SEISMIC RISK IN WESTERN CANADA*

by

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ABSTRACT

A third generation seismic risk zonation map is now in place for all of Canada. It is based on assumptions of uniformly active source zones, with reasonably well-defined recurrence relations, and self-consistent attenuation relations. The results are expressed as contour maps of peak acceleration and velocity at a probability of 10% in 50 years. In some regions of western Canada, high seismicity and large maximum magnitude earthquakes render the probabilistic calculations susceptible to model assumptions whose relative probabilities are difficult to represent in the nominal probabilities of the zoning map. Examples are alternative interpretations of modern tectonics, different assumptions about historic seismic gaps, expected ground motion from maximum magnitude earthquakes, and the possibility of very large but yet unconfirmed thrust earthquakes with long recurrence intervals along the southwest coast of Canada.

INTRODUCTION

Canada has experienced several large damaging earthquakes during its recorded history. This resulted in efforts to introduce seismic provisions into the National Building Code of Canada (NBCC). An earthquake hazard map was first introduced in 1953 (Hodgson, 1956). Four zones of relative severity of expected earthquake damage were differentiated by simple straight line boundaries. The map was completely qualitative, without numerical statements on intensity, ground motion or probability.

Milne and Davenport (1969) proposed a quantitative basis for a new zoning map that was adopted for the NBCC in 1970. It has remained in force up to and including the 1980 edition. The map uses the extreme value theory of Gumbel (1959). Contours of peak horizontal acceleration are displayed at a probability of exeedence of 0.01 per annum. The boundaries for the four seismic zones were 1,3, and 6% of gravity.

Keywords: seismicity, seismic risk, hazard

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For the essentially incomplete early observational data set, the name and claims of the extreme value method had an undeniable attraction. When the need for an update of the Canadian seismic risk program became apparent in the late seventies, the extreme value technique was reviewed (Weichert and Milne, 1979) and now found to be less appealing, largely because of its wasteful treatment of the much increased data base that had accumulated by then. The disadvantages of the extreme value statistic as used were:
- Estimation of the parameters based on only a small subset of the available data.
- No allowance for an upper limit in magnitude and/or ground motion.
- Only asymptotically valid for large numbers; the statistics of the rare large events rely on the extrapolated tails of the mathematical model.

THE NEW ZONING MAP

After reviews of alternatives to the earlier method (Basham and Weichert, 1979 Basham et al., 1979) the method suggested by Cornell (1968), was selected and a program coded by McGuire (1976) was adopted. This approach consists essentially of four steps:
- establishment of earthquake source zones on the basis of historic and recent seismicity, and on tectonic-geological considerations
- estimation of magnitude recurrence relations for each source zone
- estimation of ground motion as function of magnitude and distance attenuation for eastern and western Canada
- summation of the number of exceedences, or of probabilities, contributed by all surrounding source zones at a given site.

This is the essence of the method, but for implementation a variety of further assumptions must be made, concerning both basic seismicity and statistical treatment of data. This has been described in detail by Basham et al. (1982,1985), and we give only a short summary and comment on salient points.

SEISMICITY

The seismicity of western Canada and the adjacent United States is depicted in figure 1 (see Milne et al., 1978). Along the west coast the seismicity is caused mainly by shear between the Pacific and North American plates north of 51°N. South of here the seismicity follows two trends, those earthquakes associated with the offshore spreading ridges and fracture zones and those earthquakes associated with the subduction process along the margin. Away from the coast in the mountainous Cordillera, the seismicity is much lower but significantly higher than in the prairie regions to the east. For most of western Canada the seismicity is complete for magnitude 7 from about 1900, for magnitude 6 from about 1917, for magnitude 5 from about 1940 and for magnitude 4 from about 1965. Data up to the end of 1977 was used to calculate the new maps.

ZONE BOUNDARIES

Figure 2 shows the zones adopted for western Canada to produce the maps for the 1985 building code. The geographical boundaries of the zones represent the best consensus of Canadian seismologists after several iterations. Some arguments remain and will only be settled by future observations.

EARTHQUAKE DEPTHS

Earthquakes in the Canadian risk estimation program of this generation are considered to be point sources at 20 km depths. A justification for this depth constraint is the fact that surface breaks have never been found in Canadian earthquakes. The one exception to the depth restriction is the PGT zone where point source depths are fixed at 40 km, underlying the 20 km deep CAS seismicity. These earthquakes are within the subducting Juan de Fuca plate beneath southwest British Columbia.

RECURRENCE RELATIONS

Recurrence curves for the individual zones are calculated by the maximum likelihood method, adapted to allow for maximum magnitude earthquakes and for unequal periods of complete observation for the different magnitude earthquake groups (Weichert, 1981). Maximum magnitude is modelled by a simple truncation of the log linear event number density, so that in a cumulative logN-M plot the approach to maximum magnitude is curved. The time variability of the method allows large historical events to be formally combined with seismicity patterns that have only emerged recently.

GROUND MOTION RELATIONS

The earlier Canadian seismic risk map used peak acceleration as the parameter. In response to engineering demands, the newly proposed maps also give peak ground velocity as an independent parameter. Figure 3 shows the relations used for the Canadian program (Hasegawa et al., 1981) for two magnitudes, compared with those of others, Schnabel and Seed (1973), Joyner and Boore(1981), and Algermissen et al. (1982). It should be noted that over the range of the majority of data, the Canadian relations fit as well as others, but their extrapolations to large magnitude events and to near source distances give higher ground motions. The near source problem arises from the adoption of the same simple analytic representation for all distances: this is justified for the risk map in view of the data scarcity and it is consistent with the proposed application to earthquakes at no less than 20 km depth.

RISK MAPS

Figure 4 shows the new peak acceleration map that is in effect for the Canadian NBCC in 1985. There are 7 zones now instead of 4 in the past. The change in probability from 0.01 annually to 10% in 50 years results in an increase of about 2 to 3 in ground motion. Thus the old zone boundaries of 1, 3 and 6% g have become 4, 8 and 16% g. Each of these zones have been split into two, stepping up by factors of about square root of 2. This is currently considered the achievable limit of resolution, at least for relative risk levels. At the high end, additional zones have been added.

Figure 5 shows the velocity risk contours. Explanation and comparison of the new zone limits with the earlier ones is necessarily restricted to the acceleration map, but in fact, definitions of the new code zones are based on the velocity contour map. Numerically, the zone boundaries are the same, although their units are fractions of gravity and ms^{-1}, respectively. This is a coincidental consequence of the physical relation between acceleration and velocity for sinusoidal motion, since the corner frequency between acceleration-flat and velocity-flat parts of typical, strong motion earthquake spectra is between 1 and 2Hz. However, in a probabilistic sense the corner frequency varies throughout the country, depending on the distance to the dominant earthquake sources, and therefore the velocity and acceleration maps are not dependent.

The change in probability has generally resulted in an increase of ground motion levels by a factor of 2 to 3. This has necessitated changes in the base shear design of the code in order to arrive at approximately the same protections for similar types buildings (Heidebrecht et al., 1983).

The six principal factors that influenced the new maps are:

- Research on historical earthquakes, yielding more precise epicenters and magnitudes
- An expansion of the data base by 14 years of data with modern dense networks
- A change of the attenuation relations from the Milne-Davenport (1969) to the Hasegawa et al. (1981) relations
- A change in computational method from extreme value to the Cornell method
- A change in probability of exceedence from 0.01 per annum (i.e. 40% in 50 years) to 10% in 50 years
- Stochastic treatment of the ground motion relations. Because of the convolution with the strongly asymmetric exponential event number distribution, the resulting ground motion is increased by a factor between 1.5 and 2. (cf. e.g. Weichert and Milne, 1979).

DIRECTION OF CURRENT RESEARCH

In western Canada, seismicity is relatively well understood in terms of tectonic interaction of the Pacific and America plates and the subduction of smaller intervening plates, but many uncertainties in risk estimation remain. New earthquake data are accumulating rapidly with the deployment of increased numbers of modern seismograph stations, so that refinements to seismic risk calculations should soon become possible. We outline here some of the relevant ideas and desirable improvements.

ALTERNATE ZONE BOUNDARIES

Definitions of source zones are based on a combination of current seismicity patterns and an understanding of the causative tectonic forces, but some arbitrariness can not be avoided. We illustrate with two examples. In the southeast corner of British Columbia, a large area of low level activity was chosen as the SBC source zone (Figures 1 and 2). On the basis of the seismicity during the established periods of completeness for the different magnitudes, this seemed the most logical, despite the large apparent aseismic areas within the zone. A strongly suggested alternative would have been a separate and more seismic Columbia mountain zone, around the M6 event near 52°N. The tectonic arguments involved here concern evidence for a hotspot near this earthquake cluster (Rogers, 1981).

Another example of alternate zone boundaries is the position of the northern boundary of the PGT - CAS source zones, in Figure 2. This is in the vicinity of major urban centers. The PGT zone underlies part of the CAS zone. There is deep activity south of 49th latitude, connected with subduction but there is also an active deep cluster 1/2 degree further north, (Figure 1), that has been discovered since a network of sensitive seismographs has been deployed in the region. The intervening region, just west of Vancouver, might be a quiescent gap preparing for a future large earthquake. It was decided to model only the historical pattern of the large earthquakes here and to place the boundary at 49°N. If one wanted to extend this zone as far as the northern deep cluster, the total activity in this zone must be adjusted. In most other source zones the observed seismicity is assumed to be uniformly distributed over the whole of the zone,as in the SBC discussed above, but the revision of the PGT is a prime example where it might be more prudent to scale the seismicity up in proportion to the area increase.

UPPER LIMITS TO GROUND MOTION

It is generally accepted that the high frequency ground motion that is important for seismic risk estimation, saturates somewhere near M7 to 7.5. This is partly a consequence of the shift of dominant energy to the lower frequencies, as the earthquake size increases, but also reflects the complexity of the source. Large earthquakes are comprised of subevents that represent rupture of high-stress asperities along the fault. The Canadian risk calculations model this effect to a first order by extrapolating the dependence of both acceleration and velocity on magnitude only to M7.5. This sharp truncation could be made more gradual in many different ways, but to a first order, only the magnitude level of the cutoff is of concern. For instance, the high frequency motion of peak acceleration saturates at lower magnitude than velocity, so that perhaps M7.2 is a more realistic cutoff for peak acceleration.

Equally important is the treatment of events larger than the cutoff magnitude. Currently, they are replaced one to one by M7.5. The implication for risk estimation is that exceedence of a given groundmotion is counted only once for each earthquake, and that both the duration of strong ground motion as well as the spatial extent of the source is ignored. In several western Canadian zones, were the total seismicity corresponds well to the seismic moment rate calculated from the tectonic slip rates (Hyndman and Weichert, 1983), it would be more prudent to match the total moment of the large magnitude events by a moment-equivalent number of events with the short period saturation magnitude. Thus, an M8.1 earthquake on the Queen Charlotte fault would be replaced by about 8 M7.5 point source events distributed evenly over the fault source zone.

EXTENDED SOURCES

The treatment of large magnitude events suggested above is an easy and natural way of modelling an extended source. A fault risk model has first been developed by DerKiureghian and Ang (1977) and has been programmed by McGuire (1978). The reason that such a model has not been utilized for Canadian risk estimation is the increase in numbers of statistically very uncertain stochastic parameters that are needed to describe the model. One needs new ground motion relations and length of rupture relations with their associated distributions. Some experimentation with the risk program by McGuire (1978) for the Queen Charlotte fault zone has been carried out (Weichert et al., 1983), with the conclusion that on the mainland coast the risk is comparable for point source and fault model, while in the Queen Charlotte Island region the risk varies considerably; however, here a variety of assumptions break down in both models, and special studies become indispensable.

LARGE THRUST EARTHQUAKES

No allowance at all has been made in the new zoning map for the possibility of a megathrust earthquake on the Juan de Fuca subduction zone. Although there have been no thrust earthquakes observed on the subduction interface (Milne et al., 1978; Tabor and Smith, 1984), the possibility that the zone may be locked or accumulating strain aseismically has been recognized and concern about neglecting this seismic potential has been expressed (Milne et al., 1978; Savage et al., 1981; Weaver and Smith, 1982; Heaton and Kanamori, 1984). We would like to consider here the effect of such a megathrust earthquake and suggest a technique for introducing it into the risk calculations for British Columbia.

Ruff and Kanamori (1980) established a relationship between the age of the subducting plate, the convergence rate and the largest earthquake in a subduction zone. If the current best estimates are inserted into the relationship for the Juan de Fuca subduction zone (average age at the trench 6.5 Ma and convergence rate 4.5 cm a^{-1}), an earthquake of magnitude 8.5 is predicted. Another way of estimating maximum magnitude is by the potential length of rupture. For the Juan de Fuca zone it is maximally about 1000km from the Nootka fault zone in the north to Cape Mendocino in the south. This is about the same length, and the same age of subducting lithosphere, that ruptured during the great Chilean earthquake of 1960. The event had a magnitude of 9.5 (MW, Kanamori, 1978) and a displacement of 24 m (Kanamori and Cipar, 1974). The Juan de Fuca plate is relatively uniform and free of seamounts so that a break along its whole length cannot be ruled out, but a rupture of only the northern 600 km appears easier to accept.

The repeat time of a possible megathrust event is difficult to estimate since there is no historical evidence for thrust earthquakes of any magnitude in the region and thus a recurrence relation cannot be defined. However, if southern Chile is again used as an analogue, some estimate can be made. If the total relative motion on the subduction zone were caused by large earthquakes, the repeat time for a megathrust event would equal the average displacement during the event divided by the plate convergence rate. [In their study of seven subduction zones, Dykes and Quittmeyer (1981) found that the ratio of seismic slip to total slip varied from 0.3 to 0.9 depending on the rheology of the subduction zone, with southern Chile having a value of 0.91]. Dividing 24m into 4.5 cm one obtains an approximately 500 year return period.

There is one other set of observations that could be interpreted as indicating the same order of repeat time for a megathrust event. Griggs and Kulm (1970) found evidence of major deep-sea turbidity flows off the Columbia River every 400 to 500 years since the deposition of Mazuma ash 6600 years ago. While major earthquakes are not necessary to trigger turbidity flows, it is very unlikely that a megathrust event could occur without triggering major slumps and thus turbidity flows. This turbidity record gives therefore a minimum repeat time for major earthquakes in the range of 400 to 500 years for the Juan de Fuca subduction zone.

EFFECTS ON RISK IN SW BRITISH COLUMBIA

The inclusion of a M9.0 earthquake into the Canadian probabilistic risk formulation presents little conceptual difficulty. If we use the current M7.5 cutoff of ground motion, and an average coefficient of 1.5 between log-moment and magnitude, the M9.0 is modelled by $10^{1.5(9-7.5)}=178$ M7.5 events in about 450 years, uniformly distributed over the 700 x 100 km^2 crustal contact of the subducting plate, resulting in an event density of $0.4 \times 10^{-5}\ km^{-2}\ a^{-1}$. This is at least 40 times higher than the rate in the PGT zone. A new source zone could formally be defined, dipping from the outer coast to about 40 km depth 100 km inland. For reasonable probabilities the risk would come almost exclusively from maximum magnitude events at close distances with the attendant uncertainties, so that the probabilistic risk estimation cannot be upheld and the ground motion problem reverts to a deterministic one. It is possible that time variable risk analysis may provide guidance for some critical structures. Research efforts must thus be concentrated on maximum ground motion and on searching for evidence of a recent but prehistoric mega-event in the region. The turbidity flow record seems to indicate that a few hundred years have already passed since the last possible event!

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FIGURE CAPTIONS

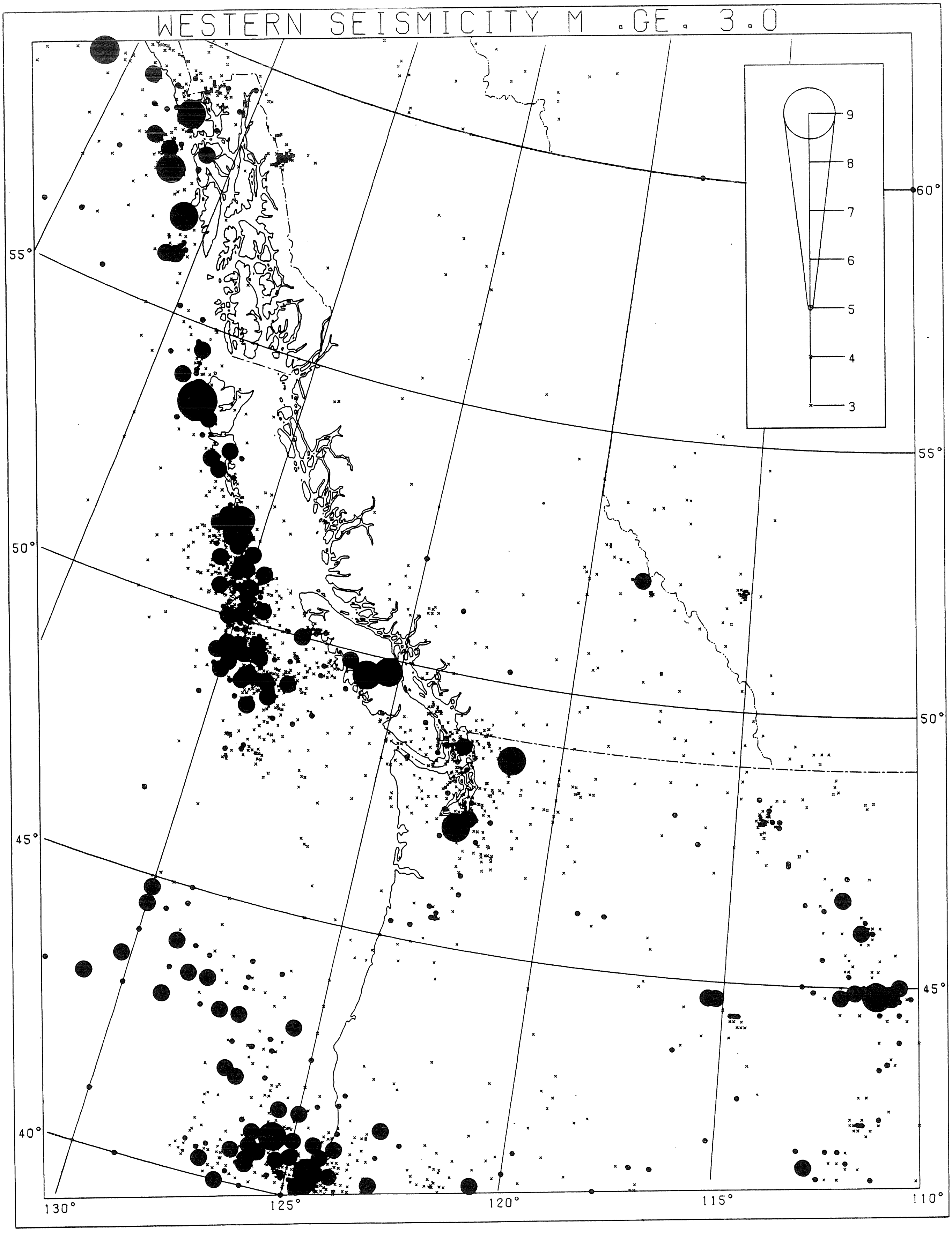
Fig. 1 Western Canadian Seismicity (data incomplete for United States territory)

Fig. 2 Western Canadian Source Zones

Fig. 3 Ground motion Relations for Western Canada: (1) Hasegawa et al., 1981; (2) Schnabel and Seed, 1973; (3) Joyner and Boore, 1981; (4) Algermissen et al., 1982.

Fig. 4 Peak Acceleration map for Canada

Fig. 5 Peak Velocity map for Canada



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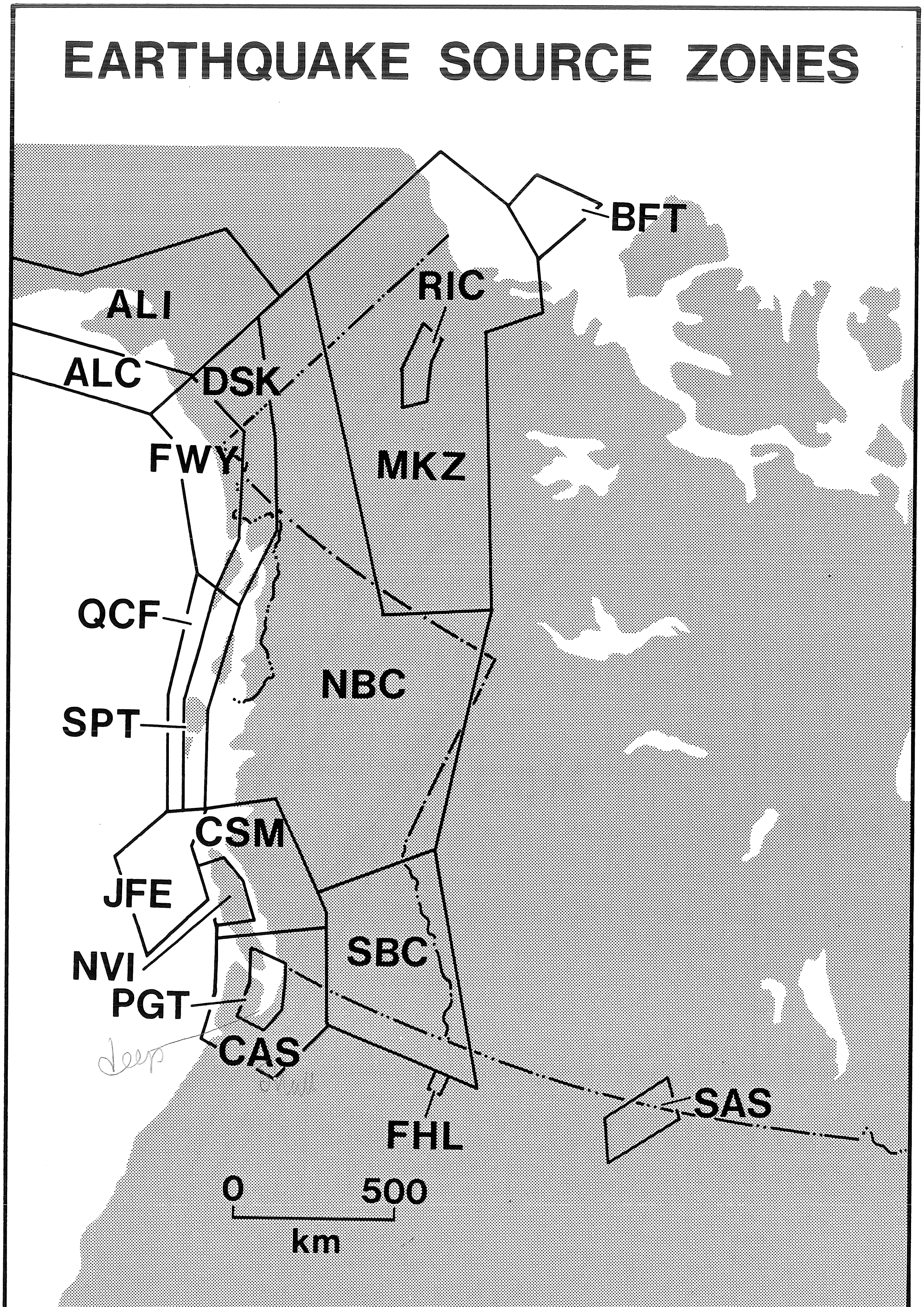

Fig. 2 Western Canadian Source Zones

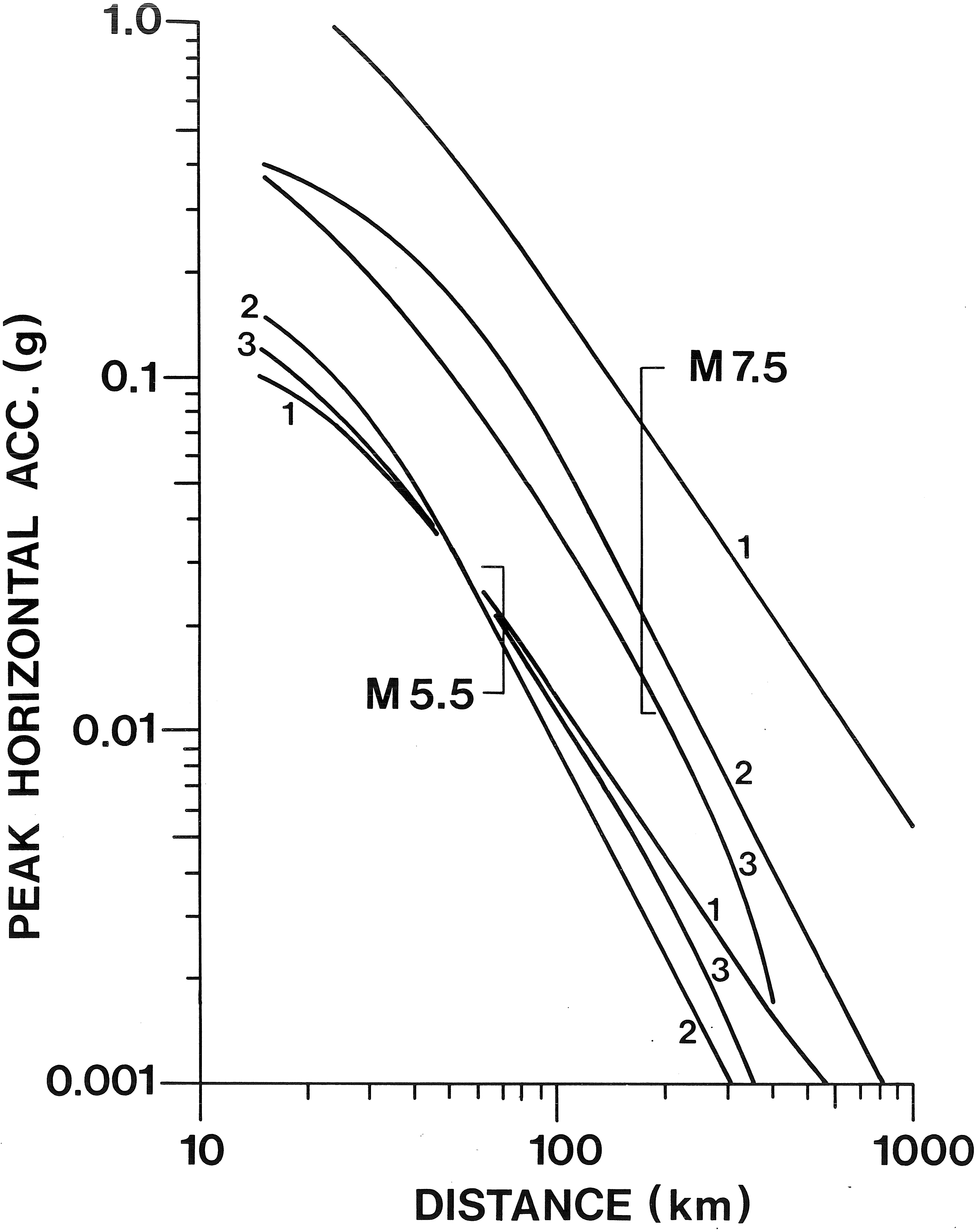

Fig. 3a Ground motion Relations for Western Canada: (1) Hasegawa et al., 1981; (2) Schnabel and Seed, 1973; (3) Joyner and Boore, 1981; (4) Algermissen et al., 1982.

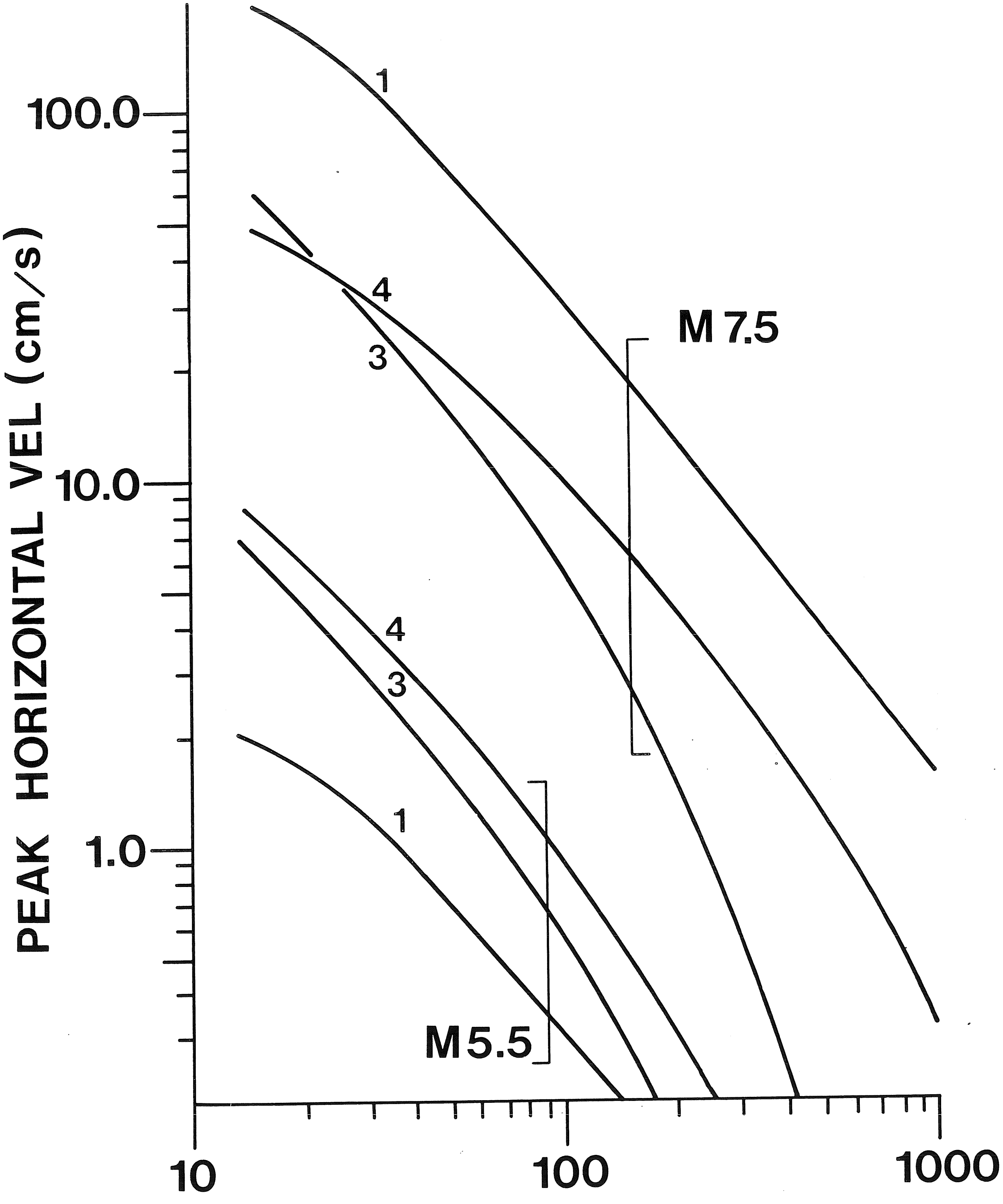

Fig. 3b Ground motion Relations for Western Canada: (1) Hasegawa et al., 1981; (2) Schnabel and Seed, 1973; (3) Joyner and Boore, 1981; (4) Algermissen et al., 1982.

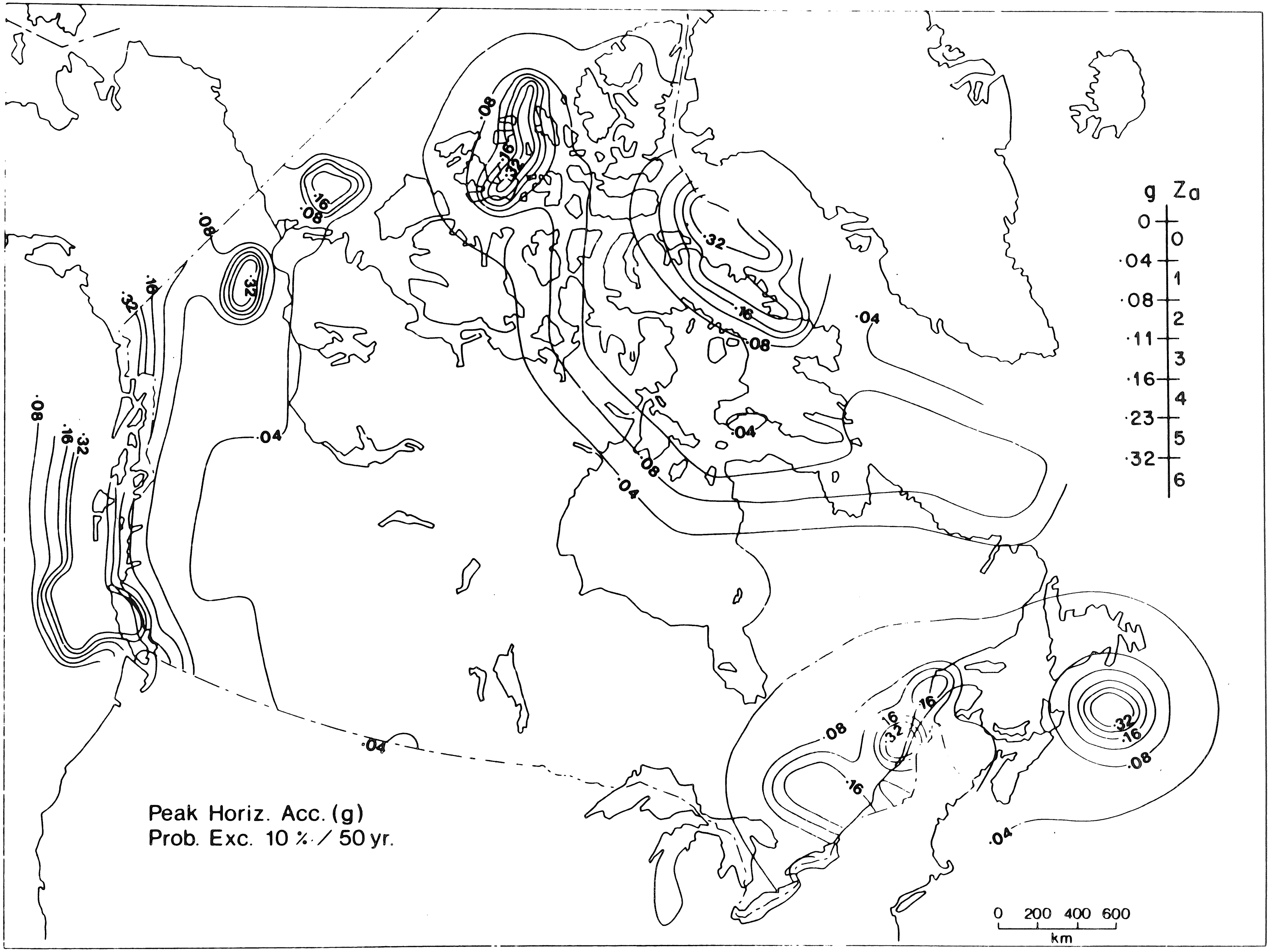

Fig. 4 Peak Acceleration map for Canada

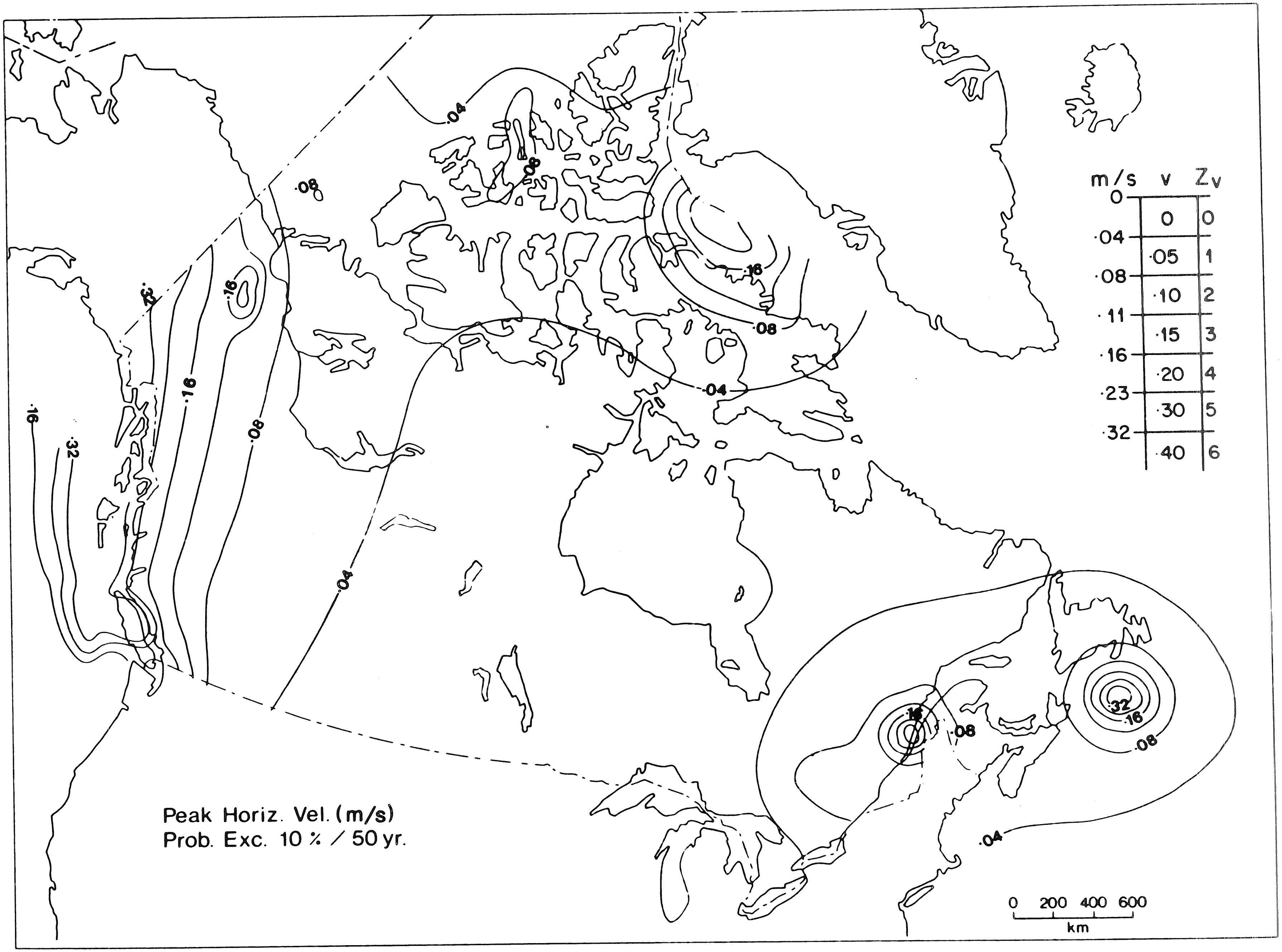

Fig. 5 Peak Velocity map for Canada