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**GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8432**

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Earthquakes and faults of the Charlevoix impact structure, Quebec

by

L. Nadeau^{1*}, M. Lamontagne², P. Brouillette^{1*}, J. Locat³, S. Castonguay¹ and A. Morin¹

ABSTRACT

This field guide was first written for the meeting of the Eastern Section of the Seismological Society of America (ES-SSA), held in La Malbaie in 2013. It has been slightly modified, mostly with new figures.

The Charlevoix Seismic Zone is the locus of the highest seismic hazard in continental eastern Canada. At the heart of this zone is the ~54 km diameter Charlevoix impact structure. This structure, located less than 125 km east of Quebec City, is one of the most accessible large meteorite impact structures in eastern North America. The Charlevoix impact structure is singled out as it overprints Iapetus rift faults and the Logan's Line marking the edge of the Appalachian Orogen.

The Charlevoix impact structure gives the region its singular landscape. The ~5 km wide peripheral ring trough forms a prominent open valley extending from St. Lawrence River (sea level) to a threshold at ~250 m altitude. The highest point in the valley is nearly 850 m below the ~1100 m mean elevation of the external Laurentian plateau. The highest point is also 550 m below the central uplift, "Mont-des-Éboulements," which stands 780 m above sea level. The overall morphology of the Charlevoix impact structure matches that of a complex impact crater. Shatter cones, mylonite injections and shock-induced planar deformation microstructures in quartz and feldspar are widespread providing compelling evidence for the extent of shock metamorphism. The age of the impact is poorly constrained. Recently acquired ⁴⁰Ar/³⁹Ar and U-Pb data from impact melt rock and pseudotachylite give a late-Ordovician age, which appears to be in better agreement with field relationships than the previously reported K-Ar Devonian-age.

Based on historical and current earthquake rate, the Charlevoix Seismic Zone is a region of high seismic hazard. Since the arrivals of the first Europeans in the early 1600s, it has been subject to five earthquakes of magnitude 6 or larger: in 1663 (M~7); 1791 (M ~6); 1860 (M ~6); 1870 (M ~6 ½); and 1925 (magnitude M_s 6.2 ± 0.3). Recently, the magnitude of the 1663 earthquake was estimated to be as large as M 7.2 to 7.9!

The field trip provides an opportunity to enjoy the panoramic view of the peripheral trough and ring structure and of the central uplift, and to visit key outcrops featuring shock-related features, including shatter cones, impact breccias, and related fault zones. The focus of the field trip is on the region's long fault reactivation history, dating back to the Iapetus Ocean rifting. The field trip also includes visiting outcrops of the St. Lawrence Platform Cambro-Ordovician sedimentary cover, allowing observation of the structural relationships with the Logan's Line marking the edge of the Appalachian Orogen. Field research in the Charlevoix region is also important because,

paired with seismic hazard, the area is known for its landslide sensitivity; stops at St. Joseph-de-la-Rive feature a major landslide caused by the February 5th 1663 earthquake.

PROLOGUE

This field trip to the Charlevoix impact structure is, so to say, “un retour aux sources.” I was introduced as a teenager, back in 1968, by Dr. Jehan Rondot to the geology of the Charlevoix region, shortly after his discovery of the impact structure. This also marked my initiation to field geology, as an insect and mineral collector, and my first encounter with a real geologist, with all the romantic imaginings that such a pioneer figure can trigger in a 14-year-old boy’s eager mind.

My subsequent geological studies and professional work kept me away from pursuing study of the Charlevoix impact structure. Accordingly, I am at best an educated geologist enthusiastic to communicate his modest knowledge of this unusual geological feature. To this day, Drs. Rondot and Roy remain by far the experts on the Charlevoix impact structure and, as such and circumstances permitting, either one would be a much more knowledgeable leader for this fieldtrip.

Jérôme Nadeau

INTRODUCTION

Regional geological setting

This field guide was first written for the meeting of the Eastern Section of the Seismological Society of America (ES-SSA), held in La Malbaie in 2013. It has been slightly modified, mostly with new figures.

The Charlevoix region displays a rich geological heritage. It is located at the present-day erosional limit of three geological landmarks in central and eastern North America. These include a tapering fringe of Cambro-Ordovician sediments of the St. Lawrence Platform which intervenes between the Mesoproterozoic crystalline rocks of the Grenville Province of southeastern Laurentia and the thrust-accreted rocks of the Appalachian Orogen. The Charlevoix region also lies along the late-Neoproterozoic to Cambrian St. Lawrence rift system, immediately inboard from the Appalachian front with thrust faulting dating back to Upper Ordovician. Orogeny-driven faulting and fault reactivation likely occurred through the Paleozoic and Mesozoic. The meteorite impact event added to an already compound geological history, significantly weakening the crust and making it more prone to subsequent seismic activity.

Given the turbulent geological history of the Charlevoix region, crosscutting and overprinting structural and tectonic relationships in the area are in places difficult to decipher, and their full significance is somewhat debatable. The evidence for a major impact structure is conclusive. Though the role of Iapetus rifting and subsequent Appalachian telescoping in the development and reactivation of the fault network and in the preservation of the St. Lawrence Platform sediment fringe is likely more important than initially anticipated.

Additionally, the present day ‘crater-like’ topographic expression of the Charlevoix impact structure does not directly portray the original crater because post-impact regional uplift and erosion led to over one to two kilometers of exhumation. Hence, the present-day topographic expression is the result of differential erosion between variably shattered rocks: the shattering density and erosional friability being related to impact crater’s deep infrastructure. There is also very little remaining of crater’s fill deposits; impact melt-derived rocks have been reported only in two small outcrops 9 and 10 km northeast of the central peak and as boulders in glacial deposits (Rondot, 1971).

The age of the impact is poorly constrained. Recently acquired $^{40}\text{Ar}/^{39}\text{Ar}$ and U-Pb data from impact melt rock and pseudotachylite give a late-Ordovician age (Whitehead et al., 2003; Schmieder et al., 2019), which appears to be in better agreement with field relationships than the previously reported K-Ar Devonian-age.

Charlevoix seismic zone

Based on historical and current earthquake rates, the Charlevoix Seismic Zone (CSZ) has the highest seismic hazard in continental eastern Canada (Figure 1). Since the arrival of the first Europeans in the early 1600s, the CSZ has been subject to five earthquakes of magnitude 6 or greater: in 1663 (M~7); 1791 (M~6); 1860 (M~6); 1870 (M~6 ½); and 1925 (magnitude MS 6.2 ± 0.3). Recently, the magnitude of the 1663 earthquake was estimated to be as large as M 7.2 to 7.9 (Locat, 2011; Ebel, 2011)!

In the 1970's, the earthquake potential of the area led the Government of Canada to conduct two field surveys that defined the CSZ's main seismotectonic characteristics (Leblanc et al., 1973; Leblanc and Buchbinder, 1977). Hypocentres cluster along or between the mapped Iapetan faults (also called St. Lawrence paleo-rift faults). The largest earthquake of the 20th century in this region occurred in 1925. The focal mechanism of the 1925 earthquake has one nodal plane consistent with a reactivation of a SE-dipping paleo-rift fault (Bent, 1992). The installation of a permanent seismograph network in 1978 has helped to define additional characteristics of the area (Figure 1). The St-Laurent fault, one of the major rift faults of the CSZ, was formed in the late Precambrian. The fault was also active after the Devonian meteor impact (Rondot, 1979), probably during the early stages of the opening of the Atlantic Ocean in late Triassic-Jurassic times (Lemieux et al., 2003). The St-Laurent fault is not particularly active, but appears to bound concentrations of hypocentres (Lamontagne, 1999). Earthquakes occur between the surface to 30 km depth in the Precambrian Shield, which outcrops on the north shore of the St. Lawrence River or is found beneath Logan's line and the Appalachian rocks (Figure 2).

Due to its concentration of earthquakes, the CSZ has been the focus of various geophysical studies (Buchbinder et al., 1988). For example, investigations of velocity structure include a seismic reflection-refraction survey (Lyons et al., 1980), microearthquake surveys (Leblanc et al., 1973; Leblanc and Buchbinder, 1977; Lamontagne and Ranalli, 1997), analysis of teleseismic events (Hearty et al., 1977), receiver function analysis (Cassidy, 1995), shear wave splitting and anisotropy studies and focal mechanisms of microearthquakes (Lamontagne, 1998; Bent et al., 2003). The concentration of earthquakes led to earthquake prediction studies in the late 1970s and early 1980s (Buchbinder et al., 1988).

Roughly 80% of Charlevoix earthquakes occur in the depth range 5–15 km in Grenville basement rocks with some as deep as 30 km (Figure 2). Comparing this depth distribution to rheological models of the region, Lamontagne and Ranalli (1996) attribute earthquakes to faulting above the brittle-ductile transition. These earthquakes reach depths of at least 25 km. If we consider the conditions prevailing on the pre-existing faults themselves, their reactivation 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. The distribution of spatially clustered earthquakes within the Charlevoix seismic zone indicates that very few earthquakes have occurred on the same fractures with similar focal mechanisms, implying that these fault zones occur in highly fractured rocks, especially those within the boundaries of the impact structure (Lamontagne and Ranalli, 1997; Figure 2). The hypocentre-velocity simultaneous inversion of local P and S waves

produced a velocity model that revealed areas of high-velocity bodies at mid-crustal depths (Vlahovic et al., 2003; Figure 2). These areas were interpreted to be stronger, more competent crust that separates CSZ earthquakes into two main bands elongated along the St. Lawrence River. CSZ focal mechanisms are quite variable in orientation and, to a lesser extent, faulting style. It is generally assumed that, on the average, most Charlevoix earthquakes occur as thrust events on pre-existing SE steeply (60°) dipping faults.

There are indications that the region itself may have sub-areas with different rheological properties due to the presence of the meteor crater and its faults. Larger events concentrate at both ends of the seismic zone outside the meteor impact (Figure 1; 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.

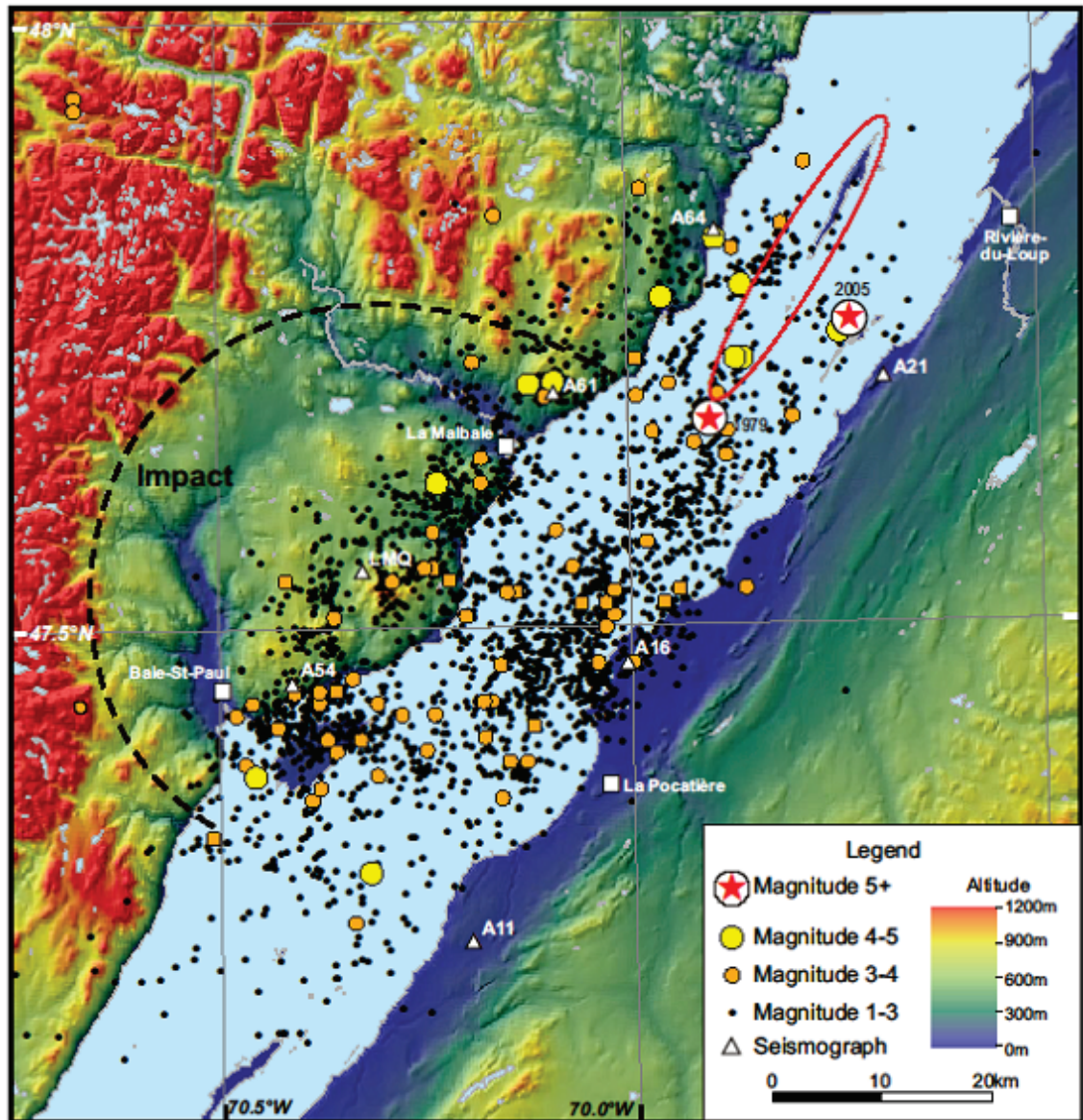


Figure 1. Digital elevation model of the impact structure with distribution of earthquakes of magnitude ≥ 1.0 recorded between 1978 and 2012 in the Charlevoix Seismic Zone. The estimated position of the 1925 earthquake's epicentre and assumed fault plane orientation is shown as a red ellipse. The semi-circle of the Charlevoix impact crater is clearly visible on this image where topography is shown using colours that range from blue for the lowest elevations to red for the highest ones. Since 1978, earthquakes have been monitored by a network of seven seismographs (white triangles).

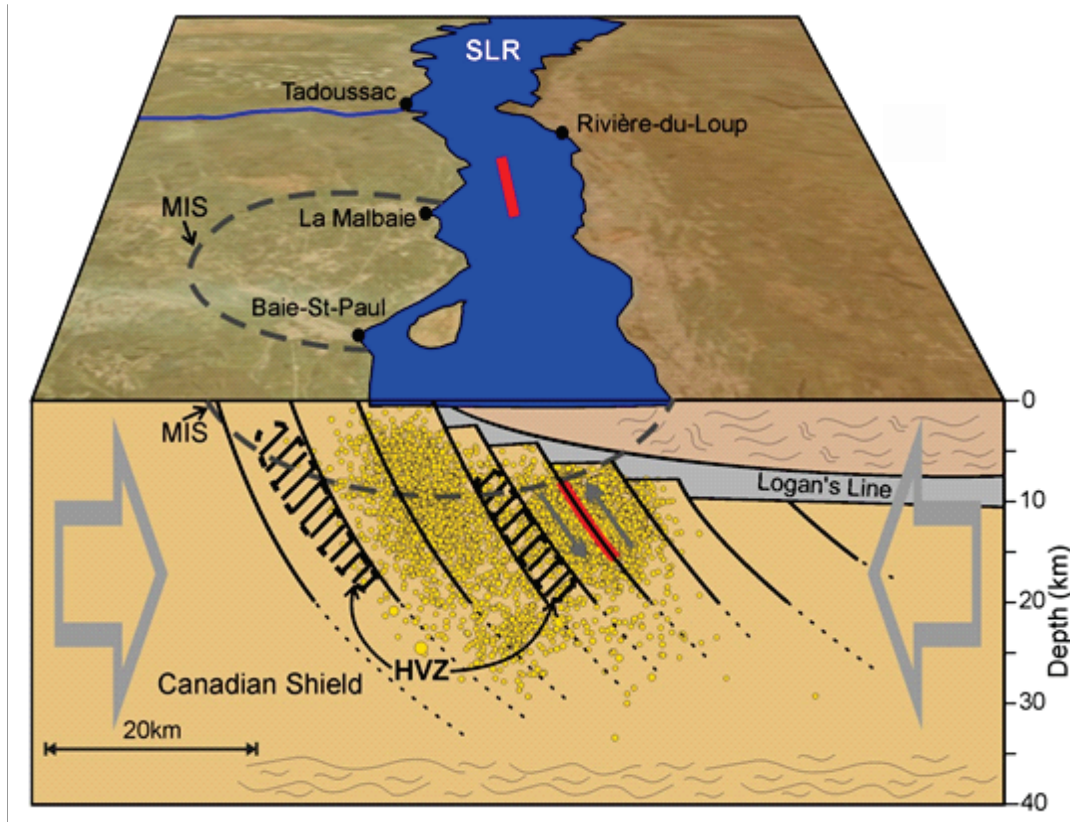


Figure 2. Idealized cross-section perpendicular to the St. Lawrence River in the Charlevoix Seismic Zone (CSZ). The earthquake activity occurs in response to ridge push stresses (arrows) and is constrained to the Canadian Shield rocks beneath the St. Lawrence River (SLR), St. Lawrence platform rocks (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).

PREVIOUS WORK AND REFERENCES

Readers are referred to the landmark contributions by Rondot (1995, 2000), Lamontagne (1987, 1999), Lemieux et al. (2003), Roy (1979), Robertson (1975), and references therein, for a comprehensive review on the impact structure. More recently, the geochronological studies of Whitehead et al. (2003) and Schmieder et al. (2019) have investigated the age of the impact. Reference list below also includes key contributions on regional geology and stratigraphy, structural evolution, and recent seismic activity in the region.

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ESSSA-2013 FIELD TRIP

The ESSSA-2013 field trip stops are limited to a subset of the sites located on Figure 3:

Field trip stop	Guidebook reference	Key element
Stop 1	Site 15	Pointe-au-Pic lookout <ul style="list-style-type: none"> Crater central uplift range La Malbaie peripheral trough
Stop 2	Site 11	Gros Ruisseau <ul style="list-style-type: none"> Typical highly fractured rocks and outcrops of the crater region Rare occurrence of suevite-type dike
Stop 3	Site 10	Saint-Irénée-les-Bains <ul style="list-style-type: none"> Soft-sediment, ductile and brittle deformation in Paleozoic sediments
Stop 4	Site 9	Ruisseau Jureux <ul style="list-style-type: none"> Shatter cones Myololisthenite dykes Cambrian quartzite faulted against Precambrian basement orthogneiss
Stop 5	Site 6	Cap-aux-Oies <ul style="list-style-type: none"> Polydeformed Paleozoic cover sequence Shatter cones Myololisthenite dykes and impact breccia Reverse faulting of crystalline basement against Paleozoic cover
Stop 6	Site 5a	Les Éboulements - rang Saint Godefroy <ul style="list-style-type: none"> 1870 earthquake epicenter area
Stop 7	Site 5b	Les Éboulements lookout <ul style="list-style-type: none"> Panoramic view on the St-Lawrence Fault, the Logan's Line and the Appalachian range
Stop 8	Site 16	Saint. Joseph-de-la-Rive <ul style="list-style-type: none"> Landslide caused by the February 5th 1663 earthquake
Stop 9	Site 17	Les Éboulements – seismograph station <ul style="list-style-type: none"> Seismograph station A54, Canadian National Seismograph Network
Stop 10	Site 3	Baie-Saint-Paul lookout <ul style="list-style-type: none"> St. Lawrence Fault Annular trough Paleozoic cover sediments in normal fault contact against Precambrian crystalline basement

Stop 11	Site 1	Highway 138 lookout <ul style="list-style-type: none"> • Charlevoix impact panoramic view
Stop 12	Site 14	Saint-Urbain <ul style="list-style-type: none"> • Vertically dipping Paleozoic rocks outcrop of the annular trough
Stop 13	Site 13	Saint-Hilarion <ul style="list-style-type: none"> • Impact structure morphology • Discovery outcrop and shatter cones • Saint-Urbain AMCG suite
Stop 14	Site 12	Pointe-au-Pic <ul style="list-style-type: none"> • Annular trough • Reverse faulting of Paleozoic cover sediments against crystalline basement

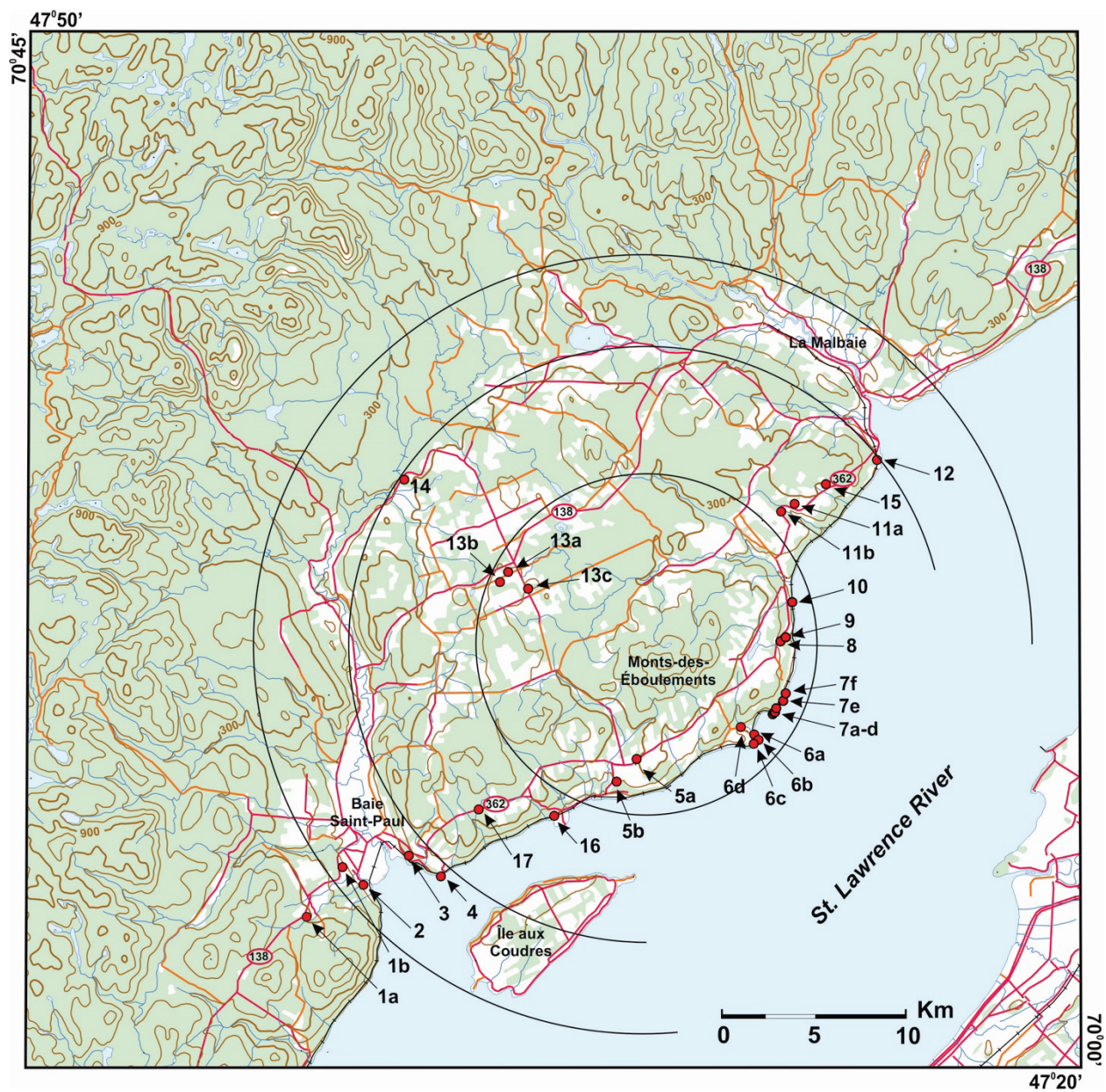


Figure 3. Location map of geological sites of special interest and of main road access.

SUPPORTING FIGURES

The following figures provide the overall geological context and background information to place the field trip stops in context.

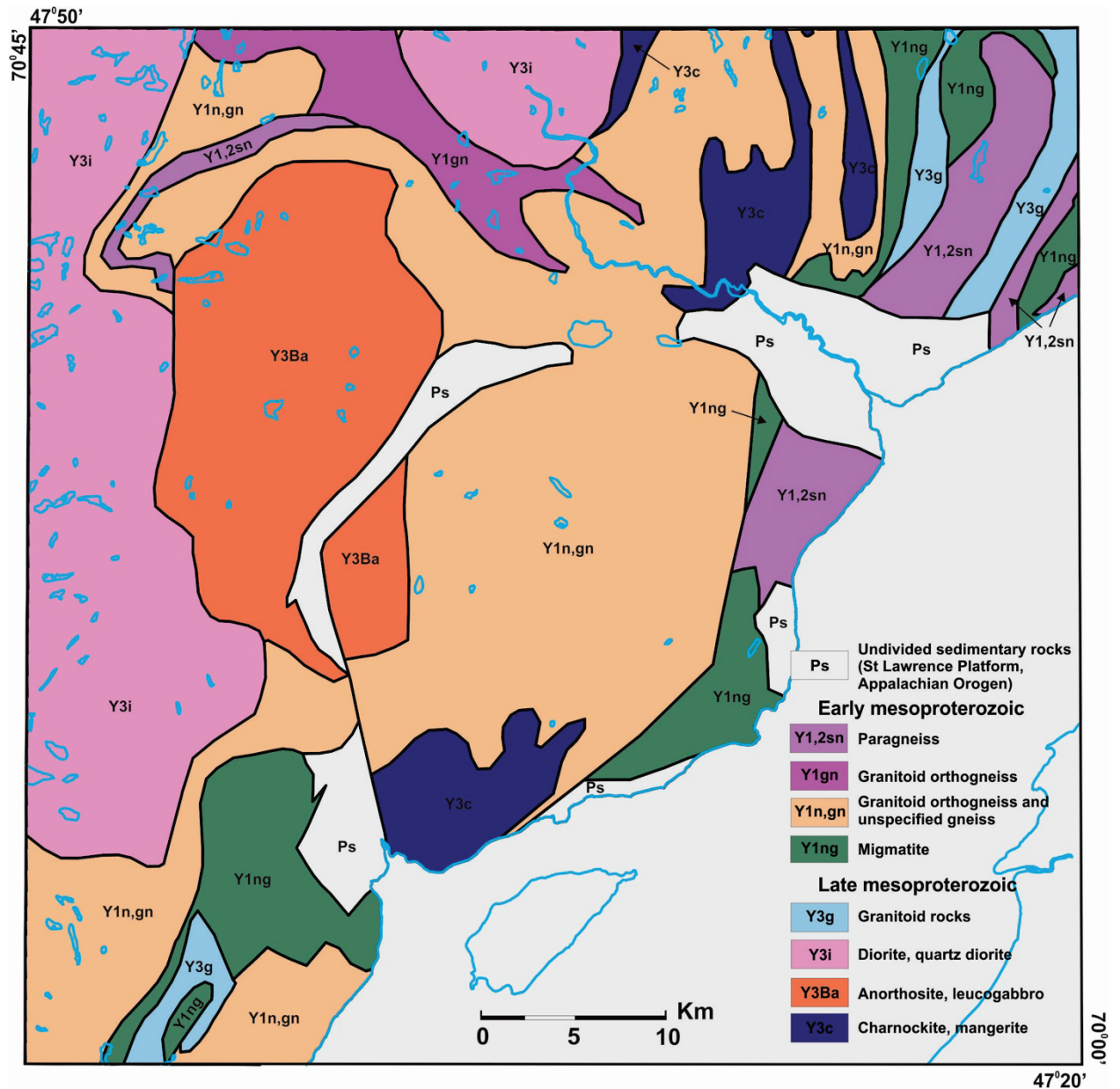


Figure 4a. Simplified geological map of the Charlevoix impact region.

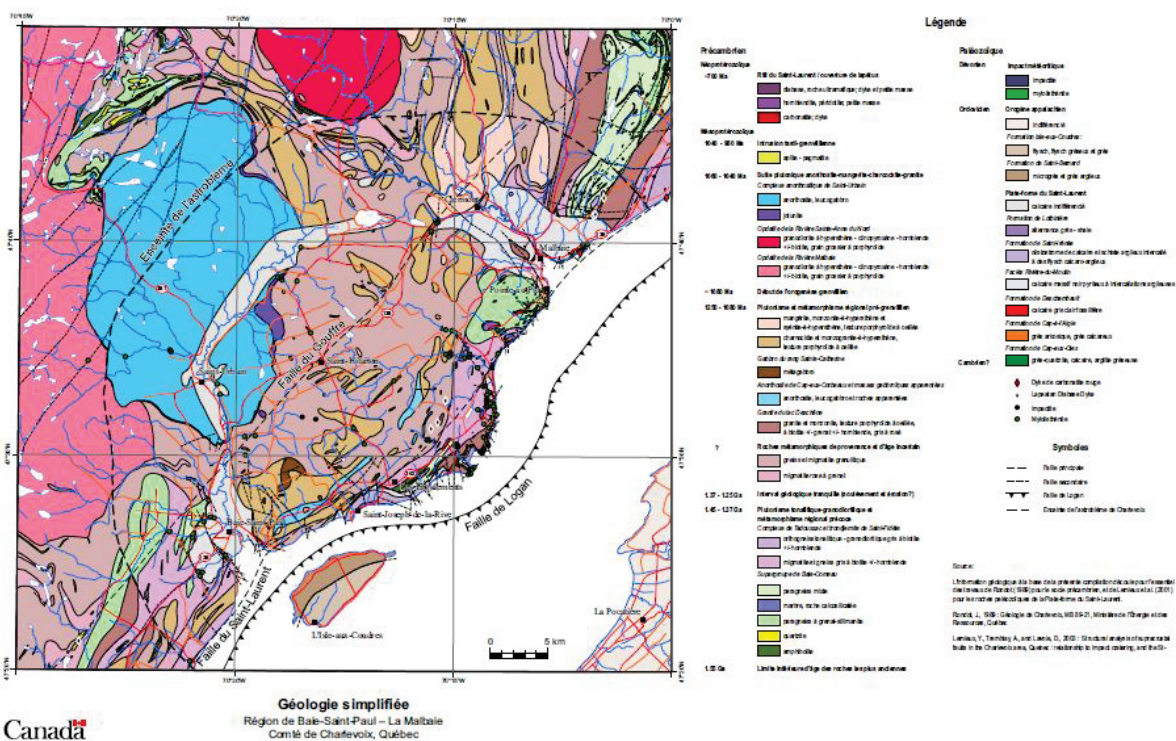


Figure 4b. Detailed geological map of the Charlevoix impact region. A full resolution version in pdf format is available in this Open File report.

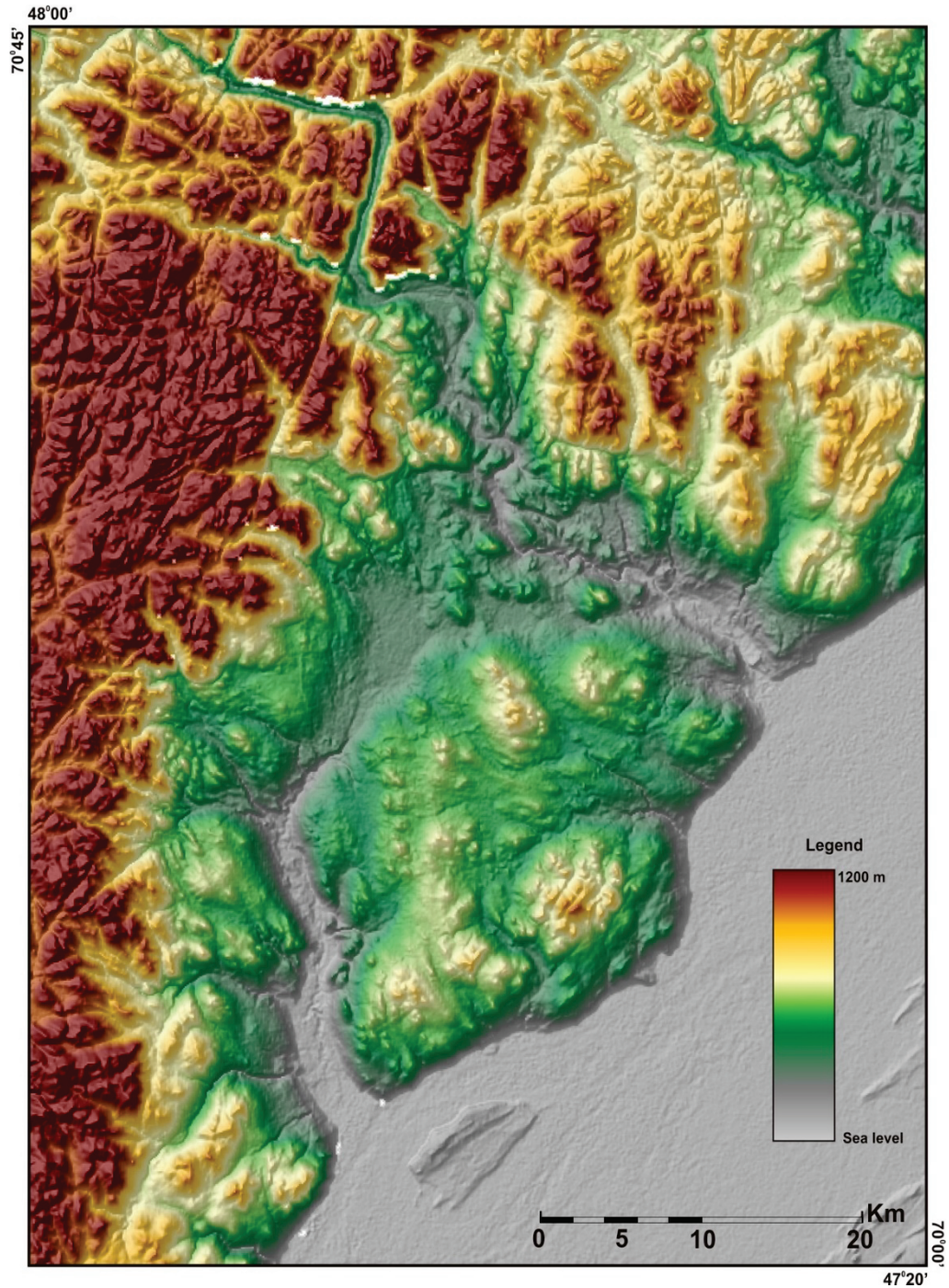


Figure 5. Digital elevation model showing the main topographic features defining the Charlevoix impact structure. The impact erosional scar is ~45km in diameter. The ~5 km wide annular trough forms a prominent open valley that locally reaches an altitude of 250 m. The highest point in the valley is nearly 850 m below the ~1100 m mean elevation of the external Laurentian plateau. The highest point is also 550 m below the central uplift, “Mont-des-Éboulements,” which stands 780 m above sea level.

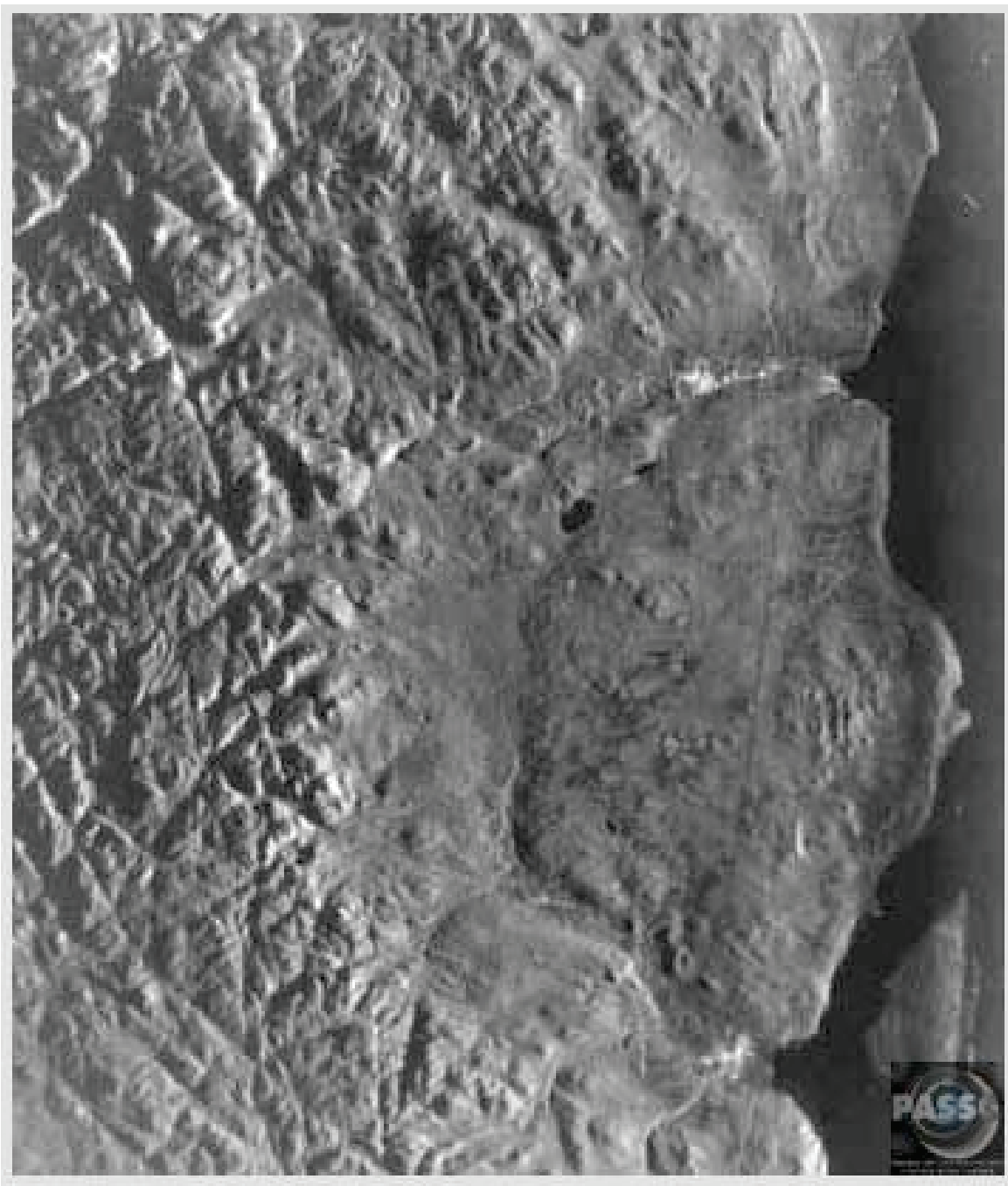


Figure 6. RADAR image illustrating the highly contrasting fracture patterns in basement rocks within and outside the Charlevoix impact region.

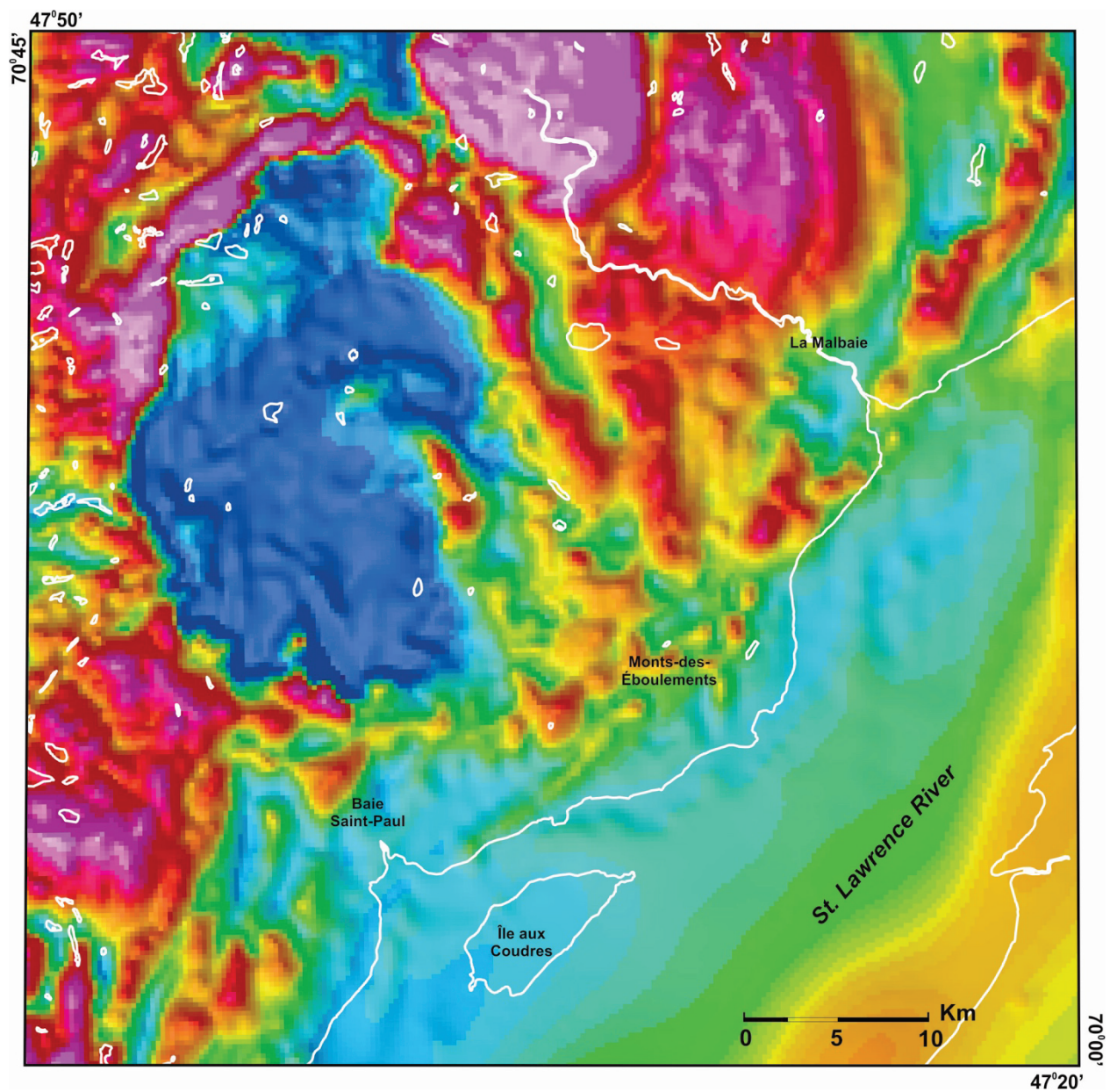


Figure 7. Total field magnetic anomaly map of the Charlevoix impact region with blue colors representing low magnetic field values and red, high values.

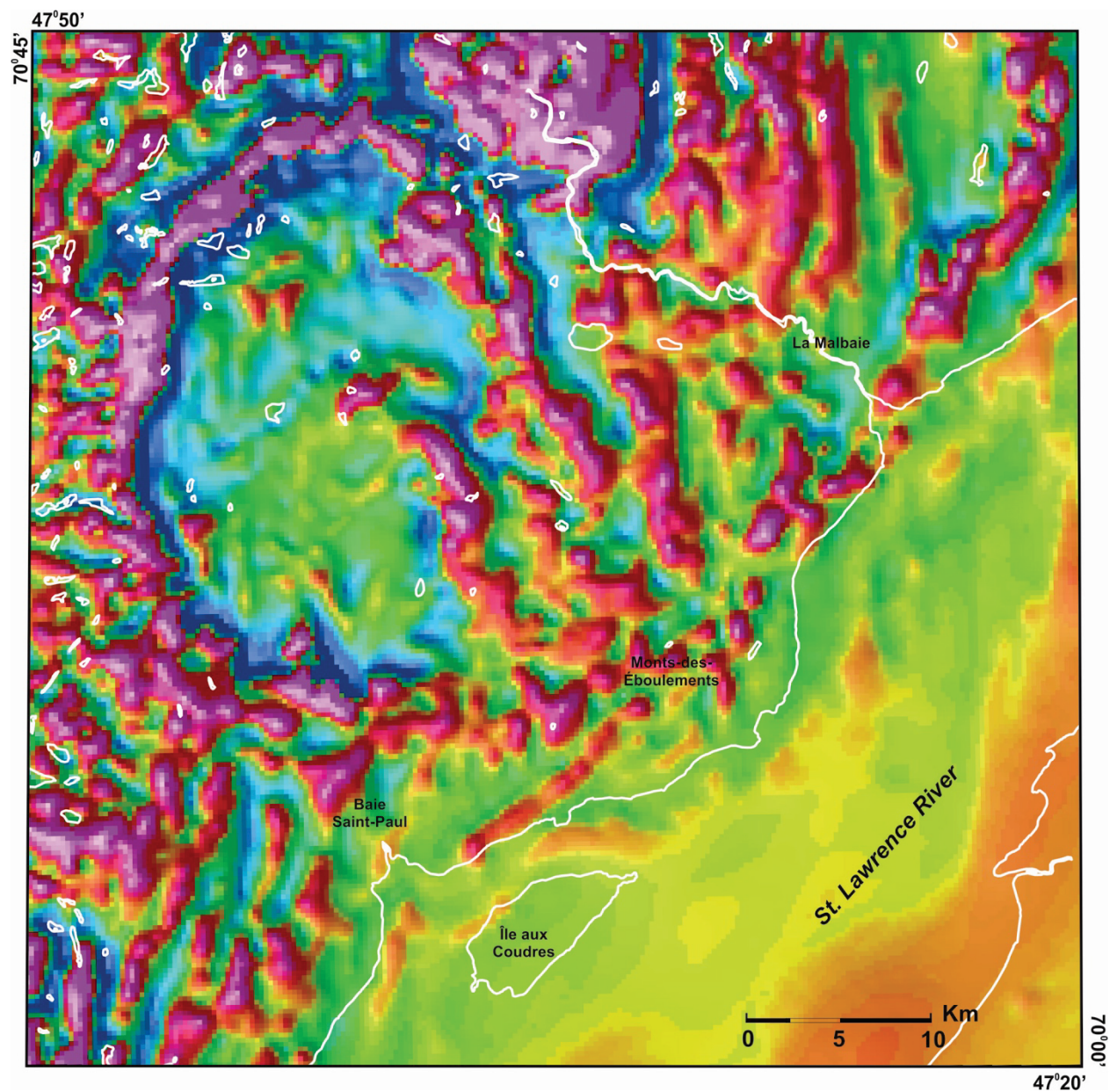


Figure 8. Vertical gradient of the magnetic anomaly of the Charlevoix impact region, with blue colors representing low magnetic gradient values and red, high values.

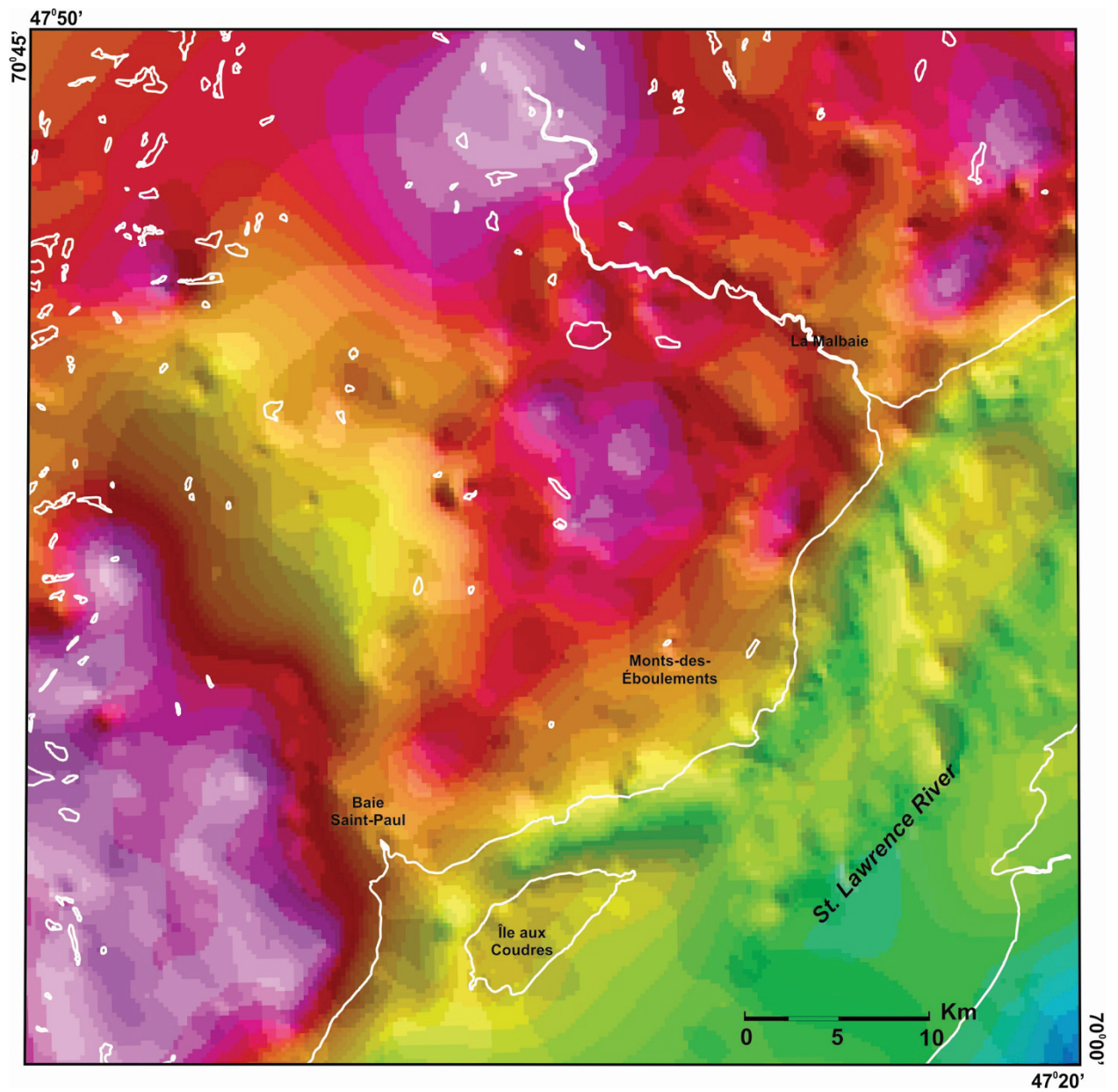


Figure 9. Bouguer gravity anomaly map of the Charlevoix impact region, with blue colors representing low values and red, high values.

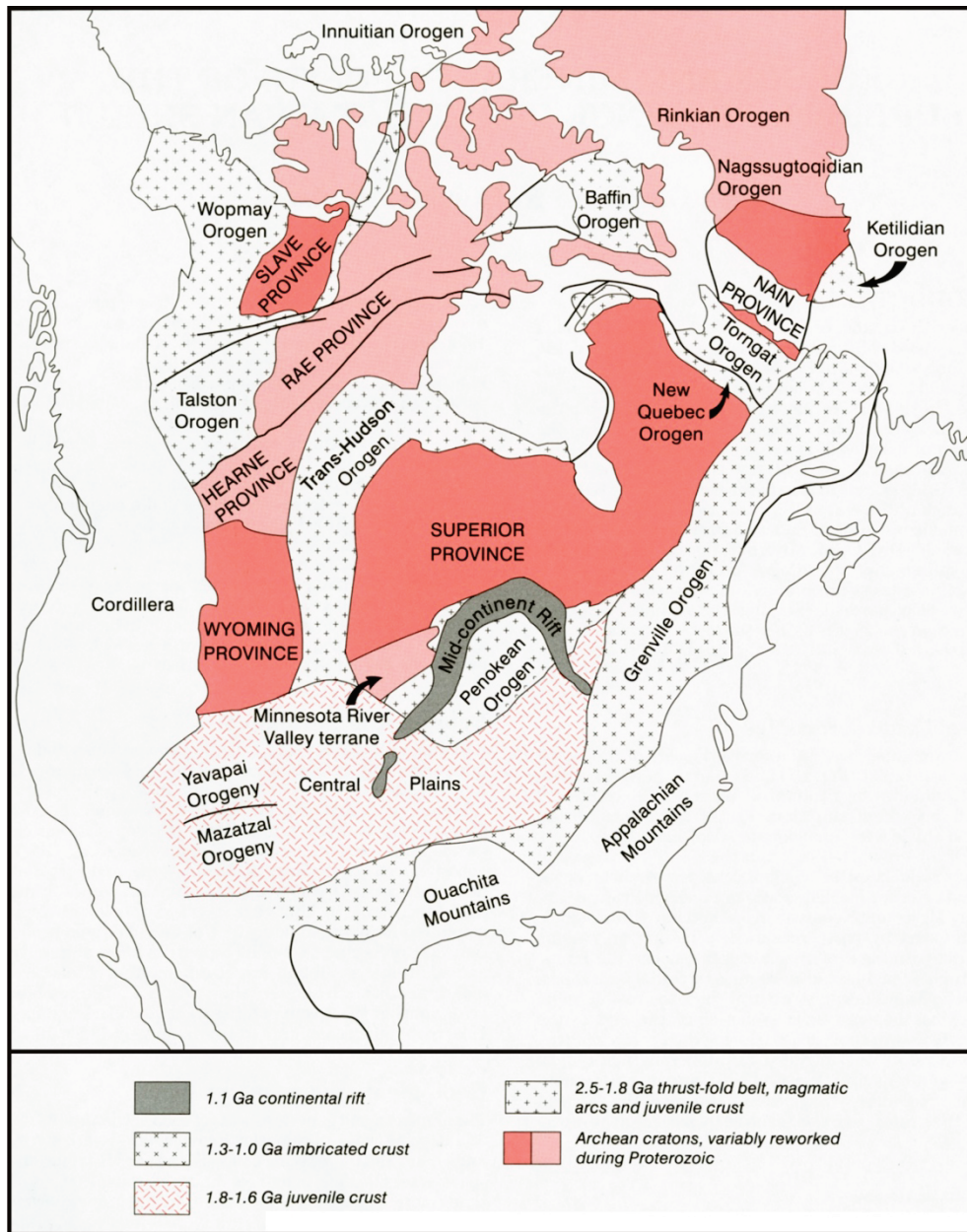


Figure 10. Principal tectonic elements of the Precambrian of North America and Greenland (modified from Hoffman, 1989).

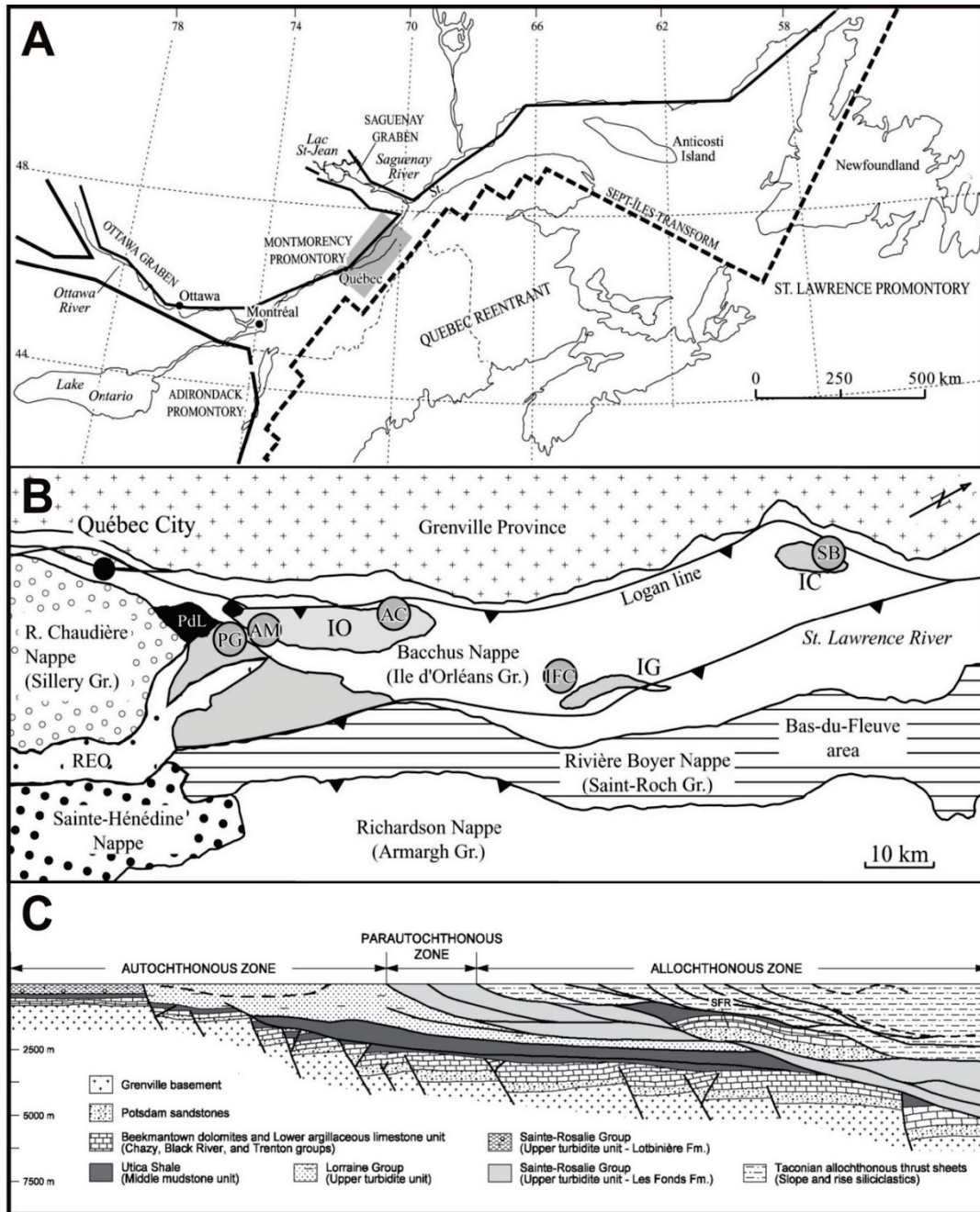


Figure 11. (A) Location map showing the restored configuration of the Laurentian margin prior to Iapetus rifting. (B) Simplified map of the Appalachians NE of Quebec City, showing Logan's Line and the various nappes or thrust sheets. IC, Ile-aux-Coudres. (modified from Longuépée and Cousineau, 2005). (C) Cross-section of the Appalachians, SW of Quebec City. The autochthonous zone represents the St. Lawrence Platform, the parautochthonous zone is the Appalachian foreland fold and thrust belt, and the allochthonous zone is the Humber zone (modified from Castonguay et al., 2010, and Comeau et al., 2004)).

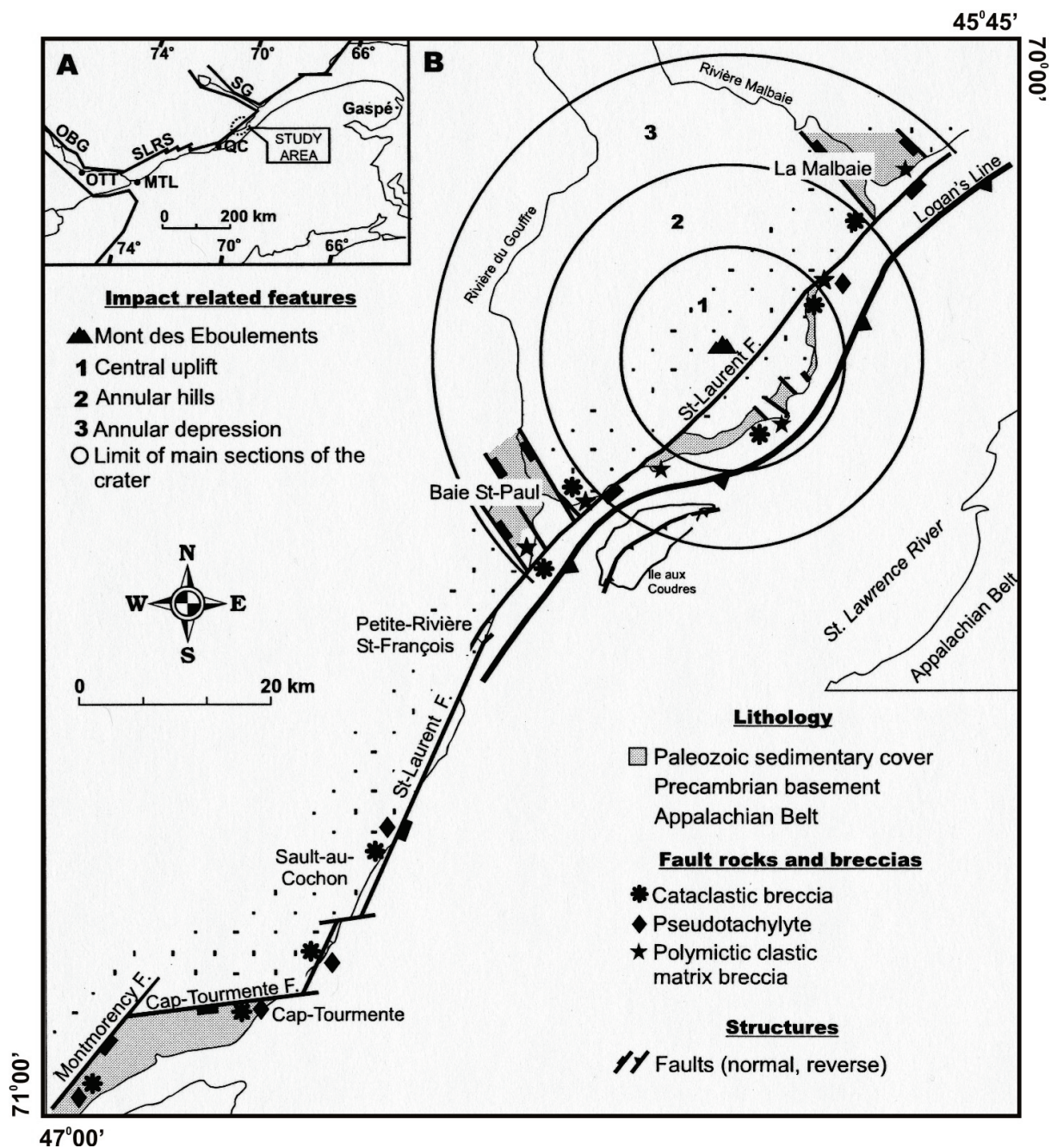


Figure 12. (A) Simplified map of the St. Lawrence rift system (SLRS) showing the location of the Ottawa-Bonnechere (OBG) and Saguenay River (SG) grabens. OTT, Ottawa; MTL, Montréal; QC, Québec. (B) Simplified geological map of the Charlevoix area. Numbers and circles represent different divisions of the impact crater morphology. Mont-des-Éboulements represents the highest point in Charlevoix and corresponds to the inferred point of impact. Map also shows the distribution of cataclasite breccia, and the

polymictic clastic matrix breccia (Rondot's mylolisthenite). Note the restriction of the mylolisthenite to the crater's limit. F., fault. (from Lemieux et al., 2003).

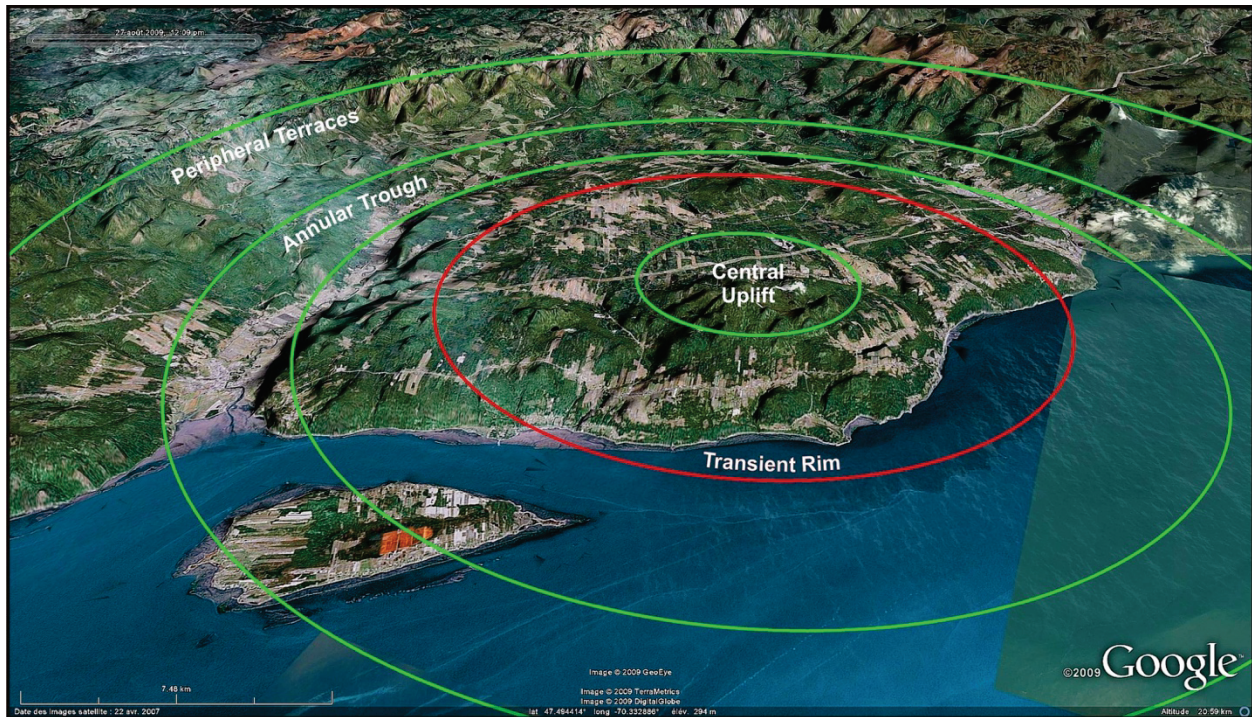


Figure 13a. Google Map view of the Charlevoix impact structure. View towards NE (24°), 30° inclination from horizontal, altitude 21 km, 3X vertical magnification. Please note that the peripheral terrace is the peripheral wall of the impact structure.



Figure 13b. Google Map view of the Charlevoix impact structure. View towards NE (31°), 23° inclination from horizontal, altitude 11 km, 3X vertical magnification. Please note that the peripheral terrace is the peripheral wall of the impact structure.

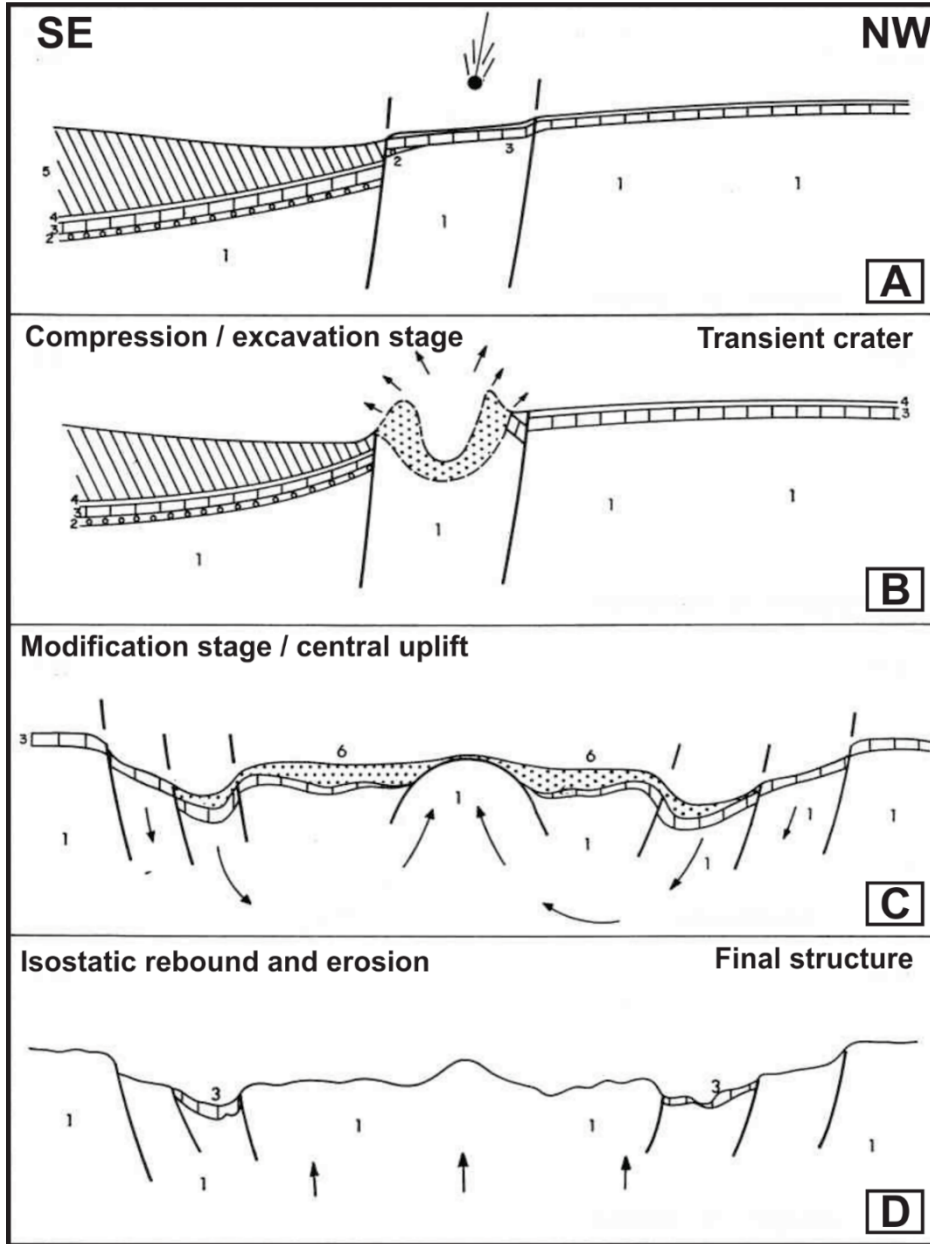


Figure 14. Schematic cross sections showing the progressive development of the Charlevoix complex impact structure. Legend: (1) Precambrian crystalline basement, (2-4) St. Lawrence Platform sequence, (5) Appalachian nappes and (6) impact melt layer. **(A)** Geological setting of the pre-impact target region. **(B)** Impact / compression and excavation stage with the development of a transient crater. **(C)** Modification stage: paired development of the peripheral collapse and central uplift, and thinning and draping of the original melt layer over the uplifted rocks. **(D)** Stabilisation stage: the final structure consists of the central uplift of deeper rocks, surrounded by undulating plateau, the annular trough and terraced rim produced by inward movement along stepped normal faults.

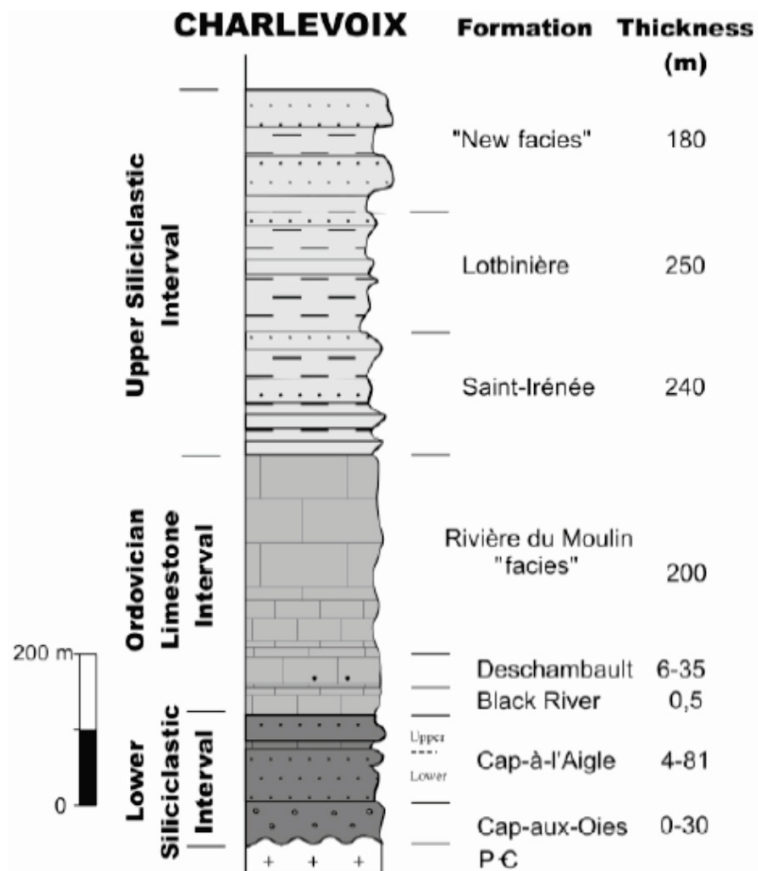


Figure 15. Stratigraphic column of the Cambro-Ordovician St. Lawrence Platform rocks of the Charlevoix area (figure not to scale; from Lemieux et al., 2003).

FIELD TRIP LOG

Note: UTM coordinates in the road log refer to the NAD 83 map projection.

SITES 1a and 1b. Panoramic view of the Charlevoix impact structure

Highway 138 – Site 1a: 382993 E, 5251491 N; Site 1b: 384970 E, 5254131 N

These lookouts are located on the outer rim of the Charlevoix impact structure. The panoramic views include the main regional-scale landmarks of the exhumed roots of the impact structure within Precambrian basement gneiss. The highland and nested hills in the far background correspond to the annular hills and central uplift centered on Mont-des-Éboulements, which stands 780 m above sea level. The lower Rivière-du-Gouffre valley and farmland corresponds to the impact annular trough comprising a few scattered outcrops of the St. Lawrence Platform sediments. Logan's Line runs outboard from the St. Lawrence River shoreline, cutting across l'Île-aux-Coudres as part of the Appalachian Belt.

SITE 2. Normal faulting after post-impact isostatic reequilibration

Rivière-du-Moulin – 386077 E, 5253156 N

The waterfall at Rivière-du-Moulin exhumes a steep, northeasterly dipping normal fault that juxtaposes Precambrian footwall gneiss against Ordovician hangingwall limestone. Polymictic breccia occurs along the fault plane. Such faults, which occur as part of the annular trough, are interpreted as post-impact readjustment structures driven in part by isostatic reequilibration.

SITE 3. Annular trough and bounding faults

388542 E, 5254685 N

This lookout provides a panoramic view of the western segment of the annular trough with the external terraces in the background.



Outcrops across the road comprise northwest striking, nearly upright tilted Paleozoic sediments in the hanging wall of a steep reverse fault bounding the annular trough. Note the abundance slickenside-ornamented surfaces.



SITE 4. “Exotic” enclave of Ordovician limestone in faulted Precambrian basement
Cap-au-Corbeau – 390242 E; 5253338 N

This outcrop features spectacular *mylolisthenite* typical of the fault zones bounding the annular trough. The steep southeasterly dipping fault zone comprises highly fractured Precambrian charnockitic basement gneiss. Clasts are abundant and appear to be derived largely from the immediate wallrock.

Remarkable among the clasts is a metre-size “enclave” of Ordovician limestone. Emplacement of such an “exotic” enclave within the fault zone may be the result of up-and-down fault readjustment whereby a slice of overlying limestone is cut off, included, and moved down within the fault zone. Alternately, such structurally ripped wedge may have been forcefully pushed down within the basement fracture zone.

The occurrence of clasts of welded brecciated rock within the mylonite matrix suggests protracted cataclasis. In the field, one can observe the variability in clast size. The outcrop also features a sharply bounded, 20 cm wide breccia dyke intruding basement gneiss.

SITE 5a. Les Éboulements - The probable epicentral region of the October 20, 1870 magnitude 6½ (or M_I 5.8?) earthquake

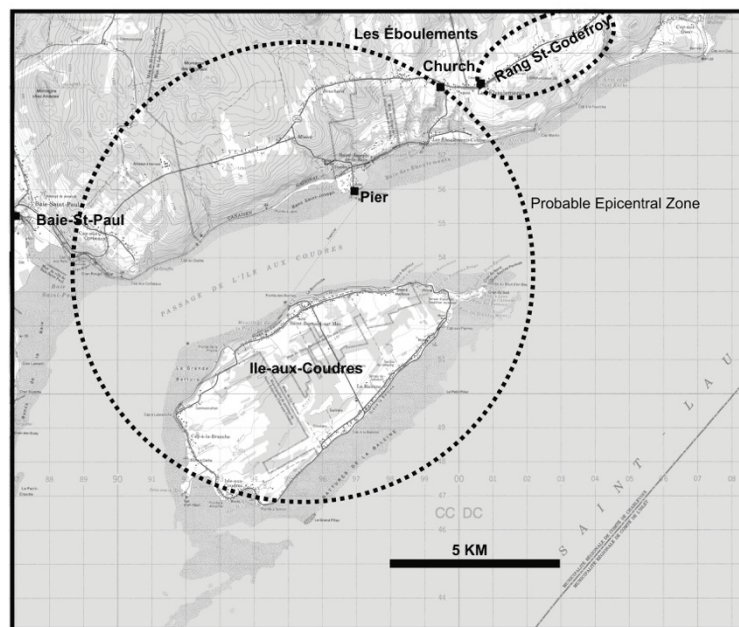
The 1870 earthquake is one of five earthquakes rated at magnitude 6 or more that were centered in the Charlevoix Seismic Zone (CSZ). The main shock occurred on October 20 at around 11:30 a.m. local time. The impact of this earthquake was reported in many newspapers of the time (Gouin, 2001). Similar to other M 6+ Charlevoix earthquakes, the main shock was felt from Nova Scotia in the east to Lake Superior in the west and as far south as Cincinnati, Ohio, some 1500 km from the epicenter. The felt area of 3,000,000 km² corresponds to a magnitude $m_b(L_g)$ 6 according to Gouin (2001) whereas the Geological Survey of Canada rates its magnitude at 6.5, mainly based on maximum damage estimates and felt area. Recently, the magnitude was revised to between M_I 5.5 and M_I 6.0, with a best estimate of M_I 5.8. (M_I : Moment Magnitude based on intensity) based on comparisons between felt reports at common locations for the 1870 earthquake and the M 6.2 1925 Charlevoix and M 5.9 1988 Saguenay earthquakes (Ebel et al., 2011). The maximum damage was reported in the surroundings of the villages of Baie-St-Paul and Les Éboulements, and at l'Île aux Coudres, which makes this area a likely location of the epicenter. There, intensity reached IX–X on the modified Mercalli scale (MMI; Gouin, 2001). Between October 20, 1870 and February 1871, aftershocks were felt almost daily in the epicentral region.

Newspapers in Quebec City reported the extensive damage caused in Charlevoix by this earthquake. In those days, Charlevoix was not linked to Quebec City by telegraph and most traveling was done by boat. In days following the main shock, boats arriving from the epicentral region provided newspapers with letters from inhabitants and stories of damage. Based on these accounts, we know that the earthquake was sufficiently powerful to cause landslides and soil liquefaction in the epicentral region. Damage was reported to most houses, including complete destruction of some dwellings in Baie-Saint-Paul, Saint-Urbain, Île aux Coudres, and Les Éboulements. At the latter place, four newspapers mention the death of two children.

Cross-referencing these reports with the census of 1861, we can pinpoint where these children were most probably living. The parish registry provides the names of the fathers of these two children (Charles Tremblay and Prospère Miville). These two persons lived in the Rang St-Godefroy. We know that this area was badly hit by the earthquake. Newspapers mention some important buildings that were damaged such as the residences of Mr. Clement, Member of the Provincial Parliament for Charlevoix, and Dr. Laterrière, owner of the grain mill and the church. In the same excerpt, we find that all houses were more-or-less damaged by the earthquake. Someone who

visited Les Éboulements in 1872 noted that most houses had greatly suffered by the earthquake of 1870, with some completely demolished.

Interestingly, the *Le Canadien* newspaper mentions that the damaged houses are of stone (wall) construction, a building type more susceptible to damage caused by strong ground motions. In addition, the neighbourhood where the two children were killed is not underlain by thick unconsolidated deposits. In fact, bedrock is about 10 m below the surface in this area. Assuming that the epicenter was very close to the damaged area, it is possible that the extreme damage reported there could be due to a near-source focusing effect or a topography effect that enhanced strong motions.



Location of the Rang St-Godefroy, where the two children were killed, with respect to the assumed epicenter of the October 20, 1870 main shock.

SITE 5b. Panoramic view of the Logan's Line and Appalachian front

Les Éboulements

Background:

The Canadian Appalachians stretch from the northernmost tip of Newfoundland through Nova Scotia, Prince Edward Island and New Brunswick into southern Quebec. The Appalachian Orogen defines a linear mountain belt that was formed by the closure of the late Neoproterozoic-Early Paleozoic Iapetus and Paleozoic Rheic oceans, which led to accretion of several oceanic and continental arc terranes, and microcontinents to Laurentia (see van Staal, 2005 for a review).

The Canadian Humber Zone occurs in western Newfoundland and southern Quebec. It is underlain by the remnants of deformed Late Neoproterozoic-Ordovician rocks deposited on the crystalline basement of the Grenville Province during rifting and passive margin development (Lavoie, 2008). Deposition was influenced by the geometry of the passive margin made of a series of re-entrants and promontories (Fig. 11A). The western boundary of the Humber zone is generally defined as the limit of penetrative macroscopic Paleozoic deformation and is commonly referred to as the Appalachian structural front. The western boundary of structurally transported rocks, which is commonly coincident or nearly so with the structural front, is referred to as the Logan's Line.

During the middle to late Arenig (ca. 475 Ma) the passive Humber margin in Newfoundland and Quebec was converted into a convergent margin as a result of progressive loading by an overriding composite oceanic terrane comprising parts of the Dunnage Zone and collision of a microcontinent (Dashwoods) during the Ordovician Taconic Orogeny. Underthrusting of the margin and obduction of oceanic terranes lead to foreland- propagating (i.e., towards the northwest in present coordinates) emplacement of the large thrust sheets onto the Humber margin, burial and regional metamorphism, and the development of a foreland fold and imbricated thrust belt (Fig. 11B & C). Rocks of the Humber zone were also variously affected by continuing closure of Iapetus and further accretion that occurred outboard of the margin during the Silurian Salinic Orogeny (accretion of Ganderia) and Devonian Acadian Orogeny (accretion of Avalonia). In addition, opening of the modern Atlantic has reactivated rift faults related to Iapetus, which have obscured the original relationships and modified structural levels between the Appalachian belt, the St. Lawrence Platform and Grenville basement.

Stop description:

At this panoramic stop, one can see the Appalachian Belt on the south shore of the St. Lawrence. The belt extends underneath the River and ends in between the northern shoreline and Ile-aux-Coudres, where faults marking Logan's Line overthrust the autochthonous units of the St. Lawrence platform overlying the Precambrian Grenville basement (Fig. 11B). Rocks of the Ile-aux-Coudres are apparently unaffected by impact-related structures. This implies that differential uplift (aided by structures such as the St. Laurent fault, which has a long and complex movement history) or post-impact reactivation of the Appalachian structural front.

SITE 6a. Shatter cones in Ordovician limestone

Cap-aux-Oies – 407220 E; 5260868 N

Striated fracture surfaces typical of shatter cones are recognizable in places at low tide on limestone bed surfaces. Note that they are preferentially developed in thick and more homogeneous beds. Cone axes generally trend towards and fan around the center of the impact structure.



SITE 6b. Mylolisthenite dyke and sill-like injections in Ordovician limestone

Cap-aux-Oies – 407445 E; 5260572 N

Outcrops along the beach feature numerous thin and variably oriented mylolisthenite dykes and sill-like injections within Trenton limestone. Note the variability in clast content and size (up to 2 cm), and in matrix colour between injections. Intrusive boundaries are commonly irregular.

Light-grey mylolisthenite injections commonly feature more abundant and larger clasts and less regular intrusive contacts than the thinner and darker injections. The presence of blue quartz fragments, presumably derived from the crystalline basement, suggests the magnitude of breccia transport.

SITE 6c. Impact fracturing in Ordovician limestone

Cap-aux-Oies – 407179 E; 5260365 N

This outcrop displays a number of impact-related, closely spaced minor faults and fractures. The occurrence of mylolisthenite injections in such fracture zones confirms their origin.

SITE 6d. Duplication of the Ordovician sequence

Cap-aux-Oies, 406499 E, 5261276 N

Arkosic sandstone and limestone are duplicated after lateral telescoping due to the central uplift. Mylolisthenite injections occur along faults. Shatter cones with well-marked striations are developed in more-argillaceous limestone beds.

SITE 7. Map- and mesoscopic-scale impact structures

Cap-aux-Oies to l'Anse-au-Sac

This group of stops is located ~6.5 km from the centre of the impact structure at Mont des Éboulements, near the outer limit of shocked quartz metamorphism. Proceeding northerly along the beach from Cap-Corneille to Pointe-au-Père, the Ordovician sedimentary succession crops out in step-faulted contact with Precambrian orthogneiss. While a number of northeast-striking fault segments are viewed as reworked splays of the rift-related St. Lawrence fault zone, segments at high angles to the latter are attributed to the impact. In view of the widespread occurrence of mylolisthenite dikes and shatter cones, the origin of minor faults and folds remains somewhat contentious.

SITE 7a. Fault contact between Ordovician Trenton limestone and Precambrian basement.

Cap Corneille – 408231 E, 5261944 N

The sedimentary succession is crosscut by variably oriented mylonite dikes up to 15 cm thick. Mylonite injections are more difficult to recognize in basement gneiss. Also note the local occurrence of vesicles in the dark-green-coloured breccia matrix and of a silicification fringe along the wallrock contact.

SITE 7b. Mylonite dike in Ordovician limestone

408302 E, 5262033 N

This outcrop shows a mylonite dike in Ordovician limestone near the contact with basement gneiss. The dike is pinched and strikes nearly at right angles to the fault segments bounding the Ordovician sediments. Note the presence of vesicles and the fluidal structure of the breccia.

SITE 7c. Shatter cones in limestone

408378 E, 5262014 N

Striated fracture surfaces in limestone are evidence for shatter cones. The latter tend to be preferentially developed in mechanically homogeneous and tenacious rock types. This is well illustrated at this occurrence, where a truncated shatter cone defined by opposite and converging striated fracture surfaces occurs in a 20 cm thick limestone bed.

SITE 7d. Fault bounded Cambrian quartzite

408573 E, 5262162 N

A fault-bounded, 30-meter bloc of contrasting Cambrian quartzite occurs encased in a fault play juxtaposing Trenton limestone and quartz pebble conglomerate of the Cap-aux-Oies Formation. Note also the occurrence of centimetre-size shatter cones.

SITE 7e. Brecciated basement gneiss within Ordovician sediments

Pointe au Père – 408810 E, 5262647 N

The outcrop is located at the edge of a kilometre-size fault-bounded wedge of Precambrian basement orthogneiss within Paleozoic sediments. The orthogneiss is brecciated and locally pulverized, forming a cataclastic breccia. The fine-grained matrix comprises fragmental crystals derived from the wallrocks.

SITE 7f. Brecciated basement gneiss and mylonitite dikes

Pointe-au-Père - 408950 E, 5263050 N

Mylonitite dikes carrying centimetre-size gneiss fragments also occur within flanking limestone. Among them, one dike appears to be aligned with the cataclastic breccia in basement gneiss, hence supporting the hypothesis of impact-driven brecciation and forceful emplacement. Note, however, that similar breccias also occur along the St. Lawrence fault zone away from and unrelated to the impact structure.

SITE 8. Impact-related fault contact between Precambrian basement and Paleozoic sediments.

Ruisseau Jureux – 408721 E, 5265850 N

This stop is located in the northeast flank of the central uplift. Precambrian basement granitic orthogneiss occurs in close proximity to Ordovician clastic sediments and limestones of the Cap-à-l'Aigle and Cap-aux-Oies formations. The granitic orthogneiss features fractured surfaces with converging sheaf lineations defining decimetre-size shatter cones.

SITE 9. Reworked contact between Precambrian basement granite and Cambrian quartzite.
409002 E, 5266060 N

Myololsthenite intervenes along the contact between Precambrian basement granite and overlying Cambrian quartzite.

SITE 10. Appalachian deformation in Paleozoic platform sediments
Saint-Irénée – 409381 E, 5267941 N

Paleozoic sediments are fault bounded against Precambrian basement gneiss. Strata are moderately dipping towards the northeast. Calcareous sandstone forms olistostromes, and locally developed schistosity matches that of the St. Lawrence fault. Although most of the deformation structures are presumed syndimentary, the nature and importance of impact and Appalachian driven deformation remain controversial.



Striated fracture surface developed after soft sedimentary deformation and lithification.

SITE 11a. Contrasting brittle fracturing in basement gneisses outside and within the Charlevoix impact structure.



Grenville gneisses outside the impact structure generally exhibit massive, meter-scale fracture spacing (left) in contrast with the decimeter-scale fracture spacing typical of the impact region (right). This makes the impacted rocks significantly more prone to erosion as illustrated by the RADAR (Figure 6). It is striking that most of Charlevoix's farmland is located within the impact structure.

SITE 11b. Suevite-type breccia dyke

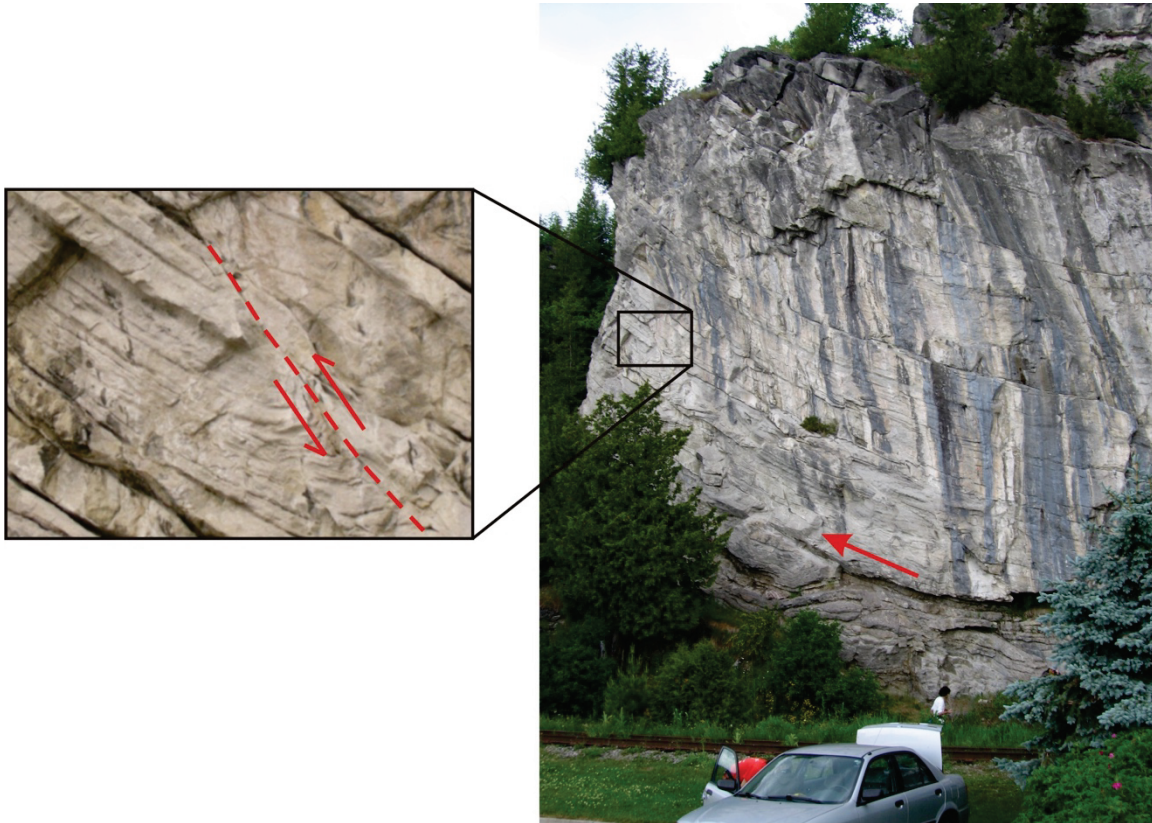
Gros Ruisseau – 408876 E , 5272811 N

This stop is located ~10 km from Mont-des-Éboulements. Basement gneiss is crosscut by a suevite-type breccia marked by glassy black matrix and vesicles. Prehnite is the chief mineral in the breccia. The gneiss contains a schistose cataclastic zone, 1 x 3 m in extent, with abundant chlorite and albitic plagioclase formed during retrograde metamorphism.

SITE 12. Thrust faulting in Paleozoic sediments

Pointe-au-Pic – 414069 E, 5275492 N

This outcrop of Paleozoic limestone is located in the impact-related annular trough, a short distance from the outermost foreland Appalachian thrust. While protected from erosion by their basal location in the annular trough, the rocks show a number of northwest-directed minor thrust faults, which could be interpreted either as post-impact rebound faults or as outermost manifestations of Appalachian telescoping.



SITE 13 a. Saint-Hilarion church

The stone walls of the Saint-Hilarion church illustrate the diversity of Precambrian basement rocks of the Charlevoix region, namely of the Saint-Urbain anorthosite-mangerite-charnockite-granite (AMCG) complex emplaced in the late stage of the Grenvillian orogeny ca. 1030 Ma.

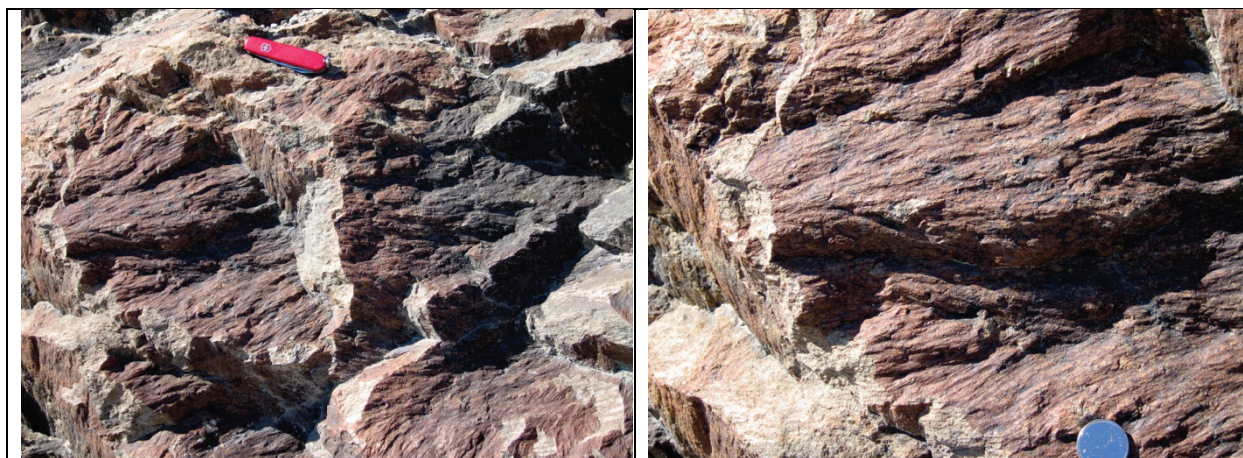
SITE 13 b. Saint-Hilarion lookout

This lookout offers a panoramic view of the Charlevoix impact structure including the central uplift, the hill ring, annular trough and peripheral terraces with the Laurentian plateau in the background.

SITE 13 c. Shatter cones at the discovery outcrop

Saint-Hilarion – 395225E, 5268892 N

Shatter cones at this stop were discovered by Dr. Rondot in 1966, providing the first evidence for the Charlevoix impact structure. They occur in Precambrian basement charnockitic gneiss at ~8 km from Mont-des-Éboulements. They lack a systematic preferred orientation due to post-impact isostatic fault readjustment along two sets of moderate- to steeply-dipping fractures oriented N162°, 64°SW dip and N78°, 56°SE dip. Prehnite occurs as small, white-coloured mats within fractured gneiss. Note also the thin breccia injections.



SITE 14. Paleozoic Outlier of the Annular Trough

Vertically dipping fossiliferous limestone beds outcrop as a kilometre size outlier in normal fault contact with recrystallized meta-anorthosite of the Saint-Urbain AMCG complex. A few similarly occurring outliers of Paleozoic rocks occur in the northern part of the annular trough. The local preservation of Paleozoic platform cover rocks in the northern part of the annular trough indicates that there was a thick and continuous platform sediments cover over the target region prior to impact.

SITE 15. Panoramic view of the central uplift range

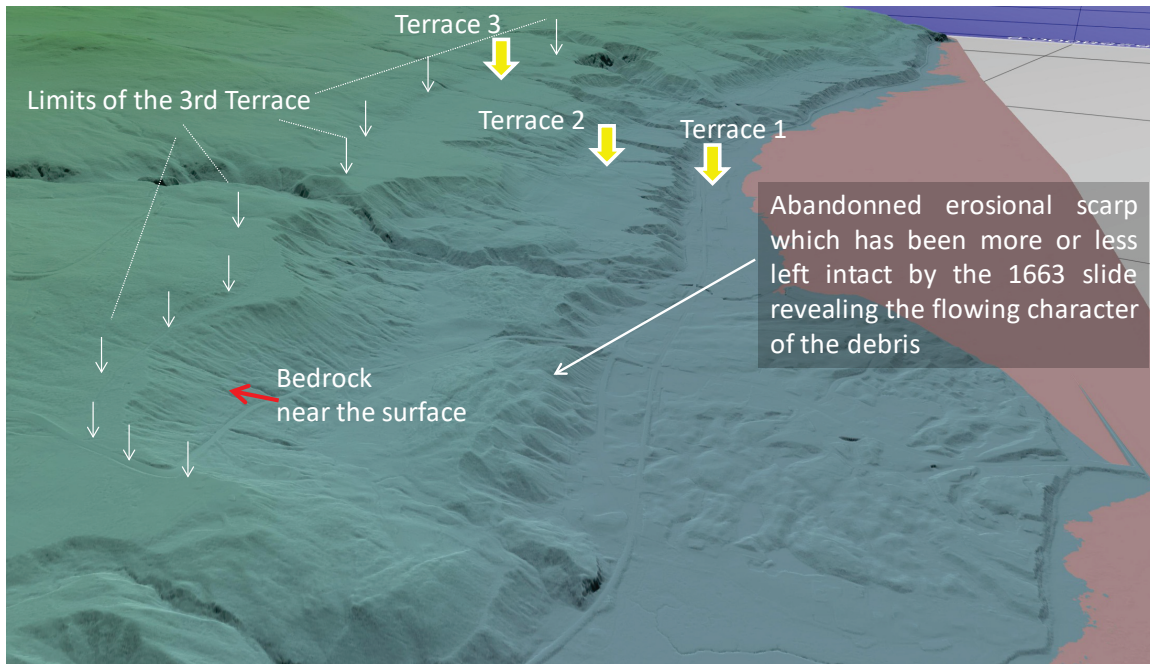
Pointe-au-Pic - Highway 362 – 412133E, 5274059N



SITE 16. Saint Joseph-de-la-Rive - Landslide caused by the February 5th 1663 (J. Locat)

The Saint Joseph-de-la-Rive landslide was caused by the February 5th 1663 earthquake and gave the name to the nearby village 'Les Éboulements' (meaning landfall). A 3D view of the landslide is shown below. The landslide extends over a distance of about 1300 m with over a vertical height of about 160m, and a width of about 700 m. It involved a total volume estimated at about 6 hm³. The slide debris consists of Quaternary sediments composed of silt and sand with some boulders. It is believed that the groundwater conditions at the contact between the Quaternary sediments and the bedrock, beneath Terrace 3, may have favored the development of some artesian pressures, making the overall sediment column more sensitive to strong earthquake shaking (lower shearing resistance). The sliding mass mainly involved sediments making up the 3rd terrace. The remoulding energy was enough to give the failed mass a sufficiently low strength to flow over the escarpment of Terrace 1 and across the tidal flat over a distance of ~ 700 m.

The February 5th 1663 SJR landslide



SITE 17. Les Éboulements – Seismograph station A54, Canadian National Seismograph Network

Since October 1977, the CSZ has been monitored by a microseismic network of between 6 to 8 stations located on both shores of the St. Lawrence River (Figure 1). Between 1977 and 1988, the Charlevoix seismograph network consisted of a six to seven component vertical short-period analogue network (A11, A16, A21, A54, A61, A64). The signals from the stations were radio-transmitted to a central node where they were archived on a magnetic tape together with a time signal from a local clock.

In November 1988, the Charlevoix local network became the Charlevoix Local Telemetered Network (CLTN), a digital three-component short-period array. The data, sampled at 80 Hz, were radio transmitted to a central node where timing was added. There, a detection algorithm analyzed each vertical component for seismic events, and, for each trigger, stored a time slice of the whole CLTN data.

Later, in January 1994, the station LMQ became a digital broadband Canadian National Seismograph Network (CNSN) station, with GPS timing and continuous archival of the data in Ottawa. Finally, in August 1994, each CLTN station was upgraded to a high gain short-period digital instrument with 100 Hz sampling rate and GPS timing.

The current local network allows the detection of earthquakes with a magnitude of about $M_L > 0.5$ (approx. $M_N > 1.0$). Based on the recognition of earthquake multiplets, we estimate the relative hypocenters locations to be approximately ± 1.5 km for hypocenters within the seven station network. Absolute locations are more difficult to estimate due to the dependence upon the velocity model.

The rate of earthquake detection and location varies between 200 and 250 per year. Of this number, about 5 are felt locally (Nuttli magnitude (m_N) ≥ 2.5), about 2 or 3 exceed (m_N) 3.0. A magnitude $m_N \geq 4.0$, occurs every three year on average and a magnitude $m_N 5.0+$ every few decades (1979; 2005). Magnitude $m_N \sim 5.0$ ($M_w \sim 4.5$) is usually the threshold where some damage occurs.

The station we are looking at is station A54 (Misère, Qc) which has been in operation since 1977, first as a vertical only, then a short period three-component in 1988 and finally as a high broadband three-component in 1994. The data is sent in real time to the Geological Survey of Canada in Ottawa where it is archived. The data can be extracted by anyone using the

autodrm protocol at www.earthquakescanada.ca . Similar to other CSZ seismograph stations, the site is located on bedrock and is known to have very low background noise.

In addition, the site also includes an ETNA digital strong motion instrument that once triggered, stores data internally. All seismograph sites in CSZ have a strong motion recorder. All together, some 12 strong motion instruments are deployed in the CSZ, plus two that belong to Hydro-Quebec.





Views of seismograph/accelerograph station A54: A) View of the antenna; B) View of the vault looking towards Ile-aux-Coudres with Pierre Archambault, retired professor, who helps us fix station problems when they occur (Thank you Pierre!); C) Inside of the vault showing the seismometer (upper right) and the Etna strong motion instrument (black box). The vault is not heated. Insulation protects the seismometer from temperature variations.

END OF FIELD TRIP