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Distribution of damages and site effects during the 1988 Saguenay earthquake

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ABSTRACT

The 1988 Saguenay earthquake caused a large variety of geotechnical and structural damages. More than 1920 claim files, most of which submitted as part of a compensation program sponsored by the Ministry of Public Safety of the Government of Québec, have been studied. Results of this study are presented in terms of correlations between damages and earthquake motion charateristics, soil conditions, and type of structures. Site effects are pointed out as the main cause of damages to buildings even at large distances from the epicentre.

INTRODUCTION

The Saguenay earthquake of November 25, 1988 constitutes for Eastern North America a unique and considerable source of data on the characteristics of the ground motions and the related damages. This earthquake, whose epicentre was located 36 km south of Chicoutimi, was felt as far as Toronto and New York City. It caused a large variety of geotechnical damages (Tuttle et al., 1989, Lefebvre et al., 1990) but minor structural damages to large buildings (Mitchell et al., 1989).

This paper presents the results of the analysis of more than 1920 files of reported damages to buildings. Some of these files were submitted as part of a compensation program sponsored by the Ministry of Public Safety of the Government of Québec. Other files, concerning public buildings, were supplied by the government. Statistical studies show that the geographical distribution of damages are related to site effects. This study also reveals relationships between ground motion, type of soil and type of structural damage. The total repair cost of damage to buildings, inventoried in the present study, reached 44 millions of dollars.

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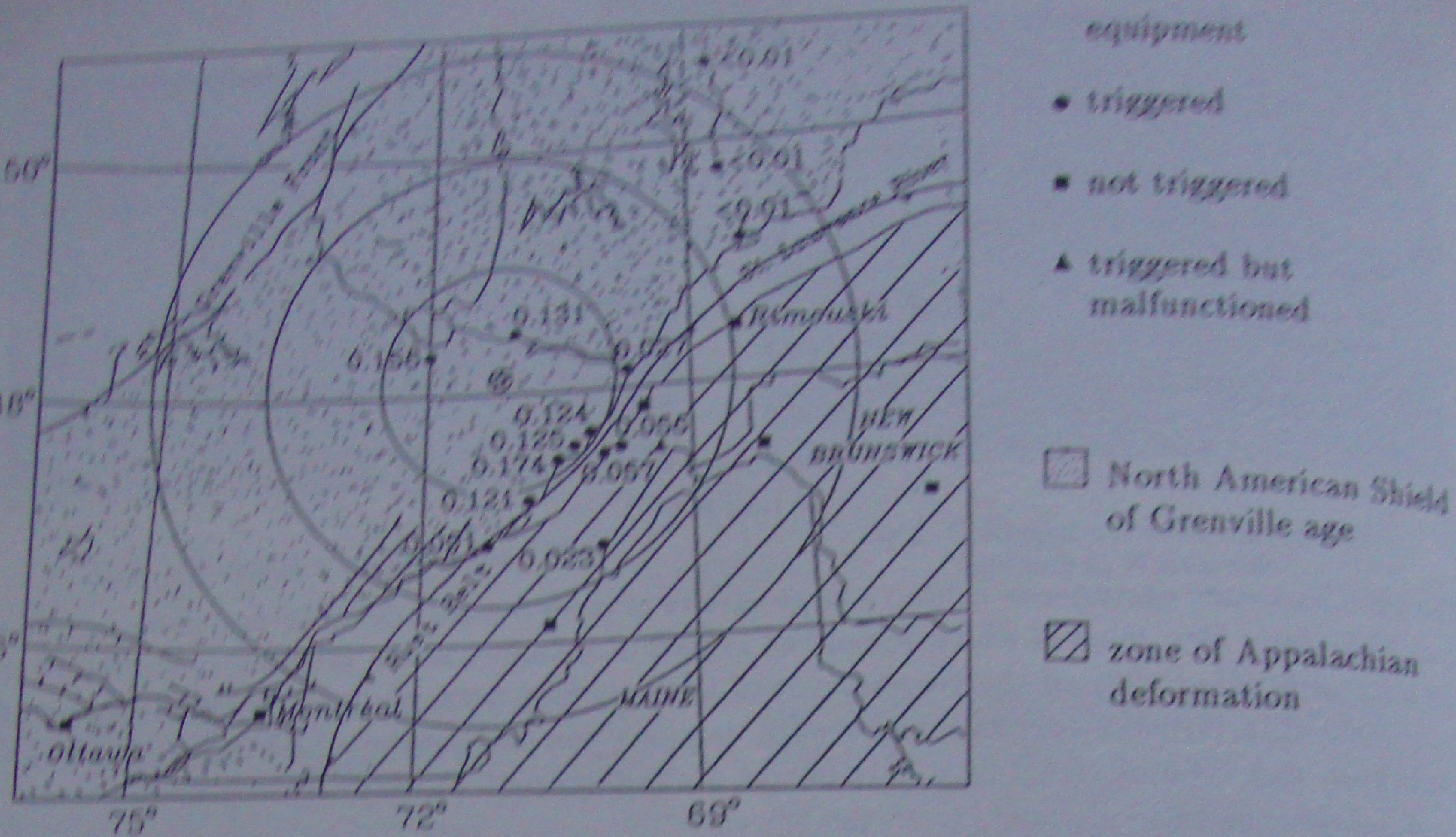

Figure 1. Maximum peak horizontal ground accelerations, in g, recorded during the Saguenay earthquake; circles: 100, 200, 300 km (after Munro and Weichert, 1989).

EARTHQUAKE MOTION CHARACTERISTICS

Figure 1 shows the largest of the two peak horizontal ground accelerations recorded for each intrumented site (Munro and Weichert, 1989). These accelerations were recorded at rock level, except at Baie-St-Paul, which was on a thick layer of alluvial deposits. This figure clearly illustrates the amplification of ground motion due to local soil effects. There is an amplification of 1.5 to 2 between the Baie-St-Paul station (on alluvial deposits) and the La Malbaie and Les Eboulements stations (on rock), at the same distance from the epicentre. The map shows a considerable decrease in the peak ground acceleration beyond a distance of 110 km from the epicentre. According to Sommerville et al. (1990), this is due to the large focal depth of the earthquake (29 km), and to the strong reflexions on discontinuities of the earth's crust along the St. Lawrence River, between the Appalachian deformation zone and the North American Shield (see Fig 1). Leboeuf and Lefebvre (1990) show that for epicentral distances of more than 110 km, the amplification for the spectral acceleration is less than 3.4 and the predominant periods are low (less than 0.075 s); whereas for epicentral distances less than 110 km, the amplification can be as high as 5, and the predominant periods vary from 0.13 s to 0.2 s.

THE DATA BASE

The 1927 files compiled made it possible to establish an identification sheet for each case indicating locality, description of the damaged building (age, number of storeys, type of foundation and structure, normalized municipal evaluation), and damages (cost of repair, damaged structural

Table 1. Distribution of claims and their amount according to usage of facilities

Usage of facilities	Number of claims	Amount (in thousands $)
Houses of less than 2 storeys	1155	5,617
Apartment buildings of more than 2 storeys	28	585
Commercial and industrial	55	474
Churches	51	2,066
Schools	226	25,000
Hospitals	36	6,678
Public services	73	2,050
Wells and aqueducts	228	1,013
Total	1852	43,928

elements). Some reserves must however be made on the objectivity of the collected data: (i) all damages due to the earthquake were not always reported; (ii) the determination of the cause of the damages was not always compiled – 25% of the files corresponding to important damages above compensation threshold were thoroughly investigated and are well documented, 5% (i.e., 75) of the claims were not attributed to the earthquake itself; (iii) the evaluation of the cost of damages caused by the earthquake has generally been made by the owner, except for public buildings and private houses with large damages where an independent assessment was made, and (iv) the normalized municipal evaluations used in this study to define the level of damage do not always reflect reality, particularly for public services buildings.

DISTRIBUTION OF DAMAGES

The geographical distribution of damages presented in Fig. 2 shows that the damages are concentrated along the St. Lawrence River where the population is denser. Some regions located more than 300 km from the epicentre, like the Boucherville region, have several damaged buildings. This map does not specify building type or the degree of damages. Table 1 gives the number of claims and their amount according to usage of the facilities. A total of 1200 claims was received for low rise buildings (detached or semi-detached houses, apartment buildings with less than two storeys), totaling 6.1 M$; 414 claims were received for medium rise buildings (appartment buildings with more than two storeys, commercial buildings, churches, hospitals and public services buildings), totaling 36.8 M$; and 228 claims were received for wells and aqueducts, totaling 1 M$.

Figures 3 a, b and c give the number of claims with respect to the epicentral distance for the three classes of facilities mentionned above. The number of claims decreases with distance except for a peak in the Quebec City region (100 to 150 km), and another peak for small buildings in the Montreal region (300 to 350 km). Figure 3 c shows three regions for damaged surface wells (drying up): the Ferland-Boileau region, where soil liquefaction occurred, the Shannon region and the south shore of the St. Lawrence River from Rimouski to the Beauce region. These hydrologic phenomena did not all occur immediately after the earthquake, some wells progressively dried up. Figure 3 d shows that the average damage ratio, DR_{av}, for single houses (ratio of damage repair cost to estimated building value), does not change much with distance. At large distances, few claims were reported but the amounts involved were important.

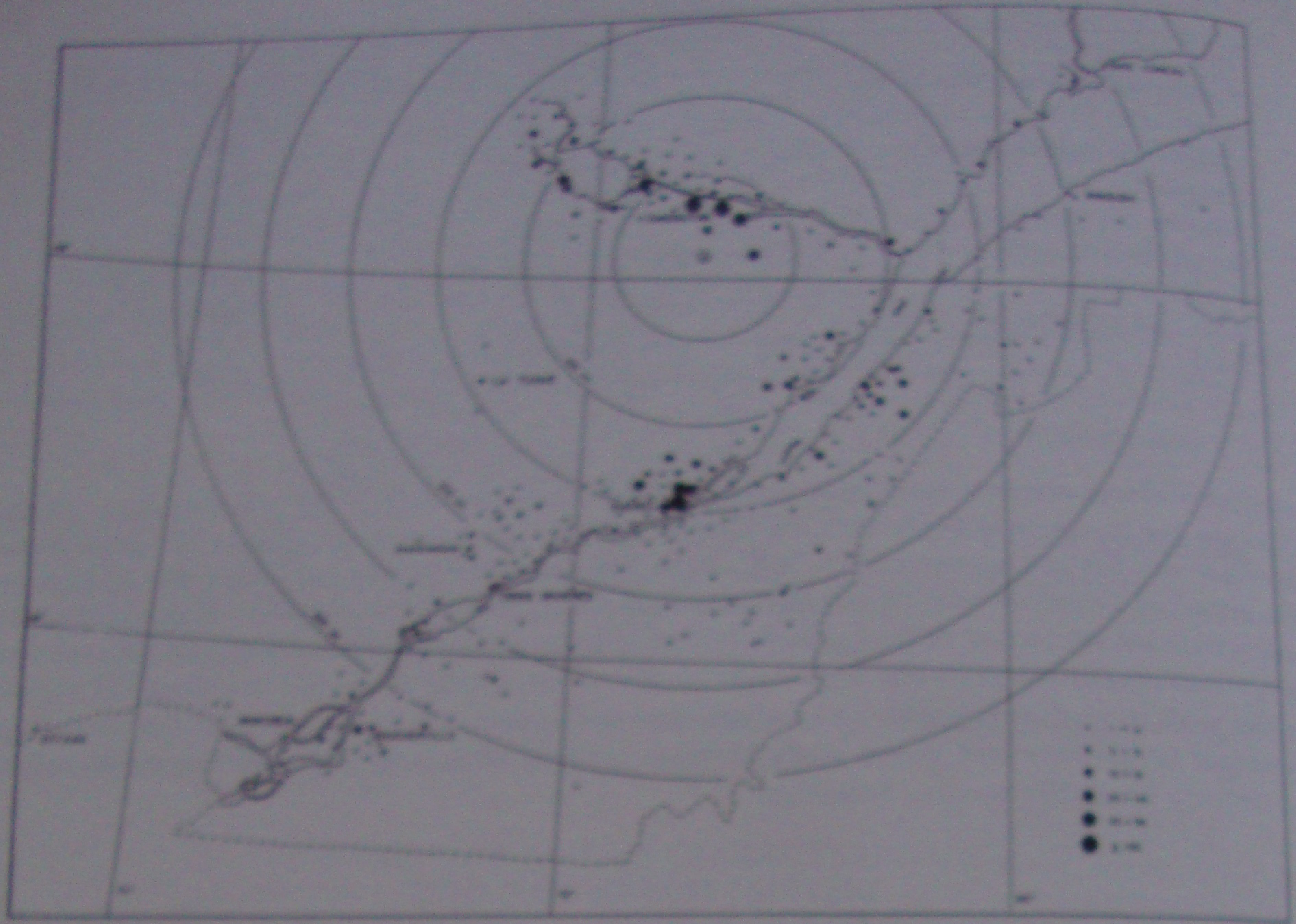

Figure 2. Geographical distribution of the total number of claims submitted to the compensation program of the Government of Quebec.

The distribution of damage to buildings less than two storeys high was examined in more details because it represents a more homogeneous type of building, constitutes a large sample (62% of all claims) and allows to consider the population density. The parameters used to evaluate the geographic distribution of damages are:

1. The house density $d_h = n_{dh}/n$ where n_{dh} is the number of damaged houses in a municipality and n is the total number of houses in that municipality obtained from the 1986 census (Statistics Canada, 1987).

2. The average damage ratio DR_{av} per municipality.

3. The average damage intensity, $DI_{av} = d_h \times DR_{av}$. This parameter is more representative than the two previous ones and can be compared to seismic intensity. The geographic distribution of this parameter is given in Figure 4.

Figure 4 shows the Ferland-Boileau, Jonquière and La Baie region which were particularly touched due to their proximity to the epicentre. Also shown are more distant regions where numerous claims were filed: Charlevoix County (Baie-Saint-Paul, Rivière du Gouffre, Saint-Siméon,

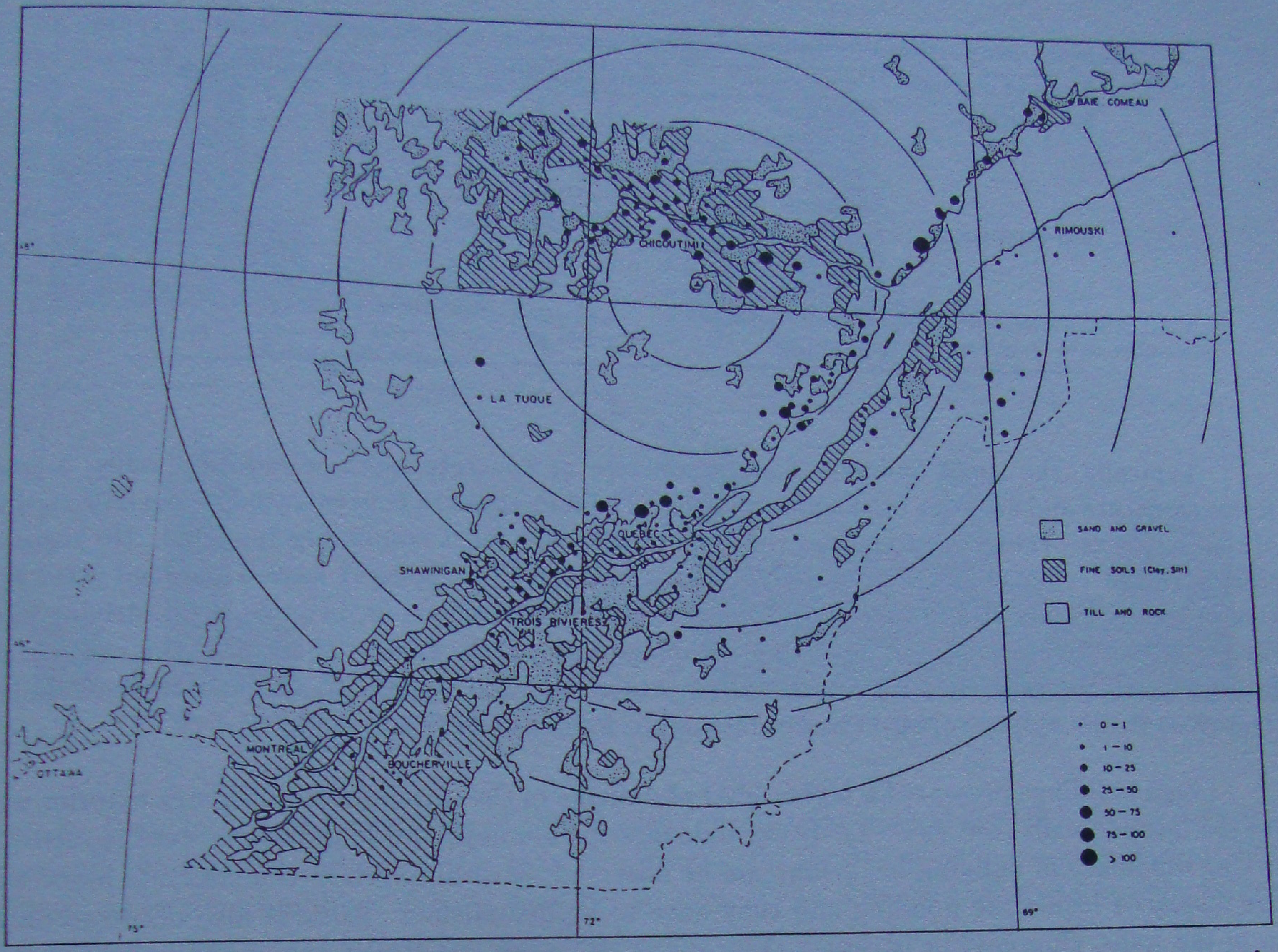

Figure 4. Distribution of the average damage intensity, DI_{av}, for houses superimposed on a surface deposits map.

profiles, 14% on sand). Damaged buildings involving clay foundations can be found at very large distances whereas comparable damages for sandy foundations are limited to an epicentral distance of 130 km.

Amplification due to the overburden is evident when comparing the damages in Chicoutimi, mostly on bedrock, close to the epicentre and the Boucherville area, mostly on clay deposits, at 320 km from the epicentre. Many damaged buildings were also associated with other local effects, such as sloping ground, proximity of a slope crest (generally clay) and foundation on fill material.

TYPE OF DAMAGES

Very few of the 1857 reported cases involved important damages. Essentially, the damages were cracks and fissures to walls and foundations. The analysis was carried out by dividing the buildings in two classes: (1) small buildings (less than 2 storeys high), and (2) large buildings (more than 2 storeys high).

Table 2. Proportion of number of claims according to damage and building types

Type of damage	Component	Small buildings (%)	Large buildings (%)
Structural	Structure	4	7
	Foundation	59	12
	Roof	3	10
	Chimney	38	4
Non-structural	Exterior walls	23	67
	Interior finish	18	45
	Openings, panes	14	19
	Staircase, steps	2	11
	Plumbing	4	4

Typically, the small buildings have a concrete or concrete block foundation walls, a wood frame structure and stone or brick exterior walls. The damages are concentrated in the stiff sections of the buildings. Table 2 summarizes the type of damages most commonly reported. No reported cases involved collapse or required demolition. Only 4.7% (54 houses) have a damage ratio DR_i greater than 50% due to the necessity of rebuilding the foundations or, in some cases, driving piles. For more than half the requests involving a damage ratio, DR_i, greater than 50%, the cause of the damages could be related to excessive settlements of fill. Soil liquefaction in the Ferland-Boileau area, close to the epicentre, also caused damage to foundations (Law, 1990).

Large buildings presented a higher level of damage in the unreinforced masonry exterior walls and the interior walls (see Table 2). Fewer damages to chimneys and foundations were reported. A striking difference in building behaviour can be observed: several unreinforced concrete block walls were displaced inside the building and they have to be demolished. Failures also occurred on the top of the walls, chimneys or parapets. Vibrations also worn out the cement bonds of the exterior masonry walls; in some cases, a separation of several inches between one non-anchored exterior wall and the building structure was noticed. Cracks occurred mostly around openings (windows, doors) or corners (walls and ceilings). It is important to note that symmetrical buildings suffered less damage than nonsymmetrical ones.

It appears that earthquake damage is controlled by the type of foundation (masonry, concrete, concrete blocks), the quality of construction, the wall construction (stucco, stones, bricks) and its connection with the structure. The age of the buildings did not seem to have played a significant role.

CONCLUSION

The comprehensive survey of building damages clearly pointed out that soil and site factors played a significant role in the damage observed and its geographical distribution. A possible explanation lies in the amplification of the seismic motions by the soil layers. Some towns, far from the epicentre, were strongly affected by the earthquake (for example, in Boucherville - 320 km from the epicentre, Shawinigan - 210 km, St. Alban - 170 km, Shannon and St-Brigitte-de-Laval - 140 km). Damages were widespread in thick overburden zones or in alluvial valleys and there are some evidences that local topography contributed to damages or failures. Damage distribution was very uneven, with a higher concentration on the North Shore of the St. Lawrence. It is also

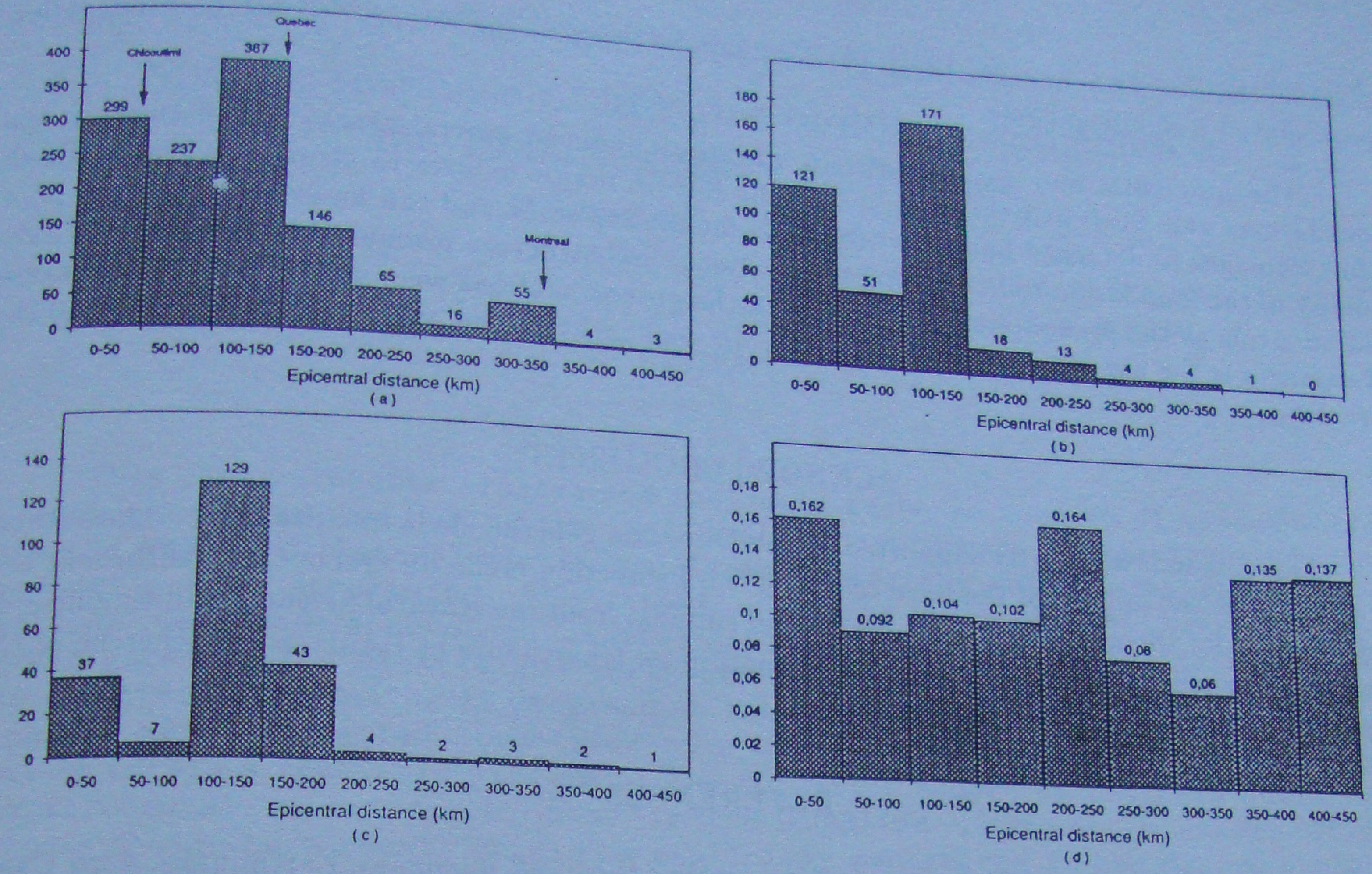

Figure 3. Distribution of the number of claims with respect to epicentral distance (a) for damaged houses and apartment buildings of less than two storeys, (b) for damaged churches, public services buildings, apartment buildings of more than two storeys, (c) for damaged wells and aqueducts, and (d) average damage ratio (DR_{av}) for detached houses vs. epicentral distance.

at 100 km from the epicentre), north of Québec (Shannon, Sainte-Brigitte de Laval, Stoneham, Clermont, at 130 km), the Portneuf region (Saint-Alban, La Pérade, at 170 km), Champlain (Batiscan, at 200 km), Saint-Maurice (Shawinigan, at 210 km), and the Montreal region (Boucherville, at 320 km).

Although with some irregularities, there is a clear trend of the average damage intensity, DI_{av}, decreasing with the distance to the epicentre. There are very few damages on the south shore of the St-Lawrence River, beyond the contact North American Shield–Appalachian zone (see Fig. 1). This is well correlated to the discontinuity observed in the recorded peak ground accelerations shown in Fig. 1.

DAMAGES AND TYPE OF SOIL

Any site effects should be examined individually. Figure 4 shows a map of the overburden deposits on which the average damage intensity DI_{av} is superimposed. It can be seen that most damages are associated with clay deposits. It should be noted that at this scale small extents of clay or mud deposit are neglected and could exist elsewhere locally. Very few damages were reported for buildings on bedrock or till foundation. For churches, the data showed that 96% of the reported cases are located on soil deposits (56% on clay deposits thicker than 20 m, 26% on multilayer soil *possible that local mechanisms (deep hypocentre) and "tectonic anisotropy" along the propagation path played a significant role.*

The horizontal and vertical seismic vibrations induced several cracks and fissures in the foundations and weakened the peripheral walls but no major failures to structures were noticed. Most damages to detached houses involved the foundation walls and can be explained by the poor quality of the foundation soil or thickness variations. Soil-structure resonance did not seem to have played a role as the predominant frequencies of the ground motions were very high. Another cause of damages is the use of unreinforced masonry for wall construction and its poor connection to the structure.

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