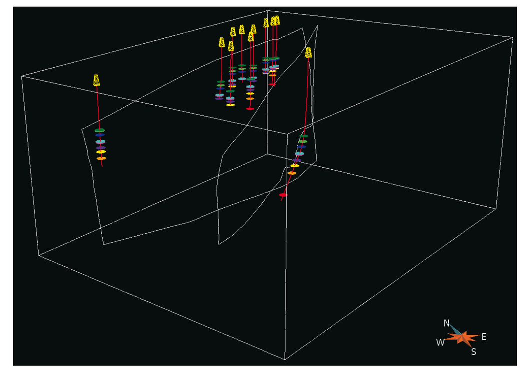
The present study is supported by the Ministère du Développement Durable, de l'Environnement et des Parcs du Québec. We are grateful to the Reservoir Development Services group within Baker Hughes Inc. for supporting the stress analysis. Special thanks are due to F. Brunner, L. Dean, R. Mireault and FEKETE Associates Inc. (Calgary) for the pore pressure evaluations from DST analyses; L. Massé and JUNEX for providing regional seismic and well log data; O. Heidbach and N. Pinet for technical advices and discussions. IHS-Seismic Micro-Technology kindly provided the seismic interpretation software used in this study.

Petrophysical characteristics and formation tops of the stratigraphic units in the St. Lawrence Platform

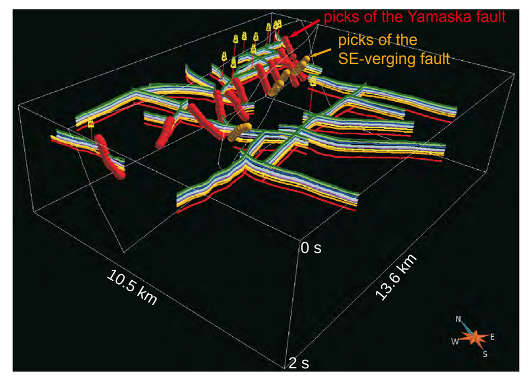


MAIN STEPS TO BUILD 3D GEOLOGICAL MODEL OF THE BECANCOUR AREA

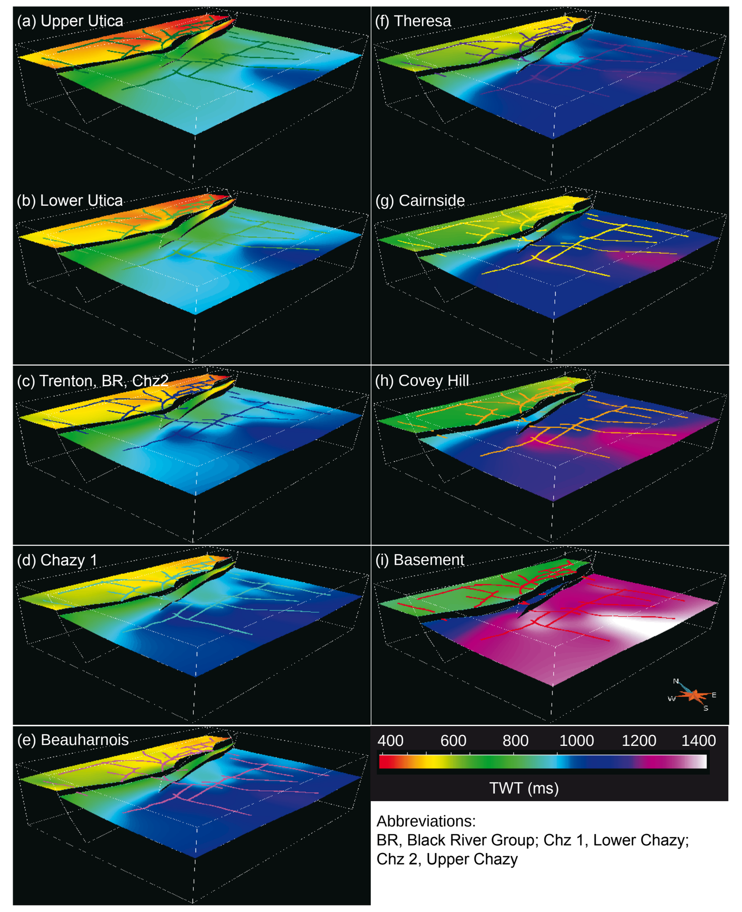
1- Identification of formation tops in depth (m)



2- Picking of seismic horizons in TWT (s)

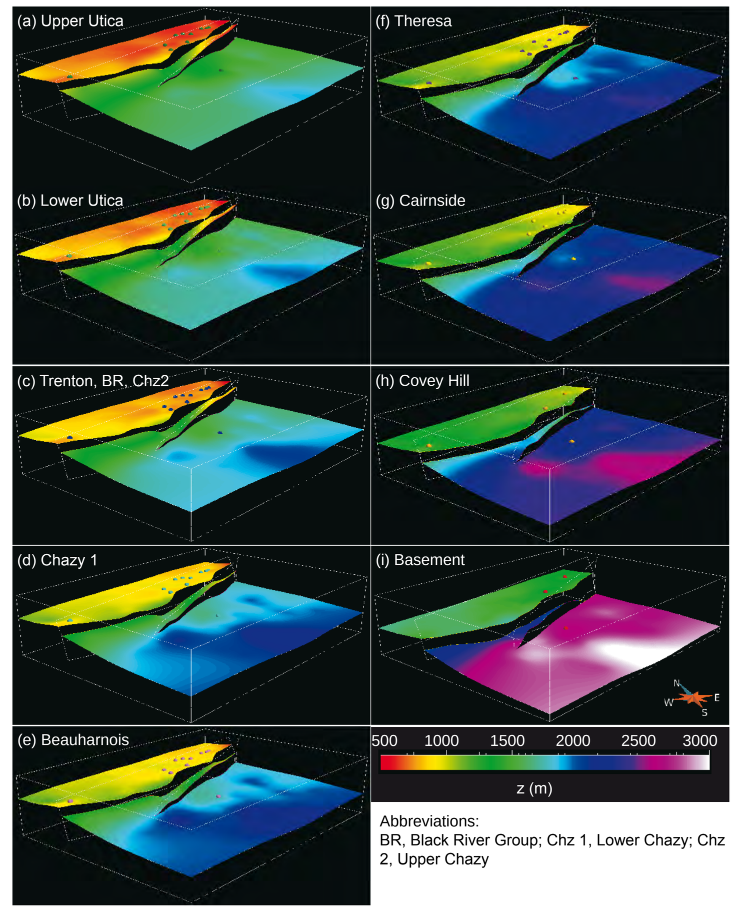


3 - Modeled horizons in TWT from seismic picks



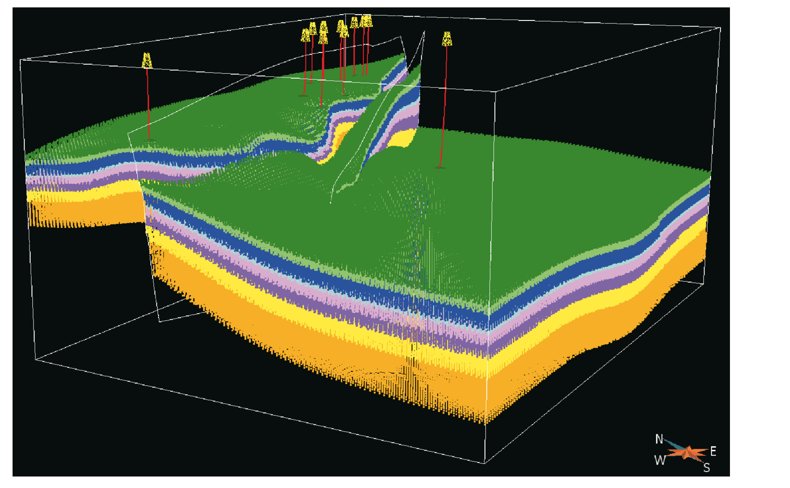
Abbreviations: BR, Black River Group; Chz 1, Lower Chazy; Chz 2, Upper Chazy

4- Kriged horizons in depth by KED



Abbreviations: BR, Black River Group; Chz 1, Lower Chazy; Chz 2, Upper Chazy

5- 3D geological model of the Becancour area in depth



The 3D geological model of the Becancour area (143 km²) is based on structural interpretation of 2D seismic lines (100 km) and well log analysis (11 wells). The main steps that were followed to build the model include:

(1) identification of formation tops in depth (m) after well log analysis
(2a) projection of formation tops on 2D seismic lines and identification of seismic horizons by picking travel times in TWT
(2b) structural interpretation of seismic lines and localisation of faults
(3) kriging with the modeled horizons in TWT as the external drift
(4) kriging with the modeled horizons in depth (m)
(5) build-up of 3D geological model

The 3D geological model is the frame for 1) geostatistical modeling to characterize the spatial distribution of petrophysical properties (porosity, permeability) in the saline aquifers and 2) numerical simulations for CO_2 injection into the Covey Hill Formation.

CONCLUSIONS

1. The Cambrian-Lower Ordovician Covey Hill reservoir sandstones represent the only unit with significant CO_2 sequestration potential in the Becancour area. These reservoir rocks are characterized by the highest porosity (6%), net pay thickness (188 m) and located at depths (>1026 m) necessary for the supercritical state of CO_2. The relatively low matrix permeability (0.26 mD) may be enchanced by natural or hydraulic fracturing.

2. The regional caprock units of the Upper Ordovician Utica shales and the Lorraine sandstones-siltstones are laterally extended with minimum thickness of 700-800 m. The extremely tight Trenton limestones and Beauharnois dolomites may provide additional aquitard levels above the reservoir rocks.

3. The maximum sustainable pore pressure that would not cause the opening of vertical tensile fractures during CO_2 operations could be preliminarily evaluated as 18.5-20 MPa for depths of 1 km.

4. The near-vertical NE-SW faults and natural fractures striking at 30° to S_{Hmax} could be reactivated as shear fractures under the in-situ stresses (NE-SW S_{Hmax}) if fluid pressures exceeded the critical threshold P_c. Further refinement of the geomechanical model of the Becancour area to estimate P_c will involve laboratory tests on cores to calibrate the log-derived empirical rock strength relationships and the determination of preferred orientation of underground fracture sets in reservoir and caprock units from image logs at local scale.

REFERENCES

1. Doughty, C., K. et al.. 2001. Capacity investigation of brine-bearing sands of the Frio Formation for geologic sequestration of CO_2. Presented at First National Conference on Carbon Sequestration, National Energy Technology Lab., Washington DC, May 14-17, 2001.
2. Goodman, A., et al., 2011. U.S. DOE methodology for the development of geologic storage potential for carbon dioxide at the national and regional scale. Int. J. Greenhouse Gas Control, 5: 952–965.
3. Konstantinovskaya E., Malo M., Castillo D.A., 2011. Present-day stress analysis of the St. Lawrence Lowlands sedimentary basin and implications for caprock integrity during CO_2 injection operation. Tectonophysics, 518–521: 119–137, doi: 10.1016/j.tecto.2011.11.022.
4. Konstantinovskaya, E.A., et al., 2010. Preliminary geological and geophysical study of a potential CO_2 storage site in deep saline aquifers of the Becancour area, St. Lawrence Lowlands, Quebec: GeoCanada 2010 Conference, Calgary, Canada, May 10-14, 4 p.
5. Span, R. and Wagner, W., 1996. A New equation of state for carbon dioxide covering the fluid region from the triple-point temperature to 1100 K at pressures up to 800 MPa. J. Phys. Chem. Ref. Data, 25 (6): 1509-1596.

For further information, including posters, presentations and reports (free), please, visit: http://chaireco2.ete.inrs.ca/en/publications_en