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Earthquake-Rotated Headstones as a Means of Re-evaluating Epicentral Location of the 1944 Massena-Cornwall Earthquake: New York, United States and Ontario, Canada

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Earthquake-Rotated Headstones as a Means of Re-evaluating Epicentral Location of the 1944 Massena-Cornwall Earthquake: New York, United States and Ontario, Canada

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ABSTRACT

The Massena-Cornwall earthquake (September 5th, 1944) is the largest earthquake in New York state history. Two epicenters have been previously proposed (Milne, 1949; Dewey and Gordon, 1984); however, they are separated by 15 km, an error that could associate each proposed epicenter with two different local faults. Due to the lack of standardized seismic-array data, there is value in approaching this event using an unconventional data set. The methodology of MacDonald and Wentworth (1952) was executed through ArcMap 10.5.1 to yield an area most likely to contain the epicenter. One-hundred fifty-four earthquake-rotated headstones from 15 cemeteries within ~35 km of Massena, New York/Cornwall, Ontario were measured for angle of rotation via a digital goniometer (0.1˚resolution). The mean angle of rotation is 1.9° (cf., 0.1° for unaffected, post-1944 headstones: $p<0.0001$), independent of rotation direction. Factoring in the average strike of headstones in each cemetery, an octant was projected based on whether the cemetery had predominantly experienced clockwise or counter-clockwise rotation. The area of densest overlap between the projected octants is an ~20km^2 area centered in the Saint Lawrence River (proposed epicenter at N45.014, W74.815) six miles northeast of Massena, NY. This area is bisected by the Gloucester Fault; an extension of the Ottawa-Bonnechere Graben. This project is an improvement on previous studies of the 1944-rotated headstones (e.g., Berkey, 1945) by analyzing quantitative rotational data within an ArcMap framework. These refined data implicate a rupture along an extension of the Gloucester Fault—a potential threat to the nearby Moses-Saunders Power Dam.

KEY WORDS: Ottawa-Bonnechere graben, Gloucester fault, Moses-Saunders power dam, Saint Lawrence Fault Zone, ArcMap

INTRODUCTION

The Massena-Cornwall Earthquake of September 5th, 1944, was the largest earthquake recorded in New York State history with a maximum intensity of VII (Modified Mercalli Intensity Scale) assigned to the Massena-Cornwall area (Milne, 1949). There is no widely accepted epicenter for the event with two epicenters proposed: the first at N44.975°, W74.898° (fig. 1), and the second at N44.958°, W74.723° (Dewey and Gordon, 1984; fig. 1). These proposed epicenters are separated by approximately 15 km, an error which could associate each epicenter with two different local faults. Attempts to revisit the 1944 earthquake using waveform modeling techniques, not available in 1944, have found themselves limited by the poor distribution of regional first-motion data (Bent, 1996). Seismographic data are lacking for the 1944 earthquake in two important ways: the earthquake did not record well teleseismically (at stations >1000km from epicenter), and it occurred before the major advances in seismic-array technology that occurred in the 1950's. For these reasons, we sought to approach locating the epicenter with an alternative data set. This earthquake in particular had been noted previously for its obvious rotational effects in the local cemeteries, providing the unique opportunity to use rotated headstones as a ground-motion proxy. Attributing the 1944 event to a specific fault can aid in assessing the hazard of a future seismic event of this magnitude, with the potential of costing local communities into the millions of dollars should reactivation occur.

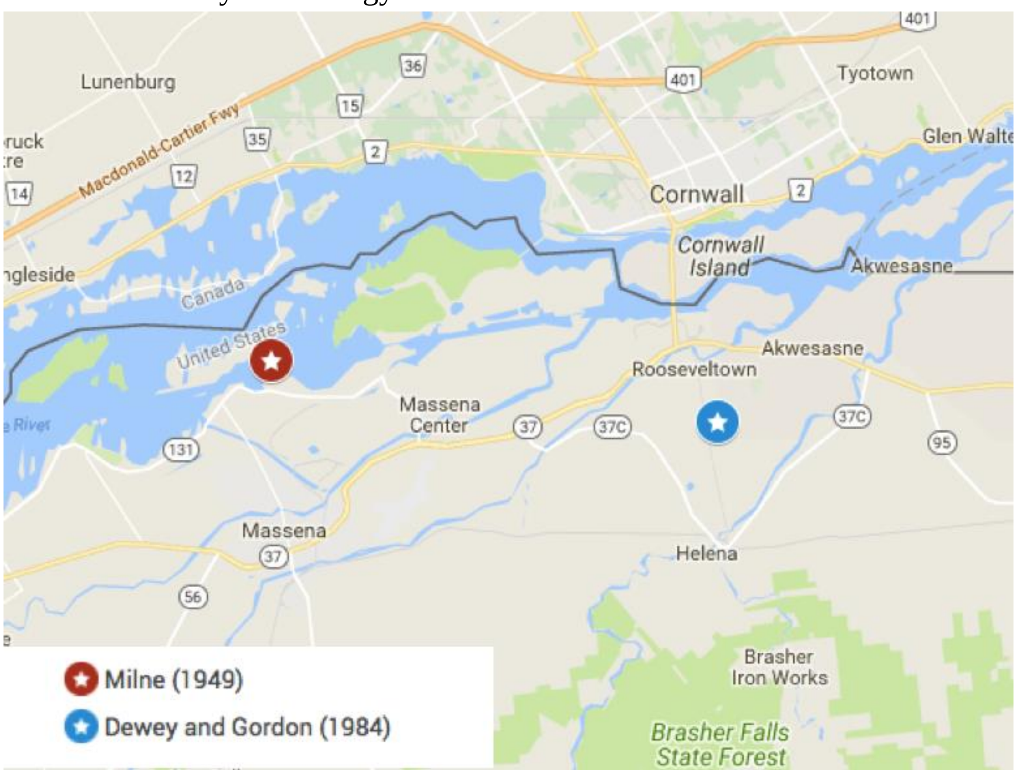

Figure 1. Epicenter locations previously suggested by Milne (1949) and Dewey and Gordon (1984)

BACKGROUND

Local Impact

On September 5th, 1944, residents of Massena, NY and Cornwall, ON, Canada were startled by a thunderous sound followed by an earthquake occurring at approximately 11:38 pm EWT (Eastern War Time). The event could be felt over an area of nearly 2,000,000 km^2 from Detroit, Michigan to Quebec City, QU, Canada and north to Moosonee (James Bay), Ontario (fig. 2). The mesoseismal area (or area of most severe damage) was concentrated in the Massena-Cornwall area. Approximately 90% of chimneys in both Massena and Cornwall and nearly every building in Cornwall required repair following the earthquake (fig. 3). Not only was there damage equivalent to approximately $28 million in today's dollar, but the shaking also caused considerable distress to citizens. Many locals knew of recently apprehended German spies with plans targeting the Alcoa aluminum plant in Massena, so they feared the rumbling was due to a foreign attack (OAN, 1942). Reconnaissance surveys of the earthquake damage conducted in the following months noted a strange phenomenon among the local cemeteries: those on the Canadian side of the Saint Lawrence River had experienced counterclockwise rotation of their headstones, while cemeteries to the south of the river experienced clockwise rotation (Berkey, 1945; Hodgson, 1945). These reports simply describe the distribution of rotated headstones and do not investigate further.

Geological Setting

The Massena-Cornwall area lies within the Saint Lawrence Fault Zone (fig. 4). The SLFZ comprises mostly normal faults paralleling the Saint Lawrence River, and is thought to be the result of failed Late Proterozoic to Early Paleozoic rifting associated with the opening of the Iapetus Ocean (cf., Kumarapeli and Saull, 1966). At the SLFZs southern limits near Cornwall, ON, a branch called the Ottawa-Bonnechere Graben traces north-west through the Ottawa Valley until terminating near Lake Nipissing, Ontario. The Massena-Cornwall area lies at the intersection between the Ottawa-Bonnechere Graben and SLFZ, implicating both fault systems as suspect for the 1944 earthquake. This seismic zone has experienced nine major damaging earthquakes since 1663, as well as a host of smaller, less significant earthquakes (fig. 4). Two magnitude 3.3 earthquakes occurred in 1981 near the 1944 Massena-Cornwall epicentral locale, followed by 17 aftershocks (Schlesinger-Miller, Barstow, and Kafka, 1983).

Though the 1944 earthquake is considered of moderate intensity, it resulted in considerable damage due to the surficial geology of the Saint Lawrence River Valley area. The depth (up to 60 meters) of loosely deposited glacial sediments makes the area particularly susceptible to infrastructure damage. The area surrounding Massena, NY and Cornwall, ON is dominated by surficial materials that range from boulder till to marine silt/clay which act as a localized control on damage intensity. Berkey (1945) noted that most damage was felt in the areas of fine marine deposits and sandy outwash.

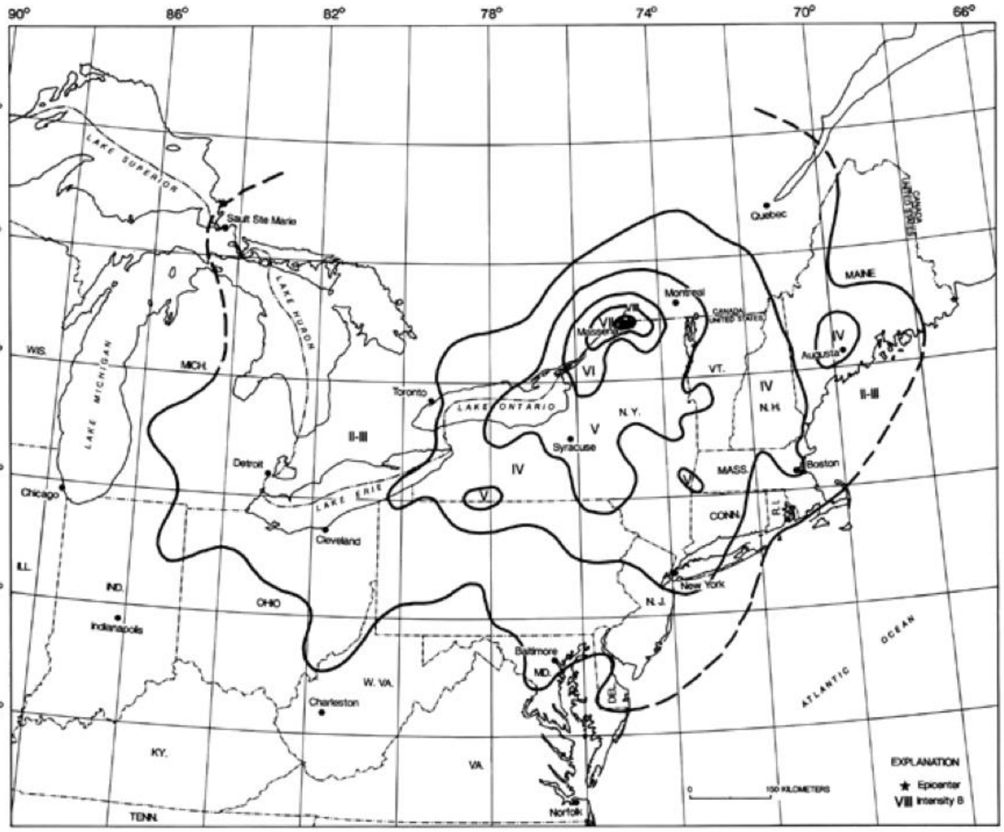

Figure 2. Isoseismal map for the September 5, 1944, mainshock defined by the Modified Mercall Scale (from Stover and Coffman, 1993).

Figure 3. Photograph of damage on the south and west sides of a houjse in Cornwall. Cracks can be seen in the corners, as weall as collapse of the outer veneer walls (Berkey, 1945).

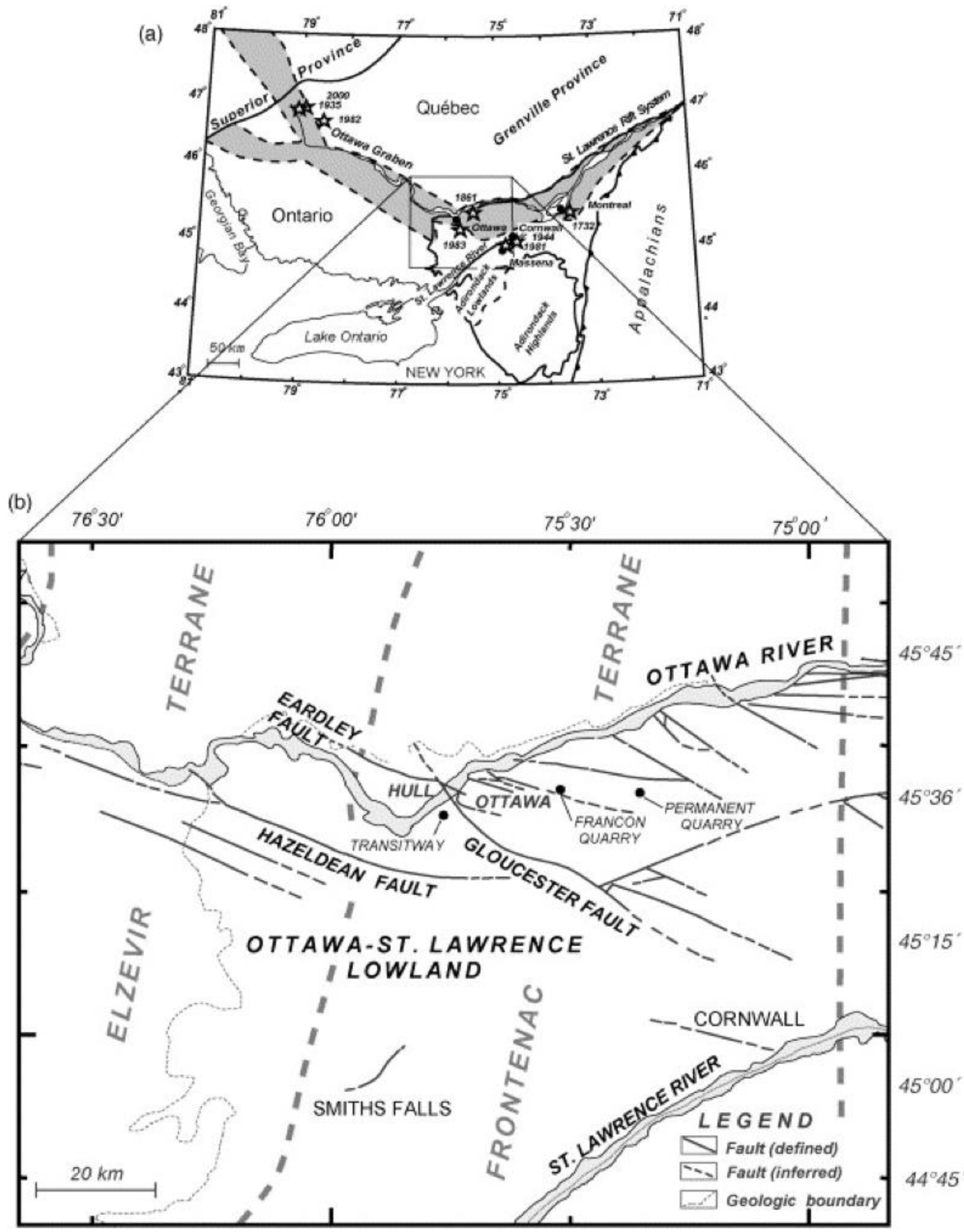

Figure 4. (a) Map of the Ottawa Graben and St. Lawrence Rift System, with major earthquakes denoted with stars. **(b)** Faulting in the Ottawa-St. Lawrence Lowland area. From Rimando and Benn, 2005.

Headstone Rotational Mechanism

Earthquake-rotated objects have been noted for many centuries, yet the first mechanical explanation for seismic rotation was not proposed until the mid-nineteenth century by Robert Mallet. Five rotational seismic models are now accepted, including Mallet's original rotational mechanisms (Kozak, 2009). The mechanism of interest to this study involves an impact on a body that is directed elsewhere than through the center of mass and will, therefore, cause the object to rotate (Knott, 1908). If the azimuth (compass direction) of earthquake motion impacting a rectangular object runs at some angle not parallel to a side or diagonal of the rectangle, rocking and rotation about a corner will be initiated. (Imamura, 1937). The resulting direction of rotation for any given headstone is dependent upon the trajectory of the impacting surface waves. A rectangular object may be divided into alternating octants that result in either clockwise or counterclockwise rotation when crossed by an impact vector (**Fig. 5**). The direction of rotation reveals the possible trajectory of ground motion through a rectangular headstone, and may act as a proxy for understanding the source direction of surface waves (MacDonald and Wentworth, 1952). Headstones are the perfect shape to display this rotational behavior, as well as being clearly dated for distinguishing headstones emplaced before/after an earthquake.

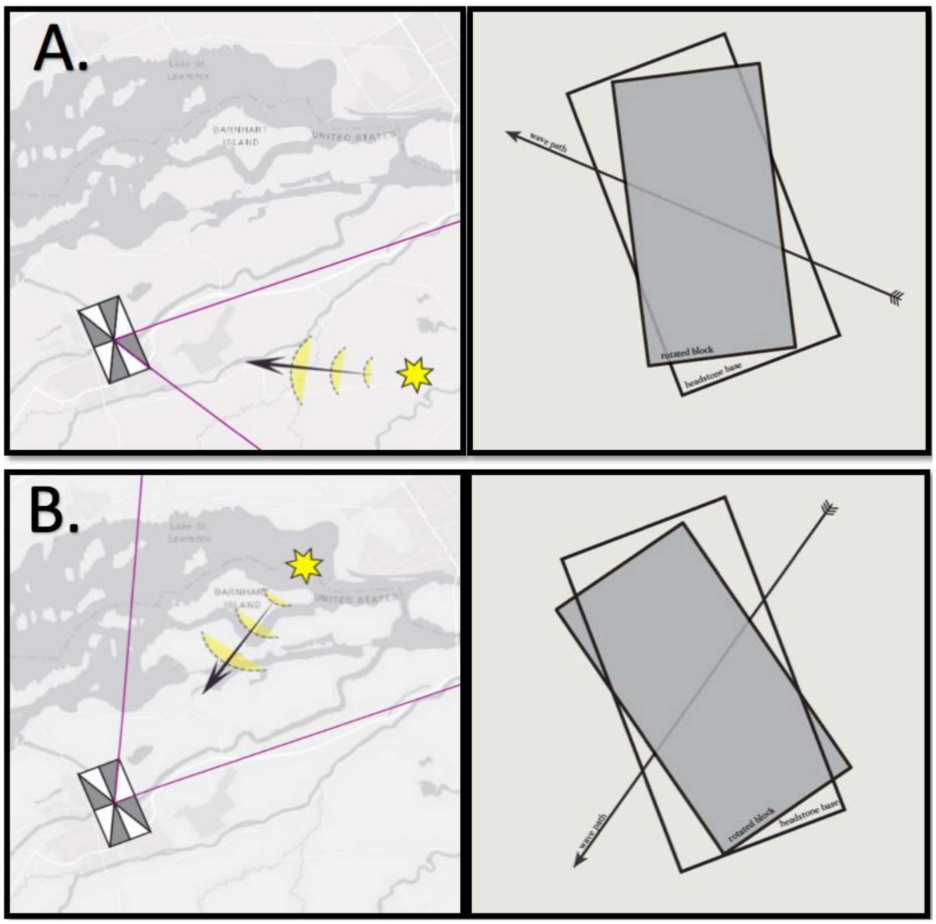

Figure 5. Diagram demonstrating how earthquake motion vector through a rectangular object determines direction of rotation. The shaded rectangle represents an enlarged headstone at the same location for both scenarios A and B. Its orientation on the map reflects the headstone's original strike. The epiocentral location (yellow star) changes between the scenarios, resulting in different surface wave impact vectors (arrow) The octant impacted by the surface wave vector is projected as purple lines. Grey octants represent motion trajectories that result in clockwise rotation, while white octants result in counterclockwise rotation. Thus, one would expect to see clockwise rotation in scenario A and counterclockwise rotation in scenario B. In the ArcMap analysis the epicentral location is not known, so either a gray or white octant is projected towards the mesoseimal area based on the observed rotation direction within each cemetery.

METHODS

Data Collection

One-hundred fifty-four earthquake-rotated headstones from 15 cemeteries within 35 km of Massena, NY and Cornwall, ON were measured for original strike and angle of rotation (Table 1 and Figure 6). Only headstones older than 1944 that displayed no obvious vertical tilt were evaluated, and cemeteries that had seen restoration efforts (e.g., fresh grout) or were in a highly neglected state were excluded. The original strike of each headstone was measured via the long-axis orientation of the anchored base stone. In the case of square headstones, the original strike is recorded as the axis parallel to the long axis of surrounding headstones. Because the final GIS epicentral analysis assumes a single generalized orientation for all headstones within each cemetery, only those headstones with approximately parallel original orientation within each cemetery were measured. A digital goniometer (0.1° resolution) was used to assess the angle of rotation from the original orientation of the anchored base stone (fig. 7). EZ-ROSE software provided the circular-statistical analyses for vector mean, circular variance, and uniformity (Baas, 1999).

CEMETERY	Long.	Lat.	# Rotated*	Av. Rotation* (Degrees)	% Preference for Rotation Direction**
Carville	-74.75396	44.91769	5	1.26	-98.4
St_Joseph	-74.66355	44.97877	2	2.7	100
Woodlawn	-74.74168	45.02093	32	1.255172414	53.9
St_Columbans	-74.74768	45.0272	13	2.4875	-98.5
Massena Center	-74.83401	44.95878	18	2.2	59.1
Nevins	-74.83277	44.93101	9	1	56.7
St_Peters	-74.88222	44.93416	9	2.011111111	77.3
Orvis Street	-74.89615	44.93105	10	3.07	60.2
Fairview	-74.77738	44.81137	22	1.540909091	85.3
St_Andrews	-74.794925	45.092687	4	3.025	100
SLV	-74.92548	45.01708	7	1.4	60.7
Winthrop	-74.78992	44.79912	8	0.65	71.2
Louisville	-75.01967	44.9004	18	1.966666667	83.3
Chamberlain	-75.10109	44.8314	4	1.775	177.5

* Independent of rotation direction.
** CCW preference expressed as negative.

Table 1. Rotational data for all cemeteries. Cemeteries selected for final epicentral analysis are highlighted.

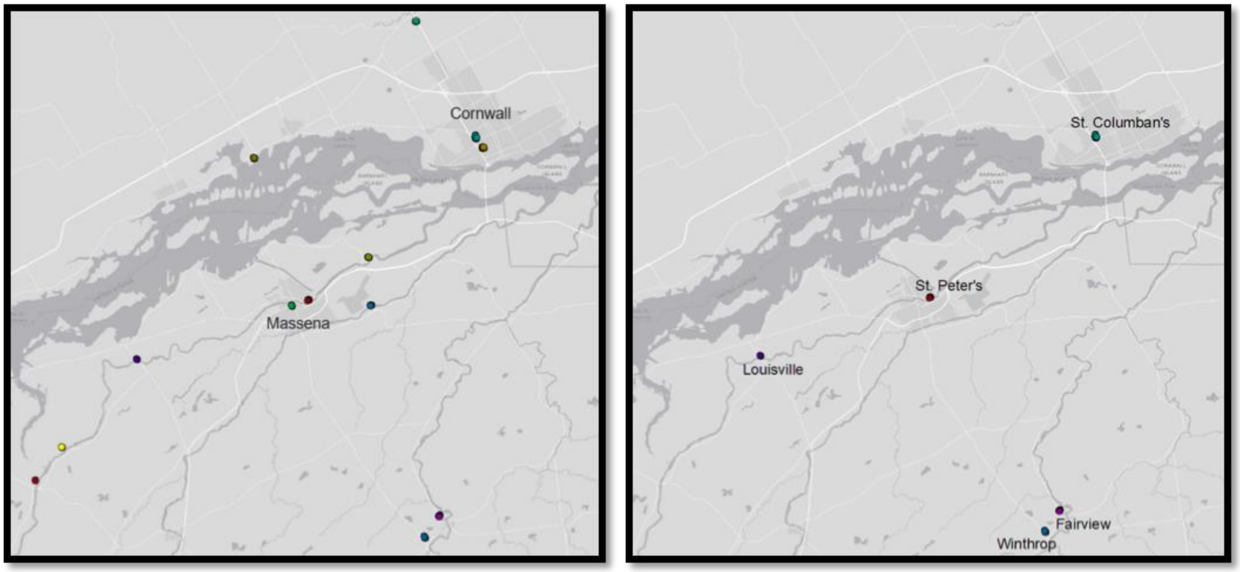

Figure 6. All cemetery locations (left). Locations and names of the five cemeteries selected for the ArcMap epicentral analysis right (see Table 1).

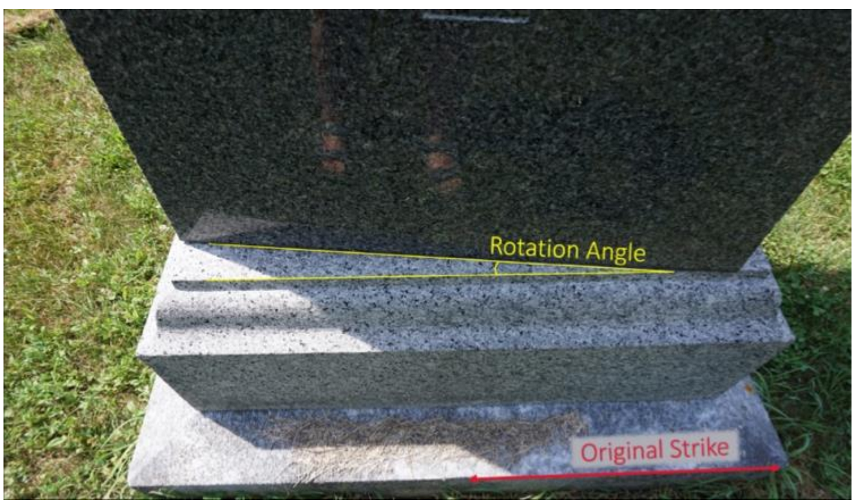

Figure 7. Close-up view of the rotational angle and original strike of a clockwise rotated headstone in Massena Center Cemetery. The anchored headstone base retains its original strike, while the unanchored upper block experiences clockwise rotation.

Epicentral Analysis

Only cemeteries with greater than five rotated headstones and at least a 70% preference for rotation in either the clockwise or counterclockwise direction were selected for the GIS epicentral analysis (Table 2; fig. 6). A cemetery is deemed to possess a ≥70% preference for rotation if ≥70% of the sum rotation measured from all rotated headstones on site is either clockwise (CW) or counterclockwise (CCW) (Table 2; equations 1 and 2)

CEMETERY	Long.	Lat.	# Rotated*	Av. Rotation* (Degrees)	% Preference for Rotation Direction**
St. Columban's	-74.74768	45.0272	13	2.5	-98.5
Winthrop	-74.78992	44.79912	8	0.3	71.2
Fairview	-74.77738	44.81137	22	1.1	85.3
St. Peter's	-74.88222	44.93416	9	1.1	77.3
Lousiville	-75.01967	44.9004	18	1.3	83.3

* Independent of rotation direction.
** CCW preference expressed as negative.

Table 2. Rotational data for the five cemeteries selected for the ArcMap epicentral analysis.

$$\frac{\sum \textit{degrees CW rot.}}{\sum \textit{degrees rot.}} \times 100 = \%\ \textit{preference CW rot.} \quad (1)$$

$$\frac{\sum \textit{degrees CCW rot.}}{\sum \textit{degrees rot.}} \times 100 = \%\ \textit{preference CCW rot.} \quad (2)$$

(NB: *the sum degrees are for all headstone values collected from the cemetery being analyzed. "∑ degrees rot." therefore is the sum of all rotation values collected within the cemetery being analyzed, independent of rotation direction.*)

The minimum number of rotated headstones and minimum percent preference for rotation direction were selected arbitrarily in order to narrow the data down to five viable cemeteries; stricter criteria could be applied in a larger data set. Narrowing the data down to five cemeteries eliminates any cemeteries with poorly defined data, as well as providing a more workable number of cemeteries for the epicentral analysis. The methodology of MacDonald and Wentworth (1952) was executed through ArcMap 10.5.1 to yield an area most likely to contain the epicenter. In order to understand the angle that the impacted headstones lie in relation to the mesoseismal area, the average original strike of the headstones were mapped at each cemetery location. Based on the orientation of headstones within each cemetery, an octant was then projected from each cemetery location (fig. 8). The octant selected for projection must a) correspond to the predominant direction of rotation observed within the cemetery and b) point more or less towards the mesoseismal area (area of greatest damage). Where the projected octants overlap is interpreted as the area most likely to have contained the epicenter, and a proposed epicenter is placed at the center of the resulting polygon.

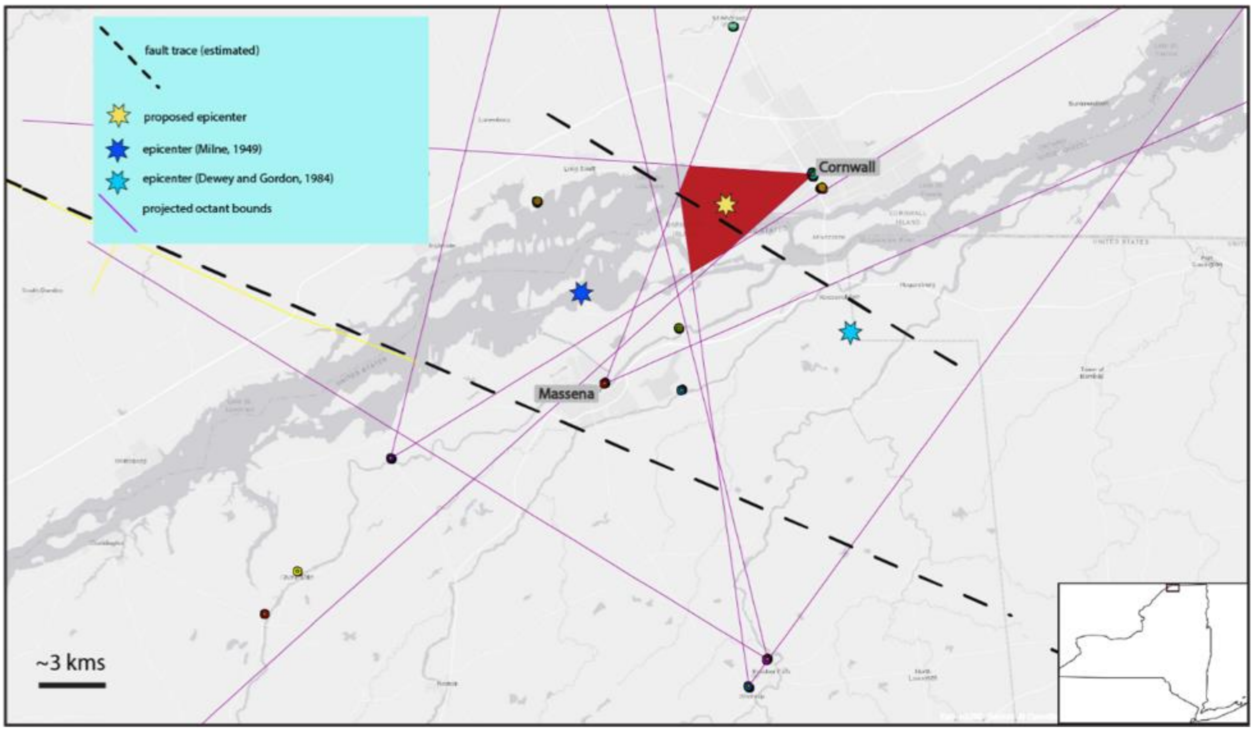

Figure 8. Map displaying the projected rotation octants from five selected cemeteries. Our proposed epicenter (yellow star) lies at the center of the epicentral area (red polygon).

RESULTS/INTERPRETATIONS

Statistical evaluation of rotational data for all headstones are non-uniform and unimodal (99% confidence), with a mean angle of rotation of 1.9° (cf., 0.1° for unaffected, post-1944 headstones, n=100) independent of rotation direction. There is a significant difference between the mean rotation of the post-1944 headstones and the earthquake-rotated headstones ($p<0.0001$). St. Columban's Cemetery, ON, was the only cemetery selected for the final analysis to experience predominantly counterclockwise rotation, with 98.5% of the sum degrees of rotation being counterclockwise. The other four cemeteries, all on the American side of the Saint Lawrence River, experienced between 71.2% and 85.3% clockwise preference (Table 2).

The area of densest overlap between the projected octants (four of five cemeteries) is an approximately 20 km^2 area centered in the Saint Lawrence River (proposed epicenter at N45.014, W74.815; fig. 8) 10 km northeast of Massena, NY. This area is bisected by the Gloucester Fault; an extension of the Ottawa-Bonnechere Graben. Many cemeteries within 10 km of the proposed epicenter display less consistency in their direction of rotation than those at a farther distance, and no observable correlation exists between distance from the epicenter and magnitude of rotation.

DISCUSSION

These data allow us to propose a new epicenter for the 1944 Massena-Cornwall earthquake at N45.014, W74.815, which likely resulted from a rupture along an extension of the Gloucester Fault within the Ottawa-Bonnechere Graben (cf., Kumarapeli and Saull, 1966). The areas affected by this fault system are populated, as well as having a number of sensitive structures. Re-activation of the Gloucester Fault could pose a considerable hazard to the nearby, approximately 1.5 km distal, Moses-Saunders Power Dam and the rather densely populated surrounding area of Massena, NY and Cornwall, ON (cf., Krinitzsky, 1991).

Our observation that the average degrees of rotation for each cemetery do not increase with proximity to the epicenter may be the result of interference between seismic waves and their interactions with the local geology. Modelling by Zhao *et al*. (2010) suggests that in areas with low velocity sedimentary layers overlying higher velocity igneous bedrock, peak ground acceleration may occur a few kilometers from the epicenter. This model proposes that seismic waves may propagate along the underlying high-velocity bedrock, eventually refracting back up through the low-velocity overburden and interfering with direct surface waves. This interference of refracted and direct surface waves results in peak ground acceleration a few kilometers from the epicenter (fig. 9). Our proposed epicenter lies in an area where approximately 550 m of Ottawa Embayment sedimentary rock (Ordovician age) overlies Precambrian Grenville metasedimentary rock (Schlesinger-Miller, *et al*., 1983), potentially creating a seismic velocity structure where this refraction interference could occur and skew the distribution of maximum rotation distal from the epicenter. Nearly all local cemeteries are built on alluvium, and thus it appears surface material did not account for spatial variability in rotational magnitude.

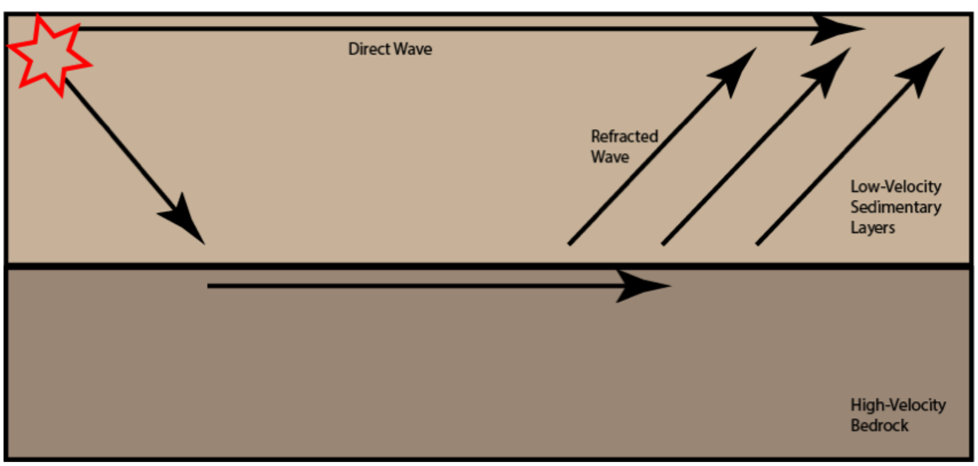

Figure 9. Seismic waves can propagate along the boundary between low-velocity sedimentary overburden and high-velocity bedrock, eventually refracting back up towards the surface. Where these refracted waves interact with direct surface waves, peak ground acceleration can occur (Zhao, *et al.*, 2010)

CONCLUSIONS

This study serves as an improvement on previous studies of the 1944-rotated headstones (e.g., Berkey, 1945) by analyzing quantitative rotational data within an ArcMap framework. The 1944 Massena-Cornwall earthquake caused millions of dollars in infrastructural damage. Opened in 1958, the Moses-Saunders Power Dam now lies directly adjacent to the extension of the Gloucester Fault that this study has attributed as the source of the 1944 Massena-Cornwall earthquake. Should re-activation occur, both the power plant and surrounding populated area will be at risk. The attribution of this significant seismic event to such a centrally located fault might serve as grounds to ensure proper seismic hazard safety protocol are evaluated and understood by local communities and institutions. Such methods using headstones or other seismically rotated objects may also have relevance to other cases where seismographic data are lacking, either due to age or technological constraints.

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