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# Attenuation of strong ground motion from the Saguenay, Quebec earthquake of November 25, 1988

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## ABSTRACT

The November 25, 1988 Saguenay earthquake, which occurred at the unusually deep focal depth of 29 km and had a moment magnitude of 5.8, produced by far the largest set of strong motion recordings of any earthquake in eastern North America. The attenuation of recorded strong ground motions is very gradual in the distance range of 50 to 120 km, and only becomes steep beyond 120 km. A profile of synthetic seismograms reproduces these features, and allows us to understand why the attenuation relation has this shape. In both the recorded and synthetic seismograms, the peak amplitudes inside 120 km are due to large postcritical reflections from the Conrad and Moho discontinuities. These observations support the model for the attenuation of strong ground motion proposed by Burger *et al.* (1987) in which the shape of the attenuation curve within 200 km of the source is controlled by focal depth and crustal structure. The distances over which ground motion amplitudes are elevated by postcritical reflections generally lie in the overall range of 50 to 200 km, with the specific distance range depending on the focal depth of the earthquake and on the crustal structure. Because of the deep focal depth of the Saguenay earthquake, the critical distances for these reflections were short, causing the ground motion amplitudes to be elevated in the distance range of 50 to 120 km. The recorded ground motions were significantly underpredicted by attenuation relations based on random process models which do not take account of these effects.


## INTRODUCTION

The November 25, 1988 Saguenay earthquake produced by far the largest set of strong motion recordings of any earthquake in eastern North America (Munro and North., 1988). These recordings provide an opportunity to test methods, presently based on a limited data set, for estimating strong ground motions of eastern North American earthquakes. The Saguenay earthquake occurred within the Grenville Province, close to the southern margin of the Saguenay Graben in southern Quebec and about 100 km northwest of the St. Lawrence River. The earthquake occurred at 23:46:04. GMT on November 25, 1988 at latitude 48.117°N, longitude 71.184°W (North *et al.*, 1989). The mechanism of the Saguenay earthquake was nearly pure thrust with a P axis oriented east-northeast, consistent with that of the larger earthquakes in the northeastern United States and southeastern Canada (Ebel *et al.*, 1986, Somerville *et al.*, 1987). The Saguenay earthquake originated at a depth of 29 km, which is greater than the depth range of 5 to 15 km that is characteristic of the larger earthquakes in eastern North America (Ebel *et al.*, 1986; Somerville *et al.*, 1987). The overall source duration $\tau$ of the earthquake of 1.8 seconds, combined with a seismic moment $M_o$ of 5 x $10^{24}$ dyne-cm, corresponds to a stress drop $\Delta\sigma$ of approximately 160 bars. This is within the uncertainty of the median value of 120 bars obtained from thirteen previous eastern North American events using the same methods (Somerville *et al.*, 1987).

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The seismic moment of the Saguenay earthquake estimated from long-period regional ($P_{nL}$) and teleseismic body waves is $5.0 \times 10^{24}$ dyne-cm, with an uncertainty of 25% (Somerville *et al.*, 1990a). This seismic moment value corresponds to a moment magnitude of 5.8 (+/- 0.07). The reported magnitudes of the Saguenay earthquake are an $M_s$ of 5.8 (NEIS), an $m_b$ of 5.9 (NEIS), and an $m_{bLg}$ of 6.5 (North *et al.*, 1989). North *et al.* (1989) noted that this $m_{bLg}$ value is substantially larger than the teleseismic $m_b$ of 5.9. It exceeds the value of 6.0 estimated from the seismic moment of the event using an empirical relation between moment magnitude M and $m_{bLg}$ for the larger historical eastern North American earthquakes. The empirical relation ($m_{bLg} = 0.89$ M + 0.90) is derived from the twelve eastern North American earthquakes listed in Table 1 of Somerville *et al.* (1987). Somerville *et al.* (1990a) concluded that the observed $m_{bLg}$ of the Saguenay earthquake is consistent with their source and crustal structure models.

## MODELING OF STRONG GROUND MOTION

Because of the small size of the strong motion data base for eastern North American earthquakes, synthetic seismogram techniques have played an important role in the development of ground motion attenuation relations for eastern North America in recent years. Burger *et al.* (1987) investigated the effect of wave propagation in the crustal waveguide on the shape of the ground motion attenuation curve. The principal seismic phases associated with wave propagation in a crustal waveguide are shown schematically in simplified form in Fig. 1a. At close distances, peak horizontal ground motions are controlled by direct upgoing shear waves. As distance increases, the reflections of the shear wave from interfaces in the lower crust (such as those at 30 and 40 km in Fig. 1a) reach the critical angle and undergo total reflection. The strong contrast in elastic moduli at these interfaces, especially at the Moho (the base of the crust) causes these reflected phases to have large amplitudes. Using synthetic seismograms (Fig. 1b), Burger *et al.* (1987) found that peak ground motion amplitudes at distances beyond about 50 km are controlled by these post-critical reflections from velocity gradients in the lower crust (Fig. 1c). They found evidence supporting this result in empirical strong motion data (Toro and McGuire, 1987, Figs. 6 through 9) that showed a flat trend in the distance range of 60 to 150 km.

Further studies of ground motion attenuation using digital network data and strong motion recordings in the northeastern United States and adjacent Canada (Barker *et al.*, 1989) lent support to the hypothesis that crustal structure and focal depth play an important role in determining the shape of the strong ground motion attenuation curve. Using procedures similar to that of Burger *et al.* (1987) and Barker *et al.* (1989), Gariel and Jacob (1989) and Ou and Herrmann (1990) analyzed the attenuation of strong motion from the 1988 Saguenay earthquake and obtained results similar to those of Somerville *et al.* (1990a) which are summarized below.

Our objective in analyzing the strong motion recordings of the Saguenay earthquake is to test the suggestion of Burger *et al.* (1987) that post-critical reflections from velocity gradients in the lower crust control the attenuation of strong ground motion in the distance range of about 50 to 200 km. Synthetic acceleration and velocity seismograms were computed using the seismic moment and focal mechanism derived from long-period body wave modeling. We used an empirical source function derived from the tangential component of motion recorded at station SM17 which allows us to simultaneously match the recorded amplitudes of strong motion acceleration, strong motion velocity, and teleseismic short-period and long-period body waves (Somerville *et al.*, 1990a).

The recorded and synthetic tangential velocity seismograms are compared in Fig. 2, with all seismograms shown at their absolute times and scaled to their peak values which are indicated by arrows. At a distance of 100 km, the arrivals are, in order of increasing arrival time, the direct S, the Conrad refraction $S_c$, the Conrad reflection $S_cS$, the Moho refraction $S_n$, and the Moho reflection $S_mS$. At the two closest stations (SM16 at 43 km and SM17 at 64 km), the direct upgoing wave produces large motions on both the recorded and synthetic seismograms. However, at 90 km, the direct arrival has very small amplitude on both the recorded and synthetic seismograms. The largest phase in the recorded data at this distance is the post-critical reflection from the Conrad discontinuity; this phase is also present in the tangential component of the synthetic seismograms. Between 110 and 120 km, the recorded seismograms show large post-critical reflections from both the Conrad and the Moho; these are also present in the synthetic seismograms, and both reflections contribute to the largest motions. Beyond 150 km, the Moho reflection is masked by the Conrad reflection, which controls peak amplitudes out to 200 km.

In summary, the recorded and synthetic profiles both demonstrate that at distances beyond about 70 km, the direct shear wave arrival ceases to control peak ground motion amplitudes; instead, peak amplitudes are controlled by post-critical reflections from the velocity gradients in the lower crust. The strength of these postcritical reflections, and the distance ranges over which they are dominant, are controlled by the focal depth and crustal structure. Thus crustal structure and focal depth control the attenuation of strong ground motion.

## ATTENUATION OF STRONG GROUND MOTION

The peak velocities and accelerations of the profiles of recorded and synthetic seismograms are compared in the lower part of Fig. 2. The attenuation of both the recorded and simulated peak motions is very gradual in the distance range of 50 to 120 km, and only becomes steep beyond 120 km. In the top part of Fig. 2, we have already shown that the peak amplitudes in this flat portion of the attenuation curve inside 120 km in both the data and the synthetic seismograms are due to large postcritical reflections from the Conrad and Moho discontinuities. These reflections become postcritical at close distances because of the depth of the source.

There is evidence that postcritical reflections from the lower crust also control peak ground motion amplitudes in at least some regions of the western United States. Preliminary analysis of accelerograms having absolute times that were recorded during the October 17, 1989 Loma Prieta earthquake shows that in the distance range of 50 to 100 km (which includes San Francisco and Oakland), the largest motions at a given station were due to postcritical Moho reflections (Somerville and Yoshimura, 1990). These motions were further amplified, presumably by impedance contrast and resonance effects, at soft soil sites. For both the Saguenay and Loma Prieta earthquakes, the short critical distance and the consequent elevation of ground motion amplitudes on rock sites between about 50 and 120 km are due to deep focal depth, or more precisely, to the proximity of the source to the base of the lower crust.

From the above analysis, it is clear that the focal depth of the Saguenay earthquake and the structure of the crust in which it occurred influenced the shape of the ground motion attenuation curve of this earthquake. Earthquakes occurring at other depths and in other crustal structures are expected to have different attenuation curves. Attenuation curves for eastern North America that are based in part on empirical strong motion data represent the averaging of attenuation curves for a range of focal depths and a variety of different crustal structures. It is therefore to be expected that the attenuation curve for the unusually deep Saguenay earthquake might differ from these empirical attenuation curves.

Several recent attenuation curves are based on random process theory (Hanks and McGuire, 1981; Boore, 1983), in which strong ground motions are modeled as segments of band-limited noise. In the simplest of these models, wave propagation effects are modeled by anelastic attenuation and by a geometrical spreading term, assumed to be 1/R within 100 km (corresponding to body wave spreading in a whole-space), and $1/\sqrt{R}$ beyond 100 km (corresponding to surface wave spreading in a half space). These effects produce a smooth, monotonically decreasing function of ground motion amplitude with distance (Boore and Atkinson, 1987; Toro and McGuire, 1987). This simple ground motion model does not include focal depth and crustal structure among its input parameters, and so it does not account for the influence of these parameters on the ground motion attenuation curve. For this reason, it is expected that the attenuation curve for the unusually deep Saguenay earthquake might differ from curves derived using simple random process theory.

The random process models are based on seismic moment as a description of earthquake size. Comparison of the Boore and Atkinson (1987) attenuation relation, computed using the moment magnitude of 5.8, with the recorded peak acceleration is shown in Fig. 3. It underpredicts the data, and allowing for a natural logarithmic standard error of 0.5, it is significantly different from the data at the 99.9% confidence level. The peak accelerations from the synthetic seismograms are also shown, and provide a better fit to the recorded data, specifically in modeling the amplitude level, the flat trend of the attenuation curve in the distance range of 50 to 120 km, and the rapid decay beyond 120 km. The Boore and Atkinson (1987) relation still underpredicts the recorded motions (at the 99% confidence level) if the $m_{bLg}$ magnitude of 6.5, converted to a moment magnitude of 6.35 by the relation given above, is used in place of the measured moment magnitude of 5.8, but the underprediction is somewhat reduced (Somerville *et al.*, 1990b).

## CONCLUSIONS

The attenuation of recorded strong ground motions from the Saguenay earthquake is very gradual in the distance range of 50 to 120 km, and only becomes steep beyond 120 km. A profile of synthetic seismograms reproduces these features, and allows us to understand why the attenuation relation has this shape. In both the recorded and synthetic seismograms, the peak amplitudes inside 120 km are due to large postcritical reflections from the Conrad and Moho discontinuities. Because of the deep focal depth of the Saguenay earthquake, the critical distances for these reflections are short, causing the ground motion amplitudes to be elevated in the distance range of 50 to 120 km.

These results support the model for the attenuation of strong ground motion proposed by Burger *et al.* (1987). According to this model, the shape of the attenuation curve within 200 km of the source is controlled by focal depth and crustal structure. Inside the critical distance for reflections from the lower crustal velocity gradient, peak ground motion amplitudes are controlled by upgoing shear waves. However, beyond the critical distance, peak amplitudes are controlled by post-critical reflections from the velocity gradients in the lower crust, which typically causes an elevation of ground motion amplitudes. Generally, the amplitudes are at most two to three times higher than those that would be obtained by extrapolating the attenuation curve from pre-critical distances. The distances over which the amplitudes are elevated generally lie in the overall range of 50 to 200 km, with the specific distance range depending on the focal depth of the earthquake and on the crustal structure. Regional variations in crustal structure therefore cause regional variations in ground motion attenuation.

When strong motion data from different crustal structures or from earthquakes having different focal depths are combined into a single data set, the detailed characteristics of regional attenuation relations are smeared out. This leaves a data set having a broad scatter that is reasonably modeled using a smooth attenuation curve which is applicable to the estimation of ground motions across eastern North America. However, the smooth character of such a curve, whether derived empirically or from simplified theoretical models such as random process theory, does not have a rigorous physical basis in wave propagation theory. If it is desired to estimate ground motions at a specific site or within a given region, then estimates having a lower degree of uncertainty can be obtained by using an attenuation curve that reflects the wave propagation characteristics of that region.

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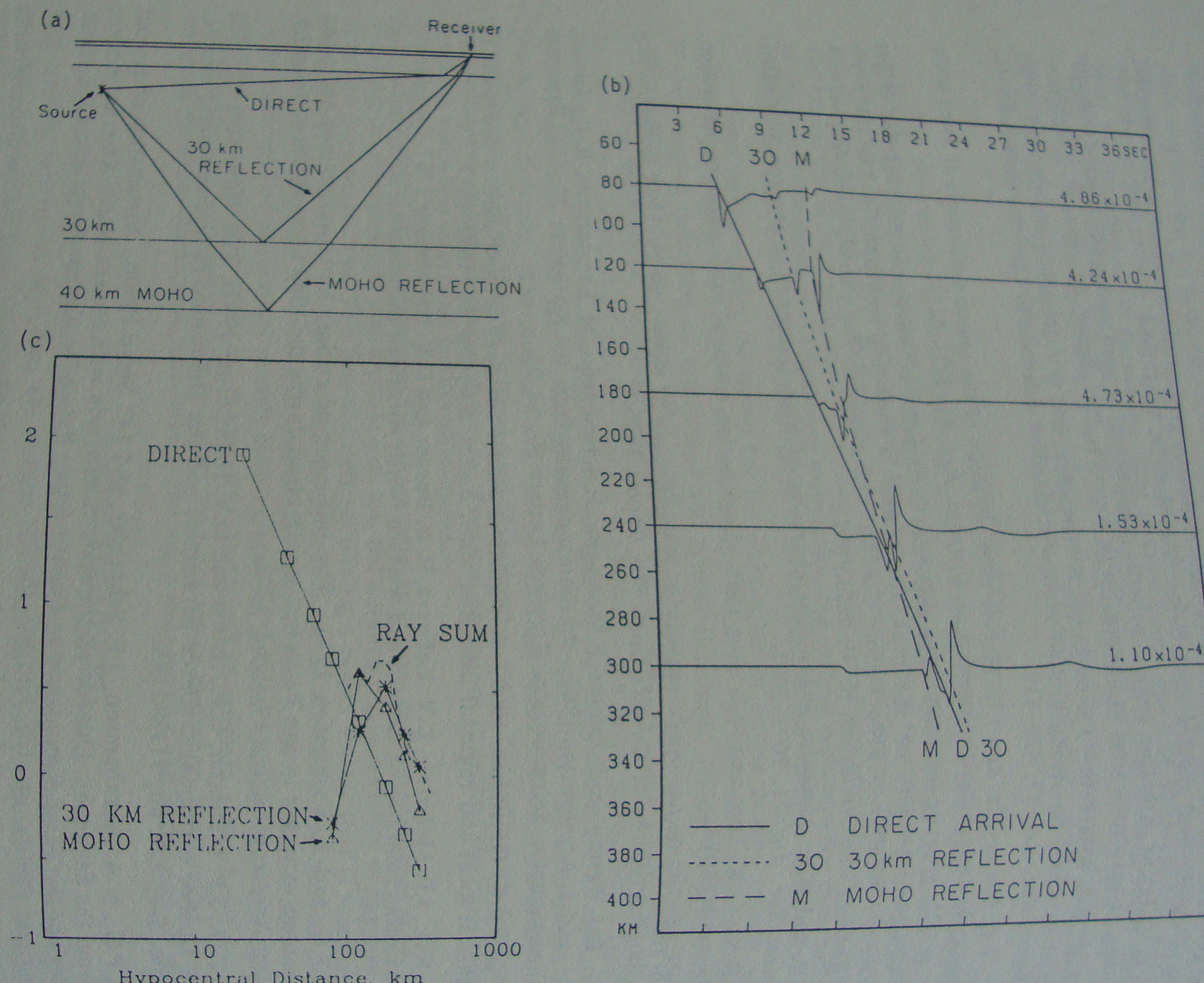


**Figure 1.** (a): Simplified model of wave propagation in a layered crust. *(b): Synthetic displacement seismograms for the crustal model shown in (a). (c): Attenuation of direct and reflected phases shown in (b). Source: Burger et al., 1987.*

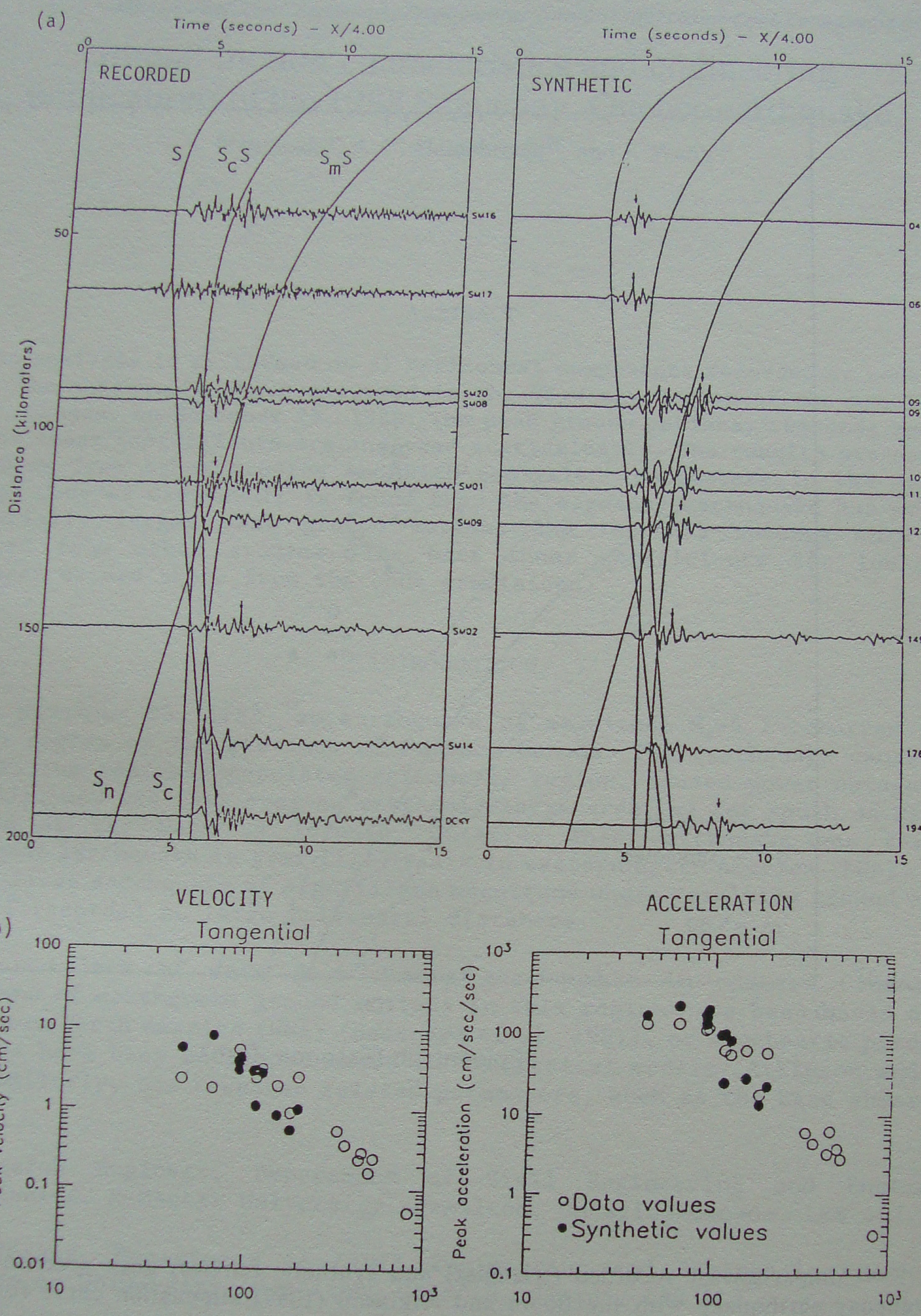


Figure 2. (a): Profiles of recorded (left) and synthetic (right) tangential velocity of the Saguenay earthquake, together with calculated travel times of principal arrivals. (b): Recorded (circles) and synthetic (dots) peak velocity (left) and peak acceleration (right) of the Saguenay earthquake as a function of epicentral distance. Source: Somerville *et al.*, 1990a.

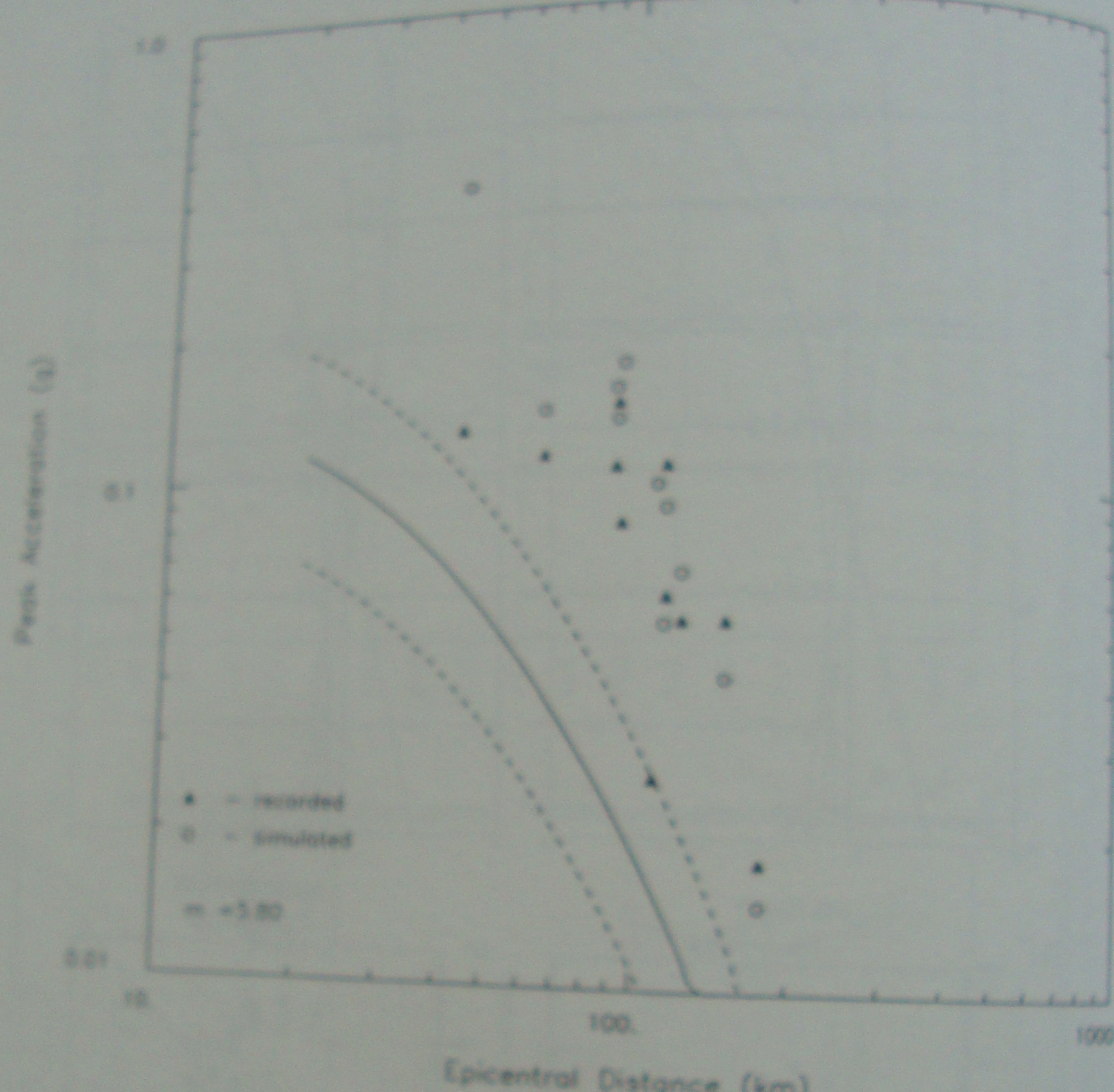


Figure 3. Comparison of recorded (triangles) and synthetic (circles) peak acceleration of the Saguenay earthquake with the Boore and Atkinson (1987) attenuation curve for epicentral distance using a moment magnitude of 5.8.