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2016

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doi:10.4095/299138

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Recommended citation
Lamontagne, M., 2016. Focal depth of earthquakes of the St. Lawrence Valley based on crustal phases recorded within 100 km epicentral distance; Geological Survey of Canada, Open File 8032, 26 p. doi:10.4095/299138

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

Focal Depth of Earthquakes of the St. Lawrence Valley

based on Crustal Phases recorded within 100 km epicentral distance

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Abstract

We have computed the focal depth of 53 earthquakes of the St. Lawrence Valley (defined as latitudes 45°N to 47°N and longitudes 70°W to 75°W) between Montreal and Quebec City using a minimum of six Pg and Sg phases from three seismograph stations or more located within 100 km of each epicentre. In addition, the epicentre had to be within the polygon defined by the seismograph stations (i.e. the azimuthal gap had to be less than 180°). Although all 607 events of the period 1980-2015 inclusively were considered, the majority of selected events were in the period 2013-2015 when the USARRAY stations occupied the region of interest. Computer scripts were written to select phases, stations and solutions that met our criteria. All resulting hypocentres locate between 10 and 21 km focal depth. Only 2 % of the 607 events had an Rg phase that suggests a focal depth of less than 5 km. Together with hypocentres computed with other methods such as the Regional Crustal Depth Determination, these new hypocentres help determine the crustal levels susceptible to fault reactivation.

Introduction

Various methods exist to compute the focal depth of the earthquake hypocentres. For small earthquakes, it is usually by using the arrivals times of the direct P (Pg) and S (Sg) waves. To locate the hypocenter, the computer program determines the optimum values of four earthquake parameters: the latitude, longitude, depth of the hypocentre, and the time of occurrence of the event. The best estimates of these parameters are those that minimize the differences between the observed and the calculated arrival times (i.e., the residuals) for each phase recorded at seismograph stations (Kissling, 1988). Residuals exist due to errors in the observed and the calculated (theoretical) arrival times. For the observed data, the errors come from the inaccuracy of the picked arrival times and of the time control of the recording system. The accuracy of calculated arrival times, on the other hand, depends mostly on how closely the velocity model resembles that of the real Earth, and to a smaller extent, on location errors of recorders, near-surface velocity perturbations and errors in the estimates of the hypocentral parameters.

Over the years, the Geological Survey of Canada (GSC) has used two programs to locate CSZ earthquakes. Between 1978 and 1993, the location program "LOC" (also named "CANCESS") was used. "LOC" uses a nonlinear regression technique, similar to the HYPO-series of programs (Drysdale et al., 1990). Since 1993, eastern Canadian earthquakes are routinely located with the GSC program "GRL" which uses a grid search algorithm. The program calculates the RMS for a series of equally-spaced grid points in the origin time, latitude, longitude and depth space. The grid is re-centred on the parameters with the minimum RMS, and the RMS is recomputed using a finer mesh. The grid search stops when the mesh is smaller than a predetermined precision for the origin time, latitude, longitude and depth. The program "GRL" currently accepts a homogeneous or a layered velocity model, with direct or refracted phases.

In eastern Canada, epicentres are located with a mix of direct P (Pg) and S (Sg) phases and refracted P (Pn) and S (Sn) phases. In general, hypocentres are computed only when Pg and Sg phases are recorded by a minimum of three stations within 100 km of the epicentre. Another constraint is that the epicentre has to be geographically located within the group of these stations. This constraint can be expressed as the maximum azimuthal gap between stations be less than 180^o. In general, for three stations, this translates into the epicentre being within the triangle that the three stations define on a map.

The GSC program "GRL", based on a grid search algorithm, locates hypocentres with a homogeneous half-space velocity model (6.2 km/s for Pg; 3.57 km/s for Sg). This velocity model does not consider the lower velocity Appalachian rocks, on which some stations are located.

The picking precision of Pg and Sg phases has changed over the years. In the location process, weights are assigned to the phases according to their quality (most picks are quality "A" (± 0.25 second; weight = 4), while some can be B (± 1 second; weight = 1) or C (± 4 seconds; weight = 0.25). It is probable that Sg phase picks are not as precise when measured on vertical records. When three-component data is available, most Pg arrivals are picked on the vertical component, while most Sg phases are measured off the horizontal components.

Other similar studies

Earthquake focal depths were also calculated with a minimum of three stations and six phases within 100 km of the epicentre in the Western Quebec Seismic Zone (WQSZ; Lamontagne et al., 1994) and in the Lower St. Lawrence Seismic Zone (Lamontagne et al., 2003). The focal depths of some WQSZ earthquakes were computed using the crustal regional depth phase method (RDPM; Ma and Atkinson, 2006). Comparisons between the two methods show that the differences in focal depths were generally within the RMS of the direct method (Table 1). This suggests that the two methods give similar depth values. Pg and Sg arrival times were also used to compute the focal depths of earthquakes in the WQSZ (Ghafoori, pers. comm.). Two of these earthquakes are within the boundaries of our region of interest.

Shallow focus earthquakes

A prominent Rayleigh phase (Rg) on the vertical component of the seismic traces indicates a shallow focal depth (less than 5 km; Kafka, 1990). In routine operations, analysts at the GSC will often add a note in the event file (often called the “pikfile”) about the presence of an Rg phase on one or more stations. In most cases, the focal depth of the earthquake will be kept at the default value of 18 km.

Quarry and mine blasts also give rise to such Rg phases. In routine earthquake analysis, quarry and mine blasts are generally recognized. Their sources are generally within a few kilometers of known quarries and mines and they occur at pre-determined times. Most often, their exact nature will be confirmed by the quarry operators. It is believed that blasts have been removed from the earthquake database and are not part of our dataset.

Study area

Our region of interest is the St. Lawrence valley (SLV) between Quebec City and Montreal (defined as latitudes 45°N to 47°N and longitudes 70°W to 75°W). We study this region to better define the depth distribution of natural earthquakes in order to compare them with earthquakes potentially induced by hydraulic fracturing activities in the years 2005-2010. The complete study will become a GSC Open File Report.

For the time period 1980-2015 inclusively, 607 earthquakes have been located in the study area and entered in the Canadian Earthquake Database. Of this number, 36 have a free depth calculated. In addition, about 55 events (all magnitude $m_N \geq 2.8$) have a computed RDPM focal depth.

Seismograph Stations

During the period 1980-2015 incl., the SLV has been mostly monitored by the permanent stations of the Canadian National Seismograph Network (CNSN; Table 2; Figure 1). Between about 2005 and the time of writing, some additional portable three-component broadband seismographs were added. Some transmitted in real-time while many required visits to retrieve the data. The latter situation led to some loss of data due to the infrequent site visits. Between Summer 2013 and Summer 2015, a series of portable broadband three-component seismographs has been added as part of the transportable array of the USARRAY deployment. For some events, seismograph stations in New York State were also used in the calculations.

Computations of earthquake focal depth from Pg and Sg waves

Similar to Lamontagne et al. (1994), we decided to compute earthquake focal depths using the Pg and Sg arrival times. As described above, the following constraints were used:

1. a minimum of three stations
2. a minimum of six phases
3. no azimuthal gap larger than 180°.

When a solution is computed with GRL, the solution line provides the information required to select the events. Consequently, it is relatively easy to screen out the events that do not match these criteria.

The procedure was: (Figure 2)

1) All earthquakes located between latitudes 45°N to 47°N and longitudes 70°W to 75°W during the time period 1980-2015 inclusively were extracted. The extracted information contains all pikfile information: the epicentral locations, comments and seismic phase information in GSC "new pikfile" (npf) format. A description of the npf format is given as Appendix 1.
2) The perl script "createnpf-stn100km" reads the pikfiles and selects only the phase information for stations at epicentral distances of less than 100 km. The phase quality (A, B, C, X) remained unchanged. Phase information for stations beyond 100 km was X'ed out, which means that the information was kept but given zero weight in the focal depth calculations. On the solution line, the "Z" flag was added, meaning that the focal depth calculation would have focal depth as a variable to be determined (instead of having it fixed at the default value of 18 km).
3) All pikfiles were relocated with the program grl
4) The perl script "selnpf-stn100km" selects only the events that met the three conditions above. The information is found on the solution lines of the individual earthquakes.

A total of 73 events met the criteria described above (Table 3). After examining at the pikfiles, we eliminated the events that were already in the database with a computed focal depth, or had potential issues with timing differences between the Canadian Network and the US networks prior to the advent of GPS timing in the mid-1990s. In addition, events in the 1980s and 1990s were only detected by vertical component stations only which may explain why some Sg residuals were high. After eliminating dubious solutions, the total number of events is 53 (Table 4). The pikfiles containing the earthquake solutions and phases are given in the computer file in the Appendix.

In Table 5, our results are compared with those obtained by Shutian Ma with the RDPM. For 3 out of 5 earthquakes, the results are very similar (within 1 km), for one it is less than 3 km whereas for one of them, it is 9 km. The first four results are within the one standard deviation error in focal depth. Interestingly, the event with the 9 km difference was located at 15 km focal depth by Peci.

Shallow Focus hypocentres

As described above, earthquakes with a hypocentre at less than 5 km can be recognized by an Rg phase (Kafka, 1990). In general, the analyst who does the epicentre location will add a comment to the pikfile that an Rg phase was conspicuous. All pikfiles of the 607 events 1980-2015 were scanned to detect a comment that mentioned an Rg phase. Twelve such events were detected (Table 6). Consequently, it appears that about 2% of events had a focal depth of 5 km or less. None of these events had sufficient stations and phases within 100 km to allow a direct focal depth determination. Considering that the number of stations has not changed significantly after year 2000, we cannot explain why most shallow events were recorded after that year. What is certain is that the number of detected earthquakes has gone up significantly after 1995 due to the increased instrumental capacity to detect very small events (Figure 4). With more numerous events, the probability of detecting shallow earthquakes has also gone up. In addition, it is possible that additional stations near the earthquake epicenters could have made the detection of Rg phases more likely.

Discussion

Due to this study, an additional 53 SLV earthquakes have focal depth information. Prior to the deployment of portable seismographs in 2005, very few events (9) had sufficient data to allow focal depth determination. In contrast, many events (20) met the criteria during the two years (2013-2015) of the USArray deployment. This signals the need for additional stations in that area.

Hypocentres of these 53 events distribute between 10 and 21 km depth (Figure 3). A minority of events (of the order of 2%) appear to occur at less than 5 km focal depth.

It must be emphasized that this is only for the data set described in this Open File. Additional hypocentral information exists from aftershock sequences, special projects and RDPM. This added information will illustrate the depth distribution of earthquakes in the SLV in an upcoming Open File Report.

Recommendation

It is recommended that the focal depth information for events with focal depth errors of less than 5 km be added to the Canadian earthquake database. The original solution and associated errors will be kept as comment lines.

Acknowledgments

I thank Shearer Ghafoori for sharing the results of her focal depth calculations with me. I also thank Allison Bent for reviewing a draft of this Open File.

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Appendices

1- npfformat.tex: format of the earthquake solutions ("new pikfile format")_
2- selnpf-stn100km.npf: solutions of the earthquakes that we suggest be entered in the Canadian earthquake database

Table 1. Focal Depths of some Western Quebec Earthquakes (Lamontagne et al., 1994)

No.	Date MM/DD/YR	Time (HH:MM)	Mag (mN)	Depth (km)	STD* (km)	M-A (2006) (km)	Diff.
1	07/24/1981	03:42	2.0	15	4		
2	07/25/1981	10:59	1.7	13	2		
3	09/18/1981	07:16	3.5	14	2	13	1
4	11/15/1981	19:48	2.5	18	5		
5	03/11/1982	10:28	1.8	18	3		
6	07/17/1983	23:12	2.3	21	1		
7	11/10/1985	14:21	2.4	13	3		
8	05/02/1986	15:05	3.3	13	3	16	-3
9	06/05/1986	12:13	3.2	11	4	8	3
10	06/16/1986	08:44	2.1	16	3		
11	08/06/1986	09:47	2.0	20	4		
12	08/06/1986	11:19	3.5	21	4	17	4
13	09/13/1986	21:52	1.9	18	1		
14	05/21/1987	14:55	2.9	16	1	13	3
15	06/02/1987	15:38	2.0	11	1		
16	11/11/1987	08:00	3.4	17	1	19	-2
17	01/13/1990	02:19	2.6	17	3		
18	11/19/1990	20:32	1.4	15	1		
19	11/23/1990	02:20	1.8	12	3		
20	12/03/1990	11:10	2.6	15	2		

*STD: standard deviation of focal depth determination

M-A (2006): Ma and Atkinson (2006)

Table 2; List of stations that were within or near the SLV

Station Name	Latitude (°N)	Lon (°W)	Elevation (m)	Start date	End date	Network
A11	47.2431	-70.1968	201	1978	-	CNSN
A54	47.4567	-70.4125	381	1978	-	CNSN
ALFO	45.6283	-74.8842	0.0	2003		Polaris
BCLQ	46.9263	-71.1728	168	2009/11/06	-	Temp
BECQ	46.3449	-72.4829	24	2012/03/07	-	Temp
CHQ	46.8900	-71.3000	145	19711111	19820704	REGIONAL
D58A	47.10	-72.88	398	2013/08/17	2015/07/22	USARRAY
D59A	47.01	-71.84	204	2013/07/31	2015/07/24	USARRAY
D60A	46.91	-70.92	40	2013/08/01	2015/07/23	USARRAY
DPQ	46.6804	-72.7774	167	19880101	19960920	ECTN
DPQ	46.6804	-72.7774	167	19960920	-	CNSN
E58A	46.37	-73.28	233	2013/07/31	2015/07/11	USARRAY
E59A	46.48	-72.51	62	2013/07/31	2015/07/23	USARRAY
E60A	46.37	-71.45	181	2013/08/07	2015/07/25	USARRAY
E61A	46.43	-70.49	527	2013/08/12	2015/07/25	USARRAY
F58A	45.87	-73.81	73	2013/07/28	2015/07/11	USARRAY
F59A	45.85	-72.78	43	2013/08/09	2015/07/10	USARRAY
F60A	45.97	-71.95	229	2013/08/07	2015/07/12	USARRAY
F61A	45.97	-70.99	350	2013/08/06	2015/07/25	USARRAY
FRNY	44.8350	-73.5883	223	2003		LCNS
G57A	45.10	-74.99	96	2013/07/24	2015/07/08	USARRAY
G58A	45.15	-74.05	53	2013/07/25	2015/07/09	USARRAY
G59A	45.08	-73.18	36	2013/09/17	2015/07/14	USARRAY
G60A	45.10	-72.33	391	2013/08/11	2015/07/13	USARRAY
G61A	45.28	-71.53	378	2013/09/25	2015/07/28	USARRAY
GNT	46.3628	-72.3722	10	19780426	19880105	ECTN
LONY	44.6197	-74.5829	440	2005		PAL
MNT	45.5025	-73.6231	112	19740224	19950501	ECTN
MNT	45.5025	-73.6231	112	19950502	-	CNSN
MNTQ	45.5025	-73.6231	112	19950502	-	CNSN
MOQ	45.3120	-72.2541	841	19910501	19960917	ECTN
MOQ	45.3120	-72.2541	841	19960917	-	CNSN
MRHQ	45.8870	-74.2127	422	2004		CNSN
QCQ	46.7789	-71.2758	91	19710924	19971201	REGIONAL
QCQ	46.7789	-71.2758	91	19971202	-	CNSN
SADQ	46.7485	-71.5365	820			Temp
SBQ	45.3783	-71.9264	265	19800812	19960917	ECTN
SFA	47.1244	-70.8266	230			Temp

SMCQ	46.6709	-72.0551	470			Temp
STFQ	46.5538	-71.5436	123	2011/12/13	2015	Temp
STOQ	47.0188	-71.3795	201			Temp
STUQ	46.3016	-73.0946	64	2011/12/18	-	Temp
TRQ	46.2222	-74.5556	853	19810316	19960711	ECTN
TRQ	46.2222	-74.5556	853	19960712	19820704	CNSN
WBO	45.00124	-75.27503	85	1980		CNSN

Table 3. List of events that passed the preliminary selection criteria: see Appendix for comments on the various solutions.

	date	time	mag	magtp	lat	lon	depth	depth_error	no_stat	no_phases	RMS
1.	19820224	0320 53.318	1.4	MN	45.1207	-74.0676	17.92	4.29	5	7	0.10
2.	19840602	0725 51.266	2.3	MN	45.9334	-74.2500	18.04	1.37	3	6	0.03
3.	19851101	2333 40.467	3.4	MN	45.2860	-73.4805	9.30	2.53	4	8	0.07
4.	19860802	0837 32.141	2.7	MN	45.3478	-73.2211	15.15	4.03	3	6	0.06
5.	19860813	1029 23.858	0.0	MN	45.1322	-74.2385	36.08	0.01	4	8	0.20
6.	19861202	0655 18.947	2.5	MN	45.1364	-74.1620	17.92	2.21	8	16	0.13
7.	19880206	1955 19.406	2.8	MN	45.4713	-74.2432	21.49	4.04	3	6	0.07
8.	19900424	1346 19.185	0.0	MN	45.8782	-72.5847	52.01	4.59	3	6	0.04
9.	19930730	2230 54.589	3.8	MN	45.2444	-74.1141	15.22	1.79	5	10	0.06
10.	19931112	0517 59.396	2.4	MN	45.1236	-74.1451	20.95	2.29	6	12	0.12
11.	19931116	0931 44.743	4.3	MN	45.1984	-73.4375	15.14	2.85	5	9	0.11
12.	19931116	0940 09.163	2.9	MN	45.1941	-73.4663	15.41	1.46	6	12	0.08
13.	19931116	1000 11.865	2.8	MN	45.1937	-73.4664	13.81	1.93	6	12	0.09
14.	19981023	0702 23.706	2.5	MN	45.6533	-73.9027	17.27	4.71	3	6	0.06
15.	20000701	1314 44.640	1.6	MN	45.7271	-74.1428	21.29	3.47	4	7	0.10
16.	20020601	1135 29.449	3.2	MN	45.5821	-73.8637	12.54	4.72	3	6	0.12
17.	20020829	0427 59.662	2.6	MN	45.1172	-73.3132	21.47	3.02	3	6	0.08
18.	20030225	1512 29.492	2.6	MN	45.2111	-73.4129	21.61	1.66	3	6	0.04
19.	20030807	1211 45.759	2.4	MN	46.0415	-73.4033	13.93	2.40	3	6	0.04
20.	20030905	1149 20.867	2.3	MN	46.8803	-71.1164	18.41	1.73	3	6	0.04
21.	20031109	1055 59.783	2.2	MN	45.2124	-73.8912	19.05	3.05	3	6	0.06
22.	20040823	0038 22.972	2.0	MN	45.6641	-74.2232	19.05	2.09	4	7	0.05
23.	20051001	1531 37.720	1.9	MN	46.2374	-73.1182	14.97	4.67	3	6	0.07
24.	20051206	1849 04.332	2.1	MN	45.9869	-72.7367	21.12	4.84	3	6	0.10
25.	20060109	1535 40.288	4.2	MN	45.0292	-73.9011	14.06	3.38	4	7	0.07
26.	20060813	2054 28.846	1.9	MN	45.2053	-73.8946	14.71	3.29	5	10	0.13
27.	20060824	0134 24.912	1.8	MN	45.4307	-73.8661	17.21	3.82	4	8	0.14
28.	20070115	1019 27.201	1.6	MN	45.5229	-74.1706	17.27	1.95	4	8	0.07
29.	20070127	1749 45.296	2.0	MN	45.0330	-74.0422	21.05	1.05	7	14	0.06
30.	20070718	0028 25.600	1.7	MN	46.9738	-70.9840	17.59	1.39	5	10	0.07
31.	20080601	0114 42.817	1.9	MN	45.1082	-73.9756	17.59	2.26	5	9	0.05
32.	20080807	1001 35.003	2.3	MN	45.3889	-73.3805	16.95	4.31	3	6	0.07
33.	20080817	1624 37.525	1.6	MN	45.0758	-74.1623	17.83	2.63	4	8	0.06
34.	20081002	0410 24.559	2.9	MN	45.2200	-73.8923	10.33	4.55	4	8	0.09
35.	20081119	0722 24.952	1.4	MN	46.7663	-71.8434	13.82	3.93	4	7	0.10
36.	20110523	1339 51.899	1.8	MN	45.1020	-74.1998	18.15	4.67	4	7	0.10
37.	20110622	1007 29.849	3.2	MN	45.2830	-73.1077	18.09	2.89	3	6	0.05
38.	20110923	0624 04.809	2.3	MN	46.9687	-71.1733	23.42	0.99	6	11	0.10
39.	20111026	0735 31.759	2.7	MN	46.8836	-71.1779	20.35	0.69	6	12	0.15
40.	20111219	0450 06.437	1.9	MN	45.3369	-74.1256	15.31	4.95	5	10	0.17
41.	20121004	1827 47.833	3.0	MN	45.1285	-74.1482	12.75	2.81	5	10	0.04

42.	20121229	1006	54.931	2.7	MN	45.7224	-72.8208	13.51	3.49	4	8	0.08
43.	20130220	0939	03.933	2.0	MN	45.1152	-74.1851	16.16	4.40	5	9	0.14
44.	20130323	1734	48.859	2.3	MN	46.7141	-72.0520	13.62	0.71	6	11	0.10
45.	20130411	1405	53.497	1.9	MN	46.8828	-71.3595	15.03	3.40	4	6	0.08
46.	20130521	2043	01.163	3.4	MN	45.4342	-74.1988	17.27	2.26	5	10	0.09
47.	20131004	2204	41.938	2.7	MN	46.9254	-71.0962	22.75	0.62	9	18	0.10
48.	20131125	2003	18.307	2.4	MN	46.2390	-72.6266	13.91	0.58	8	14	0.07
49.	20131221	0220	32.672	1.9	MN	46.4827	-70.8453	14.39	2.47	7	14	0.17
50.	20140101	1833	31.138	2.2	MN	45.5398	-74.2819	20.14	2.24	6	11	0.14
51.	20140207	1545	05.934	3.1	MN	45.0880	-73.6411	13.23	1.82	4	8	0.08
52.	20140325	1951	09.800	2.7	MN	45.4315	-74.1934	17.64	3.03	9	18	0.18
53.	20140404	0343	19.374	1.7	MN	45.5076	-73.8154	17.90	1.29	7	14	0.13
54.	20140629	2005	19.625	2.5	MN	46.1753	-72.7375	13.82	1.64	6	12	0.08
55.	20141030	0309	17.267	2.5	MN	45.9456	-74.1888	19.61	1.36	7	12	0.09
56.	20141120	0435	49.841	2.1	MN	46.7960	-72.7722	14.39	3.37	5	8	0.21
57.	20141230	0244	49.731	2.4	MN	45.1450	-74.2204	16.21	0.60	7	14	0.07
58.	20150112	1025	49.913	1.6	MN	45.7492	-73.7068	18.60	0.62	5	10	0.07
59.	20150116	1128	30.195	1.9	MN	46.2793	-72.8128	16.18	1.09	7	12	0.12
60.	20150119	1635	13.920	2.5	MN	45.1885	-74.1754	14.45	0.69	6	11	0.06
61.	20150119	1939	10.334	1.5	MN	45.1907	-74.1648	14.07	1.13	6	12	0.15
62.	20150217	0656	52.630	2.7	MN	45.9826	-73.5989	18.55	1.05	8	14	0.13
63.	20150302	0054	24.088	1.7	MN	45.1099	-73.8611	14.77	0.66	6	11	0.07
64.	20150417	0053	47.598	2.3	MN	45.1386	-73.8744	16.05	0.62	7	14	0.09
65.	20150423	0624	07.854	1.7	MN	46.0556	-74.1515	14.39	2.86	6	11	0.11
66.	20150523	2021	58.449	2.6	MN	45.0525	-74.2036	16.82	0.55	8	15	0.07
67.	20150523	2022	08.509	2.5	MN	45.0542	-74.1946	17.01	0.62	7	12	0.07
68.	20150706	0214	48.985	2.7	MN	46.6806	-72.6105	16.37	0.63	9	16	0.11
69.	20150713	1927	27.265	2.4	MN	45.1848	-73.9720	19.32	4.10	4	8	0.09
70.	20150716	1946	54.874	2.2	MN	46.8280	-71.1055	16.63	0.88	8	15	0.16
71.	20151029	1010	00.356	2.4	MN	46.9921	-70.9539	15.99	2.10	6	11	0.10
72.	20151112	1954	22.727	2.1	MN	45.3370	-73.9106	18.66	4.50	3	6	0.14
73.	20151215	0953	08.970	2.0	MN	45.9192	-72.5416	17.27	3.33	4	7	0.09

Table 4. Hypocentre solutions in the SLV; only the events needed to update the database are listed; in yellow: events with RDPM solutions (Ma) or other free depth (G: Ghafoori)

ev.	date yyyymmdd	time hhmmss.sss	mag	magtp	lat	lon	depth (km)	err (km)	stat	ph	RMS	Comment
1.	19880206	1955 19.406	2.8	MN	45.4713	-74.2432	21.49	4.04	3	6	0.07	
2.	20000701	1314 44.640	1.6	MN	45.7271	-74.1428	21.29	3.47	4	7	0.10	
3.	20020601	1135 29.449	3.2	MN	45.5821	-73.8637	12.54	4.72	3	6	0.12	Ma: 12 km
4.	20020829	0427 59.662	2.6	MN	45.1172	-73.3132	21.47	3.02	3	6	0.08	
5.	20030225	1512 29.492	2.6	MN	45.2111	-73.4129	21.61	1.66	3	6	0.04	
6.	20030807	1211 45.759	2.4	MN	46.0415	-73.4033	13.93	2.40	3	6	0.04	
7.	20030905	1149 20.867	2.3	MN	46.8803	-71.1164	18.41	1.73	3	6	0.04	
8.	20031109	1055 59.783	2.2	MN	45.2124	-73.8912	19.05	3.05	3	6	0.06	
9.	20040823	0038 22.972	2.0	MN	45.6641	-74.2232	19.05	2.09	4	7	0.05	
10.	20051001	1531 37.720	1.9	MN	46.2374	-73.1182	14.97	4.67	3	6	0.07	
11.	20051206	1849 04.332	2.1	MN	45.9869	-72.7367	21.12	4.84	3	6	0.10	
12.	20060109	1535 40.288	4.2	MN	45.0292	-73.9011	14.06	3.38	4	7	0.07	Ma: 15 km
13.	20060813	2054 28.846	1.9	MN	45.2053	-73.8946	14.71	3.29	5	10	0.13	
14.	20060824	0134 24.912	1.8	MN	45.4307	-73.8661	17.21	3.82	4	8	0.14	
15.	20070115	1019 27.201	1.6	MN	45.5229	-74.1706	17.27	1.95	4	8	0.07	
16.	20070127	1749 45.296	2.0	MN	45.0330	-74.0422	21.05	1.05	7	14	0.06	
17.	20070718	0028 25.600	1.7	MN	46.9738	-70.9840	17.59	1.39	5	10	0.07	
18.	20080601	0114 42.817	1.9	MN	45.1082	-73.9756	17.59	2.26	5	9	0.05	
19.	20080807	1001 35.003	2.3	MN	45.3889	-73.3805	16.95	4.31	3	6	0.07	
20.	20080817	1624 37.525	1.6	MN	45.0758	-74.1623	17.83	2.63	4	8	0.06	
21.	20081002	0410 24.559	2.9	MN	45.2200	-73.8923	10.33	4.55	4	8	0.09	Ma: 13 km
22.	20081119	0722 24.952	1.4	MN	46.7663	-71.8434	13.82	3.93	4	7	0.10	
23.	20110523	1339 51.899	1.8	MN	45.1020	-74.1998	18.15	4.67	4	7	0.10	
24.	20110622	1007 29.849	3.2	MN	45.2830	-73.1077	18.09	2.89	3	6	0.05	Ma: 9 km
25.	20111219	0450 06.437	1.9	MN	45.3369	-74.1256	15.31	4.95	5	10	0.17	
26.	20121004	1827 47.833	3.0	MN	45.1285	-74.1482	12.75	2.81	5	10	0.04	
27.	20130220	0939 03.933	2.0	MN	45.1152	-74.1851	16.16	4.40	5	9	0.14	
28.	20130411	1405 53.497	1.9	MN	46.8828	-71.3595	15.03	3.40	4	6	0.08	
29.	20130521	2043 01.163	3.4	MN	45.4342	-74.1988	17.27	2.26	5	10	0.09	G (15.7km)
30.	20131004	2204 41.938	2.7	MN	46.9254	-71.0962	22.75	0.62	9	18	0.10	
31.	20131221	0220 32.672	1.9	MN	46.4827	-70.8453	14.39	2.47	7	14	0.17	
32.	20140101	1833 31.138	2.2	MN	45.5398	-74.2819	20.14	2.24	6	11	0.14	
33.	20140207	1545 05.934	3.1	MN	45.0880	-73.6411	13.23	1.82	4	8	0.08	G (16.89) Ma: 12.5 km
34.	20140325	1951 09.800	2.7	MN	45.4315	-74.1934	17.64	3.03	9	18	0.18	
35.	20140404	0343 19.374	1.7	MN	45.5076	-73.8154	17.90	1.29	7	14	0.13	
36.	20140629	2005 19.625	2.5	MN	46.1753	-72.7375	13.82	1.64	6	12	0.08	
37.	20141120	0435 49.841	2.1	MN	46.7960	-72.7722	14.39	3.37	5	8	0.21	
38.	20150112	1025 49.913	1.6	MN	45.7492	-73.7068	18.60	0.62	5	10	0.07	
39.	20150116	1128 30.195	1.9	MN	46.2793	-72.8128	16.18	1.09	7	12	0.12	
40.	20150119	1635 13.920	2.5	MN	45.1885	-74.1754	14.45	0.69	6	11	0.06	

41.	20150119	1939	10.334	1.5	MN	45.1907	-74.1648	14.07	1.13	6	12	0.15
42.	20150217	0656	52.630	2.7	MN	45.9826	-73.5989	18.55	1.05	8	14	0.13
43.	20150302	0054	24.088	1.7	MN	45.1099	-73.8611	14.77	0.66	6	11	0.07
44.	20150417	0053	47.598	2.3	MN	45.1386	-73.8744	16.05	0.62	7	14	0.09
45.	20150423	0624	07.854	1.7	MN	46.0556	-74.1515	14.39	2.86	6	11	0.11
46.	20150523	2021	58.449	2.6	MN	45.0525	-74.2036	16.82	0.55	8	15	0.07
47.	20150523	2022	08.509	2.5	MN	45.0542	-74.1946	17.01	0.62	7	12	0.07
48.	20150706	0214	48.985	2.7	MN	46.6806	-72.6105	16.37	0.63	9	16	0.11
49.	20150713	1927	27.265	2.4	MN	45.1848	-73.9720	19.32	4.10	4	8	0.09
50.	20150716	1946	54.874	2.2	MN	46.8280	-71.1055	16.63	0.88	8	15	0.16
51.	20151029	1010	00.356	2.4	MN	46.9921	-70.9539	15.99	2.10	6	11	0.10
52.	20151112	1954	22.727	2.1	MN	45.3370	-73.9106	18.66	4.50	3	6	0.14
53.	20151215	0953	08.970	2.0	MN	45.9192	-72.5416	17.27	3.33	4	7	0.09

G: Solution also computed by Sherry Ghafoori with focal depth calculated with 3 closest stations

Ma: Solution also computed by Shutian Ma using the regional depth phase method (RDPM).

Table 5. Difference between the free depth calculations and the solutions by Shutian Ma

ev.	date yyyymmdd	time hhmm	mag	magtp	lat	lon	depth (km)	err (km)	stat	ph	RMS	Sol Ma	Diff.
1.	20020601	1135	3.2	MN	45.5821	-73.8637	12.54	4.72	3	6	0.12	Ma: 12 km:	0.5 km
2.	20060109	1535	4.2	MN	45.0292	-73.9011	14.06	3.38	4	7	0.07	Ma: 15 km:	1.0 km
3.	20081002	0410	2.9	MN	45.2200	-73.8923	10.33	4.55	4	8	0.09	Ma: 13 km:	2.7 km
4.	20110622	1007	3.2	MN	45.2830	-73.1077	18.09	2.89	3	6	0.05	Ma: 9 km:	9.0 km*[1]
5.	20140207	1545	3.1	MN	45.0880	-73.6411	13.23	1.82	4	8	0.08	Ma: 12.5 km:	0.7 km

Ma: Solution also computed by Shutian Ma using the regional depth phase method (RDPM)

*1: Veronika Peci found a focal depth of 15 km for the same event (i.e. a difference of 3 km with the free depth solution).

Table 6: Events that had a pikfile comment signaling an Rg phase

S 19900424 1346 19.324L 45.8709 -72.5907 2.00km 2.8MN VGA M F 0 0 1 16 21 0
82 75.41SBQ
19900424.1346002 Clear Rg phase
3 stations; 6 phases but Sg residual on MNT is too large to give reliable solution
Ma and Atkinson (2006) has 2 km focal depth

S 20010603 2242 28.463L 46.9481 -71.6343 5.00km 2.7MN FGA M 0M 0 1 12 25
0123 33.21QCQ
20010603.2242001 Strong Rg phase on QCQ. Pegged to 5km.
Only 2 stations; 4 phases

S 20010731 0100 24.831L 46.0437 -73.4093 5.00km 1.7MN FGA M 0M 0 1 6 12
0105 62.45MNT CANADA 447 0 0 <>
20010731.0100001 Strong Rg phase -set depth to 5km.
Large residuals; 3 stations; 6 phases

S 20010901 0544 16.105L 46.6812 -73.5758 5.00km 1.4MN FGA M 0M 0 1 6 10
0142 61.13DPQ CANADA 447 0 0 <>
20010901.0544001 Strong Rg - set depth to 5km.
Outside network; two stations 4 phases

S 20030413 0243 13.731L 46.9177 -71.0908 5.00km 3.4MN VGA M F 0M 0 1 7 12
0103 20.92QCQ CANADA 447 0 1 <>
20030413.0243006 Rg phase on MNT
Outside network; unstable free depth; Shutian Ma has regional depth phase at 5 km

S 20040723 0533 54.636L 46.8374 -70.8971 18.00km 1.5MN FGA M 0M 0 1 5 8
0231 78.10A54 CANADA 447 0 1 <>
20040723.0533001 Possible Rg phase on QCQ **but not clear enough to be sure**.
QCQ has timing problems; only two toher stations within 100 km

S 20081011 0247 14.231L 46.3246 -72.5413 3.00km 2.9MN FGA M F 0M 0 1 7 13
0113 43.53DPQ CANADA 447 0 0 <>
20081011.0247003 Probably a shallow event: strong Rg phase on many stations, including SADQ
Only two stations within 100 km

S 20100322 1630 53.612L 45.4767 -70.8622 5.00km 1.9MN FGA M 0M 0 1 7 13
0111 110.58MOQ CANADA 475 0 0 <>
20100322.1630001 Clear Rg-phase on several stations.
No stations within 100 km

S 20100405 0554 11.715L   46.1658 -72.6869 6.50km 2.8MN   FGA M   0M 0 1 3 6
0193 57.66DPQ CANADA 447   0   1 <>
20100405.0554002 Possible weak Rg
Only two stations within 100 km

S 20110822 0040 15.809L   46.3330 -72.5303 5.00km 1.8MN   FGA M   0M 0 1 4 8
0164 43.05DPQ CANADA 447   0   0 <>
20110822.0040003 Rg phase on DPQ.
Three stations but one of them had large Sg residual

S 20120113 2200 59.439L   45.5734 -72.4168 18.00km 2.4MN   FGA M   0M 0 1 14 21
0124 31.74MOQ CANADA 447   0   1 <>
20120113.2200002 MNTQ is very bad record; no BECQ record; **Hint of an Rg on MOQ**
Note: only three stations within 100km one of them is very bad: MNTQ

S 20150127 1430 39.843L   45.0887 -71.4639 5.00km 2.3MN   FGA M   0M 0 1 9 18
0119 66.90MOQ CANADA 447   0   0 <>
20150127.1430001 Clear Rg-phase.
Note: only two stations within 100km

Figure 1. Locations of the seismograph stations used in the analysis. Stations with code names starting with D,E, F and G are Transportable Array stations.

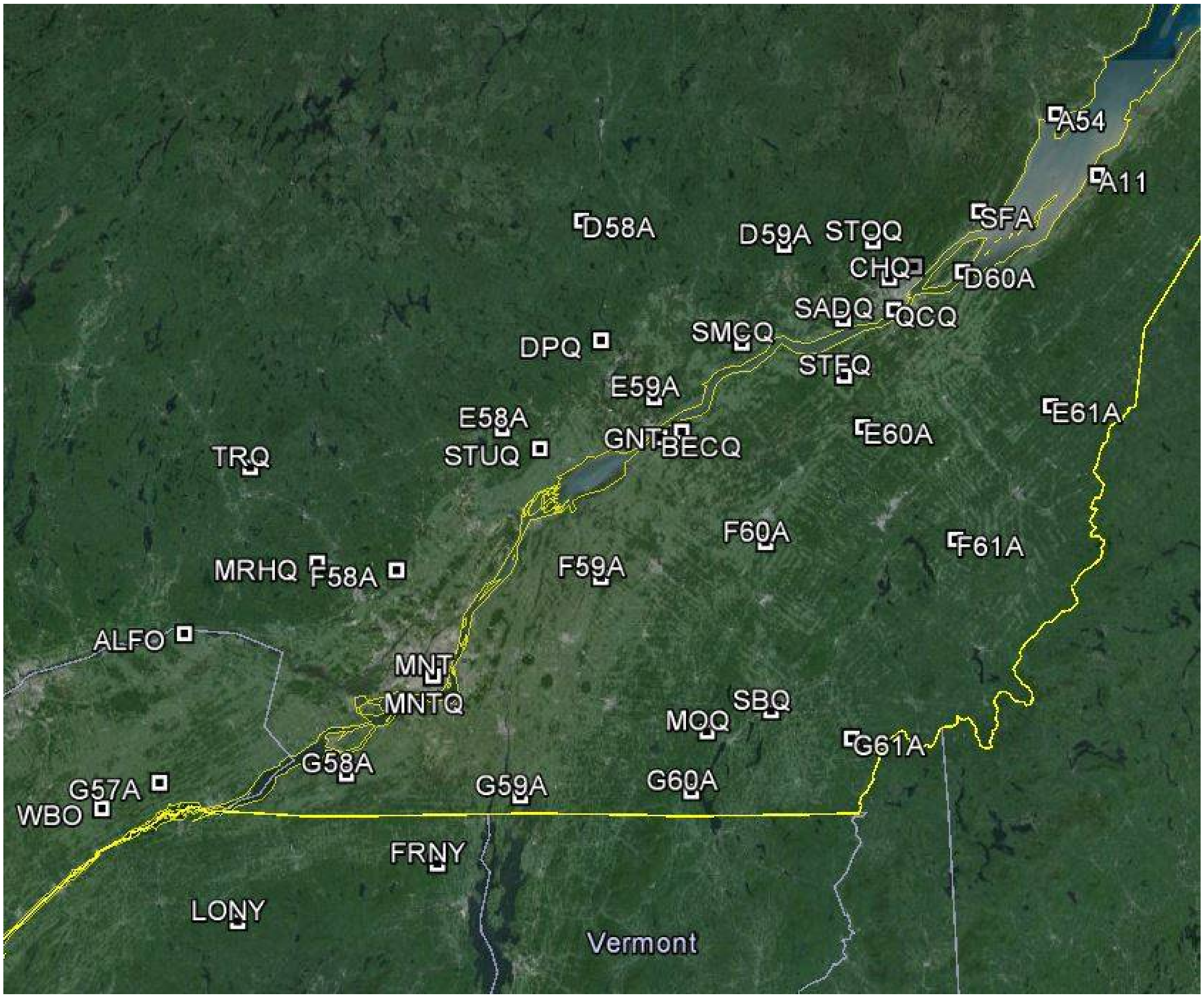

Figure 2. Flow chart of the location and selection of events (in bold: UNIX command)

1- Select events from the earthquake database:

eqi –t 19800101. –T 20160101. –x -74.2 –X -70.8 –y 45.0 –Y 47.0 –rpt n > STL-1980-2016.npf

2- copy STL-1980-2016.npf to test.npf:

cp STL-1980-2016.npf test.npf

3- Run (temp.npf is the output filename)

createnpf-stn100km > temp.npf

4- run location program:

grl temp.npf junki.npf

5- Select solutions: (input is junki.npf)

selnpf-stn100km > **selnpf-stn100km.npf**

will also create **output.txt** for summary table as Tables 3 and 4

Figure 3. Number of events per 1 km depth bin

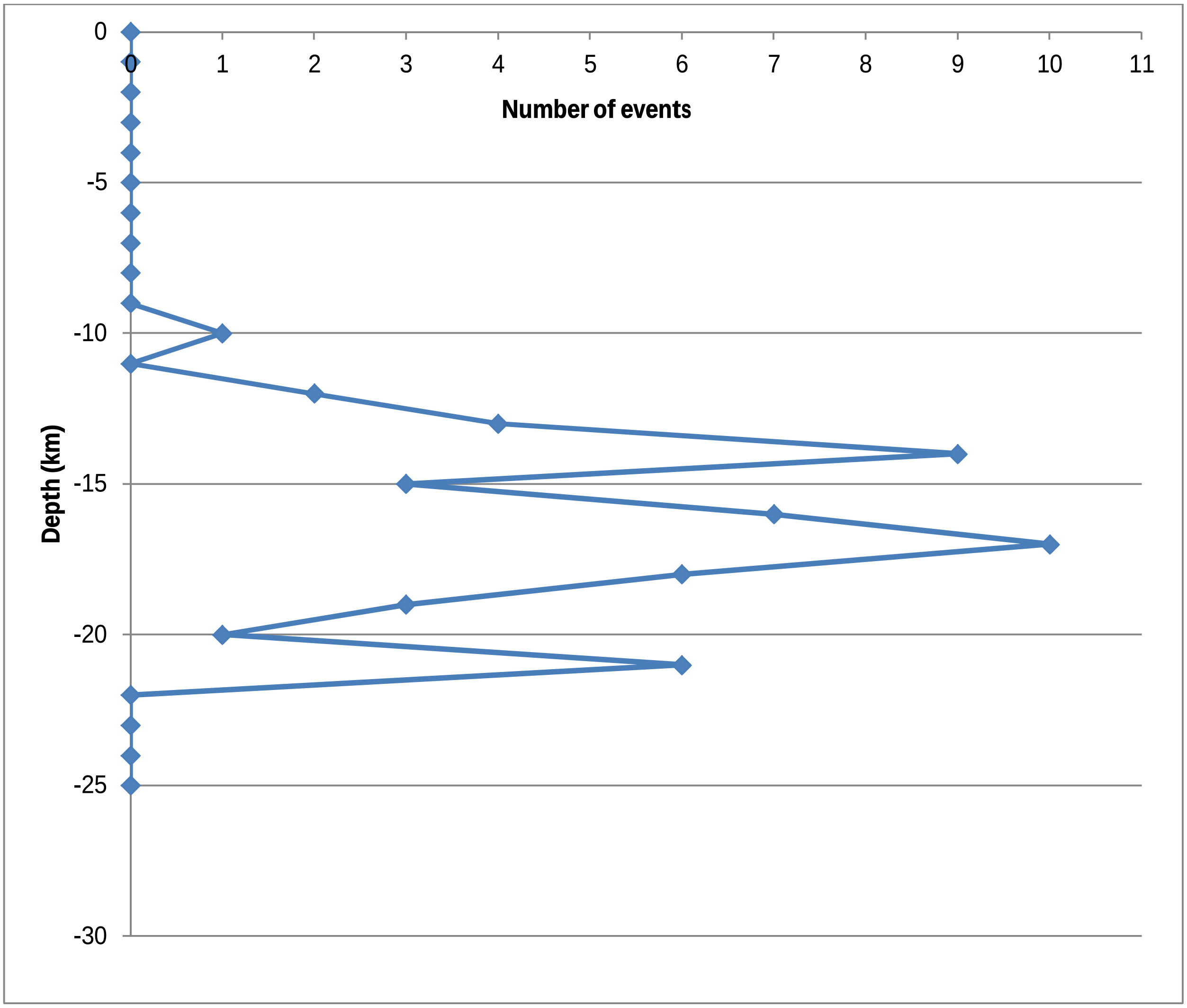

Figure 4. Number of SLV events as a function of year