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Complex Faulting Confounds Earthquake Research in the Charlevoix Seismic Zone, Québec

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Following every earthquake felt in eastern North America, journalists ask the eternal question: "Which fault is responsible for this earthquake? ". In intraplate environments, such as the Charlevoix Seismic Zone (CSZ), Québec, Canada, a definite answer seldom exists. Seismologists face major difficulties: the mid-crustal depth of most earthquakes; the geological complexity of the Precambrian basement where most earthquakes occur; and the poorly known fault locations. Fortunately, seismologists receive help from other geoscientific fields, most notably remote sensing, seismic methods and potential fields. This article describes the integration of these geophysical tools to better understand the earthquake-fault connection in the CSZ, the most seismically active zone of eastern Canada. It is found that most micro-earthquakes occur within highly fractured blocks bounded by geological faults of regional extent. Our interpretation is different from the common assumption that earthquakes, independently of their size, occur along regional faults.

The CSZ is anomalously active for an intraplate environment: five earthquakes exceeded magnitude (M) 6 since 1663 and more than 250 micro-earthquakes are recorded there every year. Between October 1977 and December 1999, the local seismograph network recorded more than 2500 earthquakes with magnitudes (M) between -1.0 and 5.0. Epicenters define a 30 by 85 km ellipse with the long axis parallel to the St. Lawrence river (Figure 1). At depth, these earthquakes occur solely in the Precambrian basement from the surface to 30 km depth, with two thirds between 7 and 15 km. Earthquakes are not distributed uniformly across the seismic zone, but concentrate in groups separated by less active areas (Anglin, 1984; Lamontagne, 1999). This fact suggested that some geological characteristics, most probably faults, controlled the earthquake distribution. To explore this hypothesis, faults of the Precambrian basement are located and compared with earthquake focal mechanisms and spatial distribution of earthquakes.

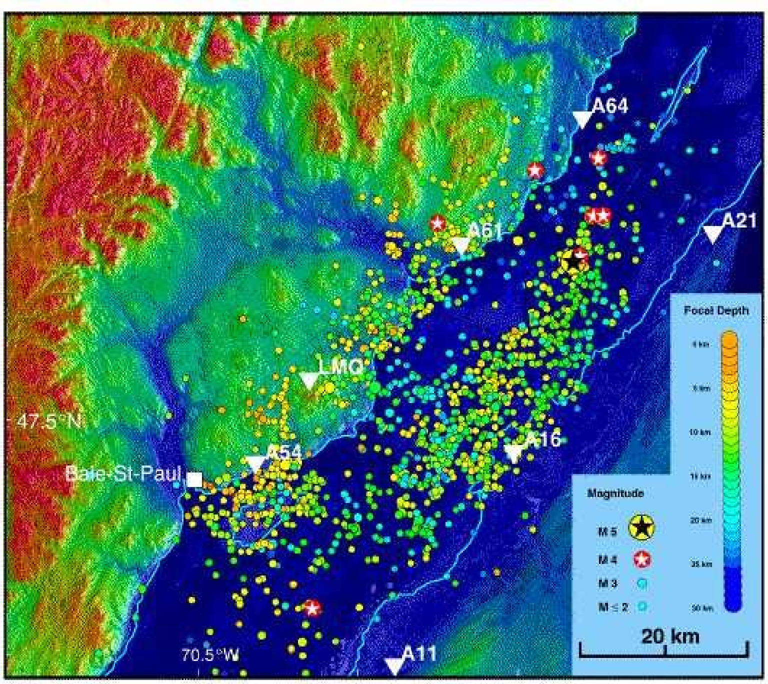

Figure 1: *Chromo-stereoscopic image (about 80 km by 90 km; 30-m pixel size) that integrates the RADARSAT-SAR ortho-image with terrain elevation and seismicity (each data set with its own colour range). For the elevation, the colour range varies from 0 m in blue to 1100 m in red. The texture of the land surface comes from the RADAR data. While the south shore is a gently rolling landscape, the north shore is a mixture of rugged highlands, plateaus and valleys, separated by dramatic changes in elevation. A Devonian meteorite impact (350 Ma) has shattered the plateau, creating a semicircular depression 56 km in diameter. The earthquake hypocenters (circles) for January 1978-September 1999 are overlain, with colors related to focal depth. White triangles are the stations of the Charlevoix Local Seismograph Network, part of the GSC's Canadian National Seismograph Network (www.seismo.nrcan.gc.ca).*

In the CSZ, the seismogenic Precambrian basement outcrops only on the north shore of the St. Lawrence River (Figure 2). It is cut by faults created during four major tectonic events: the Grenvillian collision (1100 to 900 Ma); the rifting episode related to the opening of the Iapetus Ocean (700 Ma); the Taconian reactivation of these faults at the closing of that ocean (450 Ma); and finally, a Devonian meteor impact (350 Ma; Rondot, 1979). Currently, earthquakes are interpreted as reactivation of Iapetan faults. These faults are mapped in the field and correspond to lineaments in remote sensing imagery. Under the St. Lawrence River, however, these structures are hidden by several kilometres of Appalachian nappes and hundreds of meters of Quaternary sediments. Fortunately, remote sensing imagery and geophysics (seismic methods, gravity, magnetics) can highlight geological faults of the Precambrian, at the surface and at depth under the Appalachian nappes.

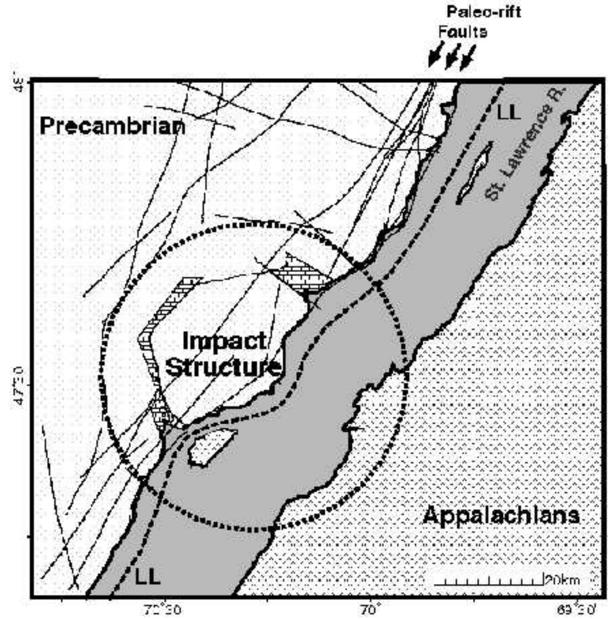

Figure 2: *Main geological characteristics of the CSZ: LL: Logan's Line; lines in the Precambrian: mapped faults (Rondot, 1979).*

Seismological information

Between 1977 and 1999, the CSZ has been the only eastern Canadian seismic zone with a seismograph network sufficiently dense (6 to 8 stations) for routine hypocenter determinations. The precision of the hypocenters (± 2 km) is sufficient to correlate earthquakes and geological faults. A total of 25 focal mechanisms of M 2.0 to 6.2 earthquakes provides for each earthquake the strike and dip of two nodal planes (one of which is the rupture plane), and the nature of faulting. In general, CSZ earthquakes are produced by strike-slip to reverse faulting on fault planes with orientations not always consistent with those of the rift faults (Lamontagne, 1999).

Remote sensing data

On land, remote sensing imagery, mainly radar, is central to our interpretation of geological faults. Passive remote sensing systems, such as SPOT or Landsat, record the energy reflected by the Earth's surface at frequencies roughly equivalent to those detected by our eyes. Landsat images of the region were examined but did not yield any structural information not already described in geological maps. Synthetic Aperture Radar (SAR), on the other hand, is an active system that sends a microwave pulse toward the Earth's surface and measures the amount of energy reflected with minimum interference from atmospheric conditions. For geological applications, a steep incidence angle of the beam best enhances terrain topography, which is often related to structural lineaments. Geoscientific applications benefit noticeably from the flexibility in image acquisition of the Canadian SAR system RADARSAT with its variety of viewing modes, beams, incidence angles (10 to 59), and products. The RADARSAT-SAR data used in this study consist of a standard beam scene (S2) acquired March 5, 1996 from a descending orbit. The image is in slant range with a pixel spacing of 8.1 m in range by 5.3 m in azimuth, and oriented along the satellite track, with approximate viewing angles ranging from 24 to 31. The illumination direction is approximately from the west to the east.

A geometric correction method developed at the Canada Centre for Remote Sensing (Toutin, 1995) is used to ortho-rectify the RADARSAT imagery with a digital elevation model (DEM) in the UTM projection. The method takes into account and corrects for all the distortions related to the full geometry of viewing (e.g., viewing angle of the sensor, position and velocity of the satellite, and curvature, rotation and elevation of the earth), and the map projection. The ortho-image has a final planimetric positioning accuracy of 30 to 40 m. A Gamma adaptive filter (Lopes et al., 1993) is incorporated during the re-sampling process to reduce the SAR speckle. All geographical and geological features are thus more accurately located and plotted on the ortho-rectified image.

The last step is the integration of the ortho-RADARSAT imagery with the DEM to generate a 3-D chromo-stereoscopic image (Figure 1). Chromo-stereoscopy is a method which enables the display and perception of depth from multi-source data, such as remote sensing and geoscientific (Toutin and Rivard, 1997). The third dimension (the terrain elevation in this study) is colour coded into the image, blue for the lowest elevation and red for the highest, then decoded with the refractive ChromaDepthTM glasses (Steenblik, 1986). The resulting chromo-stereoscopic image is a 2D colour composite image, which can be viewed and interpreted monoscopically, but which "jumps" into 3-D when viewed with ChromaDepth[4] glasses.

Geophysical data sets

Regional magnetic maps show the spatial distribution of geological units with different magnetic susceptibilities. Sedimentary rocks have the lowest average susceptibility and basic igneous rocks, the highest. In the CSZ, these differences in magnetic susceptibilities result in a highly variable field where the Precambrian rocks outcrop, and in a smooth field under the magnetically transparent Appalachian nappes. The magnetically contrasting areas correspond to variations in Precambrian lithologies and in Precambrian basement depth under the Appalachians. A convenient representation of the depth of the Precambrian basement is offered by the solutions of the Euler deconvolution. In this method, steep gradients in the potential fields are interpreted as sources of various shapes and depth (Thomson, 1982). Euler solutions with N=0 provide an estimate of the location and depth of a sub-vertical contact separating lithologies with contrasted magnetic susceptibilities (Figure 3). Therefore, where the Precambrian outcrops, Euler solutions are shallow, while under the St. Lawrence River, they deepen along with the Precambrian basement. Where the Precambrian is deeper than about 6 km (from seismic information), no Euler solutions (i.e. almost no gradient) exist.

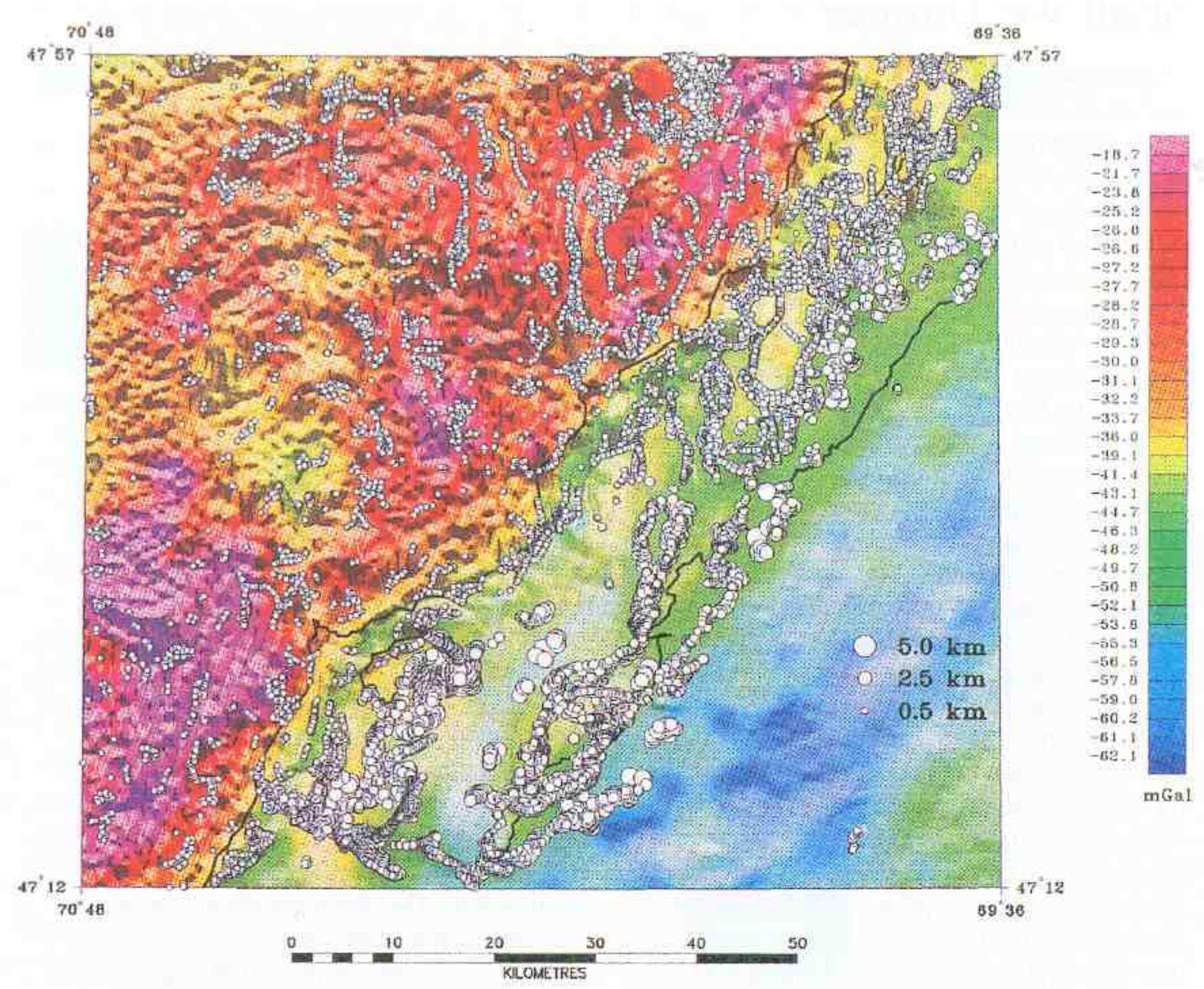

Figure 3: *Integration of the Bouguer anomaly map (colour) with the total magnetic field (shadows), and solutions of the Euler deconvolution (N=0) of the magnetic field. The circle sizes vary according to the relative depth of the solutions (shallow solutions are small due to the outcropping Precambrian Shield). Shorelines are shown as black lines.*

Bouguer anomaly maps represent the gravity field, which depends mainly on the crustal distribution of rock densities. Until 1994, the CSZ Bouguer anomaly map was based solely on 300 land measurements, leaving out the most seismogenic part of the CSZ, over the St. Lawrence River. In August 1994, the coverage was completed using a LaCoste and Romberg dynamic gravimeter installed on a small boat. Offshore, the Bouguer anomaly is now better resolved than that on land (Keating, 1998; Figure 3).

During the early 70's, the Société Québécoise d'Initiatives Pétrolières (SOQUIP) lead a series of offshore seismic reflection surveys to define the hydrocarbon potential of eastern Québec. SOQUIP kindly provided paper copies of the profiles, and later, the digital data from one seismic line for reprocessing. Although of variable quality, most profiles show sub-horizontal reflectors, some in the Quaternary deposits, some in the underlying Precambrian basement and in the Appalachian nappes. The Precambrian-Paleozoic interface is generally difficult to identify, probably due to the small acoustic impedance contrast between the indurated Ordovician platform carbonates and the underlying Precambrian.

To define the geological structures along the St. Lawrence River, the CSZ was studied along four profiles (see details in Lamontagne, 1999). Each profile had measured and computed Bouguer gravity anomalies, crustal density model, Euler solutions, structural interpretation and one or more nearby seismic profiles. For gravity modelling purposes, density contrasts with the Grenville rocks were -0.15 $g \cdot cm^{-3}$ for the Ordovician-Appalachian rocks, and -0.5 $g \cdot cm^{-3}$ for the Quaternary sequence. The structural interpretations integrate gravity, magnetics, and seismic information.

Interpretation

This analysis has brought to light the main structural features of the CSZ (Figure 4). In the NE portion, the Precambrian basement is cut by a series of long normal faults parallel, and at high angles to, the river axis. In the center, the impact crater controls fault positions, at least down to its assumed 10 km depth extent. Whereas most rim faults are conspicuous in the radar images, inside the Charlevoix impact structure, lineaments are less clear. This is possibly due to the erosion of highly fractured rocks. Beneath the St. Lawrence River, a small basin, possibly controlled by shallow faults, is found near the theoretical position of the peripheral graben of the impact structure. Finally, in the SW zone, the Precambrian basement, deep under the Appalachians, is cut by normal faults parallel, and at high angles to, the river axis. The CSZ is a transition zone between the SW part, with its steeply-dipping faults with large normal throw, and the NE part, with its en echelon normal faults with progressive deepening of the basement under the Appalachians.

With the obtained structural map (Figure 4), earthquakes clearly distribute on more than the regional geological faults. Contrasting with its conspicuous surface and potential field expression, the SE-dipping St-Laurent fault is not itself particularly active. It acts more like a boundary to the activity than as an active structure. The NW side of the St-Laurent fault (i.e. the foot-wall) has most of the shallowest micro-seismic activity, whereas the hanging-wall has weaker and deeper activity. Similarly, the South Shore fault is a SE boundary to the seismicity. Thus, the three large Iapetan faults, the St-Laurent, South Shore and Charlevoix faults, seem to bound these active volumes rather than being active themselves. Perhaps these faults separate blocks with different fracturing levels. Conceptually, the foot-walls of these three normal faults may be highly fractured, and/or subject to high pore-fluid pressures. The best correlation between an Iapetan fault and earthquakes is found in the NE part of the zone, outside the crater. There, hypocenters define a narrow steeply-dipping volume, possibly the Charlevoix fault. Inside this volume, earthquakes may or may not occur directly on the main fault, as shown by the variability in the focal mechanisms.

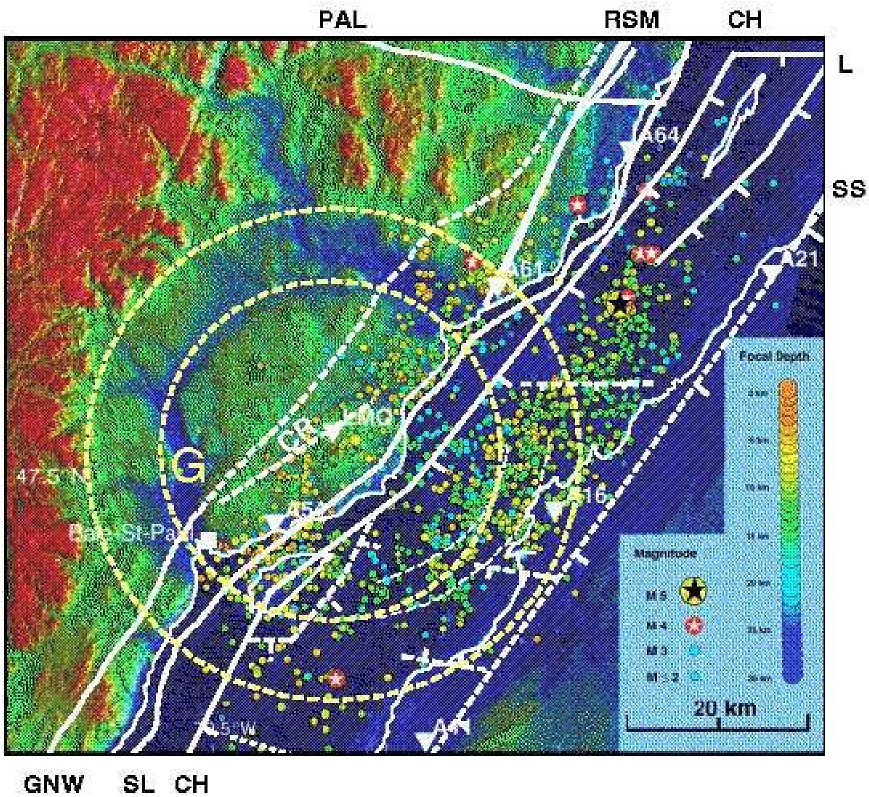

Figure 4: *Interpreted structures of the CSZ. Acronyms used: PAL: Palissades fault; RSM: Rang Sainte-Mathilde fault; SL: Saint-Laurent fault; CH: Charlevoix fault; L: Lièvres fault; SS: South Shore fault; G: peripheral graben of the impact structure; CR: crater fault; GNW; Gouffre NW fault. Epicentre and station information as in* Figure 1.

The relation between the Charlevoix impact structure and the current earthquake activity has been subject to much debate. On the one hand, those who disclaim any relationship observe that earthquakes do not distribute over the whole impact structure, but concentrate in zones parallel to the Iapetan fault (Figure 1). The lack of seismicity in the western part of the Charlevoix structure, and in most impact structures elsewhere, supports this view. According to others, however, the structure might contribute to the inherent weakness of the region. At present, it is unclear why earthquakes do not occur over the whole impact structure. Some earthquakes appear to occur on faults, possibly created as Iapetan faults, but clearly reactivated by the impact. Interestingly, most of the larger events (stars in figures 1 and 4) tend to concentrate at both ends of the CSZ, at the periphery of the impact structure. For the larger events, such as the 1925 **M** 6.2 and the 1979 m_N 5.0 earthquakes, focal mechanisms suggest that N to NE trending paleo-rift faults are being reactivated in response to regional compression. Within the impact structure, the highly fractured basement releases strain energy in small earthquakes only (m_{bLg} 3.5), with variable fault plane orientations. Concerning the possible correlations between seismic events and structural trends, some earthquakes do spatially relate to remotely-sensed and/or potential field lineaments, but not exclusively to Iapetan rift parallel faults. For lower magnitude earthquakes, smaller fractures with various orientations might be reactivated by local stresses. Since not all Charlevoix impact structure faults are currently being reactivated, it is possibly the combination Iapetan plus impact faults that gives rise to the seismicity.

For small magnitude events, the varied faulting styles imply that local stress and/or strength variations control earthquake occurrence. This contradicts the general assumption that background seismicity corresponds to regional stress systems. In our opinion, earthquakes controlled by local conditions are more likely where resistance to sliding is low, for instance as a consequence of high background pore-fluid pressures or a low friction coefficient. Interestingly, a high electrical conductivity zone has been detected by a magnetotelluric survey near station A61 (see Lamontagne, 1999). This anomaly has been explained by the presence of water or solutions in a zone of high porosity at depth deeper than 1.4 km.

The complexity of CSZ seismicity is tentatively explained by a combination of factors. CSZ fault zones may be irregular surfaces, surrounded by highly fractured rocks. The impact may have weakened some preexisting faults. These highly fractured zones respond primarily to regional stresses; however, for some smaller events, they may respond to local changes in stress and/or strength. The whole process can be enhanced, especially for deeper events, by high pore-fluid pressures (Lamontagne and Ranalli, 1996).

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