Natural Resources Canada | Ressources naturelles Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8361

# Faults and lineaments of the Western Quebec Seismic Zone, Quebec and Ontario

M. Lamontagne, P. Brouillette, S. Grégoire, M.P. Bédard, and W. Bleeker

2020

Canada

**GEOLOGICAL SURVEY OF CANADA**
**OPEN FILE 8361**

# Faults and lineaments of the Western Quebec Seismic Zone, Quebec and Ontario

**M. Lamontagne[1], P. Brouillette[2], S. Grégoire[3], M.P. Bédard[4], and W. Bleeker[1]**

[1]Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario K1A 0E8
[2]Geological Survey of Canada, Retired
[3]Département de géologie et de génie géologique, Université Laval, 1065, avenue de la Médecine, Québec, Québec G1V 0A6
[4]Geological Survey of Canada, 490, rue de la Couronne, Québec, Québec G1K 9A9

## 2020



Permanent link: https://doi.org/10.4095/321900

This publication is available for free download through GEOSCAN (https://geoscan.nrcan.gc.ca/).

**Recommended citation**
Lamontagne, M., Brouillette, P., Grégoire, S., Bédard, M.P., and Bleeker, W., 2020. Faults and lineaments of the Western Quebec Seismic Zone, Quebec and Ontario; Geological Survey of Canada, Open File 8361, 1.zip file. https://doi.org/10.4095/321900

Publications in this series have not been edited; they are released as submitted by the author

## TABLE OF CONTENTS

## LIST OF FIGURES

## CONTACT INFORMATION

For additional information on this GIS-ready, Digital Database release, please contact:

Maurice Lamontagne

Geological Survey of Canada (Ottawa)

601 Booth Street

Ottawa, ON, K1A 0E8

Phone: (613) 220-6139

Email: maurice.lamontagne@canada.ca

## ACKNOWLEDGEMENTS

The authors thank Catherine Béland-Otis and Manuel Duguet, both from the Ontario Geological Survey (OGS) for sharing their data and knowledge with us. We also thank our GSC colleagues Eric De Kemp, Greg Brooks and Kenneth Buchan, Emeritus Scientist, for their constructive reviews of a draft of this report. We also thank our Activity Leader Heather Crow and Project Leader John Cassidy for their support. The research presented here is part of the Public Safety Geoscience Program of the Geological Survey of Canada.

## ABSTRACT

This Open File contains the interpreted brittle lineaments and a compilation of mapped faults of an area bound by latitudes 44°N and 48°N and longitudes 73°W and 80°W. The area includes most of the Ottawa River watershed. It also covers most of eastern Ontario and the Laurentians, between Montréal (QC) and North Bay (ON). The study area includes the seismically active region known as the Western Quebec Seismic Zone (WQSZ). The WQSZ is an area where earthquakes as large as magnitude 6.2 have occurred in the past and where tens of smaller earthquakes are recorded yearly. Our study is an attempt to provide a homogeneous coverage of these brittle structures through an integration of visually interpreted lineaments and mapped faults. The possible relationships between these brittle faults and earthquakes will be examined later.

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). Since the final goal was to better map the brittle faults that could be reactivated in earthquakes, the clear ductile structures were not considered in this study and the more questionable ones re-evaluated subsequently against known geological information. Most of the region of interest is southeast of the Grenville Front, where all ductile structures are related to the Grenville orogeny (about 1 billion years ago). The recognition of brittle structures is based on the observation that they are essentially linear in plan view. On the other hand, the ductile structures are generally curved, enhance contact between different Grenvillian lithologies, or present a distinct structural pattern. With a few exceptions, only lineaments with a length greater than 5 km were included. 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. The interpreted lineaments were then compared with the provincial geological maps of Quebec and Ontario, which often did not distinguish between brittle faults and ductile shear zones. Lineaments that coincided with diabase dykes were recognized by consulting geological maps and by examining the total magnetic field. Our final product is a 1:750,000 scale map that can be used in the future to better understand the seismotectonics of this region.

## INTRODUCTION

The St. Lawrence Rift System (SLRS), which includes the Ottawa-Bonnechere and Saguenay grabens, is located well inside the North American plate. Most historic damaging earthquakes and the some 350 smaller events recorded yearly occur in three main seismically active zones, namely the Charlevoix Seismic Zone (CSZ), Western Quebec (WQSZ), and Lower St. Lawrence (LSLSZ). Outside these areas, most of the Canadian Shield and bordering regions have a very low level of earthquake activity.

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. Applying the second aspect faces a major difficulty: not all regional SRLS faults appear in geological maps. For the same reason, it is often difficult to correlate any new sizeable earthquake with a fault. For these two reasons, 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, including when new sizeable earthquakes occur within the SLRS.

With the final goal of mapping all faults of the SLRS, the authors first focused their attention on the WQSZ. This Open File contains the interpreted brittle lineaments and mapped faults of an area bound by latitudes 44°N and 48°N and longitudes 73°W and 80°W. The area includes most of the Ottawa River watershed. It also covers most of eastern Ontario and the Laurentians, between Montréal (QC) and North Bay (ON).

Since most eastern Canadian earthquakes occur at depth in the Precambrian Shield rocks, only the lineaments and faults affecting these rocks were considered. Lineaments were interpreted mostly from the Digital Elevation Model (DEM) of the Canadian National Topographic Data Base (NTDB) at a scale of 1:250 000. The project also includes information from the existing structural geology maps along the SLRS, most notably along the Ottawa-Bonnechere Graben on the Ontario side. Locally, along the St. Lawrence and Ottawa rivers, the faults in the Precambrian basement may also cut across the overlying Ordovician sedimentary rocks of the St. Lawrence platform. For this reason, these faults are also included. To the east of the Logan's Line, in the Appalachians, faults were not included in our analysis since they do not extend into the Precambrian basement, as revealed by seismic reflection profiles east of Trois-Rivières (Castonguay et al., 2010).

## THE WESTERN QUEBEC SEISMIC ZONE (WQSZ).

This Open File presents lineaments and brittle faults for the WQSZ and surrounding regions. The WQSZ (Figure 1) includes the Ottawa Valley from Montréal to Témiscaming, as well as parts of the Laurentian Mountains (Basham et al., 1982; Fig. 1). More recent seismic hazard studies have redefined the WQSZ into smaller source zones based on historical seismicity and tectonic considerations for the area (for example Halchuk et al., 2016). The compilation of significant earthquakes in Canada for the period 1608 to 2017 lists some 12 events within the boundaries of this study area (Appendix 1; Lamontagne et al., 2018). Historical earthquakes as large as Moment Magnitude (**M)** 6.2 (Témiscaming, 1935) are known. Over the last few decades, frequent low level seismic activity has defined two sub-zones: a mildly active one along the Ottawa River, including a more active cluster in the Témiscamingue region, and a more active one along the Montréal-Maniwaki axis.

The first concentration of seismicity, which parallels the Ottawa River, includes the epicentres of moderate earthquakes: **M** 6.2 near Témiscaming in 1935, a **M** 5.6 near Cornwall-Massena in 1944, and possibly a magnitude of about 5.8 near Montréal in 1732. This diffuse group of earthquakes appears to correlate with a zone of late-Proterozoic to Paleozoic or younger normal faults along the Ottawa River, called the Ottawa-Bonnechere Graben (Kay, 1942; Forsyth, 1981; Bleeker et al., 2011). The Temiscaming area is more active than the rest of the Ottawa River Valley and has been the site of the 1935 **M** 6.2 Temiscaming earthquake. In the year 2000, a **M** 4.7 earthquake reactivated one of the local faults (Bent et al., 2002) adding support to the previously suggested correlation between the earthquake epicentres and the normal faults of the Ottawa-Bonnechere Graben (Adams and Vonk, 2009). The lower magnitude earthquakes appear to reactivate faults smaller than the conspicuous ones near Lake Temiscaming (Lac Témiscamingue; Bent et al., 2002).

The majority of WQSZ earthquakes, mostly smaller than **M** 4.5, occur in an elongated NW-SE trending zone within the Grenville geological province with most focal depths varying between 7 and 25 km (Lamontagne et al., 1994; Ma and Atkinson, 2006; Fig. 1). Although northwest-trending structural features are known, correlating these with the epicentral trend is uncertain because of the thrust sheets that make up the uppermost crust in this area of the Grenville Province. The mid-crustal hypocentral depths of many earthquakes, the east-west trend of the fault planes of some earthquakes, and variations in regional focal mechanisms all suggest reactivation of deep structural features, which may not have a surface expression. It is possible that at the eastern end of this active band an anorthosite body may act as a stress concentrator (Lamontagne et al., 1994).

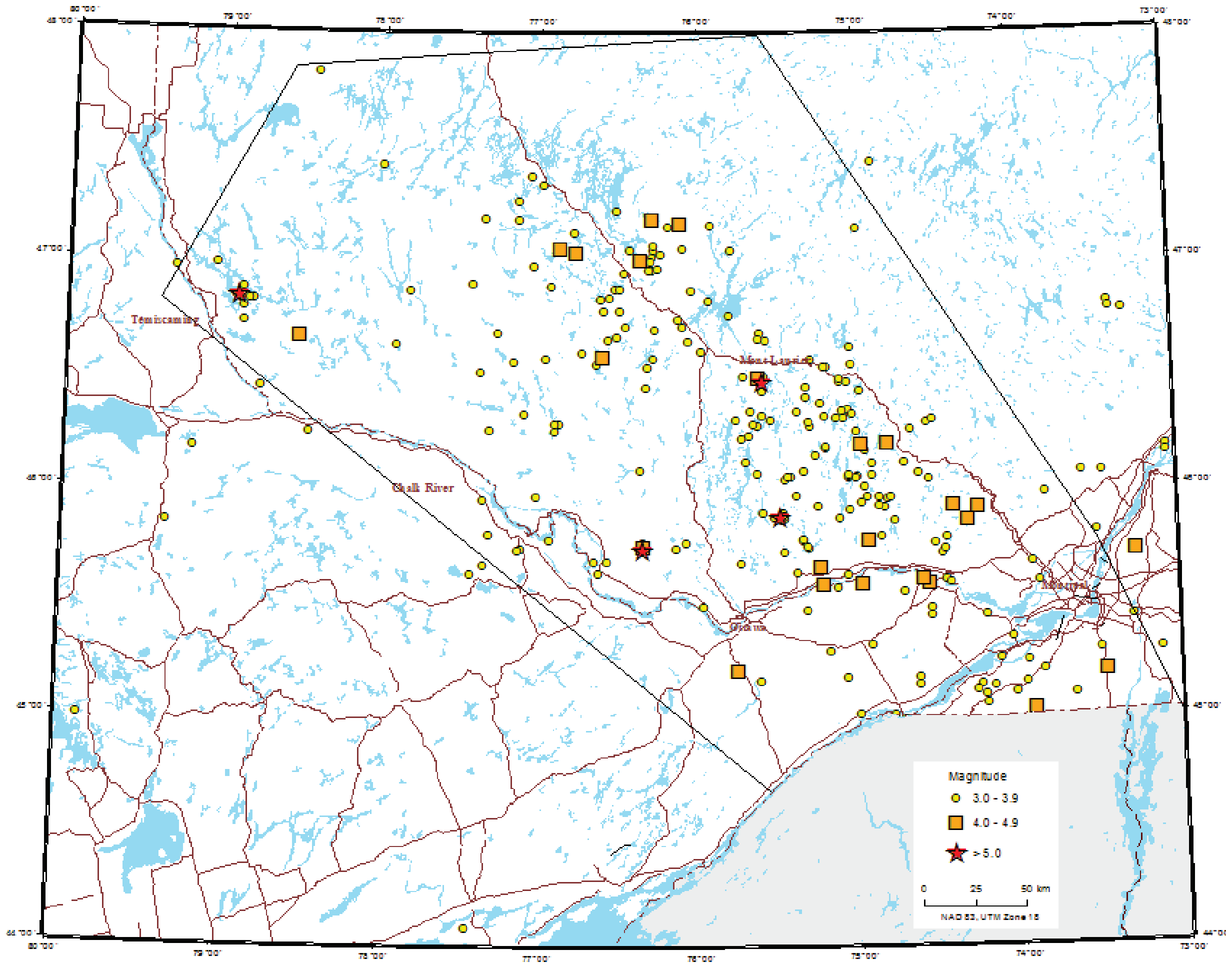


**Figure 1. The study area includes areas of the provinces of Quebec and Ontario as shown on this map. It is bound by latitudes 44°N and 48°N and longitudes 73°W and 80°W, but includes only Canadian territory. The area is centered on the Western Quebec Seismic Zone (polygon) as defined by Basham et al. (1982). Earthquakes shown on this map are those that occurred between January 1980 and April 2018.**

## 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 kilometre-long or more along the St. Lawrence Rift Valley and the adjacent Ottawa-Bonnechere 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 (brittle vs. 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). 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 analyst digitized the lineaments as observed without extrapolation beyond the topographic break or interpolation between them and considering only lineaments with a length greater than 5 km. 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 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 2 exemplifies an area characterized by both brittle and ductile lineaments. It is clearly shown that a virtual illumination[1] from an azimuth of $045^{0}$ better highlights the NW–SE ductile trend (Figure 2A and 2B) and that the 315° illumination reveals more clearly the dominant SW - NE brittle deformation (Figure 2C and 2D). Consequently, each area was examined with the DEM illuminated from various directions.

[1] All virtual iluminations mentionned in the text have been realized with a constant elevation of $45^{0}$

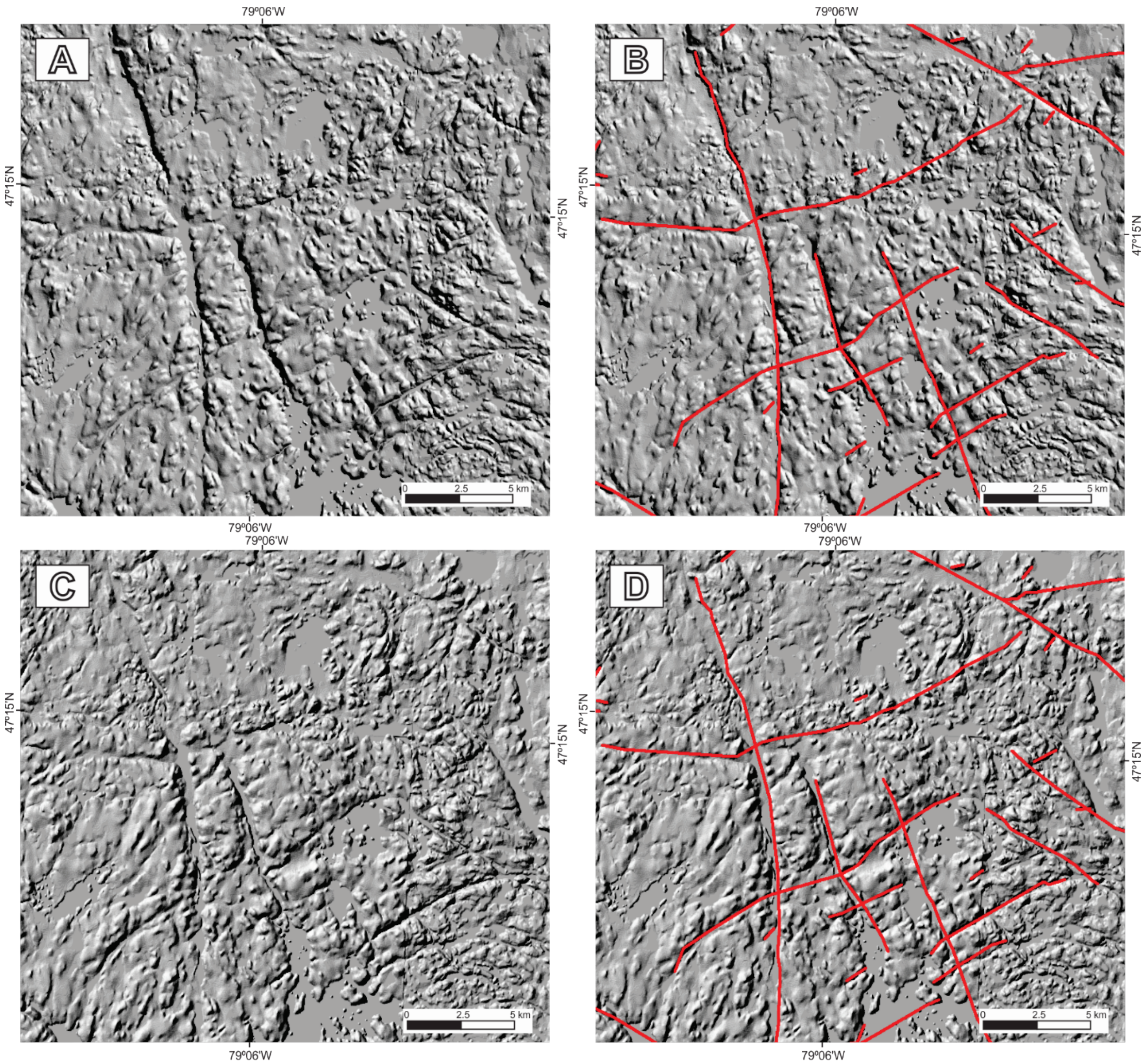


**Figure 2. Relief shading with virtual illumination at 045º (A - B) and 315º (C - D).**

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 3 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.

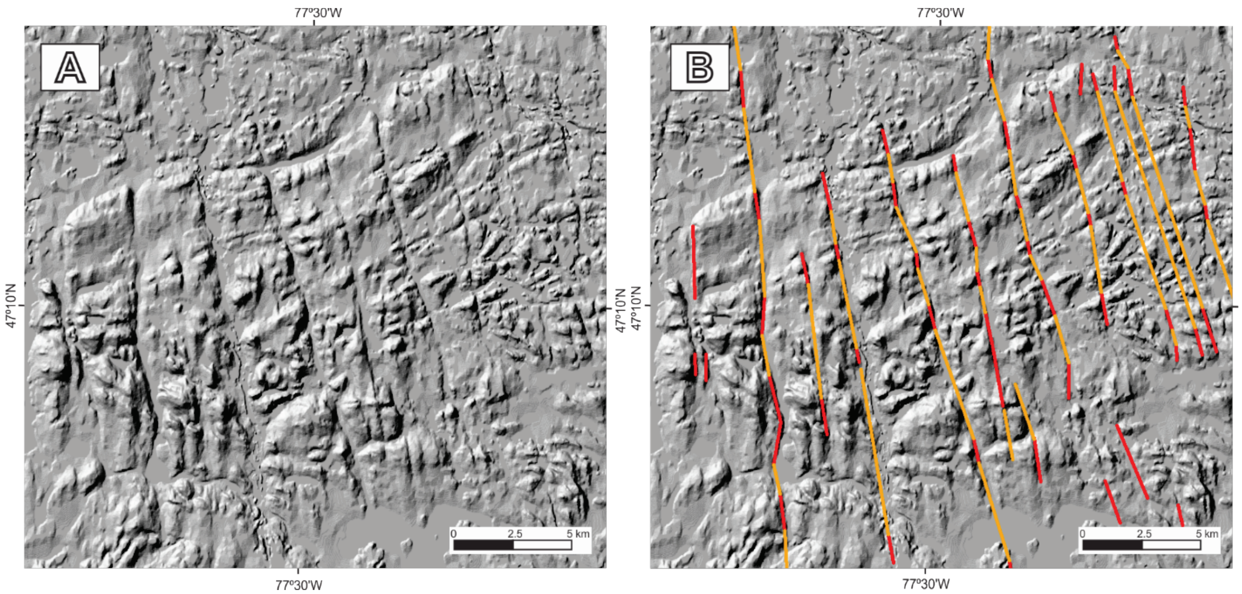


**Figure 3. A - Relief shading with virtual illumination at 315$^0$, B - First-order recognition of brittle lineaments from the topographic breaks (red lines) followed by an interpolation analysis (orange lines).**

Finally, the linear elements were examined directly on a shaded relief colour map printed at the scale of publication (i.e. 1: 750 000). This change to a smaller scale, paper-based support rather than an on-screen analysis further enhanced the analysis. It supported the interpretation of several of the first- and second-order lineaments observed previously, but also highlighted new lineaments, generally longer and more continuous than those observed on the screen at a more local scale.

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 eliminated some lineaments that correlated with intrusive diabase dykes and ductile structural trends. Most dykes within the study area have an easterly trend and belong to the 590-580 Ma Grenville dyke swarm. The swarm is largely restricted to a ~100 km wide zone along the Ottawa River (Bleeker et al., 2011, Fig. 4). A few dykes of other trends have also been mapped in the study area as summarized in the compilation map of Buchan and Ernst (2004). In the second validation test, the lineaments were compared with the two provincial bedrock geological compilations (OGS, MRD126-REV1, 2011; MERN, SIGEOM database, 2017) 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. The next figures provide some good examples of lineaments initially recognized as brittle that were reclassified following these validation tests. Figure 4B shows the lineaments as revealed during the first visual recognition step (red lines) whereas Figure 4D now reveals the segments (orange lines) that have been reinterpreted according to their coincidence with the diabase dykes as recognized on the geological map of Figure 4C. In total, some 84 lineaments were reinterpreted as intrusive dykes.

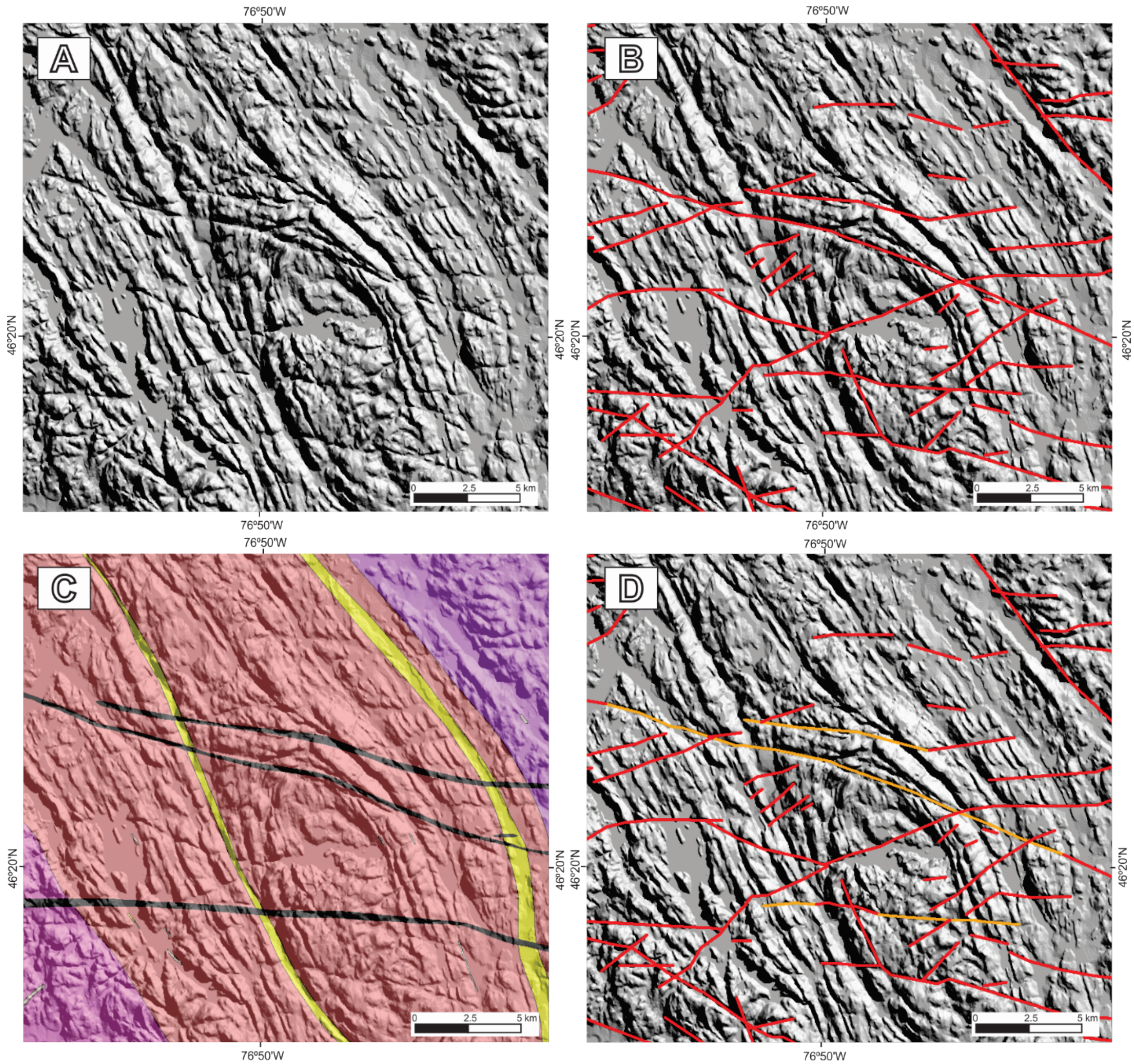


**Figure 4. A - Relief shading with virtual illumination at 045$^0$; B - Initial visual recognition of the lineaments (red lines); C - Geological compilation map showing roughly oriented E – W dykes (dark grey); D - Reclassified lineaments (orange lines).**

Figure 5 highlights the close overlap of observed lineaments with the ductile lithological trends. Similar to Figure 4, Figure 5B shows the lineaments as revealed during the first visual recognition step (red lines), whereas Figure 5D reveals segments that have been reinterpreted according to their coincidence with the ductile trend recognized on the bedrock geological map of Figure 5C. The yellow segment were reinterpreted as ductile lineament whereas the oranges segments have been reclassified in the "questionable" ductile / brittle domain. Overall, 255 lineaments initially recognized as brittle were reclassified. All changes resulting from the validation tests are documented in the database.

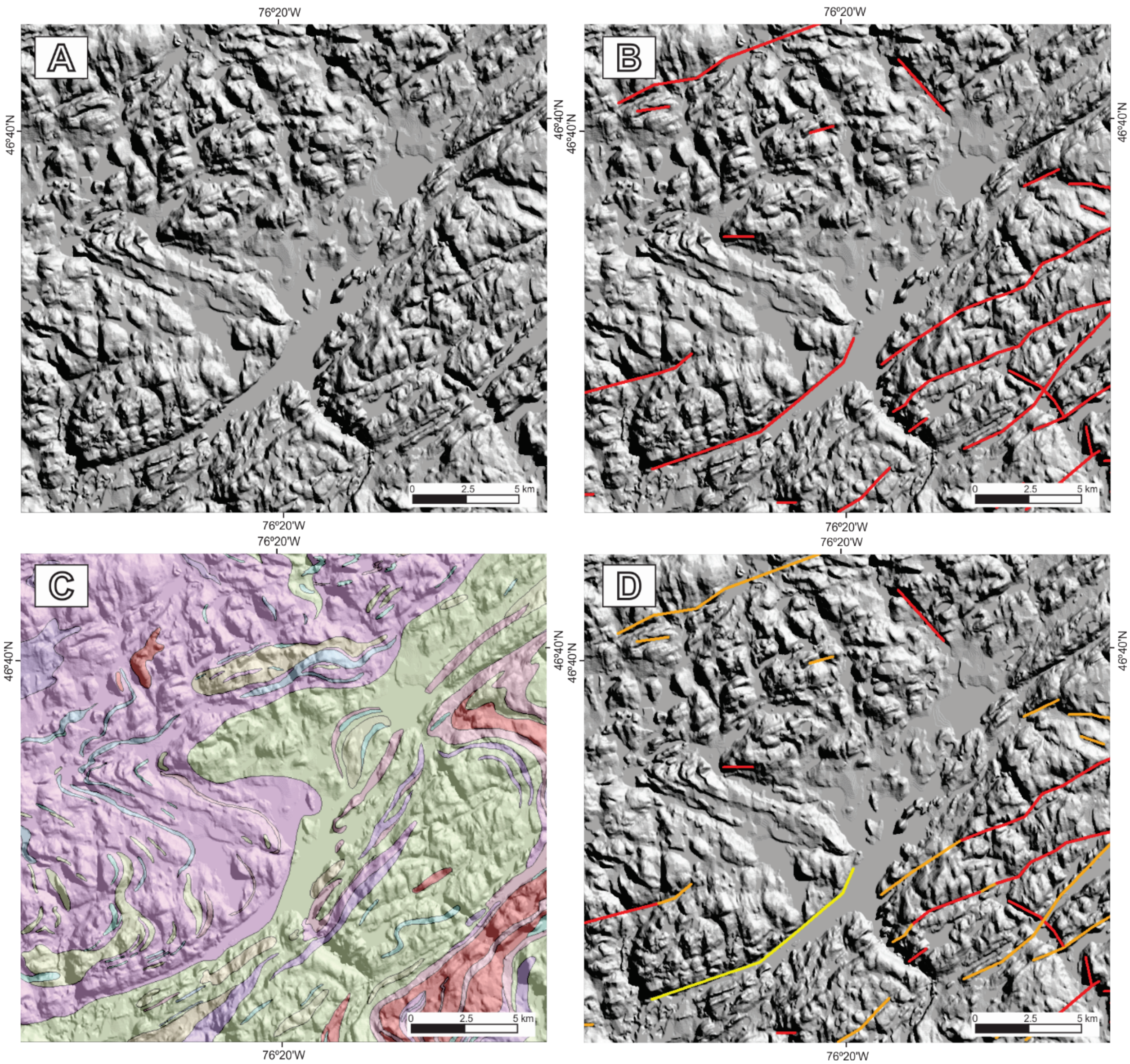


**Figure 5. A - Relief shading with virtual illumination at 045$^0$; B - Initial visual recognition of the lineaments (red lines); C - Geological compilation map; D - Series of ENE lineaments reclassified in the ductile domain (yellow line) or in the "questionable" ductile / brittle domain (orange lines).**

Although the authors made every effort 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, these deep layers have been uplifted 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 northwest corner of the map area is located in the Superior Province, an area not affected by the Grenvillian orogeny. Rocks there are metamorphosed to the greenschist facies, indicative of upper to mid crustal levels. Fewer ductile structures were recognized in that area.

Throughout the region, major shear zones exist (see for example Dufréchou et al., 2014). A survey of the literature shows that these occurred in the ductile regime and were not reactivated later as brittle structures.

The question of the dip angle of the faults is a difficult one. Except for the SLRS faults that are assumed to be steeply dipping, the dip angles of the faults are generally unknown. The first reason is that our interpretation is based on DEMs and these cannot be used to infer dip angles, just the surface expression of the fault. The second difficulty is that faults are rarely directly seen in the field: they are generally hidden by overburden.

## 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 10.2.2 or higher. All datasets reside within two *File Geodatabases*, the Western_SeismicZone.gdb that contains the geological datasets and, the CartoElement_Rift.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_OF8361.mxd.

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

Projected Coordinate System: NAD_1983_UTM_Zone_18N
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 6 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 1:750 000) within the dataset provided with this publication (Figure_OF8361.pdf).

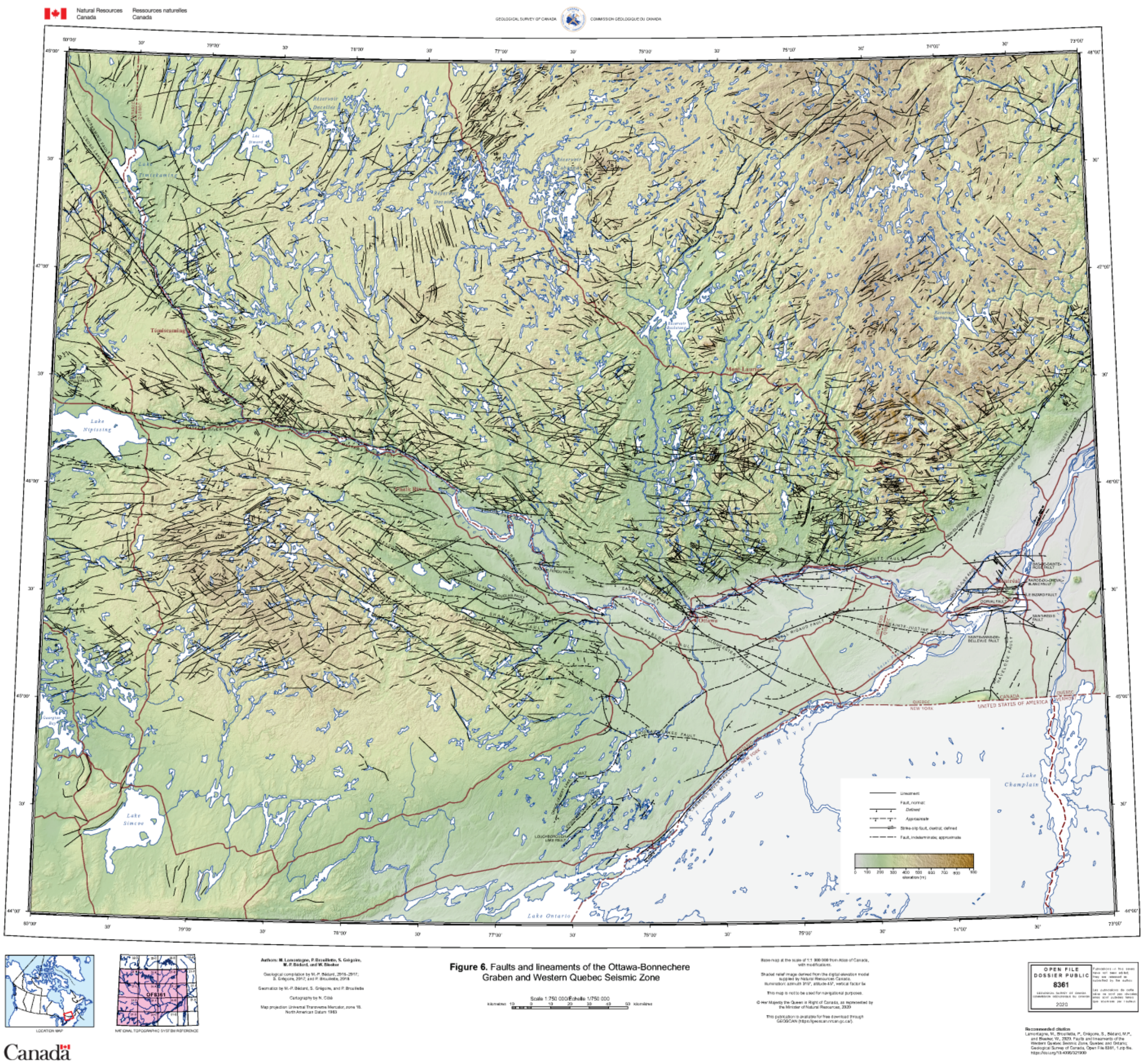


**Figure 6. Layout view of the brittle lineaments and mapped faults of the Ottawa-Bonnechere Graben and Western Quebec Seismic Zone map.**

## 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™ *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_OF8361*** *Data Frame* and more specifically, on the descriptions of geological datasets, as shown on Figure 7. The reader is invited to read the document MXD_readme.rtf for details regarding the non-geological *Data Frames* and *Group Layers*.

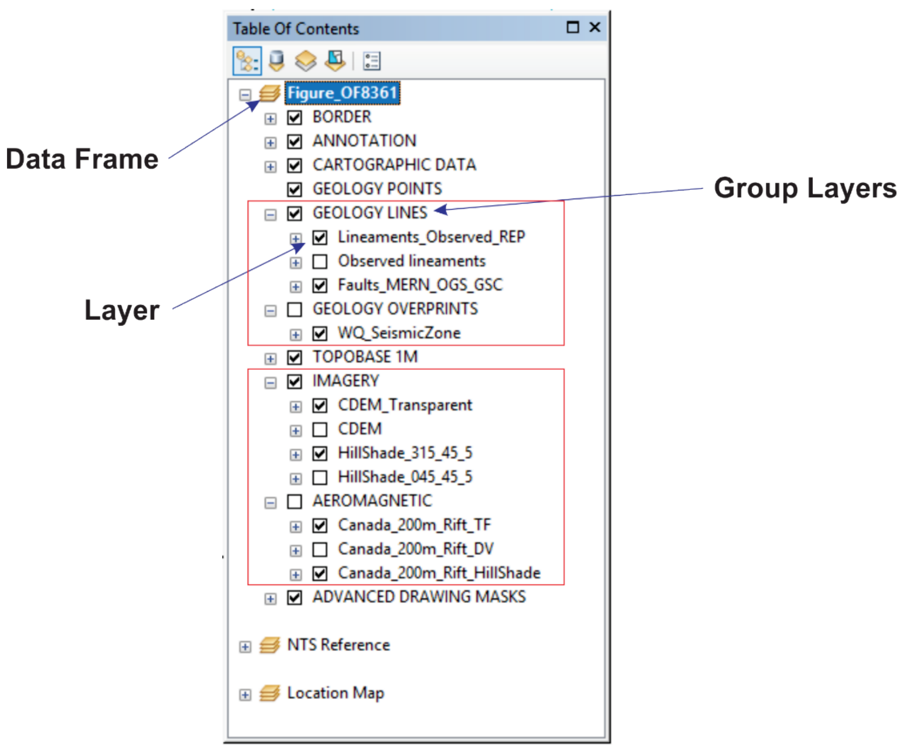


**Figure 7. ArcMAP Table of Contents highlighting the various Layers described in the following sections.**

## GEOLOGY LINES

The *Group Layer* named **GEOLOGY LINES**, contains all the linear geological information compiled for this study. The *Layer* ***Observed Lineaments*** holds the result of the fracture pattern analysis while ***Fault_MERN_OGS_GSC*** contains a selected set of faults mainly from published datasets of the Quebec and Ontario geological surveys. The

***Lineaments_Observed_REP*** *Layer* is only used to optimize the display of the lineaments on the paper map (i.e. cartographic representation).

The ***Observed_Lineaments*** *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_IDENT_METHOD*** and ***LINEAM_VALID*** (Table 1) 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 dyke following validation against geophysical dataset, 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 recognized as “dyke” or 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_MERN_OGS_GSC*** *Feature Class* contains a selected set of faults from published databases and maps of the Ministère de l’Énergie et des Ressources Naturelle (MERN), the Ontario Geological Survey (OGS) and the Geological Survey of Canada (GSC). 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 Timiskaming , Saint-Cuthbert and Sainte-Julienne faults.   In all cases when a name existed, the name was kept in the database and shown on the map.

**Table 2: Field description of the Feature Class Fault_MRN_OGS_GSC**

| 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. St-Maurice fault, Loughborough Lake fault, etc.) |
| SRC_REF1 | Source Reference1 | First level source associated with each fault. All sources come from three organizations, so they all start with one of the following prefixes: 1) Geological Survey of Canada, **GSC**, 2) Ontario Geological Survey, **OGS** and, 3) Ministère de l'Énergie et des Ressources Naturelle, **MERN**) |
| SRC_REF2 | Source Reference2 | This field is used to indicate a second source similar to SRC_REF1, or to display a complete bibliographic reference |
| GSC_SYM_CODE | GSC Symbol Code | GSC standard style codification |
| LEG_DESC | Legend_Description | Legend description from the original source/reference |
| 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 extracted from the MERN and OGS databases, they must edit the definition query of the *Layer Properties* as shown in Figure 8. Editable definition query of the Layer Properties.

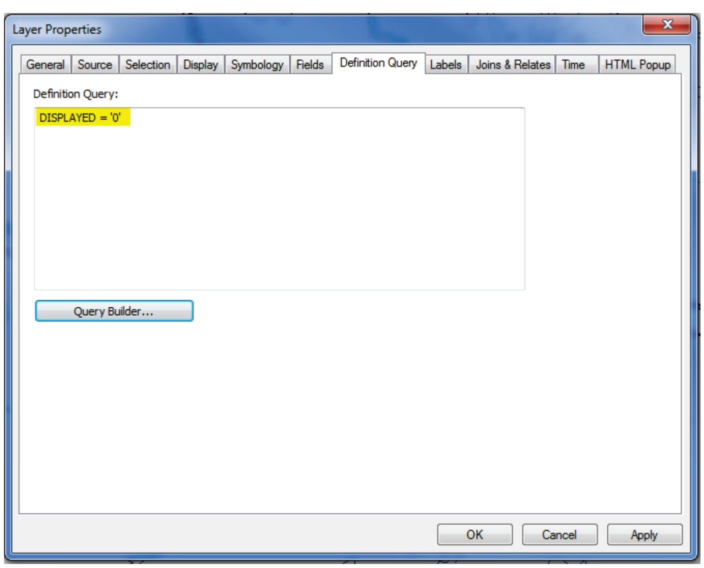


**Figure 8. Editable definition query of the Layer Properties.**

The field ***FAULT_POS*** (Table 2) provides, when available, information about the confidence in the position of the fault. This information is critical for parts of eastern Ontario and western Quebec 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 and, where available, a complete bibliographic reference.

Note that when the observed lineaments (***Observed Lineaments***) are superimposed on the faults (***Fault_MERN_OGS_GSC***), 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* ***WQ_SeismicZone*** that represents the boundaries of the Western Quebec Seismic Zone as defined by Basham et al. (1982). It is not shown on the provided full-scale paper map (Figure_OF8361.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***).

## MAGNETIC 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. The map clearly shows the major E-W trend of regional faults associated with the Ottawa-Bonnechere Graben (OBG). The NW-SE trend associated with the Temiskaming arm of the OBG is also clear. The level of brittle deformation decreases dramatically moving north from the OBG.

The faults of the OBG are assumed to be steeply-dipping normal faults. On an upper-crustal section across the OBG, Figure 9 shows the near surface attitude of these faults (Bleeker, 2011). The extension and attitude of these OBG faults at depth are undefined. On the other hand, by analogy with the faults of the Rhine Graben, one can assume that some OBG faults extend to the middle-crust. These regional normal faults could be those that are reactivated by earthquakes that occur within the OBG region. Since larger earthquake reactivate larger fault surfaces, a correlation with the regional OBG faults is more likely when earthquakes exceed magnitude 5 for instance. The correlation is even more likely if the hypocenter is upper crustal and if the regional faults have a strike and dip similar to one of the nodal planes of the focal mechanism. Such analysis will be done in the future.

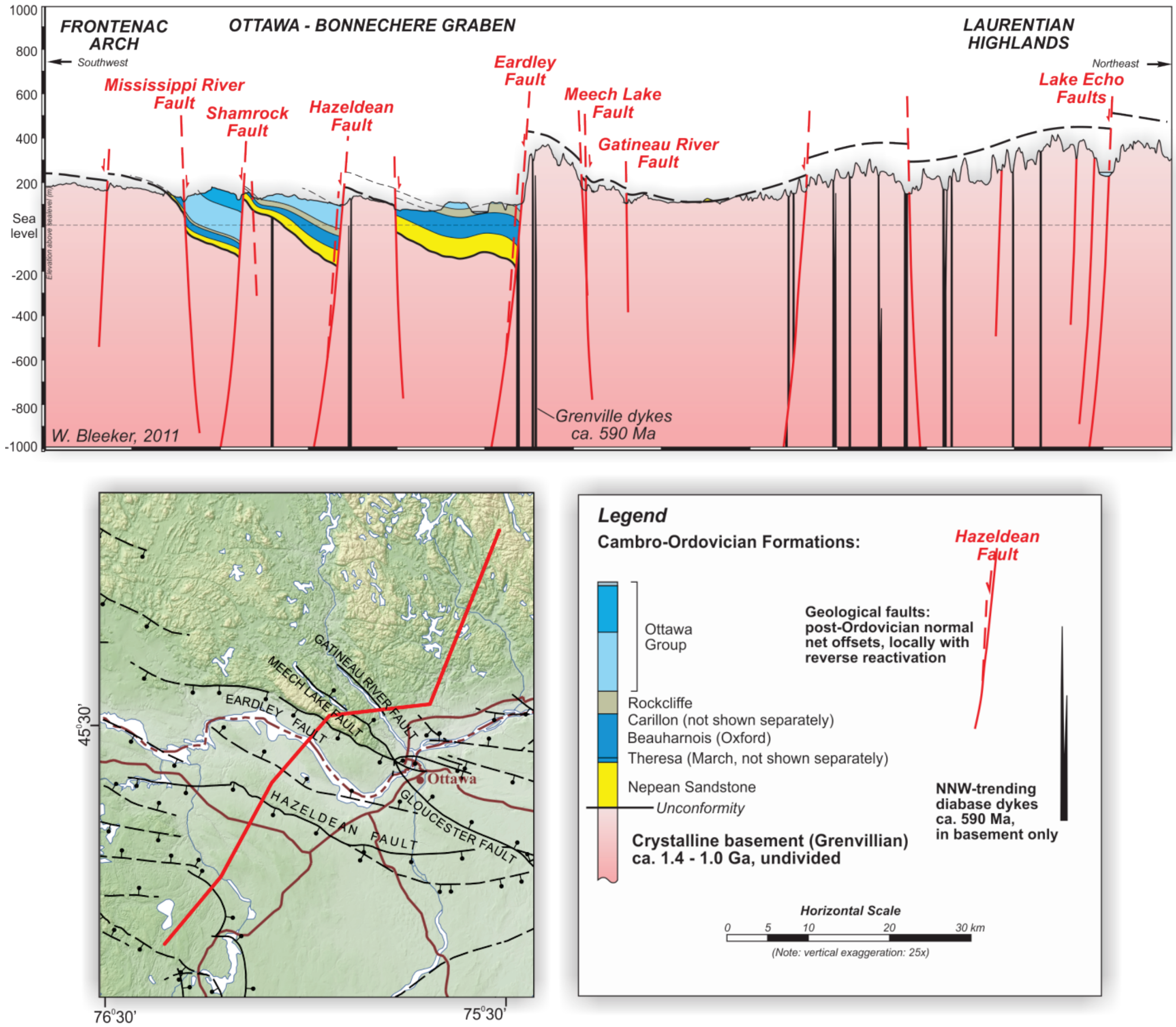


**Figure 9. The top figure shows a cross-section with the topography and the assumed depth attitude of the faults and dykes in the first 1200 m near the surface (vertical exaggeration of approximately 25 times). The legend of this figure appears in the lower right and the location of the cross-section is shown in the lower left. Figures modified from Bleeker et al. (2011).**

As an initial assessment, the seismic activity does not appear to be related to the density of brittle structures. The area near Maniwaki, Quebec, for example, is seismically active but has very few brittle lineaments. To the south of the OBG, brittle structures are found, but little earthquake activity exists. As of January 2019, work is in progress to examine the possible relationship between these lineaments and the earthquake activity.

The next phase of this work is to apply a similar methodology to the remaining sections of the St. Lawrence Rift System.

## REFERENCES


Adams, J. and Vonk, A. 2009. The November 1, 1935, M 6.2 Timiskaming earthquake, its aftershocks, and subsequent seismicity. Geological Survey of Canada Open File Report 6207, 65 pages.

Basham, P. W., Weichert, D.H., Anglin, F.M. and Berry, M.J. 1982. New probabilistic strong ground motion maps of Canada: a compilation of earthquake source zones, methods and results. Publications of the Earth Physics Branch, Open File 82-33, 202p. (Energy, Mines and Resources, Canada).

Beaulieu, A. and Clavet, D. 2009. Accuracy Assessment of Canadian Digital Elevation Data using ICESat. Photogrammetric Engineering & Remote Sensing; Vol. 75, No 1, pp. 81-86. 0099-1112/09/7501–0081

Bent, A.L., Lamontagne, M., Adams, J, Woodgold, C.R.D., Halchuk, S., Drysdale, J., Wetmiller, R.J., Ma, S. and Dastous, J.B. 2002. The Kipawa, Quebec "Millennium" earthquake; Seismological Research Letters, 73 (2): 285-297.

Buchan, K.L. and Ernst, R.E. 2004, Diabase dyke swarms and related units in Canada and adjacent regions, GSC Map 2022A. 1 sheet. : coloured map ; 170 cm. + Accompanying notes booklet. (39 pages)

Bleeker, W., Dix, G.R., Davidson, A., and LeCheminant, A., 2011. Tectonic evolution and sedimentary record of the Ottawa-Bonnechere graben: examining the Precambrian and Phanerozoic history of magmatic activity, faulting, and sedimentation. Field Trip - Excursion 1A, GAC-MAC-SEG-SGA Joint Annual Meeting, Ottawa, 97 pp.

Castonguay, S., J. Dietrich, D. Lavoie, and J. Y. Laliberté (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. Petrol. Geol. 58, 219–234.

Dufréchou, G., Harris, L.B., and Corriveau, L. 1994. Tectonic reactivation of transverse basement structures in the Grenville orogen of SW Quebec, Canada: Insights from gravity and aeromagnetic data. Precambrian Research, 241: 61-84.

Forsyth, D. A. 1981. Characteristics of the Western Quebec Seismic Zone, Canadian Journal of Earth Sciences 18, 103-119.

Ontario Geological Survey 2011. 1:250 000 scale bedrock geology of Ontario; Ontario Geological Survey, Miscellaneous Release---Data 126-Revision 1. ISBN 978-1-4435-5704-7 (CD) ISBN 978- 1-4435-5705-4

Halchuk, S. Adams, J.E., and Allen, T. 2016. Fifth generation seismic hazard model for Canada: crustal, in-slab, and interface hazard values for southwestern Canada; Geological Survey of Canada, Open File 8090, 23 pages, https://doi.org/10.4095/299244

Lamontagne, M., Hasegawa, H.S., Forsyth, D.A., Buchbinder, G.G.R. and Cajka, M. 1994. The Mont-Laurier, Quebec, earthquake of 19 October 1990 and its seismotectonic environment. *Bulletin of the Seismological Society of America*, **84**, 1505-1522.

Lamontagne, M., Halchuk, S., Cassidy, J.F. and Rogers, G.C. 2018. Significant Canadian earthquakes 1600-2017. Geological Survey of Canada, Open File 8285, 37 pages, https://doi.org/10.4095/311183 Leblanc, G., (1981). A closer look at the September 1732, Montréal earthquake. *Canadian Journal of Earth Sciences*, **18**, 539-550.

Ma, S. and G. M. Atkinson 2006. Focal depth distribution for earthquakes with mN ≥ 2.8 in western Quebec, southern Ontario and northern New York, Bull. Seism. Soc. Am., 96, 609-623.

Ministère de l'Énergie et des Ressources naturelles du Québec, Base de données SIGEOM, 2017

# 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). More details on these earthquakes can be found in the included Excel file (sig-eq.xlsx).

| Year | Area | Preferred Magnitude | Magnitude Type | Description |
|---|---|---|---|---|
| 1732 | Near Montréal, Quebec | 6.3 | Mw | Probable epicentre near Montréal, Quebec. Felt in New France, from Louisbourg to the James Bay. Considerable damage in the city of Montréal where hundreds of chimneys were damaged and walls cracked. No injuries documented. Aftershocks felt in Montréal. |
| 1842 | Trois-Rivières, Quebec | 5.0 | $M_L$ | In Trois-Rivières, Quebec, bricks fell from chimneys, fallen objects, broken windows. |
| 1861 | Western Quebec | 5.0 | $M_L$ | Felt over most of western Quebec and eastern Ontario. Epicentre probably in the Saint-André-Avellin region, Quebec, where damage to masonry walls and chimneys was reported. In Ottawa, Ontario, overturned chimneys were reported. |
| 1893 | Montréal, Quebec. | 5.1 | Mw | Damage reported in Montréal, Quebec: broken windows, fallen bricks from walls, building that was being built collapsed, fallen dishes, plaster fallen. Similar damage reported in Quebec from Coteau-Landing, Saint-Hilaire, Saint-Jean-sur-Richelieu, Ormstown (fallen chimneys) and Summerstown, Ontario. |
| 1897 | Montréal, Quebec. | 4.6 | Mw | In Montréal, Quebec, cracked walls and ceilings, one fallen chimney, some broken windows and fallen objects. |
| 1914 | Cornwall region, Ontario | 5.1 | Mw | Probably in the Cornwall, Ontario, region based on maximum damage occurrence (displaced walls, fallen plaster). Felt over eastern Ontario, Western western Quebec and eastern U.S. |
| 1917 | Western Quebec | 4.3 | $M_L$ | In Montréal, Quebec: objects fell from shelves and furniture. In Ottawa, Ontario, some plaster fell from ceilings. Location is very uncertain. |
| 1935 | Region of Témiscaming, Quebec | 6.1 | $M_w$ | The earthquake occurred approximately 10 km east of Témiscaming, Québec. This earthquake was felt west to Thunder Bay, Ontario, (then named Fort William), east to the Bay of Fundy and south to Kentucky and Virginia. Damaged chimneys were reported in Témiscaming, Quebec, and North Bay and Mattawa, Ontario. In the epicentral region, small rockfalls were observed as well as cracks in the gravel and sand at the edges of islands and borders of lakes. Some 300 km away from the epicentre, near Parent, Québec, earthquake vibrations triggered a 30 metre slide of railroad embankment. Numerous aftershocks were felt in Témiscaming and Kipawa during following months. |

| | | | | |
|---|---|---|---|---|
| 1944 | Cornwall, Ontario-Massena New York | 5.6 | $M_w$ | Cornwall, Ontario, region - New York border. Felt over most of eastern Ontario, southern Quebec and New England. Considerable damage to unreinforced masonry in both Cornwall, Ontario and Massena, New York. About 2,000 chimneys were damaged in Cornwall, Massena and several adjacent communities. |
| 1990 | Mont-Laurier, Quebec | 4.6 | Mw | Some minor damage in Mont-Laurier (cracked chimneys, water pipes broken). Widely felt up to distances of 500 km. |
| 2000 | Kipawa, Quebec | 4.7 | Mw | Témiscamingue Region, Quebec. Some reports of minor damage in the epicentral region. Felt in Témiscaming, Quebec, North Bay, Ontario, and as far away as Toronto. |
| 2010 | Near Val-des-Bois, Western Quebec | 5.0 | Mw | Felt over most of Western Quebec and eastern Ontario. Some unreinforced masonry elements damaged near the epicentre as well as in Ottawa. Two landslides reported. |
| 2013 | Ladysmith, Western Quebec | 5.2 | MN | Felt in the Ottawa-Gatineau area and out to Montréal, Toronto and Waterloo. Minor damage near epicentre, Quebec. |

## APPENDIX 2

List of publications referred to in the database Western_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** |
|---|---|---|---|
| Can. J. Earth Sci. 22, 53-71 (1985) | Kretz, R., Hartree, R., Garrett, D., Cermignani, C. | 1985 | Petrology of the Grenville swarm of dikes, Canadian Precambrian Shield |
| Current Research 95-F | Hogarth, D.D., van Breemen, O. | 1995 | Geology and age of the Lac à la Perdrix fenite, southern Gatineau district, Quebec |
| GAC-MAC-SEG-SGA, Field Trip 1A | Bleeker, W., Dix, G.R., Davidson, A., and LeCheminant, A. | 2011 | Tectonic evolution and sedimentary record of the Ottawa-Bonnechere graben: examining the Precambrian and Phanerozoic history of magmatic activity, faulting, and sedimentation. Field Trip - Excursion 1A, GAC-MAC-SEG-SGA Joint Annual Meeting, Ottawa, 97 pp. |
| GSA Bulletin, Vol. 53 | Kay, G.M. | 1942 | Ottawa-Bonnechere Graben and Lake Ontario Homocline; Bulletin of The Geological Society of America, Vol. 53, pp. 585-646 |
| GSC Bulletin 597 | Sanford, B.V., Arnott, R.W.C. | 2009 | Stratigraphic and structural framework of the Potsdam Group in eastern Ontario, western Quebec, and northern New York State |
| GSC Map 1362A | Reinhardt, E.W., Wilson, A.E., Liberty, B.A. | 1973 | Geology, Carleton Place, Ontario |

| | | | |
|---|---|---|---|
| GSC Map 1508A | Harrison, J.E., MacDonald, G. | 1979 | Generalized bedrock geology, Ottawa-Hull, Ontario and Quebec |
| GSC OF 3012 | Nadeau, L., Brouillette, P. | 1995 | Structural map (version 1.0 06/95), Trois-Rivières (31I), Grenville Province, Québec / Carte structurale (version 1.0 06/95), Trois-Rivières, Province de Grenville, Québec |
| MRN MM 82-01 | Globensky, Y. | 1982 | Région des Laurentides (SW). MRN, MM 82-01 |
| MRN MM 84-02 | Globensky, Y. | 1986 | Géologie de la région de Saint-Chrysostome er de Lachine (sud). MRN, MM 84-02 |
| MRN MM 84-03 | Globensky, Y. | 1985 | Géologie des régions de St-Jean (partie nord) et de Beloeil. MRN, MM 84-03 |
| MRN MM 85-02 | Globensky, Y. | 1987 | Géologie de Basses-Terres du Saint-Laurent. MRN, MM 85-02 |
| MRN RG 093 | Côté, P.E. | 1960 | Région de Chertsey, district électoraux de Joliette, Montcalm et Terrebonne. MRN, RG 093 |
| MRN RG 101 | Clark, T.H. | 1964 | Région de Saint-Hyacinthe (moitié ouest), Comtés de Bagot, de Saint-Hyacinthe et de Shefford. MRN, RG 101 |
| MRN RG 102 | Clark, T.H. | 1964 | Région de Yamaska - Aston, Comtés de Nicolet, Yamaska, Berthier, Richelieu et Drummond. MRN, RG 102 |
| MRN RG 127 | Philpotts, A. R. | 1967 | Région de Belleau - Desaulniers, Comtés de Saint-Maurice Maskinongé et Laviolette. MRN, RG 127 |
| MRN RG 133 | Beland, R. | 1967 | Région de Saint-Gabriel-de-Brandon, Comtés de Joliette, Berthier et Maskinongé. MRN, RG 133 |
| MRN RG 152 | Clark, T.H. | 1972 | Région de Montréal. MRN, RG 152 |
| MRN RG 155 | Clark, T.H., Globensky, Y. | 1976 | Région de Sorel et partie sud-est de Saint-Gabriel-de-Brandon. MRN, RG 155 |
| MRN RG 157 | Clark, T.H., Globensky, Y. | 1976 | Région des Laurentides (moitié est) et de Rawdon (partie sud-est). MRN, RG 157 |
| MRN RG 190 | Clark, T.H., Globensky, Y. | 1977 | Région de Verchères. MRN, RG 190 |
| MRN RG 197 | Globensky, Y. | 1981 | Région de Lacolle - Saint-Jean (S). MRN, RG 197 |
| MRN RG 200 | Globensky, Y. | 1982 | Région de Lachute. MRN, RG 200 |
| MRN RP 455 | McGerrigle, J.I. | 1961 | Rapport Préliminaire sur la région de Dégrosbois, Comté de terrebonne. MRN, RP 455 |
| MRN RP 495 | McGerrigle, J.I. | 1962 | Rapport Préliminaire sur la région du Lac Manitou, Comtés de Terrebonne et D'Argenteuil. MRN, RP 495 |
| MRN RP 586 | Rive, M. | 1970 | Géologie de la région de Rowanton - Maganasipi est. MRN, RP 586 |
| MRN TH 0666 | Goulet, N. | 1971 | Etude pétrologique, structurale et géochronologique des formations cristallines du quart NE de la feuille Saint-Gabriel-de-Brandon (province de grenville, bouclier canadien). TH 0666 |
| MRN TH 0759 | Beland, J. | 1953 | Geology of the Shawinigan map-area, Champlain and St-Maurice counties, Quebec. Princeton University, Princeton New Jersey, USA. TH 0759 |
| MRN TH 0890 | Schimann, K. | 1971 | Étude structurale, pétrographique et géochimique du Massif Sacadomie, province de Grenville (bouclier canadien). TH 0890 |
| MRNF, SIGEOM database | MRNF, Québec | 2017 | Base de données SIGEOM, Ministère des Ressources naturelles et de la Faune; © Gouvernement du Québec |
| OGS Map 2578 | Ontario Geological Survey | 1992 | Tectonic assemblages of Ontario, southern sheet; Ontario Geological Survey, Map 2578, 1:1 000 000. |

| | | | |
|---|---|---|---|
| OGS Map P3438 | Easton, R.M. | 2001 | Precambrian Geology, Clyde Forks Area, Ontario Geological Survey; Preliminary Map Series, Map P3438 |
| OGS Map P3791 | Magnus, S.J., Easton, R.M. | 2015 | Precambrian Geology of Eastern Ontario Interpreted from Aeromagnetic and Compiled Geological Data - Northwest Sheet, Ontario Geological Survey; Preliminary Map Series, Map P3791 |
| OGS Map P3792 | Magnus, S.J., Easton, R.M. | 2015 | Precambrian Geology of Eastern Ontario Interpreted from Aeromagnetic and Compiled Geological Data - Northeast Sheet, Ontario Geological Survey; Preliminary Map Series, Map P3792 |
| OGS Map P3793 | Magnus, S.J., Easton, R.M. | 2015 | Precambrian Geology of Eastern Ontario Interpreted from Aeromagnetic and Compiled Geological Data - South Sheet, Ontario Geological Survey; Preliminary Map Series, Map P3793 |
| OGS MRD126-REV1 | Ontario Geological Survey | 2011 | 1:250 000 scale bedrock geology of Ontario; Ontario Geological Survey, Miscellaneous Release–Data 126 - Revision 1. |