Canadian Magnitude Determinations
For the Sharpsburg, Northern Kentucky, Earthquake
of 27 July 1980

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INTRODUCTION

A moderate earthquake occurred near Sharpsburg, in northern Kentucky, on 27 July 1980. It was large enough to saturate virtually all the modern high-gain short-period seismographs of the various networks deployed in the United States east of the Rocky Mountains. No modern low-gain short-period seismographs were operating at the time. The earthquake was recorded on scale by some older American seismographs whose current calibration was said to be not well known.

On the day of the earthquake the initial magnitude estimate issued by the United States National Earthquake Information Service (NEIS) was 5.9, followed by a revised value, m_b 5.1, based on one Alaskan station. A Canadian estimate based on analogue records of the Eastern Canada Telemetred Network (ECTN) was $m_b(L_g)$ 5-1/2. In the days immediately following the earthquake, American data suggested a magnitude 5 or slightly larger, but reliable data were few.

No earthquake as large as magnitude 5 is known to have occurred previously in Kentucky nor within 200 km of the July 1980 epicentre (Nuttli and Herrmann, 1978). Most of Kentucky has been included by Nuttli and Herrmann in a "residual events" region of the Central United States for which the maximum-magnitude earthquake is m_b5.3, where $m_{b,\ max}$ is defined as that magnitude with a 63% probability of occurrence within a 1000-year period of time (Nuttli and Herrmann, 1978). Other estimates of seismic zones and earthquake risk have also placed much of Kentucky in an area of minor seismicity and low risk where moderate earthquakes would be rare.

Thus an accurate magnitude value for the 1980 Kentucky earthquake is highly desirable to determine to what extent the size of this earthquake is compatible with previous knowledge of seismicity and previous estimates of seismic risk. Several requests, formal and informal, have been received from American geoscientists for a determination of the magnitude of the Sharpsburg, Kentucky, earthquake from data of the Canadian Seismograph Network (CSN).

This Internal Report presents magnitude determinations for the Sharpsburg, Kentucky, earthquake using Canadian data in two independent short-period magnitude scales - $m_b(P)$ and $m_b(L_g)$. It is recognized that the resulting two average magnitude values may not be completely representative of the size of the northern Kentucky earthquake, as the azimuth coverage of the Canadian Seismograph Network is only about 120°, although the distance range is from 600 to 5000 km.

LOCATION AND ORIGIN TIME

The Sharpsburg, northern Kentucky, earthquake occurred on 27 July 1980 at 18:52:21.8 U.T. with geographic coordinates 38.174°N, 83.907°W, depth 8 km and magnitude m_b 5.2 (USGS: PDE 30-80, Aug. 15, 1980).

Uncertainties of up to a few seconds in origin time and up to 20 km in location were not significant for this magnitude study. Arrival times were computed for P and Lg only to ensure that amplitudes had been measured within the appropriate portion of each wavetrain.

CANADIAN SEISMOGRAPH STATIONS

All stations of the CSN except BMS (Big Muddy, Saskatchewan), DLY (Dezadeash Lake, Yukon) and MCE (Mica Creek, British Columbia) were operating at the time of the earthquake. Short-period vertical (SPZ) seismograms were examined for the 18 standard stations, as well as SPZ seismograms for 20 regional stations and one low-gain station (OTT), and the analogue monitor records for 7 stations of the ECTN and the 4 stations of the WCTN. Digital data and playouts of all 8 stations of the ECTN plus the modified SRO (Seismic Research Observatory) system at GAC were also studied. In total, the records of 48 different Canadian stations were examined. At three of these (MNT, OTT and PGC), independent standard and telemetred seismographs are operated.

Measurements of maximum seismogram amplitude and associated period are presented in Tables 1 and 2, along with the relevant seismograph magnification. Station codes, coordinates and calibration curves are found in "Canadian Seismograph Operations - 1979" (Lombardo _et al_., 1980) with details on additions and changes in 1980 furnished by W.E. Shannon (private communication).

MAGNITUDE SCALES

The two magnitude equations given below were used whenever data were available within the distance (Δ) and period (T) ranges for which the scales are defined. Any exceptions are noted.

All seismogram amplitudes A in these equations are vertical-component zero-to-peak values expressed in microns. All periods are in seconds. Distances Δ are geocentric, and are expressed in degrees in the equation for m_b (P) and in km for m_b (Lg).

1. $m_b(P)$

$$m_b(P) = \log (A/T) + Q (\Delta)$$

Q (Δ) was taken from tables in Gutenberg and Richter (1956) for $\Delta \gtrsim 20.0°$ and for a surface focal depth. The results would not change significantly if Q values tabulated for 25 km had been used.

A was measured within about 15 seconds of the onset of the short-period P wave. At most stations measured, the maximum seismogram amplitude occurred within five seconds of the onset.

2. $m_b(Lg)$

$$m_b(Lg) = \log (A/T) + 1.66 \log\Delta - 0.1$$

As defined by Nuttli (1973), Δ lies in the distance range 400 to 3000 km, $T = 1.0 \pm 0.3$ second and A represents the sustained maximum short-period Lg amplitude, a value reached by at least three cycles of recorded motion. In addition, $m_b(Lg)$ is defined only for stations east of the Rocky Mountains, as Lg amplitude attenuation with distance is more rapid elsewhere.

In the present study, A is the maximum amplitude, $T \leq 1.3$ seconds and $\Delta \geq 400$ km, consistent with previous Canadian use of Nuttli's scale.

RESULTS

1. $m_b(P)$

Table 1 presents the measurements and $m_b(P)$ value calculated at each of 25 different stations. The average $m_b(P)$ is 4.9 ± 0.4, with $20° \leq \Delta < 45°$. P-amplitude measurements at 22 other stations at distances less than 20° were not used to calculate m_b since the maximum amplitude in the first minute may occur in different P phases.

Stations BMS, MCE and DLY were not operating; station SKB had high microseisms. All 47 other Canadian stations recorded the P wave distinctly without saturation. In Table 1 the magnitude at PGC (m_b 4.6) was determined from the standard station. A value m_b 4.7 was calculated from the PGC analogue monitor record of the WCTN.

Figure 1 shows the 25 station magnitudes plotted on a map of Canada. With few exceptions, stations east of 120°W (northern B.C. - Alberta border) had magnitude values greater than m_b 4.9 and those to the west had values less than m_b 4.9. The density of stations west of 120°W is greater than to the east. If the three Yukon stations and the six stations on and adjacent to Vancouver Island were replaced by one station in each area having a magnitude equal to either the mean or the median of the group of stations replaced, the resulting m_b averaged from 18 more evenly-spaced stations would be 5.0.

The individual station magnitudes in Figure 1 appear to vary systematically with geographic position relative to the epicentre with few exceptions, and may be related to the focal mechanism and its associated radiation pattern for P waves. However, some of the observed geographic variation may be due to differing attenuation along Shield and Cordilleran paths. These possible relationships have not been investigated in detail.

2. $m_b(L_g)$

Table 2 presents the measurements and $m_b(L_g)$ value calculated at each of 25 different stations east of the Rocky Mountains, which span a distance range from 1000 to 4500 km. The average $m_b(L_g)$ is 5.5 ± 0.3. If the maximum distance is restricted to 3000 km, or even to 2000 km, the average $m_b(Lg)$ would be greater than 5.5, since most of the large station magnitudes were observed at shorter distances. In Table 2 the magnitude at OTT ($m_b(Lg)$ 5.9) was determined from the ECTN digital record. A value $m_b(Lg)$ 6.0 was calculated from the OTT analogue low-gain seismogram.

$m_b(L_g)$ was not calculated at the 12 stations west of the Rocky Mountains for which paths this magnitude scale is not defined. In addition, the maximum amplitudes at virtually all these stations ($3100 \leq \Delta \leq 4700$ km) were associated with periods $\gtrsim$ 1.5 seconds, outside the period range for which

$m_b(L_g)$ is defined. However, other stations east of the Rockies at comparable distances had maxima at periods near 1 second.

At ALE (5008 km), the maximum short-period amplitudes were too late to be considered associated with the L_g phase. At MBC (4593 km), T = 1.7 s, again too large for $m_b(L_g)$.

Figure 2 shows the 25 station magnitudes of Table 2 plotted on a map of Canada. With few exceptions, all stations east of 90°W (approximate longitude of LHC) had magnitude values greater than the overall average $m_b(L_g)$ 5.5, and those to the west had values under 5.5. If the four stations in the Ottawa Valley (FHO, OTT, MIQ, MNT) and in the St. Lawrence Valley (GNT, LMQ, POC, LPQ) were each reduced to one station having the average magnitude of the group, the resulting 19 more evenly-spaced stations would have average magnitude $m_b(L_g)$ 5.4.

DISCUSSION

1. Comparison of Magnitudes

Table 3 compares $m_b(L_g)$ and $m_b(P)$ magnitudes at the 12 Canadian stations for which both can be calculated. Although the average values in Tables 1 and 2 differ by 0.6 unit, the pairs of values at most of the individual stations agree quite closely. Table 3 indicates that the $m_b(L_g)$ scale is not offset significantly with respect to the $m_b(P)$ scale. Differences at individual stations such as BLC and RES may be ascribed mainly to the radiation patterns of L_g and P waves, which would not be expected to be identical.

The average magnitude values for the eight stations between 2000 km and 3000 km are: $m_b(L_g)$ 5.3 $\pm$ 0.2, $m_b(P)$ 5.2 $\pm$ 0.2. As these eight stations are well distributed in azimuth with respect to the epicentre and also with respect to the Canadian network, these averages may be considered as the best estimates of the magnitude of the Sharpsburg, Kentucky, earthquake obtainable from seismograms at the Canadian stations.

Stations of Table 3 beyond 3000 km were not included in these final averages. Nuttli (1973) defined his scale for $4° \leq \Delta \leq 30°$, but Street (1976) has suggested it be limited to less than 20°. However, routine analyses of numerous L_g amplitude data for Canadian earthquake catalogues have shown no evidence that calculations of $m_b(L_g)$ should be limited in distance range. Restrictions of periods to $T \leq 1.3$ s does in itself eliminate some of the amplitudes measured at larger distances. $m_b(L_g)$ values in Table 2 vary more strongly with azimuth than with distance.

2. Effect of Large L_g Amplitudes at Stations in Eastern Canada

Table 4 lists the seven regional, one digital and two standard stations, all in eastern Canada, at which the L_g amplitudes were too large for the maximum to be recorded clearly. Note that not only the analogue monitor, but also the 3-component short-period digital signals at GAC exceeded the dynamic range (108 db) of the modified SRO system. The digital signals at the eight stations of the ECTN remained within their dynamic range (96 db = $\pm 2^{15}$), although four analogue monitors (FHO, MIQ, LPQ and MNQ) did not. OTT and MNT have no analogue monitor. At LDQ the analogue monitor was operating at low gain due to continuous local noise. At GNT due to intermittent noise bursts the amplitude limiter switch was on, which compressed large input signals by a known relation to keep recorded amplitudes on scale. However, under normal operation, LDQ and GNT monitors would not have recorded the L_g maximum amplitudes.

At most regional and standard stations within 2000 km of the epicentre, L_g amplitudes were too large for their recording systems. At LMQ the limiter switch was inadvertently on; otherwise L_g amplitudes could not have been measured. At SIC, where the limiter was also on, the calculated magnitude value was not included in the average, since the pen pressure was too great and damped the recorded amplitudes. Even so, Table 2 shows a station value of 5.2 at SIC. Except for the OTT analogue low-gain and ECTN digital stations, all stations within 2000 km saturated, except LHC, POC, PWM and HAL. This emphasizes the importance of a low-gain station in the ECTN for rapid magnitude estimate.

3. High $m_b(L_g)$ Values at ECTN Stations

The general agreement between magnitude scales in Table 3 and the mutual independence of its 12 stations (10 standard, 2 regional) both suggest that high $m_b(L_g)$ values at individual stations such as SCH and FRB, for example, are correct, and that similarly high or higher values at the eight ECTN digital stations (5.6 to 5.9) are also correct, and not likely due to any calibration errors in the digital system. Epicentral distances were too short to permit calculation of $m_b(P)$ at any of the digital stations ($9° < \Delta < 17°$) to see whether their $m_b(P)$ values were also very high. Saturation of the digital SRO system of GAC, having the widest dynamic range, although also the most sensitive, again seemed to confirm the relatively large L_g ground amplitudes transmitted into eastern Canada from the Sharpsburg earthquake.

OTT and MNT are the only two stations of the ECTN that also have another seismograph system completely independent of the digital system. Unfortunately, as Table 4 shows, maximum L_g amplitudes could not be measured on either photographic system in order to verify the calibration of the digital system. The MNT trace had faded already in the P phase due to a weak light beam. Thus only P amplitudes at OTT could be checked. Photographic and digital amplitudes appeared to give comparable ground amplitudes. The OTT analogue low-gain signal originated from the same seismometer and pre-amplifier as the ECTN digital station, and, as noted earlier, had an even higher calculated magnitude than on the latter system, which could not be explained by either an error in calibration or in operating level.

Since the highest positive residuals in Table 2 are at the ECTN stations, it seemed important to ensure that they were not due to a systematic error in calibrating the digital system. Consequently, another earthquake was selected for which amplitudes in P and L_g could be measured at OTT and MNT on both systems. The northern Baffin Island earthquake of 03 September 1980 at 07:34 was approximately equidistant from OTT and MNT (26-1/2°). Magnitude values are: OTT $m_b(P)$ 4.8, $m_b(L_g)$ 4.7; MNT $m_b(P)$ 4.7, $m_b(L_g)$ 4.9. Ground amplitudes measured at the same time on digital and photographic systems were in agreement provided that the period of the wave whose amplitude was measured was the same on both systems. Thus calibration of the digital stations appears correct. Therefore the high L_g ground amplitudes at the ECTN stations observed from the July 1980 Kentucky earthquake must be real.

CONCLUSIONS

1. The magnitude of the Sharpsburg, northern Kentucky, earthquake of 27 July 1980 was determined from Canadian seismograms as follows:

   $m_b(P) = 4.9 \pm 0.4$, 25 stations, $20° \leq \Delta < 45°$

   $m_b(L_g) = 5.5 \pm 0.3$, 25 stations, east of the Cordillera, $1000 \text{ km} \leq \Delta \leq 4500$ km

$m_b(P) = 5.2 \pm 0.2$ and $m_b(L_g) = 5.3 \pm 0.2$, the same 8 stations, east of the Cordillera, $2000\ \text{km} \leq \Delta \leq 3000\ \text{km}$.

2. Station values for both $m_b(P)$ and $m_b(L_g)$ were strongly azimuth-dependent.

3. Stations of the digitally-recording ECTN had the highest $m_b(L_g)$ magnitude values, from 5.6 to 5.9, which was apparently due to the focal mechanism and related radiation pattern, and not to some instrumental error in the digital system.

4. Although the "true" magnitude of the Sharpsburg earthquake was about 5-1/4, the amplitudes of ground motions in much of Ontario and Québec were comparable to those expected from an earthquake of magnitude about 5-3/4. That is, actual ground amplitudes were larger by a factor of about 4.

The focal mechanism and consequent radiation patterns are not known in advance for most earthquakes in eastern North America. The Sharpsburg amplitude data show that peak ground motions may vary over a wide area by more than a factor of 2 from the mean. It is thus important to apply the usual "factor of 2 uncertainty" to increase peak ground motions calculated for a specified design earthquake. This will not lead to unduly conservative design values, as the Sharpsburg earthquake has illustrated.

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TABLE 1

m_b(P) Magnitude Data

Code	Delta (km)	Delta (deg)	Q	T (s)	Gain (K)	Amp (mm)	m_b(P)	Residual
SCH	2257.7	20.3	6.10	0.3	105	8.0	5.50	.58
FFC	2291.9	20.6	6.10	0.3	168	6.3	5.20	.27
FCC	2405.4	21.6	6.16	1.0	33	4.5	5.29	.37
SES	2535.9	22.8	6.28	0.5	126	5.5	5.22	.30
STJ	2731.0	24.6	6.46	0.5	25	0.7	5.21	.29
EDM	2807.2	25.3	6.50	0.5	121	2.5	5.12	.19
BLC	3019.4	27.2	6.52	0.9	105	2.2	4.89	-.04
FRB	3026.9	27.2	6.52	1.0	36	3.0	5.44	.52
PNT	3096.5	27.9	6.59	0.6	96	0.7	4.67	-.25
HYC	3308.6	29.8	6.60	0.5	123	0.6	4.59	-.33
PIB	3357.0	30.2	6.62	0.7	39	0.5	4.88	-.04
PGC	3365.1	30.3	6.63	0.5	59	0.3	4.64	-.29
YKC	3408.4	30.7	6.67	0.8	71	0.8	4.82	-.10
ALB	3467.5	31.2	6.70	0.7	39	0.3	4.74	-.18
IGL	3478.6	31.3	6.70	1.0	34	1.4	5.31	.39
FSB	3535.1	31.8	6.70	0.9	105	0.7	4.57	-.35
GDR	3564.4	32.1	6.70	0.5	63	0.3	4.68	-.24
PHC	3672.6	33.1	6.70	1.0	14	0.5	5.25	.33
SKB	4010.6	36.1						
RES	4110.9	37.0	6.50	0.5	195	1.2	4.59	-.33
WHC	4320.3	38.9	6.41	0.7	108	0.4	4.13	-.79
INK	4494.0	40.4	6.44	1.3	41	0.8	4.62	-.31
KEY	4508.6	40.6	6.46	1.0	30	0.3	4.46	-.46
MBC	4592.5	41.3	6.50	1.2	50	3.5	5.27	.34
KRY	4624.1	41.6	6.50	0.9	34	0.5	4.71	-.21
ALE	5007.6	45.1	6.71	0.8	79	2.2	5.25	.33

Average magnitude from above 25 stations is m_b 4.92 ± 0.36

TABLE 2

$m_b(L_g)$ Magnitude Data

Code	Delta (km)	Delta (deg)	T (s)	Gain (K)	Amp (mm)	$m_b(L_g)$	Residual
+FHO	1030.0	9.3	0.47	3.4	12.0	5.78	.33+
+OTT	1051.2	9.5	0.40	4.0	14.5	5.87	.43+
+MIQ	1120.5	10.1	0.53	3.0	10.5	5.78	.34+
+MNT	1178.4	10.6	0.67	2.2	10.0	5.83	.38+
LHC	1217.9	11.0	0.30	101.	60.0	5.32	-.13
+GNT	1314.4	11.8	0.50	9.6	18.0	5.65	.20+
LMQ	1518.5	13.7	0.50	90.	68.0	5.36	-.09
POC	1523.0	13.7	0.50	50.	60.0	5.56	.12
+LPQ	1523.3	13.7	0.50	9.6	18.5	5.77	.32+
PWM	1646.9	14.8	0.40	57.	28.0	5.33	-.12
+LDQ	1807.8	16.3	0.73	9.9	13.5	5.58	.13+
+MNQ	1821.9	16.4	0.60	8.0	14.0	5.78	.33+
HAL	1837.7	16.5	0.80	48.	31.0	5.23	-.22
xSIC	1907.2	17.2	0.50	151.	50.0	5.17	
SCH	2257.7	20.3	0.50	77.	52.5	5.60	.16
FFC	2291.9	20.6	0.70	72.	22.5	5.13	-.32
FCC	2405.4	21.6	0.70	62.	27.5	5.31	-.13
SES	2535.9	22.8	1.00	46.	18.0	5.14	-.30
STJ	2731.0	24.6	1.20	7.	2.0	4.98	-.47
EDM	2807.2	25.3	1.00	48.	12.5	5.04	-.41
BLC	3019.4	27.2	1.30	48.	46.0	5.54	.10
FRB	3026.9	27.2	0.60	79.	32.5	5.51	.07
YKC	3408.4	30.7	1.00	45.	10.5	5.13	-.31
IGL	3478.6	31.3	1.30	20.	17.0	5.59	.15
RES	4110.9	37.0	0.70	126.	22.0	5.30	-.15
INK	4494.0	40.4	1.20	50.	7.0	5.03	-.42

x not included in average
+ data from digital record, not from analogue monitor

Average magnitude from above 25 stations is $m_b(L_g)$ 5.45 ± 0.28

TABLE 3

Magnitude Comparison at Individual Stations

Code	$m_b(L_g)$	$m_b(P)$	Difference
SCH	5.6	5.5	0.1
FFC	5.1	5.2	-0.1
FCC	5.3	5.3	0.0
SES	5.1	5.2	-0.1
STJ	5.0	5.2	-0.2
EDM	5.0	5.1	-0.1
BLC	5.5	4.9	0.6
FRB	5.5	5.4	0.1
YKC	5.1	4.8	0.3
IGL	5.6	5.3	0.3
RES	5.3	4.6	0.7
INK	5.0	4.6	0.4

Average magnitude at first eight stations

$m_b(L_g)$ 5.3 ± 0.2
$m_b(P)$ 5.2 ± 0.2

TABLE 4

Stations with Lg Amplitudes too Large for Recording System

Code	Epicentral Distance		Code	Epicentral Distance	
	(km)	(deg)		(km)	(deg)
Regional Station			Standard Station (photographic)		
EFO	670	6.0	OTT	1051	9.5
SUD	953	8.6	MNT	1178	10.6
QCQ	1409	12.7	ECTN Analogue Monitor		
CHQ	1415	12.7	FHO	1030	9.3
UNB	1666	15.0	MIQ	1121	10.1
LTQ	1828	16.5	LPQ	1523	13.7
PBQ	1959	17.6	MNQ	1822	16.4
Digital (SRO) Station					
GAC	1089	9.8			

FIGURE CAPTIONS

Figure 1. Variations in $m_b(P)$ values at individual stations. Stations above the average 4.92 are denoted by a plus sign, those below by a vertical bar. Table 1 contains values of specific residuals.

Figure 2. Same as Figure 1, except that station values above and below the mean $m_b(L_g)$ of 5.45 are plotted. Table 2 contains values of specific residuals.

MB(P) MAGNITUDES (DELTA > 20. DEGREES).

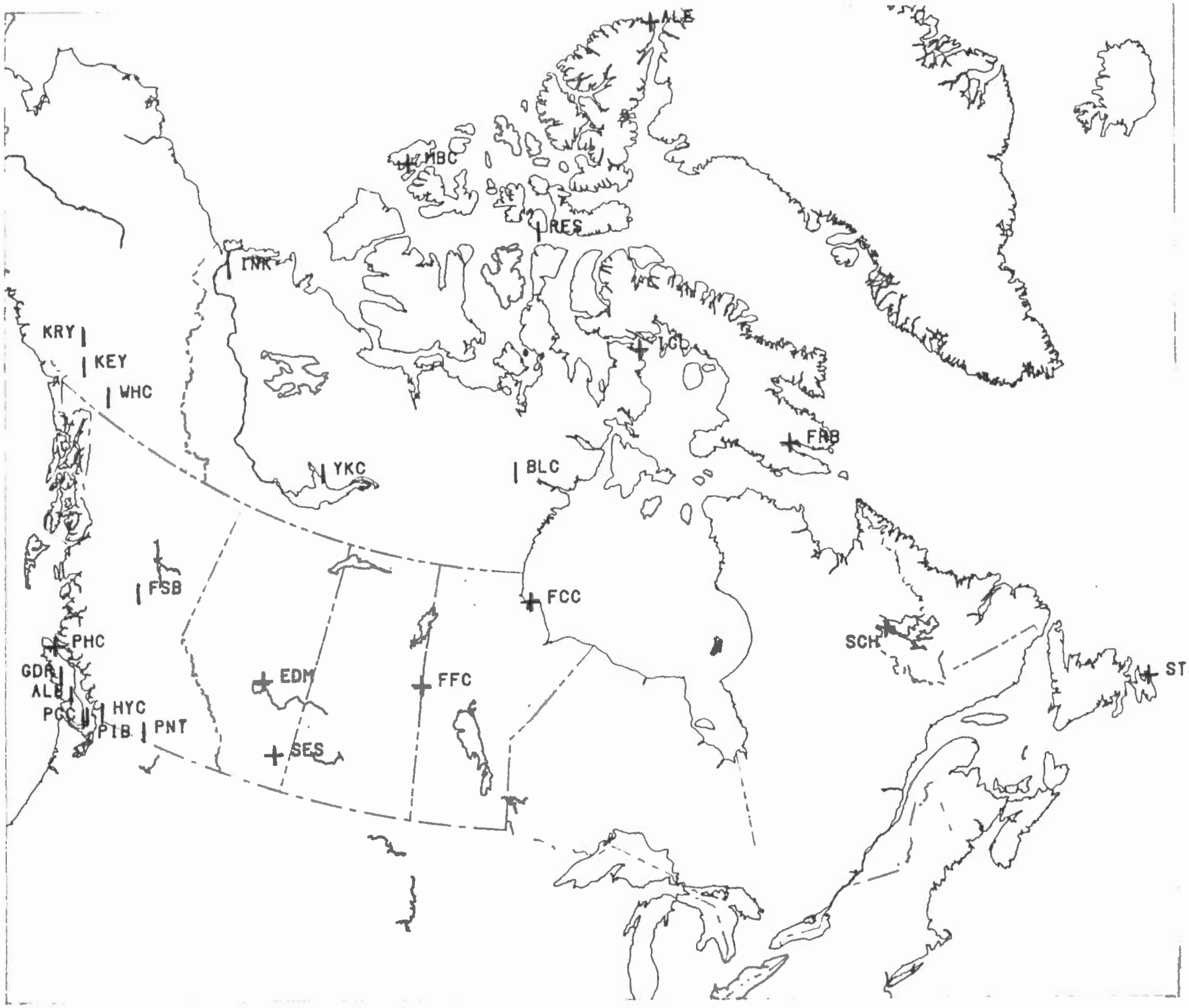

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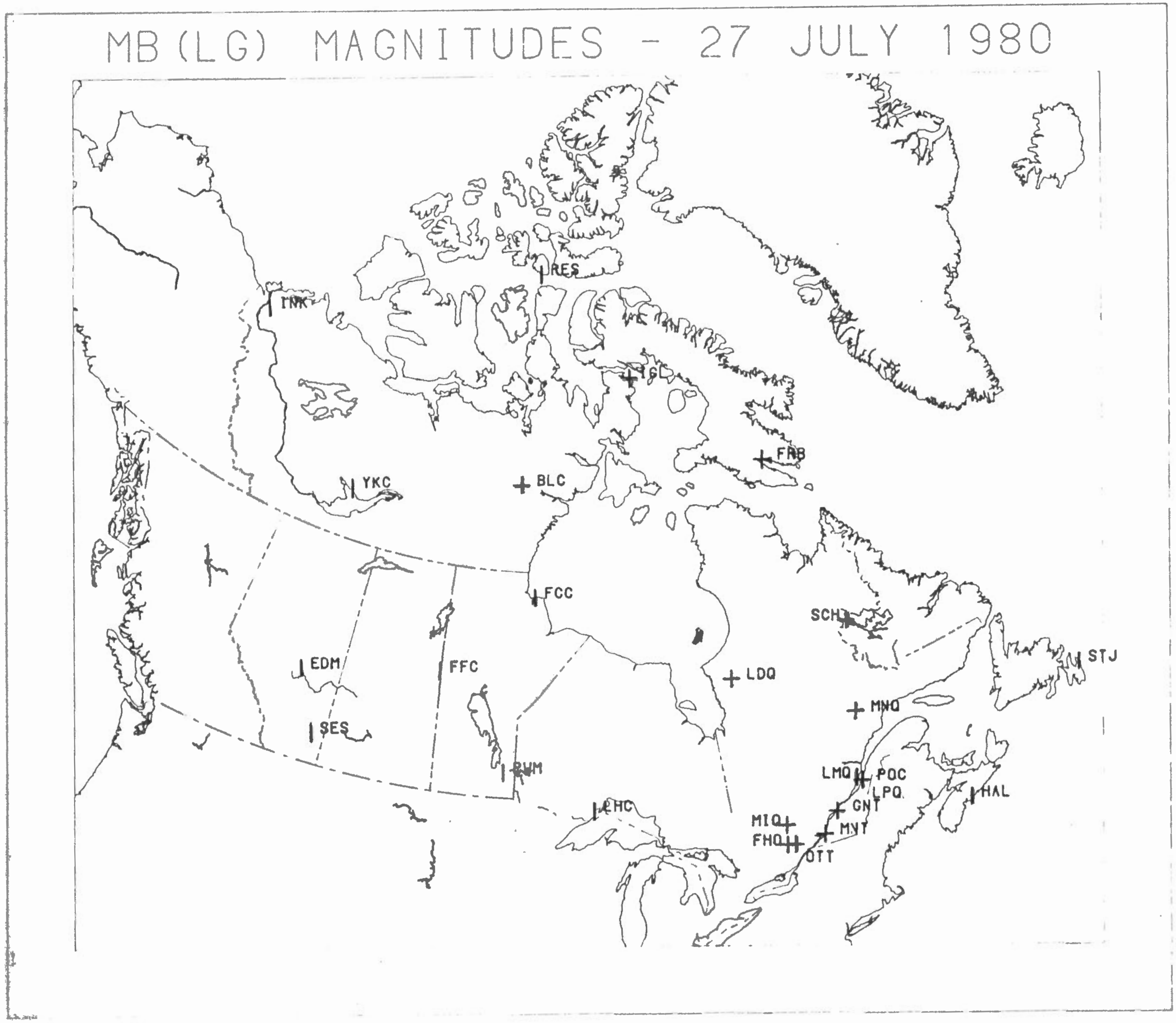
Figure 1



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PLOTTED 23.12.80 12.49.13. SCALE 1>30000000

Figure 2