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Abstract:

Folds, faults and fractures have been identified on a high-resolution satellite image that covers two sub-outcropping areas, on both sides of the St. Lawrence River, near Donnacona. Two generations of folds are superimposed over the Chambly-Fortierville syncline. The most common faults trend N100°-N120° or N30°-N60°, though their kinematics are uncertain. Fractures exhibit a relatively scattered distribution with predominant sets striking NE and WNW. Such fractures may be an important parameter for permeability enhancement during hydraulic fracturing. Future detailed analyses of brittle structures are needed in order to develop a sound conceptual framework of the deformation pattern in the St. Lawrence Lowlands.

Introduction

'Shale gas' is natural gas produced from reservoir rocks composed dominantly of fine-grained sediments. The 'shales' form self-enclosed petroleum systems where source, reservoir, seal and trap are all present within the same fined-grained unit. Organic content and thickness of the shale interval are important factors that must be present to create a potential play. In the St. Lawrence Lowlands, recent hydrocarbon exploration for shale gas targets Upper Ordovician rocks of the Utica Shale and Lorraine Group. These rock units were deposited in relatively deep marine settings within the newly created Taconian foreland basin, after the collapse of the north-American marginal carbonate platform (Sanford, 1993; Lavoie, 1994). In Quebec, the prospective Utica Shale lies at 700-1800 m depth, is 150 to 300 m in thickness, yields Total Organic Content (TOC) values generally between 1 and 3% and has vitrinite equivalent reflectance values between 1.3 and 2.0 (Lavoie et al., 2008).

Natural fractures are another important parameter for the characterization of shale prospects since known productive gas shale reservoirs have extremely low permeability and require multiple sets of open natural fractures for the commercial production of gas. In several cases, the presence of natural conduits for gas flow to the well bore is considered crucial (Engelder et al., 2009). This paper reports preliminary observations and interpretations on structural features found in the Utica Shale and Lorraine Group of southwestern Québec.

Previous work and methodology

In slightly deformed foreland areas, identification and characterization of natural fractures are typically done using remote-sensing techniques or direct observations either at the surface through outcrop studies or *in situ* through the use of geophysical logs or cores.

In the St. Lawrence Lowlands, the main tectonic features are relatively well constrained at surface (Globensky, 1987) and at depth (Konstantinovskaya et al., 2009; Castonguay et al., 2010). The primary normal faults in the autochthonous St. Lawrence platform strike NE, subparallel with thrusts and fold axes in the frontal units of the Appalachians. Few studies focus on brittle deformation patterns at a more finer scale, with the notable exception of detailed analyses of striated fault planes conducted with the aim of reconstructing paleostress regimes (Gélard et al., 1992; Faure, 1995; Rocher et Tremblay, 2001; Rocher et al., 2003; Faure et al., 2004). These studies are restricted to a small number of sites and exclude brittle structures such as joints and thus cannot be used to infer the overall deformation pattern including the length, spacing, strike and relationship of various structures. Moreover, no formation imaging logs or oriented core studies have been published for natural fracture characterization in the St. Lawrence Lowlands.

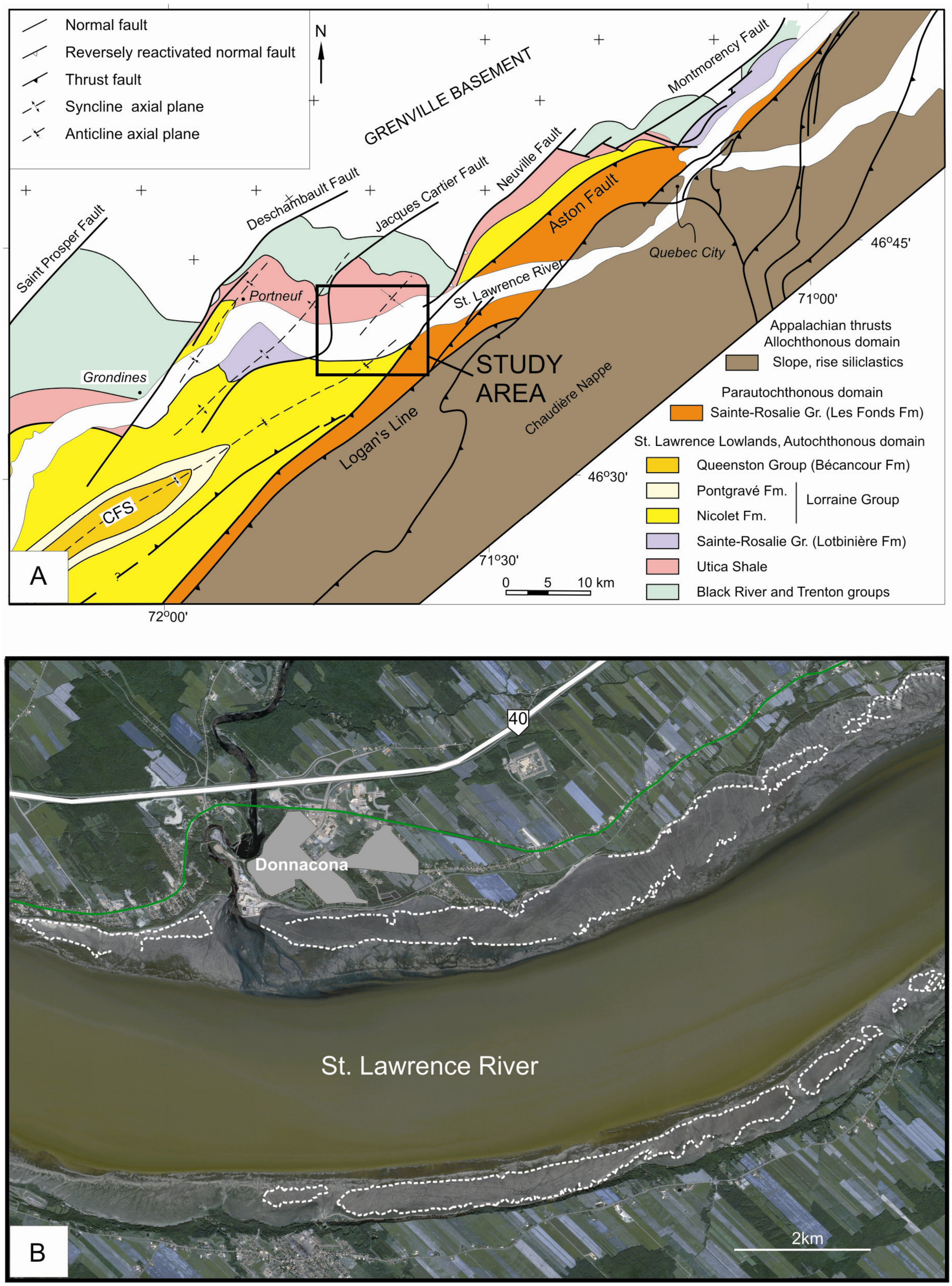

Figure 1: A- Geological map of the northern St. Lawrence Lowlands. Modified from Konstantinovskaya et al., 2009. B- Satellite image of the study area. The white dashed lines represent sub-outcrop boundaries.

In this study, a high-resolution commercial (QuickBird) satellite image with a 1 meter resolution is used to describe the deformation pattern along a segment of the St. Lawrence Lowlands. The image covers two sub-outcropping areas, approximately 8 and 12 km long, on both sides of the St. Lawrence River, in the Donnacona area (Fig. 1). The north shore floodplain is characterized by slightly (generally less than 5°) dipping Utica Shale that outcrops at low tide. On the south shore, the Lorraine Group exhibits steeper beddings that may exceed 40° on the southeast flank of the Chambly–Fortierville syncline (CFS). The Neuville Fault is located in the St. Lawrence River halfway between the north and south shores (Clark and Globensky, 1973).

On the high-resolution satellite image, faults (i.e, discrete surface with evidence of motion), fractures (i.e., discrete surface without evidence of motion) and fold axes have been identified.

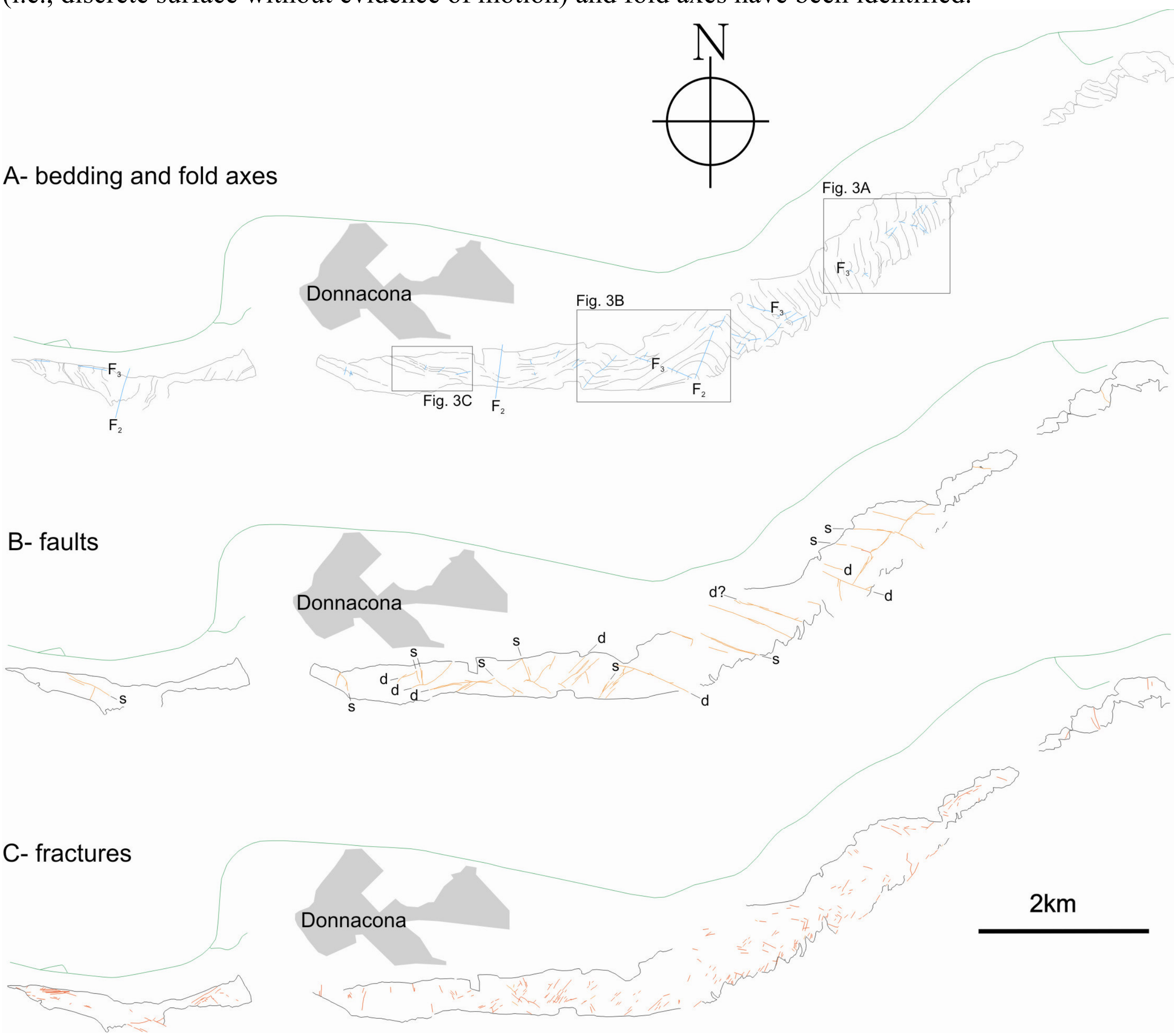

Figure 2: Main structural features of the north shore. A- bedding and fold axes (F_2 and F_3). B- faults. The apparent motion (based on the offset of marker beds) is indicated: d, dextral; s, sinistral. C- fractures.

Deformation pattern of the St. Lawrence Lowlands

On the north shore, the main folds are characterized by axes trending more northerly (approximately N20°) in comparison to the N50° axis of the Chambly-Fortierville syncline (Fig 2A). In several cases, marker beds define box folds in map view (Fig. 3B). These folds result from the superimposition of cross folds with either WNW or NE trending axes over the main folds. Late folds are located close to parallel faults suggesting a relationship with fault motion (drag fold; Fig. 3).

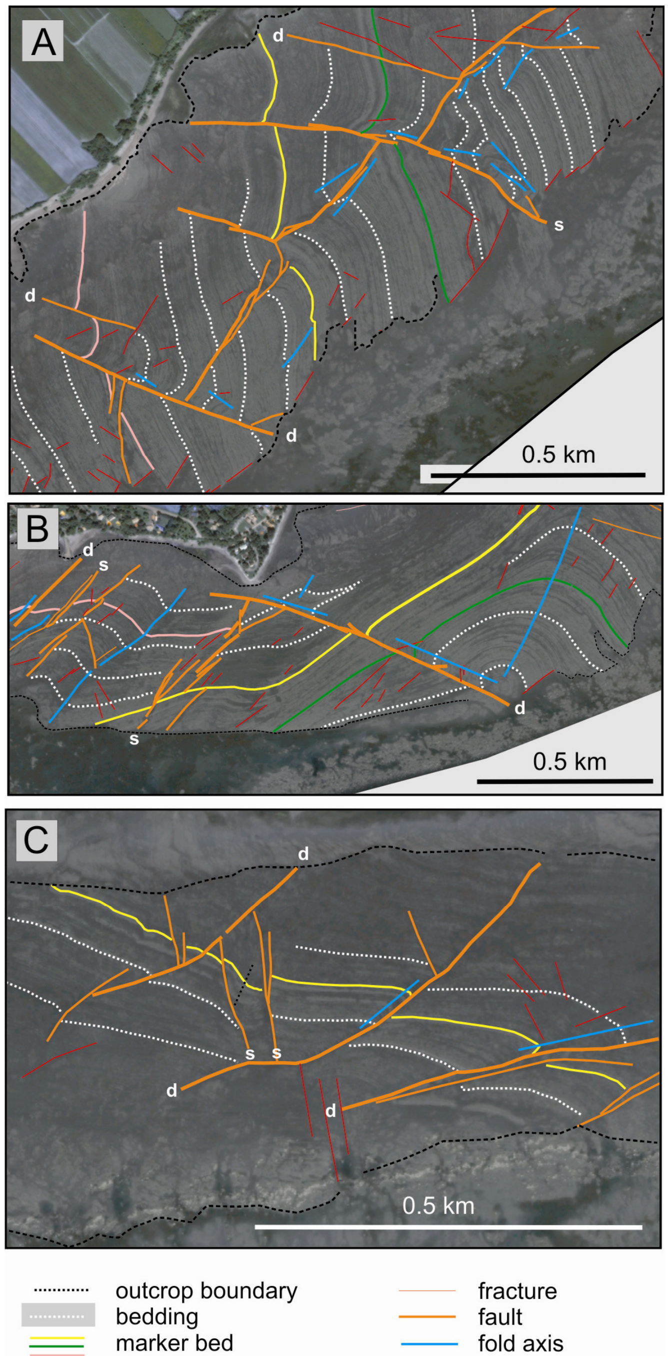

Figure 3: Detailed views of specific areas on the north shore. Location on Figure 2. d (dextral) and s (sinistral) indicate the apparent motion based on the offset of marker beds.

The most common faults on the north shore trend N100°-N120° whereas the second group of faults of importance trend N30°-N60°(Fig. 2B and 4). WNW-trending faults are more continuous along-strike and generally cut NE-trending faults (Fig. 3A and B). Apparent offsets based on marker beds may be contradictory within each group of faults (Figs. 2 and 3; see below).

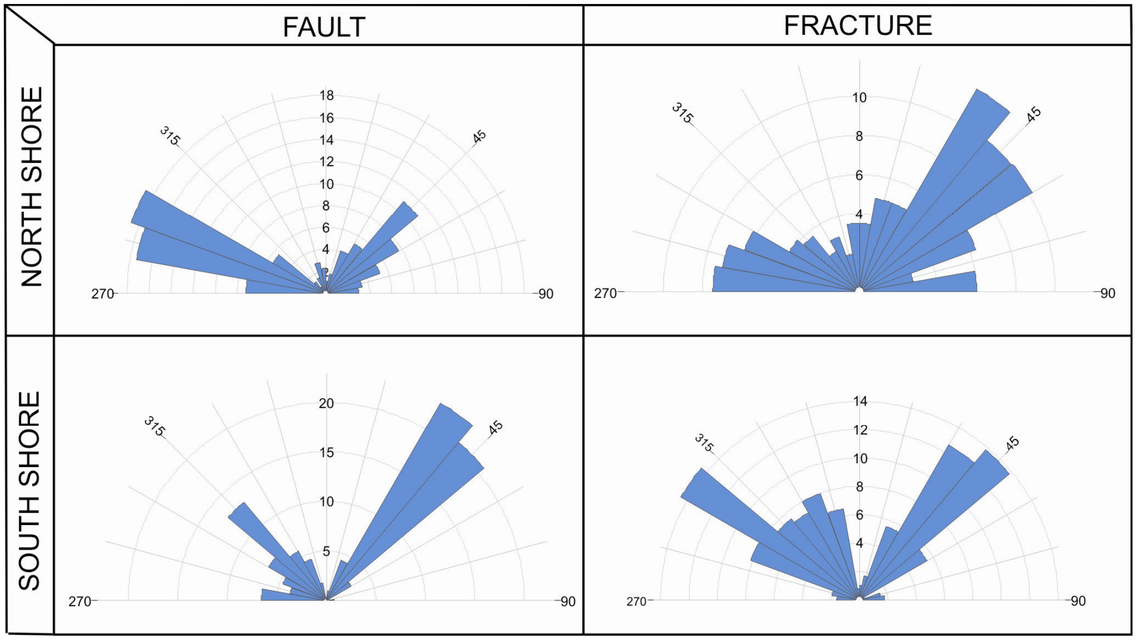

Figure 4: Rose diagrams of faults and fractures interpreted from the satellite image of the north and south shore of the St. Lawrence River.

Fractures exhibit a scattered distribution and almost all the strikes are represented on the rose diagram (Fig. 4). The primary fracture set trends NE sub-parallel with the Chambly-Fortierville syncline and with NE-trending faults (Fig. 4). WNW fractures sub-parallel to the main group of faults form the second most abundant fracture set.

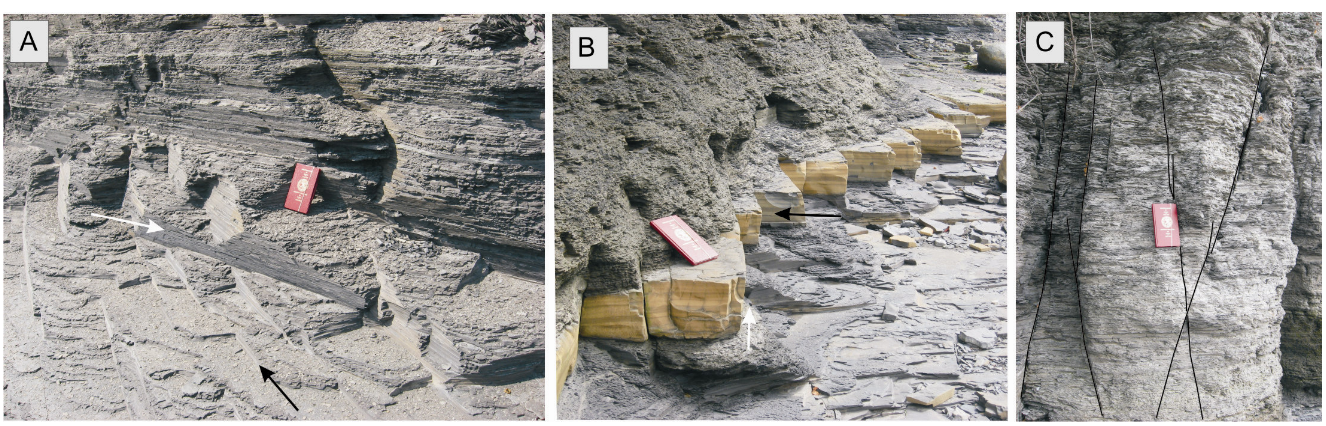

Figure 5: Photographs of fractures on the north shore. A- Two joint sets lying at an angle of approximately 60°. The fact that the joints belonging to the set enhanced by a black arrow are shorter, less planar, less regular in orientation and commonly terminate against fractures of the set noted with a white arrow suggest that they are younger. B- Two nearly orthogonal joint sets. C- Steeply dipping cross-cutting fractures.

Preliminary observations on the north shore indicate that several sets of systematic joints may be distinguished in the field. They are formed by steeply (50° to 90°) dipping fractures with spacing ranging from a few centimetres to a few meters. Zones with fractures more closely spaced than surrounding areas are locally present. Cutting and abutting relationships between joint sets has not been studied in detail, however joint sets generally crosscut each other without deflection. These sets of systematic joints intersect with a variable angle (Fig. 5A and 5B).

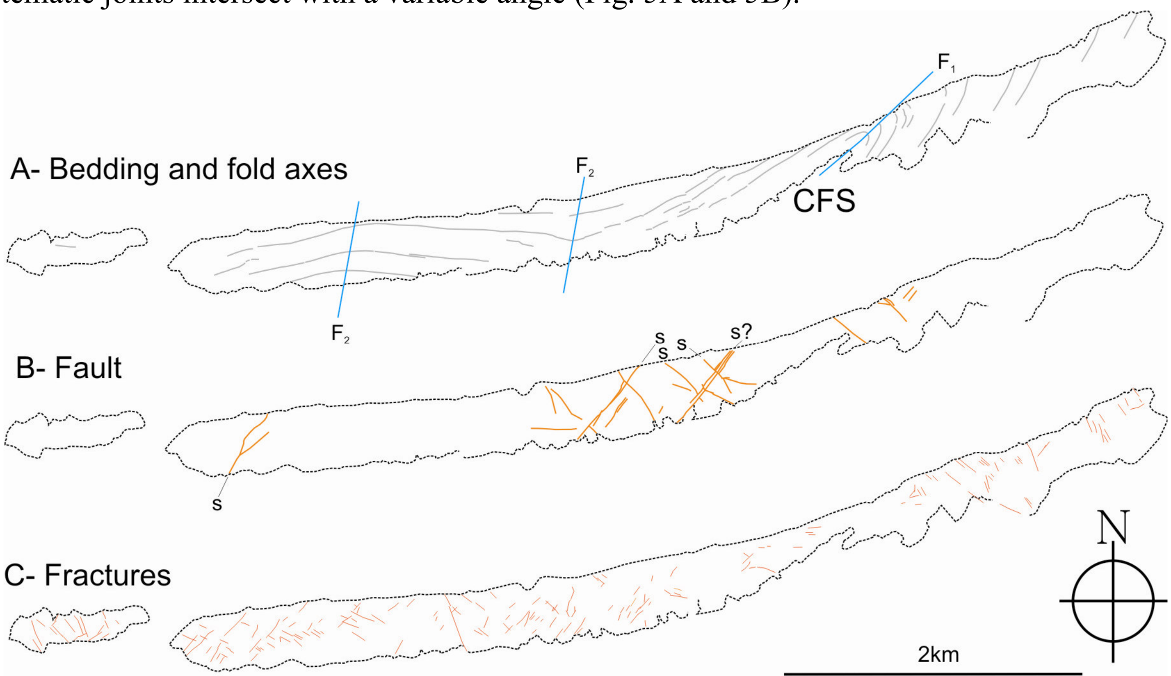

Figure 6: Main structural features of the south shore. A- bedding and fold axes (F_1 and F_2). B- faults. The apparent motion based on the offset of marker beds are indicated: d, dextral; s, sinistral. C- fractures.

The N50-trending Chambly-Fortierville syncline is the main structural feature of the south shore (Fig. 6A and 7). Changes in strike along the NW flank of the syncline is associated with late folds with a N10°-N20° trending axis.

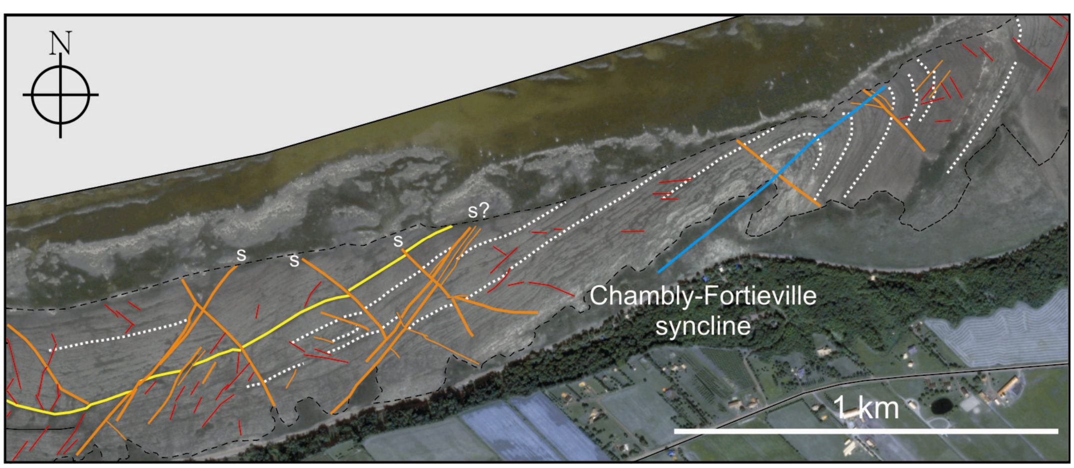

Figure 7: Detailed view of the hinge zone of the Chambly-Fortierville syncline. s (sinistral) indicate the apparent motion based on the offset of marker beds.

The most common faults on the south shore trend N30°-N50°, whereas the second group of faults of importance trend N120°-N140°(Figs. 4 and 6B). Both groups of faults are oblique to the axis of Chambly-Fortierville syncline and are characterized by an apparent left-lateral sense of motion.
On the south shore, fractures are considerably less scattered in orientation than on the north shore. The main sets of fractures trend NE and NW, subparallel with the main faults (Fig. 4).

Discussion

In the St. Lawrence Lowlands, studies of brittle faults (Gélard et al., 1992; Faure, 1995; Rocher et Tremblay, 2001; Rocher et al., 2003; Faure et al., 2004) document a polyphased structural history. In the study area, the fold interference pattern is the best evidence for the superimposition of several deformation events. Three generation of folds are distinguished in the Donnacona area. The Chambly-Fortierville syncline belongs to the first fold generation (F_1). On the south shore of the St. Lawrence River, the Chambly-Fortierville syncline is involved in broad open folds (F_2) striking N10°-N20°. These F_2 folds are correlated with the main folds occurring on the north shore where they are deformed by F_3 drag fold most likely associated with fault motions (Fig. 8). The Chambly-Fortierville syncline is generally attributed to the late phase of the Taconian orogeny (Tremblay and Pinet, 1994). Late folding events are thus loosely constrained as post-Ordovician in age.

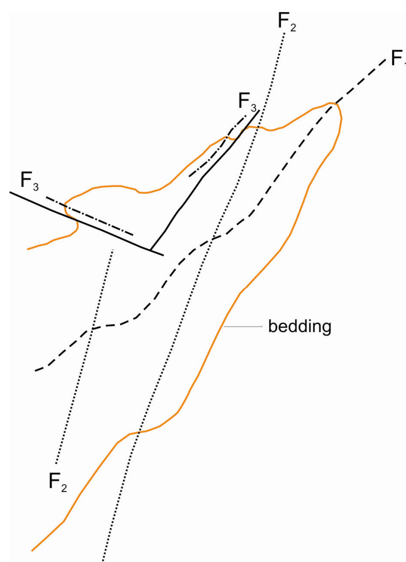

Figure 8: Schematic sketch showing the deformation pattern associated with superimposition of folds.

The true displacement along faults and their timing is presently uncertain and I thus strongly disagree with Shaw (1993) who stated that the deformation pattern on the north shore is the ‘one of the clearer published examples of a left-lateral shear set’. The fact that the apparent offsets based on marker beds may be contradictory within each of the groups of faults suggest that apparent horizontal displacement may be misleading due to the predominance of vertical motion (Fig. 9), even if the possibility that some structures have been reactivated cannot be ruled out.

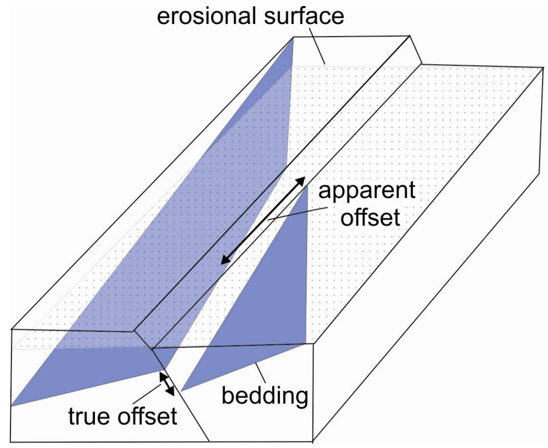

Figure 9: Schematic sketch showing how apparent offset using slightly dipping marker beds may be erroneous especially if the true motion is down-dip. The diagram shows the case of a normal fault, but a similar argument may be applied to thrust fault.

In foreland settings, fracture patterns are generally cumulative as they include fractures formed during several tectonic episodes that were preserved over time (Engelder et al., 2009; Bordet et al., 2010). In the study area, future interpretation of fractures should rely on detailed field observations and would have to answer to the following questions:

a) Are some joints are pre-folding structures?

In some well-studied examples (Engelder et al., 2009), geometric relationships demonstrate that the dominant fracture set formed prior to folding of the strata. In the Donnacona area, rotation associated with folding (as well as the superimposition of several generations of fractures) may explain the relatively scattered distribution of fractures in rose diagrams. However, this hypothesis should be tested by comparing fracture patterns on both flanks of folds.

b) Are the dominant nearly orthogonal fracture sets formed during the same tectonic event or during several distinct events?

Several detailed joint studies (Rives et al., 1994 and reference therein) suggest that orthogonal fracture sets are the result of a single tectonic event including the formation of a primary fracture set under a compressive or extensional stress field followed by a relaxation episode responsible for the formation of the secondary set. However, nearly orthogonal fracture sets may also relate to separate tectonic events (Engelder, 2009).

c) Are *some joints formed in a shear mode?*

On the north shore, fracture spacing varies and may be lower near NE- and NW- trending faults. This observation, which should be confirmed in the field, suggests that fractures may be genetically associated with fault motions. In this case, fractures do not develop parallel to the shortening axis and may be classified as shear fractures.

d) Are some of the NE-striking joints formed in the present-day state of stress.

The present-day orientation of the maximum compressive normal stress trends NE (Konstantinovskaya, 2011) and is nearly parallel to the most developed group of fractures. This geometrical relationship may be a geological coincidence as demonstrated in the U.S. Appalachian Basin (Engelder et al., 2009) or may indicate that some joints relate to the post-Cretaceous geological history. It should be noted that the youngest event documented by the analysis of striated fault planes post-dates the Cretaceous Monteregian intrusion in the Montreal area and is characterized by strike-slip motion denoting a NE-SW compression.

The answers to the questions above would determine if the observations in the Donnacona area can be applied in the entire St. Lawrence Lowlands.

Conclusion

Regional fractures have great economic significance since they may enhance permeability. Regional fractures can create highly anisotropic horizontal permeability in a reservoir. If consistent at a regional scale, fracture pattern observed at surface may help to predict their orientation at depth and to design deviated wells with an optimal azimuth.

For instance, hydraulic fracturing in a horizontal well drilled perpendicular to the present-day orientation of the maximum compressive normal stress (i.e. to the NW or SE) will likely result in the reopening and the draining of the most common structural features, the NE-striking joints.

This study shows that several knowledge gaps remain to be explored and demonstrate the need to document the kinematic of faults, the geometry of joints and determine age relations between various structures in order to have a sound conceptual framework of deformation patterns in the St. Lawrence Lowlands.

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