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Seismic Zones, Ancient Fault Systems and Post-Glacial Faulting in Eastern Canada

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1. Introduction

The distribution of intraplate seismicity in Eastern Canada is not uniform throughout the region but shows a considerable degree of clustering in several sub-regions. Based solely on judgements pertaining to the groupings of historical earthquakes, Basham et al. (1979, 1982) have identified several zones of seismic occurrence (Fig. 1). Their work is based on historical earthquake data, from 1611 to 1975, screened to minimize the effects of biases related to: (i) early earthquakes reporting only in regions first settled (ii) inaccurate epicentres and non-uniform earthquake reporting thresholds in pre-instrumental vis a vis later eras (iii) non-uniform reporting of small magnitude earthquakes in recent decades. Considering that the rate of deformation in intraplate regions is generally low and that seismic data accumulate slowly, more data are obviously needed to define the boundaries of the various seismic zones precisely. However, the fact that the pattern has persisted, essentially unchanged for over 300 years, shows that the zonal division of Basham et al. (1979) is of fundamental significance not only as a basis for evaluation of the seismic risk, but also as a framework for developing concepts pertaining to seismotectonics of the region.

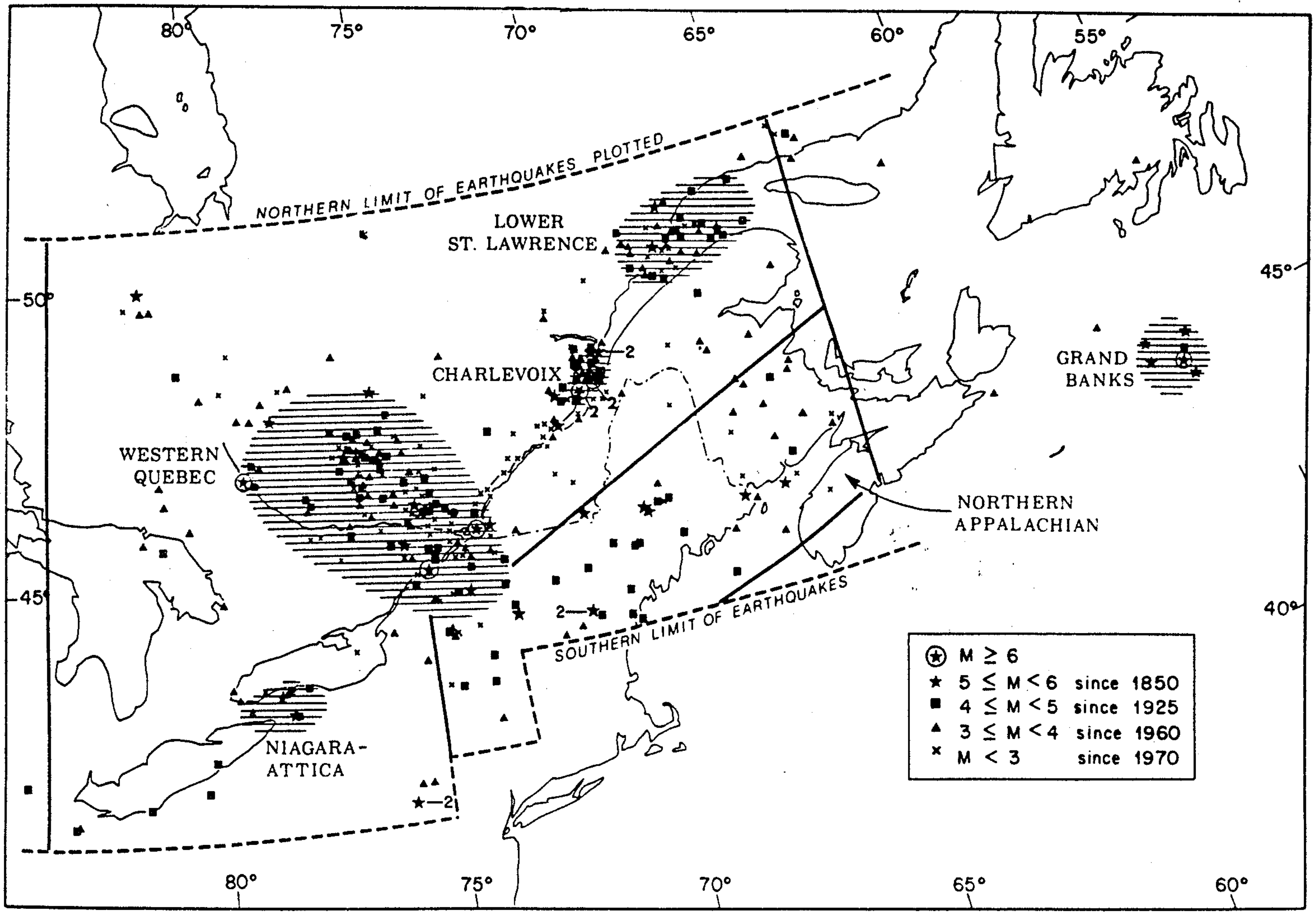

Fig. 1. Historical zones of earthquake occurrence. Time period restrictions on epicenters plotted as a function of magnitude are indicated in the legend. Multiple epicenters are indicated only for magnitudes ≧ 5. From Basham et al. 1979.

Based on spatial relations, Kumarapeli and Saull (1966) identified a high-angle fault system of regional extent as a possible tectonic framework for seismicity in Eastern Canada. The faults were considered to be elements of a major rift system referred to as the St. Lawrence Rift System. Although new and improved data have confirmed some of the space relations proposed by Kumarapeli and Saull (1966; see Anglin 1984) they also have brought to light some errors in the original concept. As first pointed out by Voight (1969), the contemporary stresses of Eastern North America are dominantly horizontal and compressional and are therefore not consistent with the concept of an active rift system. In the light of this criticism, Kumarapeli (1974) proposed a modified hypothesis that the St. Lawrence Rift System is now tectonically inactive as a rift but that the associated seismicity represents release of contemporary stresses along the ancient rift faults. The rift system itself is understood as a Mesozoic feature, formed by reactivation and integration of older faults and failed arms inherited from an episode of late Precambrian-early Cambrian continental rifting, referred to as Iapetan rifting (Kumarapeli, 1985). This rifting episode was a prelude to the formation of the early Paleozoic ocean basin - the Iapetus - which following a Wilson Cycle gave rise to the Appalachian foldbelt.

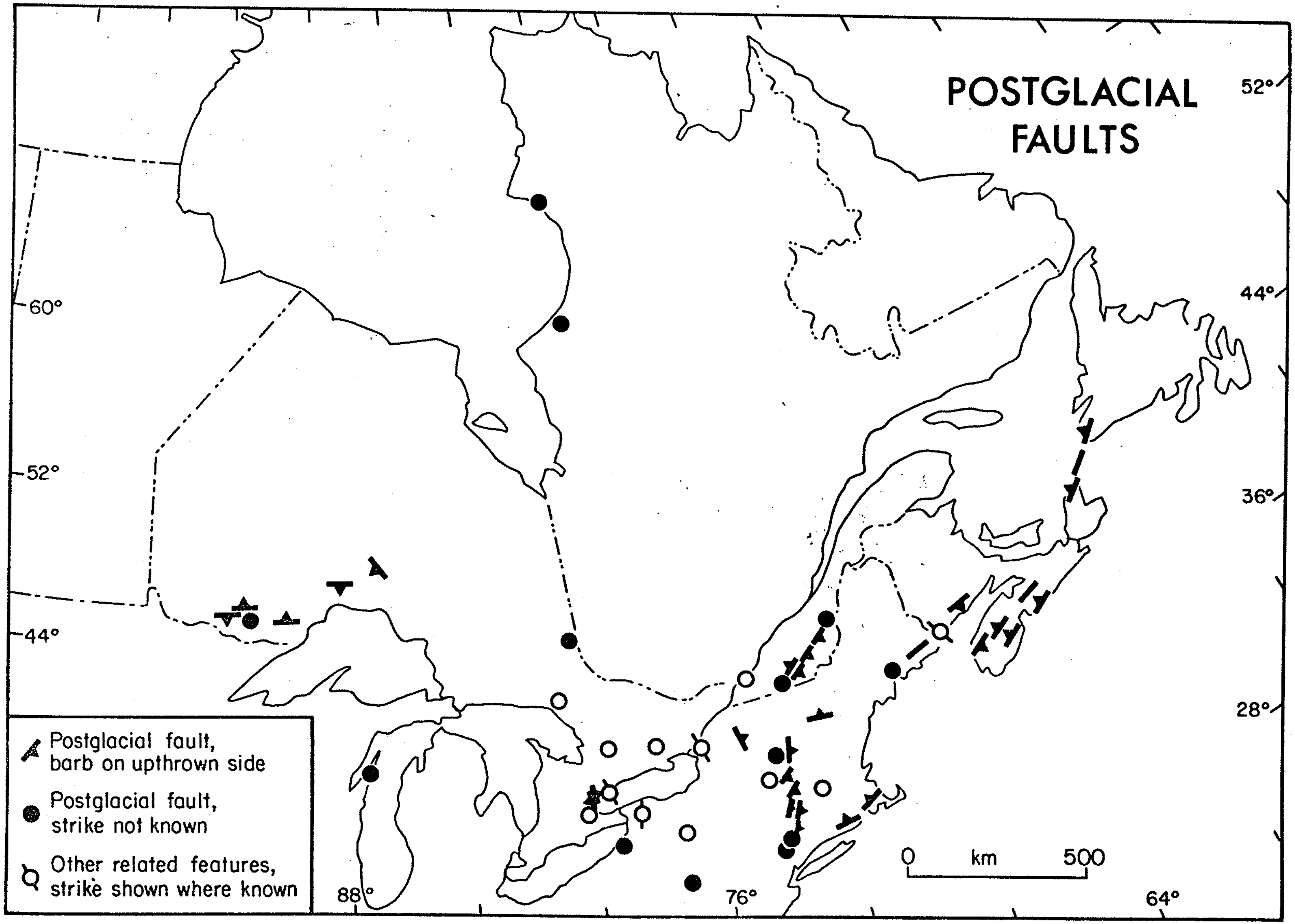

Fig. 2. Postglacial faulting and other related features in Eastern Canada. From Adams 1981.

Post-glacial faulting has been reported from a number of localities in eastern Canada (Adams, 1981, Oliver et al. 1970; Fig. 2). However no obvious correlation between the known occurrences of post-glacial faulting and contemporary seismicity has been established. In the summers of 1979 and 1980, the writer carried out a search for recent faulting in areas of Eastern Canada known to be seismically active and selected for their close spatial association with ancient, deep fault systems.

The aims of this report are two fold. One is to identify the general spatial trends in the epicentres of major seismic zones in Eastern Canada and correlate them with fault/fracture zones that are likely to control these trends. The other is to present the results of the search for post-glacial faulting.

2. Seismicity in Eastern Canada

Characteristics of seismicity in Eastern Canada have been discussed by Basham et al. (1979), and in the adjacent parts of United States by Yang and Aggarwal (1981). Three of the seismic zones, identified by Basham et al. (1979), namely the Charlevois Zone (CHV), the Lower St. Lawrence Zone (LSL) and the Western Quebec Zone (WQU), represent the most prominant clusterings of earthquake epicentres in Eastern Canada. They are the study areas of this report. The discussions are mainly restricted to the spatial trends in the epicentres, based on maps shown in Figures 6, 7, 8 which are for the period 1977-1985. High-quality data, both in terms of the density of network coverage and in the accuracy of epicentral location (variable but better than 5 km in most cases) was the main consideration which influenced the selection of this time restriction. The shortness of the period, however, is a disadvantage. Yet epicentral location maps of Eastern Canada, whether they be for long periods (few hundreds of years) or for short periods (few years) show essentially the same pattern of clustering and spatial trends of epicentres, and therefore, the shortness of the data sample is not considered to be a serious problem. Inclusion of less accurate data, on the other hand, tends to give widely diffused patterns which are difficult to relate to geological features such as fault zones.

Both CHV and LSL show distinct elongation parallel to the St. Lawrence River and these directions of elongation, approximately N30°E for CHV and N50°E for LSL, are identified as the general epicentral trends in these areas. The WQU as originally defined by Basham et al. (1979) was an elliptically-shaped area (Fig. 1), extending from Lake Champlain in Northern New York State northwestwards into Quebec, for a distance of about 500 km. The outline of this zone probably needs revision in the light of data from northern New York State, obtained since 1971, from a relatively dense network of short-period, high-gain stations

(Sbar and Sykes, 1977). These data have shown that seismicity in the northern New York State actually extends throughout the Adirondack region, so that the southeastern part of this zone is wider than estimated by Basham et al. (1979). Thus, the gross trend of this seismic zone, which will be referred to as the Western Quebec - Northern New York (WQU-NNY) seismic zone, describes an arc, convex to the northeast (Fig. 3).

The three seismic zones under study are in Precambrian areas or in areas where Precambrian rocks make up the basement. The Precambrian rocks belong to the Grenville structural province (Wynne-Edwards, 1972) whose last major thermal-structural event, the Grenville orogeny, peaked approximately 1100 Ma ago (Doig, 1977).

3. Fault systems, fracture zones and other crustal inhomogeneities: controls of epicentral trends

The rationalization of a geological basis for intraplate seismicity of Eastern Canada, or any other region of similar setting for that matter, has to be based on certain assumptions which appear reasonable in the light of overall experience. (i) Because the lateral dimensions of seismic zones are in the order of several tens or even a few hundreds of kilometres and their vertical dimensions (based on depth of foci) are of the order of 20 to 30 kilometres, any structure or structures reponsible for these zones must be of crustal scale. Such large, nearly vertical or steeply dipping, presumably planar structures are fault zones that probably originated as a product of plate tectonic processes. (ii) In the continental crust there is usually no dearth of faults, shear zones and other inhomogeneities of various ages, sizes, orientations and movement histories. Therefore, crustal stresses, rather than creating new fractures, will commonly be released on prexisting zones of weakness that are nearest the optimum failure orientation. This section describes and evaluates the various types of fault/fracture systems and other crustal inhomogeneities which have been regarded, or are likely, as candidates for the release of seismic stresses in the regions considered.

3.1 Frontal thrust zones of the Appalachian foldbelt

The soles of the frontal thrusts and klippen of the Applachian fold belt, collectively referred to as Logan's Line, because of their association and trend relations (Fig. 3) with some of the seismic zones (CHV and LSL) had earlier been regarded as contributing to seismicity (e.g. Leblanc and Buchbinder, 1977). However, these shallow dipping structures are probably elements of thin-skinned tectonics, confined to the upper sedimentary wedge of the Appalachian margin, whereas, recent analysis of data from the CHV Zone shows that its seismic activity extends to mid-crustal depths on steeply dipping seismogenic zones (Anglin, 1984).

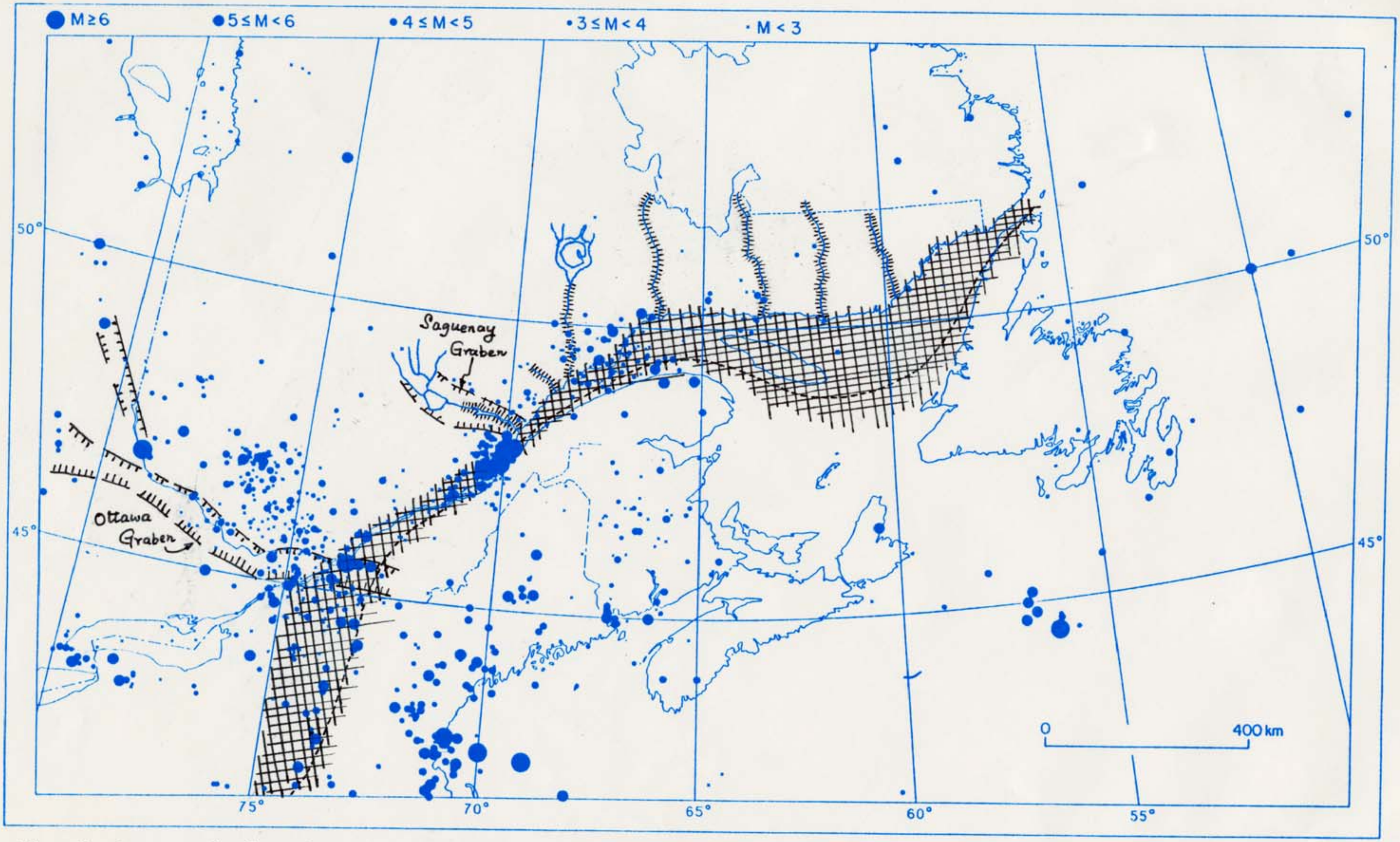

Fig. 3. Space relations between Iapetan structures and seismicity in Eastern Canada. Grid pattern: area in which Iapetan faults parallel to the ancient continental margin are known or are likely to occur. Deep valleys along possible fracture zones hachured. Dash line: Appalachian front. Base map from the files of the Geophysics Division, Geological Survey of Canada. M≥5 to 1981; 4≤M<5, 1960-1981; M<3, 1970-1981.

Therefore, it is unlikely that the structures collectively referred to as Logan's Line are seismogenic.

3.2. Iapetan Faults

The Iapetan faults that are of interest in the context of seismicity in Eastern Canada, are best described under three groups (i) faults parallel to the ancient continental margin of Laurentia, (ii) aulacogens which radiate into the continental interior from the ancient continental margin (iii) fracture zones transverse to the ancient margin.

3.2.1 Iapetan faults parallel to the ancient continental margin

Block-faulting appears to be a characteristic feature of rifted continental margins (Scrutton, 1982). It seems that listric faults, dipping towards the edge of the continent and paralleling the rifted margin are the most common type (de Charpel et al.; 1978, Morton and Black, 1975). Relatively wide (100-200km) zones are affected in some areas (see Montadert et al., 1979). The faulting is accompanied by stretching and thinning of the crust. What was initially a rifted margin may eventually become involved in collisional orogeny. As a result, faults proximal to the collisional boundary may become interlocked and sealed by processes related to

orogeny, whereas those that are distal may become reactivated in response to the accompanying compressive stresses and continue to persist in the craton as potential zones of crustal failure, susceptible to reactivation. The fault zones described below appear to be Iapetan structures of this latter type.

The margin of the craton adjoining the Northern Appalachians is in places severely block-faulted. This type of faulting is probably present along the entire margin of the craton in eastern Canada, but is best known from the St. Lawrence and Champlain Valleys and from Anticosti Island (Figs. 3 & 4). The majority of these faults show varying degrees of parallelism to the orogen and dip towards it, their cumulative effect being to step down the Precambrian (Grenville) basement (also the overlying platformal rocks) towards the orogen. Seismic reflection studies show that the step faulting of the crystalline basement continues for some distance east of the Appalachian front (SOQUIP, 1979; St. Julien et al. 1983).

The Iapetan faults, parallel to the ancient continental margin, are perhaps the most likely structures along which seismic energy is released in the CHV and LSL seismic zones because of the following reasons: (i) both seismic zones are where these Iapetan faults are known or are expected to occur, (ii) the

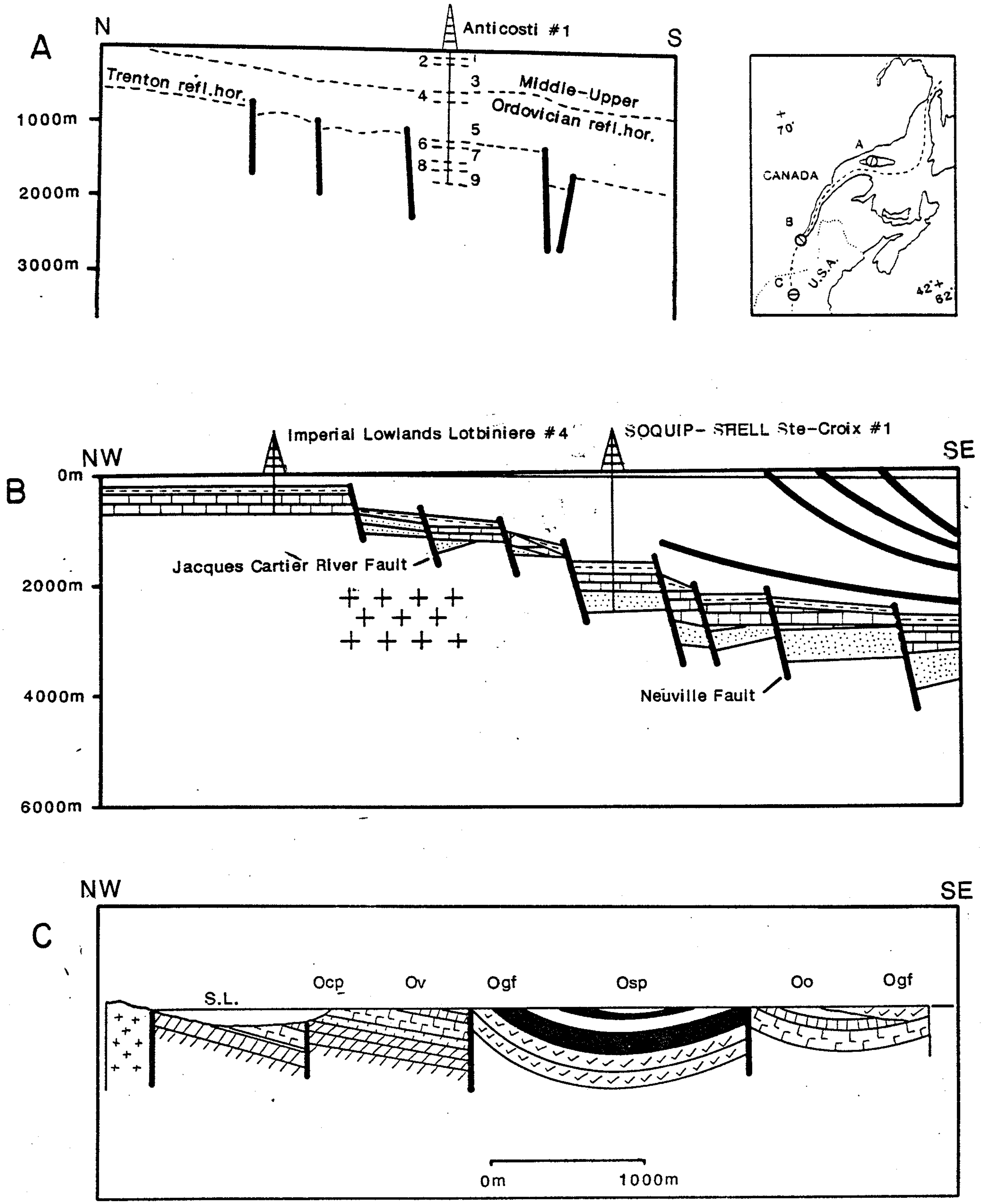

Fig. 4. Step faulting along the early Paleozoic continental margin. A: after Roliff 1968. B: after St. Julien et al. 1983. C: after Welby 1961. Key to abbreviations: Ocp - Crown Pt. Ls; Ov - Valcour fm.; Ogf - Glenn Falls Ls.; Osp - Stony Pt. Sh.; Oo - Orwell Ls. Small scale map shows the location of sections A, B and C.

seismic zones show distinct elongation parallel to the strike of the faulted zones, (iii) the faults probably originated as northeast striking faults with steep southeasterly dips and therefore are likely to extend at least through the upper brittle crust, (iv) in the case of the CHV zone, detailed studies (Anglin, 1984) have shown that almost all the activity in the zone is related to northeast trending, southeasterly dipping high-angle faults.

Another locality in Eastern North America where Iapetan faults parallel to the ancient continental margin have been identified as candidate sources for seismicity is in Giles County, Virginia (Bollinger and Wheeler, 1982).

3.2.2 Iapetan Aulacogens

Kumarapeli (1985) has shown that the Ottawa graben and the Saguenay graben (Fig. 3) have characteristics which suggest that they are Iapetan aulacogens. The role of these aulacogens in seismic energy release in Eastern Canada is not clear. The faults of the Saguenay graben are not known to be seismically active, but as noted by Anglin (1984) the northeastern termination of the CHV zone is just about where the faults of the Saguenay graben trend make their appearance, suggesting that the graben may have an influence in delimiting the seismic zone. The Ottawa graben, which is by far the larger of the two aulacogens, is also not particularly active, although a few epicentres of the WQU-NNY zone including the Timiskaming earthquake of 1935 (M>6), are located on it. Again the main role of the aulacogen appears to be to delimit the seismic zone in Quebec on its southwest side.

3.2.3 Iapetan Fracture Zones

Kumarapeli (1985) has proposed that the deeply entrenched, south flowing rivers (eg. Jacques-Cartier, Saguenay, Ste. Marguerite, Betsiamites, Manicouagan etc. see Fig. 3), in the general area of the CHV and LSL zones, are fracture controlled and follow lines of weakness which originated as fracture zones that radiated into the continental interior at large angles from the principal Iapetan rifts. Such lateral fracture zones, could develop, especially in areas where doming preceeds rifting. Like the Iapetan aulacogens, these presumed fracture zones do not appear as obviously active features on seismic maps but the fact that few epicentres occur (in the shield area) well removed from the areas of main activity in the CHV and LSL zones may be an indication of low-level activity along such fracture zones.

3.3 Pre-Iapetan tectonic elements

A characteristic feature of the shield area in which the WQU-NNY Zone is set, is the presence of numerous lineaments in the form of narrow rectilinear or zig-zag valleys with two dominent trends with maxima approximately at N35°W and N45°E (Kumarapeli, 1978). The zig-zag valleys combine the two trends, and in small scale maps, appear as north-south trending lineaments. Nonetheless a north-south trend also has been recognized locally in some areas (Forsyth 1981). Kumarapeli (1978) has presented arguments to support the view that these lineaments are the surface expression of a regional fracture pattern (RFP) which became established early in the evolution of the crust and exerted a dominating influence in controlling the directions subsequent crustal failure.

The pattern of Iapetan faults in parts of Eastern Canada shows unmistakable characteristics that their directions were controlled by the RPF. For example, Figure 5 shows schematically the dislocation pattern of Iapetan faults along the St. Lawrence Valley and the Ottawa graben. The pattern outlines part of a polygonal fracture and only two segments of this fracture along St. Lawrence and Lake Timiskaming Valleys are parallel to the components of the RFP. Accordingly, the faults in these two segments consist of well-developed

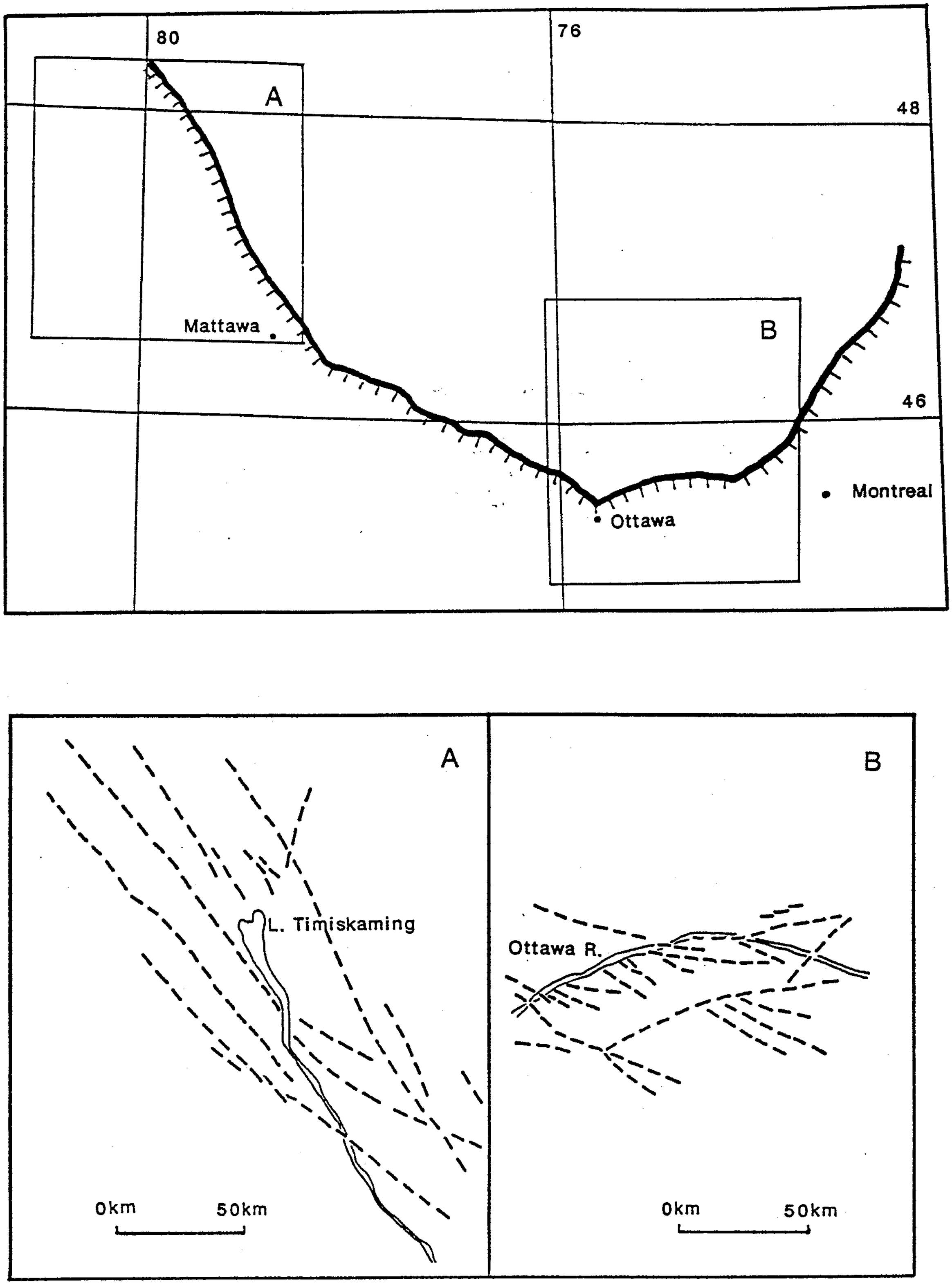

Fig. 5. Control of Iapetan faults by pre-Iapetan tectonic elements of the crust. The upper frame shows, schematically, the dislocation pattern produced by Iapetan faults along the Ottawa Graben and part of the St. Lawrence Valley. The two lower frames A and B, show detailed fault patterns of the two insets in the upper frame. For further details see text.

longitudinal dislocations that persist along strike for long distances (see insets of Fig. 5) suggesting that Iapetan rift faults propagated along preexisting lines of weakness without complication. This characteristic is particularly evident in Lake Timiskaming area. In contrast, the segment along the Ottawa Valley between Montreal and Ottawa shows the greatest departure in trend from the trends of the RFP. Whereas the trend of the Ottawa graben in this area is approximately E-W (N75°), the downfaulting is largely accommodated by movements along numerous, relatively short, oblique faults parallel to northwest component of the RFP, indicating that although the Iapetan rifting dictated an approximately east-west trending graben, the influence of pre-existing lines of weakness, provided its distinct stamp on the overall fault pattern. It will be argued later that these resurgent lines of crustal weakness acted as structral controls for seismic activity in the Quebec segment of WQU-NNY Zone.

3.4 Post-Iapetan Faults

3.4.1 Atlantic normal faults

Inasmuch as Iapetan rifting left its mark on the continental margin of Laurentia, the Mesozoic rifting episode which led to the opening of the Atlantic Ocean also left its vestiges in the continental margin of North America. The normal faults that bound the Triassic grabens, such as the Fundy graben and the Mesozoic basins detected geophysically and by drilling under the continental shelf and rise off Eastern Canada, are probably structures inherited from this younger rifting episode. Although some of these faults appear to be seismically active (e.g. Aggarwal and Sykes, 1978), they occur quite some distance to the east of the seismic zones under consideration and therefore cannot be correlated with their activity.

3.4.2 Continental extensions of Oceanic transform faults

Sykes (1978) proposed a spatial correlation between some of intraplate shocks and old zones of crustal weakness near the ends of major transform faults that were active during the early opening of adjacent ocean basins. Of particular interest in the context of the present study is the hypothesis that the epicentral clusters in the Boston region and in western Quebec form a continuous zone of activity and lie on an extension of a transform fault whose oceanic trace is defined by the New England Seamount chain (Diment et al. 1972; Fletcher et al., 1977). Recent maps, with improved epicentral locations (Yang and Aggarwal, 1981), however, do not show the continuity of the seismic trend upon which the hypothesis was based.

3.5 Crustal inhomogeneities

Features included in this section are steeply dipping discontinuities in the crust, caused by relatively abrupt changes in elastic parameters often accompanied by density changes as well. Goodacre and Hasegawa (1980) have discussed gravitationally induced stresses at structural boundaries of regional extent in general and particularly in the context of the seismic activity in the CHV zone. They suggested that gravitationally induced stresses at the Appalachian boundary may help trigger earthquakes in the CHV zone.

Yang and Aggarwal (1981), and Forsyth (1981) have drawn attention to the scarcity of epicentres within the large anorthosite bodies of the WQU-NNY zone and have proposed that these anorthosite masses, because of their greater strength relative to the surrounding rocks, act as rigid blocks in the present day stress environment. Such rigid masses also tend to amplify the stresses in the areas surrounding them (Campbell, 1978). Whether such stress amplification occurs is not evident from the epicentral patterns in those areas.

4. Seismotectonics

4.1 Charlevoix Zone

In the Charlevoix region, the installation of a high-density detection network in the seventies, has led to a better definition of the Charlevoix seismic zone

(Leblanc et al. 1973, Leblanc and Buchbinder 1977, Stevens 1980, Anglin 1984). It is now known to be a much narrower zone than earlier thought, extending parallel to be the St. Lawrence river and restricted to the river valley and a strip along the north shore (Fig. 6). Within the zone, Anglin (1984) has recognized two seismogenic zones, one under the north shore of the river and the other under the river. These two zones are separated by an essentially inactive zone of variable width (average 5 km) and extending to a depth of about 10 km. The seismogenic zone under the north shore follows closely a zone of mapped high-angle faults striking parallel to the shoreline and, like the faults, dips steeply (~70°) towards the southeast. Considering errors of epicentral location, which even at the present time cannot be determined better than within ±2.0 km accuracy (Lamontagne 1984), it is entirely reasonable to correlate this seismogenic zone with the fault zone along the north shore (Anglin 1984). The seismogenic zone under the river also dips steeply to the southeast and is probably related to another northeast-trending fault zone in the basement. Although P-nodal solutions (Hasegawa and Wetmiller 1980) and composite P-nodal solutions (Lamontagne 1984) have yielded only poorly constrained results, the preferred solutions of the former support the interpretation that the planes of

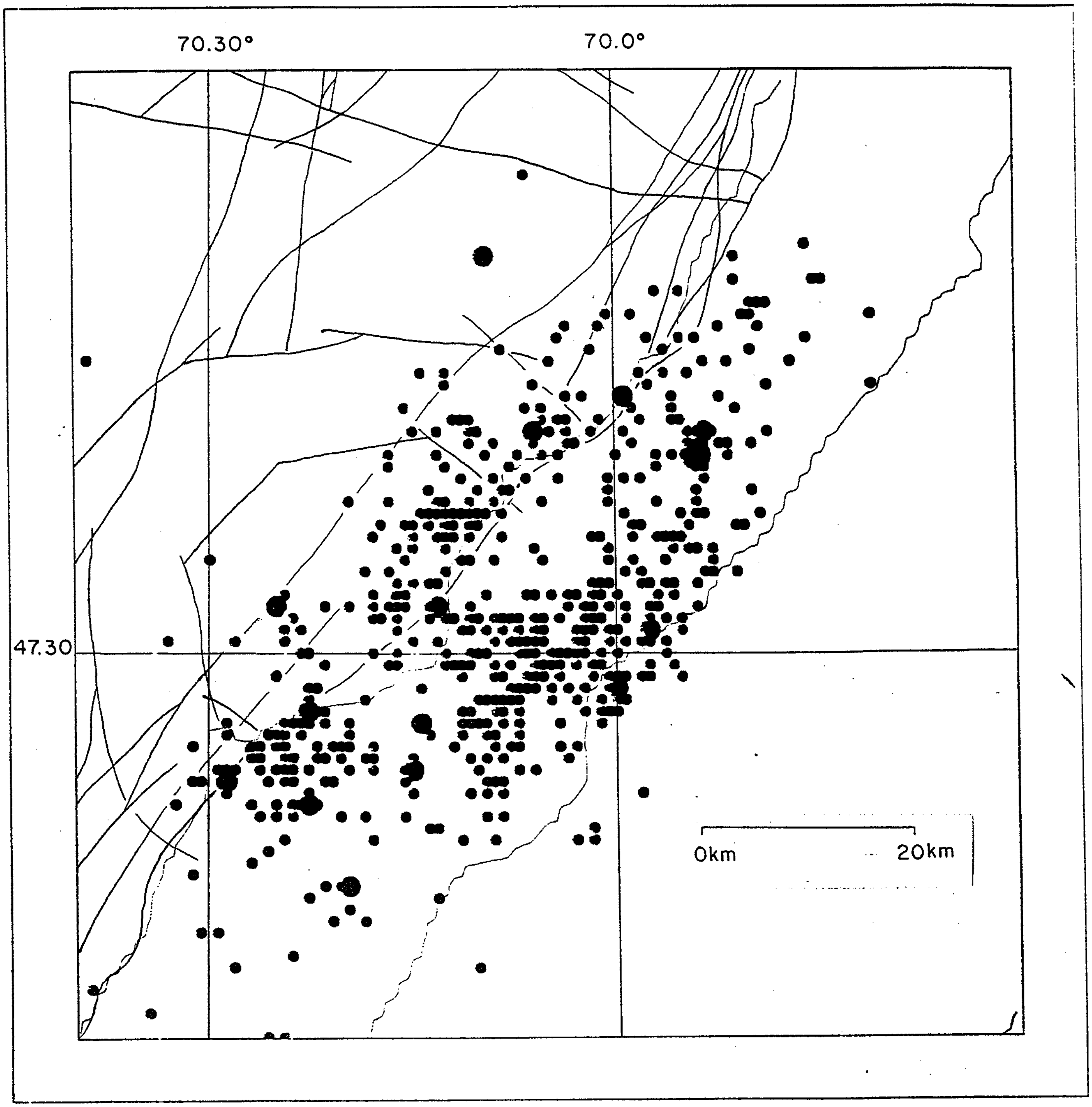

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Fig. 6. Distribution of epicentres in the Charlevoix Zone for the period 1977-1985. Large circles: 3≤M<5; Small circles: M<3. High angle faults in the shield area from Rondot 1979. The polygonal fault pattern outlines the Charlevoix impact crater.

failure in the Charlevoix zone are northeast trending, southeast dipping features which, as Anglin (1984) has interpreted, are probably fault zones as inferred by Kumarapeli and Saull (1966) and later mapped by Rondot (1979). Thus, the Charlevoix seismic zone is perhaps one of the best known examples of Iapetan faults that are being reactivated by contemporary stresses. As explained earlier, these faults are understood to have formed initially as southeast dipping Iapetan normal faults but now appear to behave as reverse faults (Hasegawa and Wetmiller 1980, Lamontagne 1984). Analyses of earthquake data have not yielded a well constrained direction for P-axis but the indications are that it is nearly horizontal and probably southeast-northwest directed.

The other structural features that had been considered as possible candidates for the seismicity of the Charlevoix Zone are Logan's Line (e.g. Leblanc and Buchbinder 1977) and the approximately 350 Ma old (Rondot 1979) Charlevoix impact crater (Leblanc et al. 1973; Roy and Du Berger, 1983; for location see Fig. 6). Their considerations were based solely on close space associations of these features with the seismic zone but in retrospect it may be said that these space associations have had the effect of diverting attention from the more probable, seismicity-related structures, the Iapetan faults. As discussed earlier, it is very unlikely that Logan's Line has anything to do with the seismicity in the area. It is also improbable that the ancient Charlevoix impact and the seismicity in the CHV Zone have a cause and effect relationship. Impacting has undoubtedly complicated the pattern of potential failure in the area (see Lamontagne 1984), and consequently may have created an environment for stress concentration in an otherwise throughgoing Iapetan fault system. Despite this possibility the impact related structures may not play a significant role in concentrating seismicity because: (i) the seismogenic zone extends beyond the limits of the area affected by the impact, (ii) the LSL Zone, also located on the continuation of the same Iapetan fault system, has no known impact located in it.

4.2 The Lower St. Lawrence (LSL) Zone

The cluster of epicentres included in the LSL zone, is downriver from the CHV zone and is located partly in the valley of the St. Lawrence and partly over the north shore (Fig. 7). Compared with the better known CHV zone, the epicentral distribution of the LSL appears diffuse. This diffuseness may be, at least in part, a result of poor epicentral locations. However, its setting along the inferred extension of the active

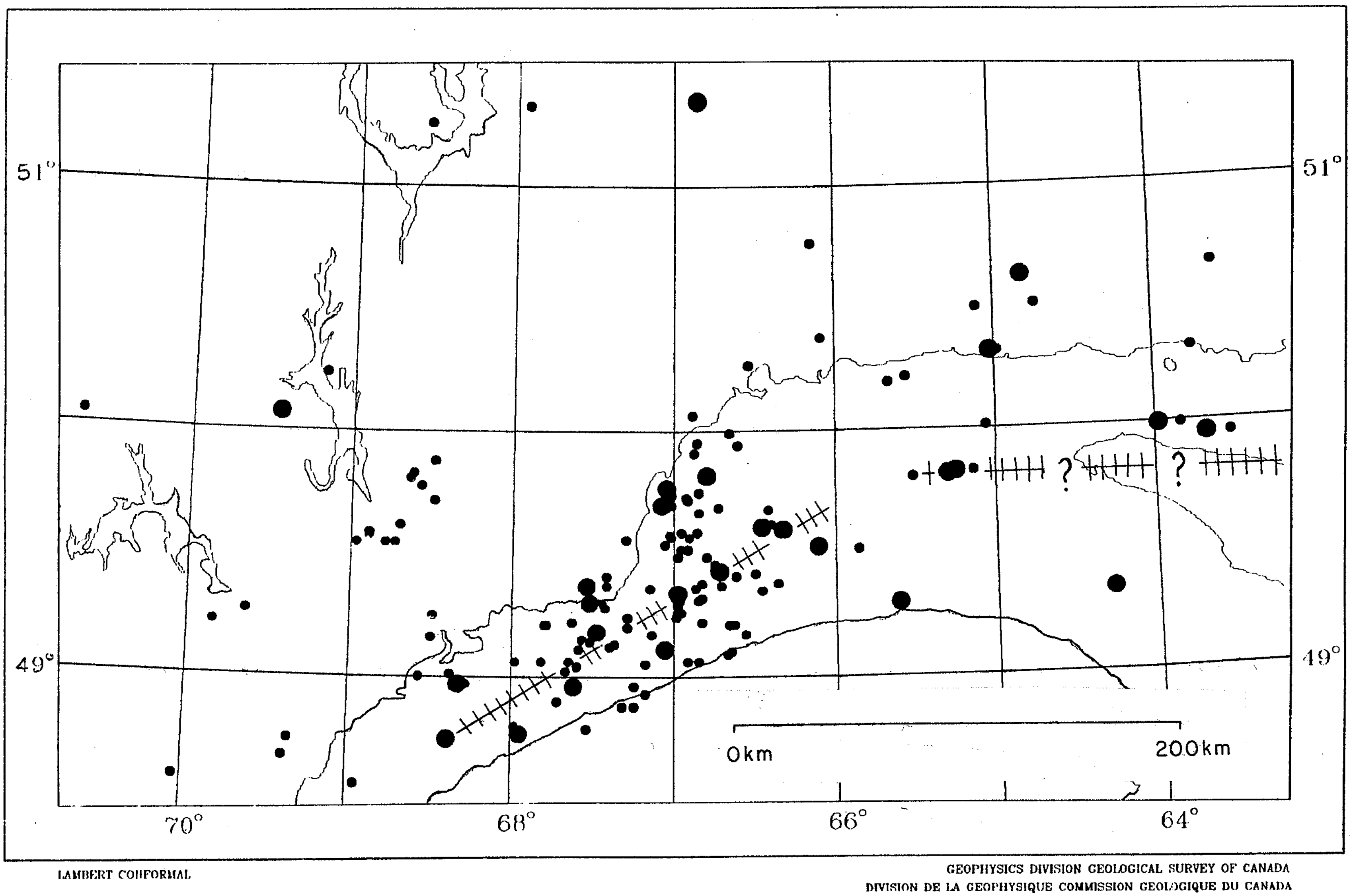

Fig. 7. Distribution of epicentres in the Lower St. Lawrence Zone for the period 1977-1985. Large circles: $3 \leq M < 5$. Small circles: $M < 3$. +++:Probable trend of the seismic zone.

Iapetan faults of the CHV zone and its elongation parallel to the inferred strike of the faults suggest that, like the CHV zone, the LSL zone is also caused by contemporary stress release along Iapetan faults.

4.3 The Western Quebec-Northern New York (WQU-NNY) Seismic Zone

The epicentral distribution of this seismic zone for the period 1977-1985 is shown in Figure 8. It forms a rather diffuse pattern with a grossly curved trend. In norther New York its trend is approximately north-south but north of the International Border the trend changes to NW. In Quebec there is a hint that a minor sub-zone extends along the Ottawa graben.

Forsyth (1981) after a detailed study of the morphological, geological and geophysical (gravity and magnetic) characteristics of the Quebec portion of WQU-NNY zone, noted that while a few epicentres are located along the Ottawa Graben, the majority of them are located either within or near the eastern and western boundaries of the Central Metasedimentary Belt of the Grenville Province (Baer et al. 1972). He further noted that while the poorly mapped western boundary of the Central Metasedimentary Belt is in places associated with zones of cataclasis, its better known eastern boundary is, in fact, characterized by a

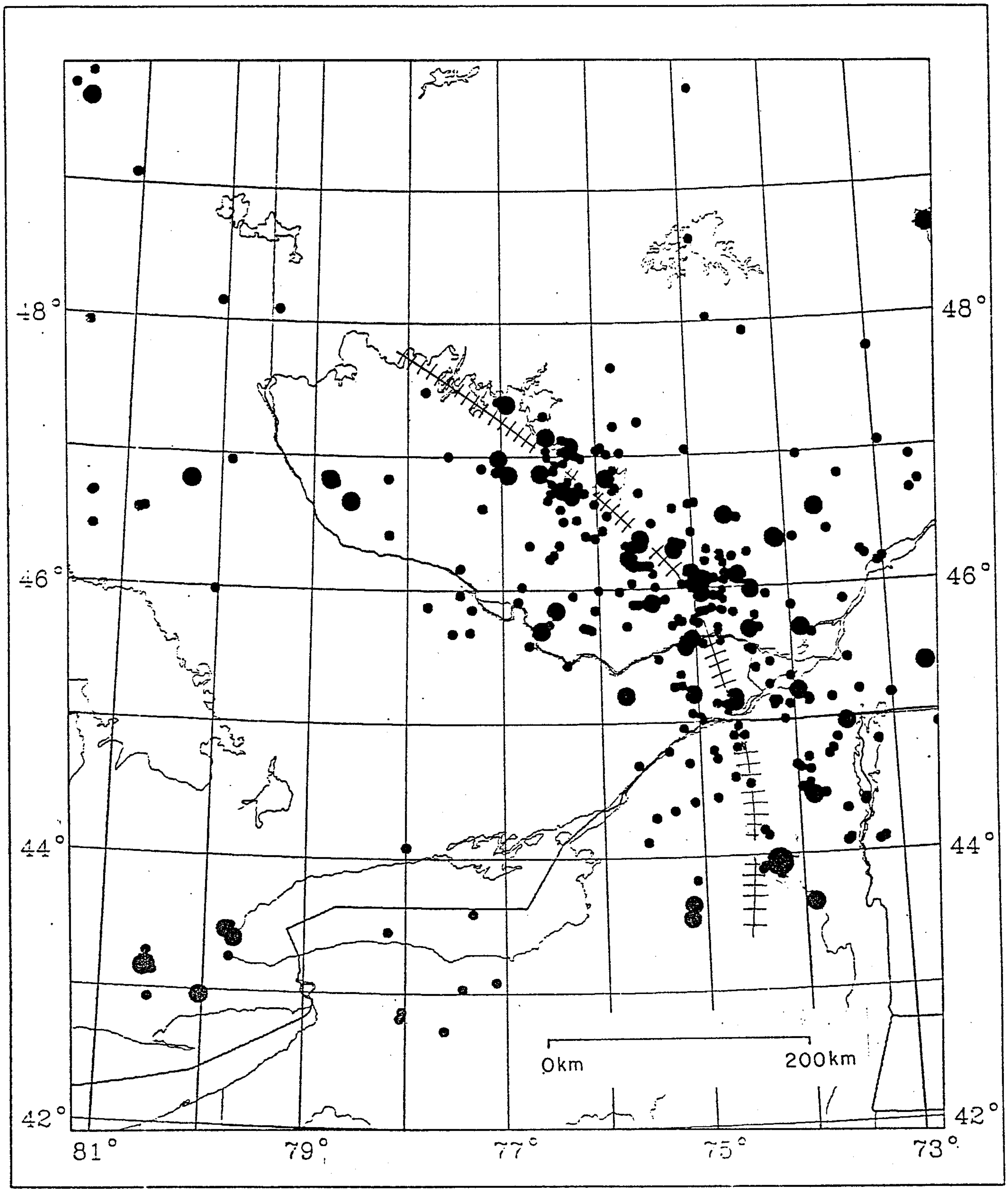

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Fig. 8. Distribution of epicentres in the West-Quebec - Northern New York seismic zone for the period 1977-1985. Large circles: M≥5; medium circles 3≤M<5; small circles: M<3. -+-+-+-: Probable trend of the seismic zone.

nearly continuous zone of mylonites. Considering that the uncertainities in epicentral locations are of the order of ±20 km for most earthquakes of the area, it is difficult to carry out a rigorous evaluation of the correlations suggested by Forsyth (1981). However, the main problem with his hypothesis appears to stem from the fact that while the overall trend of the seismic zone in Quebec is northwesterly, the general trend of the boundaries of the central metasedimentary belt, as well as the associated zones of cataclasis, is north-northeast; the seismic zone as a whole extends across the Central Metasedimentary Belt.

In the Adirondack region, the most probable seismicity-related structures are the numerous high-angle faults in the area (Isachsen and Fisher 1970). Although a few NNW to NW trending faults are known, by far the most dominant high angle fault system in the Adirondacks, has trends which are N-S along the eastern margin of the massif but away from this margin the trends change progressively into a ENE direction to produce a diverging fault pattern (Fig. 9). The history of early movements along these faults (see Wiesnet 1961) indicates that they are Iapetan faults. The nearly N-S trend of the faults along the eastern margin of the Adirondack massif is, in fact, parallel to the ancient continental margin. Westwards from this margin, the

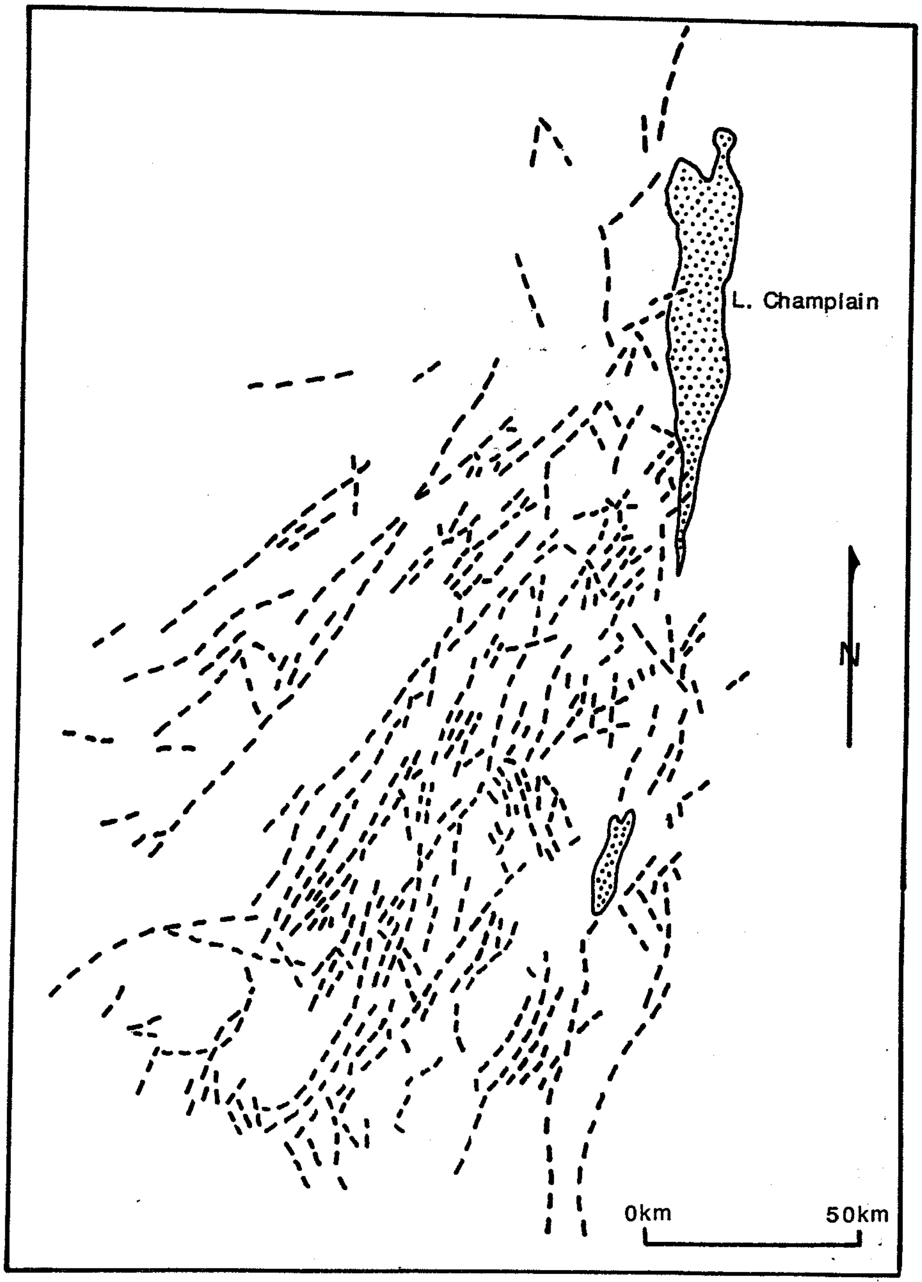

Fig. 9. Diverging fault pattern of the Adirondacks region. Data from Isachsen and Fisher, 1979.

tendency of faults to conform into a nearly NE-SW trend is probably an assertion of the NE-SW component of the RFP discussed earlier. Despite the prominence of these faults, the available focal-plane mechanism data suggest that seismic activity is related to reverse movements on the less prominent NW to NNW trending faults (Yang and Aggarwal, 1981). Although the epicentral distribution in the Adirondack region is spread over a wide area and forms a rather diffuse pattern, its gross trend appears to be approximately N-S. Therefore, it is possible that the N-S to ENE trending fault system also contributes to the overall epicentral pattern of the region.

As mentioned earlier, the dominant trend of the WQU-NNY Zone in Quebec is NW whereas the best known high-angle fault system in the general area - the Ottawa Graben - has trends varying from WSW (between Montreal and Ottawa) to WNW (west of Ottawa) to N30°W (in Lake Timiskaming area). Thus, even considering the large errors involved in locating epicentres in the area, the space relations between the seismicity pattern and the Ottawa graben are sufficiently divergent to suggest that the graben is not a tectonic guide for the main part of the seismicity, although some activity appears to be localized along the graben. As discussed earlier, a characteristic feature of the active area appears to be the well-developed regional fracture pattern (RFP) consisting of a strongly developed NW set and a less well developed NE set. Based on trend relations, the NW set appears to be the most likely candidate controlling the distribution of seismicity in the area. As argued earlier, the RFP appears to have been established as a feature of the crust in the area in the early stages of its evolution and exerted a dominating influence in controlling the directions of subsequent crustal failure. These resurgent lines of crustal weakness are probably the principal structures controlling the pattern of epicentral distribution in the Quebec segment of the seismic zone.

5. A search for post-glacial faulting in the CHV and WQU-NNY Zones

As mentioned earlier, a search for post-glacial faulting in selected parts of the CHV and the Quebec portion of the WQU-NNY Zones was carried out in summers of 1979 and 1980). Outcrops, road-cuts, gravel and rock quarries and river banks were searched for evidence of recent faulting such as off-sets in glacially striated bed-rock surfaces, faults in stratified glacial, glaciofluvial and post-glacial deposits, terraces related to recent uplift and faulting, etc.

5.1 WQU-NNY seismic zone

The search was concentrated along several selected road traverses. Well polished and well striated glaciated bed rock surfaces were plentiful in these areas but no definitive evidence of post-glacial faulting was found. Several offsets in glacially striated and polished bed rock surfaces, found near road cuts, were carefully studied but they were most likely caused by blasting and removal of support during road construction.

5.2 CHV Zone

In the CHV zone, the relatively narrow strip of the north shore of the St. Lawrence river was thoroughly searched for post-glacial faulting. Particular attention was paid to mapped faults, air photo and Landsat lineaments.

Numerous examples of faults with diverse orientations were observed both in the Precambrian and Paleozoic rocks in the area (Figs. 10, 11, 12, 13, 14). This is not surprising in view of the fact that in addition to Iapetan faulting, the area also experienced the effects of an impacting event (Fig. 15) that took place in Devonian times (Rondot 1979). In none of these cases, however, could the age of the latest movements be established as recent.

An example of small-scale (centimetre to decimetre) displacements along normal faults, in post-glacial deposits of the valley of the Gouffre

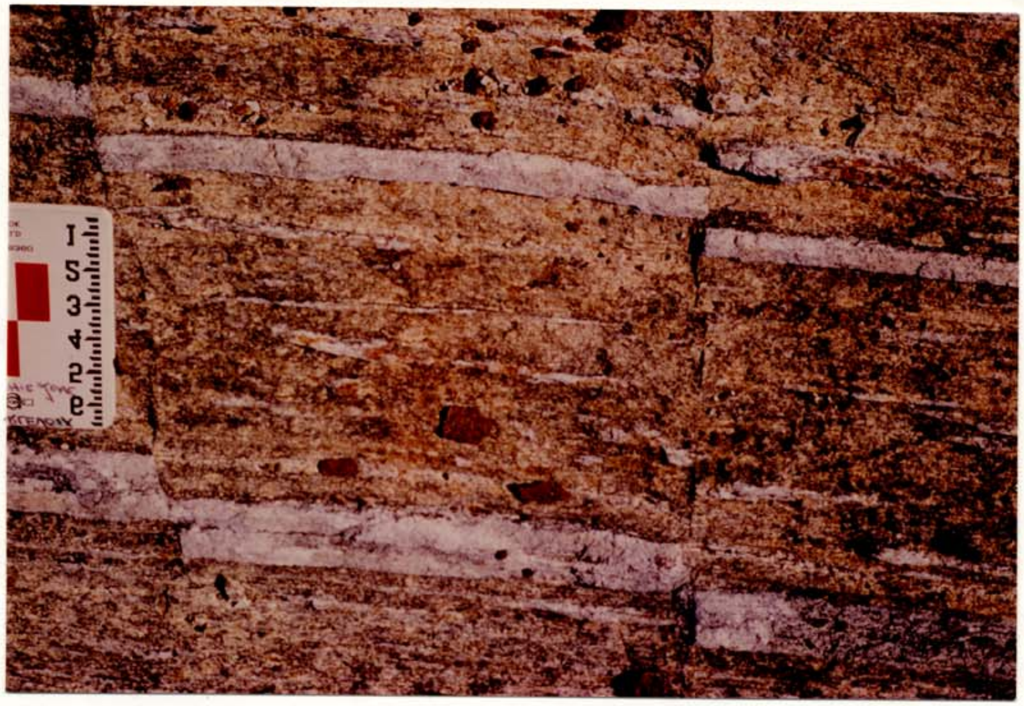

Fig. 10. Numerous left lateral faults, strike 325°, cutting charnockite gneiss with thin interbands of alaskite, strike 225°. This outcrop, approximately 100 m long, at the top of Mont des Eboulement, CHV, has about a hundred of these small faults.

Fig. 11. Migmatitic gneiss, south of Baie St. Paul, CHV, cut by numerous small faults striking 280° to 290°. Some of the faults are filled with calcite-fluorite veins.

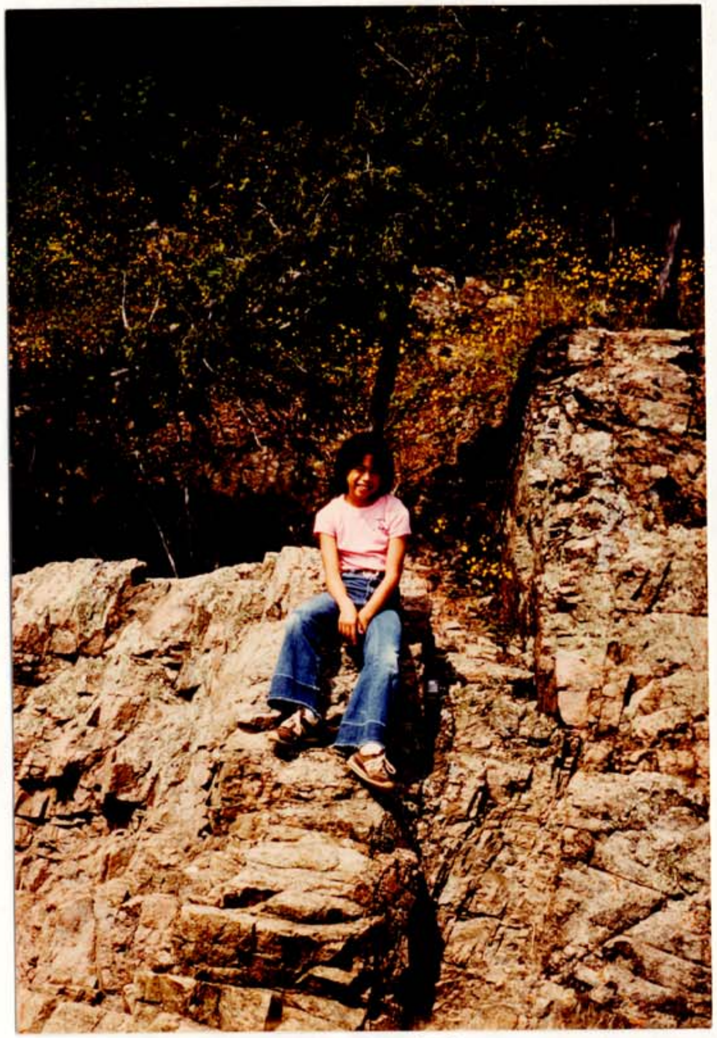

Fig. 12. Fault, strike 45°, in Cap aux Oies granite (CHV) with vertical slickensides.

Fig. 13. Paleozoic rocks northeast of Cap à l'Aigle (CHV) cut by steep SW dipping fault, striking 290°.

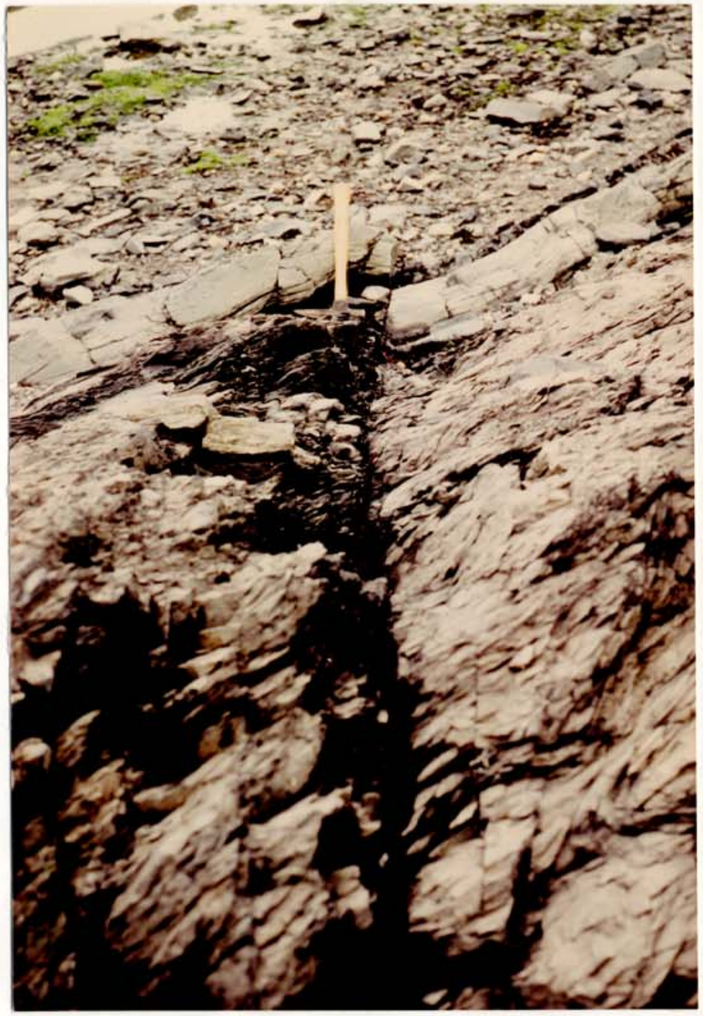

Fig. 14. Paleozoic rocks, just northeast of Cap à l'Aigle, cut by steep SW dipping fault, strike 290°.

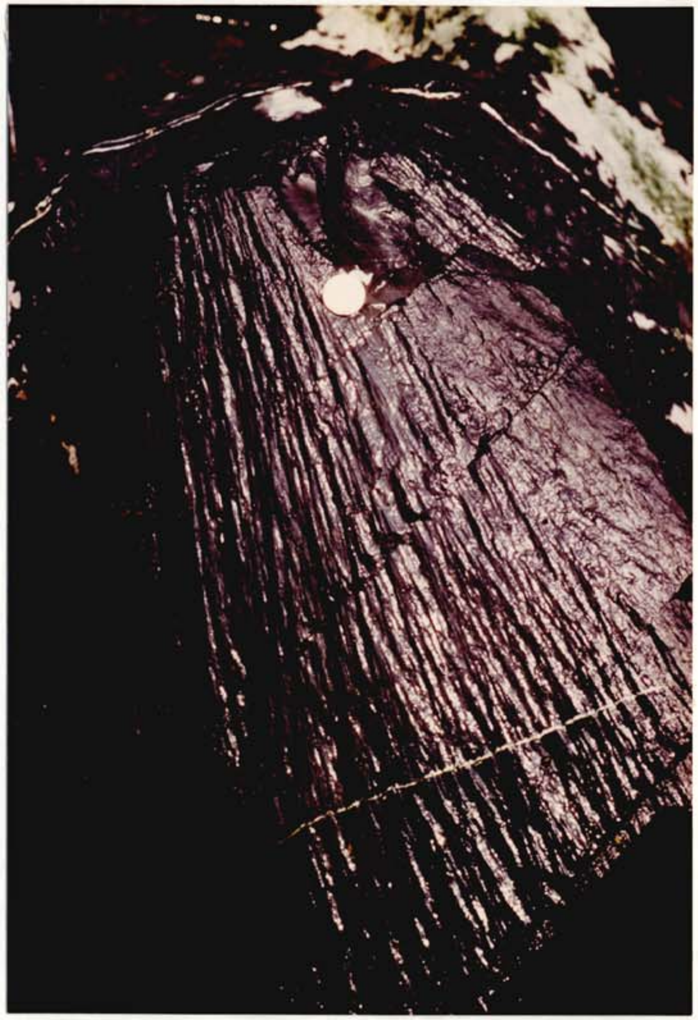

Fig. 15. Shatter cone in Trenton Limestone, CHV Zone.

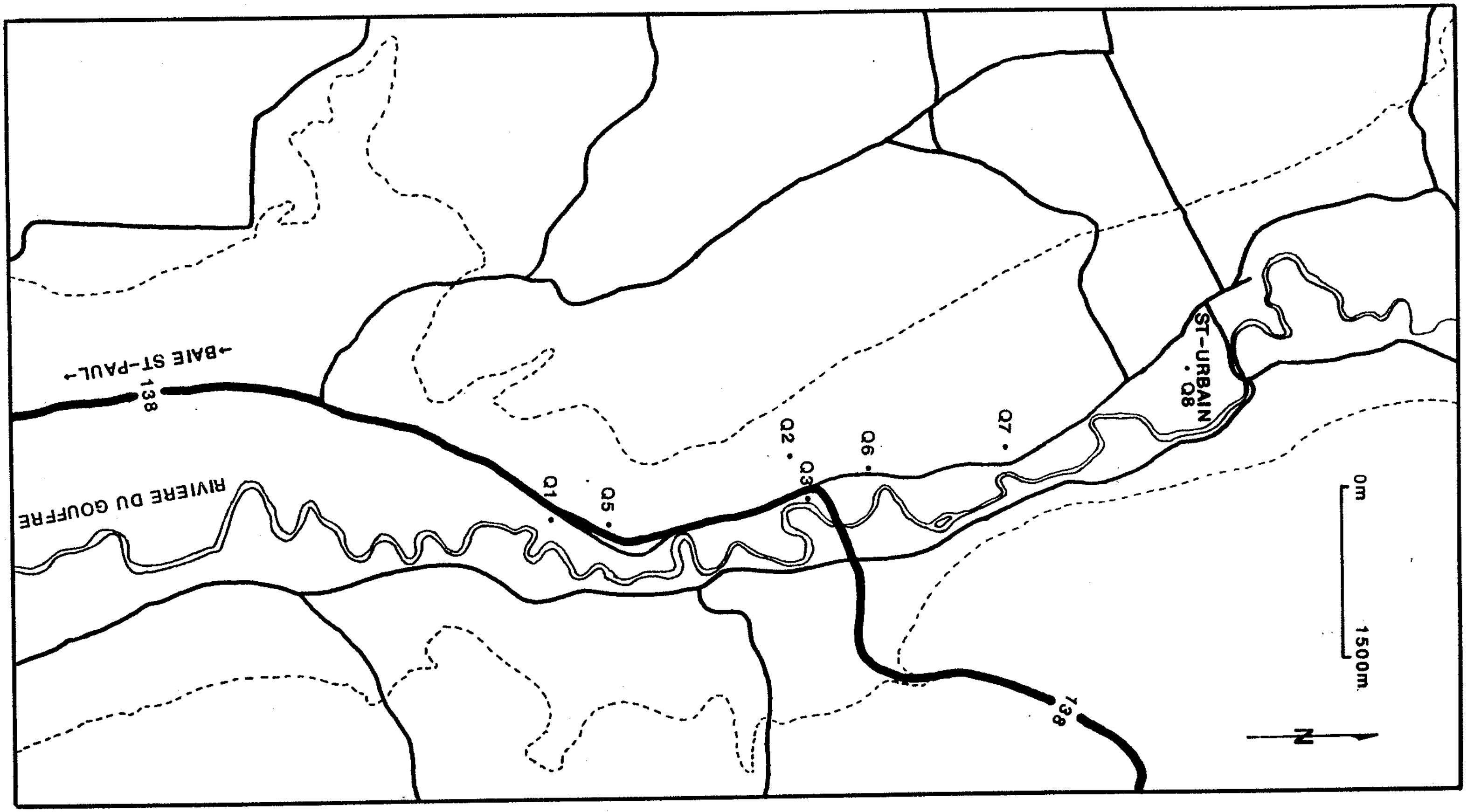

Fig. 16. Map showing the location of gravel quarries (Q1 etc.) in the Valley of Rivière du Gouffre; with post-glacial faults described in the text. The dash line (from Chagnon, 1969) shows the limit of Champlain Sea deposits.

river, was first brought to my attention by Joe Wallach of Atomic Energy of Canada Board. Study of sand and gravel quarries and river bank sections in the CHV zone brought to light seven other localities, similar to the one known to Joe Wallach. Six of the localities are in the valley of Riviere Gouffre (Fig. 16) and the other in the Valley of Riviere La Malbaie. The displacements affect Champlain sea deposits consisting dominantly of well-stratified fine to coarse sand, forming low, rounded knobs which may represent remnants of the deposits that offered greater resistance to erosion because of their internal structure (Chagnon 1969). In all of these localities, normal faults commonly with centimetre to decimetre displacements produce minature grabens, horsts and step faults (Figs. 17, 18, 19, 20). The cumulative displacement observed in any one locality is usually less than 0.5 m except in one section (Q. 7, Fig. 16), 11 m long, containing a prominent gravel bed, the cumulative displacement is slightly over 2 m (Fig. 21).

In three of the localities the faults in the Champlain sea deposits are approximately parallel to NNE trending basement faults while in three others they are nearly parallel to NNW trending basement faults, strike directions in the other locality could not be determined with any certainty. Despite these apparent

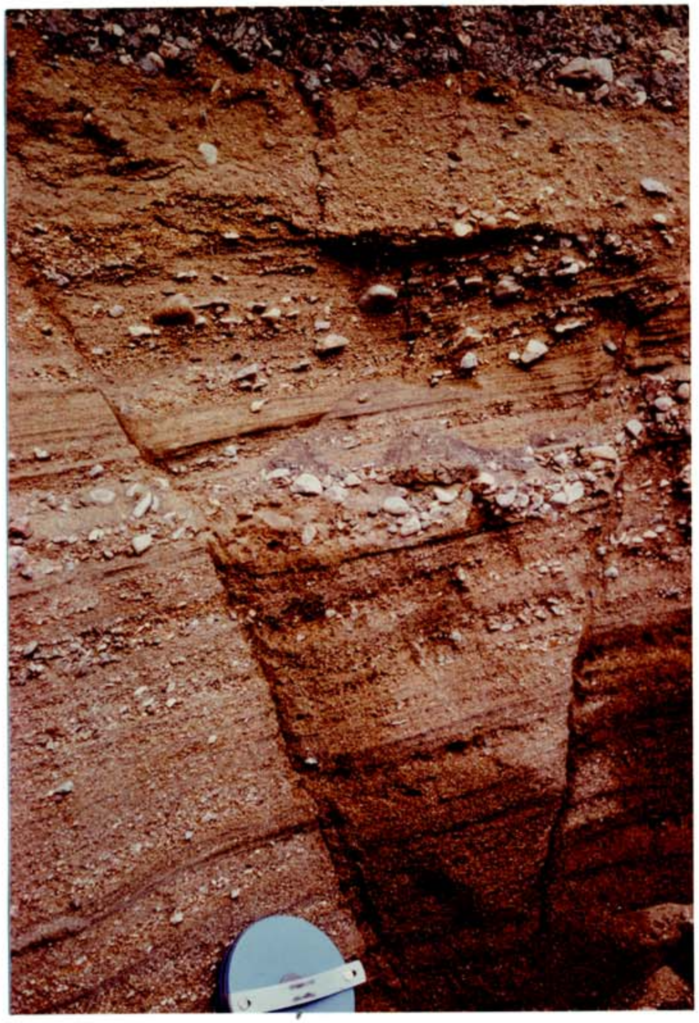

Fig. 17. Miniature graben in Champlain Sea, sand/gravel deposits at Q3.

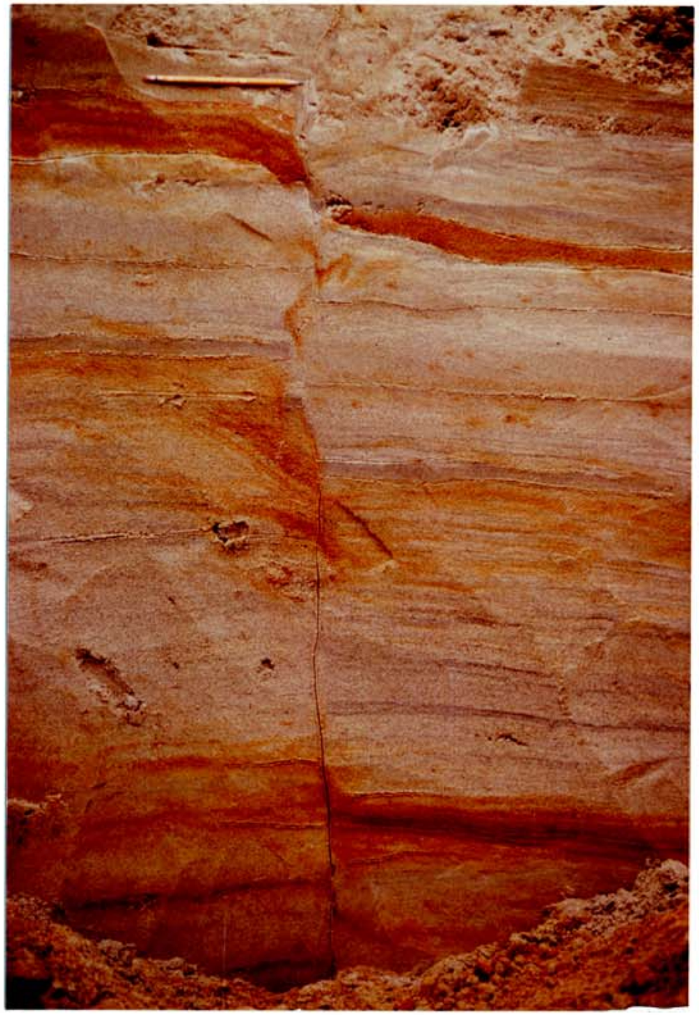

Fig. 18. Miniature normal fault, striking 210°, in Champlain Sea sand/silt deposits at Q1. Displacement decreases from about 14 cm in the lower part of the section to about 6 cm in the upper part of the section.

Fig. 19. Miniature step faults in Champlain Sea sand deposits at Q5. Faults strike at 330°.

Fig. 20. Normal faults in Champlain Sea sand/gravel section at Q7. Strike of faults 320°-335°. For more details see Fig. 21.

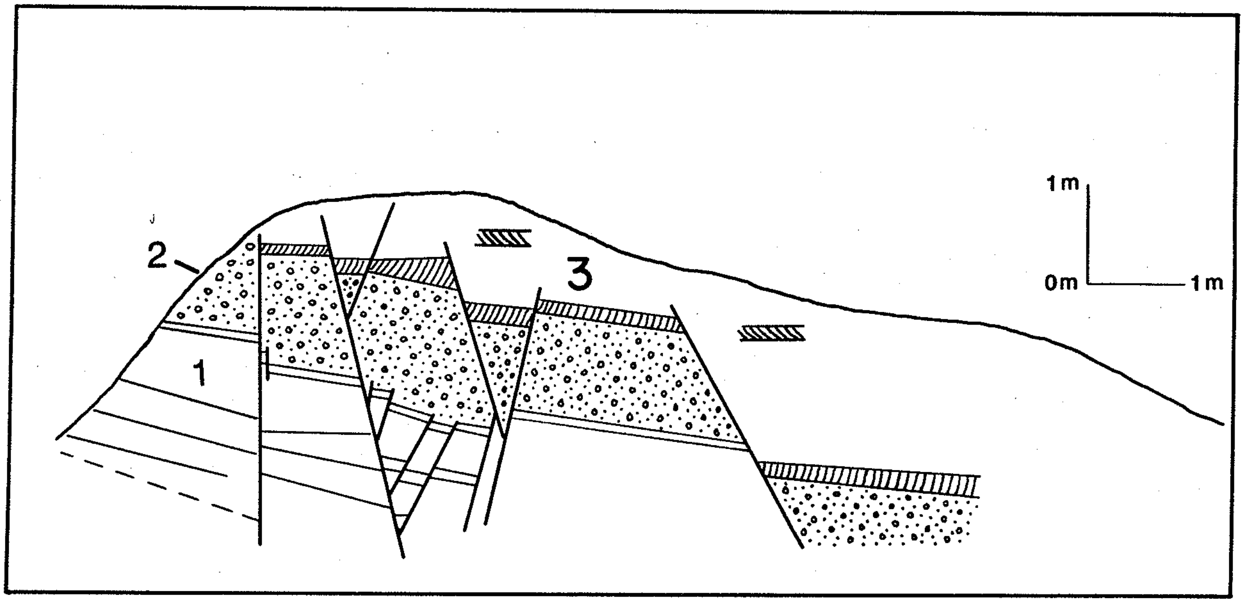

Fig. 21. Sketch of quarry section shown in Fig. 20. Legend: (1) well-bedded sand (2) bed consisting of well rounded pebbles in a sandy matrix (3) cross-bedded sand/silt. Drawn facing 330°.

correlations, the proximity and attitude of these faults to embankments, coupled with the fact that they invariably show normal movements, suggest that the majority of them are due to slumping or due to subsidence resulting from lack of support caused by dewatering/compaction in one or more interbeds. The present day slopes at locality Q.7 (Fig. 16), however, do not lend support to the view that slumping was a mechanism of faulting. Also, in view of the fact that relatively large (≥2 m) vertical displacement was observed at this locality, it is undoubtedly the most interesting find in the context of recent faulting in the area. However, even at this locality an excavation down to bed rock is a necessary test. A hammer seismic survey, conducted at this locality, to determine the depth to bed rock, did not give interpretable results.

6. Discussions and speculations: seismotectonics

A major unresolved problem in seismotectonic studies is the lack of understanding of processes responsible for generating the stresses that cause intraplate seismicity. For Eastern Canada this problem has been discussed by Hasegawa and Adams (1981) and Hasegawa et al. (1985). The main points arising from these studies are: (i) Eastern Canadian earthquakes occur largely in the upper crust (≤20 km) indicating that deformation in the lower crust is dominated by creep mechanisms, (ii) the deviatoric stress in the upper crust is horizontal and compressional, (iii) there are several possible sources of potential stress contributors such as stresses generated as a result of plate tectonic processes including membrane stresses and the elastic-viscolastic relaxation of these stresses and those related to glaciation and deglaciation including post-glacial heating. However, the relative contributions from these various sources are not properly understood although the most important contribution is probably related to spreading at the Mid Atlantic ridge, (iv) the deviatoric stress is oriented within or close to the ENE octant and appears to be a relatively uniform ambient stress field superimposed over localized stresses produced by crustal inhomogeneities, topography etc. The orientation and other characteristics of the deviatoric stress in Eastern Canada appears to be similar to those of the stress field in mid-continent United States as discussed by Zoback and Zoback (1980).

Available focal plane solutions (none known for the LSL zone) indicate that slip occurs in the CHV and WQU-NNY zones by reverse faulting, in response to a horizontal, compressional stress field (Horner et al. 1978, Sbar and Sykes 1977, Yang and Aggarwal 1981, Hasegawa and Wetmiller 1980, Lamontagne 1984). High horizontal compressive deviatoric stresses are also indicated by in situ stress measurements in the general region (Hasegawa and Adams

1985). Moreover, if the ambient regional stress field is oriented ENE (Hasegawa and Adams 1985), the probable active structures in the WQU-NNY zone (described earlier), because of their orientation nearly at right angles to the stress direction should, in fact, respond by reverse slip. As mentioned earlier, slip in the Adirondack region, as deduced from focal plane mechanism studies, seems to occur selectively on the weakly developed NNW to NW trending faults (Sbar and Sykes 1972, Yang and Aggarwal 1981) and not on the strongly developed NS to ENE trending faults. If the slip were to occur on the latter faults, it would be dominantly strike-slip (right lateral). A hypothesis advanced to explain the selective stress release in the Adirondacks is that the least compressive stress in this region is "locked" into vertical position (Sbar and Sykes, 1977). Such an explanation is not applicable to the CHV zone, and possibly also to the LSL zone, where slip appears to be taking place on approximately NE trending faults and therefore slip should be dominantly strike-slip and not reverse as indicated by focal-plane solutions. Further studies are needed to resolve this problem. Another problem that requires study is the clustering of epicentres in widely separated segments of the Iapetan fault system. A possible explanation is that stresses are concentrated in these segments because of the complexity of structure of the fault system brought about by changes in orientation of faults and/or by interaction with cross-structures, the implication being that the intervening aseismic segments are characterized by aseismic slip or small scale differential block tilting.

7. Conclusions

1. The Iapetan faults parallel to the ancient continental margin of Laurentia are probably the most important structures in the context of seismotectonics of Eastern Canada. They are most lkely the structures controlling the activity in the CHV zone and probably also in the LSL zone.
2. The clustering of earthquakes in widely separated segments of the Iapetan faults may be due to stress concentrations in these segments resulting from changes in orientation of the faults and/or from complications brought about by cross structures, the implication being that the intervening segments of the fault system reacts by aseismic slip.
3. The epicentres related to seismic activity in Western Quebec and in the Adirondack region of northern New York state, define a wide, rather diffuse seismic zone: Western Quebec - Northern New York seismic zone (WQU-NNY) - with an arcuate trend; in the Adirondack region, the trend is nearly N-S but north of the International border the trend changes gradually to an approximately NW direction.

4. The approximately NW oriented component of a regional fracture pattern, characteristic of the Grenville terrain in the Adirondack region and western Quebec, is probably the main crustal structure controlling the activity in the WQU-NNY zone.
5. If the earthquakes of Eastern Canada are produced by an approximately ENE directed, horizontal compressive stress, the faulting in the CHV and LSL zones must dominantly be strike-slip (right lateral) and not dominantly reverse as indicated by focal plane solutions.
6. The search for post-glacial faults in parts of the Quebec segment of WQU-NNY zone and in the CHV zone produced scanty results which are difficult to interpret in the context of contemporary stresses and recent seismicity.

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