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GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8826

Faults and lineaments of the Quebec City, Charlevoix and Saguenay–Lac-St-Jean regions, Québec

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ABSTRACT

This Open File contains the interpreted brittle lineaments and a compilation of mapped faults of an area bound by latitudes 46.5°N and 49.75°N and longitudes 69.5°W and 74°W. The study area includes the north shore of the St. Lawrence River in Québec from slightly north of Trois-Rivières to slightly north of Tadoussac, which includes most of the watersheds of the Saint-Maurice and Saguenay rivers and the Lake St. John (Figure 1).

The study area includes the seismically active Charlevoix Seismic Zone (CSZ). The CSZ is an area where at least five earthquakes of moment magnitudes (**M**) between 5.5 and 7 have occurred in the past and where hundreds of smaller earthquakes are recorded yearly. This study is an attempt to provide a homogeneous coverage of the brittle structures through an integration of visually interpreted lineaments and mapped faults. The possible relationships between these brittle faults and earthquakes will be examined in upcoming studies.

Lineaments were observed mostly from the Digital Elevation Model (DEM) of the Canadian National Topographic Data Base (NTDB) at a scale of 1:250 000. The DEMs illuminated from two directions were used to first visually recognize lineaments and second, to georeference their surface expressions in a Geographic Information System (GIS). The more questionable brittle features were re-evaluated subsequently against known geological information. Since the final goal was to better map the brittle faults that could be reactivated in earthquakes, the conspicuous ductile structures were not considered in this study. All ductile structures are related to the Grenville orogeny (about 1 billion years ago).

Brittle structures were recognized by their linearity in plan view. On the other hand, the ductile structures generally appeared curved, enhanced contact between different Grenvillian lithologies, or presented a distinct structural pattern. After a first detection pass, lineaments at a more regional scale were drawn by interpolating between segments of lineaments. These interpolated segments corresponded to areas where the topography was subdued and where no conspicuous trace existed. Only brittle lineaments longer than 5 km were included. The interpreted lineaments were then superimposed on geological and geophysical maps (vertical component of total magnetic field) to ensure that they did not correspond to dykes or ductile structures such as lithological unit contacts. Our final product is a 1:500,000 scale map that can be used to better understand the seismotectonics of this region.

INTRODUCTION

The St. Lawrence Rift System (SLRS), which includes the Ottawa-Bonnechere and Saguenay grabens (Kumarapeli and Saull, 1966), is located well inside the North American plate. Along its course, most historic damaging earthquakes and the some 350 smaller events recorded yearly occur in three main seismic zones (SZ), namely the Charlevoix (CSZ) (Figure 2), Western Quebec (WQSZ), and Lower St. Lawrence (LSLSZ). Outside these areas, most of the Canadian Shield and bordering regions have a low level of earthquake activity with historical events rarely exceeding magnitude 5.

The seismic zoning maps of eastern Canada are based on historical seismicity and on a geological model that considers the possible reactivation of SLRS faults. A major difficulty that faces the geological model is that not all regional SRLS faults appear in geological maps. For this reason, when a new sizeable earthquake occurs, it is often difficult to correlate it with a mapped fault. To help resolving these two issues, this project aimed at producing a digital map of the faults and lineaments of the entire SLRS. We are confident that this new digital map will help defining the relationships between earthquakes and faults within the SLRS.

With the final goal of mapping all brittle faults of the SLRS, the authors first focused their attention on the WQSZ. Lamontagne et al. (2020) presented the interpreted brittle lineaments and mapped faults of an area that included most of the Ottawa River watershed, including most of eastern Ontario and the Laurentians, between Montréal (QC) and North Bay (ON).   The same methodology is used therein to study an area to the northeast of that one (Figure 1). The study area includes the north shore of the St. Lawrence River approximately from Sainte-Anne-de-la-Pérade (near Trois-Rivières) to near Tadoussac. It comprises the watersheds of many small St. Lawrence River tributaries and those of the Saint-Maurice and Saguenay rivers and the Lake St. John (Figure 2). The study area is named thereafter the Quebec City-Charlevoix-Saguenay-Lac-St-Jean Region (QCSL).

In Quebec, even in areas where the Appalachian rocks outcrop, earthquakes occur beneath these rock units within the Canadian Shield (Lamontagne, 2018). These Appalachian faults (mostly thrust faults) were not included in our analysis because they do not extend into the Precambrian basement where earthquakes occur. The decoupling between the Appalachians and the Precambrian basement was highlighted in the seismic reflection profiles east of Trois-Rivières (Castonguay et al., 2010). These Appalachian faults are, however, included in the database but are not made visible from the outset (how to make these faults visible is explained in the following section). The database also includes fault information along the SLRS. Along the St. Lawrence River, many regional-scale faults affecting the Ordovician sedimentary rocks of the St. Lawrence platform extend into the Precambrian basement.

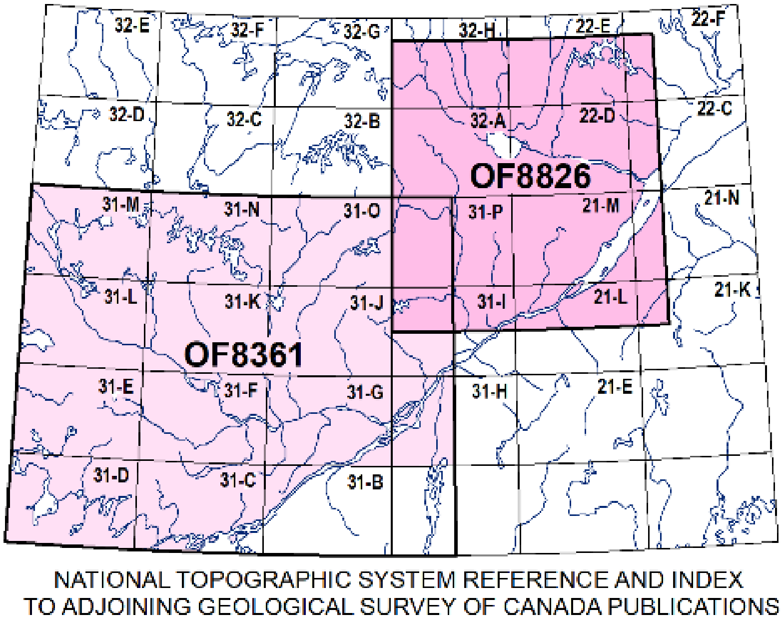

Figure 1. Study area of this Open File (OF8826). See Lamontagne et al. (2020) for the region covered by OF8361. The number and letter (for example, 21-M) refer to the National Topographic System (NTS) map number for the corresponding 1:250 000 map.

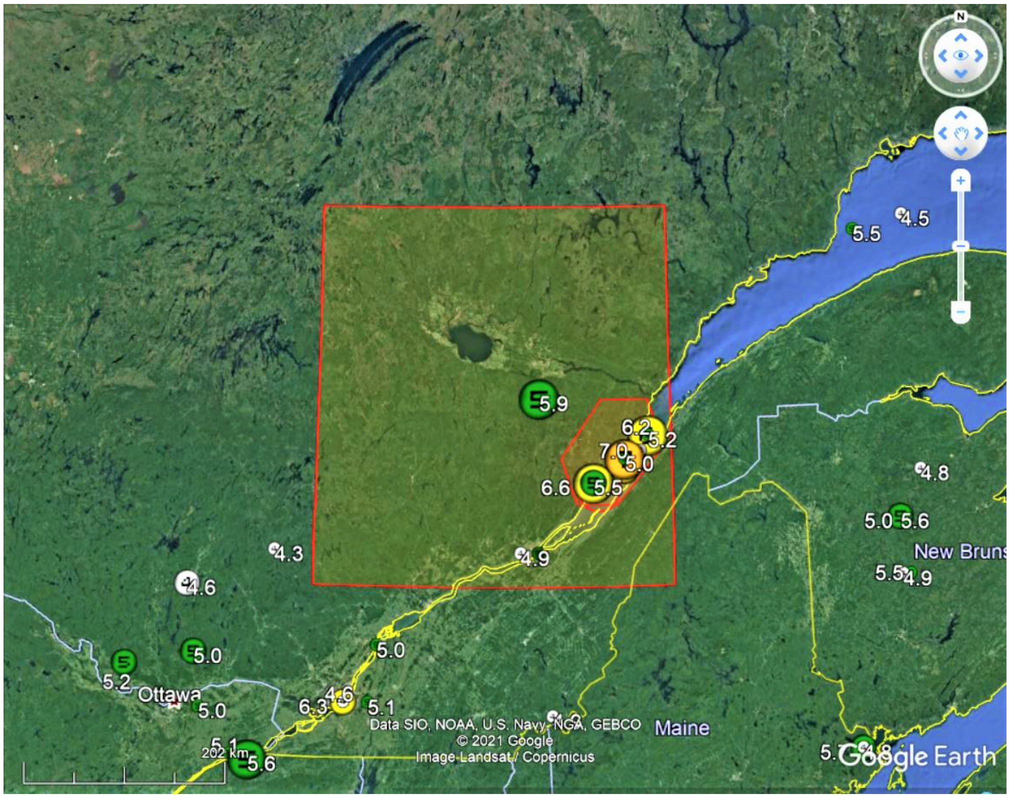

Figure 2. Location of the study area (orange rectangle), with the CSZ outline (orange hexagon) and the epicentres of the significant earthquakes with magnitudes (Lamontagne et al., 2018).

EARTHQUAKES IN THE QUEBEC CITY-CHARLEVOIX-SAGUENAY-LAC-ST-JEAN REGION

Although earthquakes can occur anywhere in Quebec, most concentrate in three distinct seismic zones: the CSZ, WQSZ and LSLSZ (Lamontagne and Ranalli, 2014). Historically, earthquakes are known since the advent of written accounts in the early 1600s when the region started to be settled by Europeans (1608 Québec; 1635 Trois-Rivières; 1642 Montréal). In the mid-1920s, seismographs capable of detecting local earthquakes were installed. Since the early 1980s, digital seismographs of the permanent Canadian network monitored the region allowing the detection of earthquakes above Nuttli magnitude (m_N) 2.0, smaller than what can be felt by the local population. The larger events described below are all rated on the moment magnitude (**M**) scale which is approximately equal to m_N minus 0.43 (Bent, 2011). In the CSZ, where the seismograph network is denser, the detection completeness is better than m_N 1.0.

Outside of the CSZ, the QCSL is, for the most part, an area with low-to-moderate seismicity with only a few significant moderate earthquakes over the last centuries. One of these significant earthquakes was the 1842 earthquake (estimated magnitude 5.0) that caused chimney damage in Trois-Rivières (Gouin, 2001; Lamontagne et al., 2018). The 1997 **M** 4.9 Cap-Rouge earthquake caused some damage to masonry walls in the Quebec City region (Nadeau et al., 1998). Its focal mechanism is consistent with the reactivation of a mapped SLRS fault a depth of 22 km (Nadeau et al., 1998). The largest earthquake outside the CSZ is the 1988 **M** 5.9 Saguenay earthquake. This earthquake occurred at lower-crustal depth (29 km) in the Canadian Shield, outside the seismic zones defined by the recurring activity (North et al., 1989). Possibly due to its focal depth, very few aftershocks have been recorded and only four M ≥ 3 earthquakes have been recorded there between 1988 and 2020. Despite the differences in orientation between the two nodal planes of the focal mechanism and the graben fault at the surface, the proximity of the earthquake epicentre to faults of the Saguenay Graben suggested a relationship between the two (North et al., 1989). Outside the CSZ, the activity rate is similar to other regions of the Canadian Shield. To the south and east of the CSZ, the Appalachians are almost aseismic with earthquakes occurring beneath the Appalachian nappes, in the Precambrian Shield. Very few earthquakes occur in the St. Lawrence valley upstream from Quebec City, and the hydraulic fracturing activity there did not create additional seismic activity (Lamontagne, 2016; 2018). A summary of the local geology (including faults) and earthquake activity can be found in Nadeau et al. (2020).

Due to its number of damaging earthquakes and its frequent lower magnitude earthquakes, the CSZ is recognized as the most active seismic zone of Eastern Canada (Basham et al., 1982). Five earthquakes rated at moment magnitude (**M**) 5.5 or more are known to have occurred there: 1663 (**M** ~ 7); 1791 (**M** ~ 5.5); 1860 (**M** ~ 6.1); 1870 (**M** ~ 6.6); and 1925 (**M** 6.2; Bent, 2009). The installation of a permanent seismograph network in 1978 has helped to define the seismotectonic characteristics of the CSZ. Earthquakes occur between the surface to 30 km depth within the Precambrian Shield (Figure 3). Roughly 80% of Charlevoix earthquakes occur in the depth range 5–15 km in Grenvillian basement rocks, with only a few deeper than 25 km.   Comparing this depth distribution to rheological models of the region, Lamontagne and Ranalli (1996) attribute earthquakes to faulting above the brittle-ductile transition to depths of at least 25 km. The main source of crustal stress is the mid-Atlantic ridge push. The reactivation of pre-existing faults could be due to high pore-fluid pressure at temperatures below the onset of ductility for hydrated feldspar at about 350°C and/or a low coefficient of friction, possibly related to unhealed zones of intense fracturing.

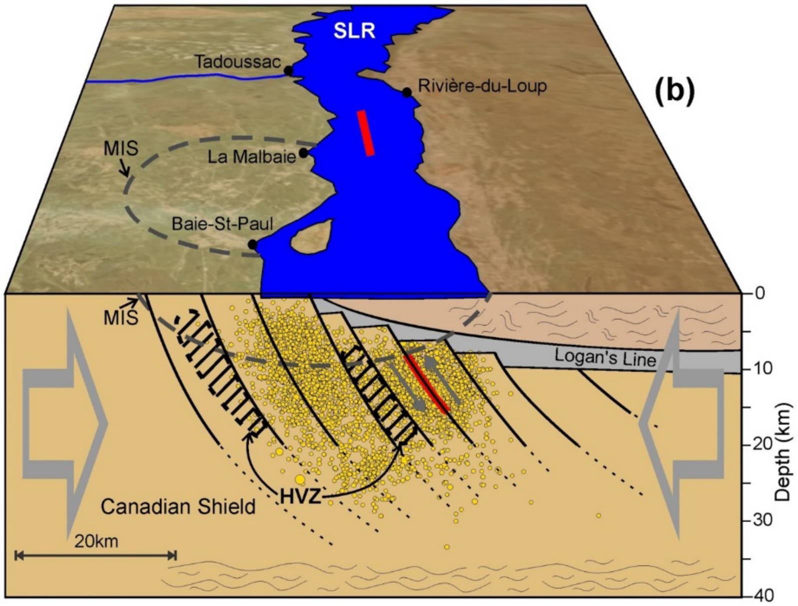

Figure 3. Idealized cross-section perpendicular to the St. Lawrence River in the Charlevoix Seismic Zone (CSZ). The earthquake activity occurs in response to ridge push stresses (arrows) and is constrained to the Canadian Shield rocks beneath the St. Lawrence River (SLR), St. Lawrence platform rocks (in gray), Logan's Line and the Appalachian rocks. The 1925 earthquake (shown in red) ruptured along one of the large SLR faults at focal depth of about 10 km at the extremity of the CSZ. A small proportion of earthquakes occur within the Charlevoix Meteor Impact Structure (MIS). Earthquakes tend to concentrate outside the zones of high velocities ('HVZ'; Vlahovic et al., 2003).

CSZ hypocentres cluster along or between the mapped Iapetan faults (also called St. Lawrence paleo-rift faults). In the study area, the largest earthquake of the 20th century was the 1925 earthquake and its focal mechanism has one nodal plane consistent with a reactivation of a SE-dipping paleo-rift fault (Bent, 1992). The St-Laurent fault, one of the major rift faults of the CSZ, was formed in the late Precambrian but was also active after the Devonian meteor impact (Rondot, 1979). The last reactivation phase probably occurred during the early stages of the opening of the Atlantic Ocean in late Triassic-Jurassic times (Lemieux et al., 2003). Currently, this fault is not particularly active but appears to bound concentrations of hypocentres (Lamontagne, 1999).

The distribution of spatially clustered earthquakes and focal mechanisms indicate that earthquakes occur in highly fractured rocks, especially within the boundaries of the Devonian impact structure (Lamontagne and Ranalli, 1997). The hypocentre-velocity simultaneous inversion of local P and S wave produced a velocity model that revealed areas of high-velocity bodies at mid-crustal depths (Vlahovic et al., 2003; Fig. 3). These areas were interpreted to be stronger, more competent crust that separates CSZ earthquakes into two main bands elongated along the St. Lawrence River.

There are indications that the region itself may have volumes with different rheological properties due to the presence of the impact crater and its faults. Larger events concentrate at both ends of the seismic zone outside the impact structure (Stevens, 1980; Lamontagne, 1999). Recently, geomechanical modelling showed that the weakening of the rift faults produces a stress increase in the region of the crater bounded by faults, leading to low magnitude events within the crater and large events outside it (Baird et al., 2009; 2010). If this hypothesis is true, the local seismicity would be caused by local conditions rather than by more regional conditions.

THE ST.LAWRENCE RIFT SYSTEM (SLRS)

Kumarapeli and Saull (1966) proposed that the series of normal faults along the St. Lawrence valley indicated rifting similar to the East African rift system. Although it is now recognized that the SLRS is not an active rift, this hypothesis provided a model that explained many of the geological characteristics of the area (including faults created in an extensional regime and carbonatite intrusions). The SLRS is now recognized as a half-graben created during the late Precambrian opening of the proto-Atlantic (Iapetus) Ocean (Kumarapeli, 1985).

The normal faults of the St. Lawrence paleorift system have been described and mapped at the surface (Du Berger et al., 1991; Tremblay and Roden-Tice, 2011; Konstantinovskaya et al., 2014)) and, in the St. Lawrence valley between Montreal and Quebec City, in the subsurface (Castonguay et al., 2010). Along the St. Lawrence River, many of the faults trend NE-SW and mark the boundary between the Canadian Shield to the NW and the St. Lawrence Lowlands to the SE. The surface trace of these normal faults can be recognized in the digital elevation model of the region (Figure 4). They often correspond to dramatic changes in topography with rocks of the Canadian Shield separated by a fault from those of the St. Lawrence platform. The change in texture often corresponds to a change in the density of lineaments and to the presence of thick sequences of post-glacial clay deposits. Many faults can be followed for tens of kilometres in the Canadian Shield. The faults of the Saguenay graben, that trend mostly WNW-ESE, is interpreted as an Iapetan failed arm (or aulacogen; Kumarapeli, 1985).

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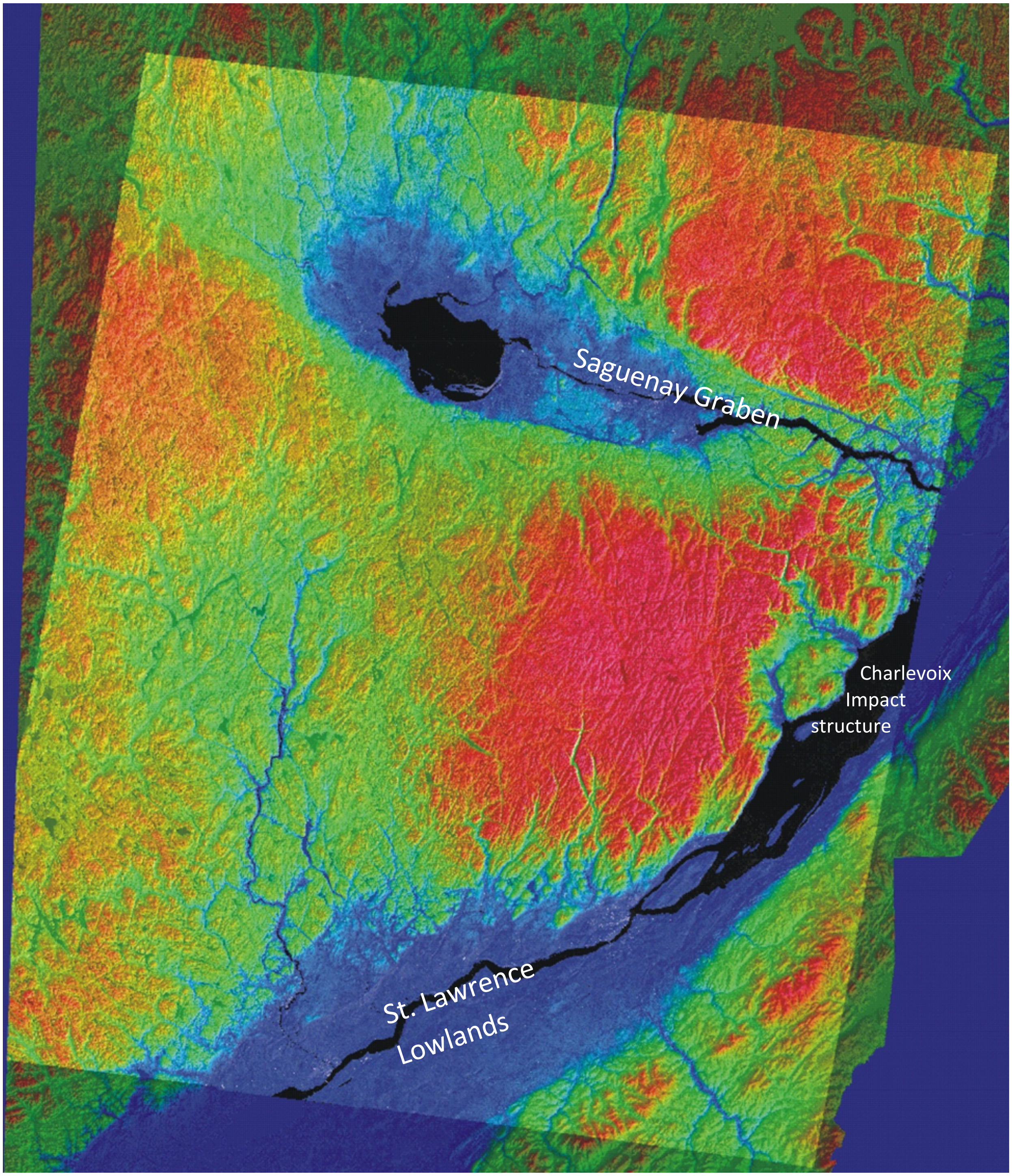

Figure 4. Chromostereoscopic fused radar and DEM image (Modified from Harris et al., 2006). The fused data provide visualizations of the terrain in which topographic and spectral patterns are enhanced to highlight geologic structures.

The SLRS faults have been studied in Charlevoix, Quebec City and in the St. Lawrence estuary. These faults consist of cohesive cataclastic rocks, with some major fault zones being marked by 10-to-20 meter-thick fault breccias, ultracataclasite and foliated fault gouge (Tremblay and Roden-Tice, 2011). The rift system is a crustal scale faulted zone formed during Iapetus rifting (late Precambrian to early Paleozoic; Sanford, 1993). Studies of the age of formation and reactivation of these faults revealed various periods of reactivation. Apatite-fission track age discontinuities between the footwall and hanging wall of these faults are interpreted as the result of normal faulting at ca. 200 Ma (Jurassic) followed by tectonic inversion about 150 Ma ago (Tremblay and Roden-Tice, 2011). The latter study provides support for Atlantic-related, extensional and compressive deformation within the interior of the Canadian Shield, more than 500 km west of the axis of the Mesozoic rift basins. The faults have been most recently active during the Late-Triassic Jurassic period which corresponds to the creation of the current Atlantic Ocean with the separation of North America and Africa.

Beneath the St. Lawrence platform and Appalachian cover, seismic reflection profiles in the St. Lawrence Lowlands have shown the upper crustal morphology of the faulted blocks (Thériault et al., 2005; Castonguay et al. 2010). SLRS faults exist at depth beneath the Appalachians and their approximate positions are revealed by their magnetic and gravity signatures (in the CSZ: Lamontagne, 1999; in the St. Lawrence Lowlands, Lamontagne et al., 2012). Although we know the positions of some of the rift faults beneath the Sedimentary rock cover, our knowledge is far from complete for those with small vertical displacement.

IMPORTANCE OF THE LINEAMENT MAPPING FOR SEISMOTECTONIC STUDIES

Earthquakes are caused by stress release and slip along pre-existing faults. Consequently, one of the first questions asked by seismologists after an earthquake occurs is “where is the nearest fault?” For this reason and for the production of geological maps, QCSL lineaments have been studied for many years. In the 1970’s, for example, Landsat images of Charlevoix were interpreted (Moore, 1978). Rondot (1979) used stereoscopic air photographs and field observation to produce a map of lineaments and faults (Figure 5) from which a simplified geological map that included regional faults was derived (Figure 6).

An analysis of lineaments between the Saguenay and the St. Lawrence rivers (Landry, 1986), was referred to in Du Berger et al. (1991). Results indicated a high density of lineaments (19.2/100 km^2) that are relatively short (10.9 ± 7.6 km) and discontinuous. Lineaments have preferential trends around 000°, 015°, 030°, 050°, 105°and 160°. According to Du Berger et al. (1991), the 015° and 030° lineament trends correspond to both NNE late Grenvillian ductile belts and to some of the post-Ordovician brittle faults which reactivated pre-existing fractures. The St. Lawrence rift reactivated the 030° trend and produced the 050° trend. South of the Saguenay Graben, the 160° trend is relatively minor but was strongly enhanced by glacial erosion (Prest et al., 1967). The 105° trend is prominent only within the Saguenay graben. It was suggested that the NNE-trending corridor along the Saint-Maurice River is the western boundary to the “Jacques Cartier” tectonic block, a horst between the Saguenay graben and the main graben of the St. Lawrence rift (Du Berger et al., 1991).

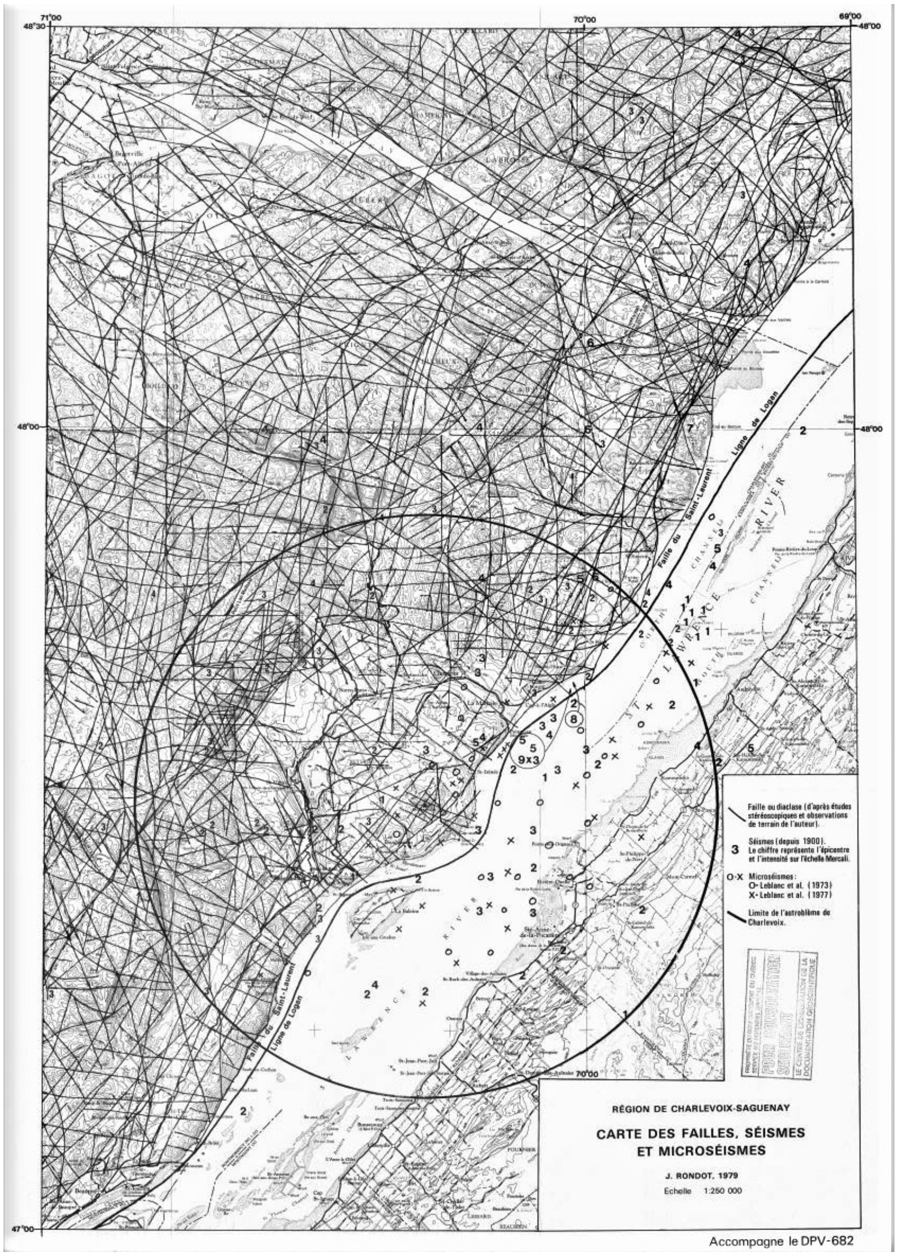

Figure 5. Map of linterpreted lineaments and some earthquake epicentres (Rondot, 1979).

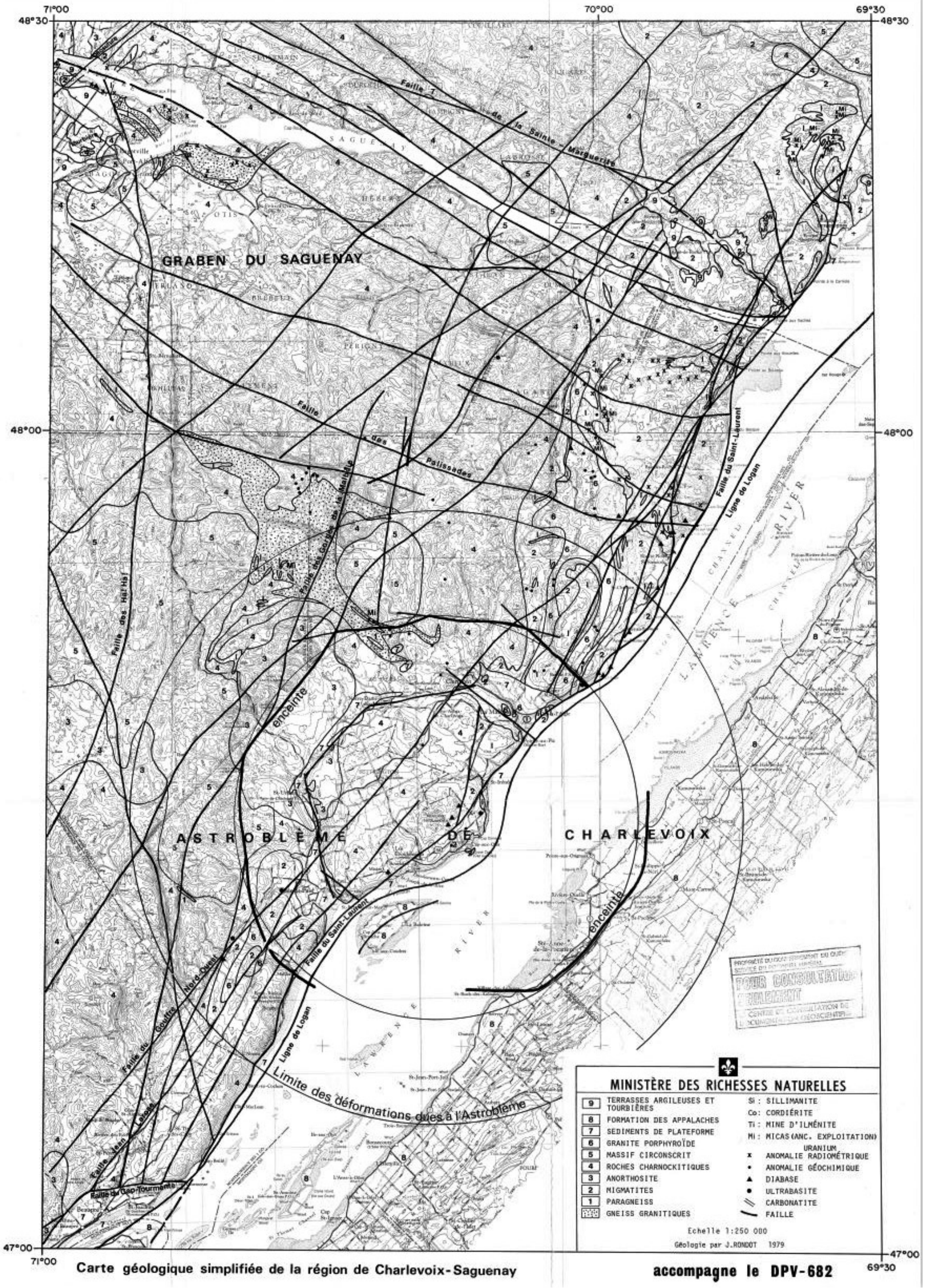

Figure 6. Simplified geological map of the Charlevoix-Saguenay region by Rondot (1979).

STRUCTURAL ANALYSIS - METHODOLOGY

The detailed structural analysis of the regional fracture pattern presented here is mainly based on visual / empirical recognition of topographic breaks interpreted as lineaments with lengths on the scale of a few kilometres along the St. Lawrence Rift Valley and the adjacent Saguenay Graben.

Most of the analysis was carried out by identifying conspicuous linear segments ("lineaments") revealed on a Digital Elevation Model (DEM), and digitizing them using ArcMap™ software, a Geographic Information System (GIS). The DEM mosaic used for the analysis was assembled using datasets from the Canadian Digital Elevation Data (CDED) made available at 1:50 000 scale by the Canada Centre for Mapping and Earth Observation (CCMEO) of Natural Resources Canada (NRCan). The resulting DEM mosaic was enhanced with shaded relief (i.e. hillshade) with various illumination directions in order to facilitate the visual recognition of lineaments of different trends.

The observed and digitized lineaments corresponded to breaks in the topography. For optimum results, our analysis used scales ranging from 1:50 000 to 1:250 000, which provided better control on the type of lineaments observed (either brittle or ductile). The estimated accuracy of the position of the digitized lineaments is essentially related to the precision of the CDED used to build the DEM, which is about 10 m at 90 percent confidence level (Beaulieu and Clavet, 2009). Naturally, the exact position of a fault at the surface can be higher than this uncertainty value. We estimate this uncertainty to be a few tens of metres. Once integrated in ArcMap, the resulting DEM mosaic has a resolution of approximately 15 x 15 metres.

At the first stage of the analysis, the lineaments were digitized without extrapolation beyond their length essentially highlighted by topographic breaks on the DEM mosaic. Only lineaments longer than 5 km were retained. The analysis was completely visual without the use of other datasets such as geological maps or geophysical surveys. For this reason, we consider the interpretation to be robust and reproducible by different analysts. The biggest challenges were first, to diagnose the nature of the mapped lineaments as brittle or ductile (see explanations below) and second, to determine the best data source to assess the lateral extent of a lineament. The shaded relief imagery with various illumination directions was found to be the best tool. Figure 7 exemplifies an area mainly characterized by brittle lineaments. It is clearly shown that a virtual illumination[1] from an azimuth of 045^0 better highlights the NW–SE ductile trend (Figure 7A and 7B) and that the 315° illumination reveals more clearly the dominant SW - NE brittle deformation (Figure 7C and 7D). Consequently, each area was examined with the DEM illuminated from various directions.

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[1] All virtual illuminations mentioned in the text have been realized with a constant elevation of 45^0

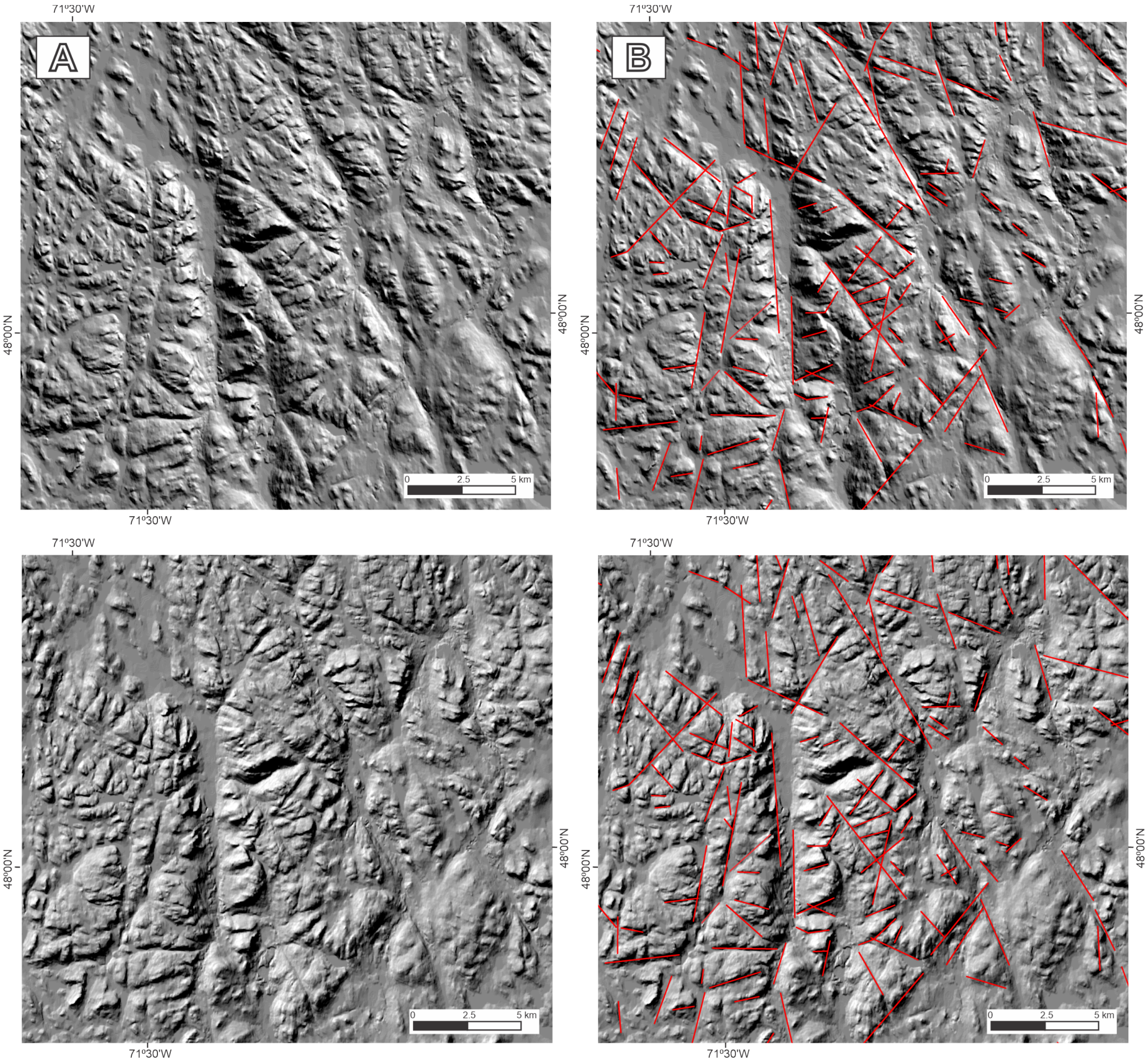


Figure 7. Relief shading with virtual illumination at 045^0 (A – B) and 315^0 (C - D).

Visual analysis of lineaments continued by zooming out to a scale of 1: 250 000. At this more regional scale, it was sometimes possible to connect lineaments through areas where the topographic expression was not as clear. These interpolated segments generally corresponded to areas with subdued topography without conspicuous linear trace. Figure 8 provides a good example of lineaments detected at the local level (red lines) followed by a second visual analysis centered on the interpolation between first-order lineaments (orange lines). In the same way, it was possible to extrapolate some first-order lineaments beyond their local visual signature (yellow lines in Figure 8B).

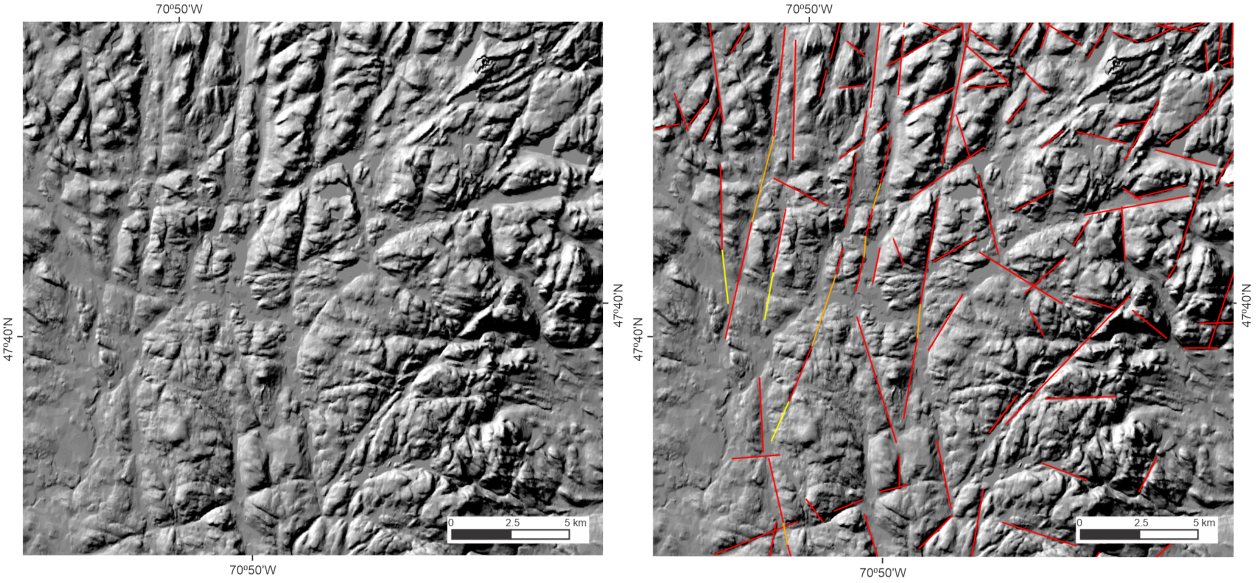


Figure 8. A – Relief shading with virtual illumination at 315^0; B – First-order recognition of brittle lineaments from the topographic breaks (red lines) followed by an interpolation analysis (orange lines) and extrapolation analysis (yellow lines).

Following the visual analysis, two validation tests were carried out using geological information available for the study area. For the first validation test, the resulting lineaments were compared with the vertical gradient of the total magnetic field. This process is designed to eliminate some lineaments that correlated with intrusive diabase dykes. In the study area, unlike in the Western Quebec Seismic Zone, the diabase dykes are not very extensive and are not clearly revealed on geophysical surveys. Therefore, no lineament was eliminated following this first validation test. In the second validation test, the lineaments were compared with the Québec provincial bedrock geological compilation (MERN, SIGEOM database, 2019) in order to eliminate ductile structural lineaments. These validation tests proved very useful in areas where the rheological contrast between adjacent lithological units is high and emphasized by the sub-vertical dip of layers. Examples shown in Figure 9 highlights the close overlap of observed lineaments with the ductile lithological trends. Figure 9B shows the lineaments as revealed during the first visual recognition step (red lines). The geological map in Figure 9C shows a clear correspondence between some geological contact and the topographic breaks interpreted as brittle lineament in the first phase of visual analysis. These coinciding lineaments were reinterpreted and reclassified in the "questionable" ductile / brittle domain. Overall, 178 lineaments initially recognized as brittle were reclassified. All changes resulting from the validation tests are documented in the database.

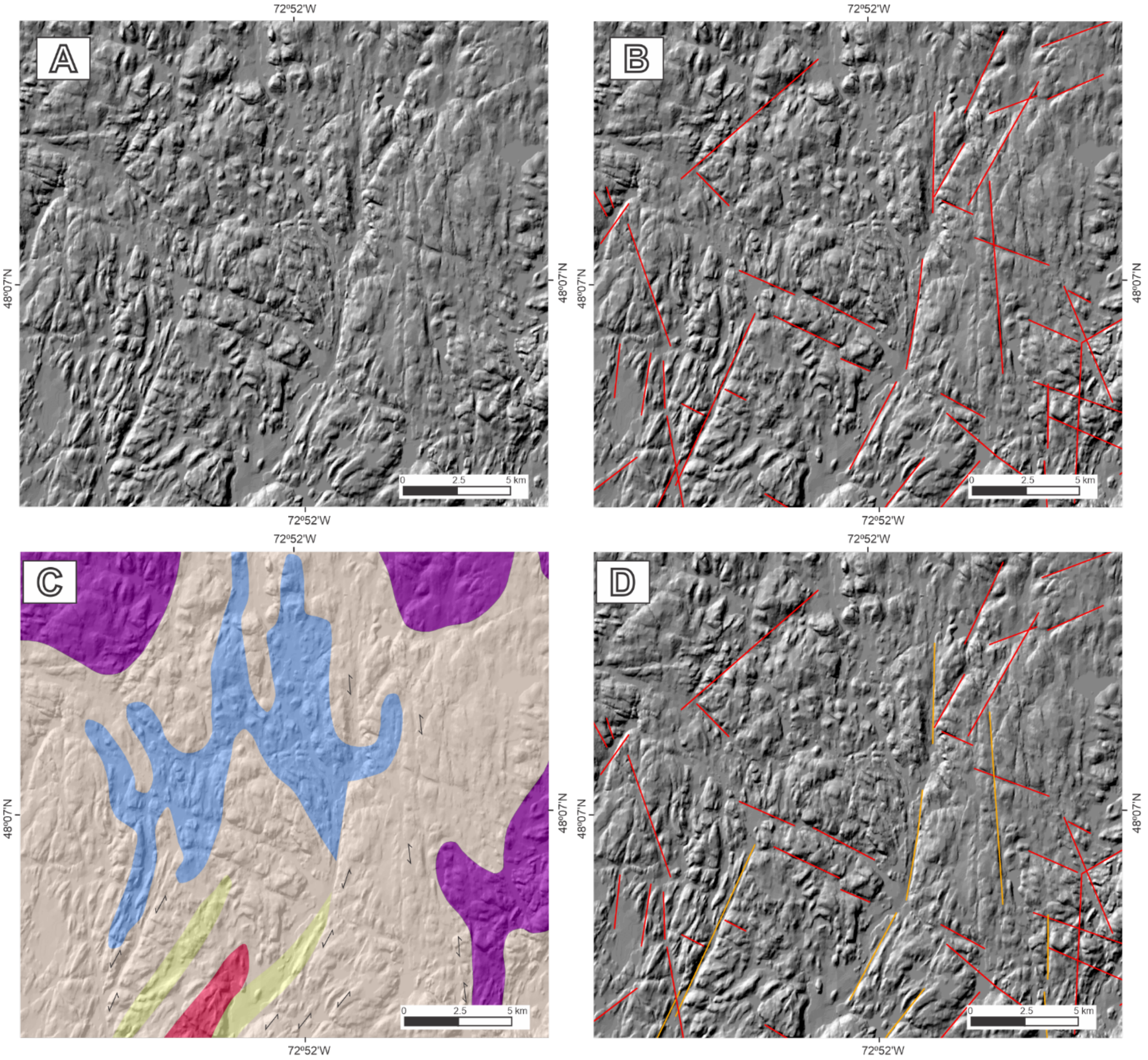


Figure 9. A - Relief shading with virtual illumination at 315^0; B – Initial visual recognition of the lineaments (red lines); C – Geological compilation map; D - Series of NNE lineaments reclassified in the ductile or in the "questionable" ductile / brittle domain (orange lines).

Although efforts were made to distinguish brittle lineaments from ductile deformation structures, it is possible that some brittle lineaments have been missed or misinterpreted if they coincided with pre-existing ductile structures or lithologies. Field mapping often reveals that brittle faulting can re-activate pre-existing planes of weakness. In the Grenville Province, rocks were formed or metamorphosed at mid to lower crustal depths and the planes of weakness can be ductile structures (such as shear zones) or lithological contacts. This is often seen in metasedimentary and metavolcanic environments. Much later, exhumation and erosion bring these metamorphic rocks to upper crustal levels where brittle deformation can occur due to lower temperatures. In this new rheological regime, brittle deformation could have occurred along these formerly ductile planes of weakness. The mouth of the Saguenay River and its northwestern extension is an area where numerous brittle lineaments (faults) have developed along Grenvillian zones of weakness such contacts of rock masses with different rheological properties or shear zones. This is especially the case for the very well-developed NNE and WNW lineament swarms at the junction of structures related to the St. Lawrence Rift and those attributed to the Saguenay Graben.

DATABASE CONTENT AND ARCMAP TABLE OF CONTENTS

The following sections provide a brief explanation of the geological datasets included in this Open File and accessible from the ArcMap™ MXD project. We provide some general information regarding the digital release as well as some font conventions used throughout this document.

COMPILATION AND MAP PROJECTION

The digital datasets have been compiled and formatted for use with ArcGIS™ desktop version 10.7 or higher. All datasets reside within two *File Geodatabases*, the Central_SeismicZone.gdb that contains the geological datasets and, the CartoElement.gdb containing the topographic base datasets and elements required for the cartographic representation and map surround information. All datasets are easily accessible from ArcMap™ *MXD's* project, the Figure_OF8826.mxd.

Data and map layers have been compiled and are displayed with the following projection parameters:

Projected Coordinate System: NAD_1983_UTM_Zone_18N (EPSG 26918)
Projection: Transverse Mercator
False Easting: 500000.0
False Northing: 0.0
Central Meridian: -75.0
Scale factor: 0.99960
Latitude of Origin: 0.0
Linear Unit: Metre

For users who do not have access to ArcGIS software or any other GIS software, Figure 10 provides a typical ArcMAP *Layout View* of the lineaments and faults compiled for this study. The figure is also available in a full scale paper map (scale 1:500,000) within the dataset provided with this publication (Figure_OF8826.pdf).

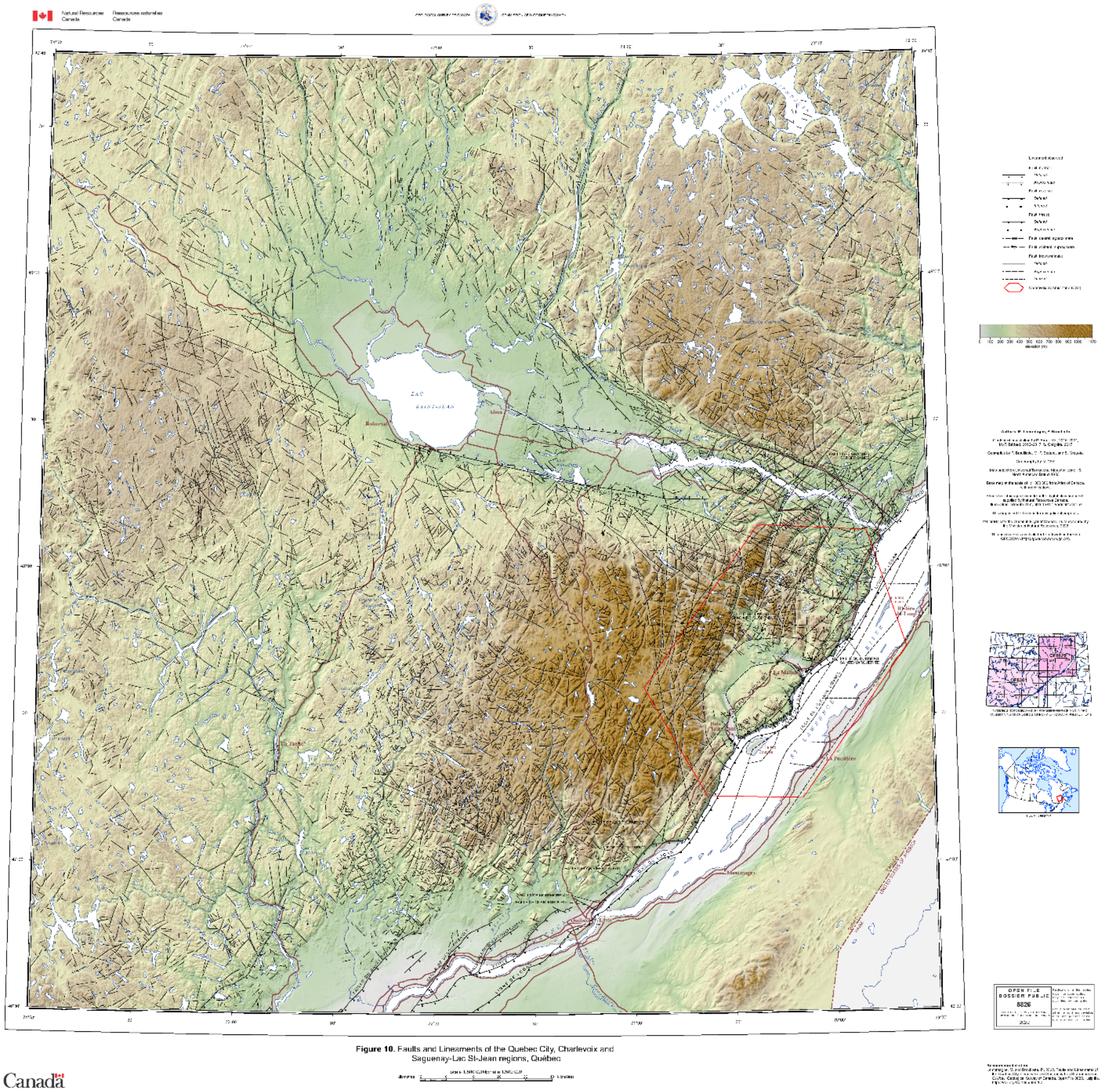


Figure 10. Layout view of the brittle lineaments and mapped faults of the Central Quebec Seismic Zone map.

CONVENTIONS

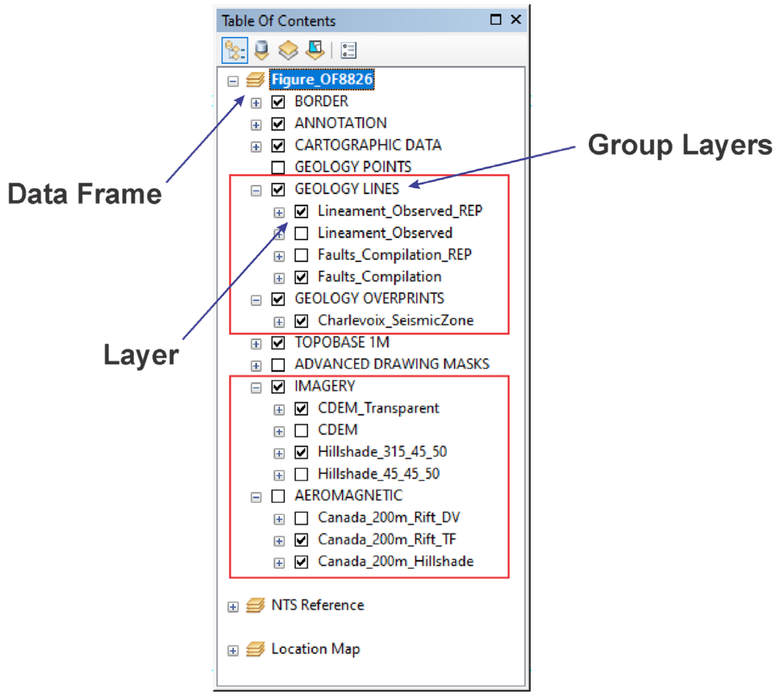
To highlight the various database components, as well as terms specific to the ArcGIS platform, the following font conventions were adopted throughout this document:

- the terms specific to the ArcCatalog^{TM} and ArcMap^{TM} software are shown in italics (e.g. *File Geodatabase, Feature Class, Layer*)

- the name of a *Group Layer* is shown in upper case, bold (e.g. **GEOLOGY LINES**)
- the name of a *Feature Class* or *Layer* is shown in upper case/lower case, bold/italics (e.g. ***Lineaments_Observed***)
- the name of an attribute is shown in upper case, bold/italics (e.g. ***FAULT_NAME***, ***SRC_REF1***)

TABLE OF CONTENTS

The ArcMap^{TM} *Table of Contents* (TOC) consists of three *Data Frames*, each containing datasets used to display the geological information as well as the topographic base and the map-surrounding information. In the following sections, emphasis will be placed on the ***Figure_OF8826*** *Data Frame* and more specifically, on the descriptions of geological datasets, as shown on Figure 11. The reader is invited to read the document MXD_readme.rtf for details regarding the non-geological *Data Frames* and *Group Layers*.



- Figure_OF8826
  - ☑ BORDER
  - ☑ ANNOTATION
  - ☑ CARTOGRAPHIC DATA
  - ☐ GEOLOGY POINTS
  - ☑ GEOLOGY LINES
    - ☑ Lineament_Observed_REP
    - ☐ Lineament_Observed
    - ☐ Faults_Compilation_REP
    - ☑ Faults_Compilation
  - ☑ GEOLOGY OVERPRINTS
    - ☑ Charlevoix_SeismicZone
  - ☑ TOPOBASE 1M
  - ☐ ADVANCED DRAWING MASKS
  - ☑ IMAGERY
    - ☑ CDEM_Transparent
    - ☐ CDEM
    - ☑ Hillshade_315_45_50
    - ☐ Hillshade_45_45_50
  - ☐ AEROMAGNETIC
    - ☐ Canada_200m_Rift_DV
    - ☑ Canada_200m_Rift_TF
    - ☑ Canada_200m_Hillshade
- NTS Reference
- Location Map

Figure 11. ArcMAP Table of Contents highlighting the various Layers described in the following sections.

GEOLOGY LINES

The *Group Layer* named **GEOLOGY LINES**, contains all the linear geological information compiled for this study. The *Layer* ***Lineament_Observed*** holds the result of the fracture pattern analysis while ***Fault_Compilation*** contains a selected set of faults mainly from published datasets of the Quebec survey. The ***Lineaments_Observed_REP*** *Layer* is only used to optimize the display of the lineaments on the paper map (i.e. cartographic representation).

The ***Lineament_Observed*** *Feature Class* contains the attributes required to support the analytical methodology used for the recognition of each lineament as well as attributes that controlled their display in ArcMAP™. The attributes ***LINEAM_POS, LINEAM_IDENT_METHOD*** and ***LINEAM_VALID*** (Table 1: Field description of the Feature Class Lineament Observed) provides information on the recognition and validation methods, while ***DISPLAYED*** and ***GSC_SYM_CODE*** control the display parameters.

Table 1: Field description of the Feature Class Lineament Observed

Field	**AliasName**	**Description**
LINEAM_POS	Lineament Position	Confidence in the position of the lineaments (e.g. Defined, Approximate)
LINEAM_IDENT_METHOD	Lineament Identification Method	Visual identification method of lineaments (e.g. Observed on DEM; on-screen analysis, Observed on satellite imagery, Interpolated between observed lineaments; on-screen analysis, etc.)
LINEAM_VALID	Lineament Validation	Short explanation justifying the reclassification of some lineaments following their validation against various geological features (e.g. Reinterpreted as a ductile structural feature following validation against various geological datasets, etc.)
GSC_SYM_CODE	GSC Symbol Code	GSC standard style codification
DISPLAYED	Displayed	Coding used to control the display in ArcMap™ (1 = displayed, 0 = not displayed)

In the current configuration, not all lineaments are visible in the ArcMap™ environment (and PDF paper map). Lineaments identified too close to selected faults or those reinterpreted as “ductile” following validation against various geological datasets, were made not visible. All lineaments have been assigned a value in the ***DISPLAYED*** field (1 = displayed, 0 = not displayed) and their visibility is controlled by the following *Definition Query* activated in the *Layer Properties*: SELECT * FROM Lineament_Observed WHERE Displayed = “1”.

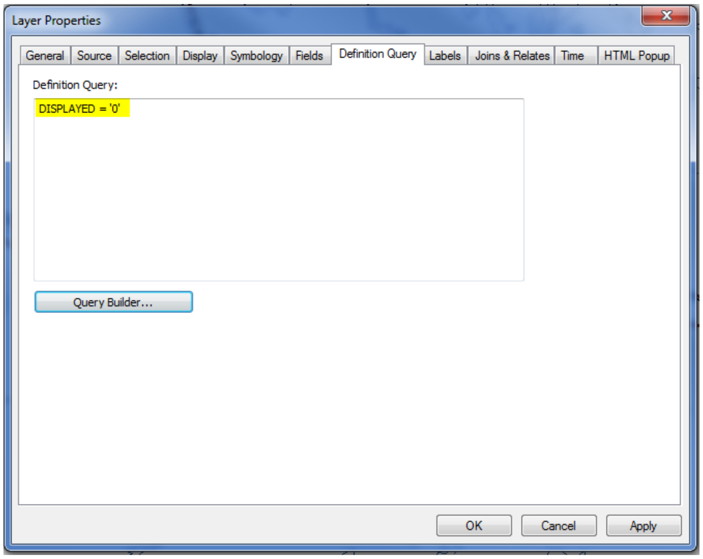
Some lineaments have their ***LINEAM_VALID*** attribute set to "Brittle / ductile" because they cannot be clearly and uniquely identified within as brittle structures. However, it was decided to make these lineaments visible and a value = “1” has been assigned to the attribute ***DISPLAYED***.

The ***Fault_Compilation*** *Feature Class* contains a selected set of faults from published databases of the Ministère de l’Énergie et des Ressources Naturelles (MERN), and the Geological Survey of Canada (GSC). Some faults along the St. Lawrence River were interpreted by Konstantinovskaya et al. (2014). As for the lineaments, a special effort was made to select only the faults developed in a brittle deformation regime. Some of the criteria that guided our selection include the age at which the fault was active or re-activated, the age of the lithology displaced by the fault and also their close spatial association and orientation with known regional brittle faults, such as the Saint-Laurent fault. In all cases, the name of the faults were kept in the database and shown on the map.

Table 2: Field description of the Feature Class Fault_Compilation

Field	AliasName	Description
FAULT_POS	Fault Position	Confidence in the position of the fault (e.g. Defined, Approximate)
FAULT_MOV	Fault Movement	Type of motion observed or interpreted along a fault trace (e.g. Normal, Reverse, Dextral, etc.)
FAULT_NAME	Fault Name	Name of the fault (e.g. Faille du Saint-Laurent, etc.)
SRC_REF1	Source Reference1	First level source associated with each fault
SRC_REF2	Source Reference2	This field is used to indicate a second source, generally characterized by the reference in which the fault was first introduced
GSC_SYM_CODE	GSC Symbol Code	GSC standard style codification
DISPLAYED	Displayed	Coding used to control the display in ArcMap™ (1 = displayed, 0 = not displayed)

The selected set of faults shown on the map have their ***DISPLAYED*** field value set to "1". For users who would like to see all faults compiled and made available in the database, they must edit the definition query of the *Layer Properties* as shown in Figure 12.



Definition Query:
DISPLAYED = '0'

Figure 12. Editable definition query of the Layer Properties.

The field ***FAULT_POS*** provides, when available, information about the confidence in the position of the fault. This information is critical where many regional faults shown on the map are not visible at surface and are not present on traditional geological maps. For these faults, as for the majority of the faults shown on the map and/or stored in the database, the fields ***SRC_REF1*** and ***SRC_REF2*** contain source information. A complete bibliographic reference is made available as an Excel file within this Open File package (Sources_Reference.xlsx)

Note that when the observed lineaments (***Observed Lineaments***) are superimposed on the faults (***Fault_Compilation***), it is possible to find inconsistencies in the location of certain faults. Errors in fault location may have arisen from inaccuracy caused by the compilation scale (e.g. compilation at 1:1 000 000 versus 250 000) and from the distortion inherent to the scanning and georeferencing of the original paper maps.

GEOLOGY OVERPRINTS

This *Group Layer* contains a single *layer* ***Charlevoix_SeismicZone*** that represents the boundaries of the Charlevoix Seismic Zone. Boundaries of the CSZ is shown on the provided full-scale paper map (Figure_OF8826.pdf).

IMAGERY

IMAGERY *Group Layer* contains the original Canadian Digital Elevation Model and the derived hillshades use for the visual recognition of the lineaments. This dataset is extracted and downloaded from the Canadian Digital Elevation Model of the Open Canada website (https://open.canada.ca/data/en/dataset/7f245e4d-76c2-4caa-951a-45d1d2051333).

In layer ***CDEM***, The Canadian Digital Elevation Model is displayed with its original black to white color ramp while a transparent customized color ramp characterize the layer ***CDEM_Transparent***. The two hillshade layers respectively show an enhanced relief shading of the CDEM with the following illumination parameters: 1) direction 315°, elevation 45° and vertical exaggeration 5 (***Hillshade_315_45_5***) and, 2) direction 045°, elevation 45° and vertical exaggeration 5 (***Hillshade_045_45_5***).

MAGMATIC FIELD

As supplementary information, a magnetic field dataset has been added and made available in the aeromagnetic *Group Layer* of ArcMap™ *Table Of Contents*. These datasets are extracted from the Geoscience Data Repository for Geophysical Data (http://gdr.agg.nrcan.gc.ca/gdrdap/dap/search-eng.php) of the Geological Survey of Canada. They include the following 200 metres resolution grids: 1) total residual field (***Canada_200m_Rift_TF***), 2) first vertical derivative of the total residual field (***Canada_200m_Rift_DV***) and, 3) digital elevation model (i.e. hillshade) of the first vertical derivative (***Canada_200m_Rift_HillShade***). The layers are ordered to facilitate and to optimize superimposed dataset viewing. In addition, a 40% transparency has been applied to the total field and first derivative grid layers in order to make visible the underlying hillshade layer that adds the relief effect to the overlying layers. Although it is recognized that the data is far from ideal (the data shows the tracks of numerous acquisition lines), we did not attempt to improve the magnetic field.

PRELIMINARY INTERPRETATION AND CONCLUSIONS

The resulting map of lineaments is the first geological map that integrates field-mapped faults and clear interpreted lineaments for the study area. The map clearly shows the major NE-SW trend of regional faults associated with the St. Lawrence paleorift and the E-W trending structures of the Saguenay Graben. The level of brittle deformation is not uniform across the region. This could be due partly to the level of tectonic deformation and to the local geological materials that may make lineaments more conspicuous.

The faults of the SLRS are assumed to be steeply-dipping normal faults. The extension and attitude of these faults at depth are undefined, but it is generally assumed that these faults are deep seated. It is likely that these faults, and the associated ones, could be reactivated by the earthquakes that occur within the SLRS.

As an initial assessment, the seismic activity does not appear to be related to the density of brittle structures. The areas near Quebec City or north of the Charlevoix structure, show a very high density of brittle lineaments but they are weakly seismic. The zone with the most active seismic activity is the CSZ, but most of it is beneath the St. Lawrence river where the brittle structures cannot be studied in detail. Future work will examine the possible relationship between these lineaments and the earthquake activity.

The next phase of this lineaments and faults mapping project is to apply a similar methodology to the remaining sections of the St. Lawrence Rift System downstream of Les Escoumins.

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APPENDICES

APPENDIX 1

List of significant earthquakes that are known to have occurred between 1608 and 2017 in the map area (Lamontagne et al., 2018).

Year	Area	Preferred Magnitude	Magnitude Type[2]	Description
1663	Charlevoix-Kamouraska	7.0	M_L	Epicentre most likely in the Charlevoix-Kamouraska Seismic Zone, Quebec; Felt in most of New France (Quebec City, Trois-Rivières, Montréal) and parts of New England (Boston) and New Amsterdam (New York City). Some damage to masonry in Quebec City, Trois-Rivières and Montréal. Landslides reported in the Charlevoix region, and along the St. Lawrence, Shipshaw, Betsiamites, Pentecôte, Batiscan and Saint-Maurice rivers. Numerous aftershocks felt in Quebec City during the following months.
1791	Charlevoix-Kamouraska	5.5	M_W	Felt strongly in Charlevoix, Quebec, and in Quebec City. Damage to houses and churches in Baie-Saint-Paul, Les Éboulements and on Île aux Coudres.
1831	Charlevoix-Kamouraska	5.0	M_L	At La Malbaie, Quebec, damage to walls (wide crack), chimneys thrown down or displaced. Also felt in Quebec City.
1842	Trois-Rivières	5.0	M_L	In Trois-Rivières, Quebec, bricks fell from chimneys, fallen objects, broken windows.
1860	Charlevoix-Kamouraska	6.1	M_W	Widely felt in Quebec and felt as far as New Brunswick, eastern Ontario and New England. Damage in the epicentral region on both shores of the St. Lawrence River: North Shore: Baie-Saint-Paul; La Malbaie; South Shore: Rivière-Ouelle. Also felt strongly in Quebec City.
1870	Charlevoix-Kamouraska	6.6	M_W	Felt over most of the Province of Quebec, in Ontario, New Brunswick, and in New England. Considerable damage to houses in Charlevoix, especially in Baie-Saint-Paul, Les Éboulements and along the South Shore of the St. Lawrence River. Damage to chimneys reported in lower town in Quebec City. Possible rock slide along the Saguenay River.
1872	Quebec City	5.0	M_L	Quebec City Region; Vibrations cracked a wall in the lower town and made objects fall.

- [2] Magnitude type:
- M_L - Local, or Richter magnitude.
- $m_b(Lg)$ - Lg body wave magnitude. Used for earthquakes in eastern Canada.
- M_w or **M** - Moment magnitude.

1924	Charlevoix-Kamouraska	5.2	M_w	Felt over most of the St.Lawrence Valley from Ottawa, Ontario, eastward through Quebec, New Brunswick and northern Maine.
1925	Charlevoix-Kamouraska	6.2	M_w	Charlevoix-Kamouraska Seismic Zone, Quebec, near Île aux Lièvres. The earthquake was felt over most of eastern Canada and northeastern U.S. It caused damage to unreinforced masonry (chimneys, walls) in the epicentral region on both shores of the St. Lawrence, and in Quebec City, (including damage to port facilities), Trois-Rivières, Shawinigan and chiney damage in northern NB causing house to burn down in Grand Falls. Possible liquefaction near Saint-Urbain, Quebec. Numerous felt aftershocks followed.
1931	Charlevoix-Kamouraska	4.9	M_w	Felt in Charlevoix, Quebec City, Montreal and Ottawa. Minor damage (fallen objects) reported.
1939	Charlevoix-Kamouraska	5.6	mb(Lg)	Chimneys damaged in Rivière-Ouelle, Rivière-du-Loup, Saint-Urbain and La Malbaie, Quebec. There, some brick walls were cracked. In Rivière-du-Loup, the plaster from the ceiling of church fell and many store windows were broken. Small ground fissures reported in Tadoussac. Felt over most of eastern Canada.
1952	Charlevoix-Kamouraska	4.5	M_w	Dishes were jarred and some store windows broken in Rivière-du-Loup, Quebec. Felt in most of the St. Lawrence Valley, northern Maine and northern New Brunswick Rockfall reported at Cap-aux-Corbeaux, near Baie-St-Paul. Powerblack out in Baie-St-Paul.
1979	Charlevoix-Kamouraska	4.8	M_w	Felt in Charlevoix, Kamouraska, and Saguenay regions. Damaged three chimneys.
1988	Saguenay Region	5.9	M_w	Laurentides Fauna Reserve, south of Saguenay (Chicoutimi), Quebec. Preceded by a foreshock 2½ days before. Damage caused to unreinforced masonry at Jonquière, Chicoutimi, La Baie, Charlevoix region, Montmagny, Quebec City, Sorel and Montreal-East. Liquefaction of soft soils in the Ferland-et-Boilleau area. Eleven cases of soil movements reported. Only one felt aftershock.
1997	Quebec City	4.9	M_w	Quebec City Region, near the Cap-Rouge suburb. Felt in Quebec City, Charlevoix, and Saguenay regions. Also reported felt in Ottawa Valley, Montreal, Maine, and Northern New York State. Minor damage reported in a school of the Quebec City region. One indirect death reported by a local newspaper.
2005	Charlevoix-Kamouraska	4.7	M_w	Near Rivière-du-Loup. No damage but felt strongly in the regions of Charlevoix, Saguenay and Quebec City. Felt as far as the Ottawa valley, Montreal, Fredericton, New Brunswick, and Boston, Mass.

APPENDIX 2

List of publications referred to in the database Central_SeismicZone.gdb. This appendix is made available as an Excel file within this Open File package (Source_References.xlsx). In addition to the information presented in the following table, the Excel file also provides an active web link to the source / reference download site.

Source / Reference	Author(s)	Year	Title
BG 2018-01	Moukhsil, A., Cote, G.	2018	Géologie de la région du lac Borgia, Province de Grenville, nord de La Tuque, régions de la Mauricie et du Saguenay-Lac-St-Jean, Québec, Canada.
BG 2019-01	Moukhsil, A., Daoudene, Y.	2019	Géologie de la région du lac des Commissaires, Province de Grenville, région du Saguenay-Lac-Saint-Jean, Québec, Canada.
BG 2020-01	Moukhsil, A., El Bourki, M.	2020	Géologie de la région de Normandin, Province de Grenville, région du Saguenay-Lac-Saint-Jean, Québec, Canada.
CG-21K13-2012-01	De Souza, S., Tremblay, A.	2011	Compilation géologique - Saint-Pamphile.
CG-21L09-2012-01	De Souza, S., Tremblay, A	2012	Compilation géologique - Saint-Magloire.
CG-21L10-2012-01	De Souza, S., Tremblay, A	2012	Compilation géologique - Saint-Malachie.
CG-21L11-2012-01	De Souza, S., Tremblay, A	2012	Compilation géologique - Charny.
CG-21L14-2012-01	Nadeau, J., Brun, J., De Souza, S., Tremblay, A.	2012	Compilation géologique - Québec.
CG-21L15-2012-01	De Souza, S., Tremblay, A	2012	Compilation géologique - Saint-Raphaël.
CG-21L16-2012-01	De Souza, S., Tremblay, A	2012	Compilation géologique - Notre-Dame-du-Rosaire.
CG-21M01-2012-01	De Souza, S., Tremblay, A	2012	Compilation géologique - Saint-Jean-Port-Joli.
CG-21M02-2012-01	Hebert, C., Bilodeau, C., De Souza, S., Tremblay, A	2012	Compilation géologique - Saint-Joachim.
CG-21M08-2012-01	Lacoste, P., Hebert, C., Bilodeau, C., De Souza, S., Tremblay, A	2012	Compilation géologique - Île-aux-Coudres
CG-21N04-2012-01	De Souza, S., Tremblay, A	2012	Compilation géologique - Sainte-Perpétue-de-l'Islet.
CG-21N05-2012-01	De Souza, S., Tremblay, A	2012	Compilation géologique - Saint-Pacome.
CG-32B01-2014-01	Moukhsil, A., Solgadi, F., Elbasbas, A	2014	Geologie - lac Decelles.
DP 177	Grattan-bellew, P E., Schryver, K.	1965	Interim report on Houde - Masson area, Berthier and Maskinongé counties.
DP 462	Berrange, J P.	1960	Antoine - La Trappe area (comte de Roberval)
DP-83-16	Rondot, J	1983	Carte géologique - Bas Saguenay (synthèse).
DPV 440	Rondot, J	1963	Rapport géologique sur la région de la Rivière aux Rats (comté de Roberval)
DPV 513	Vallieres, A	1977	Géologie de la région de Cacouna à Saint-André-de-Kamouraska (comtés de Rivière-du-Loup et de Kamouraska)
DPV 594	Rondot, J	1978	Région du Saint-Maurice
DPV 682	Rondot, J	1979	Reconnaissances géologiques dans Charlevoix-Saguenay.

Du Berger et al., 1991	Du Berger, R., Roy, D.W., Lamontagne, M., Woussen, G., North, R.G., and Wetmiller, R.J.	1991	The Saguenay (Québec) earthquake of November 25, 1988: Seismological data and geological setting: Tectonophysics, v. 186, p. 59-74.
DV 91-25	M E R N	1991	Rapport d'activité 1991 - direction de la recherche géologique
DV 92-06	Gervais, R	1993	Géologie de la région du Lac aux Grandes Pointes
ET 85-05	Rondot, J	1986	Géologie de la région de Forestville-Les Escoumins.
ET 95-01	Hebert, C., Nadeau, L.	1995	Géologie de la région de Talbot (Portneuf)
GSC OF 3778	Lamontagne, M.	1999	Rheological and geological constraint on the earthquake distribution in the Charlevoix Seismic Zone, Québec, Canada
Lemieux, Y., 2001	Lemieux, Y.	2001	Lemieux, Y., 2001. Analyse structurale des failles supracrustales de la région de Charlevoix, Québec: la relation avec l'impact météoritique. Mémoire de maîtrise, Université du Québec (INRS-Géoressources), 1 carte.
MB 2009-02	Nadeau, L., Brouillette, P., Hebert, C	2009	Carte géologique de compilation / Geological compilation map, Région de Portneuf - Saint-Maurice / Portneuf - St. Maurice region, Province de Grenville / Grenville province, Québec/ Quebec. Commission Géologique du Canada, MRNF, LCNP
MB 2012-06	De Souza, S., Tremblay, A	2012	Compilation géologique des Appalaches et des Basses-Terres du Saint-Laurent, régions administratives de Chaudière-Appalaches, Capitale Nationale et Bas-Saint-Laurent. Université du Québec à Montréal
MB 2015-07	Morfin, S., Tremblay, C., Solgadi, F., Moukhsil, A., Daigneault, R.	2015	Géologie de la région de Chambord, Roberval et Notre-Dame-de-la-Doré (feuillets SNRC 32A08, A09 et A10) et reconnaissance des feuillets 32A06, A07 et A11). MERN, CERM
MB 2015-11	Tremblay, A., De Souza, S., Perrot, M., Theriault, R	2015	Géologie des Appalaches du Québec - feuillet sud-ouest, régions de Montérégie, Cantons-de-l'Est, Centre-du-Québec et Chaudière-Appalaches. MERN, UQAM
MB 2016-07	Groulier, P A., Indares, A., Dunning, G., Moukhsil, A	2016	Géologie de la ceinture volcano-sédimentaire des Escoumins, Côte-Nord, Québec. MERN, Université Memorial de Terre-Neuve et Labrador
MB 89-21	Rondot, J	1989	Géologie de Charlevoix
MB 95-30	Laurin, A F	1995	Géologie de la région des cours supérieurs des Rivières Trenche, Windigo et Wabano, comtés de Laviolette et de Roberval
MB 96-25	Genest, S	1996	Géologie de la Rivière Portneuf-Est
MERN, SIGEOM database	Ministère de l'Énergie et des Ressources naturelles, Québec	2017	Base de données SIGEOM, Ministère de l'Énergie et des Ressources naturelles; © Gouvernement du Québec
MM 89-03	Daigneault, R., Allard, G O	1990	Le complexe du Lac Doré et son environnement géologique - région de Chibougamau - Sous-Province de l'Abitibi. IREM-MERI

RG 078	Jooste, R F.	1958	Région de Bourget, Districts Électoraux de Chicoutimi et de Jonquière-Kénogami
RG 127	Philpotts, A R	1967	Région de Belleau - Desaulniers, comtés de Saint-Maurice, Maskinongé et Laviolette.
RG 140	Benoit, F W., Valiquette, G	1971	Région du lac Saint-Jean (partie sud)
RG 148	Clark, T H., Globensky, Y	1973	Région de Portneuf et parties de St-Raymond et de Lyster, comtés de Portneuf et de Lotbinière
RG 154	Clark, T H., Globensky, Y	1975	Région de Grondines
RG 161	Laurin, A F., Sharma, K N M	1975	Région des Rivières Mistassini, Péribonca, Saguenay, (Grenville 1965-1967)
RG 183	Kehlenbeck, M M	1977	Région du lac Rouvray
RG 2009-01	Hebert, C., Van Breemen, O., Cadieux, A M	2009	Région du Réservoir Pipmuacan, (SNRC 22E): Synthèse géologique. MNRF, Commission Géologique du Canada
RG 2009-03	Moukhsil, A., Lacoste, P., Gobeil, A., David, J	2009	Synthèse géologique de la région de Baie-Comeau (SNRC 22F). MRNF, GEOTOP UQAM-MCGILL
RG 2015-04	Moukhsil, A., Solgadi, F., Belkacim, S., Augland, L E., David, J	2015	Géologie de la région de Parent, Haut-Saint-Maurice (partie ouest du Grenville). MERN, UQUAT-URSTM, GEOTOP-UQAM-MCGILL
RG 97-03	Hebert, C., Lacoste, P	1998	Géologie de la région de Poulin-de-Courval
RP 2005-04	Bandyayera, D., Caderon, S., Houle, P., Sharma, K N M	2005	Géologie de la région du lac Mitshisso (SNRC 32H/13)
RP 426	Benoit, F W.	1960	Rapport préliminaire sur la région de Chomedey - Paquet, District Électoral de Roberval
RP 488	Anderson, A T	1962	Rapport préliminaire sur la région du Lac Catherine, comté de Chicoutimi.
RP 494	Hubert, C	1963	Rapport préliminaire sur la région de Rivière-Ouelle - Ixworth, comtés de Kamouraska et de l'Islet
RP 504	Anderson, A T	1963	Géologie de la région du Lac Riverin, comté de Chicoutimi
RP 531	Schryver, K	1966	Géologie de la région de Houde - Masson, comtés de Maskinongé et Berthier
Tectonophysics, Vol. 637, pp.268-288	E. Konstantinovskaya, M. Malo, F. Badina	2014	Effects of irregular basement structure on the geometry and emplacement of frontal thrusts and duplexes in the Quebec Appalachians: Interpretations from well and seismic reflection data
TH 0138	Hocq, M	1978	Contribution à la connaissance pétrotectonique et minéralogique des massifs anorthositique et mangéritiques de la région du Réservoir Pipmuacan
TH 0356	Lunde, M	1953	The precambrian and pleistocene geology of the Grondines map-area, Quebec