2D and 3D geomechanical modeling of CO_2 storage in deep saline aquifers of the Early Paleozoic sedimentary basin of the St. Lawrence Lowlands, Quebec: risk of high-angle fault reactivation and caprock tensile failure

Elena Konstantinovskaya, University of Alberta; Jonny Rutqvist, Lawrence Berkeley National Laboratory; Qiuguo Li, Freelance consulting; Michel Malo, INRS

Summary

Safe CO_2 storage can be compromised because of fluid leakage along reactivated faults or breached caprock units. The CO_2 injection is modeled in deep saline aquifers of the Early Paleozoic sedimentary basin of the St. Lawrence Lowlands, Quebec to evaluate the potential for shear failure along pre-existing high-angle normal faults under the increasing reservoir pressure. The interval targeted for simulated CO_2 injection is the Cambrian-Lower Ordovician sandstone reservoir of the Potsdam Group (Covey Hill Formation), which is located at a depth of 1.25-1.5 km in the footwall of the high-angle Yamaska Fault (aq1, Fig. 1), one of the major regional subsurface normal faults bounding the deeper parts of the St. Lawrence sedimentary basin in the north. In 2D models, we analyze fluid-pressure buildup and lateral migration of the CO_2 plume in the deep saline aquifer, effects of fault permeability on timing, localization, rate, and length of fault shear slip. In 3D model, we analyze the modes of the Yamaska Fault reactivation under the present-day strike-slip stress regime, and quantify the area and amount of shear slip occurring at different steps of pressure increase. The potential for tensile failure in the overlying caprock units is analyzed in both 2D and 3D models (Konstantinovskaya et al., 2014; 2020).

Methods

2D (TOUGH-FLAC3D) and 3D (PETREL-VISAGE-ECLIPSE) coupled reservoir-geomechanical modeling was carried out for the Becancour area of the St. Lawrence Lowlands, located ~110 km southwest of Quebec City. In the 2D study, the spatial variations in fluid pressure, effective minimum horizontal stress, and shear strain are calculated for different injection rates, using a simplified 2D geological model. Multiple runs of the 3D model simulate steps of increasing Pp by 4, 6, 8 and 15 MPa to analyze the distribution of maximum plastic shear strain and displacement along the Yamaska Fault. The effective minimum horizontal stress is analyzed in the sandstones (aq2), carbonate rocks (int) and shales (cp1-2) overlying the Covey Hill sandstone reservoir (Fig. 1) to determine the risk of caprock tensile failure.

Results and Conclusions

The Early Paleozoic sedimentary basin of the St. Lawrence Lowlands is located between the Grenvillian basement and the Quebec Appalachian fold-and-thrust belt. The Cambrian-Ordovician sedimentary succession is affected by high-angle normal faults (Castonguay et al., 2010). The present-day strike-slip fault stress regime was estimated in depth interval from 250 m to about 4000 m (Konstantinovskaya et al., 2012). The average present-day maximum horizontal stress (SHmax) in the St. Lawrence Lowlands is oriented N59°E±20° as determined from the borehole breakouts. The SHmax orientation varies from N69.9°E±17.5° in the northeast to N62.8°E±4.0° in central area and to N35.2°E±5.6° in the southwest, generally remaining parallel to the Appalachian front. The Yamaska Fault is oriented NE-SW and extends for about 150 km in the subsurface of the St. Lawrence Lowlands. The fault strike varies from subparallel to ~35° to the orientation of maximum horizontal stress (N63°E) in the Becancour area and it dips to the SE at ~60° with ~800 m of vertical throw (Konstantinovskaya et al., 2014).

The 2D simulation results (Konstantinovskaya et al., 2014) show that in case of sealing (0.001 mD or $1e10^{-18}$ m^2) properties of the Yamaska Fault, shear failure along the fault (Fig. 1a) occurs after about 22.5 years of low-rate (0.3 kg/s) injection of CO_2, when fluid pressure buildup ΔPp in the fault zone reached 6.5 MPa. The shear slip in this case is localized along the fault segment of about 300 m long located below the caprock unit of the Utica Shale (cp1, Fig. 1). Under the same injection rate but in case of a permeable fault (0.1 mD or $1e10^{-16}$ m^2), the fault shear reactivation occurs 4 years earlier (after 18.2 years of injection), when fluid pressure buildup in the fault zone was increased by ΔPp 5.5 MPa. The plastic shear deformation is nucleated along a 60 m long fault segment above the reservoir at the interval of a thin and brittle caprock unit (Utica Shale) in the footwall and then subsequently progresses downward and up to the surface. The presence of the inclined low-permeable Yamaska Fault close to the injection well causes asymmetric fluid-pressure buildup in the reservoir and lateral migration of the CO_2 plume away from the fault (Fig. 1b), reducing the overall risk of CO_2 leakage along the fault.

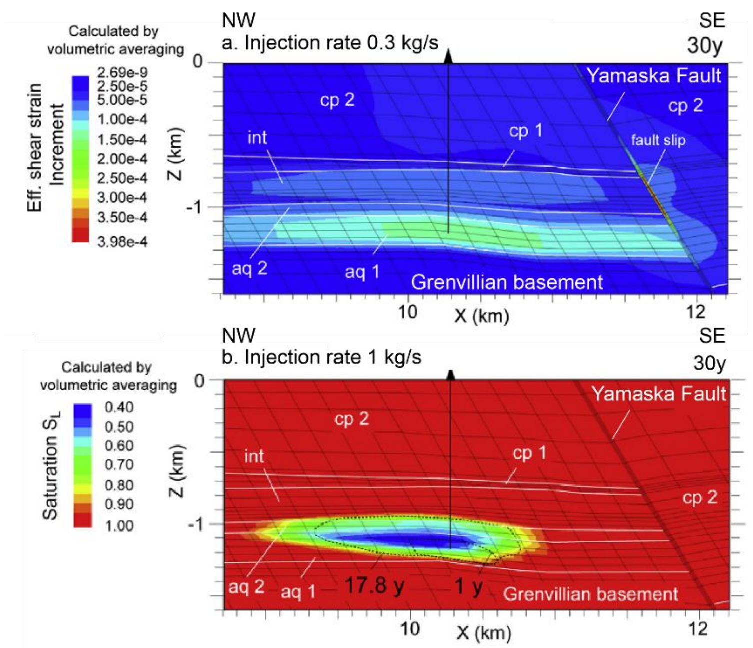

Fig. 1. The results of 2D reservoir geomechanical modeling, after Konstantinovskaya et al. (2014): (a) Changes in effective shear strain occurred around the injection zone in the Covey Hill Formation (aq1) and along the Yamaska Fault after 30 years of CO_2 injection at injection rate 0.3 kg/s, case of sealing fault behavior. Fault slip occurs after 22.5 years of injection. (b) Changes in liquid saturation S_L and geometry of CO_2 plume (cold colors) in the injection zone after 30 years of injection at high injection rate (1 kg/s).

The 3D modeling results (Konstantinovskaya et al., 2020) show that increasing reservoir pressure caused by CO_2 injection results in a dextral strike-slip reactivation of the high-angle normal Yamaska Fault under the present-day stress regime. The plastic shear deformation along the fault is initiated at the step of additional fluid pressure ΔPp of 4-6 MPa in the fault zone. More model fault elements fail when fluid pressure is increased by ΔPp 8 MPa, when the reservoir pressure reaches ~21-24 MPa, and a larger area slips during the next injection stage (ΔPp 15 MPa). The non-linear geometry of the fault results in localization of plastic shear strain on the fault segments optimally oriented at 30° to SHmax (Fig. 2), while other segments remain inactive. The dextral plastic shear deformation occurs mostly at the depth of the injection interval, propagating upward to the caprock of the Utica Shale in highly stressed fault segments.

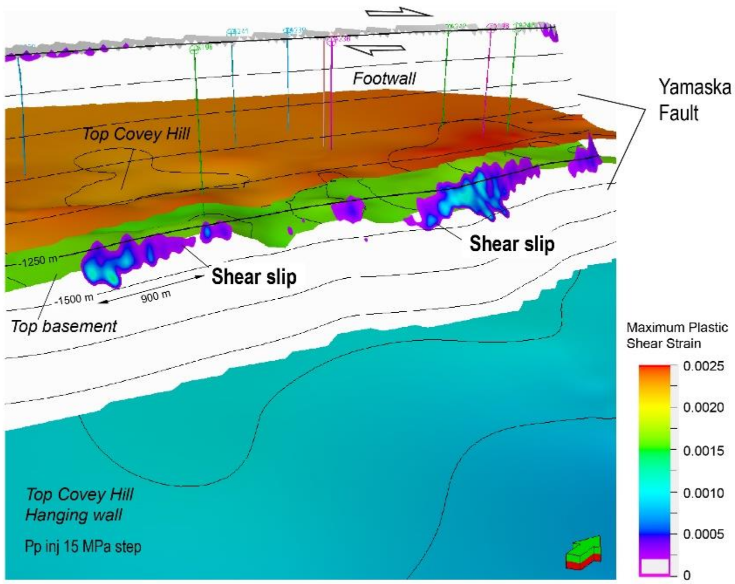

Fig. 2. The results of 3D reservoir geomechanical modeling, after Konstantinovskaya et al. (2020): area of Maximum Plastic Shear Strain that is localized along the NE segment of the Yamaska Fault optimally oriented at 30° to SHmax at the injection step of fluid pressure increase in the fault zone by ΔPp 15 MPa. The fault reactivation occurs mostly at the depth level of the simulated injection interval of the Covey Hill Formation in the footwall block.

The conditions favorable for tensile fracturing never reached the overlying ~1-km thick overburden of the Lorraine Group (cp2, Fig. 1) according to the results of the 2D and 3D modeling presented in this study. It supports the previous results of reservoir-geomechanical simulations (Rutqvist et al., 2008), indicating that the potential for shear failure along pre-existing faults is higher than the potential for tensile fracturing in caprock units.

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References

1. Castonguay, S., Dietrich, J., Lavoie, D., Laliberté, J.Y., 2010. Structure and petroleum plays of the St. Lawrence Platform and Appalachians in southern Quebec: Insights from interpretation of MRNQ seismic reflection data. Bull. Can. Pet. Geol., 58 (3), 219–234. https://doi.org/10.2113/gscpgbull.58.3.219.
2. Konstantinovskaya E., Malo M., Castillo D.A., 2012. Present-day stress analysis of the St. Lawrence Lowlands sedimentary basin and implications for caprock integrity during CO2 injection operation. Tectonophysics, 518–521, 119–137, http://dx.doi.org/10.1016/j.tecto.2011.11.022
3. Konstantinovskaya, E., Rutqvist, J., Malo, M. 2014. CO2 storage and induced fault instability in the St. Lawrence Lowlands sedimentary basin (Québec, Canada): insight from coupled reservoir-geomechanical modeling. Int. J. Greenhouse Gas Control. 22, 88-110. http://dx.doi.org/10.1016/j.ijggc.2013.12.008
4. Konstantinovskaya, E., Li, Q., Malo, M., Rivero, J. A., Faskhoodi, M. M., Campbell, B., 2020. Strike-slip reactivation of a high-angle normal fault induced by increase of reservoir pore pressure: insight from 3D coupled reservoir-geomechanical modeling, Int. J. Greenhouse Gas Control, 102, 103159, 1-33. https://doi.org/10.1016/j.ijggc.2020.103159
5. Plumb, R.A., Cox, J.W., 1987. Stress directions in eastern North America determined to 4.5 km from borehole elongation measurements. J. Geoph. Res., 92, 4805–4816.
6. Rutqvist, J., Birkholzer, J.T., Tsang, C.-F., 2008. Coupled reservoir-geomechanical analysis of the potential for tensile and shear failure associated with CO2 injection in multilayered reservoir-caprock systems. Int. J. Rock Mech. Min. Sci. 45,132–143.