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Induced Seismicity at the LG-2 Reservoir

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ABSTRACT

The construction of a rock and earthfilled dam in the La Grande river valley, Quebec has created a hydro-electric reservoir with a maximum depth of 145 m and a volume of 61.7×10^9 m^3. No seismicity in this Precambrian shield region above magnitude 0.1 was observed in the reservoir zone in the 27 months preceeding the filling. Microearthquakes of magnitude less than 1 started under the reservoir when a water depth of 90 m was reached after 30 days and this activity continued for about three months. A second series of microearthquakes began in the same active zone when the rate of filling increased two fold. The seismically active area is confined to a zone 4x7 km and no deeper than 5 km. The microearthquakes are considered to be the result of minor reactivation of old faults under the reservoir in response to the increased pore pressure.

INTRODUCTION

In 1972, the Société d'Energy de la Baie James (SEBJ) undertook the construction of the La Grande hydroelectric complex. Located on the Quebec side of James Bay (Figure 1) phase I of the complex will consist of three power stations constructed along the river, that is LG-2, LG-3 and LG-4.

The LG-2 project is the first element of the La Grande complex, with the dam and power house located on the La Grande river 120 km upstream of its mouth. The dam is a multizoned earth and rock structure. It is 160 m high and 2835 m long along at its crest. The dam rests on bedrock of Precambrian age. There are no concrete structures associated with this dam since the powerhouse water intakes are located 5 km south west of the dam and the spillway is located 1 km northwest of the dam. The reservoir is contained not only by the dam but also by a series of 31 dykes totalling 30 km in length. The maximum water height is 175 m above sea level and the reservoir contains 61.7×10^9 m^3 of water, covering a surface area of 2835 km^2 and extending 95 km eastward to the foot of the LG-3 dam. The first generator started to produce electricity in October 1979 and the last of the 16 units will come on line in 1982. At that time, the installed capacity will be 5,328 megawatts.

The bypasses have been closed under the dam by steel doors and the tunnels are blocked by concrete plugs. Without major work the reservoir level can only be lowered by 11 m to the level of the bottom of the spillway entrance.

The La Grande complex is located in a region of the Canadian shield that has very little history of seismicity. No epicentres have been located closer than 100 km to LG-2. However, in view of the induced seismicity at Manic 3 on the eastern side of the Canadian shield (Leblanc and Anglin, 1978), the height of the LG-2 dam, the known high horizontal stresses and the weak historic seismicity to the west of the reservoir sites, SEBJ was advised to augment the seismic detection capability in the vicinity of the future reservoirs.

Thus, prior to the filling of the reservoir a short period vertical component regional station, LGQ was installed in August 1976, 21 km southwest of the dam, in order to check that there was no low level local seismicity that had escaped the detection of the Canadian National Network. The regional station was augmented by a three element telemetered array (LAQ, LBQ, LCQ) from the beginning of October 1978 to the end of October 1979. Station sites were chosen so that the total of four stations formed a rough square around the reservoir in order to detect seismic activity over as large an area as possible (Figure 4). The station configuration was also considered sufficient to locate earthquakes in the deeper western half of the reservoir. One additional station was kept in reserve to be used either as a spare or for deployment close to any detected seismicity.

GEOLOGY AND STRUCTURE

The region of LG-2 is part of the north-west sector of the Superior geological province of the Canadian shield. This region consists mainly of Archean rocks of granitic to granodioritic composition.

As reported by Levay and Aziz (1978), before excavation and construction of the spillway and dam commenced, those areas were examined for faults and joint systems. Three main joint systems were identified, one striking N-S and one E-W, both being quasi-vertical. The third system was found to be a horizontal system of rebound joints. Also noted were strong NNW trending lineations between the main dam and the spillway channel. However, diamond drilling of these features showed from a civil engineering viewpoint that in general, the local rock conditions were found to be from good to excellent.

Seven kilometers to the west, geological studies (Murphy et al., 1976) in the region of the underground powerhouse also revealed the three joint systems, where the horizontal joint system was found to be present at all tested depths. Faults were also found to cut the area of the underground powerhouse and were found to have an ESE trend consisting of relatively narrow zones of the sheared mylonite material. However, the rock was also found to be "tight" with the seepage again being insignificant.

Prior to the excavation of the underground powerhouse, in-situ triaxial stress determinations were performed (Murphy et al., 1976). The stress measurements indicate a stress ratio ${}_h = 1.4$ to $1.8\ {}_v$ with ${}_v = 6200$ kpa. The principal stress component is roughly N-S inclined to 20° to the north, and has a value of 11,000 kpa. During the excavation of the underground powerhouse, spalling of the rock surfaces occurred.

HISTORIC AND PREFILLING SEISMICITY

Seventeen events to the west mostly in James Bay with none closer than 100 km to the dam are shown in Figure 3.

It must be noted that the two events designated by circled stars are based only on felt reports, implying a greater uncertainty than normal in the epicentres. Other epicentres shown in Fig. 3 have an epicentral uncertainty of about 50km. The area shown on Figure 3 has not experienced an event of magnitude greater than 5.

From September 1965 to September 1972 a standard 6 component seismic station (GWC) was in operation at Great Whale, a distance of 170 km north of

LG-2. During this time earthquakes of magnitude ML 2 should have been observed in a radius of 180 km from the station. In September 1972 this station became a three component short period regional station (PBQ). The detection threshold for events around LG-2 improved to 1.6. Since August 1976 a vertical component seismometer (LGQ) was operated at 21 km south-west of the dam of LG-2. Events with a magnitude ML 0.1 should have been observed in a radius of 30 km from the station. During this period of seismic surveillance, no seismic activity was observed in the region of the LG-2 reservoir.

With station LGQ we learned to recognize, on the seismogrames, the signals coming from the main construction sites, that is LG-2, LG-3, LG-4 and EOL (Eastmain, Opinaca and La Grande rivers). All these events looked like explosions. The difference in travel times of P and S waves (S-P) was respectively: 2-3, 13, 17 and 34 seconds. The blasting lists for most of these events, supplied by SEBJ, confirmed this interpretation.

INSTRUMENTATION AND CALIBRATION

The array deployed at LG-2 was similar to that used in the eastern and western Canadian telemetered networks based in Ottawa and Sydney B.C. The system consists of a Geotech S13 seismometer coupled to a 1 to 20 Hz bandpass filter. The signal is digitized at 60 s/s in floating point format with a 12 bit mantissa and an exponent that yields a dynamic range of 108 db with a maximum sensitivity is 10 nm/s per bit. A microprocessor serialises the data for asynchronous transmission at 1200 baud at LG-2. Digital (FSK) UHF radio links transmit the data to a convenient microwave tower where telephone company facilities complete the link to the Ottawa Data Centre computer and helicorder display facilities. During the equipment design phase a special effort was made to ensure that the equipment could operate reliably in cold weather. These efforts were later repaid when the remote stations operated reliably in ambient temperatures as low as -40°C.

Three calibration blasts were set off while the 3 component telemetered array was operating to aid in the location of the induced earthquakes and to determine the local P velocity. Two shots were set off on October 17 and 18, 1978 soon after the array started to operate, with the first just north of the dam site (south of the future site LDQ) and the second between stations LGQ and LBQ (Fig. 4). After the induced events began the array seismometer station LCQ was decomissioned as it was furthest from the active region and station LDQ was established (Figure 4). To help to calibrate this fourth station, another shot was detonated on July 27, 1979 at the first shot point, and just 1 km from station LDQ. Each shot was made up of 200 kg of explosives distributed between three 20 m deep closely spaced drill holes. The travel-times of the P waves from the shots to the stations over a distance range of 1.0 to 41.5 km indicate a P wave velocity in the upper crust of 6.00 $\pm$ 0.05 km/s to 90% confidence with no lower velocity weathered layer. The S phases were more difficult to read, but the available data indicate an S wave velocity close to 1/ 3 of the P wave velocity (i.e. a Poisson's ratio of 0.25). This relation has been found to hold in the upper crust for other regions of the shield (Leblanc and Buchbinder 1977).

INDUCED SEISMICITY

On November 27, 1978 the by-pass tunnels under the dam were closed. The delay before the first microearthquake (M_L 1) was detected was 30 days when the water had reached a depth of 90 m. Its epicenter was computed to be 4.km $\pm$ 2.km upriver of the main dam, its hypocentre was close to the surface, between 0 and 5 km. Over the following days the microearthquakes increased in number and magnitude as the water rose in the reservoir (Figure 5).

An increase in the rate of change of the water level in the reservoir that started in May 1979 was coincident with the second period of activity which occurred after a quiet period of about 45 days (Figure 5). Such an effect has been noted in other cases of reservoir induced seismicity (Simpson 1976).

With the initial station distribution, it was not possible to determine the depths of the events. Therefore, at the end of February 1979, the station most distant from the activity, (LCQ), was closed and station LDQ as installed about 4 km NE of the dam. Control on the depths of events would have been maximized if LDQ had been placed directly over the active region; however, this was not possible because the actual region was either about to be inundated or was already flooded. The change in station configuration requires that the data be analysed in two sets.

Using the station configuration LAQ, LBQ, LCQ and LGQ, the calibration shot of October 17, 1978, was mislocated 0.5 km to the north of its actual location. In locating all of the events up to and including February 26, 1979, the depths were constrained to 1 km and the bias value was then removed from all epicentres. With the removal of station LCQ and the addition of station LDQ, the calibration shot of July 23, 1979 was mislocated 1.6 km to the north and 0.8 km to the west. Again the depth of all events were constrained to 1 km and the bias value removed from all epicentres.

Depths were arbitrarily set to a shallow depth of 1 km because the surface waves from the calibration shots and some of the nearby earthquakes were very similar. After station LDQ was established, S-P times were observed to vary from 0.20 to 0.80 sec. As the events were 3 to 5 km from LDQ, this forces the hypocentres to be less than 5 km in depth.

Figure 6 shows those better located events for which at least 7 S, and P, phases were readable on the four stations, and where the velocity ratio V_p/V_s lay in the range 1.7 ± 0.2. The latter condition provided a check on the S phases and allowed obviously incorrect readings to be rejected. However most of the unplotted events are in the same region, with few events located in other regions of the LG-2 reservoir (Figure 4).

For the period December 27, 1978 to February 26, 1979, 57 events were located in the region of the reservoir, 40 of the better locations are plotted on the epicentral map (Figure 6). For the period from February 26th to September 18th 1979, when LDQ was used instead of LCQ, a further 64 events were located, 20 of which are plotted on the map. As LDQ was closer to the activity than the other three stations, more small events were located during this second period.

The epicentres in Figure 6 separate into two distinct groups. One group that is south east of the dam site and south of the old riverbed strikes WNW. The other group consists of two sections, one striking EW under the old river bed and the other section strikes NW, which is parallel to that section of the river up stream from the activity. These orientations reflect the old fault lines as now expressed by the local orientation of the La Grande river. The number of stations recording the events and the character of the first arrivals did not permit determination of fault plane solutions.

DISCUSSION

The seismicity that was observed under the LG-2 reservoir after November 1978 must be considered to have been induced. The area had been aseismic down to magnitude 3 for many years and no microearthquakes had been recorded for 3 years prior to filling of the reservoir. The induced seismicity began when the water height reached 90 m, it then tappered off and resumed again when the 9ate of filling increased by a factor of two. The events near to the dam site are separated into two groups that follow observed structural features, of which the offset in the old riverbed is the most obvious. Towards the end of the observation period two microearthquakes were observed further away from the dam site. The LG-2 reservoir is now filled to a depth of 145m and the monitoring of earthquakes is continuing at a reduced level. All events were very shallow. -

On the eastern side of the Canadian shield, minor induced seismicity was observed in the Manicouagan valley under the Manic 3 reservoir near the north-west edge of one of the seismically active zones of the St. Lawrence valley. In contrast, the LG-2 microearthquake activity occurred in an aseismic zone of the shield with the nearest zone of any activity being more than 100 km to the west under James Bay. The Manic 3 induced events were more numerous with a maximum magnitude of 4.1 in comparison to a magnitude of 1 observed at LG-2. In both cases the activity appears to be associated with pre-existing faults in regions of horizontal compression that is a thrust regime. This is quite different from induced seismicity elsewhere. Simpson (1976) has shown that all the larger reservoir induced earthquakes show fault plane solutions corresponding to normal faulting or strike-slip faulting regimes. Castle et al. (1980) examined the stress regimes at reservoirs with induced seismicity and concluded that such activity is least likely to occur in areas of thrust faulting. Thus for induced seismicity at LG-2 and Manic -3 the mechanism must be sought in a more complex stress system under the reservoirs than the one given by Simpson (1976) or in a different mechanism. Fortunately no larger or potentially damaging earthquakes occurred in either region in contrast to some cases of reservoir induced seismicity elsewhere (Gupta & Rastogi, 1976).

Detailed examination of the topography reveals that the induced events occurred near sharp bends in the topography that we believe are due to preferential erosion of the river bed along ancient weaknesses in the rock. The same can be said about the site of the induced seismicity at Manic 3.

It is interesting to compare water depth at these two reservoirs in the Canadian Shield. In the case of LG-2 the seismicity commenced when the water depth had reached 90 m. Once the reservoir was filled the part that is at least 90 m deep extends for about 25 km upstream to the confluence of Kanaaupscow and La Grande rivers, but the seismicity was confined to an area of 4 x 7 km. In the case of Manic 3 the seismicity commenced when the water depth had reached 60 m, and when filled the part of the reservoir that is at least 60 m deep extends over 50 km north of the dam, but again only an area of 4 x 4 km was active. Therefore we conclude that it is not water depth that is responsible for the location of the seismic activity, but rather the ancient weaknesses or faults in the region of the new reservoirs.

Acknowledgements

The assistance and cooperation of J. Levay and his collegues at SEBJ in monitoring this reservoir has been invaluable in providing data for the study of another case of induced seismicity in the Canadian shield. We are also indebted to R. Hayman and the Seismological Instrumentation Laboratory for the array instrumentation, which was installed at LG-2, and that was designed and built in the Laboratory. J. Levay, M.J. Berry and P. Basham critically read the manuscript and offered suggestions for its improvement.

Figure Captions

Fig. 1 Map showing the dams and reservoirs that form phase I of the La Grande complex.

Fig. 2 Map of the area around the LG2 reservoir showing the locations of mapped faults.

Fig. 3 Map of earthquakes, up to and including 1978, for the region around the La Grande complex. Circled stars represent events that have poor locations.

Fig. 4 Map of the LG2 reservoir area showing the locations of the calibration shots X, seismometer sites, microwave tower and epicentres.

Fig. 5 Graph showing the number of events per day after the filling started, the maximum magnitude per day, the filling curve and the rate of filling.

Fig. 6 Map showing epicentres immediately upstream from the LG2 dam site. Symbols denoted by x are events located using LDQ instead of LCQ as part of the materials.

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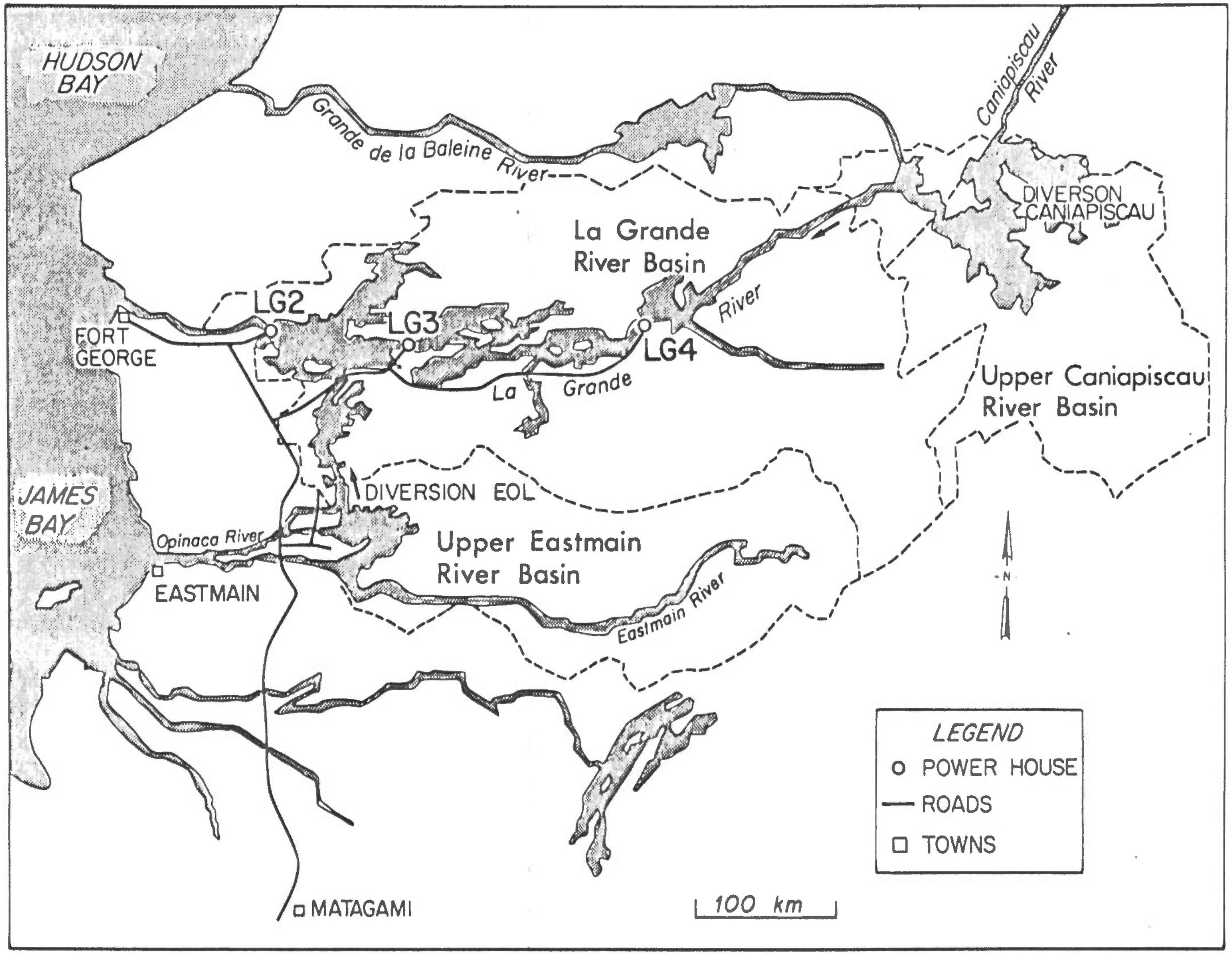
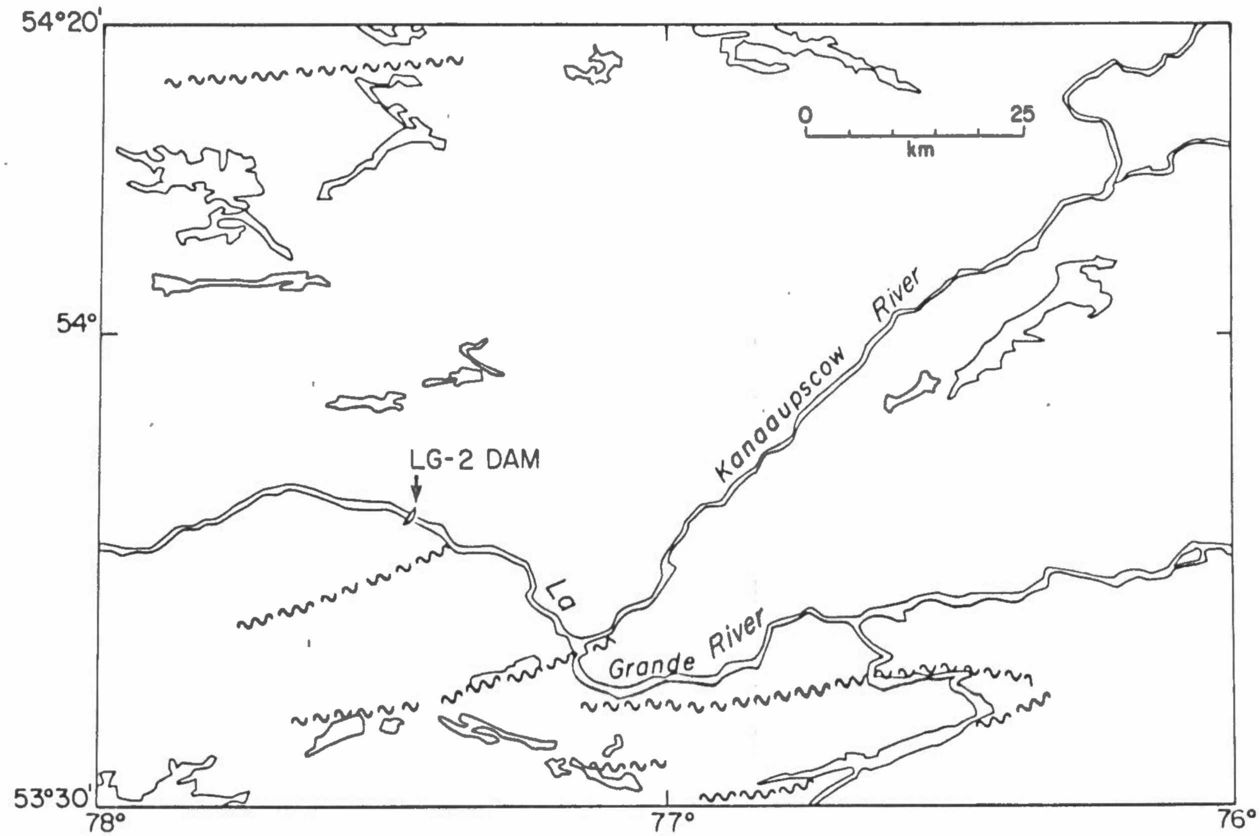

HUDSON BAY
Grande de la Baleine River
Caniapiscau River
DIVERSON CANIAPISCAU
La Grande River Basin
River
LG2
LG3
LG4
FORT GEORGE
La Grande
Upper Caniapiscau River Basin
JAMES BAY
DIVERSION EOL
Opinaca River
Upper Eastmain River Basin
EASTMAIN
Eastmain River
N
LEGEND
POWER HOUSE
ROADS
TOWNS
100 km
MATAGAMI

Fig. 1

Fig. 2


54°20'
54°
53°30'
78°
77°
76°
0
25
km
LG-2 DAM
Kanaaupscow River
La
Grande River

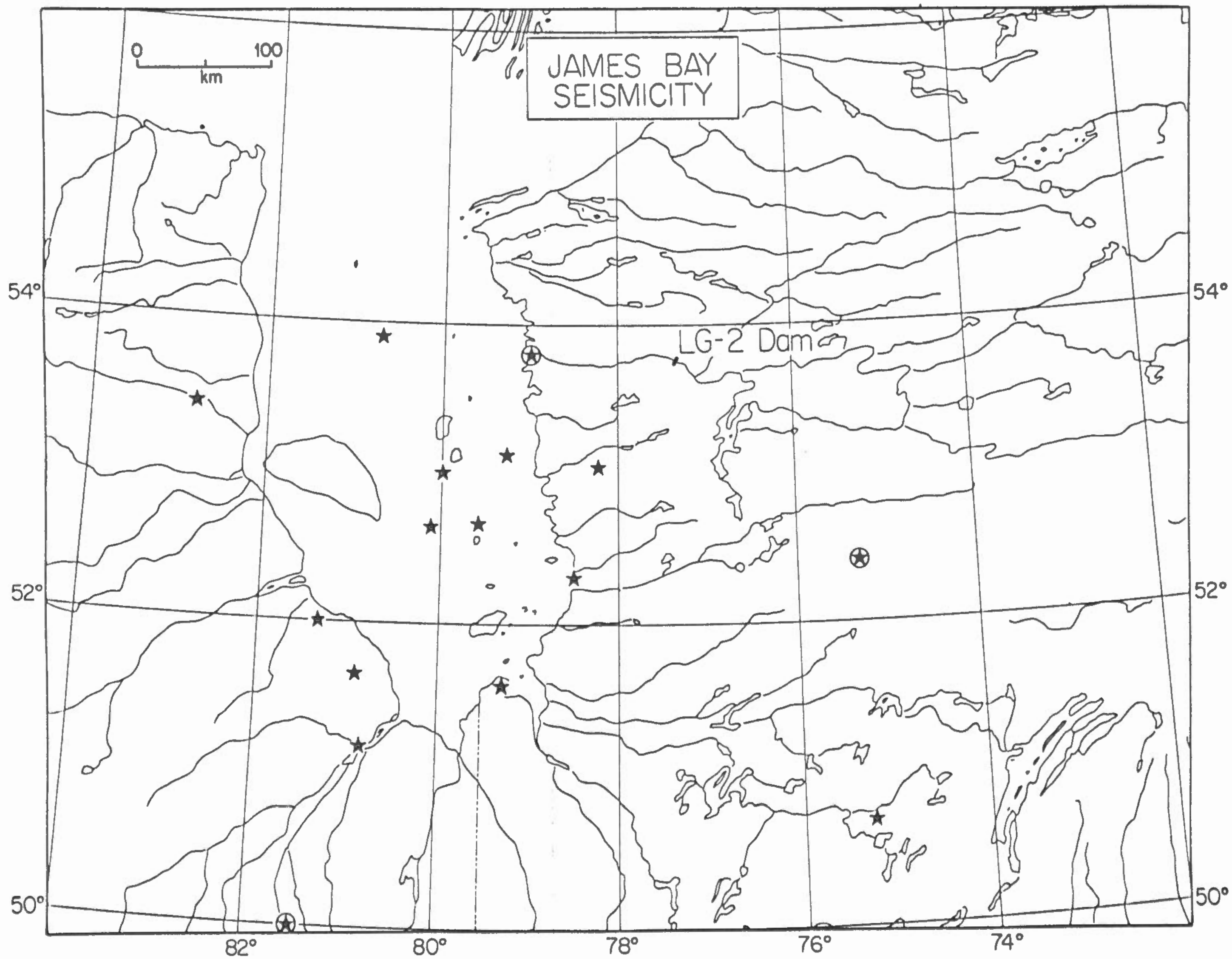


Fig. 3

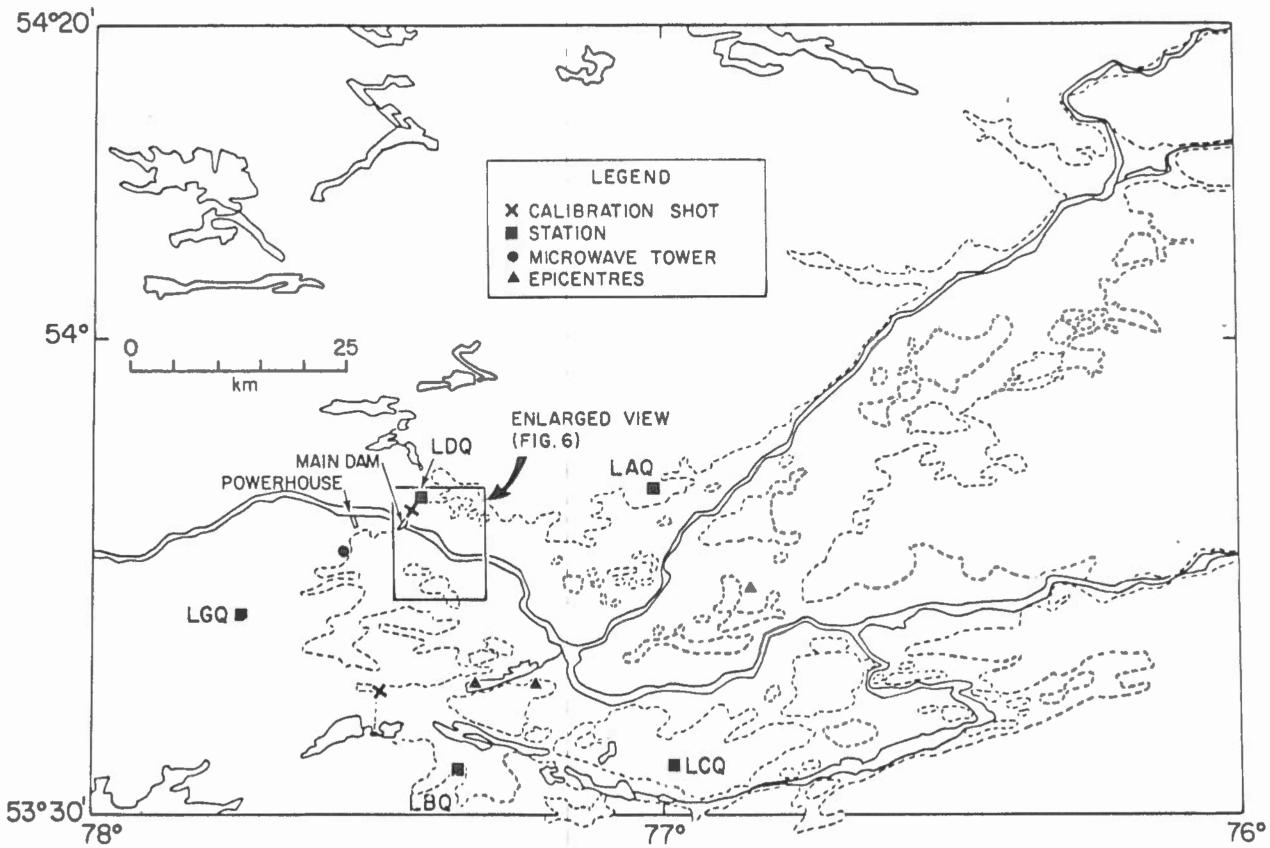

54°20'
54°
53°30'
78°
77°
76°
LEGEND
CALIBRATION SHOT
STATION
MICROWAVE TOWER
EPICENTRES
0
25
km
ENLARGED VIEW
(FIG. 6)
LDQ
MAIN DAM
POWERHOUSE
LAQ
LGQ
LCQ
LBQ

Fig. 4

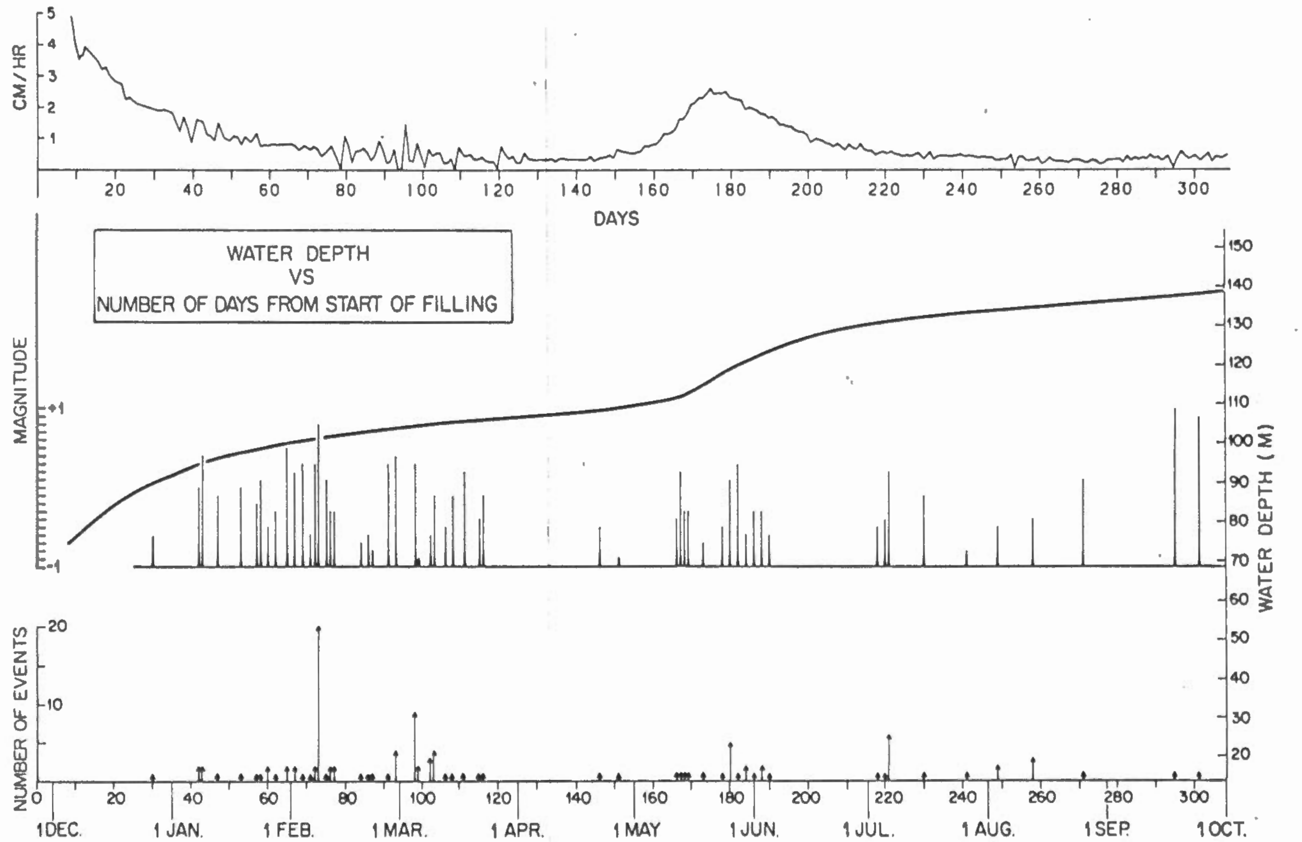

CM/HR
DAYS
WATER DEPTH
VS
NUMBER OF DAYS FROM START OF FILLING
MAGNITUDE
WATER DEPTH (M)
NUMBER OF EVENTS
1 DEC.
1 JAN.
1 FEB.
1 MAR.
1 APR.
1 MAY
1 JUN.
1 JUL.
1 AUG.
1 SEP.
1 OCT.

Fig. 5

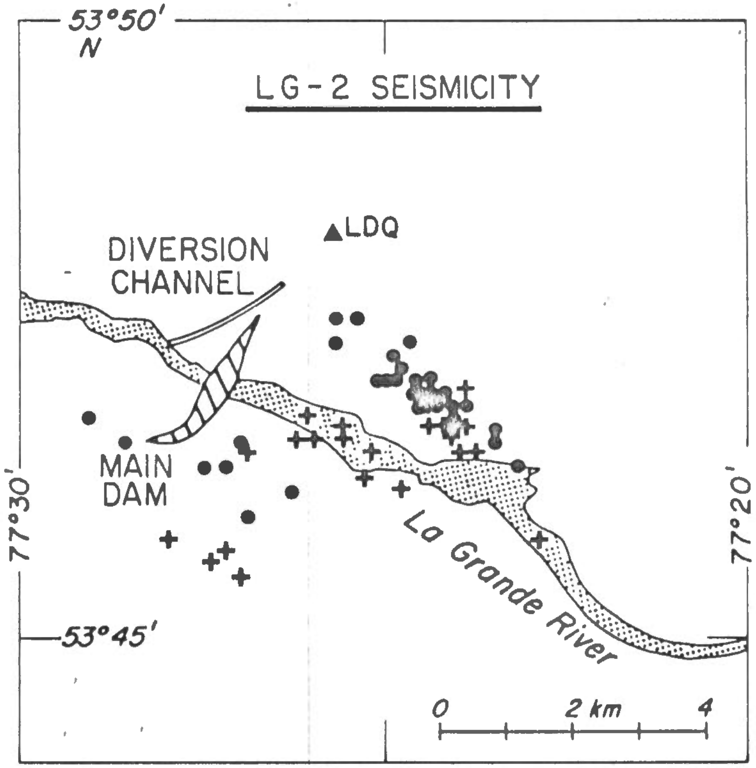

53°50′
N
LG-2 SEISMICITY
LDQ
DIVERSION
CHANNEL
MAIN
DAM
77°30′
77°20′
53°45′
La Grande River
0
2 km
4

Fig. 6