Present-Day Stress Analysis in the St. Lawrence Lowlands from Borehole Breakouts and Implications for Co_2 Injection

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Summary

The average maximum horizontal stress direction S_{Hmax} obtained from stress-induced wellbore borehole breakouts in the St. Lawrence Lowlands is oriented N59˚E±20˚. The wellbore breakouts inferred from multi-arm dipmeter caliper data in 17 wells vary from 250 m to 4 km depth. These wellbore failure features are confined to the different Paleozoic lithological units of the St. Lawrence Platform succession and frontal thrust slices of the Québec Appalachians. Our results are compatible with the regional NE-SW S_{Hmax} stress orientation pattern that is generally observed in the NE Canada and USA. Regional fault patterns affect Paleozoic sedimentary succession of the St. Lawrence Platform and are generally oriented NE-SW. A key aim of geomechanical study in the St. Lawrence Lowlands is to estimate maximum sustainable fluid pressures for CO_2 injection that will not induce fracturing and faulting or reactivation of pre-existing faults. This requires the determination of prevailing stresses (directions and magnitudes), fault geometries and rock strengths.

Introduction

Evaluation of the geomechanical response of the reservoir rock and caprock to different CO_2 injection scenarios and its long-term storage represents a necessary part of reservoir-geomechanical study in the St. Lawrence Lowlands, Québec. Present-day stress direction determinations are the initial phase of this study. The assessment of the potential shear failure and/or re-activation of pre-existing faults and fracture sets as a result of changes in the reservoir pressure due to CO_2 injection represents the next step in this direction.

Stress directions in eastern North America have been determined by Plumb and Cox (1987) to depths of 4.5 km from borehole breakouts measured by dipmeter calipers in 47 wells in Paleozoic and Mesozoic successions. The average maximum horizontal stress directions S_{Hmax} in eastern Canada were estimated as N54˚E ± 7˚ for depths up to 2 km (Fig. 1). The NE-SW directions S_{Hmax} are recognised in the NE Canada and USA based both on borehole breakouts and seismic stress directions data (Heidbach et al., 2008; 2010). Recent evaluation of the regional stress patterns in Montreal, Charlevoix and Lower St. Lawrence seismic zones (depth > 5 km) concluded a thrust fault stress regime characterizes the Precambrian basement at depth in these areas, where the major principal stress S_1 is horizontal and the minimum principal stress S_3 is vertical (Mazzotti and Townend, 2010). The maximum horizontal stress directions determined from earthquake focal mechanisms in the these seismic zones are rotated clockwise with respect to the borehole S_{Hmax} stress orientations, that could be a result of the concentration of postglacial rebound stresses by local zones of weakness, such as low-friction faults (Mazzotti and Townend, 2010), or may occur due to variation of stress orientation or regime with depth.

Methods

The maximum horizontal stress directions S_{Hmax} (Figs 1, 2) are determined from the borehole breakouts orientations measured by dipmeter 4-arm calipers in 17 wells of the St. Lawrence Lowlands. The vertical stress S_v and its gradient (Fig. 3) are calculated for 15 wells by integrating the density logs data. The least horizontal principal stress S_{hmin} has been estimated from leak-off tests. The pore (reservoir) pressure P_p (Fig. 3) is estimated from the analysis of DST data in 5 wells in the Bécancour area. The laboratory analyses on rock strength and elastic parameters for both the reservoir and caprock formations are in process. The greatest principal stress S_{Hmax} is to be modeled by incorporating wellbore failure as seen in image logs or 4-arm caliper data, taking into account S_v, S_{hmin}, P_p, rock strength, drilling experiences, well trajectory and several other factors.

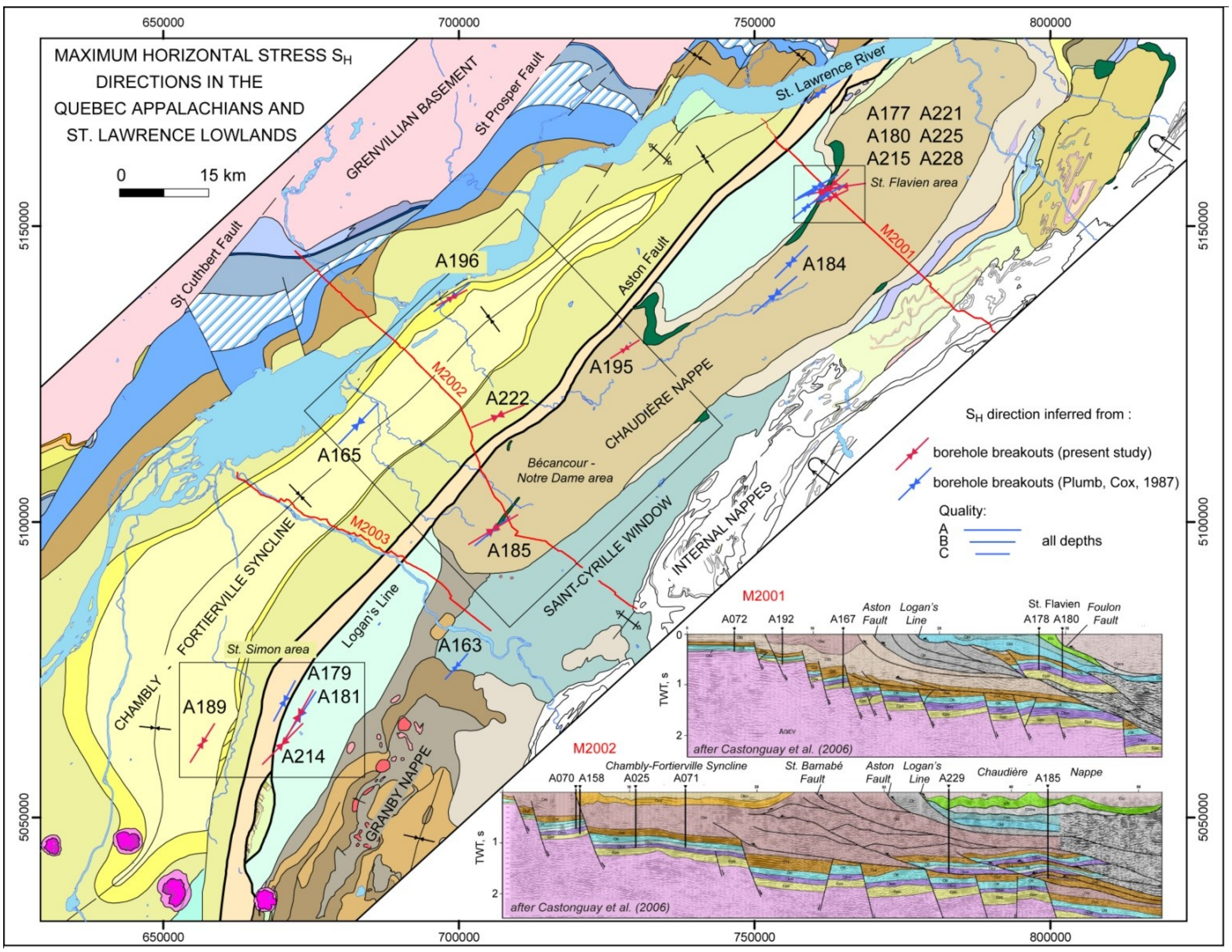

Figure 1: The maximum horizontal stress directions S_{Hmax} obtained from borehole breakouts in the St. Laurence Lowlands and Quebec Appalachians. Geological background is after Globensky (1987), Castonguay et al. (2006).

Results

The average S_{Hmax} direction (Fig. 2) obtained from borehole breakouts in the St. Lawrence Lowlands is oriented N59.7˚E±20.3˚, similar to the results of Plumb and Cox (1987). From NE to SW, the S_{Hmax} directions vary (Fig. 2) from N69.9˚E±17.5˚ in the St-Flavien area to N62.8˚E±4.0˚ in the Bécancour-Notre Dame area to N35.2˚E±5.6˚ in the St-Simon area remaining parallel to the Appalachian thrust front and structural trends in the St. Lawrence Platform (Fig. 1).

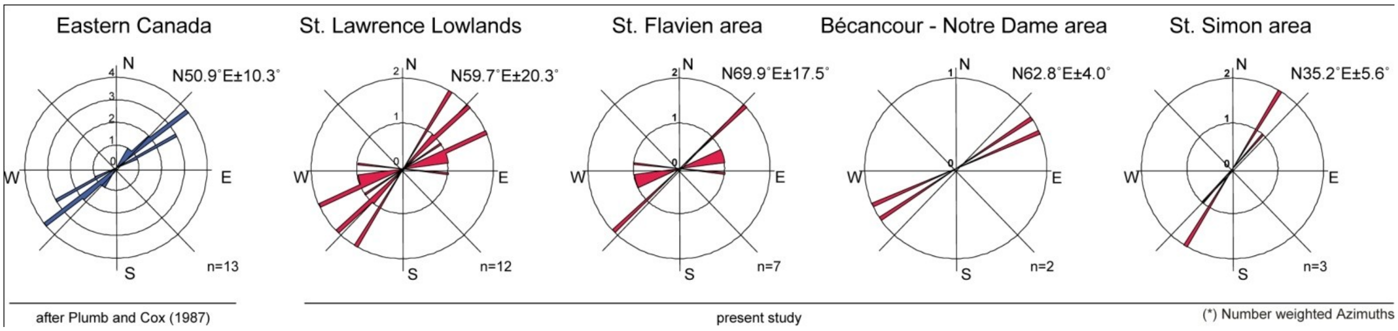

Figure 2: Summary diagrams for directions of S_{Hmax} from borehole breakouts from previous (left) and present study (right). Circular statistics after Mardia (1972), the azimuths are calculated as number weighted.

The Paleozoic sedimentary succession (Figs 1, 3) of the St. Lawrence Platform was deposited during syn-rifting extension of the Grenvillian passive continental margin and subsequent syn-orogenic subsidence of the foreland basin developed in front of the Appalachian thrusts during the Taconian orogeny. The syn-sedimentary normal faults initiated in the Precambrian basement cut through the sedimentary succession up to Utica Shale (Fig. 1, profiles). Some of the normal faults were re-activated as reverse faults at the end of the Taconian orogeny or later (Konstantinovskaya et al., 2010a). The regional normal and reverse faults are oriented generally NE-SW rotating to the NNE-SSW direction in the Montréal area (Thériault et al., 2005; Konstantinovskaya et al., 2009; 2010a).

The orientations of principal compressional stress axis S_1 of Taconian and Alleghanian paleostress fields (Faure et al., 1996a; 2004) are perpendicular or highly oblique to the present-day S_{Hmax} directions, while the S_1 orientations inherent for Late Cretaceous – Early Tertiary paleostress field (Faure et al., 1996b) are aligned with the S_{Hmax} directions, which probably remain the same since that time (Konstantinovskaya et al., 2010b). Further data of the absolute stress S_{Hmax} and S_{hmin} magnitudes and rock strengths are required to estimate whether faults were to become active under the present day stress regime as a result of CO_2 injection.

The average value of vertical stress S_v gradient is 26 kPa/m, varying from 24.2 kPa/m to 26.5 kPa/m in the analysed wells of the St. Lawrence Lowlands (Fig. 3). The S_{hmin} values determined from LOTs in different wells are slightly lower than S_v values. The regional pore (reservoir) pressure P_p gradient is 11.76-12.5 kPa/m in the Bécancour area as it is estimated from DST data (Fig. 3). This value is compatible with hydrostatic pressure gradient calculated for the brine density 1.18-1.29 g/cm^3 observed in the Bécancour area. The higher values of P_p gradient estimated locally in well A158 (Fig. 3) likely indicate the presence of a separate confined reservoir in this area.

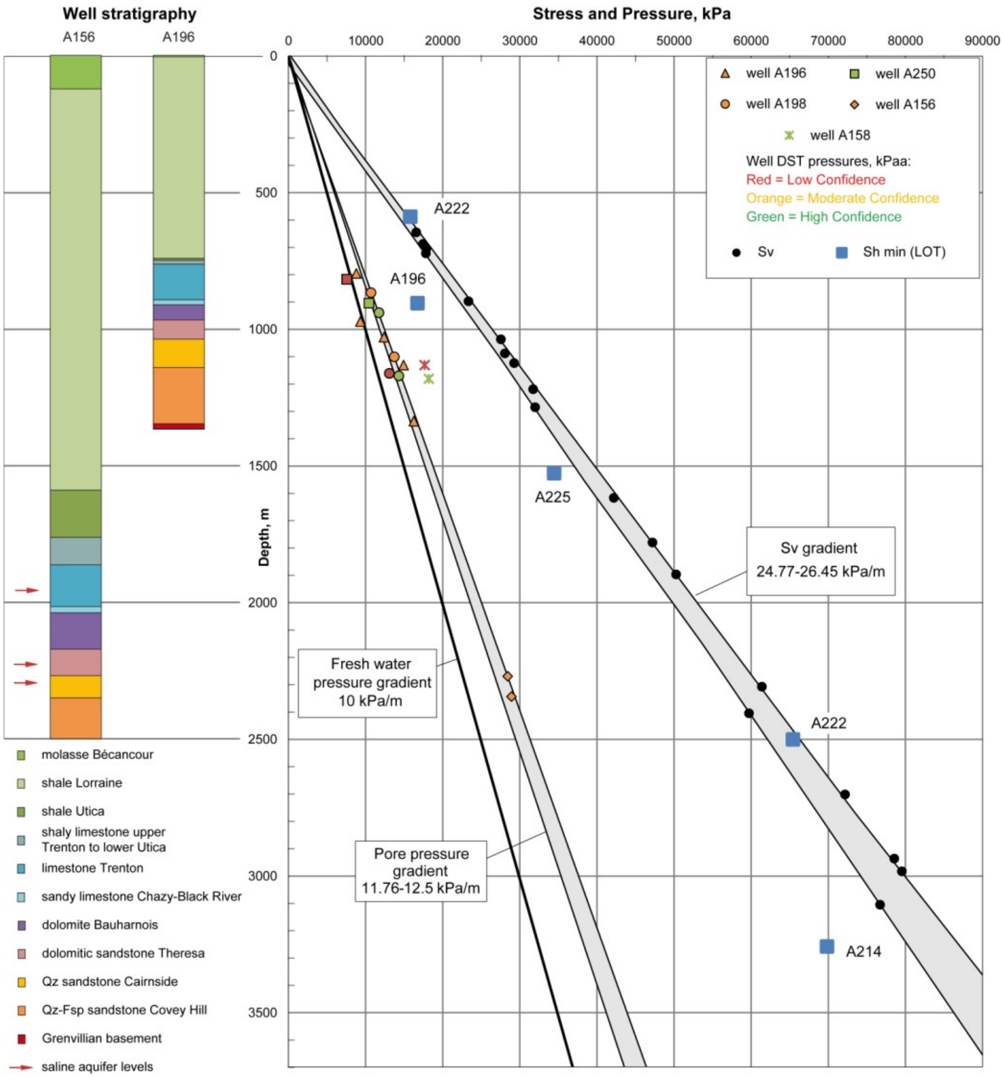

Figure 3: Summary diagram for well stratigraphy, pore (reservoir) pressure P_p estimated from DST data, vertical stress S_v calculated from density logs and S_{hmin} determined from LOTs in the St. Lawrence Lowlands.

Conclusions

The average maximum horizontal stress S_{Hmax} direction obtained from borehole breakouts in the St. Lawrence Lowlands is oriented N59˚E±20˚ (mean value) similar to S_{Hmax} borehole breakout directions from eastern Canada (N54˚E ± 7˚). First estimations of vertical and S_{hmin} stress and pore pressure variations with depth are to be completed by evaluation of stress S_{Hmax} magnitude and data on elastic properties of reservoir and caprock formations in order to perform reservoir-geomechanical feasibility evaluation for CO_2 injection and storage in the St. Lawrence Lowlands, Quebec.

Acknowledgements

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