



GEOLOGICAL SURVEY OF CANADA

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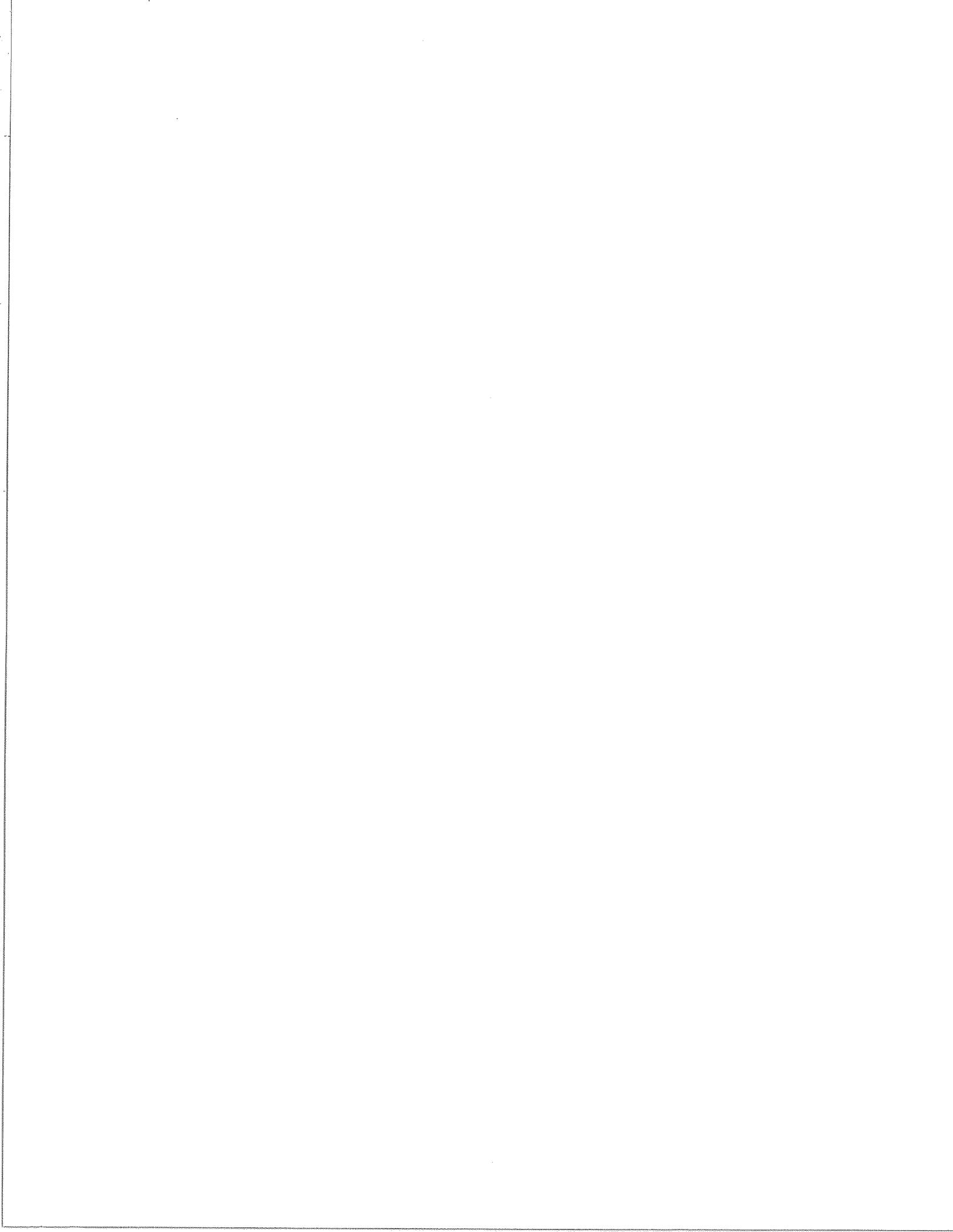
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**Proceedings,
Geological Survey of Canada workshop
on eastern seismicity source zones
for the 1995 seismic hazard maps
Ottawa, 18-19 March 1991**

Part 2

**Compiled by:
John Adams**

1992



APPENDIX 4

Written Comments received before the meeting

These comments are ordered alphabetically by contributor and are as follows:

John Bowlby on the Attica seismicity and faults in southern Ontario.

Ken Burke on seismicity in the northern Appalachians.

Reynald Du Berger on the difficulties of assigning the Saguenay earthquake to a source zone.

V. G. Milne and Phil Thurston on faults in southern Ontario.

Alan Ruffman on the higher level of seismicity of southwestern Nova Scotia, as found from historical earthquake research.

Rus Wheeler on the Iapetan margin faults and source zones.

40 Davean Drive
North York, Ontario
M2L 2R7

January 30, 1991

Dr. J. E. Adams
Geophysics Division
Geological Survey of Canada
1 Observatory Crescent
Ottawa, Ontario
K1A 0Y3

Dear John:

Thank you for your kind invitation to express personal opinions and thoughts on the delineation of seismic zones for seismic hazard maps intended for use in the 1995 issue of the National Building Code of Canada. The following is my initial response to your request for information by the end of January and for possible further consideration and discussion at the eastern workshop. I have prepared a brief outline of the type of practical approach that I think could be considered with references to the Attica Zone as an example.

I am concerned that your invitation appears to indicate that the Geological Survey of Canada, EMR is pre-supposing a restriction to and retention of a dominantly probabilistic approach for the definition of seismic source zones and that the zones are to be constrained to enclose those regions of presumed constant level of seismicity similar to the examples as given in the map enclosed. I am left with the impression that you are soliciting only those opinions which express a confirmation of the existing model. However, an increasing number of practical problems require that geology be a predictive science, through the collective understanding of active processes to project the frequency, magnitude and location of future events in the light of geological principles. Is there possibility for integrating a synthesis of pertinent geoscientific conditions and, hence, an upgrading the techniques for source zone definition and hazard analysis in Canada? It is my opinion that either this approach or some close modification could help maintain the Geological Survey of Canada in a leadership role in providing scientific and technical advice on seismic hazard matters.

A second concern is that the selected reference list appended to the invitation appears to be less than the fullest expression of professional opinion on the subject within Canada. For example, many documented discussions have occurred under the aegis of the

Multi-Agency Group for Neotectonics in Eastern Canada (MAGNEC). This group, with a mandate document and mission statement for integrated studies to improve seismic hazard assessments (MAGNEC, 1986), and the minutes of meetings and annual reports issued by this group could be of value. In addition, there have been two Special Sessions at Annual Meetings of the Geological Association of Canada (1988 and 1989) that have dealt with related issues. A third session is planned for the 1991 meeting in Toronto.

There is no denying that the dual issue of identification of potential seismic sources and quantification of seismic hazard is both technically and politically complex, especially in areas of low to moderate earthquake activity. However, the ethical demands for high integrity geological hazard mapping differ from the needs of a structural designer. The deterministic nature of hazard identification can improve the inputs for probabilistic evaluations. Utilizing diverse inputs from the many disciplines within the geoscientific community may provide strong technical support to the Geophysics Division for some of the more political aspects of the exercise.

Most certainly, there have been seismological surprises since the definition of the presently used seismic source zones. Miramichi (1982), Saguenay (1988) and Ungava (1989) may be considered to be indicator seismic events generally within the Eastern Background Zone (EBG). These events apparently do not fit well within the structured polygons placed solely around areas which were known to contain a number of seismic events, albeit based on an imperfect historical and/or instrumental record. Rather than being inclusive of the fundamental geological cause of earthquakes (i.e., rapid stress relief, however induced, by motion on a fault plane), such polygons exclude the fundamental knowledge of the geological framework of this country. Consideration of the regional fault systems is noticeably absent from the definition of seismic source zones leading to the previous seismic hazard map of the National Building Code.

There are strong evidences in geological, geophysical and remote sensing datasets, some of which have even been reported or created by staff of other Divisions within the Geological Survey of Canada and Energy, Mines and Resources, that no longer can be denied and that clearly contradict some of the simplifying assumptions previously made. Likewise, these evidences often contradict the present boundaries as drawn to constrain the seismic source zones.

It is my opinion that the seismic source zone and hazard inputs to the 1995 edition of the National Building Code of Canada may be improved, in conjunction with the use of seismicity data, by integrating the most detailed geological and geophysical framework and structural tectonic compilation that can be assembled at an appropriate regional scale for seismic hazard identification. A compilation scale of 1:1,000,000 is recommended. The compilation

of major zones of crustal weakness would include delineation and synthesis of Precambrian basement, Paleozoic, Mesozoic and Cenozoic tectonic conditions, with specific emphasis on the recognition of recent movements of crustal materials as may be observed in the record of surficial deformations of glacial and post-glacial sediments.

ATTICA Zone Example

A specific example of contradiction between available information and data with existing polygon boundaries may be illustrated with reference to the relatively small Attica Zone (ATT), perched on the south shore of Lake Ontario in western New York State. The restricted zone presented in the Figure 5 appended to the invitation is not commensurate to a somewhat different American zone, although presumably defined by seismologists in the United States on the basis of equivalent seismological data.

The presence of the Clarendon-Linden Fault was documented in western New York from oil and gas well exploration activities (Chadwick, 1920). It was noted by Chadwick that the Niagara Escarpment jogged northward about 3 miles, a right-lateral topographic offset, at the surface intersection with this fault trace and that a similar effect was also evident at the Onandaga Escarpment. These offsets were in line with each other, with a discordance of the stratigraphy at Linden and the valley of Dale. He also stated that "this displacement is an unexpected phenomenon in the flat strata of western New York, is clearly of tectonic origin and that its isolation makes it unique in New York geology".

More recently, the presence of the Clarendon-Linden Fault within and passing through the constrained area has been well-documented and mapped by Van Tyne (1975) through the use of conventional stratigraphic analysis of the Paleozoic units. Surficial rock stress relief indicators (pop-ups) were found in the immediate vicinity of the fault zone and documented (Fakundiny et al, 1978). The faultings were confirmed to penetrate into the Precambrian by Vibroseis reflection seismic techniques (Pomeroy et al, 1979).

The Clarendon-Linden Fault system has most recently been confirmed to have surface expressions in an area located along-strike to the south of Van Tyne's sub-surface determinations (Jacobi, 1990). Field investigations of remotely-sensed and visible surface lineaments in Allegheny County, New York have shown that deepseated natural gas is migrating up fractures in rock and soil and venting to atmosphere. Jacobi has reported (MAGNEC, October 23, 1990) that increased gas flow began after an episode of local strong ground shaking in the same area and which has been correlated to passage of seismic waves from the 1988 Saguenay event.

The north-northeasterly topographic expression of the extension of

this fault system into Lake Ontario is evident on bathymetric maps which illustrate a north-northeast trending ridge in the central lake area (Canadian Hydrographic Service, 1970). A bedrock scarp segment along the north-northeast trend was located in 1974, by research geologists on a scientific cruise conducted by the Geological Survey of Canada (Anderson and Lewis, 1975), and may now be interpreted to be the cause of disruption of the pattern of glacial and recent bottom sediments on the Scotch Bonnet Sill as mapped in Lake Ontario (Thomas, Kemp and Lewis, 1972; Bowlby and Lewis, 1976).

Elongate total field aeromagnetic and Bouguer gravity anomalies are visible on maps produced from surveys by the Geological Survey of Canada and by the United States Geological Survey (i.e., Energy, Mines and Resources, 1987). These anomalies, although predominantly sourced in the Precambrian rocks, are spatially associated with the known Paleozoic rock fault system within the constrained ATT zone. Other patterns of geophysical and remote sensing lineaments also exist in the area. The defined geophysical anomalies and the known extents of the fault system do not stop at the zone boundaries, but extend beyond 100 km from the zone and in more than one direction.

Culotta, Pratt and Oliver (1990) have drawn attention to the imaging of a large, and yet simple, framework system of mid-continent sutures. The Grenville Province geopotential lineaments in this area of New York were correlated with the seismogenic Clarendon-Linden fault system. The zone of moderate seismic activity in the vicinity of Attica was attributed to reactivation of a major fault in the Grenville basement (Hutchinson et al, 1979). Hutchinson also concluded that the Clarendon-Linden Fault system passed across Lake Ontario along the Scotch Bonnet Sill. Lithologic boundaries within the Central Metasedimentary Belt in the vicinity have been correlated by using the magnetic anomalies (Forsyth et al, 1988).

Most recently, sub-surface drilling undertaken in 1990 by the Ontario Geological Survey in an area to the northeast of Belleville, Ontario has confirmed faulting at depth in the Paleozoic cover, consistent with surface observations (McFall, personal communication). This geological information is spatially related to the geophysical anomalies tested by Hutchinson et al (1979) which cross Lake Ontario and link with those of the Clarendon-Linden fault system. Geological interpretation of aeromagnetic lineaments has led to the projection of significant structural features into the Lake Ontario basin area (Thurston et al, 1990).

It is most probable that causative geological circumstances which pass through the defined Attica Zone have much greater extents, including across Lake Ontario and penetration into Canada. Therefore, seismic hazard potentials associated with the Attica

Zone can no longer be confined to the zone but can be reassessed and quantified within the region, with due regard for identifiable major zones of crustal weakness now evident in the area including southern Ontario.

Additionally, sonar imaging of lake bottom sediments in selected areas within Lake Ontario show a number of surficial structures within what is believed to be a large-scale regional structural system. Vertical dislocations of up to 40 m of the post-glacial lake sediments were recorded with sub-bottom seismic equipment along one such series of structures in the Rochester Basin of southeastern Lake Ontario (Thomas et al, in prep.). These features were located in the vicinity of a postulated extension of a Paleozoic rift valley into the lower Great Lakes (Adams and Basham, 1989; Kumarapeli and Sauli, 1966). The confirmation of surface structures found along the postulated rift, and the extension of the southern rift margin through the Attica area, may be significant in the setting of seismic sources for the region.

I hope that the above example which integrates readily available geological, geophysical and remote sensing information and data illustrates the necessity of including geoscientific input to reduce the amount of uncertainty in the setting of seismic source zones, particularly for those zones that have proximity to major urban areas. To utilize less than all the geological factors for quantification of faulting potential may place the results of any related assessment of seismic hazard for populated regions in question.

In conclusion, it may no longer be prudent for the responsible scientific organization to maintain decision-making based on an apparent lack of sufficient knowledge, pertinent information or proven condition which thereby elicits the continuation of constant level seismic source zones. Bedrock faults which exhibit clear evidence of passing upward from depth in the Precambrian crust, through Paleozoic cover and into overlying glacial and post-glacial materials exist, representing locations of continuing motions and hence, seismic potential. Figure 1 attached gives a thematic overview of my thoughts on the merging of the deterministic information into the probabilistic assessment. The result is the development of a seismic source zone that is constrained to the structural geology. Justification of this model was developed in an AECL presentation (Bowlby, 1982). A copy could be made available to you if requested.

Major structures should be considered, if not wholly incorporated, into a comprehensive seismotectonic model. A compilation scale of 1:1,000,000 is recommended as an appropriate regional scale for seismic hazard identification. The synthesis of differing datasets could benefit significantly from recent advances in GIS technologies. Spatially located data can be efficiently linked to produce new derivative products that interrelate the pertinent

parameters for assessment. Factual circumstances must be given credence over assumption and ease of manipulation of seismological parameters in objective decision making. Justifications for any deletions of pertinent geological information may ultimately have to be documented.

I would be pleased to participate in and to contribute to the fullest extent possible in further deliberations if the committee charged with structuring the workshops for setting new seismic source zones for Canada wishes to have further inputs on these matters.

I look forward to receiving your response at your earliest convenience.

Yours sincerely,



John R. Bowlby, M.Sc., FGAC

Attach: Reference List
Figure 1

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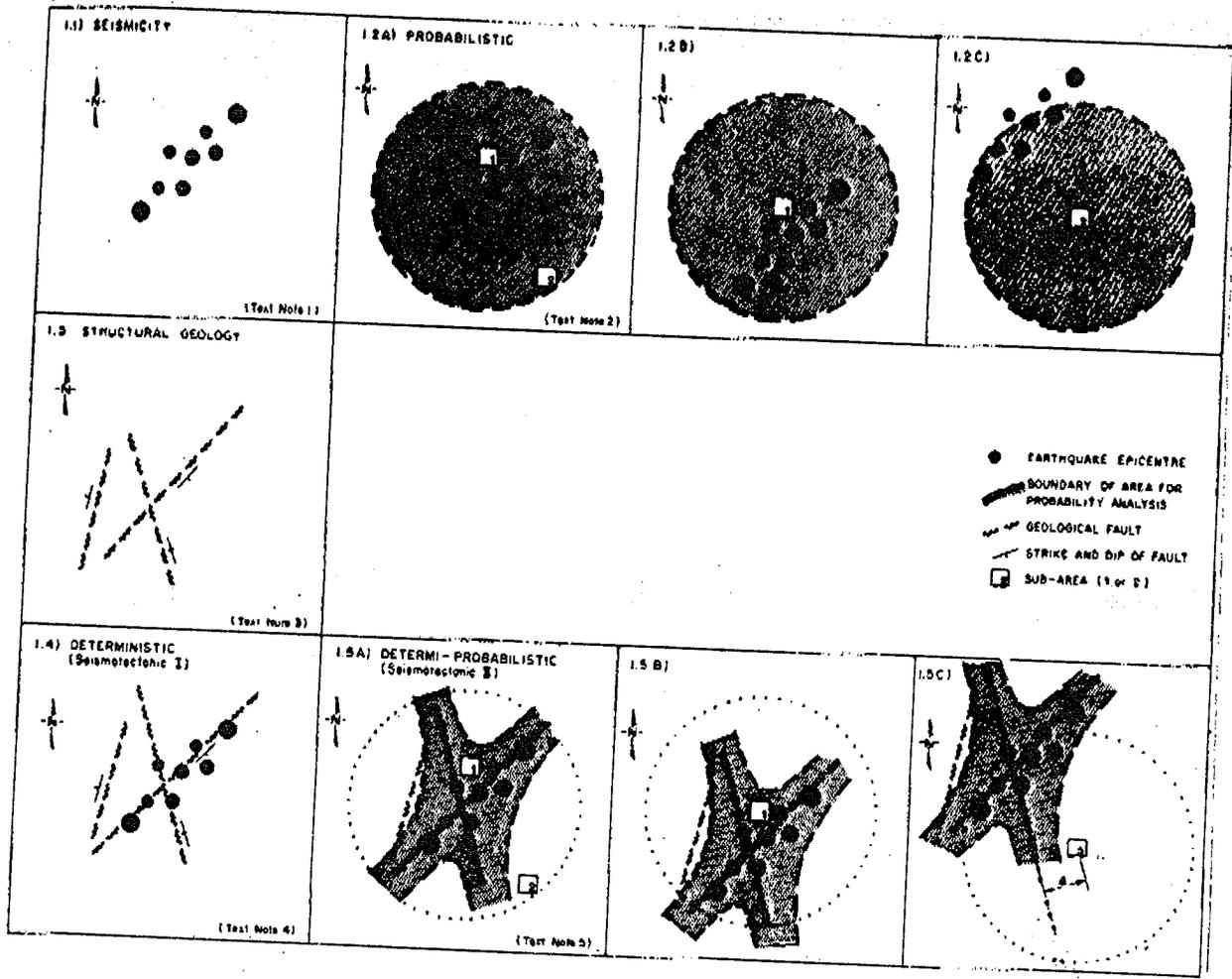


Fig. 1 PROBABILISTIC AND DETERMINISTIC ASSESSMENTS OF SEISMICITY - A CONCEPTUAL APPROACH



Department of Geology
(506) 453-4803

Telex: 014-46-202
Fax: (506) 453-5055

Anne → JA ^{ref}
28-01-91

John Adams,
Seismological Service,
Geophysics Division,
Geological Survey of Canada,
1 Observatory Crescent,
OTTAWA,
Ont. K1A 0Y3

January 16th, 1991.

Dear John,

Since I spoke to you on the telephone, I have received your memo requesting input on the earthquakes source zones for the 1995 Seismic Zoning Map for Canada. In regard to New Brunswick, I believe that we have to report that there is little new evidence that our few neotectonic features are correlated with seismogenic zones, with the possible exception of the Passamaquoddy Bay region, and we must continue to rely on the historical record and recent instrumental recorded information in the definition of source zones. The focal depth of the Miramichi earthquake and its aftershock sequence supports the concept of upper crustal earthquakes, 'rooted' in the elastic zone and adds credence to the choice of a maximum magnitude of 6, chosen for the Northern Appalachian Zone in 1985. The re-evaluation of the magnitudes of the larger historical earthquakes in the province also supports this upper limit. The southern boundary of the Northern Appalachian Zone is probably best left bracketing the few earthquakes in the Bay of Fundy because of the presence of many thrust faults in the recently released oil company seismic sections shot in this area. It also coincides

roughly with the Avalon - Meguma terrane boundary, if a tectonic justification is sought. I hope my few brief comments will be useful and look forward to hearing the results of your deliberations in due course.

Best wishes for the New Year.

Sincerely,

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Université du Québec à Chicoutimi

555, boulevard de l'Université
Chicoutimi, Québec
G7H 2B1

Chicoutimi, February 11th 1991

Dr. John Adams
Geophysics Division,
Geological Survey of Canada
1, Observatory Crescent,
OTTAWA, Ontario. K1A 0Y3

Dear John,

Maurice just reminded me of the workshop on the new NBCC which will be held in Ottawa in March. Unfortunately, I have a very heavy teaching load this semester, so I will not be able to attend unless the workshop is on a Friday. I talked to Denis W. Roy about the chances of his attending and I will keep you informed. I understood from Maurice that you would appreciate having somebody from our group at the workshop.

Personally, I do not think I can contribute much to your very important task of redefining the source zones. At best I can give you my opinion based mainly on the occurrence of the Saguenay earthquake.

The Saguenay earthquake must remain as a reminder of the possible occurrence of strong events outside previously known source zones. This event poses a problem in the context of seismic zoning and this problem could be addressed in many ways:

- We can define a new seismic source zone. What is the geometry and extent of that zone? (elongated box around the known faults bordering the Saguenay graben? - polygonal area just large enough to enclose the main event with its few aftershocks?) What will be the recurrence rate and the maximum magnitude for that zone? We have not yet succeeded to relate unambiguously the Saguenay earthquake to the Saguenay graben. If we consider the Saguenay graben as a potential structure which fits the seismotectonic rift model for Eastern Canadian seismicity, then what about the St-Maurice lineament which could also become a new rift as soon as an event strong enough to attract attention occurs in that area?
- We might create a new category of zones - a kind of temporary box which would be considered a source zone but for only a limited time which would still remain to be defined.

- We could extend the Charlevoix-Kamouraska zone the Saguenay (Lac-St-Jean?) area. Then our event would bear some more resemblance to the Timiskaming 1935 earthquake which is not only in the same range of magnitude, but is also on the rim of a zone, the Western Quebec zone which otherwise would not be so wide in the western part of the zone. It would also be in agreement with the hypothesis that the stronger events in a zone tend to occur near the borders of the zone. One is also struck by the discrepancies in areal extent of the individual seismic source zones for eastern Canada. Is the seismicity gap between Charlevoix and the Saguenay real?

- We leave the Saguenay earthquake in the "background source-zone" which is in fact a very convenient source-zone to get rid of those annoying rare events (which can sometimes be quite strong), but do not fit in the other boxes. But how rare are these events? One must admit that the window of a few hundred years (biased by the distribution of the populations in space and time) that we use to evaluate the recurrence rate of strong events is very small compared to the geological time scale. Have all the archives been searched properly? Last summer we investigated some of the local archives and our analysis suggest that the events of 1672 and 1673 attributed to the Tadoussac area by the catalogues of historical seismicity probably did not occur in Tadoussac or even Charlevoix but could rather have occurred either on the North shore of the St.Lawrence or in the Saguenay Lac-St-Jean area. The historical seismicity investigated by people like Anne or Father Gouin should continue to be supported because it constitutes an important input to the data defining the zones. The maximum magnitude for the EBZ is presently 5.0. What are the consequences of raising it to 6.0 or even 6.5? Do we have to reexamine our large dams and nuclear power stations? One could argue that the Saguenay event is an extremely low probability event and should remain so until we have more seismotectonic information about its causes and peculiar location and in the meantime should not even be included in the EBZ or any other zone for zoning purposes.

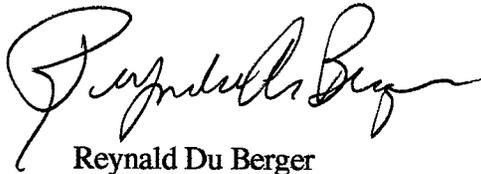
On a broader scale, I think the Cornell-McGuire probabilistic approach is essentially a sound approach and should be maintained in our hazard assessment for NBCC purposes. The deterministic approach is in no way acceptable in the framework of the NBCC although a compromise could be made between the two different approaches in the instances of critical structures which do not depend on the NBCC zoning purposes as nuclear power plants, dams and hazardous material storage facilities.

Although the most important input information to define the zones will remain the rate of occurrence of earthquakes, I think that the most intelligent way of defining the zones should be the integration of all the geological and geophysical information with the seismicity data. The faintest seismic activity such as the one near Lac-St-Jean bears a seismotectonic significance which should be questioned and investigated by all the means available. Many American studies have demonstrated that it is this kind of integration that provides the most valuable data input toward improving our techniques of hazard assessment.

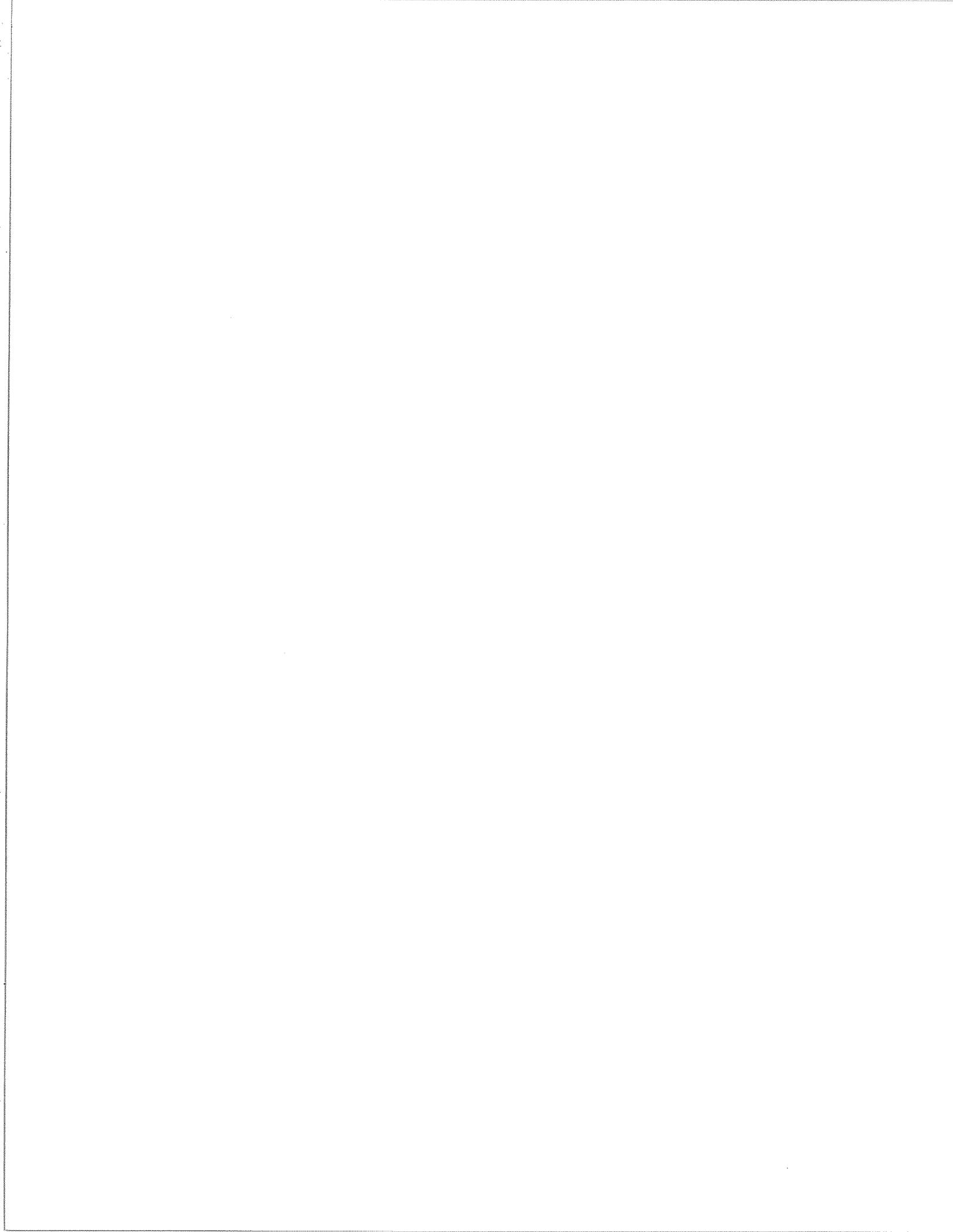
The models and hypothesis that will be used to base the definition of the zones will always be imperfect and should therefore be revised periodically, and I understand that this is the main purpose of the workshop.

I realise that I raise more questions than suggestions about the definition of source zones but I hope the workshop will adress some of these questions. I think it should bring together geoscientists who will contribute valuable information and opinions that will improve our techniques of seismic zoning. In a broader scientific perspective, it should shed some light as to why strong events can occur in such unexpected regions as the Saguenay.

Best regards.

A handwritten signature in black ink, appearing to read 'Reynald Du Berger'. The signature is fluid and cursive, with a large initial 'R' and a long, sweeping underline.

Reynald Du Berger





Ontario

Ministry of Northern Development and Mines
Ministère du Développement du Nord et des Mines

J: M S. OWT.
Screened eq.

January 28, 1991

Dr. John Adams
Geophysics Division
Geological Survey of Canada
1 Observatory Crescent
Ottawa, K1A 0Y3

Dear Dr. Adams:

RE: Workshop on Seismicity source Zones

The Ontario Geological Survey has recently produced new bedrock, tectonic, and magnetic maps of Ontario. In the course of preparation of these maps, we have become aware of several new fault systems, significant at a scale of 1:1 000 000:

- 1) Superior Province shear zones. Several hundred linear km of shear zones in the Superior Province of presumed Archean age with an emerging record of Proterozoic (Peterman and Day 1990) and some suspected Phanerozoic (Kamineni et al., 1990) reactivation have been identified.
- 2) Southern Ontario shear zones. Several newly discovered shear zones in southern Ontario appear on our new bedrock and aeromagnetic maps. Many of these shear zones cut Precambrian basement and the overlying cover sequence. They are marked by displacement of Phanerozoic strata, development of breccias, alteration and secondary cementation. The age of many of these systems is poorly constrained: movement is post lower Paleozoic but documented evidence of Recent movement is not abundant. However, it is difficult to reconcile the existing record of epicentre locations with known structures on the new maps. However, we can map many of the fault systems with the newly released aeromagnetic data.

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Page 2
January 28, 1991
Dr. John Adams
G. S. C., Ottawa

Given the above relationships, a balanced appraisal of the new structures should be part of assessing seismic risk, particularly in southern Ontario. The Ontario Geological Survey views the Geological Survey of Canada as the lead agency in assessment of seismic risk. The Ontario Geological Survey would like to be involved in the deliberations of the workshop as we have new material to pass on and we welcome the opportunity to learn more about assessment of seismic risk. Therefore, I suggest an invitation be extended to Dr. P.C. Thurston, to participate in the workshop. He is the editor of the map series, an accompanying descriptive volume and the enclosed notes on these faults.

Yours sincerely,



V. G. Milne
Director
Ontario Geological Survey
77 Grenville Street
Room 1121
Toronto, M7A 1W4

Encl:

cc: Dr. B. O. Dressler
Dr. P. C. Thurston

FAX 416 324 4933.

SOUTHERN ONTARIO FAULTS

The bedrock geological map on display at the Mines and Minerals Symposium in Dec. 1989 will be published in 1991 as part of the Geology of Ontario Project, a comprehensive review of the geology of the province. Faults and shear zones throughout the map will be shown in two fashions:

- a) those with surface expression will be shown with full colour lines.
- b) those cutting basement lithologies and forming major tectonic boundaries in the basement terrane but not cutting cover sequences will be shown as screened lines.

There will be no distinction on the map between presently active faults and those with no recent seismic activity. Major faults and shear zones in southern Ontario are described below on an individual basis.

1) Central Metasedimentary Belt Boundary Zone Fault.

This fault is a N-S trending feature intersecting the N. shore of Lake Ontario near Pickering. This fault a ductile mylonite zone several km wide at the boundary between the Central Gneiss Belt and the Central Metasedimentary Belt of the Grenville Province and is a Grenville age major tectonic boundary (Davidson 1986). Evidence for existence of this feature is as follows:

- a) Seismic: refraction data by Mereu (1982) shows a 2-3 km offset of the crust with one side dropped 2-3 km.
- b) Magnetic: Aeromag expression in Grenville similar to aeromag data on map 7334 G, 7053G.
- c) Gravity: sharp discontinuity on continental scale and local scale maps
- d) Drill data: Oil well holes show boundary on Niagara Peninsula on OPI map by T. R. Carter (MNR Petroleum Resources Lab London, Ont.) between basement lithologies of distinctly different character.
- e) Geologic evidence: The DNAG map of the Grenville shows the boundary in approximately the position shown. At surface in the Grenville Province the feature has a shallow dip, and is shown on all recent geological maps of the Grenville Province (Davidson 1986 GAC SP 31:61-74). Textures indicate that the zone is predominantly a ductile regime structure formed at a substantial depth. Recently, Wallach (1989: MAGNEC abstracts) noted the presence of brittle mylonitic textures at the Coboconk quarry (W side of Hwy 35, S. of village). Refraction data shows a steep dip some km below surface, therefore the location shown on the map is \pm 5-10 km.

Age: The feature is offset by the Presqu'île-Hamilton-Fault, therefore it is a relatively early structure with no known evidence of post-Proterozoic activity.

2) Robertson Lake Mylonite Zone

This is a brittle mylonite zone which separates the Elzevir and Sharbot Lake Terranes of the Central Metasedimentary Belt of the Grenville Province and ranges from 0.5 to 1.5 km in width. Evidence for the existence of the structure:

- a) Seismic: None available
- b) Aeromag: not particularly clear over much of its length because of lack of lithologic contrast across the structure.
- c) Gravity: Detectable on horizontal gravity gradient map.
- d) Drill data: None known in S. Ont.
- e) Geologic evidence: The zone has been mapped for most of its length in the Grenville (Easton OGS OFR 5693 {Darling area}; Easton SFW 1988). The zone contains a downdropped block of low metamorphic grade rocks juxtaposed against high-grade units.

g) Age: The zone has not affected the Paleozoic strata based on mapping of D. Williams. However as the zone is visible in the Paleozoic on Landsat imagery (Easton 1988 GAC Abstract St. Johns Mtg.) it may have been subjected to post-Proterozoic activity. As well, the structure may be cut by the Clyde River Fault of Paleozoic age in the Darling area. (Easton OGS OFR 5693)

3) Frontenac-Sharbot Lake Terrane boundary (aka Napanee-Picton Fault of McFall et al (1988 OGS SFW).

In the Precambrian this feature is a ductile mylonite zone a few hundred meters across. Evidence for the existence of the feature is:

a) Seismic: Refraction data (McFall et al 1988 OGS SFW) shows offset of velocities suggesting displacement of Paleozoic strata.

b) Magnetic: Some evidence for location of this fault on coloured mag map.

c) Gravity: Some evidence for structures with this trend on horizontal gradient gravity map.

d) Geophysics: Resistivity survey (McFall et al. 1988 {OGS SFW} Mc Fall and Allam 1990 AECB report) shows water-filled fractures.

e) Drill data: None.

f) Geologic evidence: Precambrian mapping shows a ductile mylonite zone several hundred meters wide composed of straight gneisses which mark an abrupt metamorphic discontinuity (Easton 1988 {OGS SFW}). Liberty (1961) documented a 30 m displacement of Paleozoic strata at Picton and D. Williams (mapping in progress MNDM Tweed) describes a 35 m displacement with the WNW side down. The structure also displays a metamorphic discontinuity involving juxtaposition of high and low metamorphic grade rocks.

g) Age: The fault originated in a Grenville age terrane juxtaposition event but has suffered reactivation in the post Ordovician. As there is a spatial association with Jurassic lamprophyres there is some suggestion of Jurassic activity. The lamprophyre dikes have slickensides (McFall pers. comm 1989) therefore there is some evidence for post-Jurassic activity of unknown age.

4) Rideau Fault (aka Perth Road mylonite zone)

This fault is a mylonite zone up to 1 km wide cutting granulite facies Grenville lithologies. Evidence for the feature is :

a) Seismic: None

b) Magnetic: Subtle features can be discerned on the contoured and coloured 1:250 000 mag maps only with a knowledge of the location of the feature.

c) Gravity: Discernable on the horizontal gravity gradient map.

d) Drill data: None.

e) Geologic evidence: Mapping (Friends of the Grenville Field Trip Guidebook 1987) shows the zone to be brittle mylonites up to 1 km wide cutting granulite facies rocks of the Frontenac Terrane. Displacement of Paleozoic strata is observed on the order of 25 m (D. Williams Pers. comm. 1989 {MNDM Tweed})

f) Age: The fact that upper crustal textures (brittle mylonites) occur cutting granulite facies rocks suggests relatively late movement and hence post terrane assembly (900 Ma) reactivation. This is borne out by displacement of Paleozoic strata (Williams Pers. Comm. 1989)

5) St. Lawrence Graben extension

This feature is an east-trending feature cutting Grenville and Paleozoic units. Evidence for this feature is:

a) Seismic: Recent low magnitude seismic events (Forsythe 1981; Adams and Basham 1989) are approximately located on the fault.

- b) Magnetic: Magnetic lineament on coloured mags correlates with this feature, but correlation is not good.
- c) Gravity: Weak correlation with linear features on 1:5 000 000 gravity map. No particular sign of it on horizontal gravity gradient map.
- d) Drill core: Several drill holes logged by D. Williams (MNDM Tweed) show offset of strata.
- e) Geologic evidence: The zone is the site of a metamorphic discontinuity in Grenville rocks between granulite and upper amphibolite facies units (cf. Davidson 1986 fig. 6) The Paleozoic strata are offset 45 m with the southwest side down.(Pers. comm. D. Williams MNDM Tweed).
- f) Age: The fault cuts Paleozoic and Precambrian units and is spatially associated with 400 Ma diabase dikes, suggesting a post-Ordovician age. Seismic activity correlated in general with the St. Lawrence Graben continues (Adams and Basham 1989). Most events are low magnitude. Correlation of this fault with the larger St. Lawrence Graben is based on location, and the fact that there is a central down-dropped lower metamorphic grade area within the Grenville Province.

6) Presqu'île-Hamilton Fault

This fault is postulated based dominantly upon geophysical evidence and data on its width are not available. It may be an extension of the St. Lawrence graben based upon its location (Adams and Basham 1989) and the record of seismic activity (Forsythe 1981; Halls and Mohajer 1989). Evidence bearing on the existence of this fault is as follows:

- a) Seismic: The trace of this structure is, within the limits of location precision, the locus of low magnitude seismic events (Forsythe 1981; Halls and Mohajer 1989) and is shown as the approximate location of the western arm of the St. Lawrence Graben system (Adams and Basham 1989).
- b) Magnetic: The central part of the fault (Hamilton to central Lake Ontario) is the locus of a prominent lineament on the coloured 1:250 000 mag map and the contoured mags (7334G). The prominence of the magnetic expression necessitates existence of two blocks of Grenville basement with contrasting magnetic susceptibility juxtaposed along a relatively linear zone.
- c) Gravity: The feature appears on the 1:5 000 000 gravity map and is poorly discernable on the horizontal gravity gradient map.
- d) Drill core: Any effects of this structure upon Phanerozoic strata are being investigated at present by T.R. Carter (Petroleum Resources Laboratory MNR London, Ont).
- e) Geologic evidence: In the Presqu'île area, D. Williams (MNDM Tweed) has detected an offset of 40 m (north side down) on the fault in Paleozoic strata and the available controls allow extension along strike to the west for about 40 km. At this point the fault is marked by a prominent linear topographic scarp which coincides with a magnetic lineament on both contoured (map 7334G) and coloured magnetic maps which is traceable to the western end of Lake Erie, showing kilometer-scale dextral offset of the CMBBZ fault.
- f) Age: The fault offsets Paleozoic and Precambrian strata. The presence of a topographic scarp in lake bottom sediments in Lake Ontario (map 7334G) suggests offset may be relatively young. The mobilization of crustal fluids described by Frape et al. (1989 OGRG display at Mines and Minerals Symposium) suggests the western end of the feature may have relatively recent activity. The case made by Adams and Basham (1989) and Halls and Mohajer (1989) for seismic activity in Lake Ontario may be related to this or some other structure in Lake Ontario. The fact that this structure may be related to

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the St. Lawrence Graben suggests it may be the locus of the seismic activity. In any case it is the most significant east-trending structure in Lake Ontario.

7) Campbellford-Belleville Fault

This feature is newly named here based on observed offsets in Paleozoic strata in the area. Evidence for this feature is summarized below.

a) Seismic: None.

b) Magnetic: None.

c) Gravity: Minor inflection in the horizontal gravity gradient map suggests the potential of basement involvement in the fault.

d) Drill core: Several holes were logged by Williams (MNDM Tweed) to produce a manuscript map of the Paleozoic strata showing a 40 m displacement (south side down).

e) Geologic evidence: Mapping by D. Williams based on contouring of the Gull River-Bobcaygeon Formation contact shows a 40 m displacement in the area of Stirling, Ont. Control for this interpretation is not available west of Rice Lake, although the feature may persist to the west. Also noted is the offset of the interpreted position of the Precambrian-Paleozoic contact.

f) Age: The fault cuts Paleozoic strata and Jurassic lamprophyre is spatially associated with the fault (Barnett et al. 1984 CJES). The lamprophyre dike has slickensides along the margins suggesting post-Jurassic activity. (Pers. comm. 1989 J. Wallach AECB, G. McFall). McFall also reports calcite infilling of fractures in the Paleozoic strata which may be datable by isotopic means (Pers comm. G. McFall 1989).

8) Clarendon-Linden Fault

This is a major north-trending fault which can be traced across L. Ontario into New York state. Evidence for the location and existence of the fault is as follows:

a) Seismic: The fault is the locus of M 3-5 seismic activity in the USA which continues perhaps to the Ontario shore (Forsythe 1981). The fault is rumoured to have been imaged during the GLIMPCE seismic experiment. (Pers. Comm. G. McFall).

b) Magnetic: Magnetic map 7334G shows a two magnetic highs and a low associated with the fault.

c) Gravity: The feature is clearly visible on the 1:5 000 000 gravity map and on the horizontal gravity gradient map.

d) Drill core: None.

e) Geologic evidence: Mapping of Paleozoic strata (Williams MNDM Tweed) shows a 40 m displacement (west side down) along the structure on shore and mapping suggests the zone is several km wide. The magnetic signature suggests involvement of the basement. The trend of the Robertson Lake mylonite zone (2 above) and the Frontenac-Sharbot Lake Terrane boundary (3 above) suggests these Grenville age features may be extended southward to become the feature named the Clarendon-Linden fault.

f) Age: The fault involves Grenville and Paleozoic strata suggesting a post-Ordovician age. The presence of seismic activity in the USA and Ontario suggests the fault has been reactivated and may remain active at present.

9) Picton Fault

The trace of the east arm of the Picton fault is connected with the Frontenac-Sharbot Lake boundary fault (3 above), forming a zone a few hundred meters across. Evidence for the existence of the fault is as follows:

- a) Seismic: A refraction survey (McFall et al. 1988 OGS SFW) shows the fault to be defined by a narrow valley. Seismic activity may correlate with this feature (Forsythe 1981).
- b) Magnetic: A pronounced lineament exists on map 7334G between an area of short wavelength anomalies and a relatively smoothly contoured block.
- c) Gravity: Shown on the 1:5 000 000 gravity map and the gravity gradient map.
- d) Drill core: Logging of drill core by D. Williams (MNDM Tweed) has been used to define a 35 m displacement (east side down) along the feature. The fault was drilled by Ontario Hydro (Pers comm. B. Semic to G. McFall).
- e) Geologic evidence: The fault has been mapped mainly through drill core supplemented by quarry observations by D. Williams. The zone is several hundred meters wide and shows up on Landsat images. Liberty (1961) observed a 30 m displacement in a quarry north of the fault.
- f) Age: The fault disturbs the Paleozoic strata and involves basement lithologies. It is spatially associated with Jurassic lamprophyre dikes and may be correlated spatially with seismic activity (Forsythe 1981) and hence may be currently active.

10) Salmon Point Fault

This fault is a less prominent southwest trending structure present mainly in the offshore of Lake Ontario. The position of the fault suggests it may form the southern extension of the Frontenac-Sharbot Lake Terrane boundary Fault (3 above) a ductile, lower crustal mylonite zone. Evidence for the fault is as follows:

- a) Seismic: None.
- b) Magnetic: The feature can be observed on 7333G.
- c) Gravity: the feature is discernable on the 1:5 000 000 gravity map.
- d) Drill core: None.
- e) Geologic evidence: Liberty (1961) postulated the existence of the fault. The fault has a surface expression consisting of a scarp a few tens of meters in magnitude along the north side of Salmon Point to cherry Valley with unknown displacement. Bathymetry on 7333G suggests > 15 m of displacement.
- f) Age: Age constraints on this fault are similar to the Clarendon-Linden and related faults.

11) Salmon River Fault

This fault was postulated to be a south-trending fault in Prince Edward County. Evidence for the fault is based upon field work and drilling done since the first edition of this summary. The evidence is as follows:

- a) Seismic: None.
- b) Magnetic: with more precise location, a magnetic lineament is observed on 1:1 000 000 aeromagnetic map of Ontario.
- c) Gravity: None.
- d) Drill data: drilling discloses variation in the elevation of the Phanerozoic-Precambrian contact and the presence of approximately 1 cm thick seams of fault gouge.
- e) Mapping. The proposed fault is spatially associated with anomalous values for Hg in lake sediments (McFall OGS SFW 1988?). A zone of cataclastic deformation including secondary carbonate infilling of breccia zones and slickensided fractures was observed in an exposure in a sand pit at Forest Mills. Kinematic analysis suggests sinistral displacement. The Roblindale quarry exposes slickensides and small scale folds. Bathymetry in Lake Ontario suggests perhaps 30 m of displacement associated with the geochemical anomaly. No displacement of Phanerozoic stratigraphy was detected in D. Williams's

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mapping. The data suggest the structure may be a splay or an extension of the clarendon-Linden structure, given the trend of the feature.

RECOMMENDATION: The above work is too recent to show on the bedrock map.

12) Electric Fault

This fault cuts Paleozoic strata in the Chatham area. Evidence for the structure is listed below.

a) Seismic: Seismic profiling done during hydrocarbon exploration indicates the fault cuts basement units (T.R. Carter, MNR London, Pers. Comm.).

b) Magnetic: None.

c) Gravity: None.

d) Drill data: The location and extent of the fault is constrained by well logs of several hydrocarbon wells.

e) Geologic evidence: The fault is evident on structure contour maps e.g. the top of the Rochester shale. The fault cuts units low in the section and is not known to cut every unit from basement to surface and the surface trace is nowhere exposed.

f) Age: The fault is Paleozoic in age, with no evidence of later reactivation.

13) Georgian Bay Linear Zone

This zone is described by Wallach (AECB report 1990) as a southeast-trending zone extending from Georgian Bay through Lake Ontario into northern New York state. Evidence for this structure is as follows:

a) Seismic: none.

b) Magnetic: a lineament appears on the 1:1 000 000 aeromagnetic map of Ontario, trending approximately southeast.

c) Gravity: A southeast-trending linear discontinuity appears on the 1:5 000 000 Gravity Map.

d) Drill data: Logs of drilling for Ont. Hydro Bruce Penins. heavy water plant should be examined.

e) Geologic evidence: Southeast-trending zones of mylonitization occur in Georgian Bay (Pers. Comm. S.B. Lumbers, ROM) These zones have not been systematically mapped so as to define any potential linear or curvilinear zone.

f) Affects Grenville units, based on geophysical evidence, effect on Paleozoic cover is not known to occur.

RECOMMENDATION: Insufficient evidence is available to suggest that this zone is clearly a fault. further work in both the Phanerozoic and Precambrian is required. This zone will not appear on the Bedrock Geology Map of Ontario.

14) Small Faults- S.W. Ontario

A number of faults have been identified in the Precambrian basement and the lower part to the Paleozoic section, principally through inspection of structure contour maps. With the exception of the north-trending fault east of Point au Pins, there is no evidence these structures reach the bedrock surface. Evidence for the faults is as follows:

a) Seismic: Seismic lines done for hydrocarbon exploration have shown most of these structures. (Pers. comm. T.R. Carter, Petroleum Resources Lab. MNR London).

b) Magnetic: None.

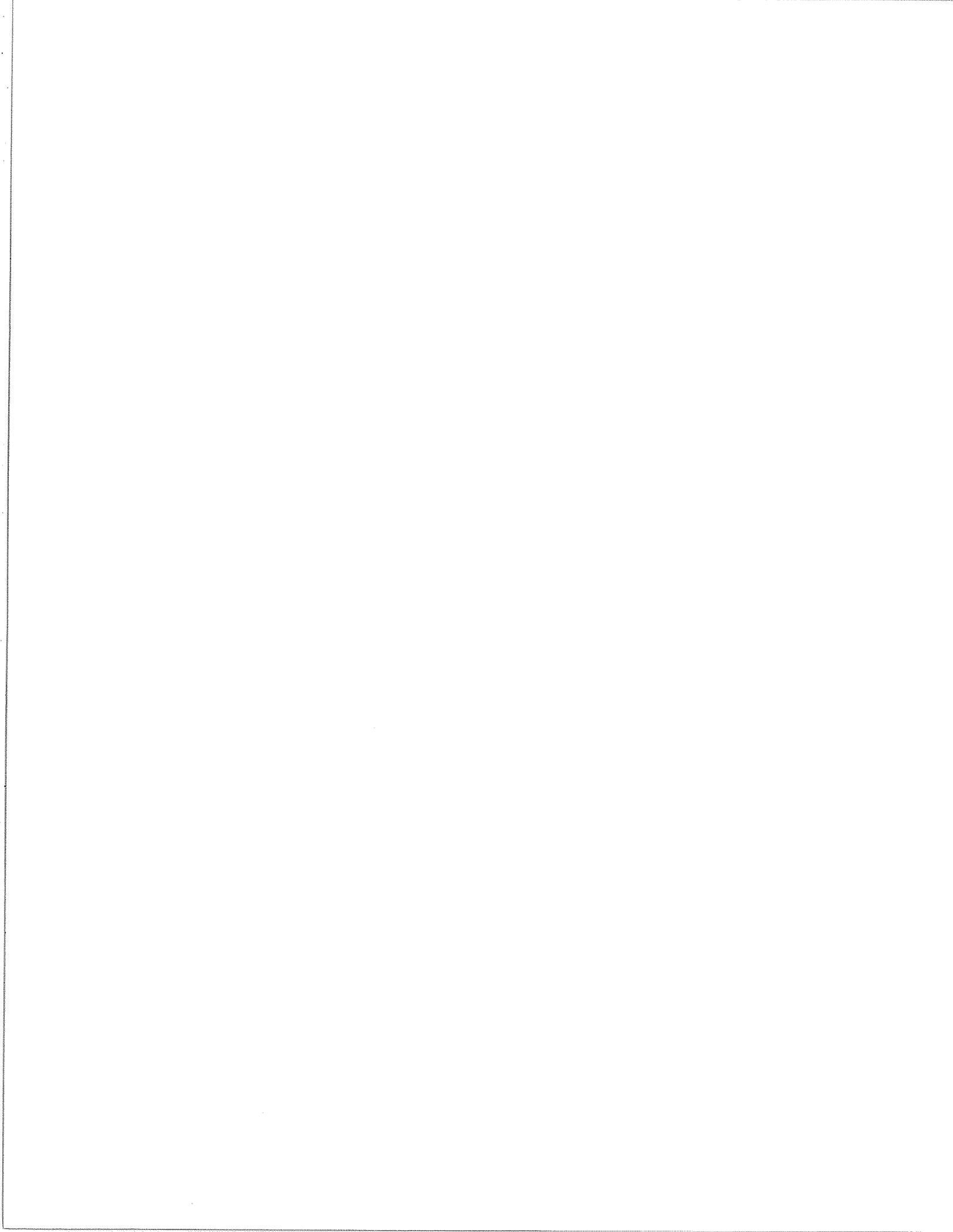
c) Gravity: None.

d) Drill data: The fault locations are based on structural contour maps constrained by drill hole data (OGS OFR 2659 and OFR 5555). Only faults

with displacement greater than possible sources of error and of strike length sufficient to allow display at final scale are shown.

e) Geological evidence: Several Cambrian and Trenton age pools are associated with the faults (e.g. Willey and Clearville pools [Brigham 1971]).

Note: Numerous other faults and lineaments are discussed by Bailey and Cochrane (OGS OFR 5498) and in Sanford et al., (1985). However the Bedrock Geology Map will portray only the major structures.





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91-3

February 8, 1991

Dr. John Adams
Geophysics Division
Geological Survey of Canada
Bldg. #7
1 Observatory Crescent
Ottawa, Ontario
K1A 0Y3

Dear John:

Thank you for your earlier communication on the "Workshop on Seismicity Source Zones for the 1995 NBCC Seismic Hazard Map of Canada", for our chat of February 4, 1991 and for your taped message on Thursday, February 7, 1991 confirming that the Workshop is now firmly scheduled on March 18-19, 1991. John, the original (and only mailing to date) did not include (to me at least) the enclosed "draft showing the type of justification that will be required by the end of 1991" (unless it was the included Earthquake Source Zone map?).

Let me express an interest in attending the Workshop in March and indicate that I believe my contribution based on my various historic studies will be limited to:

1. Indicating the general aseismic nature of much of Nova Scotia
2. Indicating the apparent increased incidents of felt events in Western Nova Scotia west of circa a Windsor-Chester N-S line. I would be prepared to make a presentation on this and if there is to be a workshop proceedings, prepare a note on this topic. I believe such a note will indicate a grater risk of events offshore of S.W. Nova Scotia and offshore of the mouth of the Bay of Fundy "somewhere" than previously perceived.
3. Reviewing the known incidence of tsunamis in eastern Canada (overheads) [which could include, if you wished, a crackerjack slide presentation of the damage from the 1929 event in Newfoundland - perhaps a dinner talk?]. I could prepare a written piece for the workshop proceedings specifically on tsunamis, aftershocks and other felt events as they pertain, or may pertain, to the 1929 Laurentian Slope Seismic Zone. It is my feeling, and my intuition, that this seismic zone may be more active than the Geophysics Division believes - it is certainly more active than David Piper's work indicated - at least as I have read it.
4. Possibly I could do a very brief piece on the Western Star results vis-a-vis northern Notre Dame Bay, Cape St. John and the other event recorded in this area integrating Staveley's work, etc.

5. If you want a neat piece (but I am not sure I have got quite all the slides I would want), I could do something almost by way of entertainment on the origin of the folk song "A Great Big Sea Hove In Long Beach". I have taken it much further than EPB's historian who simply wondered to me if there was a tsunami connection and further than Michael who suggested it might be a tsunami event.

I could also play a folk song I 'collected' on the 1929 event from Roundabout, a community that no longer exists, and another song that I found in Memorial's Folklore centre. I suspect I have pinned down the "Great Big Sea" to an event and a place and can almost show you a slide of Keough's Parlour. I can show you Keough's shop and perhaps, if I press, his gravestone.

Anyway, those are my thoughts John. I am not prepared to go to any great expense to prepare new material. I do not have the funds. But I can do a credible job with material on hand, as you suggest, from the above.

I will also apply for the full degree of travel or related support for which I am eligible and will scout about now for friends to billet with. They seem to all have come back to Halifax over the years!

Many thanks for the invitation.

Regards,



Alan Ruffman
President

AR:gch

United States Department of the Interior
GEOLOGICAL SURVEY
Branch of Geologic Risk Assessment
Box 25046, M.S. 966
DENVER FEDERAL CENTER
DENVER, COLORADO 80225

January 28, 1991

John Adams
Geophysics Division
Geological Survey of Canada
1 Observatory Crescent
Ottawa, CANADA K1A 0Y3

Dear John:

Here are some unpolished suggestions for new Canadian source zones, as requested by your recent letter of invitation. The suggestions deal only with southeastern Canada because it adjoins the central and eastern U.S., for which I am developing new source zones for a new U.S. map. This required me to zone southeastern Canada also. What follows comes mostly from letters, reprints, and preprints that I've sent to you or Peter Basham over the last year and a half. I've cited these below and listed them later under "REFERENCES". Figures included here are cannibalized from other sources and so contain some information not pertinent here.

Independently, Paul Thenhaus is updating source zones for the western U.S. by incorporating the abundant new information that postdates the zones used in our 1982 U.S. map (Thenhaus and Wheeler, 1989). I've given him a copy of your letter of invitation, but he is in Indonesia this month and so might not be able to respond.

I've cast my suggestions into a manuscript-like summary of the zones I've developed, followed by suggestions as to how the zones of Basham and others (BSSA, 1985) might be modified to be similar. My aims are to minimize the subjectivity of your new zones, to maximize their geologic defendability and useful lifetimes, and to minimize inconsistencies between our two new maps at the international border.

Thank you for the opportunity to make these suggestions. Our exchanges over the last year or two have helped me a lot, and I offer what follows in the same spirit.

Best wishes,


Russell L. Wheeler

cc: S.T. Algermissen, D.M. Perkins, P.C. Thenhaus
Enclosures

INTRODUCTION

"East of the Rocky Mountains seismicity is sparse and most active faults are not exposed at the surface. Accordingly, relations between seismicity and geology are more ambiguous in the East than in the West. This fundamental difference between the regions has caused two problems in defining source zones for earlier hazard assessments.

"First, in general it has been difficult to combine geology and seismicity in the East to define source zones in a clear, logical way. The few exceptions to this difficulty are zones with abundant seismicity that has clear spatial associations with particular groups of faults, as is the case at the Reelfoot and St. Lawrence rifts and the Charlevoix impact structure.

"Second, source zonation has depended on changeable hypotheses about the geological causes of eastern seismicity. If source zones change, the ground-motion maps based on them also change But hypotheses rise and fall, so it is not always clear at the time whether a change is an improvement or an error. Examples of changing hypotheses are the controversies over the Ramapo fault . . . and the Atlantic Coast stress province . . ." (Wheeler and Thenhaus, 1989, p. 45).

Paul Thenhaus suggested a way to attack both problems by treating eastern geology and eastern seismicity separately. I am treating the geology and Dave Perkins will treat the seismicity. I've defined geologic source zones that are based only on geologic information and not on seismicity; traditional source zones have been based on both types of information. The geologic source zones are restricted to those that can be based on accepted regional geologic characteristics or analogy to worldwide patterns found by EPRI's maximum magnitude project. I do not draw a source zone boundary between adjacent areas unless I can argue that the seismogenic faults in the two areas differ in age or type. In practice these restrictions mean that the geologic source zones are few and mostly large--I've defined eight in the central and eastern U.S., four of which are germane to southeastern Canada.

Afterward, Dave Perkins will calculate hazard from the seismicity within each geologic source zone, as illustrated by Perkins and Algermissen (1987). The calculation is slightly more subjective than defining the geologic source zones. However, it can be developed objectively and the subjectivity can be confined to choices of values for a few smoothing parameters (Perkins and Algermissen, 1987). In this way we avoid the ambiguity and most of the subjectivity that have plagued previous attempts to define traditional source zones by mixing geology with seismicity.

GEOLOGIC SOURCE ZONES--METHOD

Most of the East comprises continental crust that has evolved through a long, complex series of contractional and extensional deformations, and contains faults of diverse ages, orientations, and styles. Also, eastern North American

earthquakes large enough to cause damage tend to have foci at depths of about 10-30 km and only two surface ruptures are known, one of them prehistoric (Wheeler, in prep. 1, and Wheeler and Johnston, 1990). Thus, only at a few places has painstaking geologic and seismological work identified the type and age of seismogenic fault. Examples include Charlevoix, Giles Co. in southwestern Virginia, the Reelfoot rift, and the Meers fault.

Known regional geologic structure and geologic history allow one to map the area underlain by faults of the same type and age as those identified as seismogenic. Such an area is a geologic source zone. Its definition uses seismicity only to identify the type and age of fault that is seismogenic at one or several places, and is otherwise based only on geologic evidence. Faults of this type and age are assumed to be potentially seismogenic throughout the zone. We do not know why the presently active faults within the zone have been selected for reactivation from all those available throughout the zone.

Thus, the geologic source zones are characterized and distinguished "by their tectonic styles and histories, their crustal ages and thicknesses, and related geological and geophysical properties. We assume that these regional differences in tectonic and crustal properties determine most regional differences in seismic activity rates and maximum magnitudes" (Wheeler and Thenhaus, 1989, p. 45). This assumption is reasonable because these geologic differences between geologic source zones are closely related to those between the few faults known to be seismogenic. Most of "the geologic source zones will differ from the background source zones that are common in probabilistic hazard analysis. Often background zones are made up of areas that are left over after other source zones are defined, whereas our geologic source zones will be defined independently of other kinds of zones" (Wheeler and Thenhaus, 1989, p. 46).

Once the geologic source zones are defined, their seismicity can be examined separately to estimate maximum magnitudes. This does not involve any further assumptions about the relation between eastern geology and eastern seismicity. "Because eastern seismicity is sparse, estimation of the ... maximum magnitudes of geologic source zones will be aided by analogies to geologically similar areas worldwide" as documented in EPRI reports and journal papers by A.C. Johnston and coworkers (Wheeler and Thenhaus, 1989, p. 46).

GEOLOGIC SOURCE ZONES--RESULTS

The most important geologic source zone is the late Proterozoic Iapetan passive margin (Wheeler, in prep. 2, 1991; figs. 1, 2). Network seismicity at Charlevoix (represented by the letter a in fig. 1), Giles Co. (letter e), and eastern Tennessee (f) has been attributed to compressional reactivation of north-to-northeast-striking, steeply dipping, Iapetan normal faults that cut the middle Proterozoic Grenville continental crust. Adams and Basham (DNAG paper, in press) suggested that the seismicity of the lower St. Lawrence River has a similar origin, and I suspect that seismicity at and near Attica, New York, might also. Adirondack seismicity remains enigmatic.

All six of these areas are in the northwest part of the Iapetan margin, northwest of a northeast-trending line that represents hinge zone of the Iapetan margin. Northwest of the hinge zone Iapetan faults are comparatively few or

small and Iapetan extension thinned the crust but little, so the crust has remained comparatively intact. The hinge zone is recognized on deep seismic-reflection profiles (fig. 2), and separates the comparatively intact part of the margin on the northwest from more extensively thinned, aseismic Grenville crust on the southeast. Figure 2 labels the hinge zone the "intact-thinned boundary". The comparatively intact part of the margin extends from the most cratonward recognized Iapetan faults on the northwest to the hinge zone on the southeast. The comparatively intact part of the margin is a geologic source zone, and hereafter I'll refer to it in abbreviated form as the Iapetan margin.

Everything southeast of the Iapetan margin comprises a second geologic source zone, Appalachian orogenic crust. The contact between the margin and the orogenic crust dips southeast (fig. 1). The orogenic crust includes extensively thinned and fragmented blocks of Grenville crust that were overridden by and incorporated into Appalachian thrust sheets and nappes; the metamorphic and igneous rocks of the Appalachians themselves; and the Appalachian rocks that were thinned progressively southeastward by Mesozoic extension. Orogenic crust extends offshore to the East Coast Magnetic Anomaly.

Network seismicity in the Appalachian orogenic crust is more complex and less well understood geologically than that of the Iapetan margin. This includes the seismicity of New England (b in fig. 1), central Virginia (d), and Charleston (h). Hypocentral depths tend to be less in the orogenic crust than in the Iapetan margin (Wheeler, in prep. 1, and Wheeler and Johnston, 1990).

The rifting event that produced the Iapetan margin also formed three aulacogens -- the Ottawa rift, the Reelfoot rift, and the southern Oklahoma aulacogen. All three are seismically active, at least sporadically, although the only evidence for that activity in the southern Oklahoma aulacogen is the late Holocene surface rupture of the Meers fault. The Ottawa and Reelfoot rifts underwent Mesozoic reactivation, but I know of no evidence that the southern Oklahoma aulacogen did. Analysis of network seismicity and associated geological and geophysical work attribute the earthquakes of the Reelfoot rift (g of fig. 1) to compressional reactivation of the rift faults. The Meers surface rupture formed by oblique compressional reactivation of a probable border fault of the aulacogen. I know of no evidence linking individual earthquakes of the Ottawa rift to individual rift faults, but the results just mentioned from the other two aulacogens show that faults of the same type and age as those of the Ottawa rift are seismogenic. Because faults of the aulacogens are or can be seismogenic, the area of their occurrence can be a geologic source zone. This area occurs in three parts, one coextensive with each aulacogen, so each aulacogen is a geologic source zone.

Arch Johnston and colleagues supervised for EPRI a worldwide survey of large earthquakes in stable continental interiors similar to central and eastern North America. Their results identified Phanerozoic continental rifts and passive margins as particularly active, especially if they were reactivated by Mesozoic rifting. Thus, global analogies support the definition of the Ottawa rift and its two more southerly brothers as geologic source zones. Only the Ottawa rift is germane to southeast Canada. I've defined its boundaries to follow the limit of the area of faults and dikes as compiled by Forsyth (CJES, 1981).

The rest of the continental interior is not particularly active, and the few medium-sized or larger instrumental earthquakes known there remain enigmas -- Anna (c of fig. 1), Ungava, Payne Bay, Nahanni, and some in the Canadian Arctic archipelago (Wheeler, in prep. 1, and 1990). Thus, I defined a background geologic source zone, the central craton. With the addition of the Gulf Coast and Florida, this gives me eight geologic source zones. Four are of interest to southeastern Canada -- the Iapetan margin, Appalachian orogenic crust, Ottawa rift, and central craton.

COMPARISON TO SOURCE ZONES OF BASHAM AND OTHERS (1985)

Our different treatments of Charlevoix illustrate the difference between geologic and traditional source zones. It might seem surprising that I don't treat Charlevoix as a geologic source zone. The tabular concentrations of hypocenters at Charlevoix are one of the main bases for identifying Iapetan extensional faults as potentially seismogenic and for defining the Iapetan margin as a geologic source zone. Also, the seismicity at Charlevoix is confined between the outer faults of the meteorite impact structure and the cross faults of the Saguenay graben. However, the seismicity at Giles Co. and in eastern Tennessee is almost as tightly grouped, but at those two localities the overlying thrust sheets prevent us from observing any confining faults like those at Charlevoix. We recognize the geologic reason for the clustering of seismicity at Charlevoix but not at Giles Co. or eastern Tennessee because the thrust sheets are eroded from Charlevoix, not because of any property of the source rocks themselves. We don't know whether the spatial association of the Charlevoix seismicity with the impact structure is unique or fortuitous, so we can't be sure that Charlevoix-sized earthquakes and Charlevoix-like activity rates can't occur elsewhere in the Iapetan margin.

That is, it is reasonable to infer that the meteorite impact weakened the crust at Charlevoix and that the weakening has selected the area for preferential strain release over the last few centuries. However, we don't know what else might lead to similar strain release elsewhere in the Iapetan margin at other times. The lack of large accumulated deformation at Charlevoix indicates that the area cannot have been the dominant locus of strain release in the Iapetan margin over millions of years. This indication implies either that Charlevoix's present activity is unique or nearly so in the half-billion-year history of the Iapetan margin, or that other Charlevoix-like areas have waxed and waned throughout the margin and will continue to do so. The second implication is the more likely.

I've defined the Ottawa rift as a geologic source zone that excludes the western Quebec seismicity north of the rift. Dave Perkins will address the excluded seismicity with the methods of Perkins and Algermissen (1987). Awhile ago Peter Basham wrote that you were considering defining two traditional source zones to encompass the same area. I responded that our two approaches are likely to produce similar results, and I still think that.

In contrast, perhaps the northern Appalachian zone NAP of Basham and others (1985) needs revision (fig. 3). It appears to be defined mostly by the eastern New England seismicity. However, it includes the Adirondacks seismicity, which occurs in autochthonous Grenville crust that is not part of the Appalachians.

NAP appears to be extended northeast to include the Miramichi earthquakes, yet I know of no geological basis for distinguishing the seismogenic potential of that part of the northern Appalachians from the potentials of the Gulf of St. Lawrence or Newfoundland.

Finally, the eastern background zone EBG of Basham and others (1985) coincides approximately with the Iapetan margin and Appalachian orogenic crust through most of its extent (fig. 3). However, I don't understand the basis for extending EBG northwestward to Hudson's Bay.

Therefore, I suggest the following changes to the zones of Basham and others (1985). The suggestions are in terms of traditional source zones. The suggestions should produce a source zone map similar to the 1985 map in the small, active areas that will dominate the hazard. However, the resulting map would look more reasonable in light of geological advances of the last decade. The resulting map should also achieve the aims listed at the start of this letter--it should be comparatively long lasting, objective, defensible, and consistent across the international border.

First, retain zones LSL, CHV, ATT, and probably LSP.

Second, retain zone WQU but add another adjacent on the southwest to outline the Ottawa rift.

Third, split most of NAP into two zones coextensive with the Adirondacks seismicity and that of eastern New England. Leave Miramichi outside unless there is seismicity between it and eastern New England ... even large zones with low activity rates will have large earthquakes once in a great while, and Miramichi might have been one of them. Until Miramichi's causative faults are identified and characterized we could regard it as an "anywhere, anytime" earthquake for the Appalachian orogenic crust.

Fourth, either delete the northwest projection of EBG or make it a separate zone, so that the northwest boundaries of EBG and the Iapetan margin approximately coincide. Both are poorly defined and probably gradational so their exact locations don't matter.

Fifth, split the remainder of EBG along the approximate location of the Iapetan hinge zone, to produce two long zones corresponding to the Iapetan margin and the Appalachian orogenic crust.

MAXIMUM MAGNITUDES

The choice of maximum magnitudes is especially difficult for source zones with low area-normalized seismicity rates. I used as many as four different approaches to try to converge on estimates of maximum magnitudes for the geologic source zones (Wheeler, 1989). However, in the end I had to admit that "these magnitudes should really be viewed as lower bounds to the maximum magnitudes. Whether and how much to increase the maximum magnitudes beyond the tabulated values is a decision for seismologists and hazard modelers, but not for me as a geologist. The decision should be influenced by consideration of the consequences of being wrong" (Wheeler, 1989).

Therefore, I suggest a maximum magnitude of at least M_s 7.3 for the Ottawa rift, Iapetan margin, and Appalachian orogenic crust geologic source zones, and at least M_s 6.7 for the central craton geologic source zone. These values can be increased in light of your experience with the repercussions of any large earthquakes since the mid-1980's that have exceeded the maximum magnitudes used in the present Canadian hazard map.

Small traditional source zones that are defined by concentrations of seismicity, such as LSL, CHV, ATT, and LSP, should have the same maximum magnitudes as the geologic source zones within which they are embedded. This recommendation comes from considering a small concentration of seismicity as a part of the surrounding geologic source zone but one that is temporarily more active than the rest of the zone. In general, the cause of the excess activity is unknown. That is, usually we do not know why some faults within the geologic source zone have been reactivated while most have not; Charlevoix is the exception to this rule. The structures and crustal properties that characterize the geologic source zone continue under the concentration of seismicity, where some other factor or factors, perhaps random, also act to select certain faults of the zone for reactivation. Therefore, all faults of the geologic source zone can be capable of producing an earthquake at least as large as the largest observed in the concentration of seismicity. For example, the largest Charlevoix earthquake is one estimator of the maximum magnitude both at Charlevoix and throughout the Iapetan margin.

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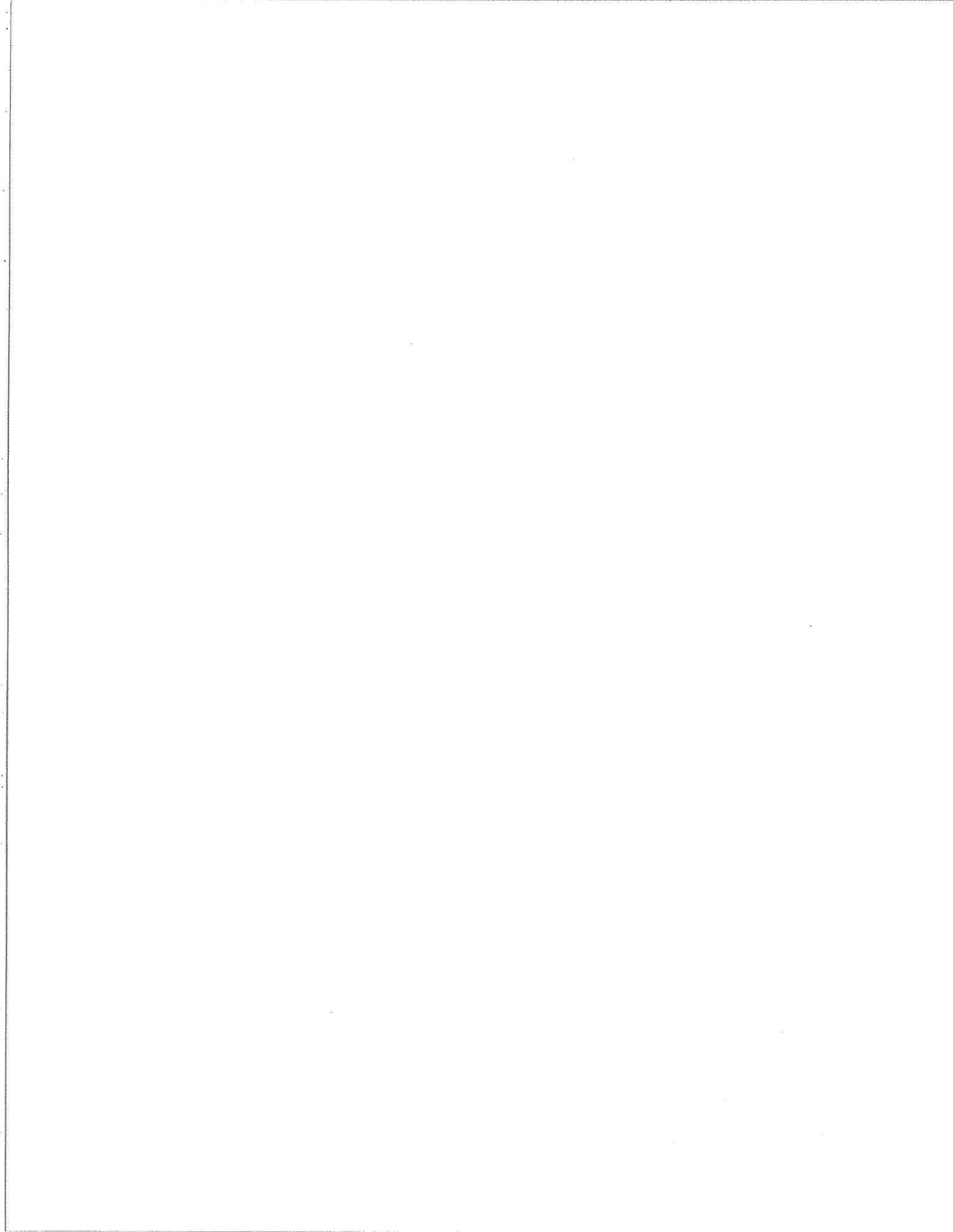
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FIGURE CAPTIONS

FIGURE 1. Tectonic setting of seismicity in southeastern North America. The unscaled sketch represents a typical cross section across the Appalachian orogen. Anna, Payne Bay, and Ungava earthquakes occurred in central craton. Ossipee and Miramichi earthquakes occurred in overthrust orogenic crust. Approximate locations of most network seismicity are shown by lower-case letters, as projected along trend into the cross section. Main mass of orogenic crust is mostly metamorphic and igneous rocks. Shallow thrust sheet of orogenic rocks to northwest of main mass is mostly sedimentary rocks. Basal thrust sheets do not crop out everywhere along length of orogen. From Wheeler (in prep. 1).

FIGURE 2. Boundaries and localities. Circled numerals show locations of known and probable Iapetan normal faults identified by geological and geophysical investigations. Heavy line segments and boxed numerals show locations of deep seismic reflection profiles. Dashed lines, from northwest to southeast, are (1) the northwest boundary of the Iapetan margin and its extensional faults, (2) the boundary or hinge zone between relatively intact and relatively thinned Precambrian crust within the Iapetan margin, (3) the southeast edge of Grenville crust thinned by Iapetan rifting and perhaps also by later processes, and (4) the landward edge of the East Coast Magnetic Anomaly (ECMA). From Wheeler (in prep. 2).

FIGURE 3. Geologic source zones (dashed lines, partly from figure 2) superimposed on the traditional source zones of Basham and others (1985). Zones are sketched freehand here, so their boundary locations are approximate.



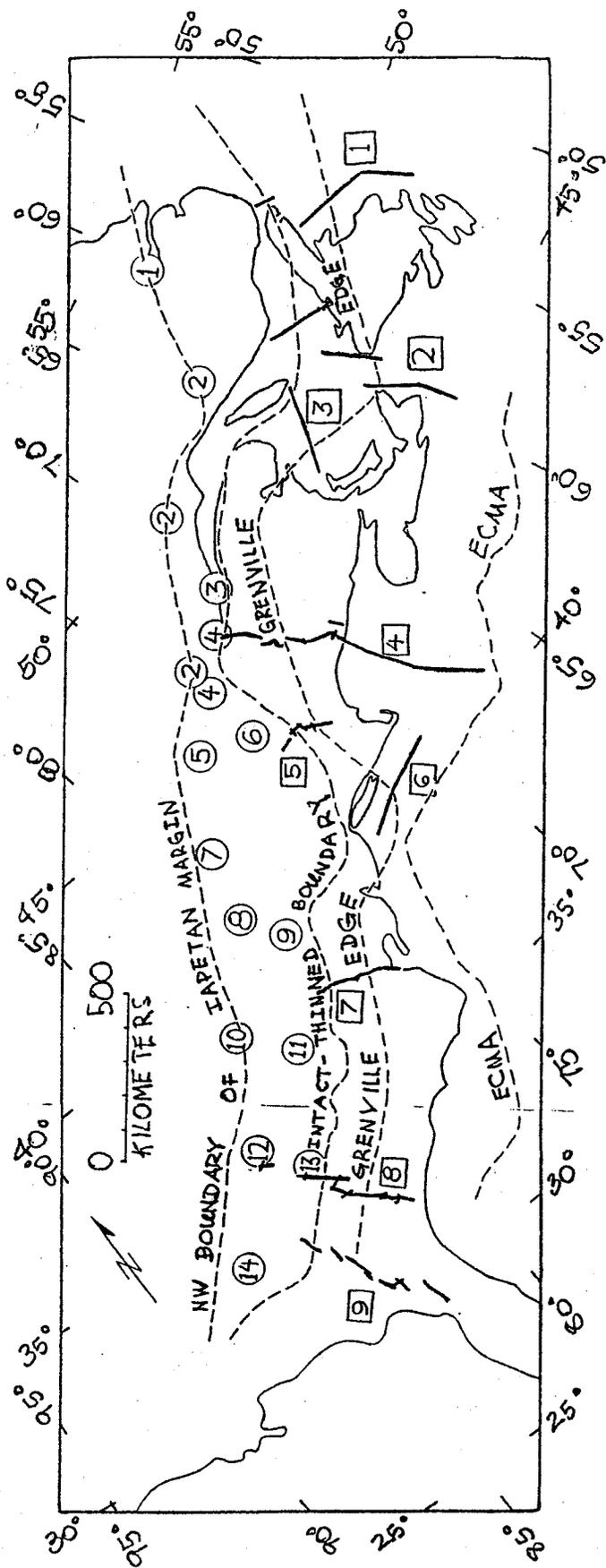


fig. 2

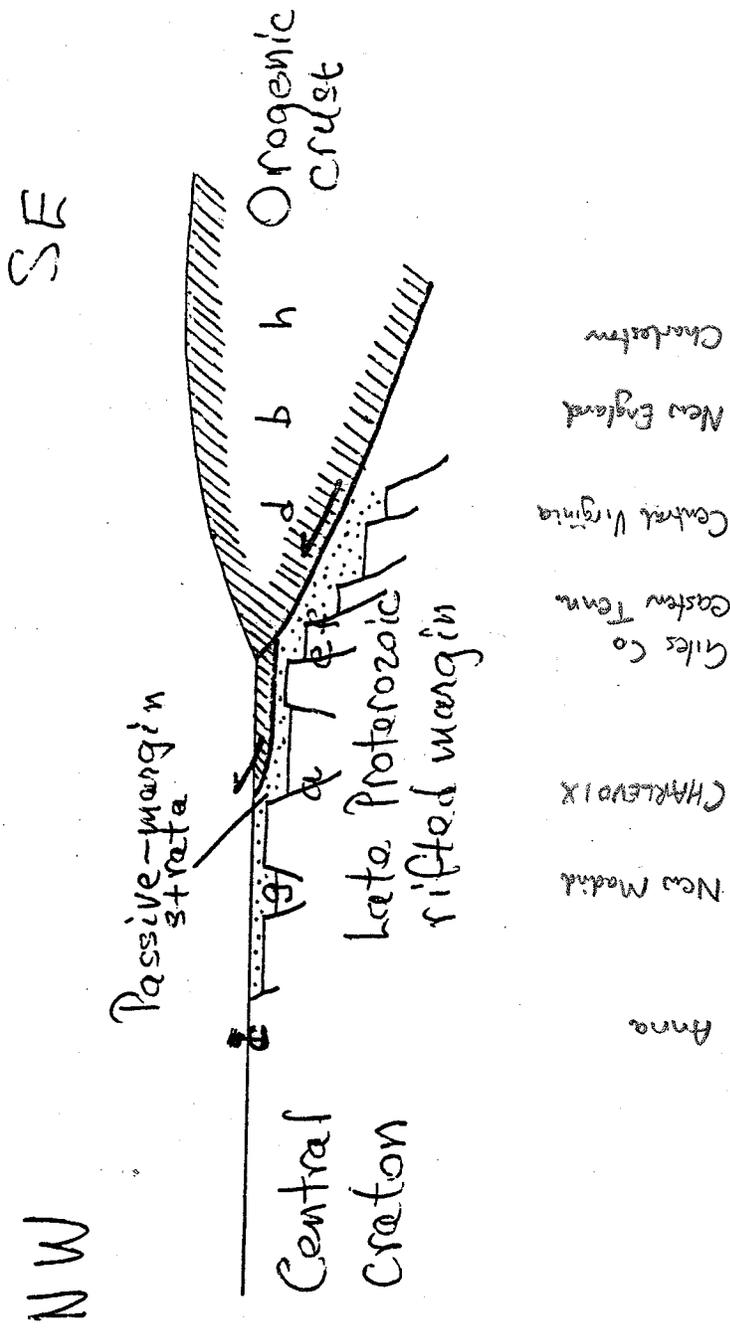


fig. 1

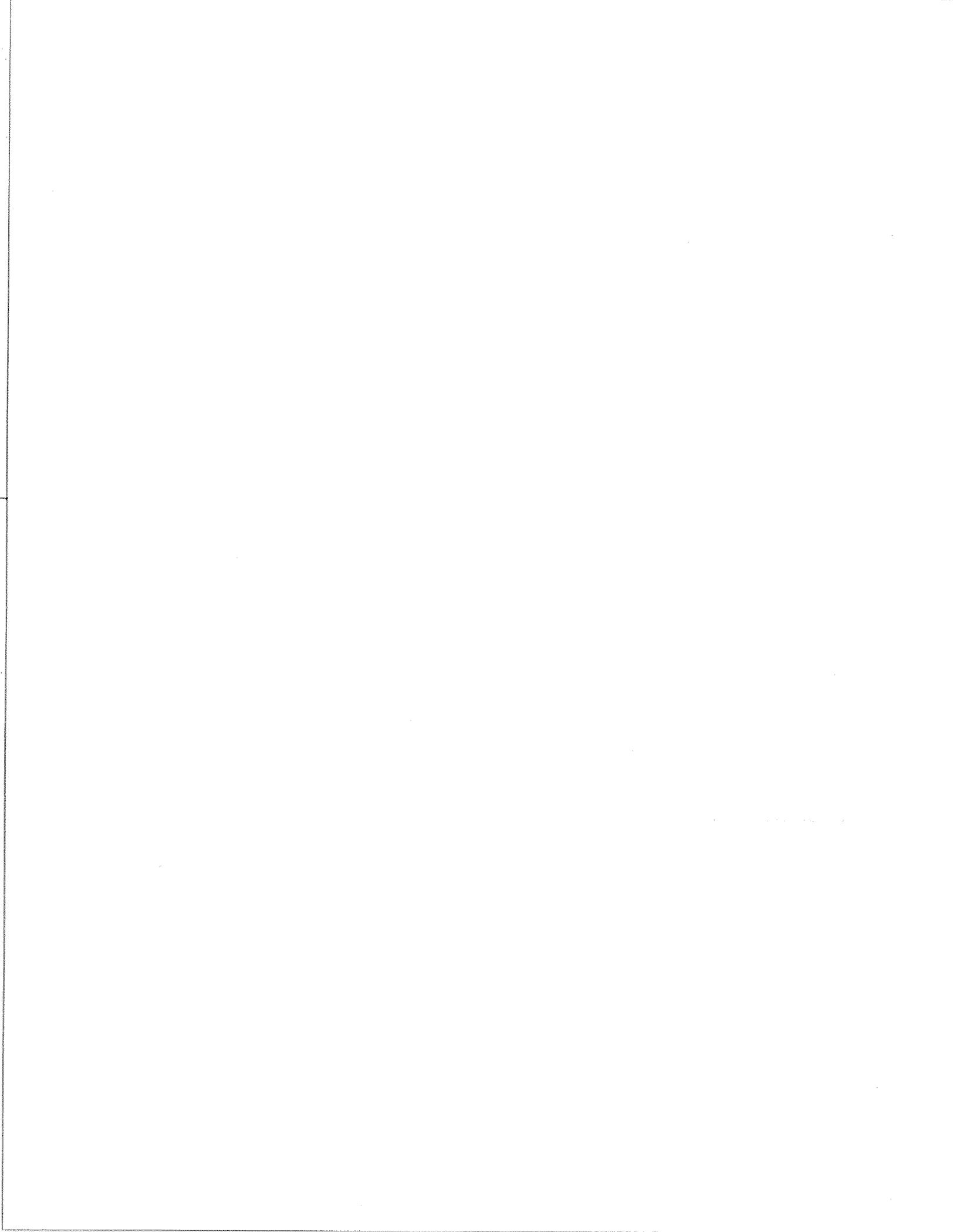
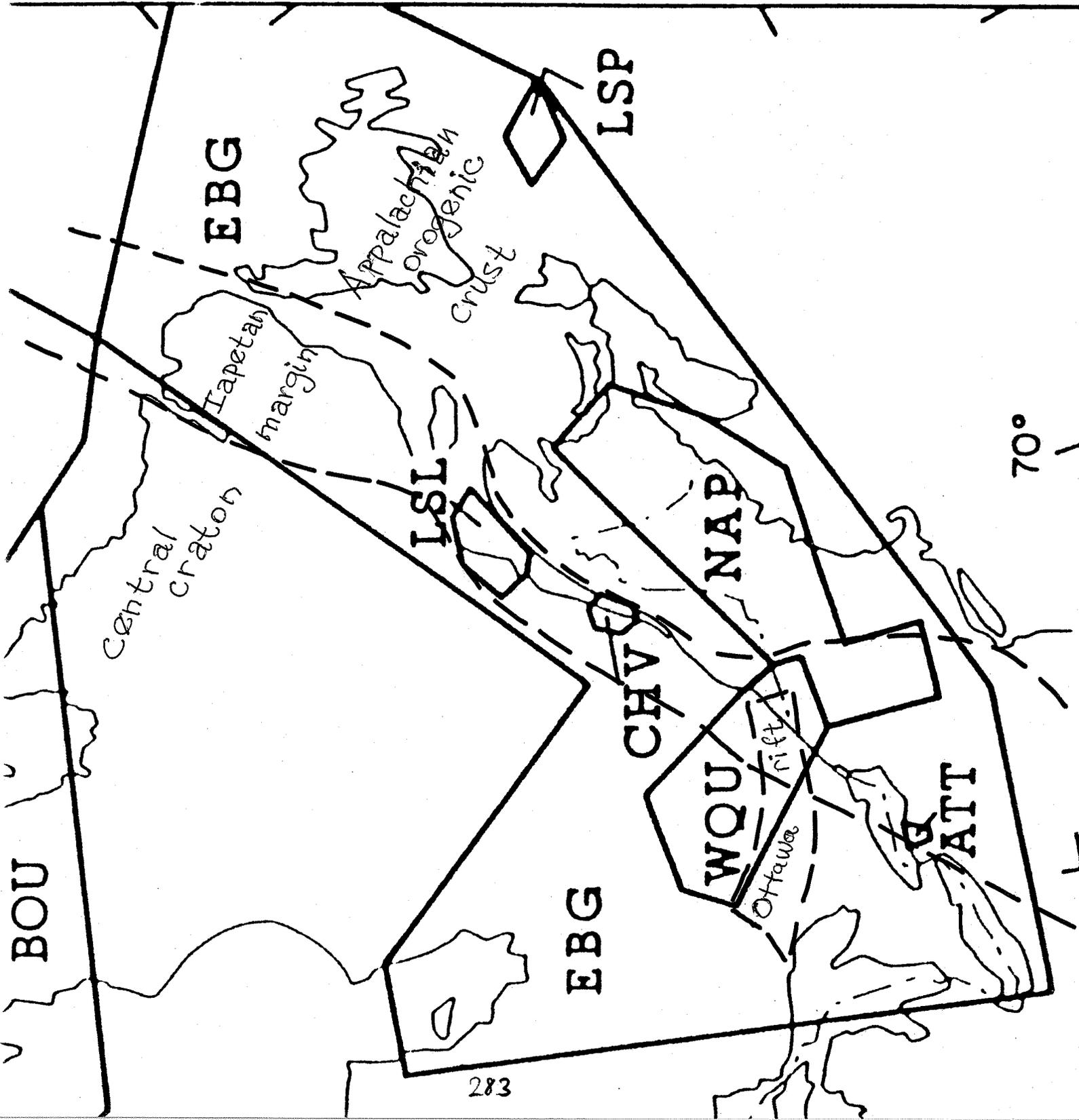


Fig. 3



APPENDIX 5

Written Comments received after the meeting

These comments are ordered alphabetically by contributor and are as follows:

Gail Atkinson with comments on the workshop.

John Bowlby on "Recent surficial deformation provides geologic constraints for seismic source zoning in the Lake Ontario region".

John Bowlby with comments on deep structure under the Great Lakes.

Arch Johnston on "Estimating maximum magnitude for stable continental regions".

George Klimkiewicz on "Spatial and temporal characteristics of seismicity of the southern Great Lakes and implications for probabilistic seismic hazard assessments".

Steve Kumarapeli on "Tectonic framework of a geological source zone in the rifted craton west of the Canadian Appalachians".

Bernd Milkereit and Dave Forsyth on "Evidence of Grenville deformation interpreted from seismic images of structure beneath western Lake Ontario and eastern Lake Erie".

Alex Mohajer on "Seismic source zone characterization in western Quebec and southern Ontario".

Richard Quittmeyer on "Seismicity of north-central New York State and southern Lake Ontario".

Denis Roy on "The Saguenay earthquake and geology".

Alan Ruffman on "The case for a seismic zone off southwest Nova Scotia in the Gulf of Maine or along the edge of the continental shelf/slope".

Alan Ruffman on "Notes on the recurrence rate of a November 18, 1929-like event in the Laurentian Slope (LSP) seismic source zone or of similar shelf-edge/slope events off eastern Canada".

Paul Somerville with comments on the workshop.

Pradeep Talwani with comments on the workshop.

Joe Wallach on "Pop-ups and seismic hazard".

Joe Wallach on "Northwest-trending tensional and compressional features and their implications for seismic hazard assessments".

Rus Wheeler Wheeler and Stewart abstracts from the 1991 Northeast-Southeast GSA meeting.

Gail Atkinson: General Comments

1. If zones are being defined based on a 'rifted' model (or any other geologic structure), it is essential to clearly state the criteria for recognizing the existence and extent of the structure. (Ideally, seismicity should not be a criterion.) If the evidence varies in quality for various portions of the feature, leading to uncertainties in the definition, these should be documented. Don't forget to discuss the ambiguous features that you choose to exclude.
2. There is no logical connection between historical rates of seismicity and M_X . The historical record is too short to provide constraints on M_X . The study of global intraplate environments could be used to argue that $M_X \approx 7.5$ for the Paleozoic rift structures, $M_X \approx 7$ for unrifted craton. Possibly, you could argue $M_X \approx 6.5$ for unrifted craton without evidence of significant tectonic structure; this is a subjective judgement which would be difficult to defend very convincingly. Since a probability distribution is allowed for M_X , I would use a wide distribution, with the probability weighted towards values lower than those given above.

e.g. Western Quebec	$M_X = 6.0$	$\omega_i = 0.3$
	$M_X = 7.0$	$\omega_i = 0.6$
	$M_X = 7.5$	$\omega_i = 0.1$

RECENT SURFICIAL DEFORMATION PROVIDES GEOLOGIC CONSTRAINTS FOR SEISMIC SOURCE ZONING IN THE LAKE ONTARIO REGION

John R. Bowlby*
40 Davean Drive
North York, Ontario M2L 2R7

This summary provides a record of discussion of significant information on previously known and recently discovered geological features observed in lake bottom sediments for the workshop participants and the decision-makers with the responsibility for determining seismic source zones in eastern Canada. Overheads and slides of the original data presented at the workshop are included as figures.

The observed sedimentary features have spatial relationships with prominent geological structures and with geophysical lineaments which, in turn, have implications for geological constraint of seismic sources. These constraints aid in reducing uncertainty in seismic hazard analysis in the region. The use of lake sediments to disclose the presence of geological phenomena, such as recent surficial faulting, is of utmost importance in that deposits create the record, whereas on-land extensions of identified offshore features are often masked, having been subjected to subaerial erosion and may have been subjected to intense agricultural activity and urbanization. It is anticipated that similar surficial conditions would be found in other lakes if the appropriate investigations were undertaken.

The regional structural setting of master fractures in the Lake Ontario region includes the newly-documented South Ontario Structural Zone in the area of the St. Lawrence Rift extension as postulated by Adams and Basham (1989), the Clarendon-Linden extension through Lake Ontario and joining to the Salmon River Fault, the Niagara-Pickering magnetic expression of the Central Metasedimentary Belt Boundary Zone (CMBBZ) (Figure 1) (McFall et al, in prep.). There are other known and mapped faults around the lake basin area and extended through water covered areas on the basis of aeromagnetic signatures (Energy, Mines and Resources, 1987; Forsyth et al., 1989). Figure 2 is a schematic diagram of the Paleozoic rifts of eastern Canada, including the postulated Lake Ontario-Lake Erie extension (Adams and Basham, 1989). The speculated extension of this rift segment indicated the existing data to be examined more closely and lake bottom sections in Lake Ontario to be revisited and reexamined by geologists and geophysicists.

The eastern Lake Ontario - Rochester Basin area with the 1988 and 1989 echosounding track lines (A-K) and interpreted structural trends (a-g) in the South Ontario Structural Zone is given in Figure 3. Records obtained during 1988 and 1989 (Figure 4), using a conventional Atlas navigational echosounder operating at 32 kHz on track lines "A-K", show the interpreted traces

* Presented at the Workshop on Eastern Seismicity Source Zones for 1995 Seismic Hazard Maps, Observatory Hall, Geophysics Division, Geological Survey of Canada, Ottawa. March 18-19, 1991.

of faults "a-g". Steeply-dipping stratigraphic breaks are observed in the glacial and postglacial strata. These breaks are interpreted as post-depositional normal faults, rather than as topographically-controlled sediments deposited across a bedrock scarp, because neither slumping debris nor any obvious thinning of strata is evident. The interpreted linkages between the structures on adjacent lines are oriented at approximately 060°.

A southeast-northwest traverse towing a boomer reflection seismic system was made through the South Ontario Structural Zone in the epicentral vicinity of the 1925 May 23, Intensity III earthquake felt at Sodus Point, New York. The boomer reflection record (Figure 5), shows a normal fault cutting till, glaciolacustrine clay and Holocene basin muds. The reflection system did not penetrate to bedrock but did provide confirmation of the presence of major structures detected during the earlier echo soundings. This normal fault involves a consistent 13 m displacement of the stratigraphic horizons, indicating relatively recent movement. There is no means to determine a horizontal component, if any at this location, from this record. (Alan Ruffman later discussed this earthquake event in his after-dinner talk on tsunamis. It resulted in a tidal wave along 26 miles (42 km) of the American shoreline of Lake Ontario (Smith, 1962)).

The Lake Ontario bathymetry with 20 m contours (Figure 6) is a base for showing the outline location of the South Ontario Structural Zone (SOSZ), side scan sonar aviation investigation sites located at A, B and C, the approximate epicentral location for the 1987 July 23 Port Credit earthquake at D, a 1972 echosounding line (E) run southeasterly from Toronto, and the mid-lake Scotch Bonnet bathymetric rise and location of the 1974 echo-sounding line (F).

The 14.25 kHz echosounding line (F, Figure 6) obtained in 1974 over the Scotch Bonnet rise shows disruption of continuity of bedrock and overlying Quaternary materials across the bathymetric feature (Anderson and Lewis, 1975) (Figure 7). It is now widely believed that this is a surface expression of a part of the Clarendon-Linden Fault System in central Lake Ontario. It is important to note that the postglacial disturbance of the lake bottom on the Scotch Bonnet rise is located on the Iapetus margin (Wheeler, as presented by Adams, this meeting), perhaps documenting recent propagation, if not continuing rejuvenation, of this segment of the postulated Precambrian margin.

Figure 8 is a side scan sonar image of the lake bottom obtained in 1987 from south of Gibraltar Point, Toronto Island (A, Figure 6) showing the strong linear features rising to 2 m height above the lake bottom with sharply defined hinges characterized by what appear to be extension fractures. These linear features are interpreted to be pop-ups that have pierced through the relatively smooth clayey sediments. Figure 9 shows an angular bedrock pop-up rising above the surrounding soil cover near Plum Hollow, Ontario. Pop-ups are considered to be the cause of small earthquakes around the western end of Lake Ontario (Basham et al., 1982, p. 86). The presence of pop-ups, in addition to indicating relief of high horizontal stress in the rock, can therefore be used to define areas in which small earthquakes have occurred in the past. These events must have occurred either below the local instrumental detection threshold or they appear as a surficial expression in the geological record of prior earthquakes which are not otherwise being considered.

A plan view of the lake bottom near Toronto Island showing the pattern and abundance of the

linear pop-ups and their intersections is given in Figure 10. The lower diagram is a rose diagram of the orientations of the pop-ups, indicating a strong maximum orientation at 290°.

A laydown of side scan sonar records obtained from the Bronte site (B, Figure 6) showing dark linear patterns commonly caused by coarser particle sizes in a finer grained matrix (Figure 11). A working hypothesis for the formation of these features is liquefaction of a lower sandy horizon with ejection to and distribution on the present mud surface. (A preliminary evaluation of a postglacial sand dyke found in the Toronto area, attributed to earthquake-induced liquefaction and indicating two different seismic sources was presented by Mohajer at the workshop.) Also faintly visible in this figure is a plumose structure. Figure 12 illustrates a plumose structure observed in the side scan sonar records from site B. This sedimentary disturbance is about 1.5 km long, 70 m wide and is oriented at about 060°. A similar plumose feature was also observed at site C in Humber Bay. Sites B and C are located southwest and northeast respectively from the July 23, 1987 M3.4 earthquake located offshore from Port Credit at D in Figure 6. Strong northeasterly-trending aeromagnetic lineaments are present through this vicinity of the lake (Energy, Mines and Resources, 1987).

An echogram from Lake Ontario (Figure 13) shows a gas related disturbance or "pock-mark", features commonly found to be associated with disturbance of the stratified glaciolacustrine deposits. A side scan sonar record from Lake Ontario (Figure 14) shows an elliptically-shaped disruption of the surface sediment commonly interpreted as a natural gas blow-out scar. In cross-section, this feature could appear as a "pock-mark" in echosounding records. In New York State for example, information on fault-related degassing along the Clarendon-Linden Fault System, apparently initiated by local strong ground shaking related to the 1989 Saguenay earthquake, has been recently presented (Jacobi, 1990; Jacobi and Fountain, 1991).

A 14.25 kHz echogram (E, Figure 6), obtained in 1972 under the International Field Year for the Great Lakes, traversing to the southeast of Toronto and to the vicinity of the Central Metasedimentary Belt Boundary Zone (CMBBZ) aeromagnetic lineament is given in Figure 15. This section illustrates the steep bathymetric slope known as the Toronto Scarp and which is spatially related to an aeromagnetic lineament (Energy, Mines and Resources, 1987). Further offshore is the relatively smooth bathymetry of the lake bottom surface sediments and a faulted disruption of the glaciolacustrine clays found in the vicinity of the prominent CMBBZ aeromagnetic lineament. Similarly, highly faulted laminated sediments have been reported from bedrock lakes located more northerly along the CMBBZ (Kaszycki, 1987). In addition to the documentation of numerous reverse faults, fluid escape structures were interpreted on sub-bottom seismic profiles and a dike of fluidized sand was observed in an exposure. Figure 16 is of a side scan sonar record showing an elongate scar-like feature in the recent surface sediments of Lake Ontario, similarly located in the vicinity of the CMBBZ aeromagnetic lineament. The orientation of the scar-like feature is about 020°, similar to that of the Precambrian CMBBZ in the region. Degassing of bedrock fractures, and passing through the sediment in a manner similar to that reported on the Clarendon-Linden System in 1989, is postulated as a mechanism for formation of this recent feature.

It is apparent that many recent disturbances of the postglacial lake sediments exhibit spatial relationships with bedrock structures and to prominent geophysical anomalies in the lake area.

There is geological evidence in the South Ontario Structural Zone to support the southwesterly extension of the St. Lawrence Rift through Lake Ontario. In the Toronto to Burlington northwestern lake area, there is abundant evidence of recent deformation of bedrock and of overlying sediments. This identifiable area, which lies on the western side of the CMBBZ, has been named the Burlington-Toronto Structural Zone in Lake Ontario (Thomas et al, in prep.). The surficial deformation features have spatial relationships to aeromagnetic and Bouguer gravity anomalies which comprise and define the Zone. Earthquakes are known to have occurred and to be occurring in this area. The Burlington-Toronto Structural Zone may be traced, following the south-southwesterly trend of the CMBBZ aeromagnetic anomaly through the Niagara Peninsula, across Lake Erie to join the Akron Magnetic Boundary in eastern Ohio.

Sufficient information is now available that compels the forming of conclusions relevant to the delineation of seismic sources. If these conclusions are deemed to be alarmist, a thorough and professional review of all appropriate information by the decision-makers and responsibility-holders is required. It will be necessary to guard against using unwarranted assumptions, accepting opinion over fact, using biased analytical methods, failing to ask the right questions, failing to ask any questions of those who might know the answer, perpetuating a lack of research depth and breadth and supporting a lack of basic knowledge. It is necessary either to include and account for the geological facts in the derivation of seismic source zones in this populated area or to clearly and unequivocally state reasons for the non-inclusion of that which is widely considered to be pertinent information.

It is considered that there are means to reduce the high degree of uncertainty found in earlier attempts at seismic source zoning in this region. Seismic sources may be responsibly defined on the basis of integrated geological and geophysical information. Opinions which express little or no seismic hazard in the western Lake Ontario region should be changed.

Acknowledgements

Sincere appreciation is extended to colleagues in the Multi-Agency Group for Neotectonics in Eastern Canada (MAGNEC) for open discussions of geological and geophysical information at meetings held over the last few years and on which this presentation was based. Specific acknowledgement is made to Richard Thomas for materials utilized from a manuscript currently in preparation on studies in Lake Ontario. Recognition is also extended to the Canadian Aviation Safety Board and to the crew of the CSS LIMNOS.

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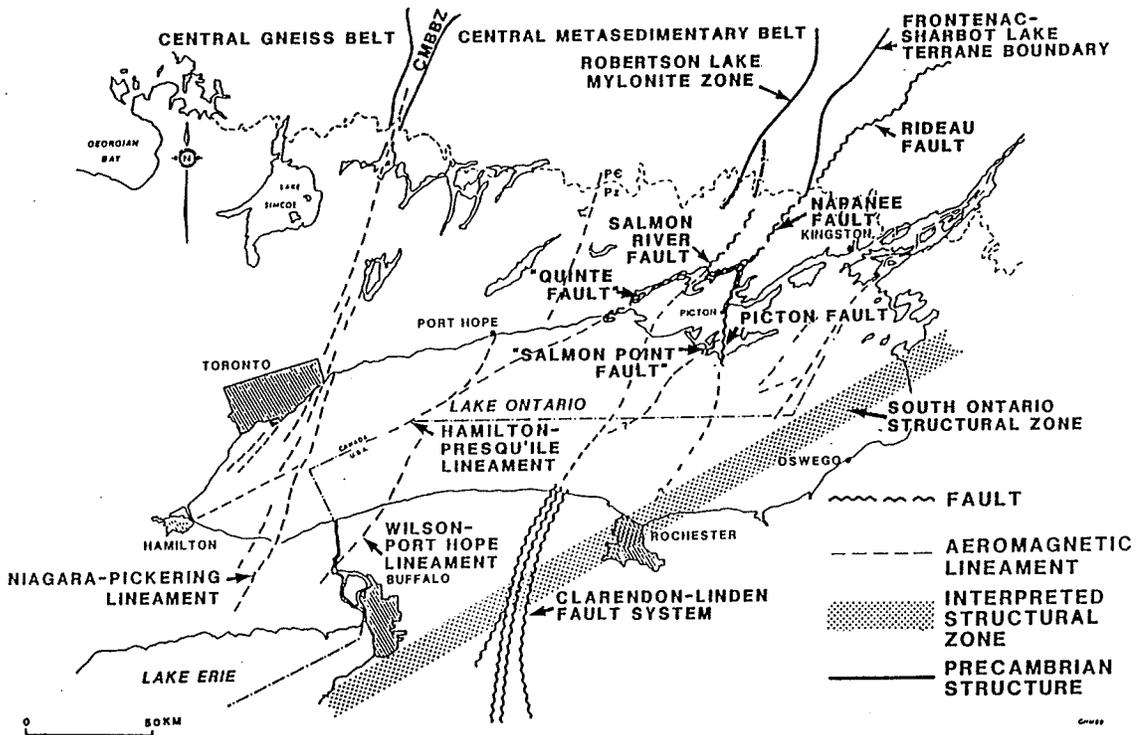


Figure 1: Fracture Framework model for the Lake Ontario region. Interpretation is based on known faults, preliminary identification of aeromagnetic lineaments from Geological Survey of Canada Maps 7333G and 7334G, Precambrian geology taken from Easton et al. (1990) and Ontario Geological Survey (1991), and the South Ontario Structural Zone taken from Thomas et al. (in prep).

FIGURE 1.

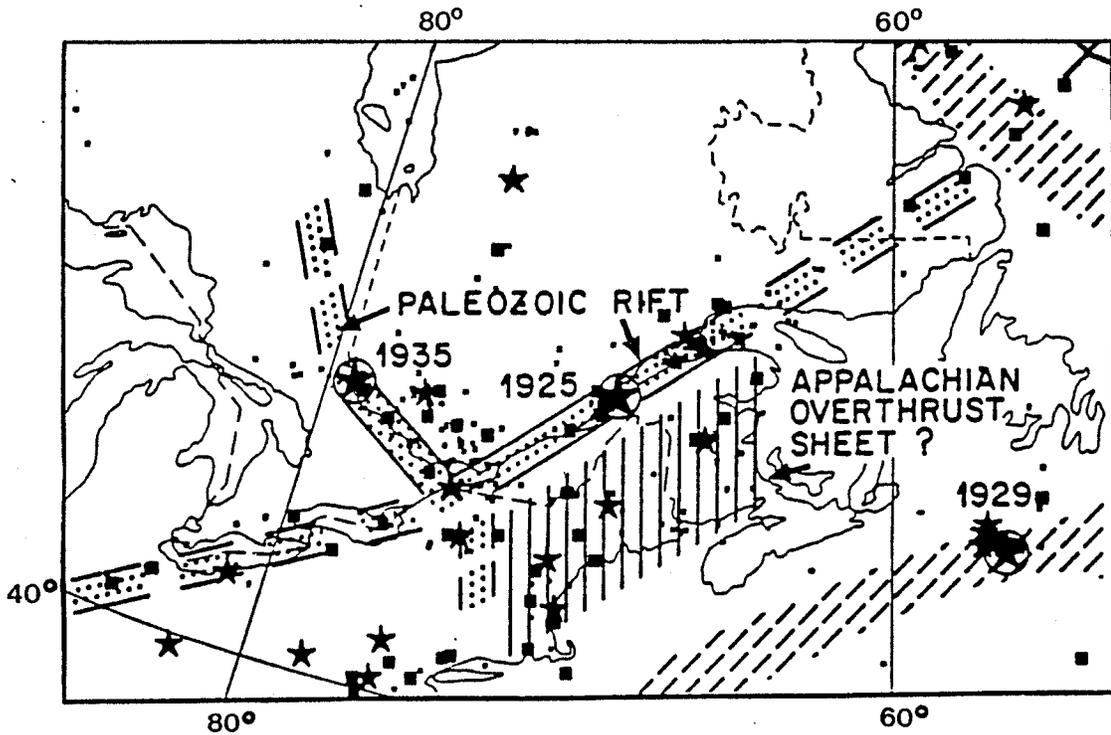


FIGURE 2.

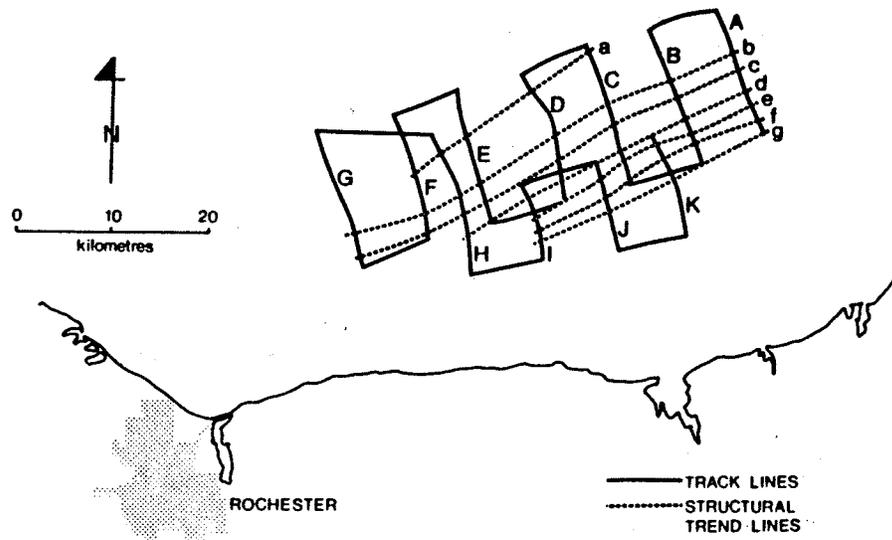


FIGURE 3.

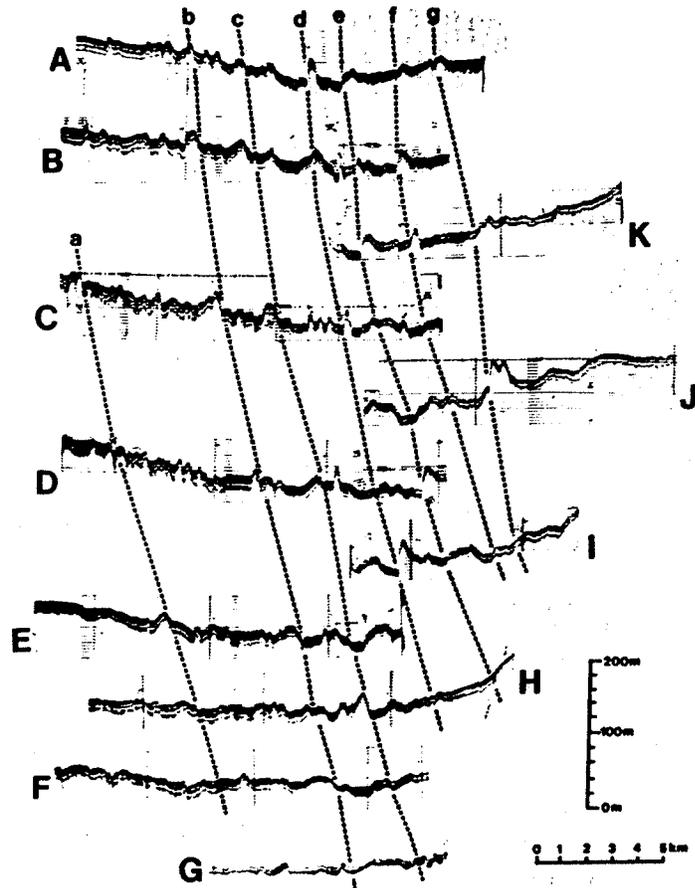


FIGURE 4.

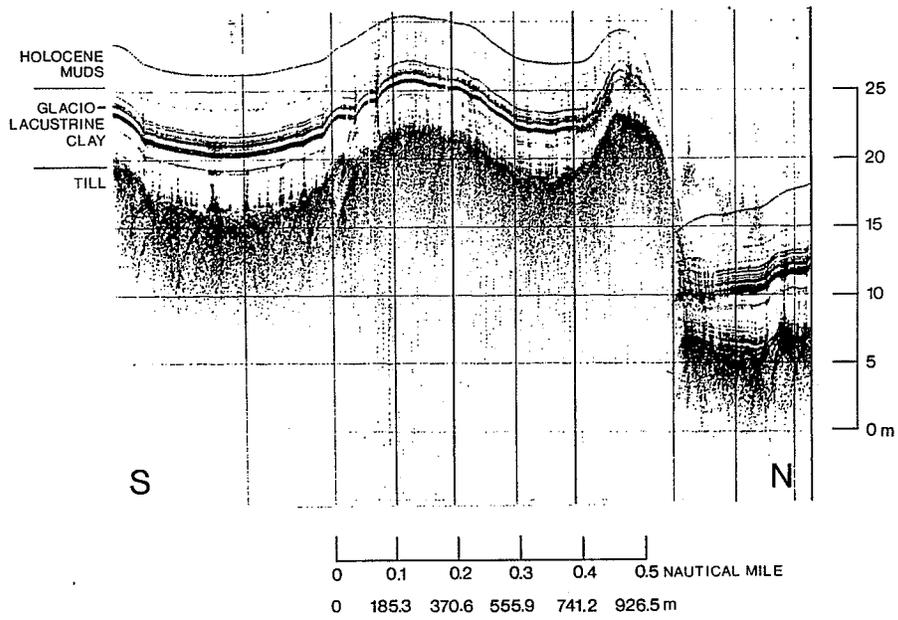


FIGURE 5.

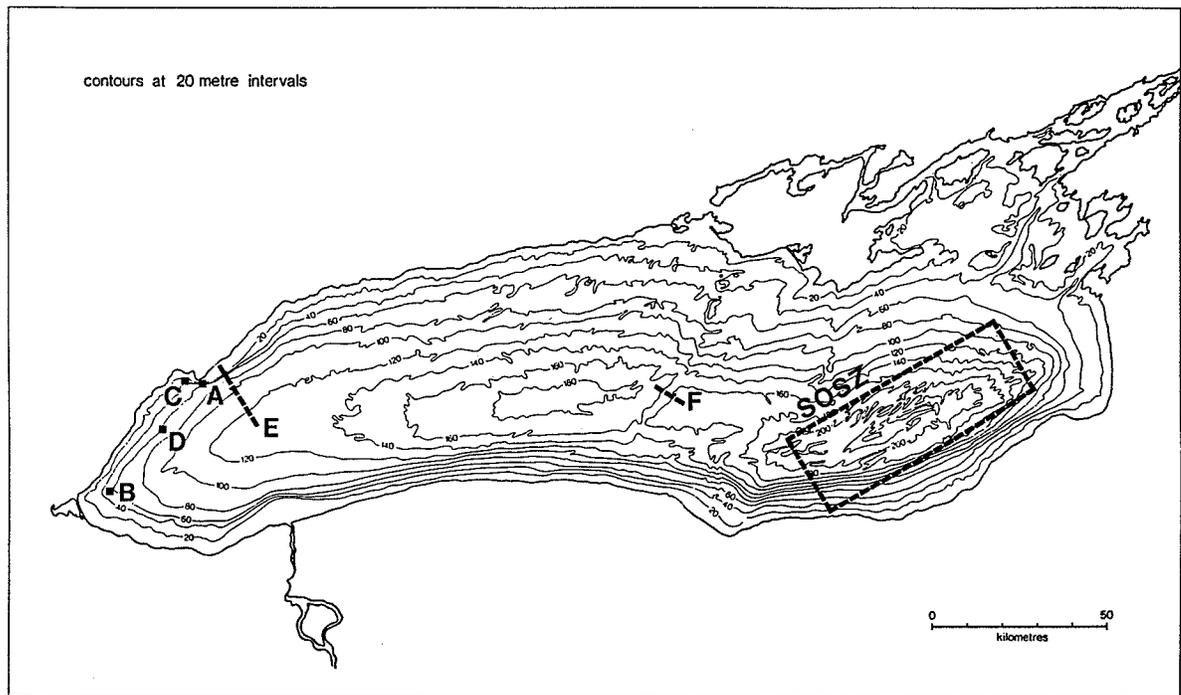


FIGURE 6.

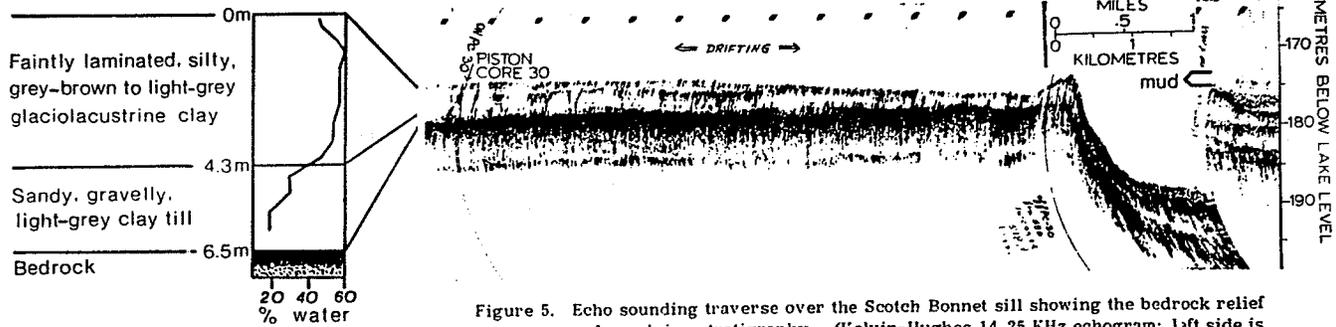


Figure 5. Echo sounding traverse over the Scotch Bonnet sill showing the bedrock relief and overlying stratigraphy. (Kelvin-Hughes 14.25 KHz echogram: left side is southeast and right side is northwest.)

375

FIGURE 7.

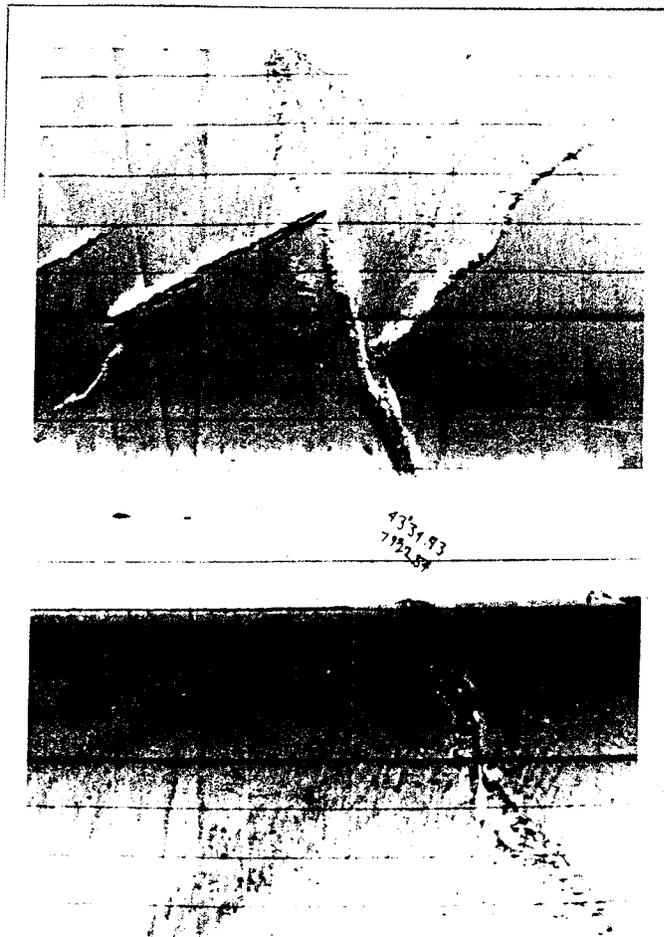


FIGURE 8.



FIGURE 9.

POP-UP IN NEPEAN SANDSTONE BEDROCK AT PLUM HOLLOW

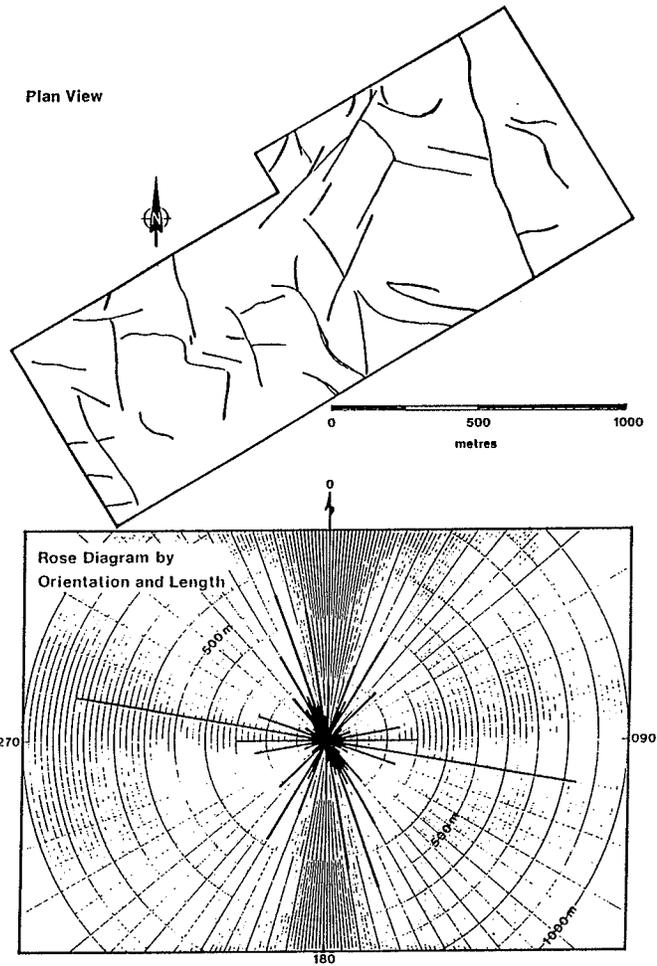


FIGURE 10.



FIGURE 11.

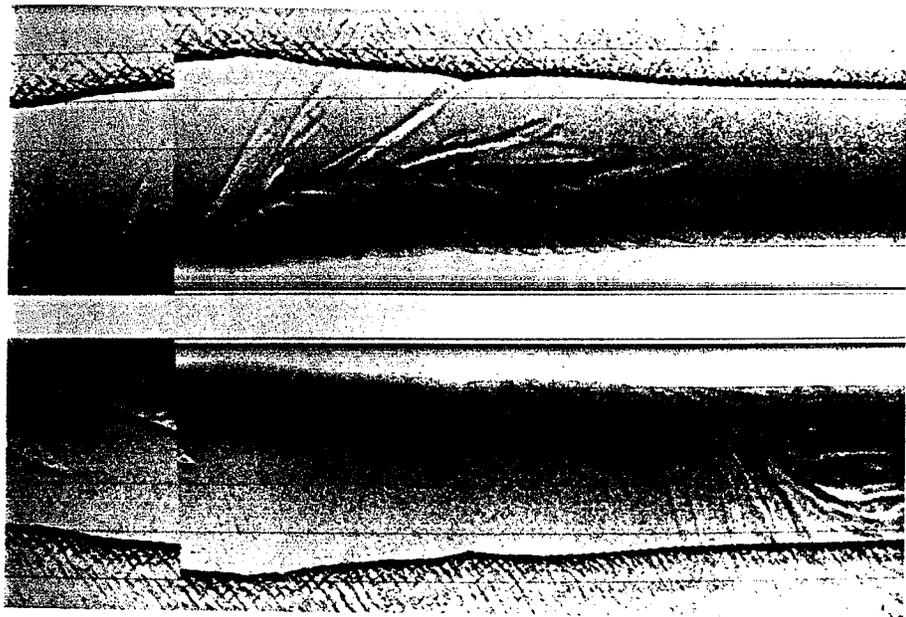


FIGURE 12.

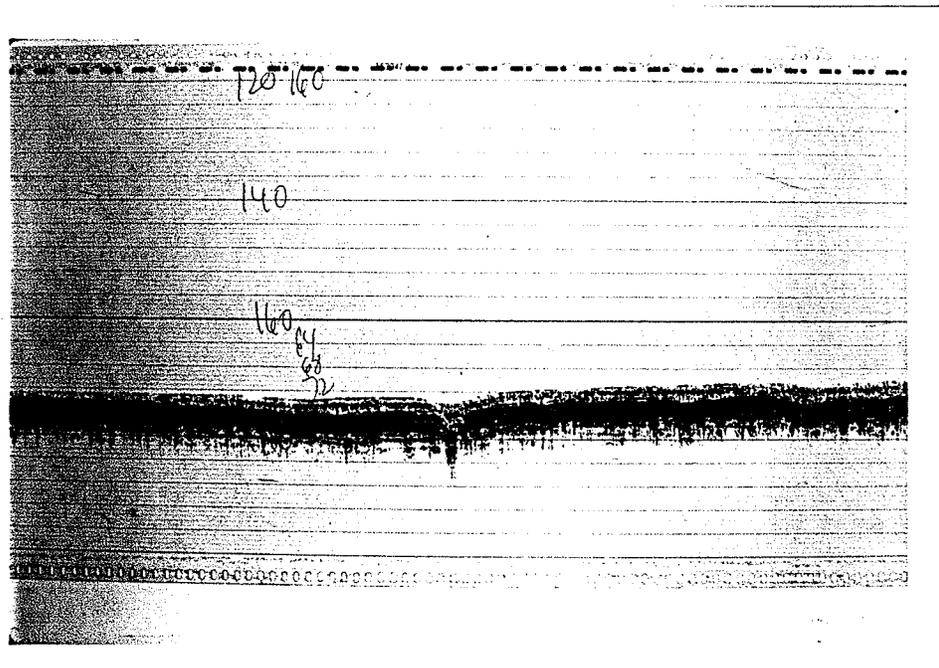


FIGURE 13.

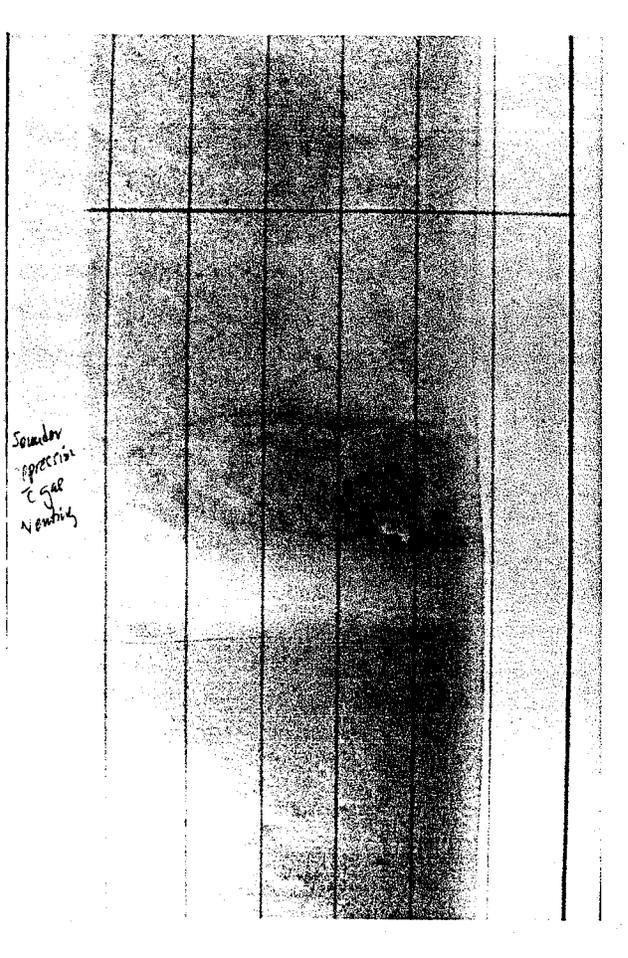


FIGURE 14.

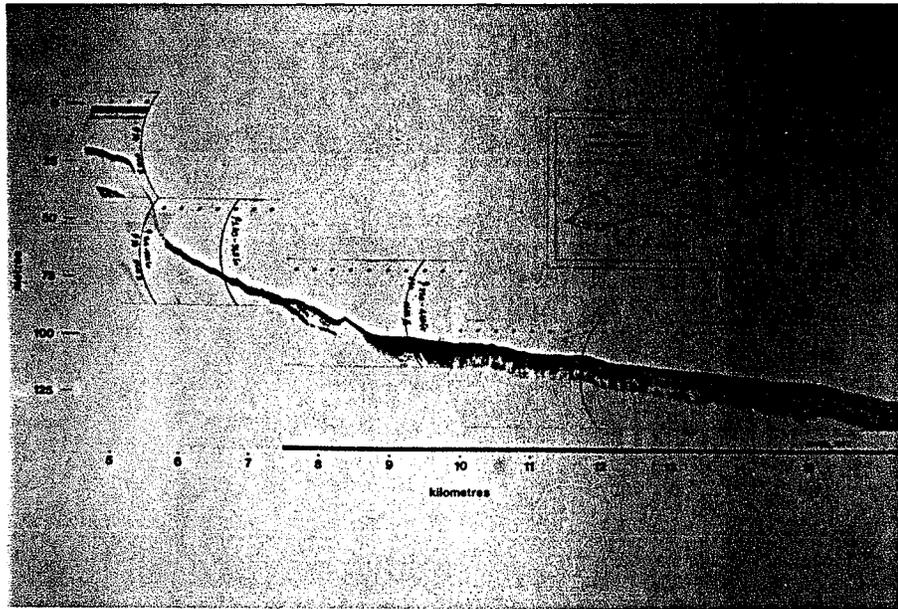


FIGURE 15.

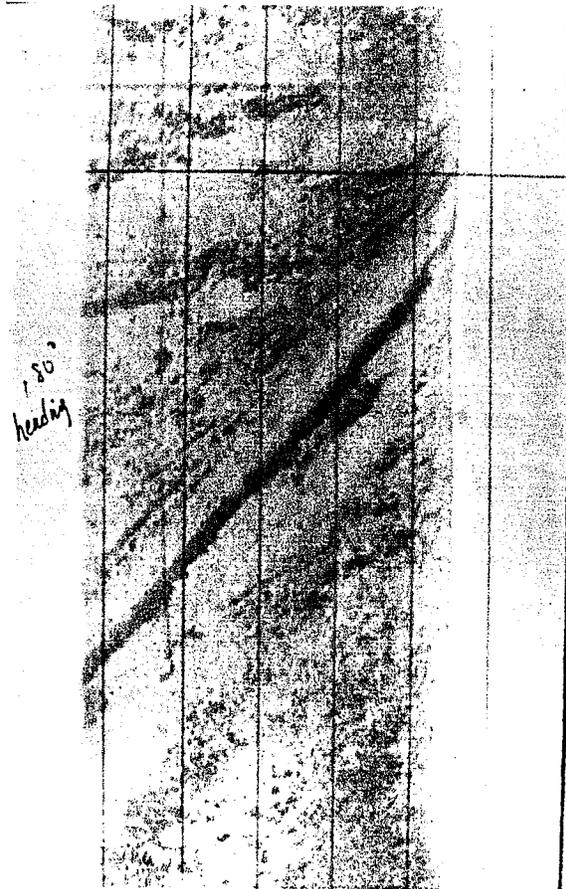


FIGURE 16.

NEOTECTONICS ASSOCIATES

GEOLOGY - GEOPHYSICS - REMOTE SENSING
40 Davean Drive
North York, Ontario M2L 2R7
Telephone: (416) 449-2174 Fax: (416) 596-8270

April 15, 1991

Dr. J.E. Adams
Seismology, Geophysics Division
Geological Survey of Canada
1 Observatory Crescent
Ottawa, Ontario
K1A 0Y3

Dear Dr. Adams:

Re: Workshop on Eastern Seismicity Source Zones

As requested at the close of the above Workshop, I enclose a prepared summary of my presentation made at the Workshop on Eastern Seismicity Source Zones for the 1995 Seismic Hazard Maps of the National Building Code of Canada. Please include this as my contribution to the Workshop.

Geological evidence of deformation along the extension of the southern margin of the postulated St. Lawrence Rift (Adams and Basham, 1989) and through the southeastern part of Lake Ontario was presented. Geophysical evidence for a sub-parallel, northern margin of this postulated lower Great Lakes extension through the north and northwestern part of the lake was also discussed. It seems incongruous that there was no record made of the geological evidence for extension of this major geological feature, especially with the presence given to the SLX "geology-controlled" model for the definition of the more easterly St. Lawrence Rift in the record of the meeting (for example Adams, this document). The Lake Ontario geological information should be included in the record of the meeting and somehow factored into future seismic hazard assessments of the urban areas in southern Ontario around the lower Great Lakes.

There are some aspects of Milkereit's presentation on Deep Great Lakes Structure that must be addressed. I feel that it is not accurate to report that "no" vertical offset on the Trenton unconformity is observed without providing more detailed information on the data processing techniques applied. For example, the common depth point, either selected or default, for output display of the processed data in each of the sections should be known. The sections shown by Milkereit were located within the boundaries of the speculated extension of the St. Lawrence Rift (Adams and Basham, 1989) and did not cross the postulated or proposed margins in the lower lakes. The central issue in the discussion is that the summary deep seismic profile shown was

represented as an east-west section in Lake Ontario and particular emphasis was placed on the crossover area of the Central Metasedimentary Belt Boundary Zone (CMBBZ) structure in western Lake Ontario. It was acknowledged that the profile section in question had been constructed from various separate sections located in eastern Lake Erie and central and eastern Lake Ontario. The section, represented by Milkereit as being in western Lake Ontario, was in fact transposed more than 75 km from eastern Lake Erie.

A pertinent observation made in the discussion period was that the eastern Lake Erie section line, as illustrated by Milkereit on an aeromagnetic base, did not appear to extend far enough to the west to include the aeromagnetic signature of the CMBBZ in Lake Erie. The probable link between the Akron Magnetic Boundary in eastern Ohio and the Niagara-Pickering magnetic lineament expression of the CMBBZ in Lake Ontario had previously been clarified by Klimkewitz (this meeting). The contrasting aeromagnetic character juxtaposed across the CMBBZ in Lake Ontario (GSC Map 7334G) can be followed to the southwest and traced into the eastern Ohio feature. The seismic section from Lake Erie was apparently taken from a line located wholly to the east of the CMBBZ and within the Central Metasedimentary Belt. This profile was represented as coverage of, from east to west, the Elzevir terrane, CMBBZ and the Central Gneiss Belt in Lake Ontario. The completeness of this interpretation is questioned, even at the source location in eastern Lake Erie. The thrust fault reported as dipping at 30° to the southeast is most probably found within the Elzevir terrane portion of the Central Metasedimentary Belt and therefore does not mark either the boundary or the boundary zone.

The Paleozoic strata in this region are extensively documented to have southwesterly to southerly regional dips and are observed and reported to be faulted. The Precambrian surface is also known from deep boreholes to exhibit a similar regional trend and it is well documented that major crustal sutures such as the CMBBZ are present within these rocks. The Ordovician Trenton strata are deeply eroded to form the bedrock underlying much of Lake Ontario, whereas overlying Silurian and Devonian strata form the bedrock underlying Lake Erie. To transpose a complete Trenton section from Lake Erie misrepresents the real geologic condition found in Lake Ontario.

In summary, the transposition of data across both the regional geophysical and structural geology trends to make the statement of "no vertical offset on the Trenton unconformity within the Paleozoic rocks" leads to the unsubstantiated conclusion that there is, therefore, evidence for no faulting of the Paleozoic rocks in Lake Ontario. This is misleading. The data presented by Milkereit on the Paleozoic strata do not permit such an encompassing assessment to be made.

As had been indicated in my presentation and is included in the attached summary, it is apparent that there are geological evidences for recently faulted disturbances and displacements of the lake bottom and possible postglacial rejuvenation of the structural system along and throughout the postulated extension of the rift system. Consequently, the conclusion by Milkereit that "there is no through-going post-Paleozoic rift in Lake Ontario" may not be valid, and may be spurious.

I hope that the record of the session can reflect the issues that were revealed in the discussion because of the potential uses and impacts which may arise from opinions expressed in this workshop. The significant question which was placed before this workshop was whether or not

the faults, folds and fractures found in Quaternary materials and Paleozoic rocks, both in and nearby to Lake Ontario, are genetically related to the underlying and deep-seated Precambrian faults and may thereby have a direct bearing on the quantification of seismic hazard parameters for this region.

I trust that the enclosed material will help meet the need for improved information on the surficial locations of deformations which may, in turn, be related to seismic sources in the region. It is my opinion that such geological information should be included in seismic hazard assessments for the urban areas in southern Ontario around the lower Great Lakes. If I may be of any further assistance, please call me at (416) 449-2174.

Yours sincerely,



John R. Bowlby, M.Sc., FGAC
Geologist

Enclosure

cc:

Dr. J.S. Scott

Dr. J.L. Wallach

Dr. P.C. Thurston

Dr. P. Talwani

Chairman, MAGNEC

Secretary, MAGNEC

Ontario Geological Survey

University of South Carolina

ESTIMATING MAXIMUM MAGNITUDE FOR STABLE CONTINENTAL REGIONS

A report for the Geological Survey of Canada
Workshop on Eastern Seismicity Source Zones
for 1995 Seismic Hazard Maps
March 18-19, 1991

Arch C. Johnston
CERI/Memphis State University
Memphis, Tennessee 38152 USA

I will begin this report by stating a few of my opinions—or prejudices—about seismic hazard characterization in stable continental regions (SCR).

- Defining seismic source zones (SSZ) is the weak link in the whole process of seismic hazard estimation. It's not pure science, but at best, judgment; at worst, guesswork.
- A SSZ is not a physically real, distinct entity; it is an admission of ignorance, an acknowledgment of our lack of knowledge of the true seismic sources (faults!) in the SCRs.
- The process of delineating an SSZ is controlled by two factors: (1) grossly dissimilar crust should not be combined into a single SSZ, i.e., foldbelts with cratons or recently rifted crust with either of those categories; (2) the maximum magnitude, M_{max} , earthquake that you're willing to assign.

Thus I would argue that within general crustal geological constraints, SSZ choice is controlled by M_{max} not a or b values from a frequency-magnitude relation. Let me illustrate this briefly using as an example the region I'm most familiar with—the central United States.

Figures 1-3 show the seismicity of the central U.S. at progressively higher magnitude limits. Even at the lowest cutoff level of all felt events—roughly $M \sim 2.5-3.0$ —the distribution of epicenters is decidedly non-random, exhibiting a concentration in the upper Mississippi Valley. For $M \geq 5$, the concentration is even more apparent. At $M \geq 6$ the only known central U.S. earthquakes are in the relatively young extended-crust environment known as the Reelfoot rift complex of the upper Mississippi embayment (from Johnston and Nava, 1990).

Within the Reelfoot rift, which has undergone several episodes of crustal extension from late Proterozoic/early Paleozoic to Cretaceous, present-day seismicity concentrates tightly in several linear clusters (Figure 4), commonly taken as delimiters of the source zones of the great earthquakes of the 1811-1812 sequence. Aside from seismicity, however, until recently there was no geologic/tectonic reason to zone the seismically active areas separately from the rest of the rift complex. Now a subsurface arch of disrupted reflectors has been imaged for the SW and part of the central zone of seismicity (Hamilton and McKeown, 1988; McKeown et al., 1990). Thus for the overall rift complex, I assigned an M_{max} of $m_b = 6.5$ ($M = 6.6$) (see Figure 5; Johnston and Nava, 1990)—which I would now most likely increase to $M_{max} = M7.0$ —but I

break out a subzone for which $M_{max} \geq M8.0$ on the basis of the historical great earthquakes and a specific tectonic structure in association with enhanced current seismicity.

New Madrid admittedly is a special case because we believe it has experienced its maximum earthquake in historic time. For other areas in SCRs other methods are necessary. The traditional methods for estimating M_{max} either flatly don't work in SCRs or don't inspire confidence. They include:

- taking the maximum historical event and to be conservative adding +0.5 magnitude units. One problem is that the magnitudes of the larger historical earthquakes are poorly known, hence controversial.
- extrapolation of a zone's frequency-magnitude relation to the earthquake with a 1000-year recurrence interval. This is also usually area normalized, eg, per 100,000 km². While this approach will yield an answer, its prominent drawback is that it is arbitrary, hence not especially defensible.
- maximum fault dimensions. (a fault is the seismic zone in active tectonic regions). This doesn't work in SCRs because only in very rare cases can we identify the fault on which an SCR earthquake occurred. Note that SSZ dimensions have nothing to do with the M_{max} fault dimensions except in special cases like New Madrid and perhaps Charlevoix and Giles County, Virginia.
- Relating M_{max} to strain/slip/moment release rates. This technique is just beginning to be explored in the literature. It may be quite useful when these rates become better known, but for now it could not be generally applied in SCRs.

An approach that I would like to outline in the remainder of this paper is more straightforward (or simpleminded), but it is one that can be applied in stable continental regions. One can examine the global record for continental regions similar geologically and tectonically to eastern North America (ENA) and use it as a guide for M_{max} . In this sense a more widely cast net over the spatial data base is substituted for an inadequately short ENA temporal window. One must admit and be aware that even the global SCR record is incomplete, but significant exceptional events should be so rare they can be tolerated in hazard analysis in a probabilistic sense.

Global Characteristics of Stable Continental Crust

For the past five years I've been involved with a project for the American Electric Power Research Institute (EPRI) doing just such a global analysis of stable continental region seismicity (EPRI, 1991). I'll now take a brief look at some of the conclusions of that study and apply them to the problem of M_{max} estimation in eastern North America.

A generalized definition of SCR crust is continental crust that has not experienced significant compressional (orogenic) tectonic activity since the early Cretaceous (~65-75 mya), nor significant tectonic extensional activity (principally rifting) since the Neogene (~25-30 mya). For a

more detailed definition, refer to Figure 6. Extensional tectonics were allowed to be active to more recent times in order not to exclude the SCR passive margins or some important imbedded rifts such as the Rhinegraben of Europe. Thus SCR North America (Figure 7) includes all of the continent east of the Rocky Mountain Cordillera. The reader is referred to EPRI (1991) for a detailed description of the SCRs of Australia, North and South America, Europe, Africa, Asia (Russia), India, southeast China, and Antarctica.

Young (post-early Mesozoic/late Paleozoic) rifted continental crust is emphasized in the EPRI study because its major and unanticipated result is that large SCR earthquakes strongly concentrate in such crust. This type of thinned and stretched or extended crust comprises only about 25% of SCR crust (which itself comprises nearly two-thirds of all continental crust), but fully one-half (51%) of the EPRI seismicity data base has an extended crust association. Moreover, the association becomes stronger for larger magnitudes: 68% of the SCR data base, $6.0 \leq M < 7.0$, is associated with extended crust and 100% of the SCR $M \geq 7.0$ earthquakes occur there.

Older, Paleozoic-age rifts also have produced some large magnitude-6-range events, but all SCR earthquakes $M \geq 7$ are found in crust that suffered extension in the Mesozoic or Cenozoic (Figure 8; Johnston and Kanter, 1990). These rare, $M7$ events are found almost equally in failed intracontinental rifts (two-sided) and the bordering regions of successful, one-sided rifts (passive margins). Major passive margin earthquakes can occur on or near to the continental slope (Baffin Bay, Grand Banks, Exmouth Plateau, South Tasman Rise) or well inboard of the slope (Charleston, Libya, Nan'ao, Taiwan Straits), but where presumably young faults that developed during the rifting process are still available for reactivation.

What about the three-fourths of SCR crust that has not undergone a significant extensional tectonic phase in the Phanerozoic? I am by no means suggesting that such a crustal environment may be ignored, for significant earthquakes capable of structural damage have occurred in such regions. It's just that from a global perspective such crust—along with intraplate ocean basins—is the most aseismic on earth. Preliminary seismic moment release rate computations indicate it is nearly two orders of magnitude less seismically active than SCR extended crust, which itself accounts for only ~0.5% of the earth's total seismic moment release.

One major category of non-rifted SCR crust is Paleozoic/early Mesozoic foldbelts. Examples are the Ouachita/Appalachian system of North America, the South African Cape foldbelt, eastern Australia (which may be better characterized as an accreted terrain complex), the Transantarctic Mountains, and the Urals of Eurasia.

In defining Paleozoic foldbelts as a separate type of SCR tectonic domain, I have differed somewhat with Rus Wheeler's Iapetan margin model. As applied to the Appalachians, he emphasized the basement faults from the previous Wilson cycle rifting episode rather than crust involved in the foldbelt evolution itself. Such a model works well for ENA, but I believe it would be difficult to apply to foldbelts in general. In any case, in comparison with young extended SCR crust, Paleozoic foldbelts worldwide are very aseismic, on a par with the

Precambrian cratonic areas. Major orogenies, such as the Ouachitas and the Urals, have no known seismicity above the low magnitude 5 level.

Finally we come to the continental shields and cratons. Large ($M \geq 6$) earthquakes in such regions are rare. In Figure 9 I list these events that are known with confidence from good instrumental or exceptionally good intensity data. They are very few; Australia's Precambrian crust produced an inordinately large percentage of them and also has more known instances of surface rupture than any other SCR despite its comparatively small craton/shield area. Why this might be so is not well understood. Perhaps it is because the crust is subjected to a higher level of deviatoric stress than other SCRs, arising from the continent-continental arc collision along its northern boundary. If this is the cause, however, one would expect SCR India to exhibit a similar level of cratonic activity, which is not the case.

Conclusions

From this brief overview of global seismic activity in stable continental regions I will conclude by letting the SCR data base serve as a guide for M_{max} estimation in ENA.

- For passive margins and well-oriented, (perhaps "wet") intra-continental rifts, Mesozoic or younger: $M_{max} = M \sim 7.5-8.3$. For Paleozoic extended SCR crust (such as the St. Lawrence rift): $M_{max} = M \sim 7.0-7.5$.
- The EPRI (1991) study provides little input to the question of how to subzone for M_{max} within extended crust SSZs. I don't think post-glacial rebound, sedimentation rate, or transform-vs-rifted margin works well in this regard. Perhaps intersecting features or observed level of seismicity are most useful by default; we have no reliable guides at present. Most seismologists would assign a considerably higher M_{max} to the Canadian Atlantic passive margin than the U. S. Gulf of Mexico margin without good physical reasons other than the observed level of seismic activity.
- For cratons and shields: $M_{max} = M \sim 7$ for Australia and $M \sim 6.5-6.8$ for all others, although I don't have firm explanations why Australia should be higher.
- For Paleozoic foldbelts: $M_{max} = M \sim 6.5-6.8$, same as for cratons.

References

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Central United States Seismicity 1627-1985

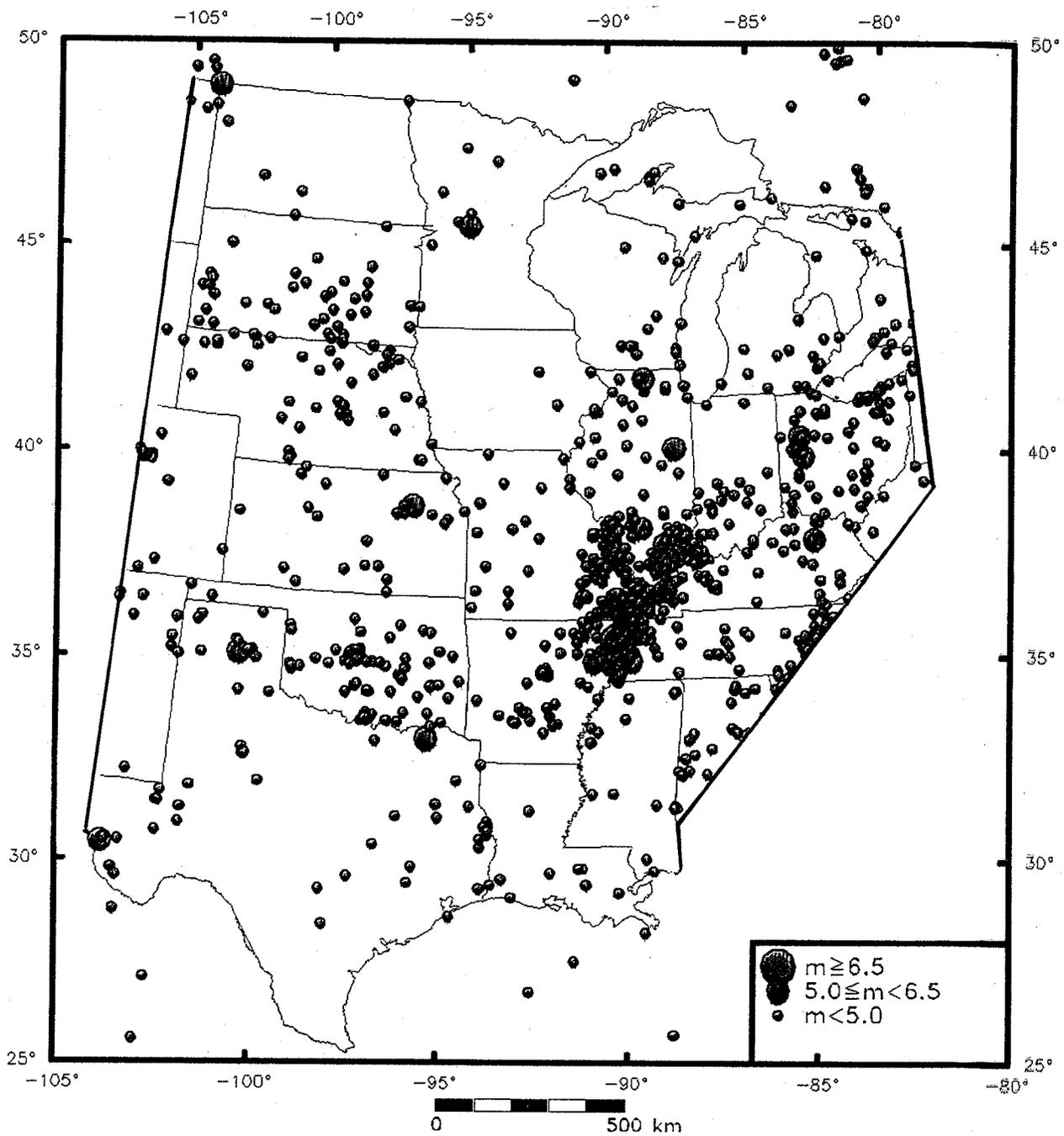


Figure 1. Felt earthquakes ($M > 2.5-3.0$) of the central United States.

Central United States Seismicity 1811 – 1987 Magnitude ≥ 5.0

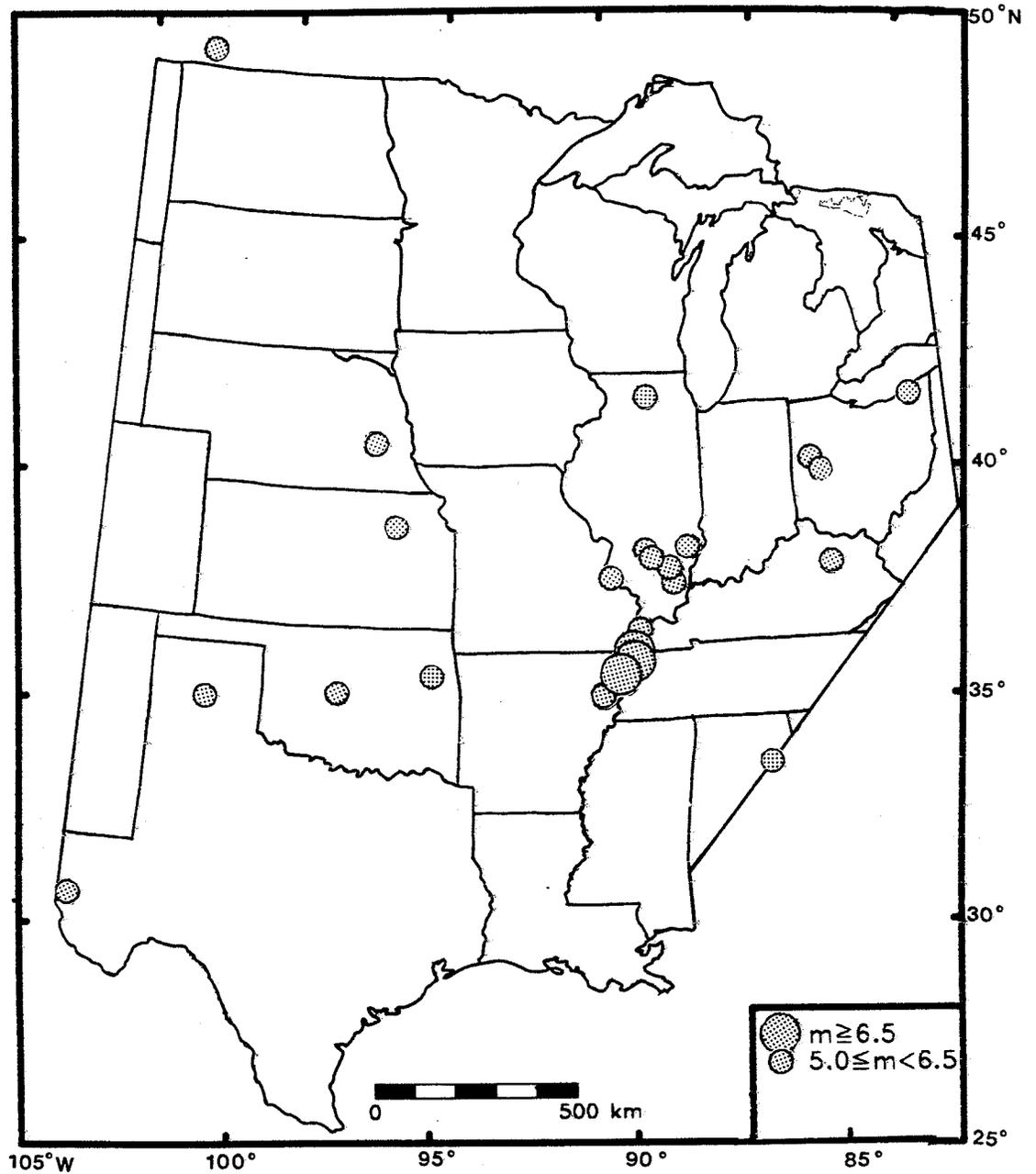


Figure 2. Seismicity of the central United States, $M \geq 5.0$.

New Madrid Seismic Zone 74 -87

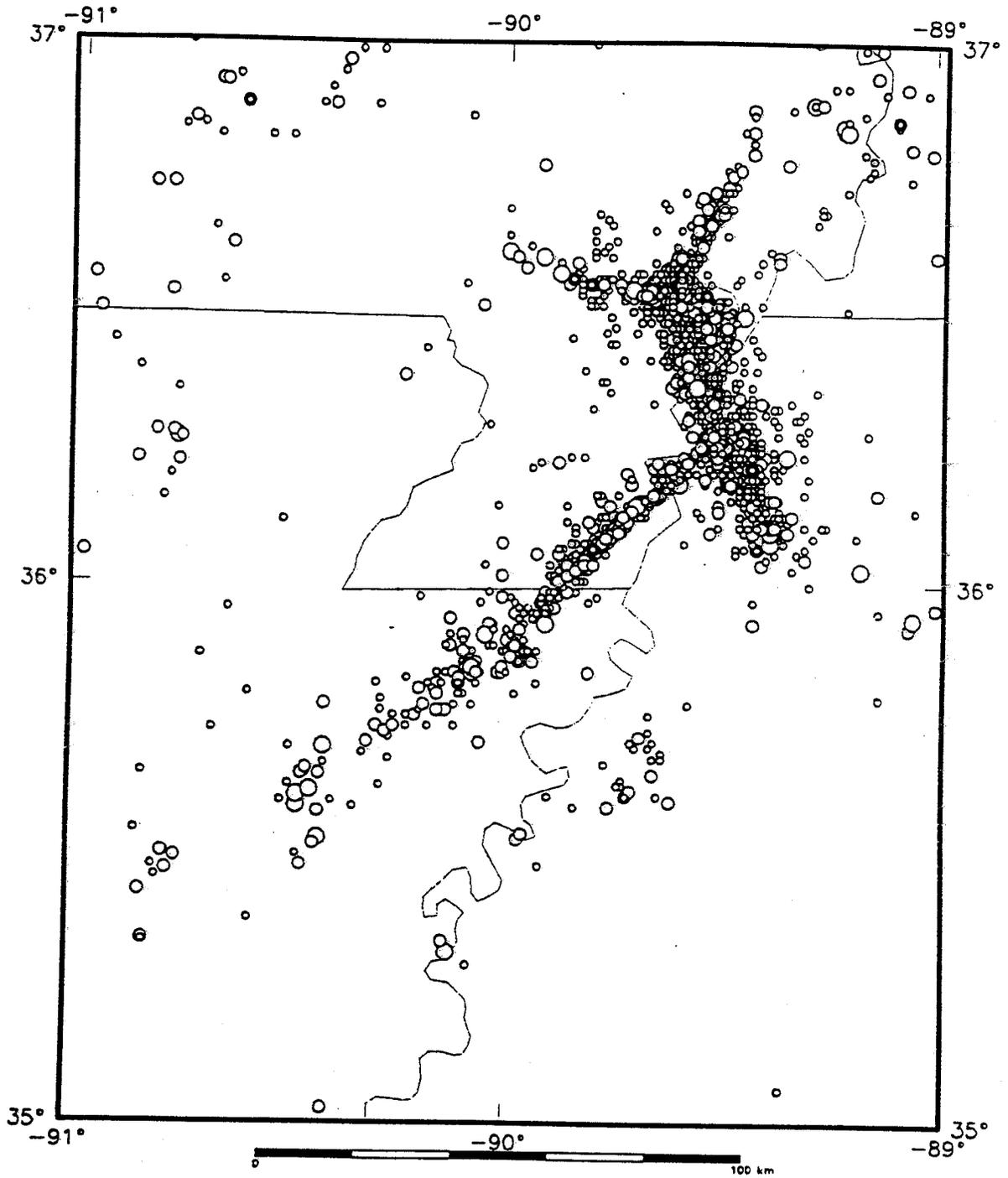


Figure 4. Recent instrumental seismicity of the New Madrid seismic zone, central U. S.

Central United States Seismicity 1811 - 1987 $M \geq 6.0$



Figure 3. Seismicity of the central United States, $M \geq 6.0$.

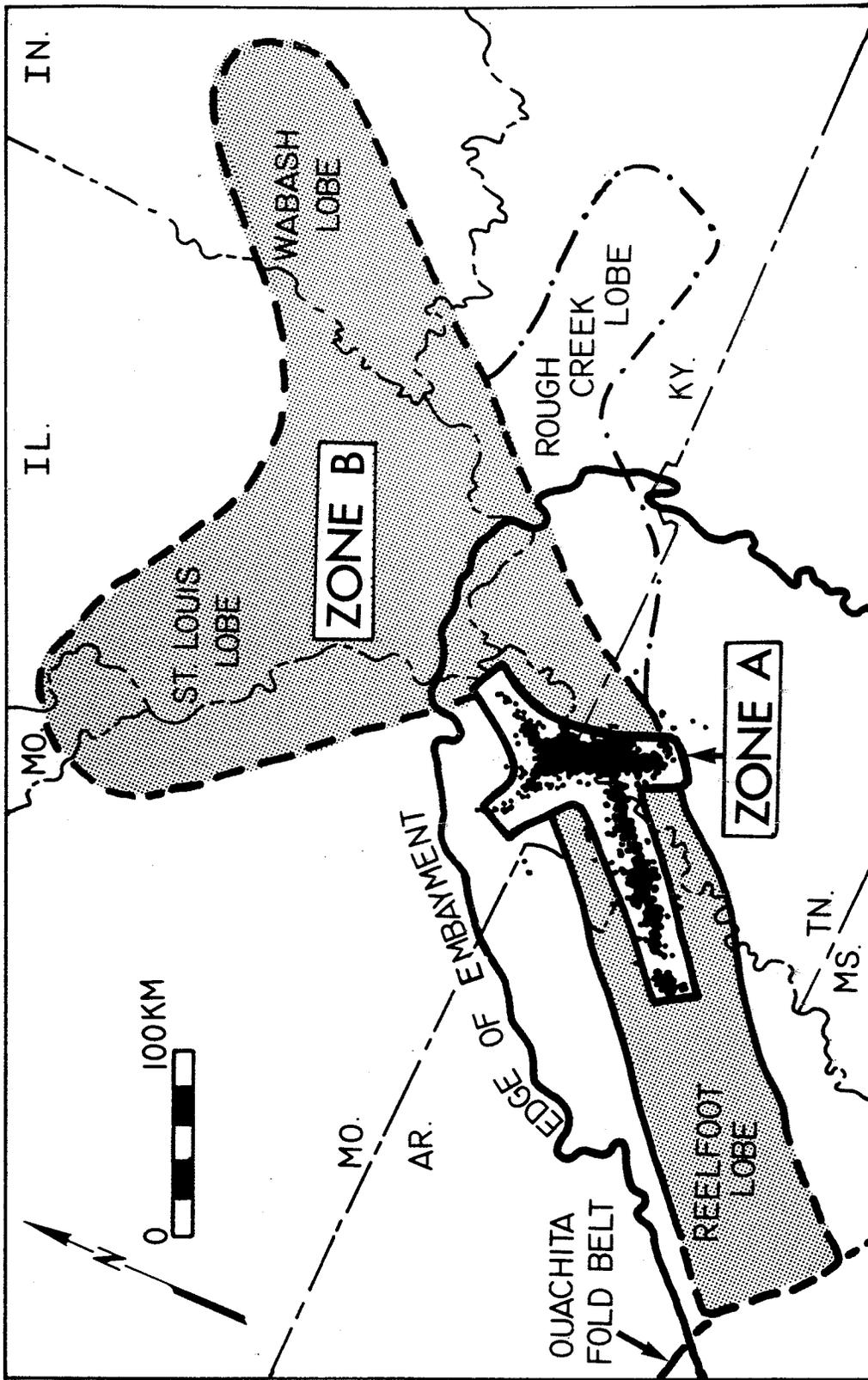


Figure 5. Seismic source zonation of the New Madrid seismic zone (from Johnston and Nava, 1990).

DEFINING STABLE CONTINENTAL REGIONS

REQUIREMENTS:

1. Any orogenic activity is Early Cretaceous or older
2. Any rift/strike-slip activity is Paleogene or older
3. Deformed forelands of post-Cretaceous orogenic belts are excluded

INCLUDES:

1. Shields and platforms
2. Ancient orogenic belts
3. Ancient embedded (failed) rifts
4. Passive margins, including crust transitional between continental and oceanic

Figure 6. Detailed criteria for stable continental crust
(from *EPRI*, 1991).

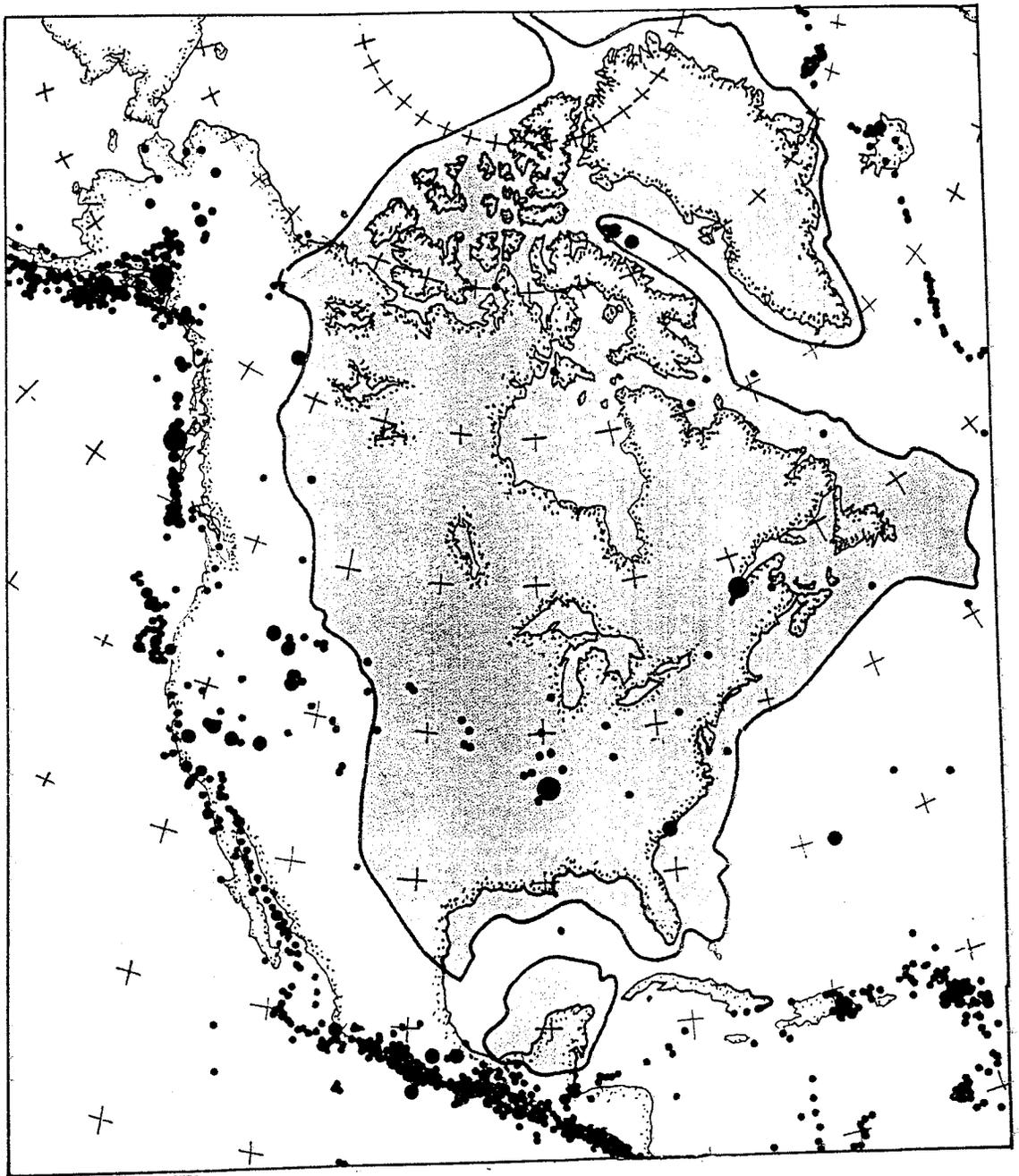


Figure 7. The North American SCR (bold outline)
(from EPRI, 1991)

Figure 8. The largest ($M \geq 7$) SCR earthquakes
(from Johnston and Kanter, 1990; EPRI, 1991).

	<u>Continent</u>	<u>Event</u>	<u>Host Structure</u>	<u>Method for M</u>	<u>M (uncert.)</u>
1.	North America	New Madrid, 1812	rift	Isoseismal radii	8.30 ± .5
2.	North America	New Madrid, 1811	rift	Isoseismal areas	8.20 ± .35
3.	North America	New Madrid, 1812	rift	Isoseismal radii	8.09 ± .5
4.	India	Kutch, 1819	rift	Fault area, slip/MMI	7.79 ± .3
5.	North America	New Madrid (aftershock)	rift	Isoseismal radii	7.76 ± .5
6.	North America	Baffin Bay, 1933	passive margin	Surface wave M_0	7.70 ± .2
7.	China	Taiwan Straits, 1604	passive margin	Isoseismal areas	7.65 ± .35
8.	North America	South Carolina, 1886	passive margin	Isoseismal areas	7.56 ± .35
9.	China	Nan'ao, 1918	passive margin	Instrumental M_S	7.42 ± .25
10.	North America	Grand Banks, 1929	passive margin	Surface Wave M_0	7.38 ± .2
11.	China	Hainan Isl., 1605	rift	Isoseismal areas	7.26 ± .45
12.	Australia	Exmouth Plat., 1906	passive margin	Instrumental M_S	7.20 ± .25
13.	Africa	Libya, 1935	passive margin	Instrumental M_S	7.09 ± .25
14.	Europe	Portugal, 1858	passive margin	Isoseismal areas	7.09 ± .45
15.	Australia	S. Tasman Rise, 1951	passive margin	Instrumental M_S	6.99 ± .25

Figure 9. Precambrian Craton/Shield Earthquakes
 $M \geq 6$ (mostly instrumental)

	<u>EVENT</u>	<u>MAGNITUDE</u>	<u>FAULT TYPE</u>	<u>SURFACE RUPTURE</u>
<u>Australia</u>	1941 Meeberrie	$M = 6.8$	thrust	no
	1968 Meckering	$M = 6.6$	thrust	yes
	1970 Cadoux	$M = 6.0$	thrust	yes
	1979 Calingiri	$M = 6.1$	thrust	yes
	1988 Tennant Creek	$M = 6.2$	thrust	yes
		$M = 6.3$	thrust	yes
		$M = 6.6$	thrust	yes
<u>India</u>	1956 Moradabad	$M = 6.1$	—	no
	1967 Koyna (reservoir assoc.)	$M = 6.3$	strike-slip w/normal comp.	no
<u>Africa</u>	1912 South Africa	$M = 6.0$	—	no
	1963 Zambia (L. Kariba, reservoir assoc.)	$M = 6.2$	normal	no
	1983 Guinea	$M = 6.3$	normal with strike slip	yes
<u>Europe</u>	[1819 Norway	$M = 6.4]$	(not instr.)	no
<u>S. America</u>	1955 Brazil	$M = 6.1$	thrust	no
<u>N. America</u>	1989 Ungava	$M = 6.0$	thrust	yes
<u>SE China</u>	1944 North Korea	$M = 6.7$	—	no
	1952 North Korea	$M = 6.2$	—	no
<u>Asia (Russia)</u>		none known		
<u>Antarctica</u>		none known		

**Spatial and Temporal Characteristics of Seismicity of the Southern Great Lakes
and
Implications for Probabilistic Seismic Hazard Assessments**

SUMMARY OF PRESENTATIONS

by

George C. Klimkiewicz
Weston Geophysical Corporation
Westboro, Massachusetts, USA 01581

Presented at the

Workshop on Seismicity Source Zones for the
1995 NBCC Seismic Hazard Map of Canada
Ottawa, Canada March 18, 19, 1991

INTRODUCTION

At the request of the Geological Survey of Canada (GSC) 1995 NBCC Workshop organizers, the following presentation summaries were prepared to document verbal presentations made on March 18 and 19, 1991 in Ottawa, Canada. Two presentations were made. The first was delivered on March 18. At the request of the GSC program sponsors, the topic was "Seismicity of the Southern Great Lakes." The purpose of this first presentation was to 'kick-off' a discussion of possible seismic source models for the region. The second presentation was an 'ad hoc' discussion of the influence of selections of seismic source zones and maximum magnitudes on probabilistic seismic hazard results. This summary of information discussed at the Workshop is provided into three integrated sections. The first is a discussion of three distinct zones of seismicity observed in the Southern Great Lakes region. The second section contributes a review of issues that are deemed to be important to producing a defensible seismic hazard evaluation. The final segment includes a discussion of certain observed temporal characteristics of Southern Great Lakes seismicity. Copies of most of the presentation slides were supplied to GSC's staff at the Workshop. A complete set of presentation figures is attached.

SOUTHERN GREAT LAKES

The discussion of seismicity of the Southern Great Lakes included an introductory overview of historical and recent seismicity observed in the region spanning from western New York State southwestward to west-central Ohio (Fig. 2). Three clusters of enhanced seismic activity were discussed; these include: a) the Attica-Dale region; b) the Anna, Ohio region; and c) the NE Ohio region, including the epicentral area of the January 31, 1986 earthquake.

T.2
etc

Attica-Dale Region

The Attica earthquake of August 12, 1929 produced local intensities evaluated at VIII (MMI). The magnitude of this event is approximately 5.2 m_b . The relatively high maximum intensity is attributed to a shallow focal depth of about 5 to 8 km. Also, it should be noted that various authors have attempted to re-evaluate the maximum intensity to MM VII, or VII-VIII. Relocation of the 1929 Attica earthquake by Dewey and Gordon, using a joint hypocentral location algorithm, is shown on Figure 3. Relocations of smaller events that occurred in the 1960's are also shown on the Figure.

Earthquakes in this zone are spatially correlated with the north-northeast-trending Clarendon-Linden Fault Zone (CLFZ). This system of faults is known to offset both the basement rocks and overlying Paleozoic cover. A causal association of the seismicity with the (CLFZ) is complicated by WNW-trending structural features and focal mechanism solutions (Herrmann, JGR, vol. 84, July, 1979) that include nodal planes oriented parallel to the strike of the CLFZ, as well as oriented to the WNW. In addition, a WNW trend of seismicity originates at the CLFZ and terminates near the western shore of L. Ontario (see Fig. 2). The confluence on NNE and WNW-oriented structural elements may contribute to localization of seismicity in this region.

Anna, Ohio Region

Seismicity of the Anna, Ohio region is shown on Figure 4. The largest of a series of earthquakes documented for the Anna Seismic Zone in the 1930's occurred on March 9, 1937. Magnitude estimates for this event range from 5.3 to a recent reassessment of approximately 5.0 m_b . Known and/or inferred faulting in the Anna region and earthquake epicenter locations are shown on Figure 5 (Christensen et al, 1987, NUREG/CR-3145). Seismicity is shown on this figure to concentrate near the juncture of the NE-trending Auglaize Fault and the NW-trending Anna-Champaigne Fault. Earthquake recurrence frequency for a 2 degree block encompassing the Anna region is shown on Figure 6.

NE Ohio Region

An earthquake of magnitude 5.0 m_p occurred in southern Leroy County, NE Ohio on January 31, 1986. A focal depth of about 4 to 5 km was determined for the main shock; the maximum intensity was MM VI. The epicentral region of this event has been seismographically monitored at a very low magnitude threshold (-0.5 and greater location capability) from several hours after the occurrence of the main shock to the present. Seismicity of the NE Ohio region is illustrated on Figure 7. Please note that seismicity shown on this figure does not include events that occurred during the past 4 years. This region is shown to have been active since the early 1800's, the approximate time-frame of earliest settlement.

The 1986 earthquake occurred near a geopotential lineament entitled the Akron Magnetic Boundary (AMB) (see Figures 8 and 9). No clear association of the AMB with the occurrence of the 1986 earthquake is presently supported. The AMB is interpreted to be a boundary zone that defines a distinct change in magnetic pattern west and east of the boundary. To the west, the magnetic pattern is characterized by short wavelength, relatively high intensity, high gradient, and generally northeast striking anomalies. This subterrain of high magnetic intensity is referred to as the Eastern Midcontinent Magnetic Belt (EMMB). The EMMB can be traced from southern Ontario southward into the state of Tennessee. East of the AMB, the magnetic signature becomes less conspicuous. Interpretation of this change in geophysical anomaly pattern (Figure 8) is that the Grenvillian subterrain that produces the intense magnetic signature to the west of the AMB is overlain by a less magnetic granitic gneiss to the east of the AMB.

Additional interpretations regarding the AMB include the feature to be a low-angle, ductile boundary zone between distinct Precambrian lithologic or structural terrains that formed at great depth. The differing terrain subdivisions are identifiable by contrasting aeromagnetic patterns. Similar terrain subdivisions are mapped in exposed Grenville rocks in Canada. Extension of the AMB is inferred to mark the western limit of the Elzevir terrain of the Central Metasedimentary Belt in southern Canada.

To improve the resolution of the local magnetic pattern, an aeromagnetic survey was flown in the epicentral region of the 1986 earthquake. Flight lines had an approximate 0.4 km spacing; tie lines were spaced at about 4 km. The survey was flown at a barometric elevation of 550 meters. Results of this detailed survey are shown on Figure 10. Interpretation of the high resolution magnetic survey indicates that the 1986 earthquake occurred within the more intense magnetic terrain about 10 km west of the magnetic boundary zone entitled the AMB.

The location of the 1986 event is plotted on a simple Bouguer gravity anomaly map on Figure 11. The hachured square represents the areal distribution of the main shock and aftershock sequence. This illustration shows the position of the event near the eastern gradient of a positive gravity anomaly. A residual gravity map is shown on Figure 12; the epicentral area of the 1986 earthquake sequence is similarly shown on this map depicting locations of shorter wavelength, shallower basement anomalies.

Absence of the positive gravity anomaly (seen on Figure 11) on the residual map (Figure 12) is interpreted to imply a mid-crustal source depth for the gravity high, well below the focal depth of the 1986 earthquake sequence.

Northwest-trending brittle structures were identified in the NE Ohio region. These brittle structures are observed to transect, displace, and interrupt the NE-trending AMB. Evidence for the brittle deformations include: interpretation of lineaments on bandpass filtered gravity maps, aeromagnetic maps, and aerial imagery. In addition, structural and lithologic facies mapping of the Paleozoic section employing an abundance of gas well logs support the present of minor disturbances in the relatively thin Paleozoic cover (approximately 2 km thick). Finally, direct evidence of brittle structural fabrics was found by field geologic mapping.

In addition to the subtle NW-trending brittle structures observed in the NE Ohio region, two prominent NW-trending lineaments bracket the epicentral region of the 1986 earthquake. The Pittsburgh-Washington lineament passes south of the epicentral region to the vicinity of Cleveland, Ohio. Further to the north, the Tyrone - Mt. Union lineament passes through the extreme NE corner of Ohio. Satellite imagery supports the presence of additional NW-trending features in this NE Ohio region.

It was noted above that structural mapping was performed on the Paleozoic sequence. Stratigraphic units of the Lower Paleozoic Sequence are shown on Figure 13. The section is well known due to the abundance and wide distribution of gas wells, and deep waste injections wells, several of which penetrate 10's of feet into the Precambrian basement. A structure contour map was prepared at the top of several stratigraphic units. The structure contour for the top of the Packer Shell (a common driller's name assigned to a regionally continuous carbonate unit above the gas-producing Clinton sandstones) is shown on Figure 14. Location of the 1986 earthquake sequence is plotted on this map. The structure contour illustrates a regional, south-trending dip of about 4.5 meters per km. A structural disturbance, striking NNE, is mapped in the vicinity of the 1986 epicentral area. The maximum East-West elevation difference associated with this feature is about 10 meters. This feature terminates at structural highs located about 5 km north and south of the epicentral area. The exact nature of this feature (i.e. fault, fold, or sedimentary depositional origin) is presently not known.

Microseismicity

Presently, two seismographic networks are operating in the region of NE Ohio. The first of these networks, maintained by Weston Geophysical Corporation (for Cleveland Electric Illuminating Company (CEI)) includes 6 stations. The second, operated by John Carroll University, includes 5 stations deployed in the area of the 1986 earthquake. These seismographic networks are shown on Figure 15.

Shortly after the occurrence of the 1986 earthquake a theory emerged that the event may have been induced by waste fluid injections in deep wells located about 10 km north of the epicentral area. A monitoring network was mandated by licensing agencies to aid in the interpretation of the origin of the local seismic regime. After a period of monitoring with portable seismographs, a fixed, digital, event-triggering network (i.e. WGC/CEI network) was installed. As mandated, the network operates at a low magnitude location threshold of -0.5 coda magnitude. Seismological data collected by the two NE Ohio networks are routinely exchanged and integrated for the purpose of computing hypocentral locations and focal mechanism solutions.

Since the commencement of seismographic monitoring, approximately 12 microevents/year have been located within the aperture of the WGC/CEI network. In addition, a similar number of local events with epicenters outside the WGC/CEI network aperture have been recorded during certain years. Figures 16, 17, and 18 list parameters of microseismic events located in NE Ohio during the time period from early 1986 through December, 1990.

Cumulative seismic activity from January 31, 1986 through 1990 is plotted on Figures 19 and 20. Figure 20 is an enlargement of the seismographically monitored region. A large majority of seismic activity located within the array has small magnitudes (< 0.5) and shallow focal depths (about 2 km, i.e. top of Precambrian basement). Events located outside the array typically have larger magnitudes ranging to 3.6 for the Ashtabula earthquake of July 13, 1987.

A group of small events located between stations SCH and FORD (see Figure 20) exhibit some clustering in the NE terminus of the seismicity pattern, as well as northeasterly and northwesterly intersecting trends. A gap of about 4 km in length exists between this group of shallow microevents and the epicenter of the January, 1986 earthquake located near station RAD (Figure 20). To reiterate, the cluster of small microevents have very uniform focal depths of about 2 km, whereas events in the 1986 epicentral area have focal depths that range from 4 to 5 km. Finally, shown on Figure 21 is an earthquake recurrence relationship determined for a 2 degree block of NE Ohio encompassing the 1986 epicenter.

At this point in the seismic monitoring program, and on the bases of geological and geophysical studies, the following observations are provided on seismicity in NE Ohio:

1. The January 31, 1986 earthquake has a tectonic origin. The available data do not support the theory that this event was induced by fluid injections in deep wells located 10 km north of the epicenter.
2. Small microseismic activity (located NE of the 1986 epicentral region) could possibly be induced by deep well fluid injections; however, no temporal correlations have been found between injection activities (volume and/or injection pressure conditions) and occurrences of seismic activity.
3. Focal depths of microseismic activity (cluster NE of the 1986 epicentral region) is consistently at the Precambrian-Paleozoic boundary at a depth of about 2 km.
4. Microseismic activity appears to best support a block tectonic model (intersections of NE and NW-trending lineaments), versus a single fault model.

Frequency of seismic activity in the two prominent zones of seismic activity in Ohio, namely the Anna Seismic zone and the cluster of activity in NE Ohio (1986 earthquake epicentral region) are compared on Figure 23. Over the historical period the Anna region has exhibited a higher rate of seismic activity (about 2.5 times greater than the NE Ohio region). Over the most recent several decades, the two zones exhibit an approximately equivalent rate of seismic activity.

POSSIBILITIES, PROBABILITIES, AND PROBABILISTIC ASSESSMENTS

As a preface to the discussion of temporal characteristics observed in 'Southern Great Lakes' seismic activity, the following ideological discourse is presented on the viability of performing continental scale probabilistic assessments. Participation on two continental scale probabilistic seismic hazard assessments performed in the U.S. (LLNL, 1989, NUREG/CR-5250; EPRI, 1986, NP-4726) has evoked a critical examination of the site specific applicability of such broadly-scoped studies.

An attractive feature of contemporary revisions of standard computer codes that determine probabilistic seismic hazard is the ability to evaluate any number of alternative hypotheses on seismic zonation, seismicity parameters, or attenuation models. These algorithms can literally output thousands of seismic hazard curves, each associated with one permutation of the input seismicity models. Because of this ability to analyze multiple hypotheses, the pitfall arises that a substantial number of potentially unsupported, or even meaningless, hypotheses may be included among the large number of input models.

Shown on Figure 24 is a characterization of the distinction between the realms of possibility and probability. In the context of performing a probabilistic seismic hazard assessment, for example, to provide the basis for the revised NBCC, technical expertise will be assimilated from various expert sources. Four basic issues need to be addressed; these include, a) definition of seismic zonation, b) definition of earthquake recurrence frequencies between low and maximum magnitude limits assessed for a fault or seismic zone, c) attenuation of earthquake-induced, frequency-dependent strong ground motions, and d) the analytical methodology used to compute ground motion exceedance probabilities, given a variety of definitions for parts a) through c) accumulated from various expert sources.

The caricature shown on Figure 24 is intended to portray a realistic pitfall that can result when soliciting expert opinion on a topic whose understanding is severely impaired by a large level of scientific uncertainty. It is clear that the relatively new science of earthquake prediction and the associated goal of mitigating the effects of future seismic activity are severely hampered by our present embryonic understanding of intraplate tectonism. Experts, requested to supply the information described above in points a) through d), which are necessary to perform a formal probabilistic seismic hazard assessment, will imperatively invoke theories that reasonably explain the recorded pattern of seismicity and associations with geologic structure and geophysical signatures. These theories will then be used to forecast the "seismic future." Figure 24 illustrates that theories can best be indexed under the heading of "possibilities." As the level of scientific uncertainty increases, so does the number of theories that may be promoted to explain a phenomenon in the presence of limited or contradictory data. As can be observed on the figure, the realm of "probability" is a small subset of the domain of "possibilities." The size of this subset of probabilities is related to the volume and quality of data collected to study a particular problem. Not shown on the figure is the confirmed "actuality", a single bill. For the purpose of seismic hazard assessments, the single piece of currency would be a precise determination of the true seismic future. Given that most would agree that it is impossible to write the catalog of eastern North American earthquakes for the next 50 years starting with the present, thus solving the seismic hazard issue, it is relevant to understand the distinction between possibilities and probabilities.

The experience of participation on two major sub-continental scale probabilistic seismic hazard assessments (LLNL,1989 and EPRI,1986) has provided a basis for the following observations. Each of the referenced studies relied on solicitation of information needed to perform the hazard evaluation from individual experts (LLNL), or from teams of experts (EPRI). It is well known that seismic hazard results provided by these two studies substantially disagree. The reason for the large hazard discrepancy can be traced to several factors. First, experts were asked to define seismic zones and seismicity parameters for the entirety of eastern North America. An individual expert may have a sound understanding of geoscientific data collected for certain localized regions; however no expert likely has an equivalent level of understanding for the entire sub-continental scale study region. Nonetheless, the expert needed to provide an evaluation. Given the circumstance, the expert delved into the realm of "possibilities" to provide responses for those unfamiliar regions, or regions of poor data quality and quantity. Upon solicitation of similar theoretical ("possibilities") responses from each expert retained for the study, site specific hazard results were derived by averaging hazard resulting from each expert's vision of the future seismic regime. In simple terminology, the premise underlying these hazard assessments, is that averaging of a diversity of expert opinion will yield a reasonable representation of the "true seismic future." If this premise is valid, then the two referenced hazard studies would have obtained similar results. The fact is that averaging diverse opinions, conflicting opinions in many cases, can only fortuitously reach the correct conclusion.

A more rational approach to performing seismic hazard assessments is to work as diligently as is feasible in the realm of probabilities. This implies a more extensive use of science, and a reduced reliance on expert opinions, in particular, opinions offered on topics that may not be carefully studied by a particular expert. As noted above, the transition from the domain of theoretical "possibilities" to that of subset of realistic "probabilities" involves the stripping away of scientific uncertainty. A possible approach to accomplishing this scientific effort is to subdivide the national scale hazard study into specific subregions and to convene a series of workshops dedicated to careful examination of scientific information, including proposed tectonic models, earthquake catalogs, in particular results of microseismic monitoring. Attendees should include a core of experts well versed in the given subregion due to prior, or continuing study, of that region. The foci of discussions should be to define a set of scientifically supported hypotheses on future seismicity of the subregion.

It should be noted that the EPRI (1986) probabilistic seismic hazard assessment endeavored to reduce the amount of scientific uncertainty by distributing to the expert teams a uniform data base including earthquake catalogs, and geopotential maps plotted at different scales, among other products. In addition, a series of workshops was convened. Some were dedicated to having formal presentations made to the expert teams by prominent scientists. Topics presented at these workshops included recent findings on the state and origins of intraplate stress, possible causes of the observed intraplate

seismicity, and structural domains considered to have a high likelihood of generating future significant earthquakes. Other workshops were held to allow expert teams to present their preliminary interpretations of regional tectonic features, assessed probabilities that the features are seismogenic, definitions of seismic source zonations (alternative interpretations were permitted), and definitions of seismicity parameters (i.e. recurrence models, maximum magnitudes, and weights assigned to the distribution of maximum magnitudes attributed to a seismic source zone).

The intention of the workshop format and dissemination of standard data bases to all expert teams was to seek a convergence of opinion on hypotheses on the seismotectonic regime by reducing scientific uncertainty attributed to experts having a variable level of specialization within the broad, continental scale study region.

The degree to which the original intent of reducing scientific uncertainty was fulfilled in the EPRI (1986) hazard assessment can be gauged by the contents of the expert teams' final reports. Review of these reports illustrates a wide range of opinions on seismic zonations, seismicity parameters, and maximum magnitude estimates. On this basis, it can be concluded that the goal of reducing scientific uncertainty was not achieved.

One possible explanation for the apparent lack of success of this aspect of the total program relates to the scale of the study. Ultimately, the expert teams were required to define tectonic models and seismicity parameters on a continental scale. Data that were disseminated, with the exception of geopotential maps and seismicity plots, varied greatly in type and quantity throughout the study region. Well-known and well-studied seismic zones, were endowed with a large volume of quality data and published seismotectonic interpretations. Expert teams' zonations for the New Madrid Seismic Zone, for example, illustrated great similarity. Vast areas of the study region, the less seismically active ones, and thus less studied regions, however, had an insufficient volume of data to achieve a convergence of opinion on the possible seismic zonations and seismicity attributes. Given the requirement, nonetheless, to provide evaluations for the entire study domain, expert teams' responses likely were theorized "possibilities", the likely reason for the overall divergence of opinion for broad regions, except for those few well-documented seismic zones.

TEMPORAL CHARACTERISTICS

Temporal Characteristics of Moderate to Large Earthquakes

Figure 25 shows epicentral locations of magnitude 5 and larger earthquakes observed in eastern North America, south of 50° North Latitude. This plot was prepared prior to the occurrence of the Saguenay earthquake of November 1988, thus it does not appear on the figure. The temporal distribution of the earthquakes shown on Figure 25 is illustrated on Figure 26. An obvious catalog incompleteness is observed from 1600 to 1800 A.D. for magnitude 5 events. Spatial and temporal attributes of the larger seismic events can be examined on this plot. For example, the more recent seismicity, since the occurrence of the 1925 La Malbaie earthquake, has primarily been located in the Northeast quadrant. Several exceptions include events that occurred in southern Illinois and in northern Kentucky. As in the previous figure, the recent Saguenay earthquake is not shown Figure 26. Prior to this apparent more active period in the Northeast, more significant seismicity is observed to have occurred in the New Madrid Zone, as well as along the central Atlantic Coastal region, including the areas of the Carolinas and Virginia. Several events occurred in the Northeast during this time period, however, the majority of events occurred in the central and east-central regions of the sub-continental area shown on Figure 25.

The annual frequency of earthquakes shown on Figure 25 is presented on Figure 27. Cumulative and incremental annual rates determined from segments of the catalog inferred to be completely reported are plotted on the Figure. Annual exceedance frequencies of magnitudes 5.0, 6.0, and 7.0 are about .49, .062, and .0078, respectively. These estimated annual rates translate into mean return intervals of about 2, 16, and 130 years for magnitudes 5.0, 6.0, and 7.0, respectively.

Temporal Characteristics of Southern Great Lakes Seismicity

Spatial/temporal clustering of seismic activity observed on a sub-continental scale inspired an examination of temporal characteristics of Southern Great Lakes seismic activity. The focus of this evaluation was on the three clusters of enhanced seismicity including the Attica, NY, Anna, OH, and NE Ohio zones.

Figure 28 illustrates the chronology of seismic activity in the Anna, NE Ohio, and Attica zones during the period from 1800 to the present. The most noticeable aspect of this plot is the simultaneous onset

Figure 28 illustrates the chronology of seismic activity in the Anna, NE Ohio, and Attica zones during the period from 1800 to the present. The most noticeable aspect of this plot is the simultaneous onset of seismic activity in each of the three zones during 1929 and 1930. Following onset of this activity, each of the zones remained moderately active. The Anna zone, however, exhibited a higher frequency of activity during the 1930's.

Figures 29 and 30 show the sequence of earthquake activity in these zones on an expanded time scale to improve the ability to correlate timing of events within the three zones. These plots show an interesting, yet unexplained, time-synchronicity of earthquake activity among the three zones. Early in the historical record, events occurred in the Attica and NE Ohio regions in the late 1850's. Later in the 1870's, an event at Attica was followed shortly thereafter by activity in the Anna zone. No event was reported for the NE Ohio region (Should we search the newspapers in NE Ohio during the 1870's for any evidence of a seismic event?).

In the more recent record (Figure 30), the three zones became active at about the time of the 1929 Attica earthquake. Since that time, other moderate magnitude events that occurred in the NE Ohio zone are observed to be closely followed subsequently in time by activity in the Anna zone. This temporal correlation of seismic activity between the NE Ohio zone and the Anna zone is best illustrated on Figure 32 which is a plot of the times of occurrence of earthquakes larger than magnitude 3.0 since 1940. Figure 31 shows the chronology of seismic activity in these zones during the period from 1900 to 1940. More recent events (Figure 32) larger than 3.5 in NE Ohio are observed to be followed, with an average lag time of about 10 months, by a moderate magnitude event in the Anna Zone.

A typical assumption adopted in standard probabilistic seismic hazard computational techniques is that earthquakes occurrences are Poissonian in nature, namely they occur randomly in space and time. The observed temporal characteristics of southern Great Lakes seismic activity very likely exhibits a non-Poissonian behavior. This observation is supported by spatial clustering of earthquakes in three distinct co-linear zones that are uniformly separated by distances of 280 km. In addition, seismic activity in the zones located in Ohio illustrate a non-random temporal pattern wherein, for more than the past half-century, a moderate magnitude event in NE Ohio was closely followed in time by a moderate magnitude event in the Anna zone. These spatial and temporal characteristics of Southern Great Lakes seismic activity can not be explained using the standard assumption of Poisson earthquake occurrences. An implication of these observed temporal correlations of the observed seismicity is the possible need to critically examine the continued usage of standard seismic hazard methodologies that assume random earthquake occurrences, both in space and in time, within a defined seismic source zonation.

SEISMIC HAZARD CONSIDERATIONS

Seismic source zone modeling can have an important effect on computation of probabilistic seismic hazard at a site. Other factors incorporated into the calculation also contribute with a variable level of significance to the final result. These other factors include:

Frequency vs. Magnitude Relationships for Seismic Source Zones

Strong Ground Motion Attenuation Models

Response Spectrum Shapes

Maximum Magnitude Estimates

Relative Effects of Seismic Source Zonation and Maximum Magnitude Selection

A short presentation was made on March 19 to illustrate the relative importance of seismic source zonation versus choice of maximum magnitude attributed to a given seismic zone. Figure 34 is a plot of seismicity for central and southern New England. Circles of radii of 50 km, 100 km, and 200 km are drawn around a site situated in SE Massachusetts. Seismic zones, defined for purposes of illustration, as blocks encompassing the radial distances from the site are shown on the figure. Z.2

It can be seen on Figure 34 that the 50 km block has a lower frequency of historical seismic activity, relative to the 100 km and 200 km blocks. This is more rigorously demonstrated on Figure 35 which is a plot of earthquake recurrence relationships, normalized to a common area of about 2,000 square km. Z.3

In order to illustrate the relative importance of selection of seismic source zones (which implicitly defines earthquake recurrence frequency), versus selection of maximum magnitude assigned to a seismic zone, example probabilistic seismic hazard calculations were performed using the Cornell (1968) / McGuire (1976) methodology. Results of these computations are given on Figure 36. Seismic hazard results are given for peak horizontal ground accelerations of .05, .10, and .25 g. Two seismic zones were evaluated in the computations, the 50 km and 100 km blocks shown on Figure 34. The less seismically active 50 km block was assigned alternative maximum magnitude earthquakes of 5.5 and 7.2. The maximum historical event reported for this zone is less than magnitude 4.0. The more seismically active 100 km block, which includes the 1755 Cape Ann earthquake (magnitude 6.0), was assigned alternative maximum magnitudes of 6.25 and 7.2.

2.4

Results of the seismic hazard sensitivity analyses, given on Figure 36, show that at small peak ground accelerations (.05 g) characterized by relatively high annual exceedance frequencies (.0035 to .001; mean return periods of about 300 to 1,000 years), the effect of substantial variation in maximum magnitude on computed hazard is slight in comparison to zonation effect; i.e. difference in hazard computed for the 50 km block vs. the 100 km block. The maximum magnitude effect on hazard results at this peak acceleration level (.05 g) is in the range of 10 to 20 %, whereas the zonation effect is substantial, about a factor of 4.0. The maximum magnitude effect becomes significant only for the case of analyses of extremely remote events, such as the very low frequency of exceeding 0.25 g illustrated on Figure 36. In the analyses of remote events, varying the maximum magnitude can have a substantial effect on hazard results, as is shown for the 50 km block for exceedance of 0.25 g.

Commonly, building codes specify seismic design criteria on the basis of reasonable likelihoods of earthquake occurrence. For example, seismic zones are typically contoured on the basis of a uniform non-exceedance probability of 0.90 during a 50 year time frame. This probability equates to a mean annual earthquake exceedance frequency of 0.0021 (equivalently, mean return period of 475 years). As was shown above, at this order of magnitude of ground motion exceedance frequency, selection of maximum magnitude has a small effect on computed hazard. It thus seems prudent to not minimize the size of the maximum magnitude earthquakes attributed to relatively inactive seismic zones, or seismically nondescript regions designated as background seismicity zones, because of the small impact on computed hazard. The consequence of limiting the size of the maximum magnitude for relatively inactive zones is a higher likelihood that the estimated maximum magnitude event could be exceeded, thus potentially technically undermining the entire hazard assessment. A valid approach to assigning maximum magnitudes to the relatively inactive zones is to specify a best estimate, such as 6.0 with some weight (.75), and a higher magnitude such as 6.5 weighted at .25. Obviously, this philosophy can be expanded to include even extreme events with a very small weight, which would further reduce the likelihood that an actual event would exceed the maximum magnitudes estimated for the purpose of

executing a probabilistic seismic hazard assessment.

The maximum magnitude considerations noted above are important for characterization of the relatively inactive seismic zones and for relatively small ground motions with reasonably high exceedance probabilities, such as employed in Building Code specifications. For the cases of highly active zones that have produced large historical events, or other less seismic but tectonically analogous regions, the process of maximum magnitude assignment is reduced to selection of events in the upper range of observed intraplate magnitudes. There is a smaller potential for erring on the maximum magnitude specification for these more highly active zones. The concentration of effort therefore needs to be more dedicated to the less active areas. As illustrated by the example hazard computation, future hazard assessments for Building Code applications would benefit from understanding the relative importance of maximum magnitude selections on final hazard estimates.

Tectonic Framework of a Geological Source Zone in the Rifted
Craton West of the Canadian Appalachians

Stephen Kumarapeli, Department of Geology, Concordia University,
Montreal, Quebec, H4B 1R6

1. The following are some of the main developments that have taken place since Kumarapeli and Saull (1966) and Kumarapeli (1974) proposed a causative relationship between the seismicity pattern in the craton west of the Canadian Appalachians (CRATON) and the fault zones of the St. Lawrence Rift system.
 - 1.1 The seismicity pattern of the region has become better resolved (Adams and Basham, 1989). For example, what was once a diffuse zone of epicentres extending from Quebec City to Anticosti Island has become resolved into two zones. However, the basic conclusion (Kumarapeli, 1974) that the greater part, by far, of the seismicity of the general region is closely associated with the St. Lawrence Rift Zones, has been borne out.
 - 1.2 The main rifting episode which initiated the rift faults of the St. Lawrence System took place not in the Cretaceous as earlier thought (Kumarapeli and Saull, 1966), but in the late Proterozoic (~600 Ma) as a part the major rifting episode (Iapetan rifting) which led to the opening of the Iapetus Ocean (Kumarapeli, 1985). This rifting episode not only produced the deep faults of the St. Lawrence system but also led to more pervasive fracturing of the CRATON (Kumarapeli, 1987).
 - 1.3 The Cretaceous was a time of epeirogeny (Crough 1981) and anorogenic magmatism (Jansa and Pe-Piper, 1988) in the general region. It is likely that some reactivation of Iapetan faults accompanied the epeirogeny and magmatism but there is no evidence for an episode of major rifting during this period (Kumarapeli, 1991 in preparation).
 - 1.4 The Iapetan rifting in the region was probably initiated by a mantle plume which may account for the rather special characteristics of the CRATON, in particular the unusual width of the area pervasively affected by Iapetan faults and fracture zones. This aspect has to

be kept in mind in comparing the seismogenic potential of this region with areas of the craton further to the south (see Bollinger and Wheeler, 1988).

- 1.5 The St. Lawrence Rift System is clearly not an equivalent of the East African Rift System (Ottawa graben probably is!) as proposed by Kumarapeli and Saull (1966) but a combination of rifted zones and failed arms inherited from Iapetan rifting and has the pattern of a large continental rift system. This does not diminish its importance as a regional fault system in the St. Lawrence Region. However, it should perhaps be referred to as the St. Lawrence rift-fault system rather than the St. Lawrence Rift System (Kumarapeli, 1991 in preparation).

2. Iapetan faults and fracture zones

Iapetan faults and fracture zone are probably the most important structures which control seismicity in the CRATON. They can be classified into three groups: (i) Iapetan faults parallel to the continental margin of Laurentia, (ii) Iapetan failed arms, (iii) Fracture zones transverse to the continental margin of Laurentia.

- 2.1 Iapetan faults parallel to the continental margin of Laurentia: Faults of this type probably occur along the entire margin of the CRATON (Fig. 1), but are best known from the St. Lawrence and Champlain Valleys and from Anticosti Island. They dip steeply towards the Appalachian orogen and their cumulative effect is to step down the Grenvillian basement towards the orogen. This type of faults are the most likely structures which control the activity in the Charlevoix and Lower St. Lawrence regions. The clustering of earthquakes in widely separated segments of the faulted margin of the CRATON may be due to stress concentration in these segments resulting from changes in the orientation of faults and/or from complications brought about by cross structures (Kumarapeli, 1987). Although step faulting continues as a feature of the basement beneath the Appalachian nappes, the level of seismicity seems to drop to the east of the Appalachian front. The weight of the superincumbent nappes and the effects of deformation, metamorphism and igneous activity related to collisional orogeny may have rendered the faults less conducive to stress release.

2.2 Iapetan Failed arms

The mantle plume which is thought to have initiated rifting in the region, produced an RRR (rift-rift-rift) triple junction - the Sutton Mountains triple junction (Kumarapeli et al., 1981) which was the location of a massive volcanic outburst in the early Cambrian. The Ottawa graben is the failed arm related to the triple junction. The Saguenay graben may not be a failed arm in the strictest sense. It is probably a minor branch of the principal Iapetan rift in the area. The role of these grabens in seismic energy release in the CRATON is not clear. For example, the Ottawa graben faults are not particularly active, although a few epicentres, including the Timiskaming earthquake of 1935 (M >6), are located on it. The main role of the graben appears to be to delimit the seismicity of western Quebec on the southwest side.

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 1), 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 precedes 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 well removed from the areas of main activity in the Charlevoix and Lower St. Lawrence zones may be an indication of the seismogenic potential of these fracture zones.

3. Pre-Iapetan tectonic elements

A characteristic feature of the CRATON in the seismically active area of western Quebec is the presence of numerous lineaments in the form of narrow rectilinear or zig-zag valleys with two dominant trends with maxima approximately NW and NE (Kumarapeli, 1978). The zig-zag valleys combine the two trends, and in small scale maps, appears as north-south trending lineaments. These lineaments appear to be the surface expression of a regional

fracture pattern which existed prior to the Iapetan events and exerted a dominating influence in controlling the directions subsequent crustal failure. Kumarapreli (1987) proposed that this fracture pattern is probably the main crustal structure controlling the seismic activity of western Quebec. Mohajer (1987) has shown that alignments of epicentres do occur in these two directions.

4. The CRATON as a Geological Source Zone

As shown in sections 2 and 3 above, the integrity of the CRATON is broken by four identifiable types of structural elements which have to be considered in rationalizing the seismogenic potential of the region. They are: (i) a pre-Iapetan NW and NE trending fracture pattern, (ii) Iapetan faults parallel to the rifted continental margin of Laurentia, (iii) Iapetan failed arms, (iv) probable Iapetan fracture zones radiating into the continental interior from the margin of the CRATON. In some areas these structural elements intersect each other. For example, in Montreal area faults of the Ottawa graben and faults parallel to the continental margin of Laurentia intersect. Thus, it is not always possible to separate regions with seismogenic faults that differ in age and type. Therefore, my recommendation at this point is to consider the entire CRATON (Fig. 2) as a geological source zone. I will leave the task of assigning a suitable M_x value for this zone to the seismologists.

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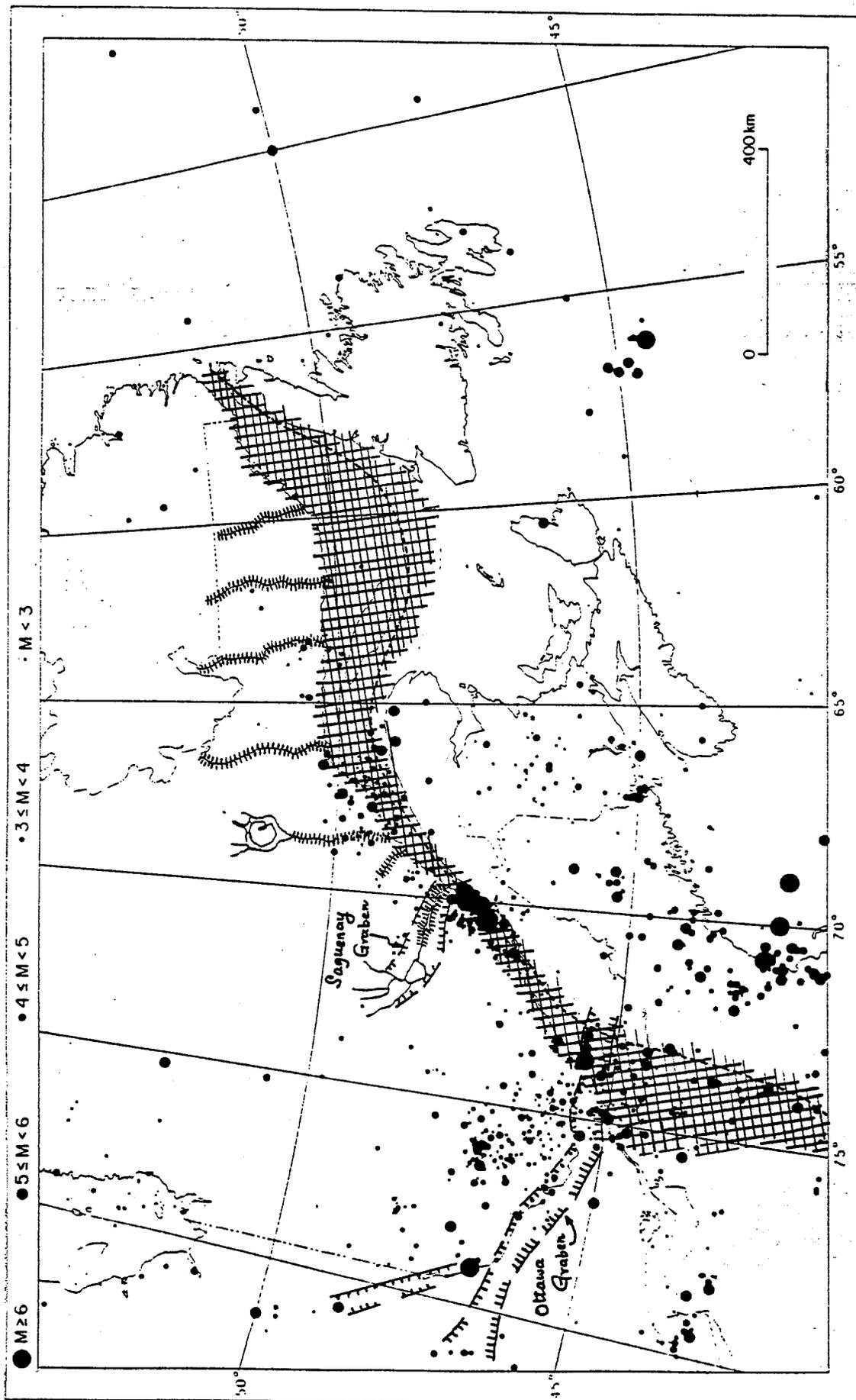
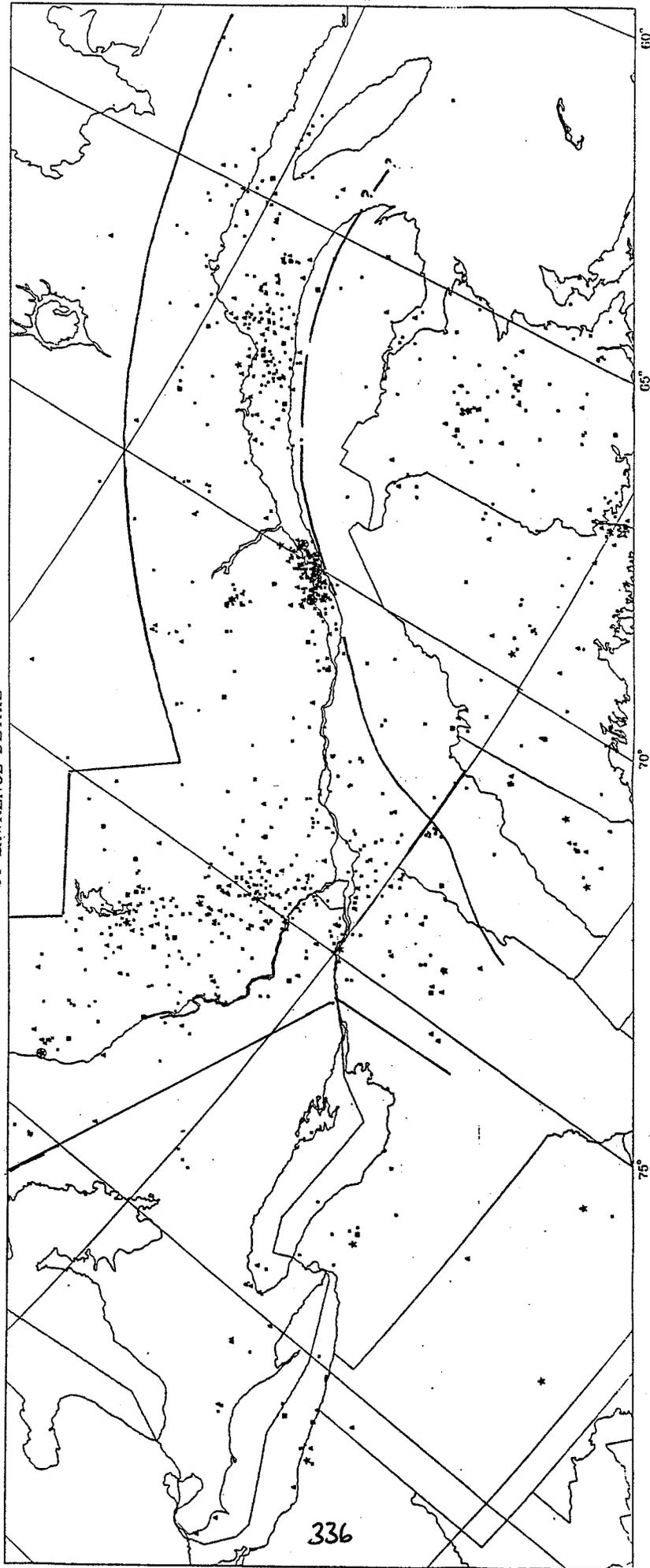


Fig. 1. Space relations between Iapetan structures and seismicity in Eastern Canada. Grid pattern: area in which Iapetan faults parallel to the ancient continental margin are known or are likely to occur. Deep valleys along possible fracture zones hachured. Dash line: Appalachian front. Base map from the files of the Geophysics Division, Geological Survey of Canada. $M \geq 5$ to 1981; $4 < M < 5$, 1960-1981; $M < 3$, 1970-1981. After Kumarapeli 1987.

DEFINITIONS

- M ≥ 2.0 1980+ •
- M ≥ 3.0 1975+ *
- M ≥ 3.5 1968+ *
- M ≥ 4.0 1963+ *
- M ≥ 4.5 1937+ *
- M ≥ 5.0 1900+ *
- M ≥ 6.0 1870+ ⊗

ST LAWRENCE DETAIL



SEISMICITY BRANCH, COMPARISON SHEET # 214
 DRAWING NO. 1-8 (REVISED) 1980

Fig. 2. St. Lawrence Geological Source (seismicity) Zone

EVIDENCE OF GRENVILLE DEFORMATION INTERPRETED FROM SEISMIC IMAGES OF STRUCTURE BENEATH WESTERN LAKE ONTARIO AND EASTERN LAKE ERIE

Prepared by Bernd Milkereit & Dave Forsyth

- * Seismic reflection data from western Lake Ontario and eastern Lake Erie provide images of basement structures of the western Central Metasedimentary Belt (CMB) and Central Gneiss Belt (CGB) divisions of the Grenville Province.
- * Seismic images from the western boundary of the CMB support geological models of northwesterly accretion of allochthonous terranes accompanied by ductile deformation.
- * The CGB appears as basement for rocks of the CMB and extends significantly to the east beneath the CMB.
- * Late Proterozoic to possibly Cambrian sedimentation was affected by extension along reactivated Grenville structures.
- * The nature, distribution and relationship of Grenville basement structures to subsequent sedimentation has important implications for:
 - (i) Conditions and models for regional hydrogeological studies and waste disposal including deep-well disposal.
 - (ii) Hydrocarbon potential: Exploration wells have discovered post-Grenville sedimentary material variously described as arkose, granite wash or metaclastics. Basement structures may have controlled deposition and preservation of much of this material, some with hydrocarbon shows, as well as affected the distribution of hydrocarbon sources in the lower Palaeozoic strata.
 - (iii) Seismic Hazard: Seismic reflection images are providing new structural information to lower crustal depths equal to the focal depths of seismic events beneath lakes Ontario and Erie. No indication has been found of major or cumulative movement or rejuvenation of structures since the deposition of Trenton strata.
 - (iv) Further subdivision of the CMB and CGB: Large scale deformational features may indicate subdivision of known terranes is warranted.
 - (v) Correlated seismic images from parallel lines together with continuous potential field anomalies support a general southwest extension of the CMB. No evidence has been found to support significant Mesozoic rifting beneath lakes Erie and Ontario.

Seismic Source Zone Characterization in Western Quebec and Southern Ontario

A. A. Mohajer *

SEISMICAN Geophysical Ltd.

239 Dunview Ave. North York, Ontario M2N 4J3

Extended Abstract:

Known seismic activity in eastern Canada has occurred in areas where no obvious or simple association with surface geological features has been established. However there is a growing recognition that pre-existing structures or weak zones and fault geometry influence the location of seismic events and therefore the general seismicity pattern. Although reactivation of a Palaeozoic rift fault system along the Ottawa and St. Lawrence rivers and Mesozoic rift margins has been suggested in recent years (Adams and Basham, 1988), there are many events which cannot simply be linked to known geological structures. Typical examples include the apparently dispersed seismic activity in western Quebec and the southern Ontario.

In order to understand the seismotectonic framework in western Quebec and southern Ontario, and to define the seismic source zones which could potentially affect the regional earthquake hazard assessments, an attempt has been made to improve the database by re-computing hypocentres (Mohajer, 1987; 1990). Original seismographic records in the Record Centre of the National Archives of Canada for the events that occurred prior to 1960 were examined. A sensitivity analysis was carried out on the basis of the new phase readings. The results of this investigation show that the inaccuracies in the location of older events are related to biases in the geometrical spread of the seismographic stations and time base correction. Consistency in phase identification has some bearing on data improvement, but it is usually masked by other sources of error in hypocentre computations.

A detailed study of the recomputed location of the earthquakes (Figure 1) together with lineaments identified from Thematic Mapper Multi-spectral satellite image, geological maps and geophysical potential field data, revealed several active linear features in this region (Mohajer, 1990). The recomputed locations together with more reliable hypocentres determined by Geological Survey of

* Presented to the Workshop on Eastern Seismicity Source Zones, for 1995 NBCC Seismic Hazard Maps, GSC, Ottawa March 18-19, 1991.

Canada were used for detailed cross-correlation with geological features and other geophysical information.

A conspicuous southeast-trending linear seismic distribution coincides with a physiographic lineament extending southeast from the Baskatong Reservoir in Quebec. There is another locality where spacial correlation of seismicity with a lineament is demonstrated. This feature is a northeast oriented seismic trend which passes near Bancroft and Pembroke, extending into western Quebec at a distance of about 100 km west of Ottawa. This seismic trend passes near the western boundary of the Central Metasedimentary Belt (CMBBZ) which continues southwest toward Lake Simcoe and ultimately joins the Niagara-Pickering Linear Zone (NPLZ, Wallach and Mohajer, 1990) just east of Toronto. Alignment of epicentres along this geological structure is more conspicuous in western Quebec than in southern Ontario. Nevertheless, the occurrence of several historical seismic events and recent microearthquakes in the western part of Lake Ontario and in the Niagara region may indicate that the full length of this prominent geological boundary could be potentially active.

Several earthquake locations for post 1980 events, published by the Lamont Doherty Geological Observatory and the Geological Survey of Canada, also coincide with the above suggested seismotectonic trend. Indications of fracturing and brittle faulting along the CMBBZ near Coboconk and Norland, Ontario (Wallach 1990; Wallach and Mohajer 1990), as well as normal faulting and liquefaction deformations, and sand dykes in the Rouge River valley near Pickering (Mohajer and Eyles, 1991), which may be induced by severe ground shaking of a nearby seismic source, lend additional support for the suggested seismogenic potential of the CMBBZ.

A new seismic source zone following the surface expression of the western boundary of the Central Metasedimentary Belt is postulated here. This zone is named the CMBB source zone which includes CMBBZ in western Quebec and southern Ontario, Niagara-Pickering Magnetic Lineament (NPML), Burlington-Toronto Structural Zone (Thomas et al., in preparation) and a band of seismicity associated with them which extends 20 Km or more to the east of the CMBBZ surface trace.

On the basis of the existing data base, the rate of seismicity is not uniformly distributed along this source zone. Nevertheless, the suggested seismic source zone coincides with a prominent geological boundary with indications of brittle faulting, fracturing and nearby liquefaction in several places along its 600 Km length. Although, the time span of the available seismicity data is relatively short and detection threshold of the seismic instruments has not been uniform along its entire length (Mohajer,

1987), one can argue in favour of various rate and probability of future activities at several segments along this zone. In particular, there is a widely held view (e.g. Mohajer 1975, Talwani, 1988; Bolinger and Wheeler, 1988) that the seismogenic potential is higher at tectonic-knots (sharp bends in dip and strike or intersections with other structures). It is therefore, suggested to divide the CMBBZ into three segments with slightly different seismic hazard parameters as shown in Figure 2. A constant b-value of about 1.05 and an a-value which varies as a function of number of recorded earthquakes ($a = \text{Log } N, M \geq 3$) and P_a (assigned probability of activity) of 0.50, 0.20 and 0.40 are suggested, respectively, for the northern section (Baskatong to Pembroke) Central section (Pembroke-Lake Simcoe) and southern section (Lake Simcoe - Lake Ontario).

Other prominent seismic sources are the Georgian Bay Linear Zone (GBLZ, Wallach and Mohajer, 1990) and the NW-SE extending western Quebec seismicity trend (Mohajer 1990). Extension of the St. Lawrence Rift Zone along Lake Ontario and Lake Erie as suggested by Adams and Basham in 1988 and Thomas et al., (in preparation) could be considered as a new seismic source which is called the Lower Great Lakes Seismic Zone in here. The seismogenic characteristics of these newly defined source zones are summarized in the following table.

Table 1: Probabilistic Seismic Hazard Parameters for the Suggested Source Zones in Western Quebec and Southern Ontario

	SEISMIC SOURCE ZONE	b-VALUE A		M_x	P_a	BETA
1-	St. Lawrence Rift	1.05	LogN(M _≥ 3)	7.5	.80	2.45
2-	Saguenay Graben	0.90	"	7.0	.50	2.09
3-	Western Quebec	1.05	3.5	6.5	.80	2.45
4-	Ottawa-Bonnechere	0.90	2.0	7.0	.60	2.09
5-	CMBB Northern Section	1.05	3.5	6.5	.50	2.45
6-	CMBB Central Section	0.90	1.5	6.0	.30	2.09
7-	CMBB Southern Section	1.05	1.8	6.5	.40	2.45
8-	Georgian Bay Linear	0.90	1.5	7.0	.30	2.09
9-	Lower Great Lakes (St. Lawrence Rift Extension)	0.90	1.8	7.5	.20	2.09

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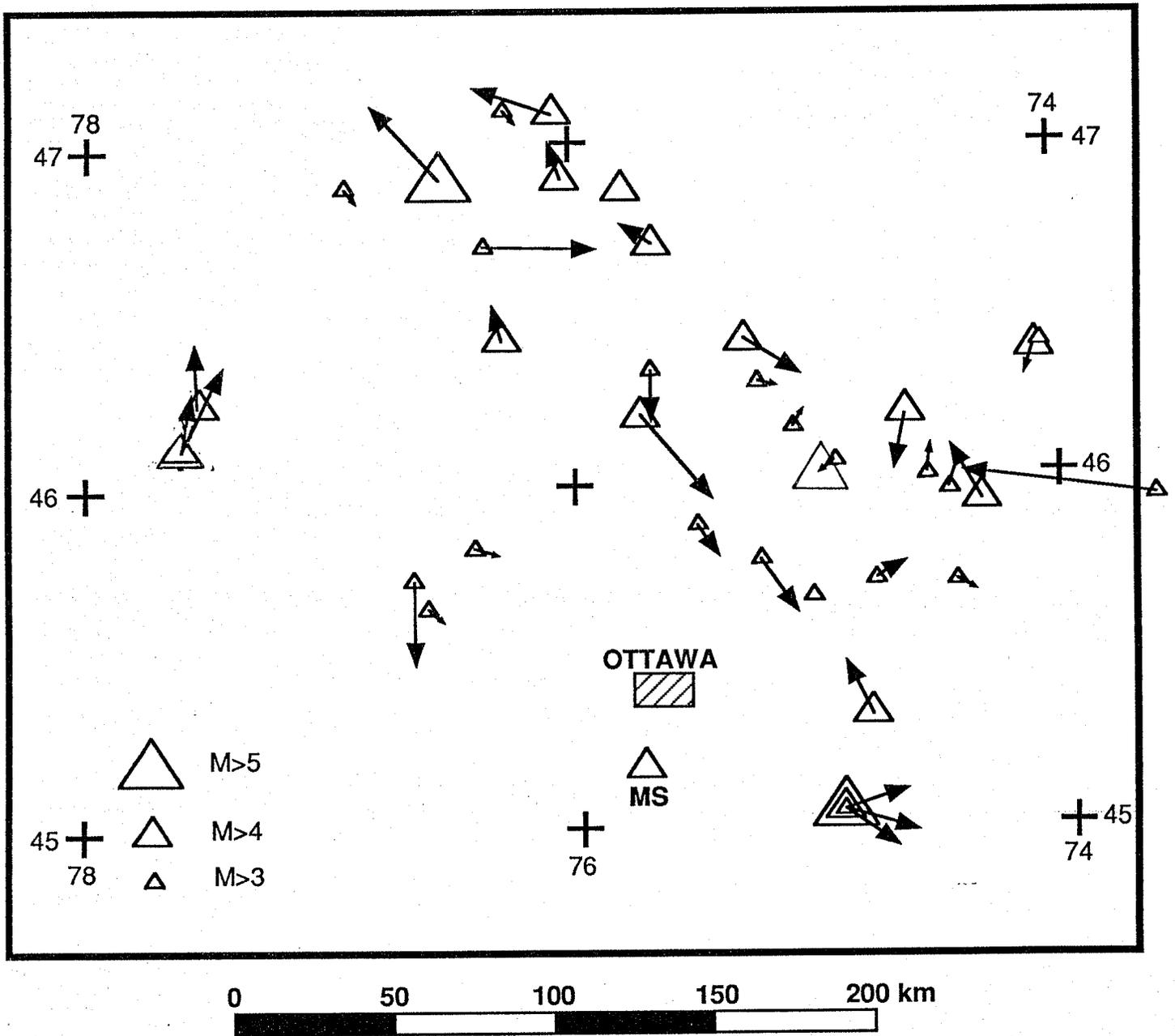
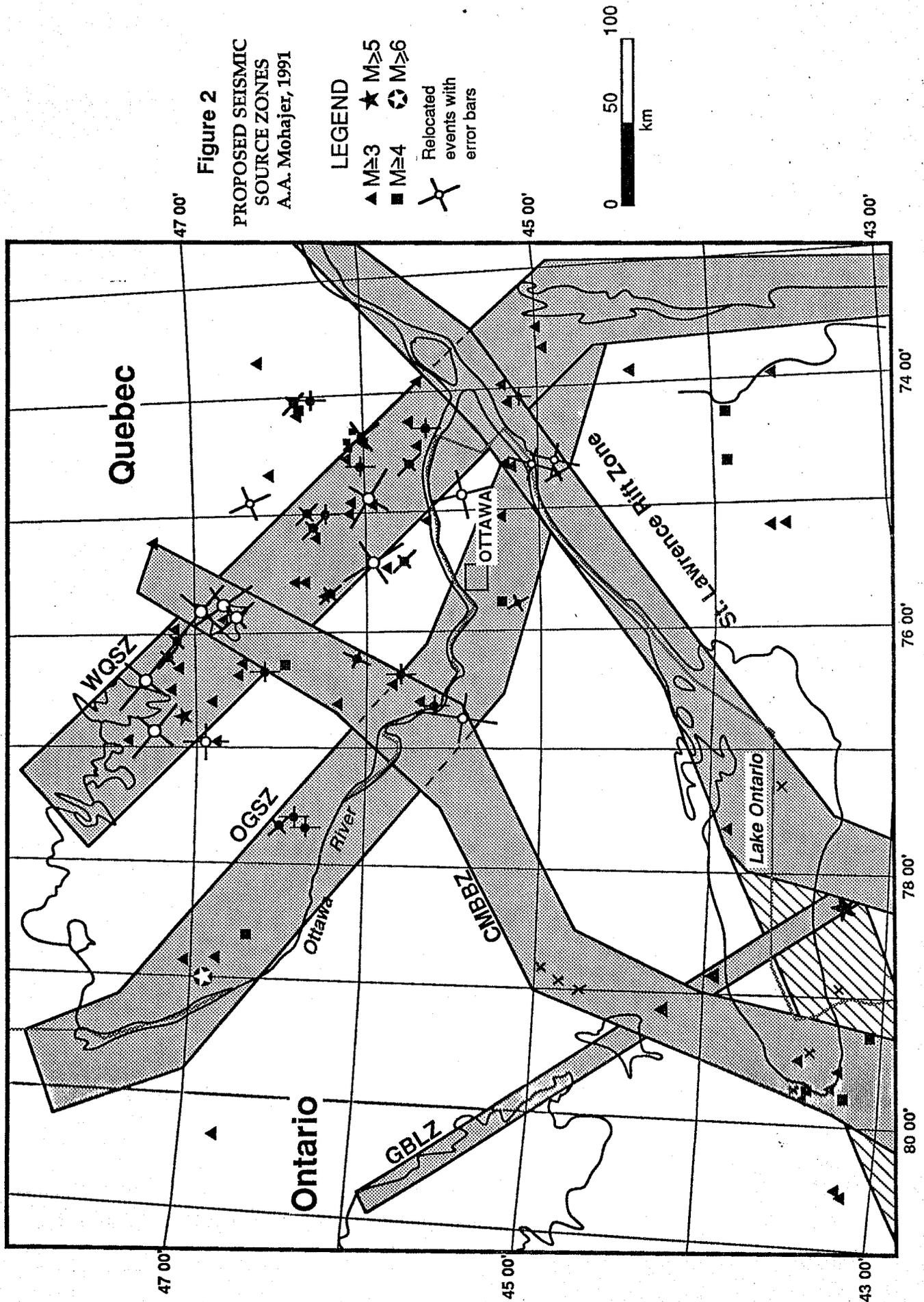


Figure 1. Joint Epicenter Determination (JED) of selected earthquakes, in the West Quebec Seismic Zone (WQSZ), for which sufficient reliable phase readings were available. Triangles show the existing locations in the GSC files. Arrows point to the recomputed new location. MS = Master Event used for JED recomputation (a M4.1 event which occurred on 1983/10/11 25 km south of Ottawa). Coordinates are given in Appendix 2.



SEISMICITY OF NORTH-CENTRAL NEW YORK STATE AND SOUTHERN LAKE ONTARIO

Richard C. Quittmeyer
Woodward-Clyde Consultants
201 Willowbrook Blvd.
Wayne, NJ 07470
U.S.A.

Abstract

Microseismicity monitored by seismic stations in north-central New York indicates a low level of activity. Earthquakes are scattered in an apparently random distribution, except for a concentration of activity near Attica, New York. Several events occurred beneath Lake Ontario. Association of these earthquakes with geological and geophysical lineaments that cross the lake is limited by the poor precision of locations. The only spatial association of epicenters with the Clarendon-Linden fault system occurs near Attica, a region of recurring seismicity since 1929. Away from the Attica region, however, the Clarendon-Linden system currently appears aseismic. A fault-plane solution for an earthquake south of eastern Lake Ontario shows strike-slip faulting in response to a maximum compressive stress that is horizontal and directed east-northeasterly.

Introduction

Woodward-Clyde Consultants operated a network of seismic monitoring stations in north-central New York (USA) from late-1981 through mid-1990 for the Empire State Electric Energy Research Corporation (ESEERCO). The network was composed of twelve stations from 1981 through 1987 at which time a thirteenth station was added near Attica, NY (Figure 1). Each station employed a vertical component seismometer; the two stations along the lake shore and the one at Attica also included two orthogonal horizontal seismometers. Detection within the network was complete at least down to magnitude 2.

During the more than eight years of monitoring, the network detected 28 local earthquakes in north-central New York and Lake Ontario that could be located (Figure 2). Arrival times for hypocenter determination were taken from seismograms recorded by the ESEERCO stations and, in some cases, supplemented with data from the

Canadian Geological Survey and the Lamont-Doherty Geological Observatory. Coda durations provide the basis for magnitude determination. Recorded events are listed in Table 1.

Distribution of Seismicity

Earthquake epicenters exhibit a scattered distribution. The only concentration of events is located in the vicinity of Attica and Batavia, NY (Figure 2). Attica was the site of a magnitude 5 earthquake in 1929, and two earthquakes of about magnitude $4\frac{1}{2}$ in the mid-1960's. Two of the recent microearthquakes are located very near to the reported epicenter for the 1960 events. Fletcher and Sykes (1977) also reported a clustering of microearthquakes in this region between 1970 and 1975.

The earthquakes near Attica are spatially associated with the Clarendon-Linden fault system. Fletcher and Sykes (1977) showed that solution mining of salt in this area induced earthquakes on a shallow portion the fault system. Whether the tectonic events that occur in this region are associated with slip along strands of the Clarendon-Linden system is less clear. Except for the Attica region, the Clarendon-Linden is seismically quiet.

Information from fault plane solutions is also inconclusive. Fletcher and Sykes (1977) could not determine a fault plane solution for non-triggered earthquakes. Herrmann (1978) showed that the two earthquakes in the mid-1960's resulted from strike-slip motion on either a north-northeasterly or a west-northwesterly striking plane. One of these planes is parallel to the Clarendon-Linden system, but the other is not. Consideration of the Clarendon-Linden system as an active feature along its entire length remains an open question.

Of interest with regard to the Clarendon-Linden system is an earthquake that occurred in Lake Ontario in January 1986. This event plots about 10 km east of the Scotch Bonnet Rise, a topographic ridge that crosses Lake Ontario along the projected strike of the Clarendon-Linden system. Unfortunately, the small size of the event and its location outside of the network, result in a poor quality hypocentral determination. The closest station was approximately 65 km from the epicenter, and the maximum azimuthal gap between recording stations was over 245 degrees.

Fault Plane Solutions from Seismic Monitoring

A fault plane solution was determined for a magnitude 2.8 earthquake near Fulton, NY. The solutions indicates strike-slip faulting along either a north-northeasterly trending plane or a west-northwesterly striking plane. The maximum compressive stress direction inferred from the solution trends east-northeasterly. This result is in general agreement with other stress determinations in northern New York State.

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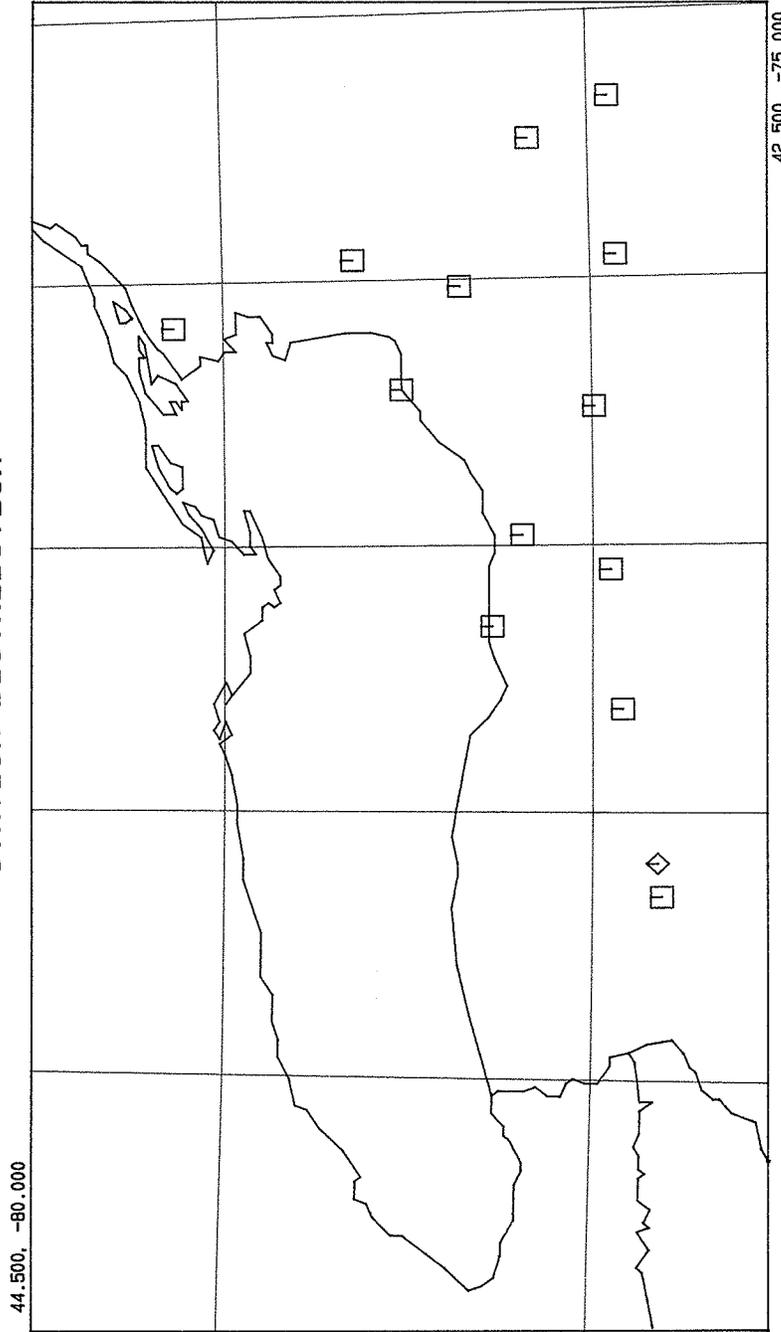
TABLE 1

LAT (DEG)	LONG (DEG)	DEPTH (KM)	MAGNITUDE (MC)	DATE/ORIGIN	QUALITY	CRUSTAL MODEL	LOCATION
44.3513	-75.2742	4.8	2.5	81:06:20:02:10	cd	nnyadir	Balmat, NY-Adirondacks
42.9505	-76.1318	0.7	1.6	81:09:07:06:16	ad	ncny	Lafayette, NY
43.4080	-76.3980	2.8	2.5	81:09:16:14:41	ac	ncny	Fulton, NY
43.6500	-76.5958	2.3	1.6	81:11:03:11:06	cc	ncny	Lake Ontario
43.6542	-76.5945	11.7	1.5	81:11:03:11:42	cd	ncny	Lake Ontario
42.7053	-77.6093	8.8	2.2	83:03:14:20:37	ad	ncny	Conesus, NY
42.9548	-77.1812	9.2	1.5	84:04:12:09:38	ac	ncny	Near Phelps, NY
43.2035	-75.1622	2.1	2.3	84:06:01:21:28	bc	ncny	South Trenton, NY
43.2020	-75.1703	4.2	0.0	84:06:01:21:57	cd	nnyadir	
43.3548	-76.2818	4.1	2.1	84:08:08:02:33	bd	ncny	Palermo, NY
42.9650	-77.0408	4.1	2.9	84:09:29:13:05	ac	ncny	Phelps, NY
45.1900	-75.0473	9.7	0.0	84:11:26:09:03	ac	nnyadir	NY/Canadian Border
42.7465	-77.2912	9.6	1.6	85:08:12:12:54	ad	ncny	Vine Valley, NY
43.5032	-77.6783	8.3	2.0	86:01:12:17:43	ad	ncny	Lake Ontario, NY
44.2700	-76.0008	10.7	2.2	86:03:22:08:39	ad	ncny	Lafergeville, NY
43.3567	-78.8274	8.2	2.4	87:03:20:22:50	cc	ncny	Near Lake Ontario, NY
44.6710	-75.5510	4.9	2.8	87:07:05:02:37	bd	ncny	NY/Canadian Border
43.4724	-79.3935	0.1	3.5	87:07:23:09:32	ad	ncny	South of Toronto, Canada
42.9342	-78.0665	2.0	1.5	87:08:23:21:36	cc	attica	Attica, NY
42.9143	-78.0577	2.8	0.5	87:08:23:21:40	cd	attica	Attica, NY
44.7538	-75.1043	0.8	2.6	87:09:04:08:57	cd	nnyadir	Potsdam, NY
42.9730	-78.1310	6.1	2.2	88:05:01:04:52	cc	wny	Batavia, NY
43.9247	-77.3926	0.4	1.9	88:09:09:10:22	cd	nnyadir	Prince Edward Co., Canada
42.8762	-78.7679	2.9	2.1	88:10:08:05:25	ad	ncny	near Buffalo, NY
42.9376	-78.2868	4.0	1.2	88:10:09:07:31	cd	wny	near Batavia, NY
43.8708	-76.1758	5.9	2.5	89:05:29:19:18	ad	ncny	Henderson Bay, NY
42.8667	-78.2359	6.4	1.5	90:02:14:22:49	cd	wny	Attica, NY
42.8682	-78.2328	5.7	1.4	90:02:15:00:45	cd	wny	Attica, NY

Notes:

Crustal Models					
ncny		nnyadir		wny	
Velocity (km/sec)	Depth to Top of Layer (km)	Velocity (km/sec)	Depth to Top of Layer (km)	Velocity (km/sec)	Depth to Top of Layer (km)
4.25	0.00	6.10	0.00	4.50	0.00
6.31	0.25	6.60	4.00	5.00	1.00
6.69	13.00	8.10	35.00	6.00	6.00
8.10	42.00			8.10	35.00

STATION DISTRIBUTION



KEY

- MCC STATIONS
- ◇ LD60 STATIONS

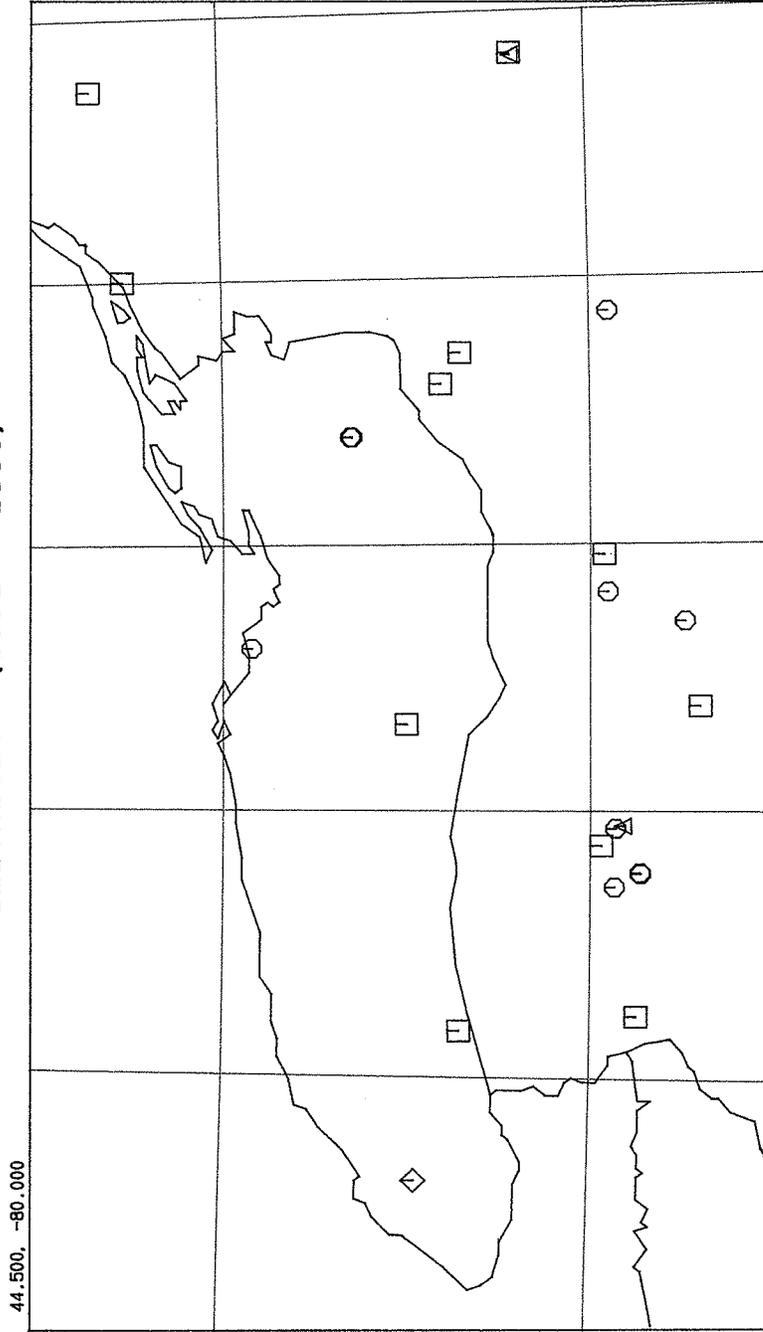
FIGURE 1

WOODWARD-CLYDE CONSULTANTS

GEOLOGICAL SURVEY OF CANADA WORKSHOP:
Seismic Source Zones in
Eastern North America

seismic/misc/gsc/plots/d012f01.plt

SEISMICITY (1981 - 1990)



KEY

- MC data
- + = - .99 to - .01
 - △ = .00 to .99
 - = 1.00 to 1.99
 - = 2.00 to 2.99
 - ◇ = 3.00 to 3.99

DATA SOURCE:
Woodward-Clyde Consultants (1989)

FIGURE 2

WOODWARD-CLYDE CONSULTANTS

GEOLOGICAL SURVEY OF CANADA WORKSHOP:
Seismic Source Zones in
Eastern North America

seismic/misc/gsc/plots/d012f02.plt

SEISMICITY FROM EPRI (1986) CATALOG

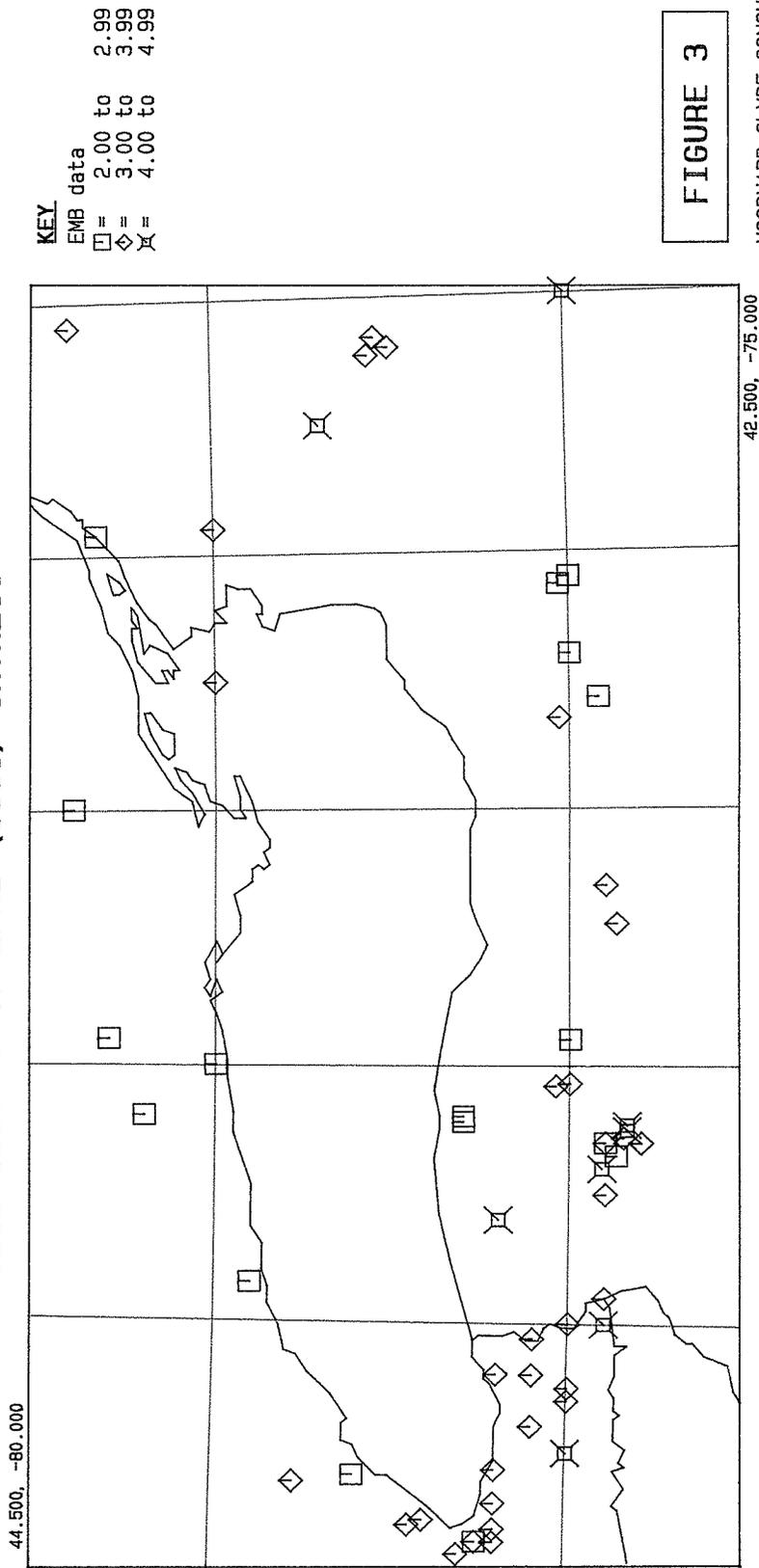


FIGURE 3

WOODWARD-CLYDE CONSULTANTS

GEOLOGICAL SURVEY OF CANADA WORKSHOP:
Seismic Source Zones in
Eastern North America

seismic/misc/gsc/plots/d012f03.plt

THE SAGUENAY EARTHQUAKE AND GEOLOGY

Comments by DENIS W. ROY, Univ. Qué Chicoutimi,
WORKSHOP ON SEISMICITY SOURCE ZONES FOR THE 1995 NBCC SEISMIC HAZARD MAP OF CANADA
Ottawa, 18-19 MR 1991.

A- SAGUENAY GRABEN AND JACQUES CARTIER HORST.

The Saguenay earthquake occurred within the Jacques Cartier tectonic block about 10 km south of the eastern end of the south wall of the Saguenay graben. The Jacques Cartier block is a horst between the Saguenay graben to the north and the St-Lawrence normal fault system to the south-east; it is limited to the west by the St-Maurice lineament which may be a prolongation, north of the Montreal plain, of the Hudson river - lake Champlain lineament. The position of the boundary between the Jacques Cartier block and the Saguenay graben is unknown east of lake Kenogami beyond which neither on geological nor on topographical grounds can lengthwise extension of the dividing normal fault be supported.

The boundary faults of the Saguenay graben and of the Jacques Cartier horst often are parallel and/or re-activate late to post Grenvillian ductile shear zones which may exhibit either strike-slip or dip-slip motion or both. The boundary faults of these two tectonic blocks, and the less developed internal faults, may have been formed or re-activated during any of the following Phanerozoic extensional tectonic events: 1- the opening of the Iapetus ocean (560-540 Ma), 2- the loading of the Appalachian allochthon (450 Ma, Taconic orogeny), 3- the down-drop of the Gulf of St-Lawrence basin (Carboniferous), 4- the opening of the central Atlantic ocean (190-175 Ma) and the intrusion of the Monteregian Hills (120-90 Ma). It is proposed that the Saguenay graben results from events 1- and 4-, and that the normal faults along the St-Lawrence between the Saguenay and the St-Maurice rivers result from events 1-, 2-, and 4-. Events 3- and 5- appear to be respectively restricted to the Gulf of St-Lawrence and to the Montreal area.

B- RADAR LINEAMENTS AND ALIGNMENT OF AFTERSHOCKS.

Four overlapping radar images were taken from the north, west, south and east around the epicenter of the 1988 Saguenay earthquake. The covered area includes the central part of the Saguenay graben and the northern part of the Jacques Cartier block. These images exhibit well defined lineaments of various sizes trending into several orientations. The most frequent orientation in the vicinity of the epicenter parallels the strike of the 325 67 NE nodal plane defined by the main shock.

Most of the epicenters of the aftershocks are distributed along two lines: to the SSE of the main shock along a 325° trend and to the ESE, along a 105° trend. The first group of aftershocks hypocenters were projected along the "b" axis of the focal plane solution on a plane perpendicular to the nodal planes and on each of the nodal planes. On the "perpendicular" plane, the aftershocks form a cluster about the projection of the main shock; on the 325 67 NE nodal plane, they are widely dispersed; and on the 208 41 NW nodal plane, they are grouped along the trace of the other nodal plane, suggesting that the 325 67 NE orientation represents the fault plane of the main shock.

The 105° trend is parallel to the axis of the Saguenay graben. The aftershocks of that group are located near important ESE trending lineaments in the lake Hal Hal area. These lineaments may correspond to an en echelon southward jump of the south wall of the Saguenay graben. However, the exact nature of these lineaments remains to be documented.

C- SEISMICITY.

• **Around the Jacques Cartier block:** The St-Maurice lineament shows some moderate seismic activity: the river Croche earthquake of late 1990 and several recent small earthquakes at its intersection with the south wall of the Saguenay graben south of lake St-Jean. The secular vertical motion of the Jacques Cartier horst suggests it is tilting (NW up and SE down) with respect to the general isostatic recovery of the Canadian Shield. Such a tilt is consistent with reverse motions on the St-Lawrence faults and corresponds to an incipient overriding of the

Jacques Cartier block by the terrains to its south-east.

• **In Charlevoix:** The Charlevoix impact structure affects three different tectonic terrains: I- "intact" crystalline basement of the Canadian shield (i.e.: the Jacques Cartier block), II- down-faulted crystalline basement (i.e.: the basement of the St-Lawrence lowlands) and III- Appalachian allochthon (emplaced during the Taconian orogeny - ca 450 Ma). All of the earthquakes occur in the terrain II. Plotting the hypocenters on a graph "radius - depth" (radius = horizontal distance to the center of the Charlevoix structure - ca 350 Ma) suggest that the impact has a secondary control in the location of the events, thus that it may explain their frequency in the area. Another contribution to the high Charlevoix seismicity is the merging of the Saguenay graben with the St-Lawrence fault system.

D- SEISMIC ZONING ALONG THE ST-LAWRENCE VALLEY.

• **Designation:** I have reservations about designing the belt of seismic activity along the St-Lawrence river as the "St-Lawrence rift". Indeed, the large area of faulted crystalline basement that extends along the St-Lawrence river from the great lakes to the Labrador coast results from a combination of late Precambrian and Phanerozoic events, only one of which is properly termed the "St-Lawrence rift" (event 1 in A above). In addition, the term "rift" implies extension while the present-day stresses are compressive. So the expression "St-Lawrence rifted terrains" is suggested in order to avoid the confusions that the other designation may carry.

• **"Belts" of seismic activity:** In eastern Canada, the St-Lawrence rifted terrains and the northern Appalachian allochthon appear to be two distinct belts of seismic activity; the "Brompton-Baie-Verte" line is the geological boundary between these two belts: it corresponds to the suture of the Iapetus ocean and roughly marks the limit of strong Acadian structural and metamorphic overprinting. The north-west limit of the St-Lawrence belt should be placed outside the known extensions of the Melville, the Saguenay, the Timiscaming and the Ottawa-Bonnechere grabens. The maximum magnitude for the background

of the St-Lawrence belt, outside of the branching corridor and special areas described below, should be the same as the actual Eastern Background zone, that is 5.

• **Branching corridor:** Narrow zones of more intense seismic activity (observed or potential) should be defined along the faulted limits of the tectonic blocks within the St-Lawrence belt: these would include a 30 to 50 km wide corridor following the scarp line along the north shore of the St-Lawrence river (10 km to the north-west and the remainder to the south-east), with branches along the Saguenay, the Ottawa, the Timiskaming and other grabens (width and length), and a 20 km wide zone centered on the St-Maurice river between Shawanigan and lake St-Jean. These zones together form a single branching corridor. Similar branches were suggested for Ontario at the meeting. The branching corridor could be given a maximum intensity one degree of magnitude higher than the maximum historically observed within it (excluding the special areas below).

• **Special zones:** There are at least three zones of well defined historic seismicity to add to the seismic zoning: 1- The lower St-Lawrence zone, bounded by two E-W deviations of the St-Lawrence north shore scarp line and spanning the local width of the St-Lawrence estuary. 2- The Charlevoix zone which covers the impact structure and extends to the north-east to the area where the Saguenay graben and the St-Lawrence normal faults system merge. 3- The western Quebec zone where broad arching seems to have occurred in post-Ordovician time (post-Paleozoic?). The location of the Timiskaming earthquake should be looked at closely to see whether it lies within the Timiskaming graben or not, and, if so, new limits should be drawn for the western Quebec zone. These special zones could be given a maximum intensity one degree of magnitude higher than the maximum historically observed in each.

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DENIS W. ROY, UNIVERSITE DU QUEBEC A CHICOUTIMI

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The Case for a Seismic Zone Off
Southwest Nova Scotia in the
Gulf of Maine or along the edge
of the Continental Shelf/Slope

by
Alan Ruffman
Geomarine Associates Ltd.
5112 Prince Street
P. O. Box 41, Station M
Halifax, Nova Scotia
B3J 2L4

Nova Scotia's record of historic and instrumental seismicity in the Canadian Earthquake Epicentre File (CEEF) indicates that the province has a relatively low seismic hazard for onshore areas (Smith, 1962; Fig. 1; CEEF). Recent historic seismicity studies indicate that the majority of the onshore felt earthquakes in Nova Scotia have been felt in the southwestern half of the province with communities to the very southwest reporting most of the felt events (Ruffman and Peterson, 1986); i.e., Digby, Yarmouth, Liverpool, etc. Most of these communities are on the coast because of the nature of Nova Scotia's urban geography and its historic development as a fishing economy.

Epicentres that are shown to the west of Nova Scotia tend to be clustered in the Bay of Fundy area and appear to be mainly related to the Passamaquoddy Bay seismic zone (Fig. 1). However, the historic seismicity work done to date in eastern Canada may indicate that some epicentres should be located offshore.

The Sunday, August 12, 1832 event at 0640 AST (1040 GMT; average of six times) was given by Smith (1962) as intensity IV on the Modified Mercalli Intensity Scale of 1931 (MM) at 45.0 N, 64.0 W east of Windsor, Nova Scotia; this has been translated to a magnitude of 3.7 on the CEEF. Ruffman and Peterson (1986) greatly amplified the information on this event. Felt reports are now documented for Yarmouth and area, Nictaux, Annapolis, Liverpool, Spa Spring (near Windsor), Brier Island, Windsor and Shelburne. At the latter two communities, some plaster was shaken down and at Brier Island, "Many rocks on the cliffs of the island were shaken down" (Fig. 2).

The August 12, 1832 event has not had an exhaustive event-specific search done in New Brunswick and New England sources to accurately map its felt area or to possibly better determine its epicentre. At this point, one can only note that the Nova Scotia felt reports could suggest an offshore source off western Nova Scotia (or a source in a remote part of west central Nova Scotia

onshore). This event deserves a detailed event-specific search similar to the detailed work LeBlanc and Burke (1987) have done on four historic New Brunswick events.

The Tuesday, February 1, 1848 event was felt in southwest Nova Scotia and in the Halifax area. Smith (1962) lists the event as in-

tensity III (MM) at 43.5 N, 65.5 W which is at Cape Sable Island at the very southwestern tip of the province; the CEEF lists the event as having a magnitude of 3.7. Smith and the CEEF also list Nova Scotia events on January 1, 1848 and on January 1, 1847; Ruffman and Peterson (1986) have shown these two possible events as ghosts and they should be removed from the CEEF.

This event appears to be two events - one "just before daybreak" and one about 0800 local time. The earlier event appears to have been felt at Yarmouth and Shelburne, while the later event on the same day was felt both in southwest Nova Scotia and in the Halifax area, at Pier's Mills, Hammonds Plains and at Lawrencetown, Porters Lake and Dartmouth, where "the ice in the lakes was shivered into fragments" (Fig. 3). The 0800 event seems to have been felt over a wide area of Nova Scotia, but good primary sources are thin (Ruffman and Peterson, 1986).

The February 1, 1848 event has not had an exhaustive event-specific search done in New Brunswick and New England sources to accurately map its felt area or to possibly better determine its epicentre. At this point, one can only note that the Nova Scotia felt reports could well indicate an offshore source. The earlier event at circa 0735 AST may be a foreshock of the larger, offshore event some 35 minutes later. This event deserves a detailed event-specific search. If the two events are totally unrelated, then two offshore sources for the two events are still in order or at least quite possible.

The Sunday, December 31, 1882 New Year's Eve events are by far the most suggestive of an offshore source. Smith (1962) cites the event as a single event at 2156-2205 local time with an Intensity V (MM) at 45.0 N, 67.0 W in Passamaquoddy Bay. The CEEF gives a magnitude of 4.3. The felt report data compiled to date clearly indicate more than two events, possibly further events on Monday, January 1, 1883 and in all probability an offshore epicentre is indicated (Ruffman and Peterson, 1986).

Figure 4 shows the felt localities presently known from mainly work on Nova Scotian sources. Ruffman and Peterson (1986, p. 285) report the following Summary of Events:

Felt in Machias, Eastport, Rockland, Bangor, Maine; in Dover, New Hampshire; in St. Stephen, Saint John, Sussex, Rothesay, Fredericton, Indiantown, New Brunswick and in Halifax (with flashes), Dartmouth, Windsor, Rockhead (Halifax), 3 miles off Seal Island enroute from Boston to Halifax by steamer EUREKA (with flashes), [Cape] Sable Island Light, off Yarmouth, Chester, [St.] Margarets Bay Road (with flashes), Truro, Meteghan, Annapolis, Prospect, Port Mouton, "In the Western portion it seems to have been more severe than in Halifax, the people residing in the fishing settlements on the Western shore of this county [Halifax County] feeling it very heavily.", Yarmouth (with flashes), Waterville, Carleton, Brier Island, Shelburne, Kempt, Westport, Bridgewater (with flashes) and Antigonish, Nova Scotia.

Just the number of reports and correspondents' communications to Nova Scotia newspapers as opposed to reports from New Brunswick indicate to the authors of this compilation that this event was felt more heavily in Nova Scotia than in New Brunswick. The transcripts below cite damage in wouthern Nova Scotia whereas we see no such reports for New Brunswick or Maine.

Smith (1962) indicates that the New Year's Eve event was felt over "80,000 square miles". However, this event has not had a thorough event-specific search done on it and cries out for examination in New England, New Brunswick, additional Nova Scotian and possibly Prince Edward Island and Newfoundland sources. Such a complete documentation should let one obtain a better idea of the epicentre and magnitude and perhaps resolve whether or not one of the three or more events was a non-tectonic event resulting from a meteor impact or meteor termination. At this point, the felt reports would seem to indicate an epicentre offshore of southwest Nova Scotia.

The Ruffman and Peterson (1986) historic seismicity report also noted apparent tsunamis in 1813 and 1843 in southwestern Nova Scotia. The Tuesday, January 19, 1813 event in Liverpool Harbour may be some sort of an atmospherically-induced seiche, but Ruffman and Peterson (1986) concluded that it was a probable tsunami. There is virtually no doubt that the Tuesday, April 18, 1843 event was a tsunami. It was seen at Yarmouth Harbour, Bunkers Island, the Cove and Cook's Harbour, however the apparent earthquake was felt only at Cooks Harbour. The schooner BEE's experience is well-documented by her captain and all evidence points to a fairly local earthquake offshore. No Atlantic-wide search of historic earthquake epicentre databases has been initiated to try and run this event to ground or to locate a teleseismic source.

Lander and Lockeridge (1989) document an apparent tsunami on Saturday, January 9, 1926 at Bass Harbour, Bernard, Mt. Desert Island, Vinalhaven and Corea in the Penobscot Bay area of Maine. Some fishermen referred to the event as a "bore wave". There were reports of apparent small earthquakes (or foreshocks) prior to the tsunami of 8 to 10 ft of withdrawal and of circa 10 ft of runup.

The 1813, 1843 and 1926 events (Fig. 5), if all are tsunamis, could indicate an offshore seismic zone off southwest Nova Scotia. There is, however, no way of being able to determine the epicentres of such historic events if they are offshore.

Conclusions

None of the above seismic or tsunami events can be used at this stage as conclusive proof that there is some sort of a sporadically-active seismic zone off southwest Nova Scotia; nor can one put an epicentre on a map or attach a true magnitude to the seismic events. Clearly, more work is needed and this is possible on the seismic events. However taken in their totality, the above events - especially the December 31, 1882 event, do seem to indicate that one should consider some sort of an area or zone of increased seismic hazard offshore of southwestern Nova Scotia. This zone could be at the shelf edge or on the slope at the mouth of the Northeast Channel and therefore could be analogous to the Laurentian Slope (LSP) seismic zone.

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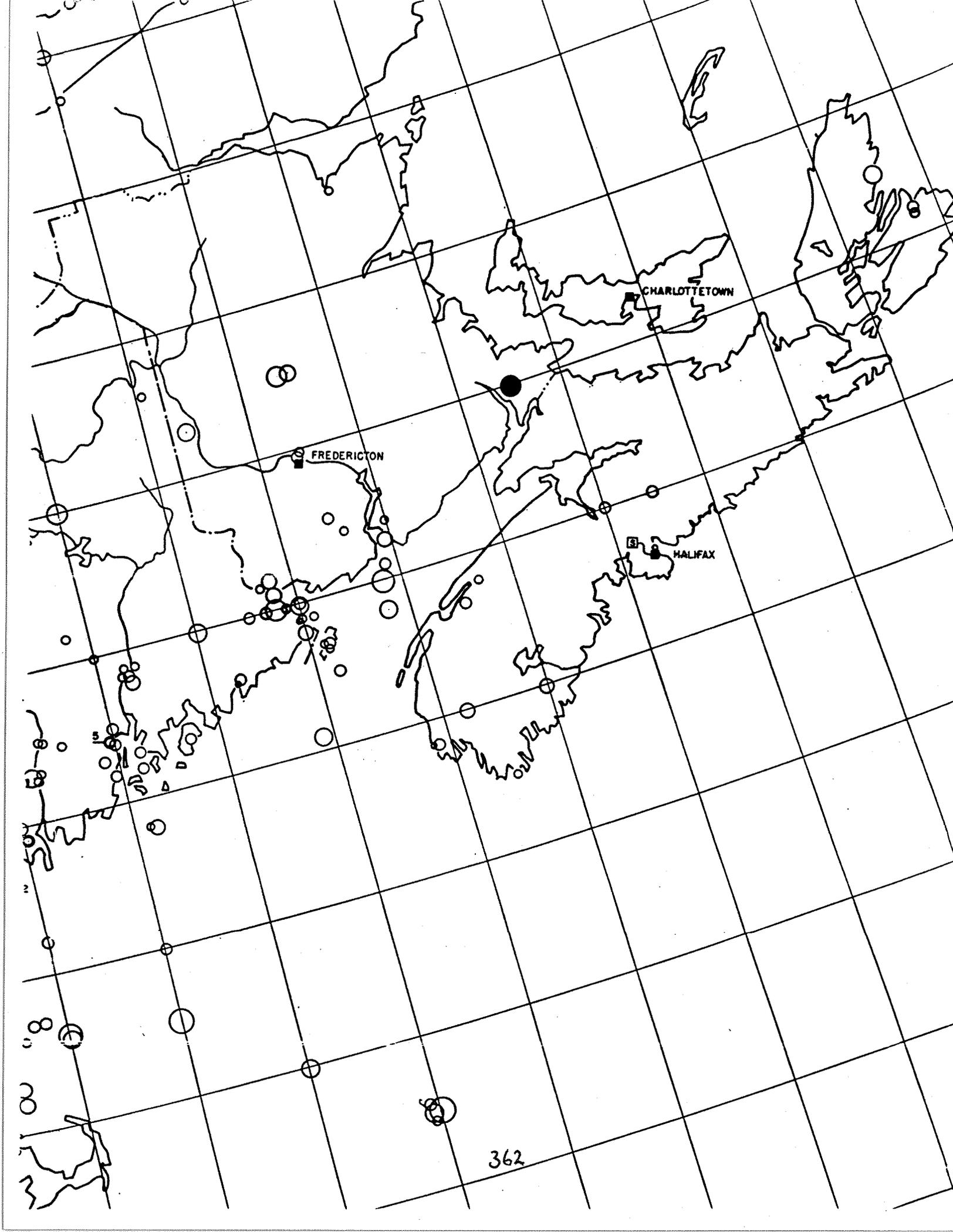
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Figure 1

Earthquake epicentre map from Smith (1962) showing five events in southwestern Nova Scotia. Any events shown offshore are either in the Bay of Fundy and Passamaquoddy Bay area or about 250 km southwest closer to, and east or northeast of, Cape Cod.



FREDERICTON

CHARLOTTETOWN

HALIFAX

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Figure 2

Map showing the known reported felt localities of the August 12, 1832 earthquake (solid dots). The letter 'D' indicates reports of minor damage. These felt localities could reflect an offshore epicentre off southwest Nova Scotia, perhaps in the vicinity of the mouth of the Northeast Channel.

Figure 3

Map of known reported felt localities for the February 1, 1848 earthquake events (solid dots). These felt localities could reflect two fairly small offshore earthquakes or could reflect a single larger event somewhat farther offshore off southwest Nova Scotia.

NEW BRUNSWICK

MONCTON

SAINT JOHN

TRURO

BAY OF FUNDY

NOVA SCOTIA

HALIFAX

DARTMOUTH

+ ?

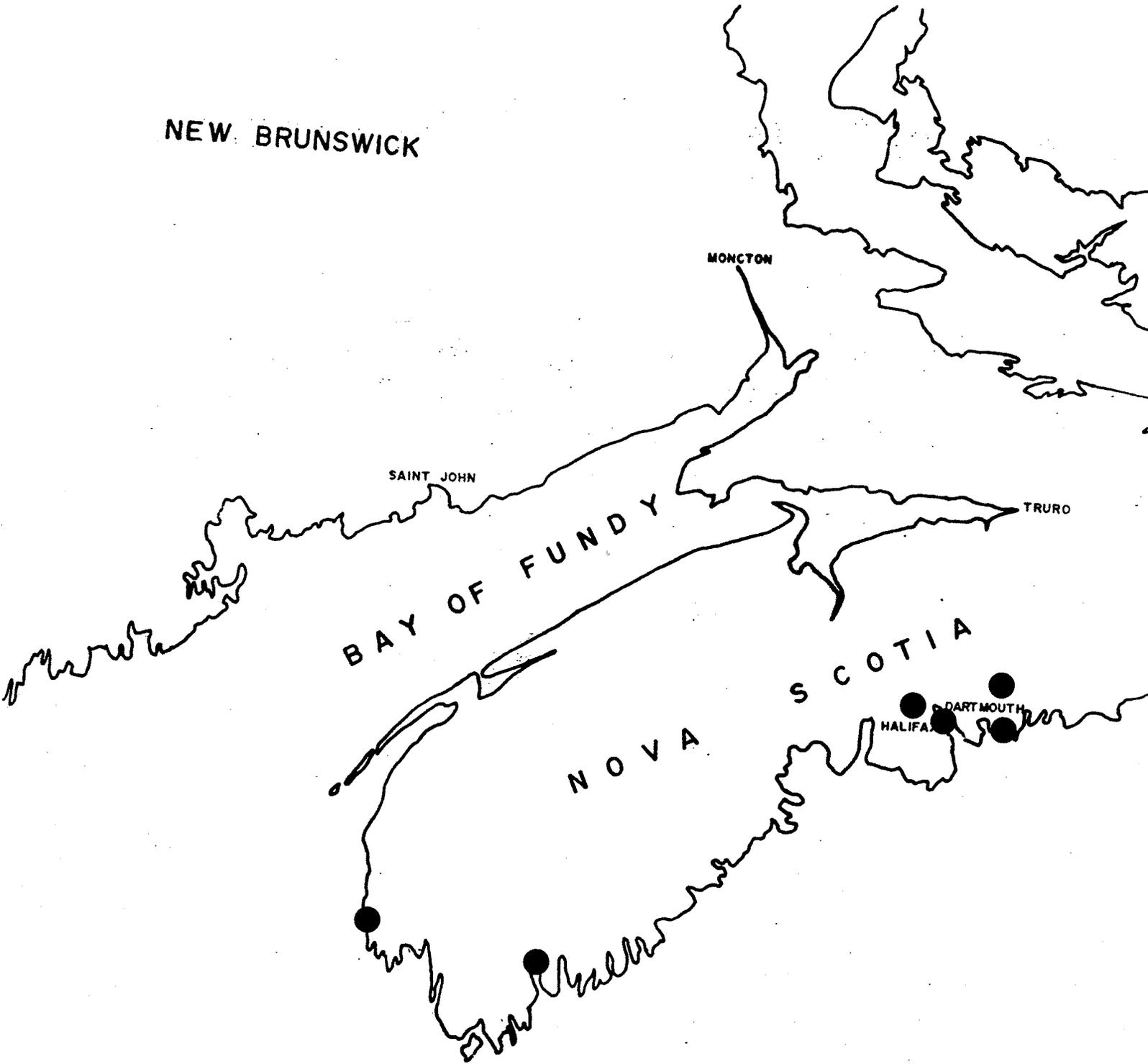
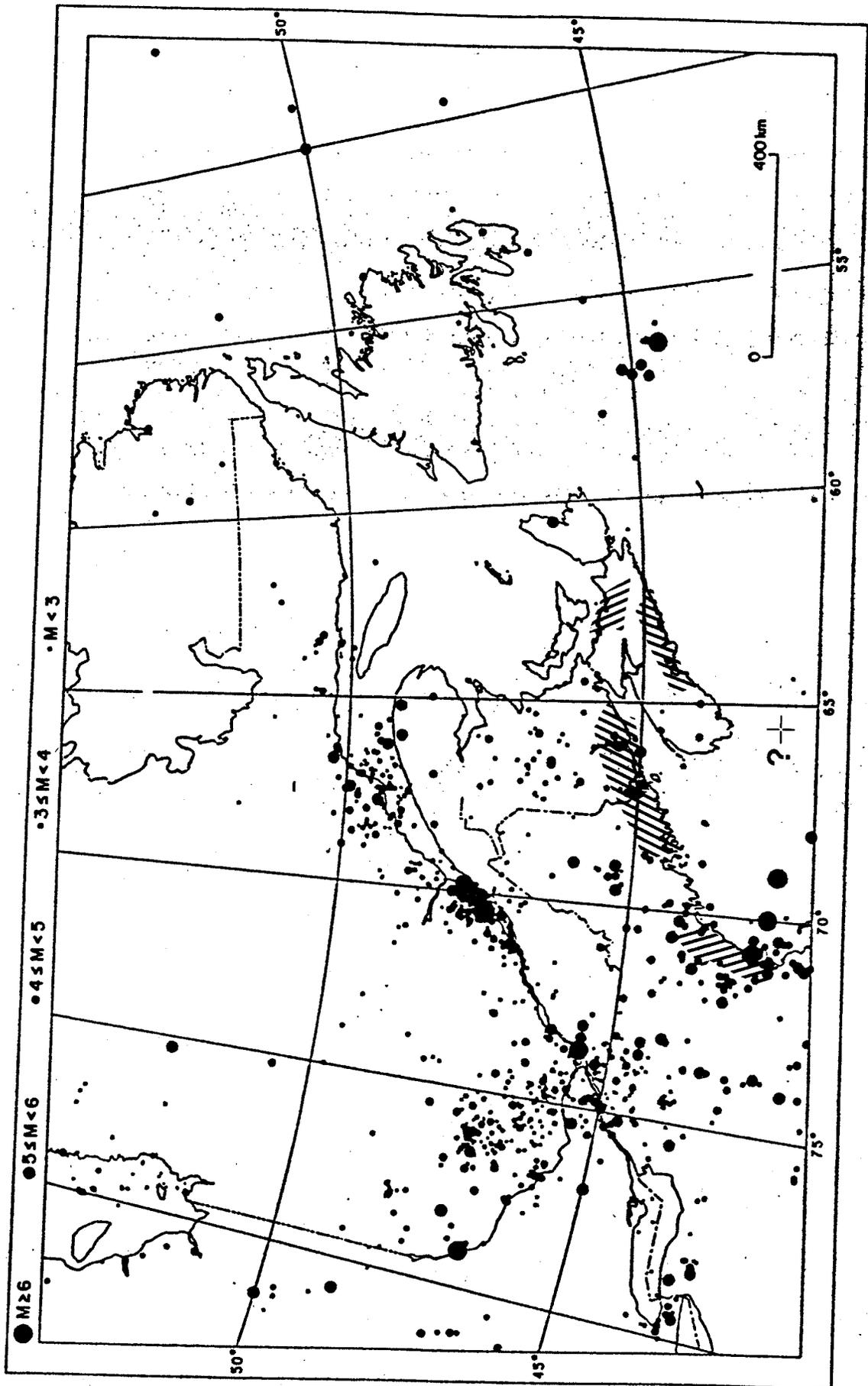


Figure 4

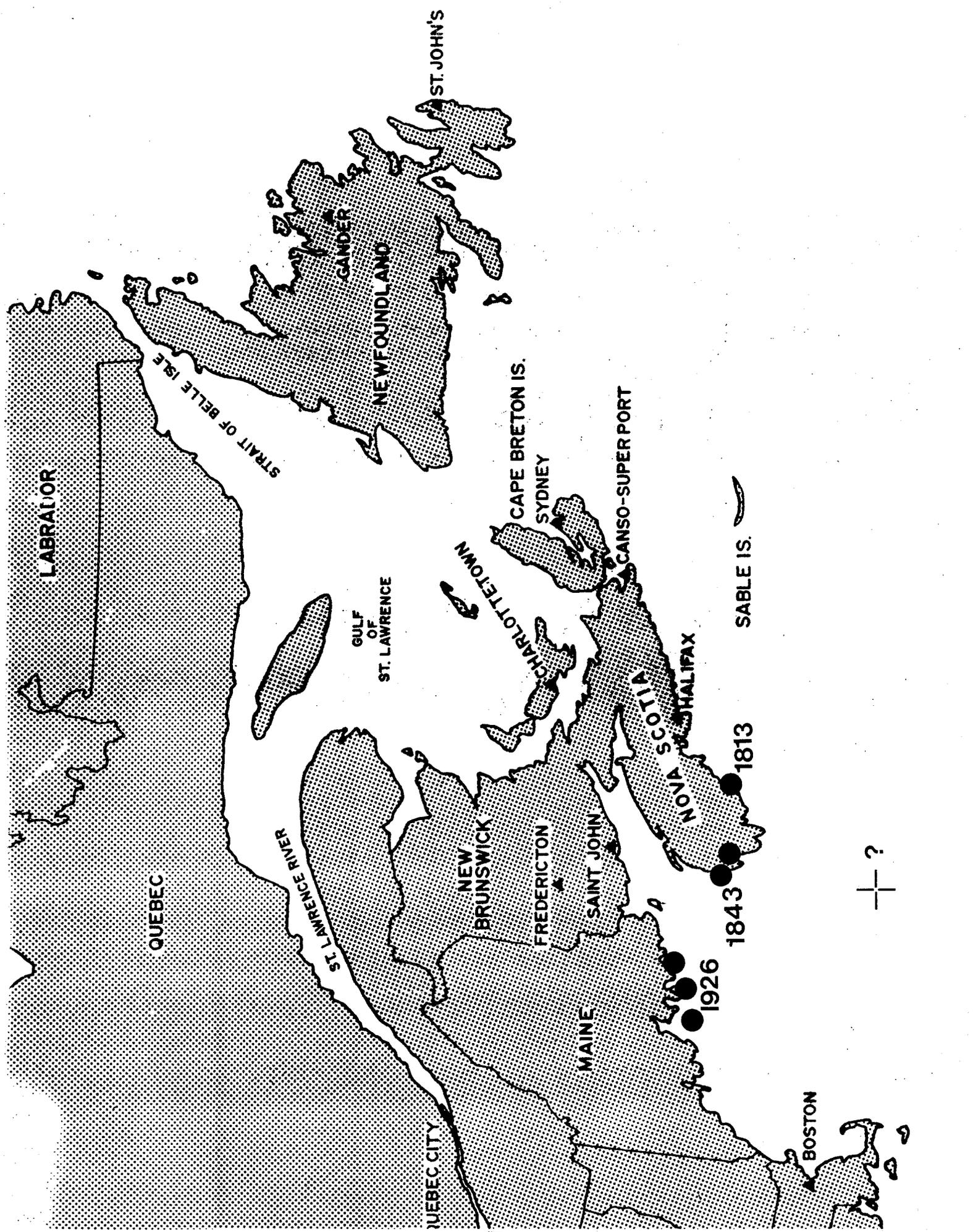
Map of the seismicity of eastern Canada from Morel-a-l'Huissier and Anglin (1982) with a shading superimposed to reflect the presently-known general felt area of the New Year's Eve (December 31, 1882) earthquakes. The large felt area indicates that the source could be a moderately-sized event with an offshore epicentre off southwest Nova Scotia.



Seismicity of eastern Canada. Earthquakes with magnitudes 4-5, 3-4, and less than 3 are shown for time periods since 1950, 1960 and 1970, respectively. From Basham, Morel-à-l'Huissier and Anglin (1982)

Figure 5

Map showing the location of the January 19, 1813 apparent tsunami at Liverpool, Nova Scotia, the April 18, 1843 tsunami in the Yarmouth area and the January 9, 1926 tsunami in the Penobscot Bay area of Maine. If each of these events is a tectonically-induced tsunami, then the epicentre could be off-shore off southwest Nova Scotia.



Notes on the recurrence rate of
 a November 18, 1929-like event
 in the Laurentian Slope (LSP) Seismic Source Zone
 or of similar shelf-edge/slope events off
 Eastern Canada

by

Alan Ruffman, President
 Geomarine Associates Ltd.
 5112 Prince Street
 P. O. Box 41 Stn "M"
 Halifax, Nova Scotia
 B3J 2L4
 TEL: (902) 422-6482
 FAX: (902) 422-6483

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Introduction

Only one large earthquake event has been recorded in the Laurentian Slope (LSP) seismic source zone, with numerous smaller 'aftershock' events known (Doxsee, 1948). The 1702 NST, November 18, 1929 (1632 AST, 2032 GMT) "Grand Banks" earthquake of magnitude 7.2 (Ms) occurred beneath the continental slope (Dewey and Gordon, 1984) at the mouth of the Laurentian Channel (Figure 1). The underwater slump that ran down the continental slope and onto the Laurentian Fan and the Sohm Abyssal Plain, cut 12 trans-Atlantic telegraph cables and the resultant tsunami killed 27 persons in the Burin Peninsula area of Newfoundland when it arrived about 2.5 hours after the earthquake. Another Burin child died subsequently as a result of injuries and a Nova Scotian man is now known to have died in southern Cape Breton Island (Ruffman *et al.*, in prep. 1991).

Numerous aftershocks followed the 1929 event with magnitudes as large as 6.0 and earthquakes in the magnitude 5.0 range have occurred in 1951, 1954 and 1975 within the LSP seismic zone (Figure 1; Basham and Adams, 1982). Recent historical seismicity work that is still in progress has defined some apparent additional aftershocks (Ruffman, Peterson and Boylan, in prep. 1991) and it is now known that the February 10, 1930 aftershock also coincided with a telegraph cable being cut offshore (Ruffman *et al.*, in prep. 1991).

The 1929 slump or turbidity current travelled at great speed down the continental slope and 1700 km well out across the abyssal plain towards Bermuda (Piper and Normark, 1982; Piper *et al.*, 1987). David Piper at the Atlantic Geoscience Centre of the Bedford Institute of Oceanography has run a series of high resolution 3.5 kHz profiler lines and 16 kjoule digital sparker lines across the Laurentian Fan and St. Pierre Slope. Piper and Normark (1982) state:

The absence of earlier slump events revealed in the sedimentary sequences on 3.5 kHz profiles of both the slope off St. Pierre Bank and the upper Laurentian Fan suggests that no other major shaking event of the same style occurred during the accumulation of the upper 40 ms of sediment. The sedimentation rate data of Stow (1977) and Alam (1979) suggest that this interval corresponds to at least the past 100,000 years. Therefore, we conclude that the 1929 event was the only earthquake of that magnitude to occur at the edge of the Laurentian Channel within at least the past hundred thousand years. Large earthquakes, however, may have occurred farther northwest on the Gloscap fault system, and smaller earthquakes may well have occurred, with effects less visible on 3.5 kHz profiles. (p. 150)

Recent seismic profiling work by Piper in the area allows him to now state that it has been about 300,000 years since a similar earthquake event has occurred (personal communication, David Piper, Atlantic Geoscience Centre, April, 1991).

These findings seem to be in contrast with Hacquebard *et al.* (1981) who have found evidence in cores on the Sohn Abyssal Plain of a turbidity current deposit with a fairly clear Laurentian Channel source, aged about 35,000 years B.P. (see also Hacquebard, 1989 and Vilks *et al.*, 1985). This finding is not inconsistent with Piper and Normark (1982), who note that, "Turbidites of Wisconsinan (latest Pleistocene) age, which are common on the lower Laurentian Fan and Sohn Abyssal Plain (Stow, 1977; Wang *et al.*, [1982]), appear to be more common than seismic events of the magnitude of the 1929 earthquake." Piper and Normark suggest that the more ubiquitous "turbidites may well have been formed by slumping of glaciomarine sediment transported down the Laurentian Channel; this slumping may well have been initiated by sediment overloading on steep slopes or by small earthquakes that triggered slumps only very close to the epicentre" (p. 150). David Piper now suggests that catastrophic under-ice glacial outbursts during the Pleistocene could have provided the material for the many lesser turbidites seen (personal communication, Science Hour, A.G.C., May 3, 1991).

Presumably to cause the kind of debris flow-turbidity current event that would leave the kind of seismic signature that Piper and Normark demand one needs, not only a large magnitude earthquake in the LSP seismic zone, but also a large supply of sediment on the upper Laurentian or St. Pierre Slope that can shake loose and move downslope. One could argue that a second 1929-like event in the years immediately following 1929 would have had little sediment to liquify or to shake loose and would not have left a seismic signature. One could argue that the 100,000+ to 300,000 year periodicity that Piper and Normark find reflects, not the recurrence rate of magnitude 7.2 earthquakes in the LSP seismic zone, but rather the recurrence rate of

significant sediment accumulation on the upper continental slope at the mouth of the Laurentian Channel.

Basham *et al.* (1982b) noted that "the rate of 1929-sized earthquakes is poorly determined by the magnitude recurrence data." Their cumulative magnitude recurrence relation for the LSP seismic source zone at the mouth of the Laurentian Channel (Figure 2):

"assumed that magnitude 7 earthquakes would have been completely reported since 1800 although we are by no means certain that reports of effects would even approximately locate such an offshore event in the early 1800's, had one, occurred, nevertheless, the result is a recurrence relation that shows reasonable agreement between the rates of larger earthquakes and the rates in the magnitude 4-5 range, although the slope of the curve tends to be lower than that of most other source zones. [Figure 2] ...

Implicit in the adoption of this model is the assumption that the next large earthquake in the region will occur within the restricted [LSP source] zone at the mouth of the Laurentian Channel, i.e., rather than at some other location on the Newfoundland or Scotian Shelf. The evidence to support this assumption is not very strong, but we consider the model to be the best available for the present purposes. The result, however, is that the remainder of the Newfoundland and Scotia shelves falls within a zone of low background seismicity which may under-estimate the real risk in these regions. (p. 83 and 86)

Basham and Adams (1982) drew upon the piston core work of the Atlantic Geoscience Centre on the distal end of the 1929 turbidite:

Cores off Bermuda show that the 1929 turbidite has a distinctive red colour quite unlike the olive-grey Holocene and recent sediments, but like those deposited on the Scotian Shelf and slope during the Pleistocene (Piper and Normark, 1982). This suggests that much of the sediment that slumped in 1929 was originally deposited during the Pleistocene, a suggestion that is confirmed by cores taken in the slumped area that show Pleistocene sediments exposed at the seafloor and not covered by the olive-grey Holocene muds that occur outside the slumped area (Piper and Normark, 1982). Hence the sediments that slumped in 1929 had remained stably on the slope for more than 10,000 yr. This might suggest that 1929-sized earthquakes are very infrequent (say 1/10,000 yr) within about 100 km of the 1929 epicentre. By contrast, the Laurentian Channel source-zone model used for the regional

probabilistic ground motion mapping is about 1/300 yr (Basham et al., 1982b). (4th page of paper)

They expanded on these comments in Basham and Adams (1983) under a discussion, "Can Future Earthquakes Occur Anywhere Along the Margin?":

As the seismotectonic models for both the continental margin as a whole, and for the regions of historical earthquake concentration are very poorly defined, evidence must be sought to determine the possibility of future large earthquakes at other locations along the margin. The present evidence is speculative and involves a considerable lack of knowledge about the recurrence intervals of the larger earthquakes and their associated long-term crustal deformations.

In the models of historic seismicity employed for probabilistic seismic risk estimates of the eastern margin for National Building Code applications (Basham et al., 1982b), it is difficult to estimate stable magnitude recurrence relations for source zones that contain only a single large earthquake. For such single events the return period is unknown, but it is believed to be longer than the historical period. This is the case for both the Laurentian Slope and Baffin Bay source zones. The only independent evidence on recurrence intervals is provided by preliminary marine geophysical and sediment sampling experiments in the area of the 1929 Laurentian Slope earthquake (Piper and Normark, 1982). Much of the sediment that slumped in 1929 was originally deposited during the Pleistocene and hence had remained stably on the slope for more than 10,000 years before being shaken loose. This, and the paucity of Holocene turbidites on the deep sea floor, suggest that 1929-sized earthquakes are very infrequent within about 100 km of the 1929 epicentre. If they are infrequent at any one location along the margin, there may have been similar events at other locations in prehistoric times for which no marine geological or continuing seismicity evidence has yet been found (p. 459).

A model that claims ignorance as to where along the margin the large earthquakes are likely to occur, distributes them equally along the entire 5500-km length of the continental slope [ESX seismic source zone - 'Eastern Slope Experimental seismic source zone]. A magnitude recurrence relation for this model derived from known Laurentian Slope, Labrador Slope and Baffin Bay seismicity seems to provide a reasonably stable

estimate of the rate of significant earthquakes. If they are equally likely at any location, the recurrence estimate suggests one earthquake of magnitude 7 or greater per thousand years per thousand kilometers along the slope. This rate is comparable to that suggested by Wentworth and Mergner-Keefe (1981) for the eastern seaboard of the United States. Such earthquakes would significantly shake a 200-500 km length of the margin.

If we postulate that each of these large events has a long aftershock sequence, of the order of 100-200 years, i.e., that current seismicity on the Laurentian Slope and in Baffin Bay represents aftershocks of the 1929 and 1933 earthquakes, it is possible that the current Labrador continental slope earthquakes are late aftershocks of a similar large event. Were one or more such events felt in Labrador fishing villages in the early 1800's? Any [sic=And?] by extension of the argument, are some of the gaps in contemporary seismicity along the margin the locations of even older events for which the aftershock sequence has died down? These speculations are depicted graphically in Figure 4 [here Figure 3]. (p. 460)

Thus, we have two quite different views as to the recurrence rate of a 1929-like event and indeed we have two radically different seismic source models to choose from. We have a suggested recurrence period for the LSP source zone of circa 100,000 to 300,000 years and one of at least 300 years and perhaps 10,000 years. One model suggests that the next 1929-sized event will occur inside the LSP source zone at the mouth of the Laurentian Channel (Figure 1) while the other suggests that in the ESX seismic source zone a similar event could occur anywhere along the continental slope with a recurrence rate of one earthquake of magnitude 7 or greater per 1,000 years per 1,000 km along the slope. The recurrence rate and the lack of a clear understanding of a source mechanism is subject to ongoing discussion (Basham *et al.*, 1983; Adams, 1986; Basham, 1989; Adams and Basham, 1989).

Are there data that might challenge the assumption of a 100,000 to 300,000-year period or the suggested 300 to 10,000-year estimate of Basham and Adams? The data are perhaps circumstantial, thin and still in progress, but they do seem to point towards the shorter return period. Or point toward other shelf-edge events in the general area at the mouth of the Laurentian Channel (Figure 1). This evidence includes three telegraph cable breaks in 1884, known tsunamis and other felt events. These events are:

- a) September 24, 1848 tsunami, northeast Nfld. and Labrador
- b) June 27, 1864 felt event and tsunami, St. Shotts, Nfld.
- c) October 4, 1884 slump, Tail of the Banks
- d) August 21, 1904 felt event, St. Pierre et Miquelon
- e) December 23, 1909 felt event, Isaacs Harbour Mouth, N.S.
- f) May 7, 1914 tsunami, Northern Cape Breton Island, N.S.
- g) January 22, 1915 felt event, M/V ALEPPO Sable Island, N.S.
- h) April 11, 1940 felt event, southern Newfoundland
- i) dans les années 1940 mini raz-de-marée, St. Pierre, S.P.M.

September 24, 1848, Tsunami, northeast Newfoundland and Labrador

By including this tsunami in this compilation I do not mean to imply that it may have originated in the Laurentian Slope seismic zone; its origin is most likely northeast of Newfoundland and it could have resulted from a teleseismic event. The event could, however, have originated from a shelf-edge event 250-400 km northeast of the island. It is also a good demonstration of the value of a careful systematic search of primary sources in one area yielding unexpected results in another.

The September 24, 1848 tsunami was first found by Jeannie Peterson and reported in Ruffman and Peterson (1986). The previously-unrecorded event was found in a systematic search of the Halifax Acadian Recorder of Saturday, October 21, 1848 citing an October 3, St. John's, Newfoundland report which in turn cited "an extract of a letter from Bonavista dated 26th September":

"On Sunday last, between the hours of three and four in the afternoon, a most strange phenomenon (if it may be so called) was observed here, namely the sudden receding of the water in this harbour, to such a frightful extent, that some of the boats grounded at their moorings on the collars, and by a return or flow of the water in a few minutes, to a considerable extent, covering the bedding or floor of the fishing stages in the place. Nothing of this kind has been known in this quarter since 1755, the time of the destruction of Lisbon by earthquake. I expect this has been observed in other harbours in the Island."

The unknown correspondent was quite correct in her/his supposition. Michael Staveley at Memorial University was provided the above source and his researchers did an event-specific search. Staveley *et al.* (1986) established that the tsunami event with an amplitude of up to 3 m was observed in southern Labrador at Fishing Ships Harbour (but probably not farther north at Hopedale and Hebron), at Bonavista and at nearby Catalina and to a minor degree in St. John's harbour itself (Figure 4). Ruffman *et al.* (in prep., 1991) have found some additional reports of this tsunami.

The 1848 tsunami was observed over about a 500 km-length of coast with an amplitude of up to 3 m. It appears to have commenced between 1500 and 1600 with a significant withdrawal then a sudden rise about 10 minutes later. In both Bonavista and Fishing Ships Harbour, Labrador (Figure 4) the noticeable pulsing

of the tsunami continued with a 5-10 min period for at least an hour.

No felt seismic event was reported from Newfoundland. The edge of the continental shelf in this area is from 250 to 400 km offshore and clearly a large seismic event of magnitude 6 to 7 should have been felt onshore. The source of the tsunami could also have been as far away as the Mid-Atlantic Ridge and this event should be checked in Atlantic-wide sources.

June 27, 1864, St. Shotts event, Avalon Peninsula, Newfoundland

Smith (1962) lists this event as occurring on July 28, at 7:00 p.m. local time and assigned a modified Mercalli (MM) intensity of V to the event which he located at 46.5°N, 53.7°W close to the Avalon Peninsula. Smith states:

Off the coast of Newfoundland. The shock caused a "tidal wave" at St. Shotts Harbour, Nfld. Reported in a letter from a resident of Newfoundland.

The letter has not been found at present. Staveley *et al.* (1984) corrected the date from July 28 to June 27, 1864 and found two newspaper accounts and a secondary source. Adams and Staveley (1985) dismissed the possibility of a very local earthquake because they found no reports of local ground shaking and felt that an event in the LSP source zone was unlikely. They felt that "none of the earthquake alternatives seem very probable".

Ruffman *et al.* (in prep., 1991) have found a report of this event being felt in the Avalon Peninsula and have further revised the detail about the tsunami event in St. Shotts by doing a wider, or at least a longer, event-specific search and finding some additional reports in Newfoundland sources. This 1864 event, which did not cause any deaths, is only reported in the Avalon. However, it came at a time of very poor communications and low population densities in Newfoundland so one should not be surprised at a lack of other reports from the Burin or south coast areas of the Province. Therefore, one cannot dismiss a seismic event in the LSP source zone or at the shelf-edge south of the Avalon Peninsula (Figure 1). Nova Scotia and Saint-Pierre et Miquelon sources have not been searched, nor have vessel logs been sought for the offshore regions.

October 4, 1884 slump, Tail of the Banks

Milne (1897) reported the near simultaneous breaks in three cables. He reports:

North Atlantic. -- Through the kindness of an engineer, whose experience in the laying and repairing of cables has extended over many years, I am enabled to give the dates at which various cables have become ruptured, or been restored to working order. The only case of alteration in depth which he noticed was

during the repairs of November, 1884, but this was not great. It seemed as if the picked-up cable had to be pulled from under a bank of earth which had slipped down from the eastern slope of the Newfoundland bank.

The following is a table of North Atlantic cable-interruptions.

North-eastern Slope of Flemish Cap.-- (37°W. to 44°W. long.) July, 1894 (about); June, 1888 (about); September, 1889; September, 1881; June 10, 1894; July 28, 4.40 a.m., 1885; April 18, 8 p.m., 1885; July 25, 8 a.m., 1887; June, 1895.

Near South-eastern Slope of the Newfoundland Bank.-- (46° W. and 50° W. long.) September, 1887 (about); October 3, 9.15 p.m., 1884; October 4, 4.8[*sic*] a.m., 1884; October 4, 4 and 8 a.m., 1884; September, 1889.

A striking feature connected with these Atlantic troubles is that nearly all have occurred in deep water near to the base of the eastern slope of the Flemish Cap, 330 miles from St. John's, Newfoundland, or the south-eastern slope of the Newfoundland bank. ...

In one case only has the cause of failure been attributed to a landslide, which it is just possible was caused by, or accompanied with, seismic phenomena. A very significant fact is the case when three cables running in parallel lines about 10 miles apart, broke at points nearly opposite to each other, on the same straight line. This was on October 4, 1884. At first, the accidents were attributed to the grapnel of a cable vessel, but as no grappling was done then, this hypothesis had to be abandoned. Because three cables broke apparently at the same time in the same locality, one inference is, that the cause resulting in rupture was common to all, and this may have been a sudden change in the configuration of the ocean bed. (p. 261-262)

Heezen and Ewing (1952) were the first to suggest that these cable breaks had a similar cause as the November 18, 1929 cable breaks that were caused by a rapidly moving turbidity current. Adams and Staveley (1985) stated "It is imprudent to attribute these cable breaks to an earthquake. ... and nothing is known to have been felt on the nearest land, St. John's. Since 1937, the seismograph network has been sufficiently sensitive to detect magnitude 5 earthquakes offshore, but so far none have been located in the area of the slump... Consequently, an earthquake is considered dubious."

While Milne (1897) gave only "[between] 46° W. and 50° W. long." as a location for the "Near South-eastern Slope of the Newfoundland Bank" breaks which he listed in the above table, one can do much better in locating the October 4, 1884 breaks. If one examines the 1884 telegraph cable maps available on the charts of the day (Hydrographic Department of the Admiralty,

1958) then one looks for "... three cables running in parallel lines about 10 miles apart", "near the South-eastern Slope of the Newfoundland Bank" (Figure 5). There is really only one location possible and one can then suggest the location of the breaks was at about 42°N, 50°W (a position on the middle Commercial Cable Co. telegraph cable) and one can very approximately estimate a line of the slump and turbidity current as seen on Figures 4 and 5.

Did an earthquake occur at the same time? To say "no" because it was not felt at St. John's, Newfoundland, more than 600 km distant is dubious reasoning. I suspect that a magnitude 6 earthquake could have occurred 600 km from St. John's and 975 km from Halifax on October 4, 1884 and not been felt onshore especially if there was a storm blowing. Staveley et al. (1984) did not report the weather for this date; nor did they report the length of their event-specific report. They only state that they searched "for dates around 4 October, 1884."

Staveley et al. (1984 and 1986) did not expand their event-specific search outside of Newfoundland or to vessel records and may not have searched for a long enough period after the event to recover vessel reports of a possible seismic event from vessels arriving back in port in Newfoundland or elsewhere in Atlantic Canada or New England. While such an effort would be time consuming, it perhaps can occur in the course of other historic seismicity work. The author is carrying out some additional work to further identify the 1884 cables involved. Certainly this event does suggest a turbidity current similar to the November 18, 1929 event and does suggest the possibility of a shelf-edge or a slope event that might lend weight to the proposed ESX seismic source zone (Basham et al., 1982b).

Devine and O'Mara (1900) report that on "July 23rd: Two shocks of earthquake felt at the Block-house by signal man M. Cantwell, at 7 o'clock this morning, 1890." [in St. John's on Signal Hill, altitude 525 ft]. Staveley et al. (1984) found no supporting newspaper accounts in the St. John's papers or in five other papers and conclude that "a very low credibility must be attached to this account". (p. 17) and Adams and Staveley (1985) categorically dismiss it, "Not an earthquake:" (p. 54).

This author is not so quick to dismiss a Devine and O'Mara entry in Notable Events in the History of Newfoundland made in 1900 just 10 years after the supposed event. There is no reason for such an entry to have been invented and I would hold the memory of such an event on July 23, 1890 as a possible indication of another offshore seismic event though clearly one cannot even begin to define an epicentre with one unconfirmed felt locality.

August 21, 1904 Saint-Pierre et Miquelon

This event is known only from E. Aubert de la Rue (1937). Staveley et al. (1984) first noted the reference and Ruffman and Peterson (1986) located a copy from a French source. E. Aubert de la Rue noted on his p. 25-26:

Bien que les secousses séismiques soient très rares à Saint-Pierre et Miquelon, du moins celles suffisamment violentes pour être ressenties par les habitants, car la colonie ne possède pas de séismographe, il était intéressant de recueillir quelques données sur celles dont on conserve le souvenir. J'ai pu seulement obtenir, jusqu'à présent, des renseignements relatifs à deux tremblements de terre.

Le plus ancien se produisit le 21 août 1904. Des secousses furent ressenties ce jour là à Saint-Pierre à 20 heures (heure locale). Venant du Sud-Ouest et se dirigeant vers le Sud-Est, elles durèrent pendant quelques secondes.

The second earthquake which E. Aubert de la Rue found had been felt in Saint-Pierre was the November 18, 1929 event (see also Romer, 1932).

The 1904 event was not found in the Newfoundland papers by Staveley et al. (1984) but we do not believe an event-specific search has been done in either Saint-Pierre or in Nova Scotian sources and we might advocate a wider or longer search in Newfoundland sources. The event is of interest because it could easily reflect a felt report of an earthquake in the Laurentian Slope seismic source zone. Saint-Pierre is ideally located to feel such events and being a marine-related smaller community such events are perhaps more apt to be noticed and reported upon than in the larger cities in Nova Scotia or Newfoundland. However, seismic events that occur during Atlantic storms are not going to be easily felt in Saint-Pierre et Miquelon (or for that matter in southern Newfoundland); this area has more than its fair share of such storm events each year.

December 23, 1909 Isaacs Harbour Mouth, Nova Scotia

This event is not reported in Smith (1962) and is not in the Canadian Earthquake Epicentre File (CEEF). It was found by Ruffman and Peterson (1986) in doing an event-specific search on the Monday, December 20, 1909 Cape Breton Island event. It depends upon only one report which was found in the above event-specific search and was printed in the Halifax Morning Chronicle of Saturday, December 25, 1909, p. 10, col. 1:

Word was received here yesterday that at half past three o'clock Thursday a distinct earthquake shock was felt in the vicinity of Isaac Harbour Mouth. The party who reported the shock stated there was no noise but simply a quivering of the ground which made some of the houses tremble.

Ruffman and Peterson (1986) note:

While a number of other newspapers were searched past Thursday, December 23, 1909 this event occurred at almost the worst time to get recorded; a number of the newspapers did not publish on Saturday, December 25,

1909 (Christmas) and the issues leading up to Christmas were full of revenue-producing advertising. No event-specific search was initiated for this event since it was caught in passing thus not all possible sources for this earthquake have been searched even with the Christmas holiday problem; often we broke off on Friday, December 24, 1909 because the search had been initiated for the Monday, December 20, 1909 event on Cape Breton Island.

Any other newspaper sources for this event should be carefully run to ground in the hope of getting more reports and at least confirming the event. The time of 1530 AST is close to the generally reported 1500 AST time of the Monday, December 20, 1909 event and for this reason there is a suspicion that the Isaac's Harbor Mouth event of Thursday, December 23, 1909 may be a 'ghost event' of the Monday, December 20, 1909 event.

However, Ruffman and Peterson (1986) go on to note that this location on the Atlantic coast of eastern mainland Nova Scotia (Figure 1) should be well outside of the felt area for the Monday, December 20, 1909 Cape Breton Island event as detailed by their event-specific search for the earlier event (p. 326). For this reason and because the above report mentions a specific day of the week (Thursday rather than Monday) and mentions "a distinct earthquake shock ... which made some of the houses tremble" Ruffman and Peterson accepted the above event as a previously-unreported earthquake and suggested that the epicentre could be offshore in the Laurentian Slope seismic source zone.

Clearly, this event needs more attention in primary sources before one will feel entirely comfortable with it. This is a pre-instrumental event for eastern Canada and its detailing is entirely dependent on the historical record.

May, 1914, Tsunami, Northern Cape Breton Island

This event is not noted in Smith (1962) and is not in the CEEF. Cowie's (1914) report of May, 1914 has under "Notes" on p. 3 the following:

Eastward of Halifax and in the Gulf generally the weather was unfavourable. Eleven small fishing boats were wrecked at Meat Cove and vicinity, Victoria County, N.S., while two Inverness county fishermen, and one Guysboro fisherman, were drowned in the course of the month.

Such a note would not be of any significance except for Professor D.S. McIntosh's April 12, 1915 presentation to the Nova Scotian Institute of Science; "Notes on an Abnormal Wave Occurrence on the Northern Cape Breton Coast". McIntosh (1919) draws from an account from Mr. A.H. McIntosh of Pleasant Bay who, in turn, corresponded with Mr. Joseph O'Brien of Dingwall, Aspy Bay, Cape Breton Island:

The following statement is given as what occurred. "On the evening of the night on which the boats were lost, the fishermen had hauled them up on the beach to a place where they were considered to be in safety. A light wind began to draw from the land, and all the usual signs in which fishermen believe promised a fine night. Judge of the surprise of those men when on coming to the beach in the very early morning not only were their boats gone, but they were not even in sight on the sea. Eventually, one or two were found along the shore, but others were found only after some days had elapsed, picked up at great distances from the starting place. The marks on the beach showed plainly that the tide had come up very much higher than usual, and while at this place, it seemed to have been the highest, it was also noted as an unusually high tide at Pleasant Bay on the west, and Bay St. Lawrence and Aspy Bay to the eastward. One man near Bay St. Lawrence, at about eleven o'clock, saw it come in the form of two large seas succeeding each other, and rushing on shore. A fishing schooner lying some two miles off shore also reports several heavy seas striking the vessel about the hour mentioned; otherwise the night was calm. Some six years before, this same vicinity was visited by something of the same nature, but as it came in the day, it occasioned no loss."

No other accounts of this event have been found to date, though two Sydney and one Pictou newspaper have been searched for all May and June, 1914 (Ruffman and Peterson, 1986). Ruffman and Peterson had no doubt that this event was a tsunami even though no felt event was reported. They suggested that the event be pursued to establish its exact date and then they advocated that do an event-specific search to look for reports of a causative seismic event.

While the source zone of this tsunami is unknown and we are in the pre-instrumental period for eastern Canada it is not unreasonable to suggest a source for this event in the Laurentian Slope seismic source zone.

As for the circa 1908 event wherein "this same vicinity was visited by something of the same nature ... " Professor MacIntosh showed some perception in writing at the end of his 1919 paper:

From the occurrence of a similar wave disturbance at Bay St. Lawrence some years before, as reported, it would be inferred that the surface of the sea bottom is unstable off the coast of Northern Cape Breton, and that such disturbances may recur until the area has arrived at a state of stability.

Ruffman and Peterson (1986) were able to report in a footnote (p. 314) with the help of information from Professor Ken B.S. Burke of the University of New Brunswick that a tsunami occurred in September 11, 1908 in the Baie des Chaleurs region during daylight hours. Ruffman et al. (in prep., 1991) have done an

event-specific search for this event and have concluded that the unknown source zone for this tsunami, for which there was no reported felt event, had to be within the Gulf of St. Lawrence. The apparent report of seeing the tsunami at Bay St. Lawrence then would have to be a refracted portion of the wave that escaped from the Gulf and got by St. Paul's Island.

January 22, 1915 SS ALEPPO, southeast of Sable Island

Reid first published this report in 1916 noting it as "about 300 miles southwest of Halifax." J.B. Woodworth (1917) published the Seventh Annual Report of the Harvard seismographic station for the year 1915 and revised the direction from Halifax presumably on the 'personal information' which he cites. His entry indicates that he wonders if he might have seen this on the Harvard seismograph record but he does not sound convinced nor does he list it on p. 112 or 127 of his report. His note on this event on p. 147-148 is as below (in part):

According to Professor H.F. Reid (American year book for 1915, New York, 1916, p. 596, and personal information) the British ship "Aleppo" encountered a heavy shock at sea 300 miles southeast (not southwest) from Halifax on January 22, 1915. On that day and for several days prior thereto the instruments at the Harvard Station recorded violent jars which were not considered at the time to be of seismic origin.

Ruffman and Peterson (1986) noted that Smith (1962) was the first to put an epicentre location on this event. He somewhat arbitrarily used 41.0°N, 60.0°W as a point about 276 nautical miles or 318 statute miles southeast of Halifax perhaps uncertain as to Reid's (1916) units. The SS ALEPPO almost certainly would have reported in nautical miles. A point 300 nautical miles southeast (rather than southwest) of Halifax is at about 40.6°N, 59.7°W (Figures 1 and 4). Clearly such a point is not an exact estimate of the epicentre. This event could possibly have its origin in the LSP seismic source zone or along the edge of the shelf to the west of the mouth of the Laurentian Channel.

Time did not permit Ruffman and Peterson (1986) to do an event-specific search of this pre-instrumental event. The superintendent's records on Sable Island should be checked for this day. If there was not a major storm one would expect such a large event to possibly be felt on Sable Island and possibly along the coast of Nova Scotia. If the SS ALEPPO felt a strong shock so might other Nova Scotian vessels and there may have been comment in the local press as the vessels returned to port. Various local sources including Sable Island records and newspapers should be checked for this period.

April 11, 1940, Southern Newfoundland

This event is not found in Smith's (1966) compilation. This event was felt at 0110 local time along the southwest coast of Newfoundland in communities stretched along at least 90 km of the coast from Burgeo to Ramea, Cape la Hune, Francois, Rencontre

West and to New Harbour (Staveley *et al.*, 1984; Figure 4). Staveley and Adams (1985) assign a probable magnitude of 3.6 to this event with a maximum possible magnitude of $M = 4.5$. They then discuss the possibility of this event originating in the Laurentian Slope seismic zone and state that at is, "highly improbable that a magnitude 4.5 or smaller earthquake located there could have been felt in the way the 1940 event was described. The source may be in the recently (re)activated 1989-1990 earthquake zone in the Laurentian Channel (Figure 4).

Therefore, this event seems unlikely to be related to the LSP seismic zone. However, the primary Saint-Pierre records have not been examined (if they exist). No systematic historical seismicity work has been done on Saint-Pierre et Miquelon primary sources, yet the French community has existed for many, many years and may have a fairly rich written record. Certainly its position is ideal for recording felt events or visible tsunamis originating from the LSP seismic source zone.

Dans les années 1940 mini raz-de-marée, Saint-Pierre et Miquelon

This item is included if only to tantalize and frustrate readers - and to bring home my thesis that historical seismicity study of primary sources of Saint-Pierre et Miquelon (SPM) could well be rewarding in documenting the LSP seismic source zone (or the larger earlier events that may have occurred in the recently (re)activated 1989-1990 earthquake zone in the Laurentian Channel at 46 N).

I have been in correspondence with a Rodrigue Girardin in St. Pierre. M. Girardin has a strong interest in history and clearly has some facility in using the local sources. He has assisted me in obtaining photos of damage and accounts from the November 18, 1929 tsunami and earthquake.

In his most recent letter of March 14, 1991, M. Girardin added a postscript:

Il apparaît qu'un mini raz-de-marée aurait inondé les quartiers proche du port (zone: Pointe aux Canons-Anse à Rodrigue) dans les années 1940. Tsunami ou inondation?

One can only speculate that this possible tsunami is related to an event in the LSP seismic zone or a shelf-edge event? This event will be pursued further to the limit of present resources and time. Good and complete historical seismicity work is often slow and painstaking work that in the absence of travel budgets depends upon the post and upon the interest, good will, and volunteer help from others. At this point, the historical seismic record of SPM is spotty and will only emerge gradually unless there is a pointed effort made to fund systematic work by knowledgeable local researchers.

Conclusion

Of the above events, six could indicate shelf-edge seismic events and five of these could be the result of events in the LSP seismic zone. While we do not know, and perhaps can never know the precise origin of these offshore events, the fact we have had five or six in a 50-year period at least gives pause for thought - and perhaps lends credence to the use of a shorter, rather than a longer, recurrence rate for potentially hazardous events originating at the shelf-edge or in the general area of the presently-defined LSP seismic source zone.

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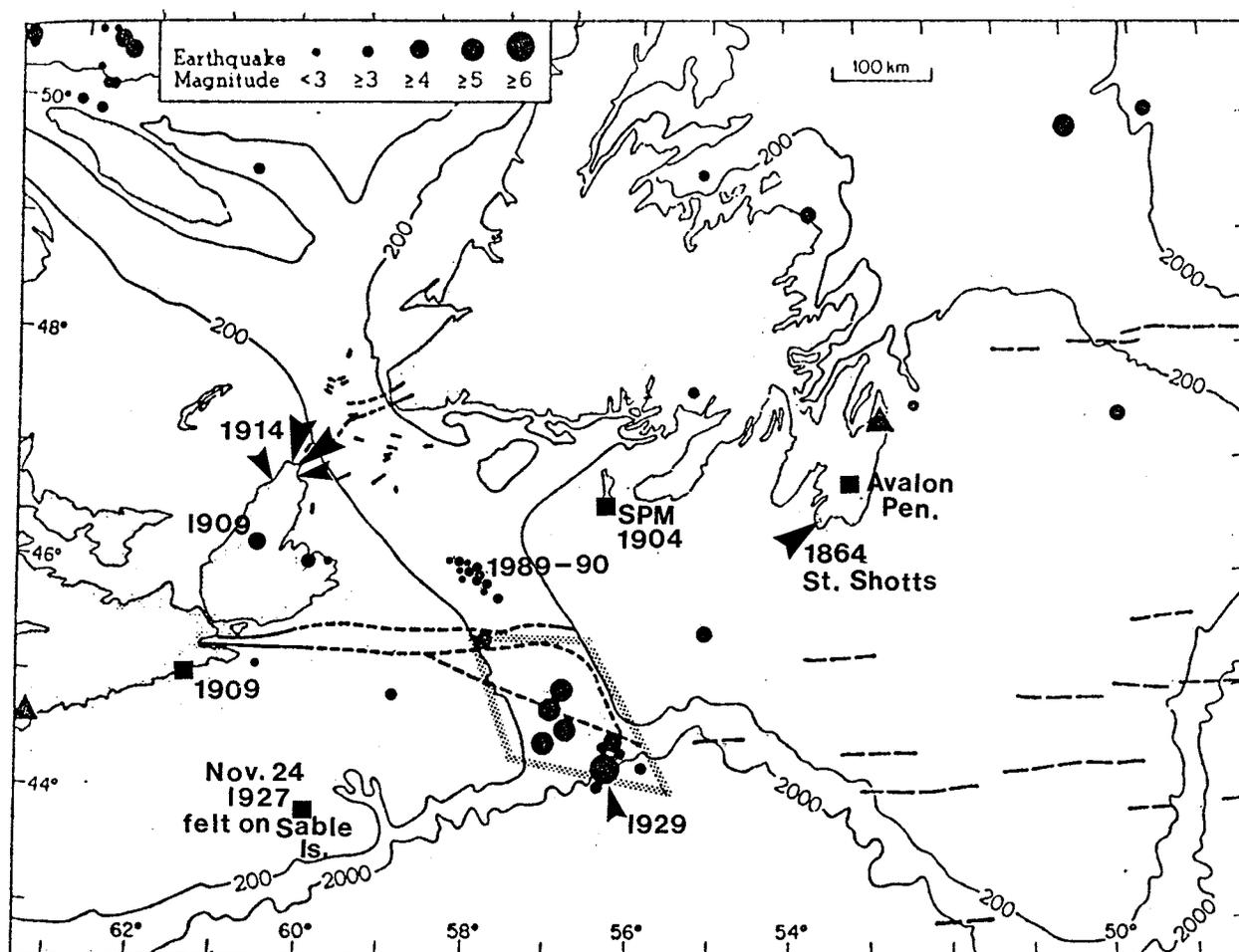
Note added in afterthought:

Smith (1962) notes a November 24, 1927, "Light earthquake felt by persons on Sable Island and reported by radio to the Seismograph Station at Halifax, N.S." I have added this felt locality to figures 1 and 4. While Smith (1962) uses the position of the felt locality as the epicentre this clearly need not be the case. The November 27, 1927 event may be centred along the shelf-edge close to Sable Island or may possibly reflect a felt locality of an event in the LSP seismic source zone.

Note added in proof September 25, 1991:

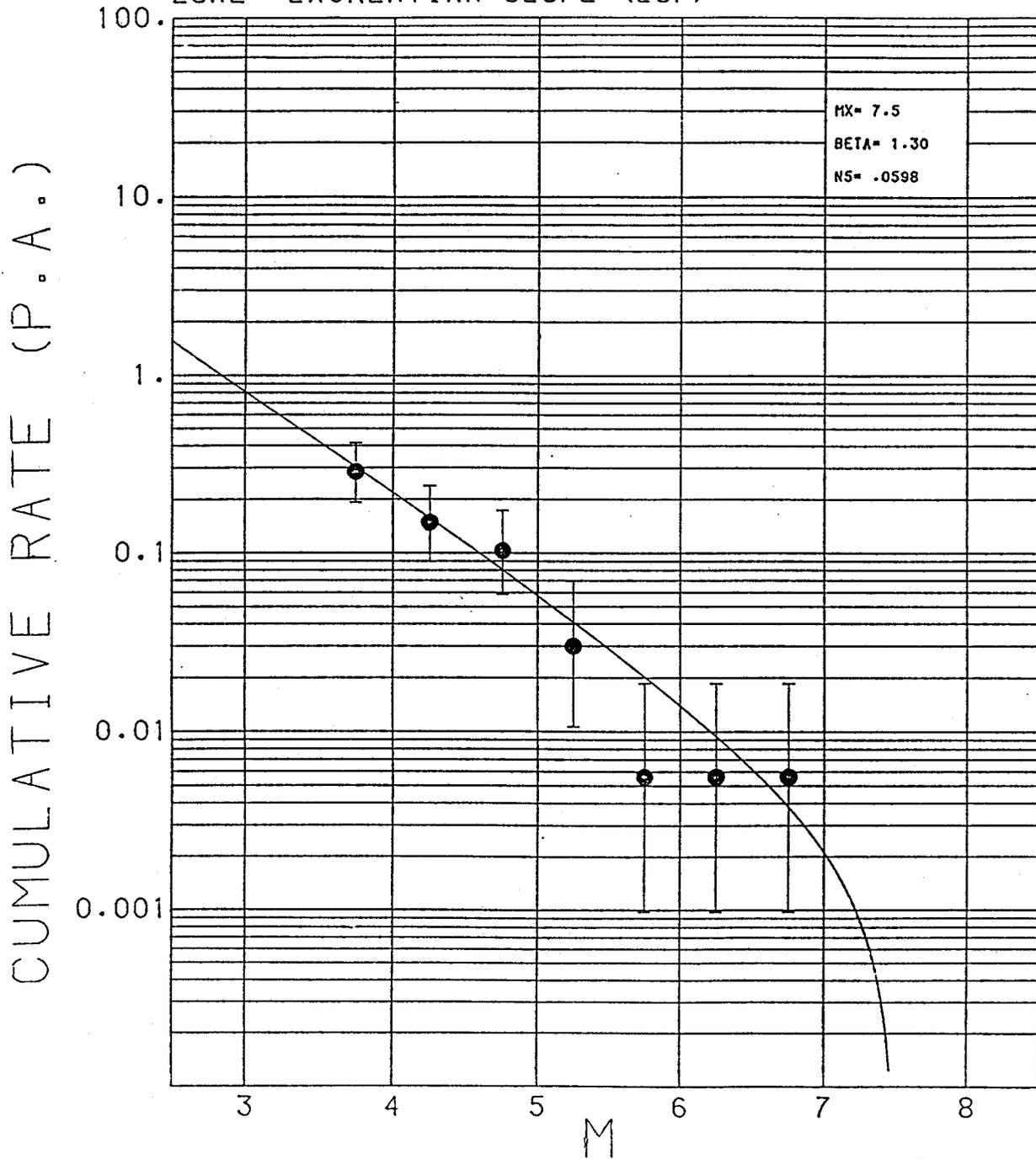
When the following map was found and interpreted, it was assumed that it showed all trans-Atlantic cables. It now is realized that it does not and that it shows only post-1897 cables south of the Tail of (Grand) Banks. The three cables marked as the zone of the October 1884 slump were not laid until 1898, 1900 and 1923 (which is the meaning of the dates to the east). The map does not show the pre-1885 out of use (oou) cables. Since realizing this the author has attempted to penetrate the cable companies' corporate memory banks with intermittent success.

It is now known that six telegraph cables passed south of the Tail of the Banks in October 1884 having been laid in 1884, 1884, 1881, 1882, 1879 and 1869, from north to south (order of 1884 cables may be in error), by the Commercial Cable Co., Commercial Cable Co., Jay Gould (later Western Union), Jay Gould, Compagnie Française des Câbles Télégraphiques and La Société du Câble Transatlantique Française (later the Anglo American Telegraph Company) respectively. To date, only general route maps have been found and only one detailed as-laid chart has been unearthed but it is now fairly certain that the zone of the October 1884 slump will be interpreted to be close to the hachured area shown on the following map - even using the correct cable route data!



1915
 ■ S.S. ALEPPO

Figure 1 Epicentre map of Basham and Adams (1982) slightly modified to show the 1989-90 earthquake zone at 46° N in the Laurentian Channel. The stippled boundary of the Laurentian Slope seismic source zone was drawn by Basham *et al.* (1982b) to reflect the edges of the Laurentian Channel, the interpreted faults to the north and known earthquakes to the south. The general felt locality of the 1864 event on the Avalon Peninsula and the location of the St. Shotts tsunami are shown along with the observations of the May, 1914 tsunami. The August 21, 1904 event was felt on Saint-Pierre et Miquelon (SPM) and the nominal position of the SS ALEPPO 300 nautical miles southeast of Halifax on January 22, 1915 is shown. The felt locality of the December 23, 1909 event at Isaacs Harbour Mouth is well outside of the known felt area of the December 20, 1909 event shown here slightly relocated away from the eastern coast of the the north peninsula of Cape Breton Island where Smith (1962) placed it.



EARTH PHYSICS BRANCH EMR OTTAWA CANADA,
 DIRECTION DE LA PHYSIQUE DU GLOBE OTTAWA CANADA

15/11/82

Figure 2 Magnitude recurrence relation for the Laurentian Slope seismic source zone, taken from the Basham et al. (1982b) Open File Report of the Earth Physics Branch.

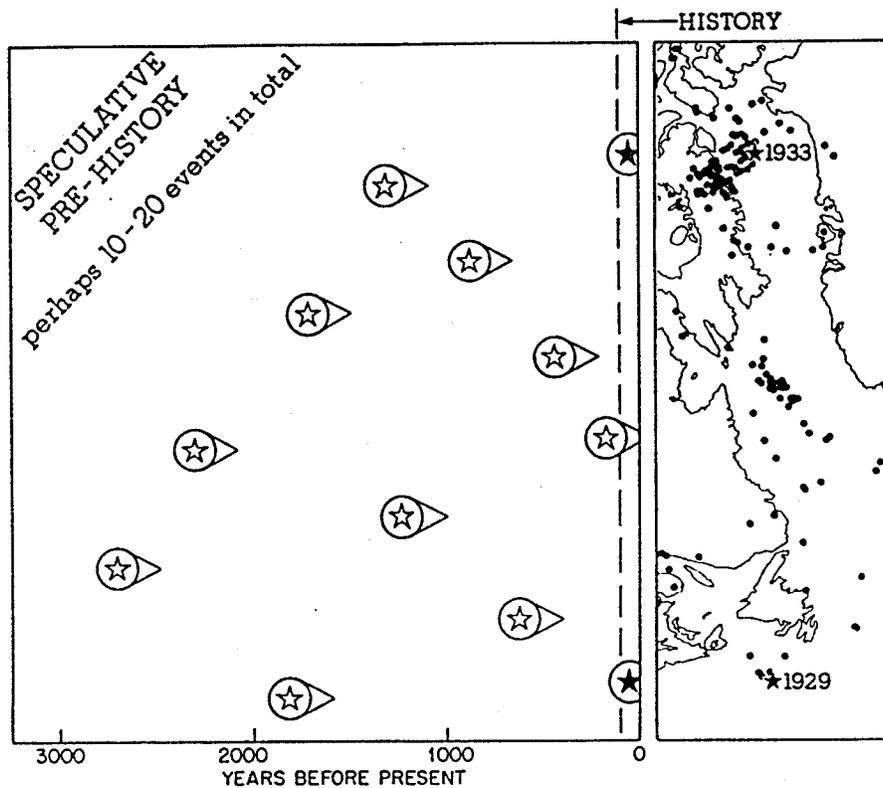
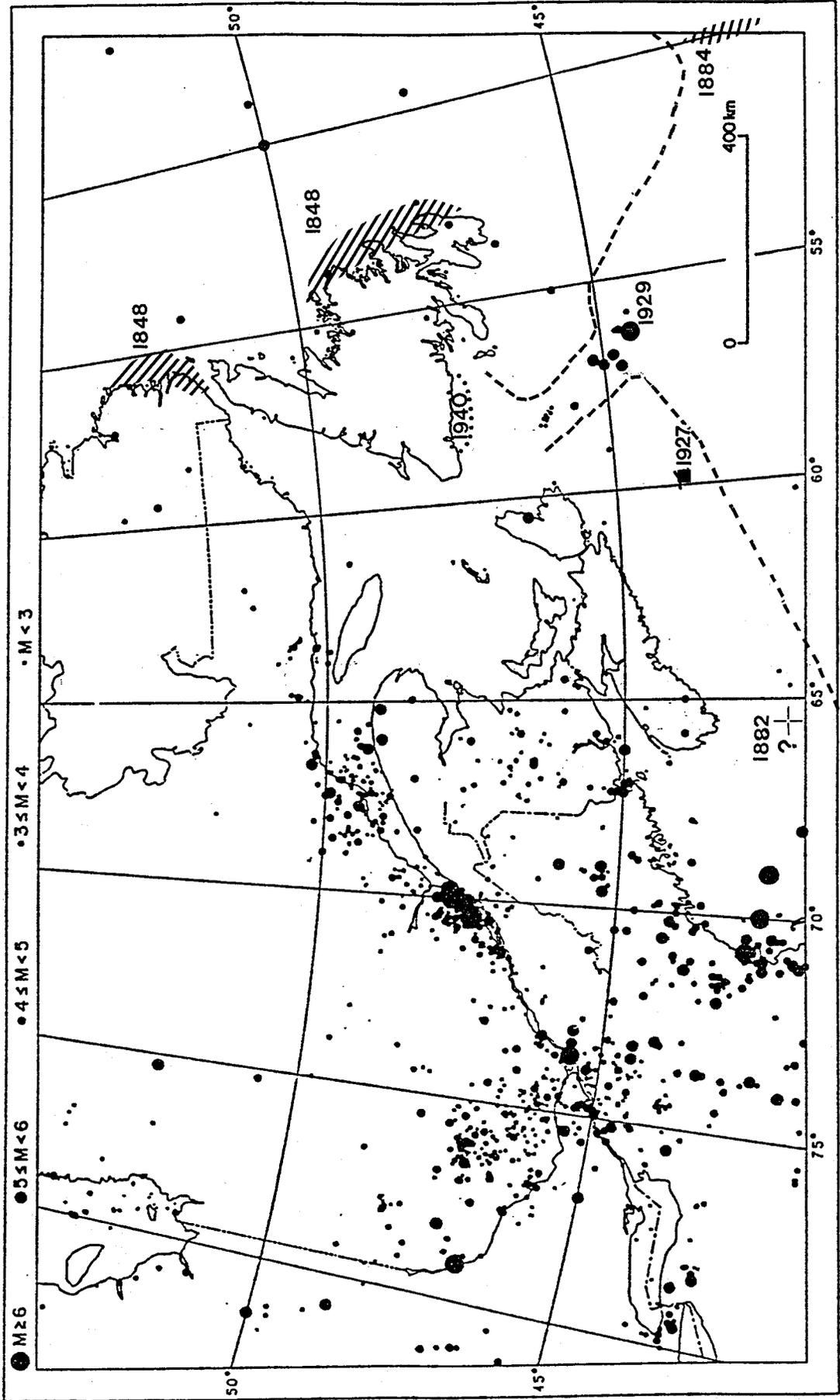


Figure 3

A cartoon taken from Basham and Adams (1983) to illustrate a speculative history and pre-history of significant earthquakes each with an aftershock "tail" sequence of events lasting circa 100-200 years. The epicentre map of the east coast of Canada is shown on the right. The significant events are assumed to occur at rates of only 1 per 1,000 years per 1,000 km of the continental margin. Thus, the 1933 Baffin Bay and the 1929 Laurentian Slope earthquakes are just the most recent events in what Basham *et al.* (1983) have suggested could be a shelf-edge ESX seismic source zone.

Figure 4 Seismicity map of eastern Canada modified from Basham *et al.* (1982a). Earthquakes with magnitudes 4-5, 3-4, and less than 3 are shown for time periods since 1950, 1960 and 1970 respectively; the 1989-90 earthquake zone at 46° N in the Laurentian Channel has been added. The dashed line marks the approximate edge of the continental shelf. Indications of other historic shelf-edge or slope events are shown. The known observations of the September 24, 1848 tsunami are shown by the patterned area along the coast of northeast Newfoundland and southern Labrador. The nominal position of the SS ALEPPO 300 nautical miles southeast of Halifax in 1915 is shown as is the zone of the 1884 cable breaks southeast of the Tail of the Banks. The totally arbitrary possible position of the 1882-83 New Year's event off southwest Nova Scotia is also shown (Ruffman, this volume).



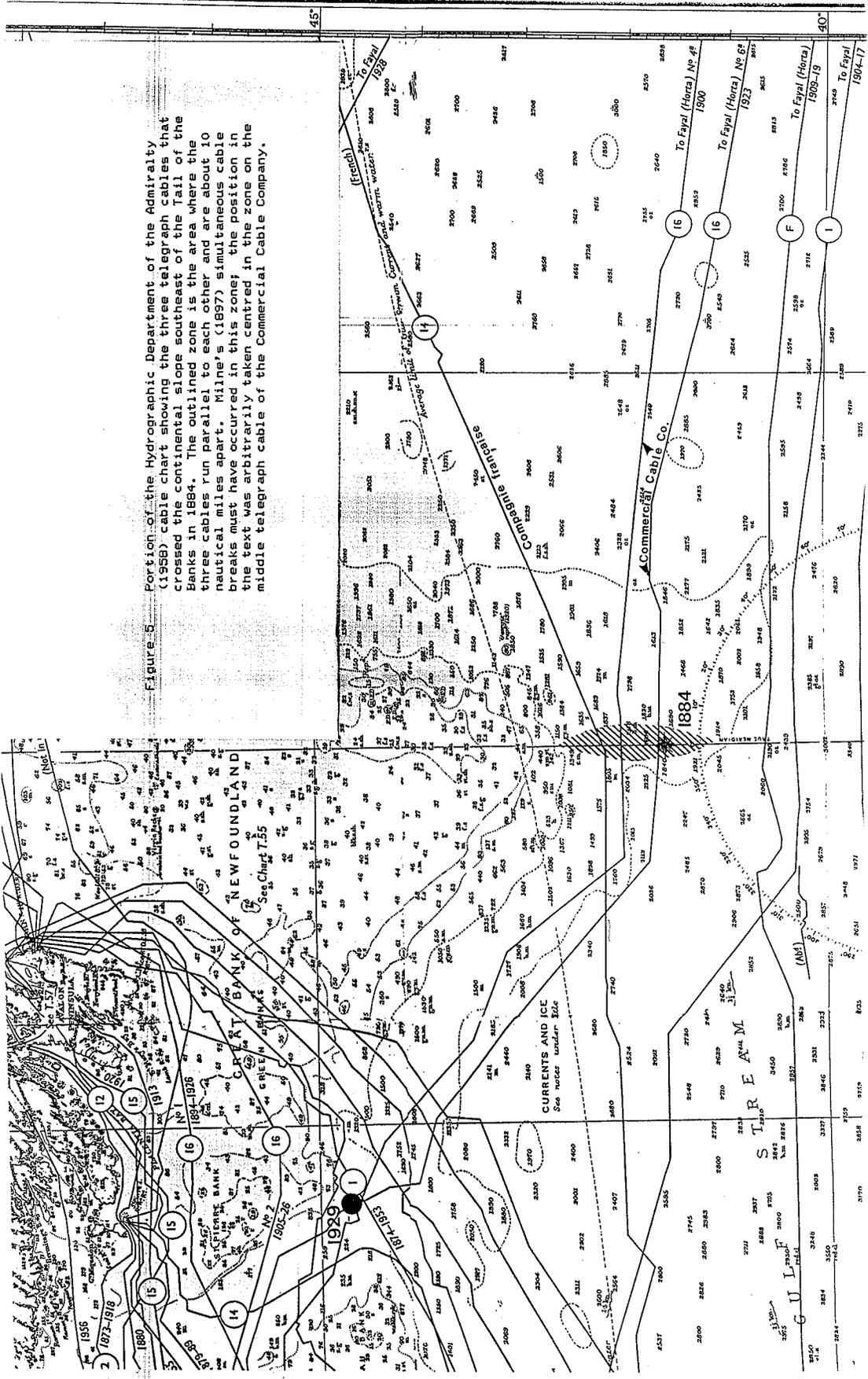


Figure 5
 Portion of the Hydrographic Department of the Admiralty (1958) cable chart showing the three telegraph cables that crossed the continental slope southeast of the Tail of the Banks in 1884. The outlined zone is the area where the three cables run parallel to each other and are about 10 nautical miles apart. Milne's (1897) simultaneous cable breaks must have occurred in this zone; the position in the text was arbitrarily taken centered in the zone on the middle telegraph cable of the Commercial Cable Company.

COMMENTS ON WORKSHOP ON SEISMIC SOURCE ZONES FOR EASTERN CANADA, March 18-19, 1991

Prepared by Paul Somerville, March 22, 1991

1. From a variety of evidence presented, there appears to be a correlation of seismicity with linear geologic features, suggesting reactivation of old faults as a mechanism for current seismicity. However, it is not clear to me that earthquakes necessarily recur repeatedly on the same fault in eastern Canada, otherwise there would be more evidence of fault scarps. For this reason, it may be difficult to come up with a meaningful definition of an active fault. The use of source zones seems suitable for describing the seismic potential of old geologic structures that may be reactivated.
2. The magnitude estimates of the New Madrid and Charleston earthquakes presented by Arch Johnston seem to be very large. My idea of a very large earthquake in a stable continental region is an average slip of 5 meters on a fault plane 100 km long and 20 km wide down-dip, for a moment magnitude of 7.6. It would take an average slip of 50 meters (or larger fault length and width) to get a moment magnitude of 8.3.
3. Strong ground motion amplitudes of the 1988 Saguenay earthquake were elevated by critical reflections from the lower crust; these were large and occurred at close distances because of the deep focal depth of that earthquake. Consideration should be given to other potential locations of deep crustal earthquakes.



UNIVERSITY OF SOUTH CAROLINA

COLUMBIA, S.C. 29208

DEPARTMENT OF GEOLOGICAL SCIENCES

March 25, 1991

Dr. John Adams
Seismology, Geophysics Division
Geological Survey of Canada
1 Observatory Crescent
Ottawa, Canada K1A 0Y3

Dear John,

I enjoyed the workshop on East Seismic Source Zone. I am jotting down thoughts following the workshop. I agree with the approach taken by Russ Wheeler and Arch Johnston in trying to define generic seismological tectonic features.

However, I strongly feel that where adequate geological, geophysical, and seismological data exist, a site approach needs to be adopted. Another bias of mine is that intersecting zones of weakness are more likely to be foci of larger events than single, long through going features. As such, I would assign a higher maximum magnitude to the northwest trending Ottawa seismic zone as to the Charlevoix than to the northeast trending St. Lawrence seismic zone.

Following my experience with Epr1 and some of these studies we have been engaged here, I would examine the following physical characteristics at any location: (i) spatial association with seismicity, (ii) background seismicity, (iii) evidence of neotectonic activity, (iv) evidence of prehistoric seismicity, (v) geometry of the features relative to the stress field and (vi) evidence of deep crustal expression.

Enclosed please find copies of some recent papers that you might find useful and also an extract from a recent study that I did for LLNL. I am also enclosing my expense form.

Sincerely,

P. Talwani

Pradeep Talwani
Professor of Geophysics

enclosures

PT/pz

4. Identification of Seismogenic Features

In the study area we have made the tacit assumption that potentially active seismogenic zones can be identified using seismological, geological, geophysical and other data. The 'other' data include geomorphological and geodetic data. As discussed in Section 2 above, we take the orientation of S_{Hmax} to be uniform, around $N60^{\circ}E$ in South Carolina, and close to E-W in central U.S. Although the orientation of S_{Hmax} is assumed to be known, we have little information about the spatial and temporal variation of its magnitude.

The various data helped to identify potential seismogenic structures, but did not yield unambiguous information regarding the seismic potential of these features. Therefore there was a fair degree of subjectivity in assigning the seismic potential, and in estimating the maximum earthquake at any location. A number of physical characteristics of tectonic features that are most useful in evaluating earthquake potential were identified. The information available at various locations was not uniform and hence the subjectivity. The physical characteristics that were examined include the following.

- i. Spatial association with seismicity
- ii. Background seismicity
- iii. Evidence of neotectonic activity
- iv. Evidence of prehistoric seismicity
- v. Geometry of the features relative to the stress field

vi. Evidence of deep crustal expression.

Although the necessary information for the various areas was not uniform, all available information was considered in estimating the seismic potential at any location. Some comments about each of these characteristics are in order.

4.1 Spatial Association with Seismicity

Here we sought evidence for the spatial association of moderate to large ($M \geq 5.0$) earthquake(s) with a tectonic feature. In the southeastern U.S. several faults have been mapped in the Piedmont province. These faults are generally aseismic, and in historical times have not been associated with large earthquakes. The source of most seismicity in the Coastal Plain is under a sedimentary cover, and those in eastern Tennessee, Giles County, Virginia and central Virginia seismic zone are under a thick layer of crystalline rocks. Hence in all cases, evidence of any spatial association of seismicity with a buried structure is by indirect means. We compared hypocentral location of well located microearthquakes, their inferred focal planes from fault plane solutions, with inferred buried structures from geophysical and geological data (Section 4.6).

4.2 Background Seismicity

In this category we considered three seismological elements as follows.

By studying maps of historical and instrumentally recorded seismicity it was possible to estimate the regional seismic flux. A comparison of these maps revealed that there was remarkable stationarity in the pattern of seismicity. Thus a tacit assumption was made that the stationarity in seismicity would continue for the next few hundred years - the period of interest. A moderate earthquake was considered more likely in regions of (current) higher seismic flux than in relatively aseismic ones.

Where adequate seismicity data were available, the frequency-magnitude relationships were examined. The b-values so obtained could be used to estimate the

magnitude of the largest event in a given period of time.

4.3 Evidence of Neotectonic Activity

In the eastern U.S. where there is a general absence of surface faulting, some sense of recency of tectonic activity can be gauged from a study of neotectonics. Neotectonics describes the tectonics of the past few million years, or from the latest Neogene and Quaternary times. Information on neotectonic activity was observed from seismological, geodetic, geomorphic and geological data (see e.g. Talwani, 1990). In addition to the spatial and temporal distribution of seismicity (Section 4.2), these data can also be used to infer the geometry of nodal planes (and hence the inferred fault planes), the style of faulting, and from the direction of the P, T and B axes, the orientation of S_{Hmax} and S_{hmin} . In eastern U.S. available geodetic data consist of triangulation and leveling data. An examination of these data yield information on local horizontal and vertical deformation. This deformation of the surface can sometimes be related to tectonic activity on buried faults - thus establishing their seismogenic nature. The rates of deformation can also be used in estimating the seismic potential and magnitude of maximum earthquakes that can be expected.

Sometimes tectonic activity on buried faults can influence surface features. Thus a study of these geomorphic features can be used to infer tectonic activity. Some geomorphic features - such as stream morphology have been correlated with leveling data to infer uplift and subsidence in a region. The presence of fault scarps and other features on the surface (related to tectonism) can sometimes be detected from aerial or satellite photographs or other remote sensing data. These remote sensing data are useful for establishing spatial but not causative association with seismogenic features (Section 4.1).

Seismic activity on buried faults is usually associated with brittle deformation. However it can plastically deform the overlying shallow sediments. Continued activity on buried faults can also influence the thickness of shallow sediments. Thus mapping

of shallow unconformities in sedimentary formations can lead to the identification of subsidence, and warping of the sediments. Isopach maps are also useful in identifying border faults of buried basins. By mapping these unconformities (either by seismic reflection method or by shallow stratigraphic drilling) it is possible to assess the time and rate of deformation and relate it to tectonic activity on buried faults (see e.g. Talwani et al., 1989).

4.4 Evidence of Prehistoric Seismicity

The historical seismicity data base in southeastern U.S. goes back only about 300 years. In recent years evidence of prehistoric earthquakes (paleoseismicity) has been obtained by an examination of paleoliquefaction features in shallow sediments (e.g. Talwani and Collinsworth, 1988). Of the hundreds of locations investigated in a recent study (Amick, 1990) datable paleoliquefaction features were obtained at a few locations along the South Carolina coast. Analyses of these data provided an estimate of the recurrence times of earthquakes with magnitudes of 5.5 and greater (those likely to generate paleoliquefaction features). Thus evidence of prehistoric seismicity and an estimate of the recurrence time at any magnitude threshold provides an important element in assessing the seismic hazard at any location.

4.5 Geometry of Features Relative to the Stress Field

With the assumption that the seismicity in the region occurs in response to a uniform stress field (Section 2), and that major intraplate earthquakes are associated with strike slip faulting (Section 3.2) it is possible to evaluate if the geometry of a given fault plane is favorable for the occurrence of a moderate to large earthquake. In a recent study of geometrical factors common to well documented cases of intraplate earthquakes, Talwani and Rajendran (1990) found that the main fault plane was oriented at about 45° to the direction of S_{Hmax} . They also discovered that in a large number of cases the main fault was associated with an intersecting fault. The geomet-

rical and seismological data supported the intersection model for the generation of intraplate earthquakes (Section 3.3.1). Thus in this study we seek not only favorably oriented faults as potential seismic sources but also intersecting ones. For S_{Hmax} oriented $N60^{\circ}E-S60^{\circ}W$, fault planes oriented within about 15° of $N15^{\circ}E$ and $N75^{\circ}W$ would be favorable directions for the main fault. The orientation of the intersecting fault would control the type of faulting - pure strike slip on vertical orthogonal faults and with a degree of vertical movements when the intersecting faults are not orthogonal or vertical.

Thus, with the assumptions stated at the beginning of this section, and with the knowledge of the orientation of the stress field, it is possible to comment on favorable orientations for faulting.

4.6 Evidence of Deep Crustal Expression

Moderate earthquakes in eastern U.S. ($M \geq 5.0$) occur at midcrustal depths (usually around 7-15 km). At shallower depths the stresses are usually not large enough to cause these larger events. However the crustal thickness can vary greatly - depending among other factors on the presence of mountain roots and heat flow rates. The depth to the brittle-ductile boundary is thus variable and the largest earthquakes occur near the bottom of the brittle part of the crust. Thus knowledge of the crustal thickness, lithology and heat flow rates are important elements in assessing the depth of the seismogenic zone.

Evidence of deep crustal expression of faults can be obtained from geophysical, and seismological data. Geophysical data that have proved useful consist of potential field maps (and variations of those - such as filtered and derivative maps) and seismic reflection data. Useful seismological data consist of hypocentral locations and inversion of travel time data.

4.7 Summary

A variety of data are needed to identify a potential seismogenic zone. Among the elements that we have considered are spatial association of buried structures with seismicity; regional seismic flux and pattern of seismicity; evidence of neotectonic activity from seismological geodetic, geomorphic and geological data; evidence of prehistoric seismicity and recurrence rates estimated therefrom; geometry of potential seismogenic features with respect to the stress field; and the evidence of deep crustal expression of the identified faults.

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Pop-ups and Seismic Hazard

J.L. Wallach
Atomic Energy Control Board

Pop-ups develop at the surface in response to high horizontal compressive stress and are present both in open fields (e.g. Dames & Moore, 1974) and on quarry floors (e.g. Saull and Williams, 1974). In order for them to form there is a need for decoupling, thus the presence of horizontal planes of weakness is a prerequisite. If planes of weakness do not exist, or are steeply dipping, in which case they effectively do not exist, pop-ups will not form even if stress conditions are, otherwise, favorable. Pop-ups have, thus far, been identified in a broad belt which extends in a generally southwest direction from the Miramichi area in New Brunswick into the east-central United States (Figure 1). Most of them occur along the St. Lawrence Fault System and its projected extension into the lower Great Lakes as proposed by Adams and Basham (1989).

Pop-ups generally trend northwest, or perpendicular to the prevailing orientation of the greatest principal stress in eastern North America. An illustrative example, furnished by Duncan McKay, shows p-stress and pop-up orientations from the Roblindale Quarry, north of Napanee, Ontario (compare Figure 2 and Table 1). Despite the predominant northwest orientation recognized to date, the pop-ups display other orientations as well (Figure 3).

TABLE 1 POP-UP ORIENTATIONS IN THE ROBLINDALE QUARRY

315°

300°

280°

322°

322°

280°

315°

Average Orientation-305°

From Duncan McKay

The age of pop-ups occurring in open fields cannot be established unequivocally, although there are criteria for determining age relative to glaciation. For example, if glacially-polished or striated surfaces are deformed by pop-ups, the pop-ups are post-

glacial. Examples have been recognized in the 1000 Islands region of northern New York State (Dames & Moore, 1974). In quarries pop-ups form following excavation of the overlying rock, thus they are obviously young.

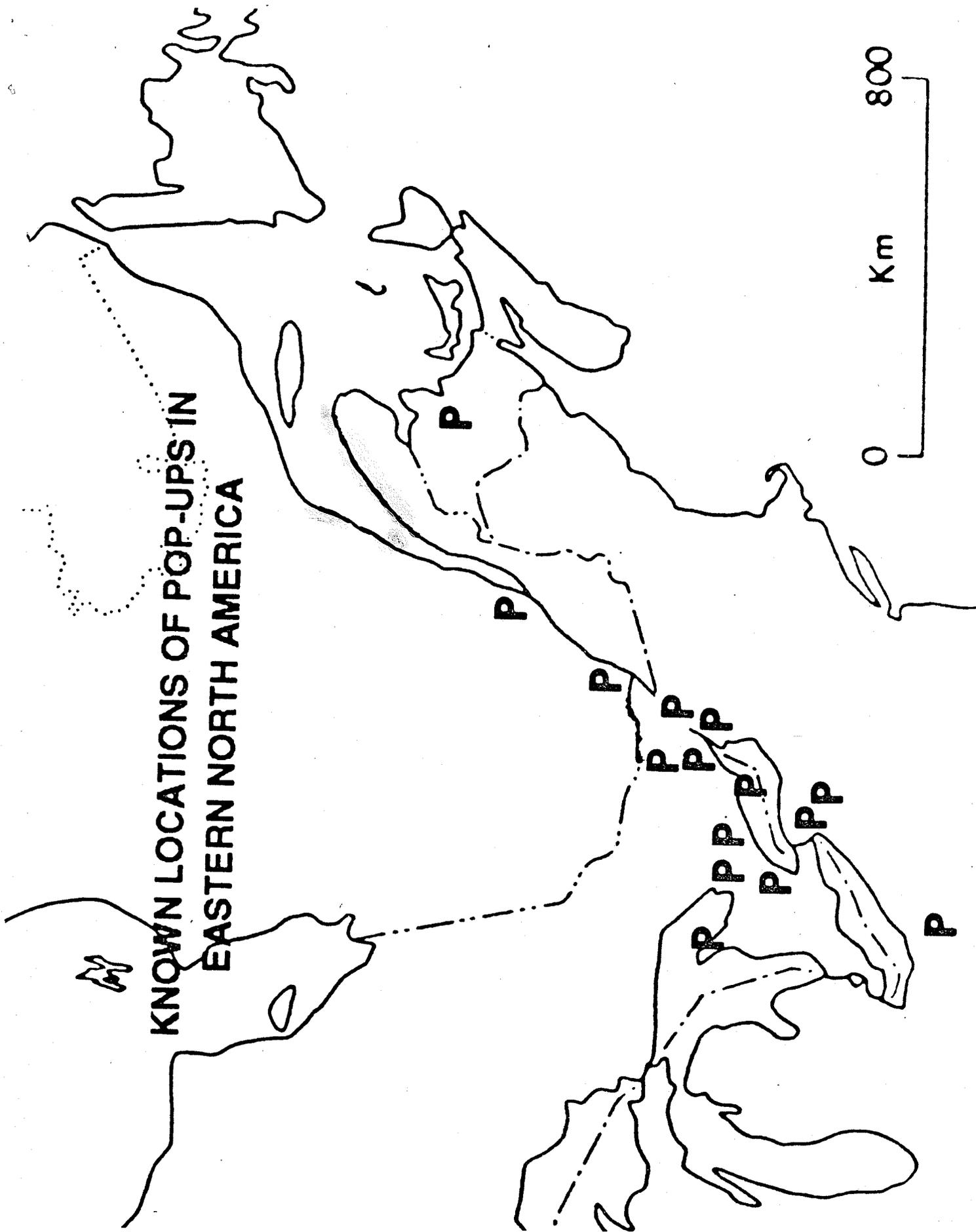
Pop-ups have been recognized in areas in which several of the largest earthquakes in eastern North America have occurred. These include the 1732, estimated $M_{bLg}=5.6-6.0$, Montreal earthquake (Leblanc, 1981), the 1929, $M=5.8$ Attica earthquake (Ontario Hydro, 1969; 1974; 1978), the 1944, $M=5.9$ Cornwall-Massena earthquake (Smith, 1966), the 1981, $M_b=5.2$ Sharpsburg, Kentucky earthquake (Mauk and others, 1982), the 1982, $M_b=5.7$ Miramichi earthquake (Burke, 1984), and the 1986, $M_b=5.0$ Leroy, Ohio earthquake (Nicholson and others, 1988).

The general orientation and mechanism of formation of pop-ups relative to the contemporary stress field, along with the demonstrable post-glacial age for many, point to the existence of pop-ups as generally reliable indicators of neotectonic activity. Because pop-ups have been identified in the vicinity of at least moderate earthquakes ($M=5.0$ to $M=5.9$), their presence in areas presently considered aseismic may indicate that those areas had been subjected to pre-historic, moderate to large earthquakes and/or are likely to be so affected. Since both pop-ups and earthquakes are stress-relief phenomena forming in response to the current ambient stress field, it is logical that evidence of stress application on the surface strongly implies stress application at depth. Thus, in estimating the seismic hazard of an area, pop-ups should be considered as indicating the potential for earthquakes of at least $M=6$.

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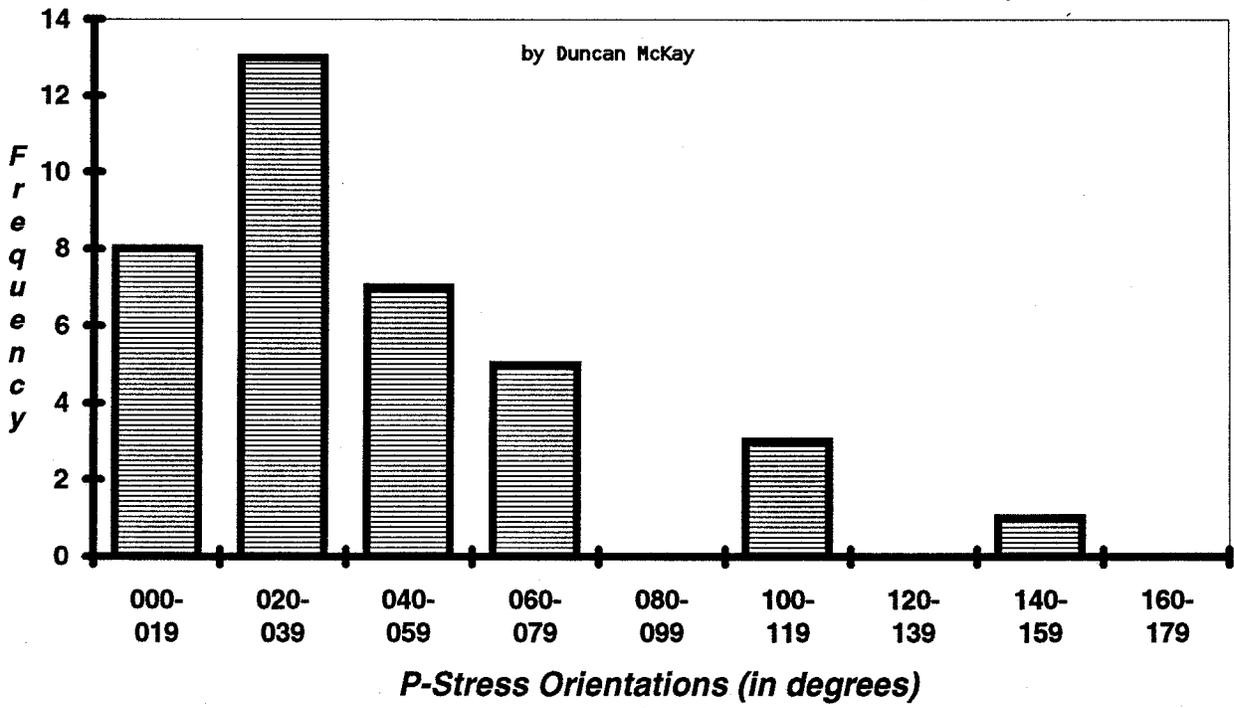


**KNOWN LOCATIONS OF POP-UPS IN
EASTERN NORTH AMERICA**

0 800
Km

Figure 1

P-Stress Orientations In The Roblindale Quarry



**POP-UP ORIENTATIONS
vs.
FREQUENCY OF OCCURRENCE
EASTERN NORTH AMERICA**

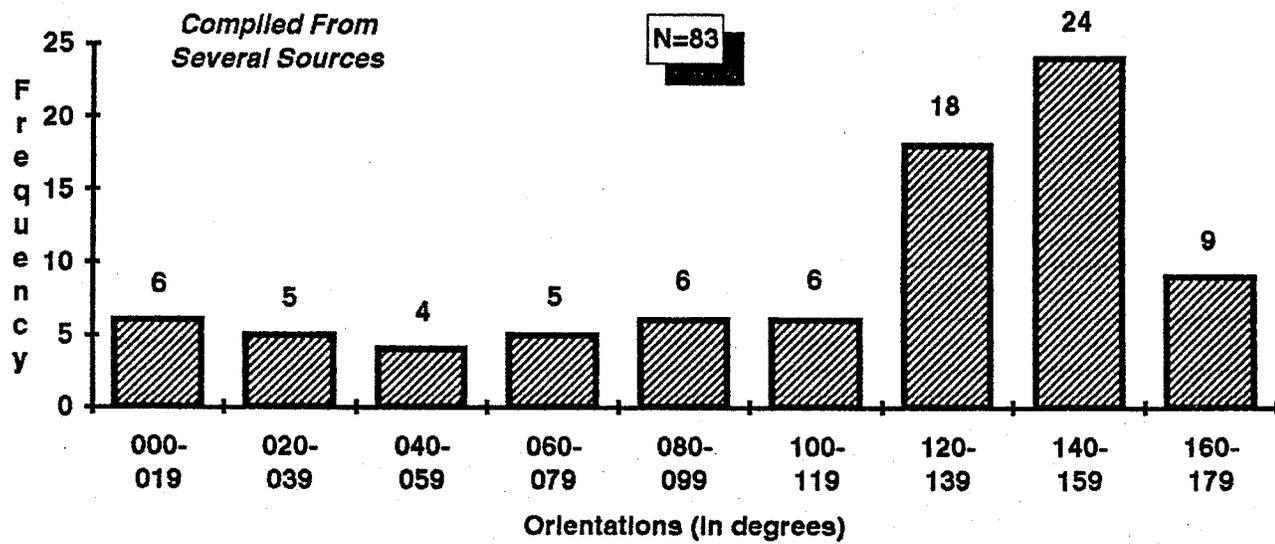


Figure 3

Distribution of Northwest-Trending Tensional and Compressional Structures and their Implications for Seismic Hazard Assessments

J.L. Wallach
Atomic Energy Control Board

Crough (1981) postulated that the Monteregian Hills were emplaced over a hot spot as the intruded crust (in what is now the Montreal-Eastern Townships area of Quebec) migrated across it. Adams (GSC) has adopted this model to account for stretching and concomitant fracturing of the crust providing zones of weakness which are currently being reactivated to produce seismicity in the West Québec Seismic Zone. However, $^{40}\text{Ar}/^{39}\text{Ar}$ ages of about 124 ± 1 my for six of the Monteregian Hills (Foland et al, 1986) strongly argue for a single episode of igneous activity, rather than a protracted one. Furthermore, seismicity within the current West Québec Seismic Zone lies between, and beyond, the outcrop areas of each of the individual Monteregian Hills. This, therefore, indicates that if the seismicity in the West Québec Seismic Zone is due to fracturing synchronous with the intrusion of these alkaline masses, the process resulting in the fracturing of the crust was geographically more extensive than that accounted for by Adams adaptation of Crough's model.

An alternate model is proposed, based on the work of Kumarapeli and Saull (1966) who suggested that the Ottawa-Bonnechere graben, a segment of the more extensive Ottawa graben (Jacobs, et al, 1973), may be cogenetic with the emplacement of the Monteregian Hills, thereby making the graben Cretaceous in age. Recently, Kumarapeli (personal communication) stated that the Cretaceous was a time of epeirogeny and igneous activity in eastern Canada, during which the Monteregians were emplaced and deep, Iapetan faults were probably reactivated. He added that this activity may well have been related to a hotspot, but not in the way that Crough conceived it and Adams uses it. Kumarapeli's current thinking regarding the cogenesis of the Monteregian intrusives and the rejuvenation of earlier formed faults is supported here.

Northwest-trending normal faults have been recognized in an area extending from the Saguenay Graben to Toronto and Lake Simcoe, Ontario; they may well extend even beyond these limits. Combining this with the Kumarapeli and Saull model of 1966, and Kumarapeli's current thoughts, it is suggested that there was a period of widespread crustal tension (quite possibly the epeirogenesis of Kumarapeli) during the Cretaceous Period. The effects of this episode would have extended well beyond the limits of the current West Québec Seismic Zone facilitating the emplacement of the Monteregians, reactivating pre-existing northwest-trending faults as normal faults and forming Cretaceous-age, similarly oriented normal faults. Because the faulting and fracturing attendant upon emplacement of the Monteregian Hills are considered by Adams as having seismic hazard implications, then there should be a seismic zone which is co-extensive with the area now marked by the northwest-oriented normal faults. This implies that the limits and name of the "West Québec Seismic Zone" be changed.

Northwest trending compressional structures, other than pop-ups, have been recognized

predominantly in unmetamorphosed Paleozoic carbonate rocks in an area extending from Quebec City to Syracuse (New York) to Toronto. Several occur in the Ottawa area and a significant number have also been identified in and near Prince Edward County, Ontario (McFall and Allam, in press). They appear as curvilinear, upright flexural-slip folds, asymmetrical overturned folds, kink bands, buckles which resemble large-scale pop-ups, and reverse faults. The curvilinear fold hinges, seen today in rocks at the surface, must have originated under elevated confining pressures, implying formation at a substantial depth and, consequently, a relatively old age. The geometry and kinematics of these structures are dynamically compatible with the surface and sub-surface structures forming, or being reactivated, in response to the present-day ambient stress field.

Some of the compressional structures are proximal to northwest striking normal faults and, in places, one type is superimposed upon the other. In some cases a unique interpretation is not possible and in others the normal faults **appear** to be younger. However, an exposure in Ottawa reveals what appears to be a graben that has been rotated on one of the northwest-trending anticlines indicating that the bounding faults are older. Sub-horizontal slickensides on normal fault surfaces point out that normal faulting has been succeeded by strike-slip movements. Pop-ups, which extend along normal faults on the floors of some quarries, formed following excavation of the quarries and are, therefore, younger than the normal faults. Thus, where a relative age relationship **can be established unequivocally** between northwest-oriented tensional and compressional structures, the latter are always shown to be younger.

The similarity of the current stress field to that inferred from the earlier curvilinear northwest-trending folds suggests that those folds are among the earliest structures to have formed in response to the current stress field. It is also consistent with the age relationships, where discernible, between the older normal faults and the younger, northwest trending compressional structures. The implied rather thick supracrustal sequence which must have existed during the time of emplacement of the Montereian Hills suggests that the current stress field may have evolved as early as Cretaceous time.

The area known to have been affected by the regional compressive phase resulting in the northwest oriented folds and reverse faults is similar to that in which the northwest-trending normal faults occur. This shows that this area has been subjected to repeated major tectonism throughout geological time and is likely to continue to be so affected. The largest known earthquakes within this area are those of $M \approx 7.0$ in the Charlevoix area, the $M_{blg} = 6.5$ Saguenay earthquake, and the $M = 6.25$ Timiskaming event.

Therefore, the new "West Québec Seismic Zone" should extend from at least the Saguenay Region through to Syracuse, New York and Toronto, and should be assigned a maximum magnitude of $7.0 + 0.5 = 7.5$, and recurrence rates similar to those for the $M \approx 7$ earthquakes in the current Charlevoix Seismic Zone.

Selected References

- Foland, K.A., Gilbert, Lisa A., Sebring, Cheryl A., and Jiang-Feng, Chen, 1986. $^{40}\text{Ar}/^{39}\text{Ar}$ ages for plutons of the Monteregian Hills, Quebec: Evidence for a single episode of Cretaceous magmatism; Geological Society of America Bulletin, v. 97, pp. 966-974.
- Jacobs, J.A., Russell, R.D. and Wilson, J.T., 1973. *Physics and Geology*. McGraw-Hill, 622 pp.
- Crough, S.T., 1981. Mesozoic hotspot epeirogeny in eastern North America. *Geology*, v. 9, pp. 2-6.
- Kumarapeli, P.S., and Saull, V.A., 1966. The St. Lawrence valley system: a North American equivalent of the East African rift valley system. *Canadian Journal of Earth Sciences*, v. 3, pp. 639-658.
- McFall, G.H. and Allam, Ahmed, in press. Neotectonic investigations in southern Ontario. Prince Edward County-Phase II. Atomic Energy Control Board, Ottawa, Ontario, 98 pp.

No 18297

SEISMICITY AND THE IAPETAN PASSIVE CONTINENTAL MARGIN

WHEELER, Russell L., U.S. Geological Survey, Box 25046, MS 966,
Denver Federal Center, Denver, CO 80225.

Precisely located earthquakes in southwestern Virginia, eastern Tennessee, Charlevoix, Quebec, and the St. Lawrence estuary concentrate in tabular or elongated zones that strike northeast and dip vertically or steeply southeast. Map relations, hypocentral depths (typically 6-22 km), and tectonic evidence indicate that Iapetan normal faults are being compressionaly reactivated. Assessing the resulting seismic hazard requires determining the geographic limits of such faults.

The location, geometry, and fault style of the late Proterozoic-early Paleozoic Iapetan margin are defined by geologic maps, well and potential-field data, seismic refraction profiles, industry reflection profiles, analogies to younger passive margins, and nine deep reflection profiles that cross most of the Appalachians. The Iapetan margin trends northeast in Grenville-age continental crust for 3700 km from Alabama to the shelf edge northeast of Labrador. Its extensional fault system varies from 275 to 600 km wide. Most large faults strike northeast, dip southeast, and formed mostly by normal slip. The faulted margin is split lengthwise by a hinge zone that roughly follows the Appalachian gravity gradient southwest of Vermont. Crust northwest of the hinge zone contains Iapetan faults but was little thinned by them. The aforementioned earthquakes and enigmatic Adirondack seismicity occur there. In contrast, crust southeast of the hinge zone was severely thinned and reformed by Iapetan extension, telescoped and reworked by Paleozoic compressions and accompanying heatings, and extended and reformed again during Mesozoic rifting. This crust is aseismic; known seismicity is in Appalachian rocks thrust onto the Iapetan margin.

Thus, the relatively intact part of the Iapetan margin northwest of the hinge zone has a distinct, uniform style of seismicity apparently associated with a distinct, uniform style of reactivated faults. Only a few Iapetan faults are seismogenic now but others throughout the intact part of the margin might become active in the future.

P. 147

Northeastern and Southeastern Sections 147

No 18354

HYPOTHESIS FOR CONSTRAINT OF SEISMICITY IN SOUTHEASTERLY PORTIONS OF THE APPALACHIAN OROGEN TO DEPTHS <20 KM

STEWART, David B., U.S. Geological Survey, MS 959, National Center,
Reston, VA 22092

Synthesis of results from seismic refraction and reflection profiles in New England, New York, and adjacent Quebec by Stewart and Luetgert (GSA Abstracts with Programs, 22, 7, A192, 1990) indicates that the present configuration of the lower crust and its strength and lack of detectable through-going faults were formed by ductile extension and recrystallization in late Paleozoic to pre-middle Jurassic time. Earthquake hypocenters in the region of extended crust occur only above the top of the lower crust (22±2 km), which is defined by the top of a 4-km-thick gradational zone where compressional wave velocity increases from 6.4 to 6.8 km/s. The top of the lower crust in the extended region is a surface having broad troughs and swells and less than 5 km of relief overall; the top becomes indistinct below the wedge of allochthonous sheets that were thrust upon the Iapetan margin of the craton during Paleozoic orogenesis. Strong seismic reflectors from the base of the allochthons die out into the uppermost newly reformed lower crust; the lack of reflectors explains why locating the decollement root zones has been controversial. Border faults of Carboniferous and early Mesozoic basins also become listric into the uppermost lower crust and, in some cases, overlie a rapid thinning of the crust of up to 4 km. The region having newly reformed lower crust has a well-defined reflection and refraction Moho which contrasts with the gradational Moho beneath Proterozoic crust to the north and west.

These observations support the hypothesis that a swath of newly reformed lower crust that is as much as 600 km wide acts with stiff upper mantle as a thick, strong aseismic plate or pad to confine seismicity to brittle upper crust that is made up of a highly faulted collage of early Paleozoic terranes.

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1991 NE-SE GSA

APPENDIX 6

Maps showing source zones sketched by the participants

2 - ZONE IS TAPERED AS $e^{-\frac{r}{200m}}$ (6) $\approx 200m$

3 - RECURRENCE IS A REGIONAL VALUE = CONSTANT, EG. WQUEBEC β

4 - ACTIVITY PROPORTIONAL TO MOMENT MAG. IN EACH EA

5 - MAXIMUM MAGNITUDE ALSO REGIONAL

ADVANTAGES NO FURTHER PROBLEMS OF MOVING A SITE ACROSS A ZONE BOUNDARY

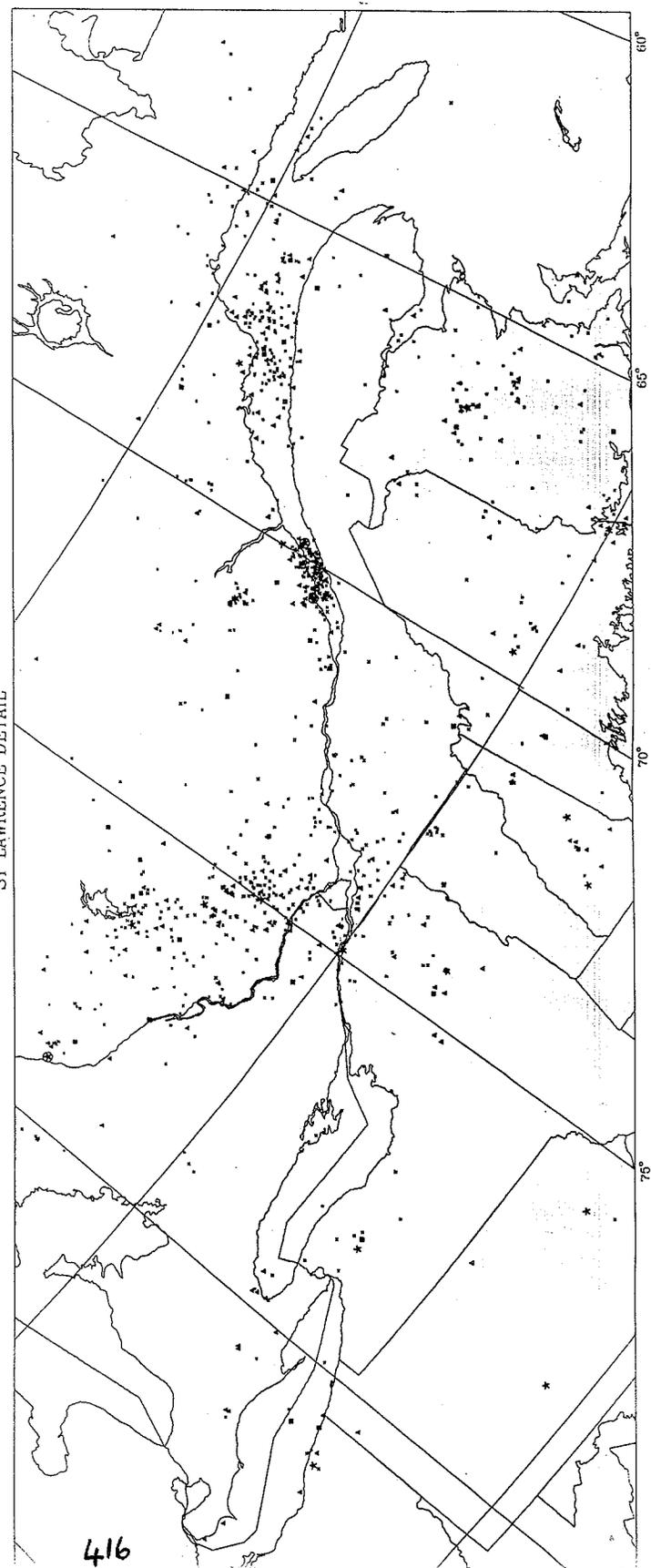
$$e^{-\frac{r}{200m}}$$



DEFINITIONS

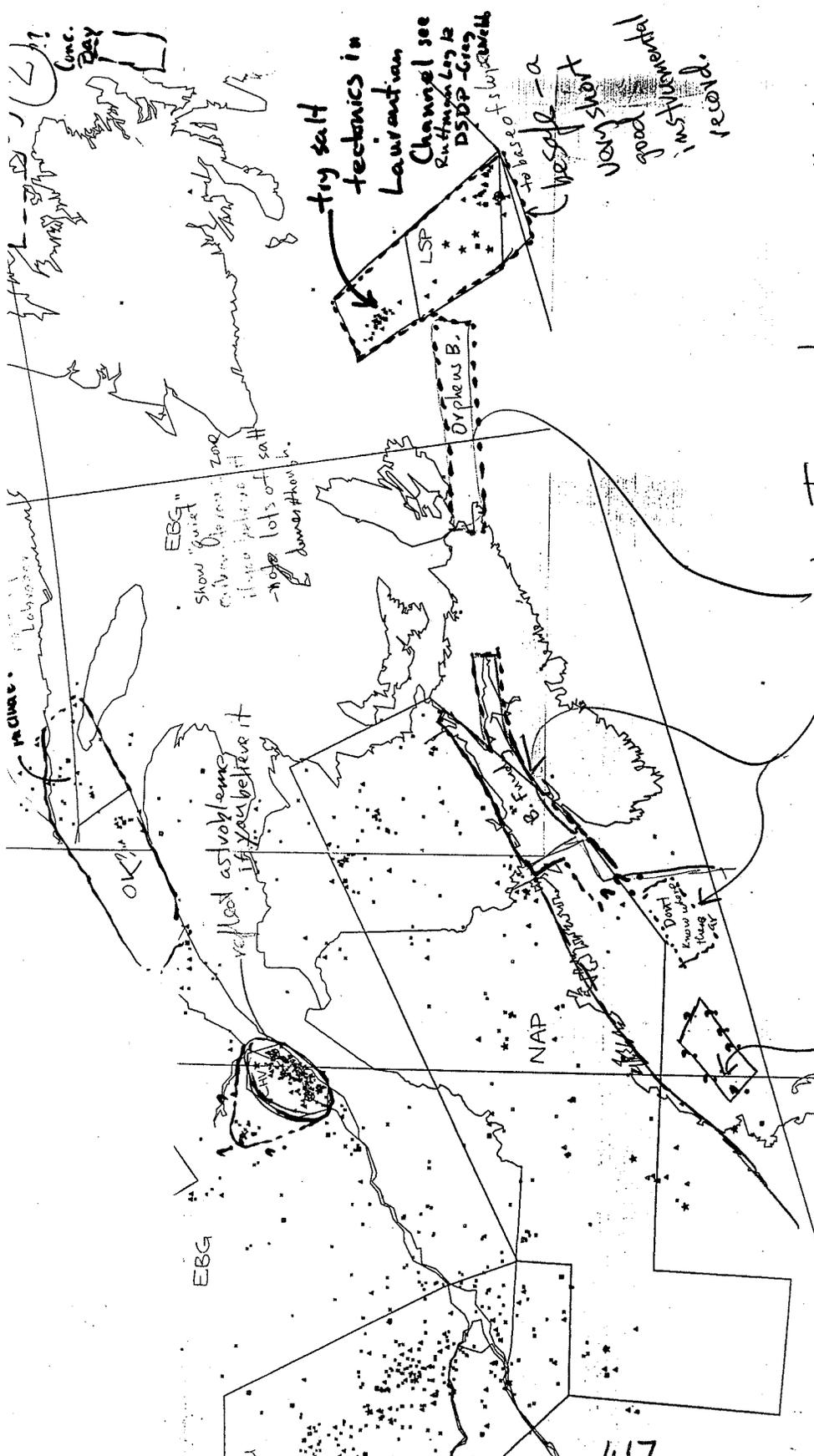
M ≥ 2.0	1980+	*
M ≥ 3.0	1975+	*
M ≥ 3.5	1968+	*
M ≥ 4.0	1963+	*
M ≥ 4.5	1957+	*
M ≥ 5.0	1900+	*
M ≥ 6.0	1870+	⊗

ST LAWRENCE DETAIL



COMMISSION INTERNATIONALE D'ÉTUDES SÉISMologiques
BUREAU DE LA CLASSEMENT DES ÉVÉNEMENTS SÉISMologiques





try salt tectonics in Laurentian Channel see Rutherford is DSDP-Gies to base of fibrocell

EBG " Show "burst" of salt - note lots of salt down through B

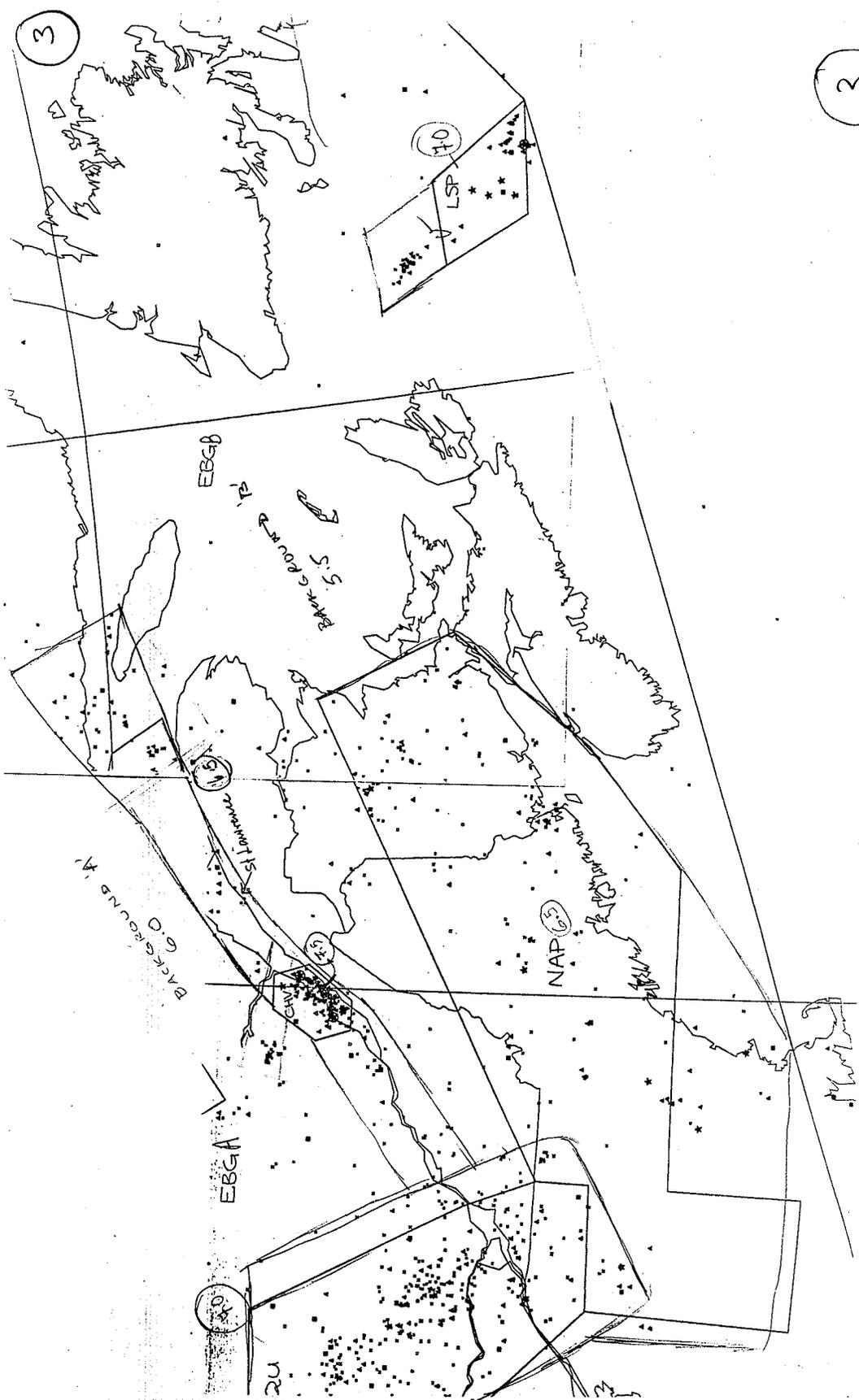
OK? - look as volume if you believe it

very short good 1400m 15m record

Consider Triassic basins - even though there are no events ???

1755 could well be further offshore - in a Triassic basin ???

2



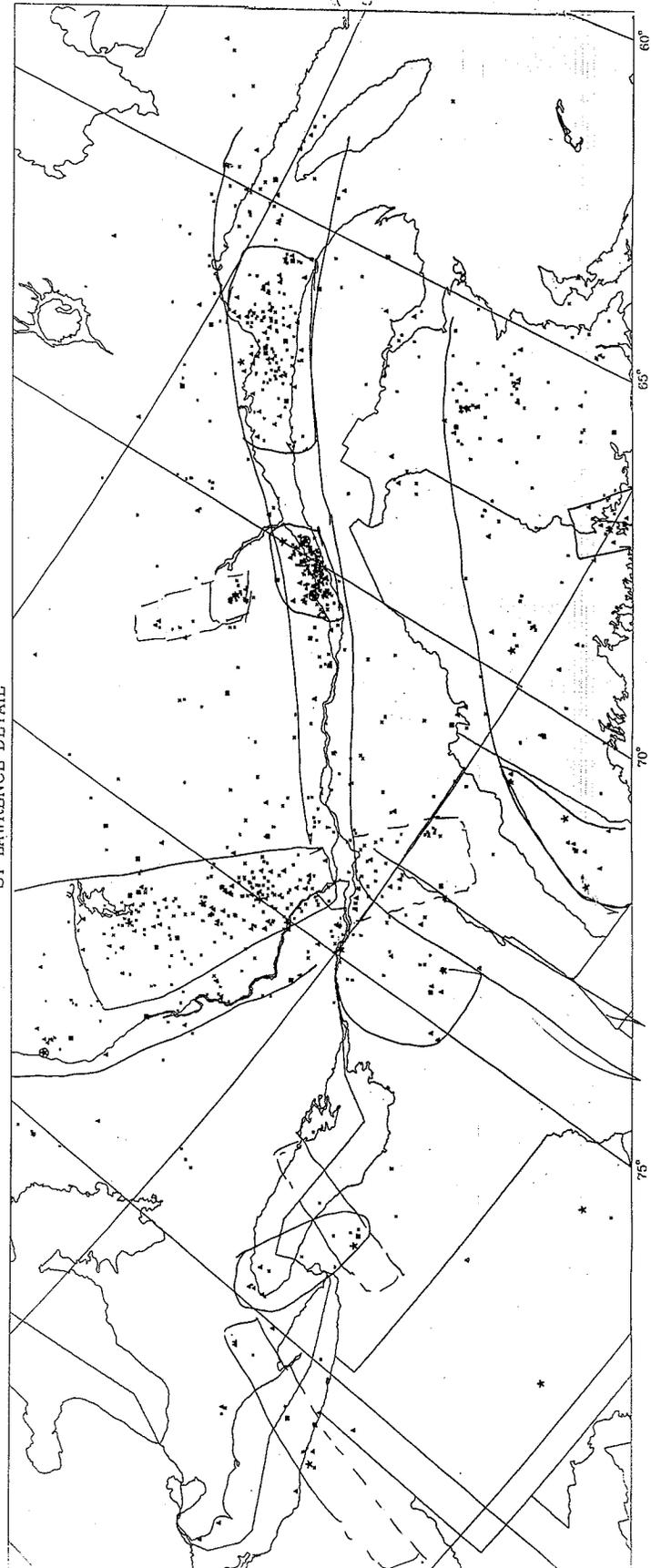
n lim kiewicz

(4)

DEFINITIONS

- M≥2.0 1980+ *
- M≥3.0 1975+ *
- M≥3.5 1968+ *
- M≥4.0 1963+ *
- M≥4.5 1937+ *
- M≥5.0 1900+ *
- M≥6.0 1870+ *

ST LAWRENCE DETAIL



SEISMICITY INTERPOLATED SURVEY W-1
Map Scale 1:250,000 (1 inch = 2.5 miles)

60°

65°

70°

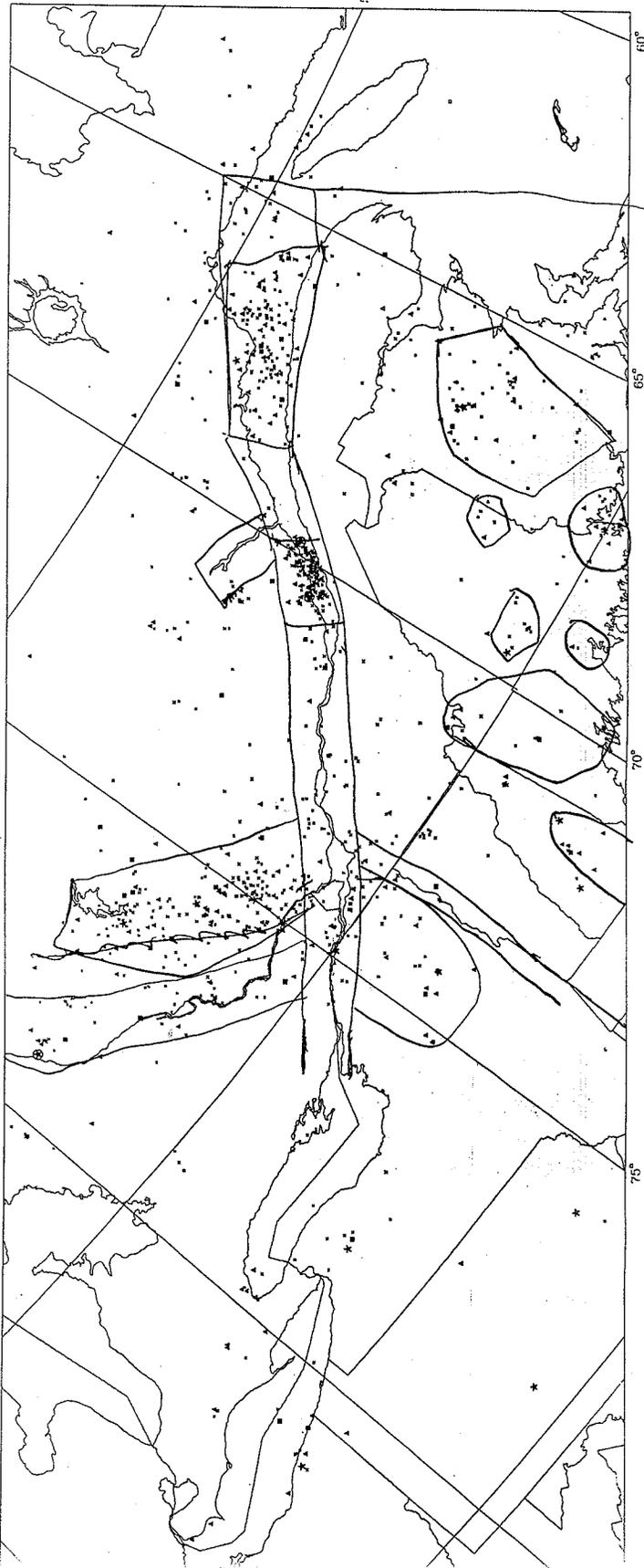
75°

(4)

DEFINITIONS

- M≥2.0 1960+ •
- M≥3.0 1975+ *
- M≥3.5 1968+ ▲
- M≥4.0 1963+ ■
- M≥4.5 1937+ ◆
- M≥5.0 1900+ ✱
- M≥6.0 1870+ ⊗

ST. LAWRENCE DETAIL

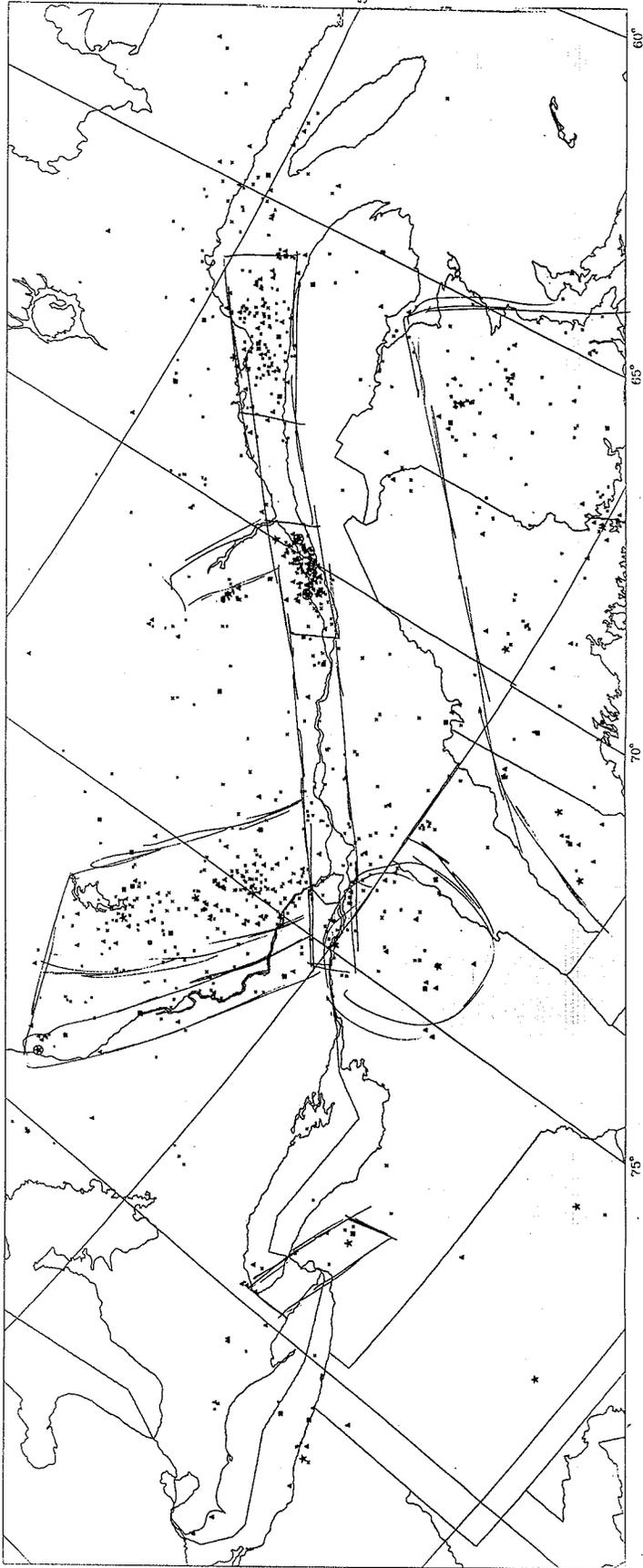


GEOPHYSICAL RESEARCH BOARD OF CANADA
 BUREAU DE RECHERCHES GÉOLOGO-ÉNERGÉTIQUES
 1000 AVENUE DES ÉTIENNES, OTTAWA, K1P 8S1

5

- DEFINITIONS
- M₂≥2.0 1980+ .
 - M₂≥3.0 1975+ *
 - M₂≥3.5 1968+ ▲
 - M₂≥4.0 1963+ ■
 - M₂≥4.5 1957+ ●
 - M₂≥5.0 1900+ *
 - M₂≥6.0 1870+ ⊗

ST LAWRENCE DETAIL



60° 65° 70° 75°

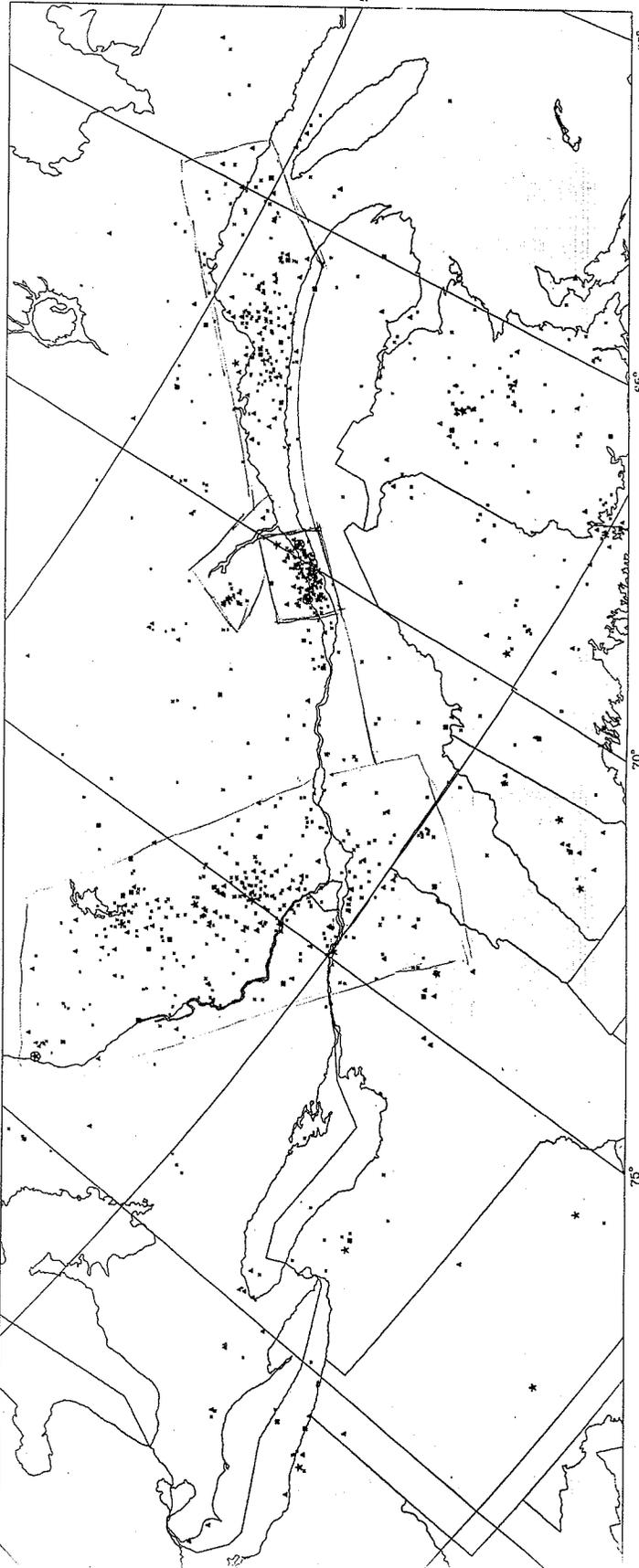
EXPLANATION: UNITED STATES COAST AND GEODETIC SURVEY OF CANADA
 HYDROGRAPHIC DEPARTMENT, OCEANOGRAPHIC DIVISION, 1911

6

DEFINITIONS

- M≥2.0 1980+ -
- M≥3.0 1975+ *
- M≥3.0 1968+ *
- M≥4.5 1963+ *
- M≥4.5 1937+ *
- M≥5.0 1900+ *
- M≥6.0 1870+ *

ST LAWRENCE DETAIL



UNIVERSITY OF TORONTO LIBRARY
 130 St. George Street, Toronto, Ontario M5S 1A5

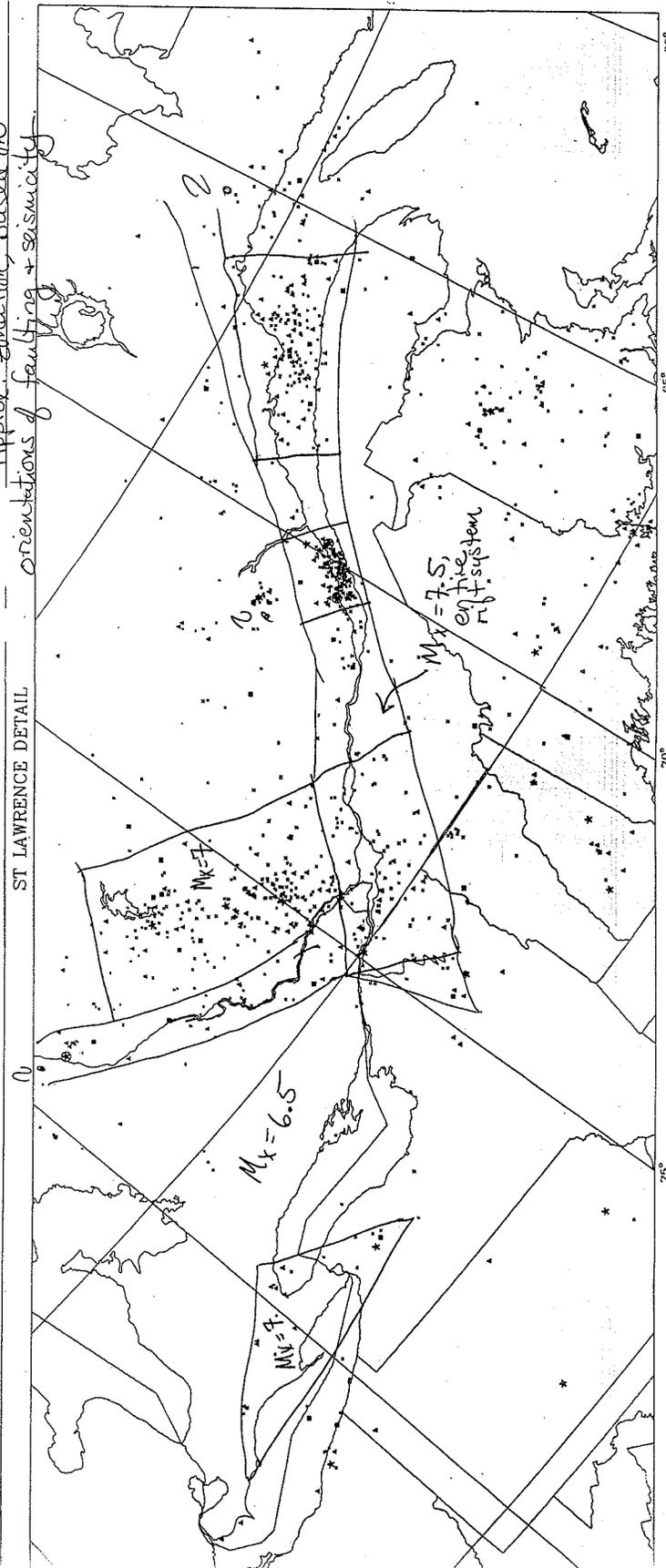
8

DEFINITIONS

- M ≥ 2.0 1880+
- M ≥ 3.0 1975+
- M ≥ 3.5 1860+
- M ≥ 4.0 1863+
- M ≥ 4.5 1837+
- M ≥ 5.0 1800+
- M ≥ 6.0 1870+

- Approx. zonation, based on orientations of faulting + seismicity

ST LAWRENCE DETAIL



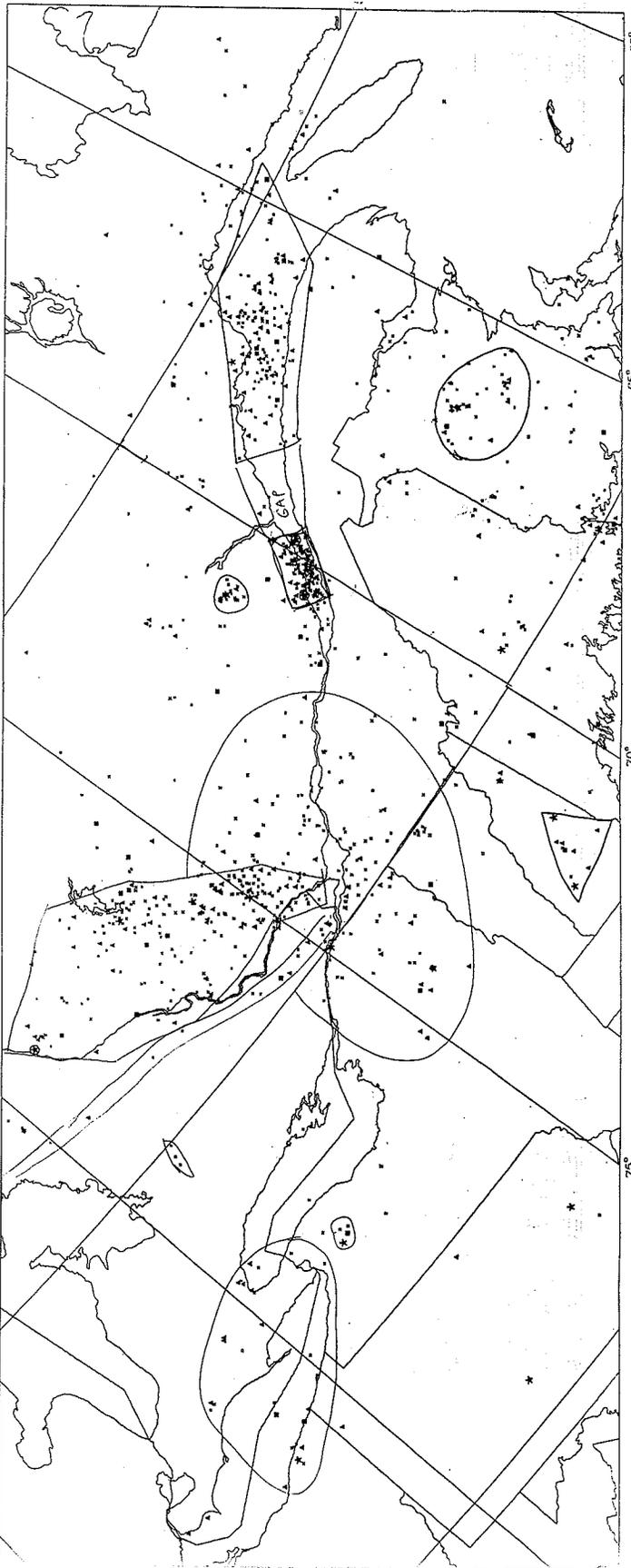
UNIVERSITY OF ALBERTA LIBRARY ARCHIVES

Include a distinctive Charlevoix zone.

DEFINITIONS

- M≥2.0 1980+ .
- M≥3.0 1975+ *
- M≥3.5 1968+ *
- M≥4.0 1963+ *
- M≥4.5 1937+ *
- M≥5.0 1900+ *
- M≥6.0 1870+ ⊕

ST LAWRENCE DETAIL



DEFINITIONS

- M22.0 1980+ *
- M23.0 1975+ *
- M23.5 1968+ *
- M24.0 1963+ *
- M24.5 1937+ *
- M25.0 1900+ *
- M26.0 1870+ *

ST LAWRENCE DETAIL



GEOPHYSICAL SURVEY OF CANADA
 IMPROVED AND REVISED EDITION

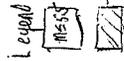
West A } Do these need
 West B } dividing??
 not sure
 MAY 2 7.0

CHV - max 8.0
 ST LAWRENCE - max 7.5

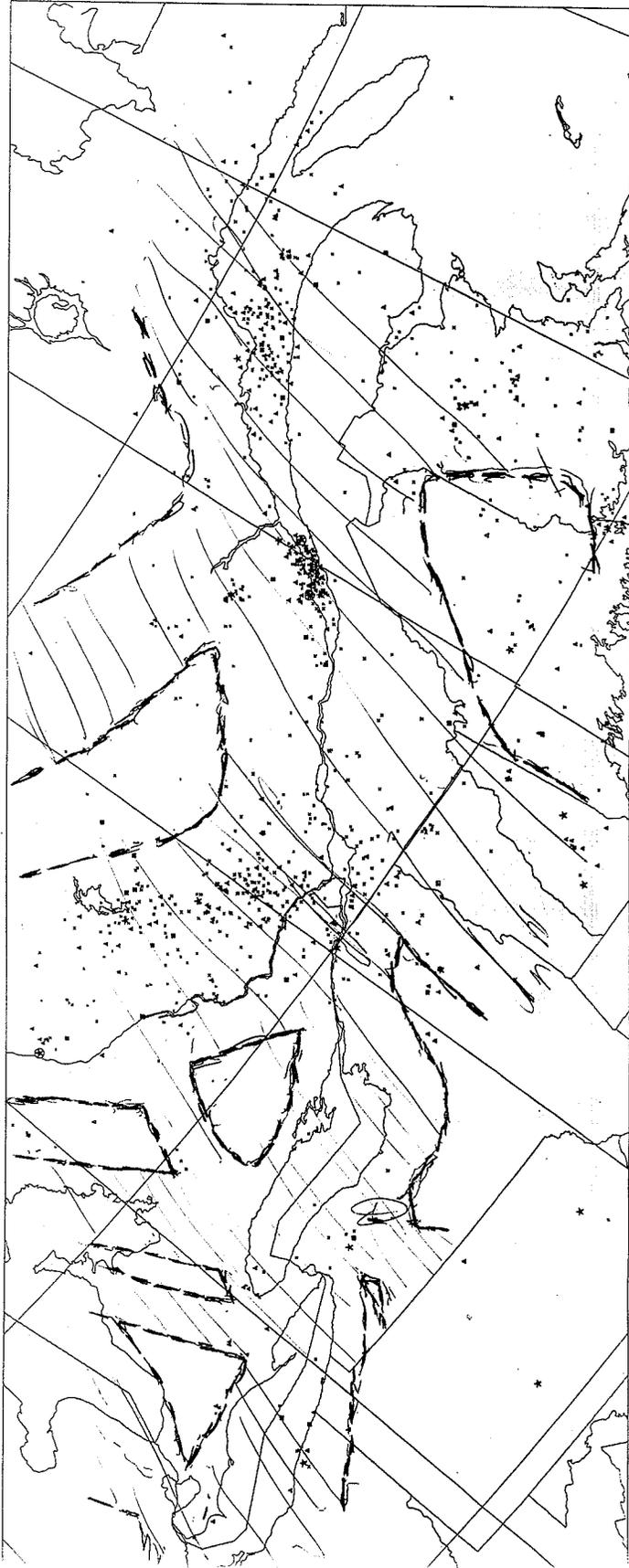
ONT ARCH - max 5.0
 NAP - max 6.5

DEFINITIONS

- M≥2.0 1980+ .
- M≥3.0 1975+ *
- M≥3.5 1968+ *
- M≥4.0 1963+ *
- M≥4.5 1937+ *
- M≥5.0 1900+ *
- M≥6.0 1870+ *



ST LAWRENCE DETAIL



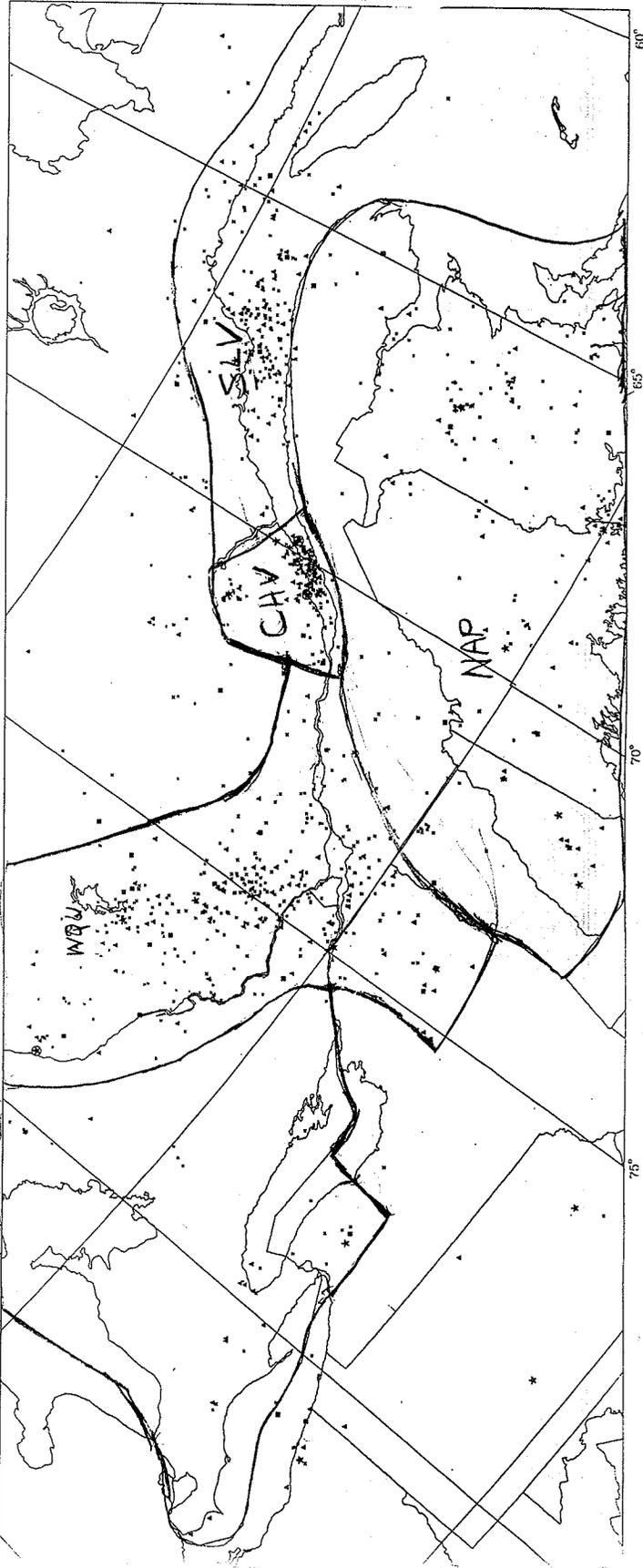
60° 65° 70° 75°

COMMITTEE ON SEISMICITY OF THE ST. LAWRENCE REGION

DEFINITIONS

- M≥2.0 1980+ .
- M≥3.0 1975+ *
- M≥3.5 1968+ ▲
- M≥4.0 1963+ ■
- M≥4.5 1937+ ◆
- M≥5.0 1900+ ✱
- M≥6.0 1870+ ⊕

ST LAWRENCE DETAIL



GEOPHYSICS DIVISION, GEOLOGICAL SURVEY OF CANADA
 REPORTING BY T. A. GUYER AND J. H. BOYD

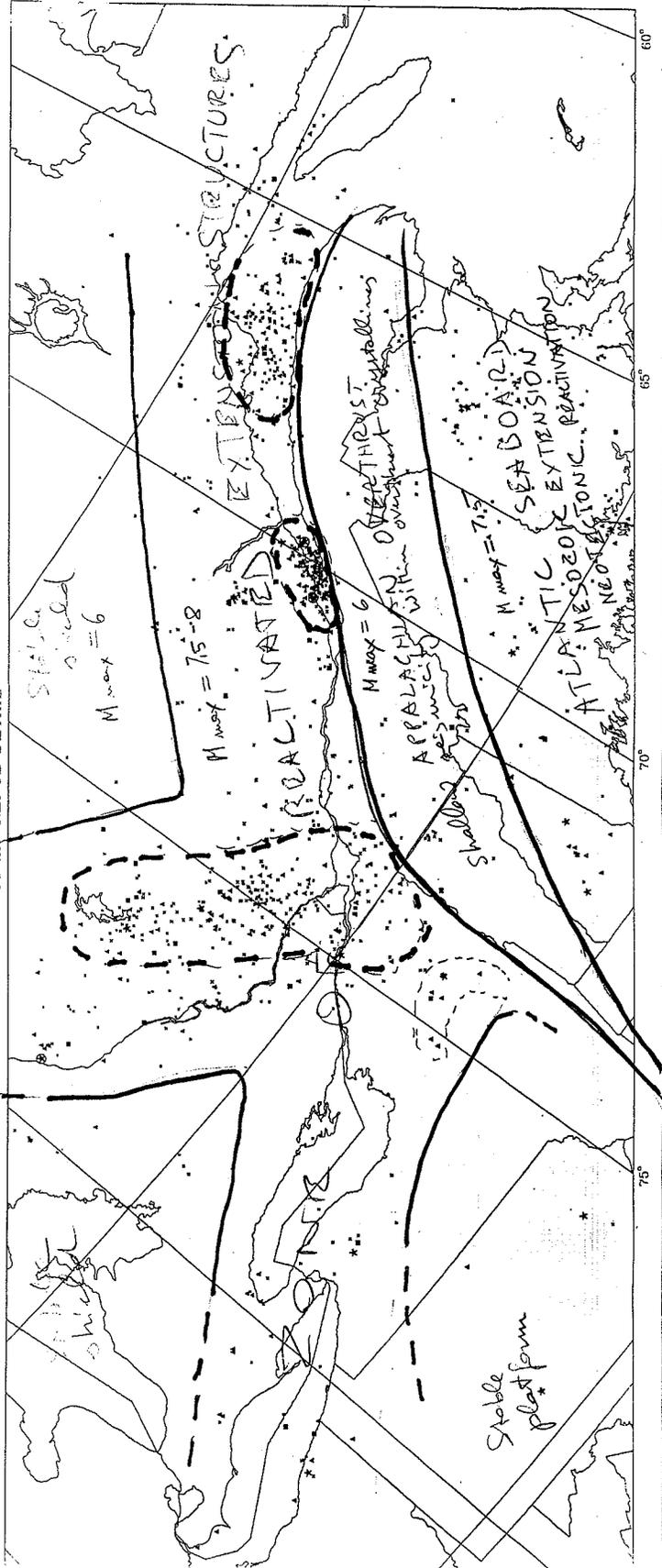
13

DEFINITIONS

- M2.0 1980+ *
- M3.0 1975+ *
- M3.5 1968+ *
- M4.0 1963+ *
- M4.5 1937+ *
- M5.0 1900+ *
- M6.0 1870+ *

Regions of current seismicity may be temporary - Recurrence of large eqs is higher in these regions, but Max Mag may be the same within each zone

ST LAWRENCE DETAIL

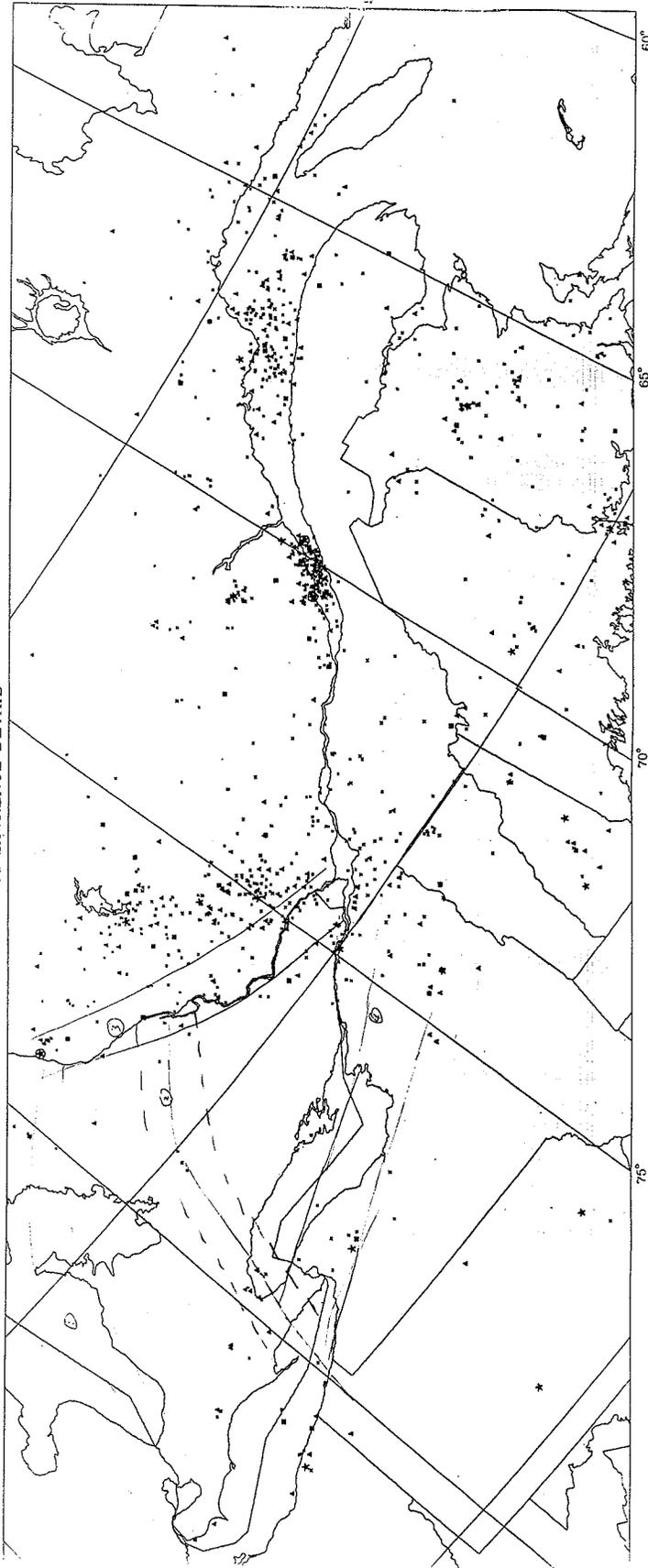


3/1/82
 4117
 S.O. of St. Lawrence

DEFINITIONS

- M≥2.0 1980+ *
- M≥3.0 1975+ *
- M≥3.5 1968+ *
- M≥4.0 1963+ *
- M≥4.5 1937+ *
- M≥5.0 1900+ *
- M≥6.0 1870+ *

ST LAWRENCE DETAIL



EDWINSON JUNIOR GEOLOGICAL SURVEY OF CANADA
 1500 SANDHILL AVENUE, OTTAWA, ONTARIO K1P 6L7

15

430

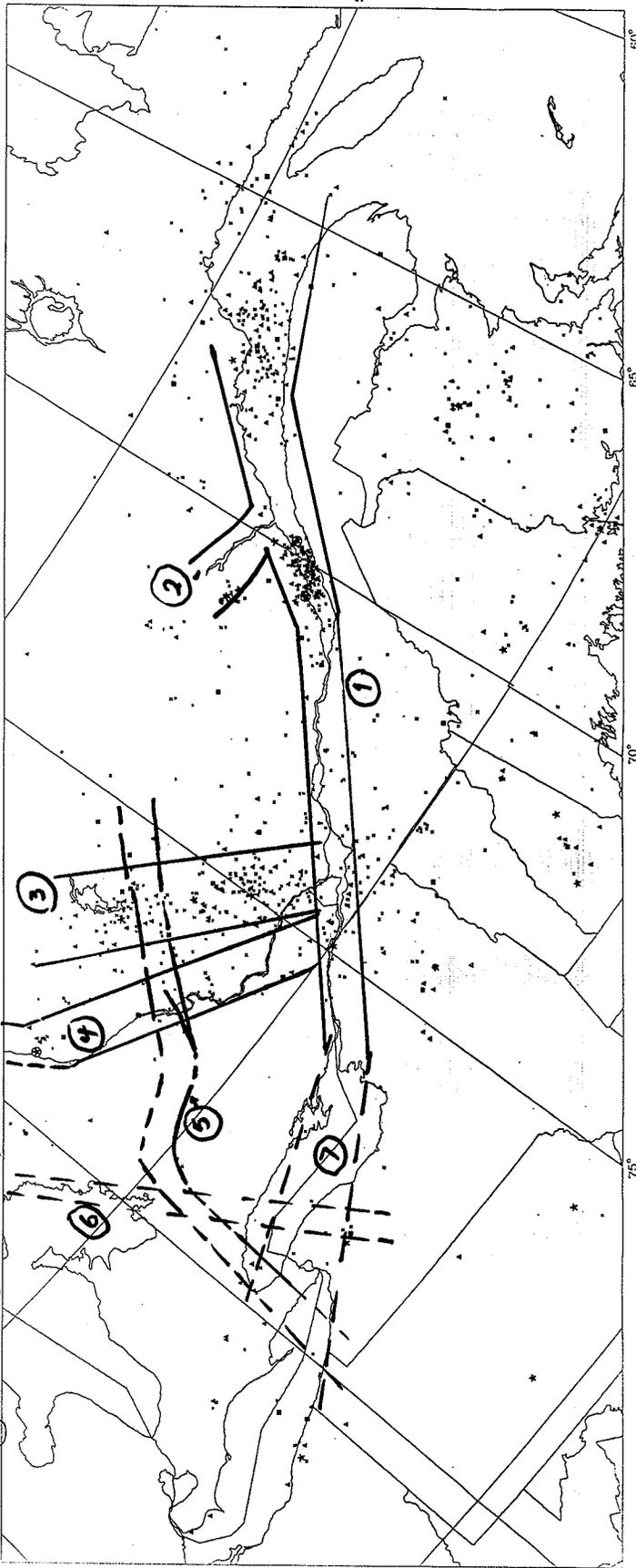
... parameters for the seismic zoning;

	b-value	a-value	Mx	Pa (assigned probability for activity)
① st. Lawrence structural zone	1-1.05	log N, M > 3	7.5	60 %
② Sagouway "	0.9	"	7.0	
③ western Quebec seismic zone	1.05	"	6.5	70
④ Ottawa river structural zone	"	"	7.0	60
⑤ CMBBZ	"	"	6.0	2.0, ⑤ 40 %
⑥ Georgian Bay lineament	"	"	6.0	2.0
⑦ Southern Great Lakes structural zone	"	"	6.0	2.0

DEFINITIONS

M ≥ 2.0	1980+
M ≥ 3.0	1975+
M ≥ 3.5	1968+
M ≥ 4.0	1963+
M ≥ 4.5	1957+
M ≥ 5.0	1900+
M ≥ 6.0	1870+

ST LAWRENCE DETAIL 7.0

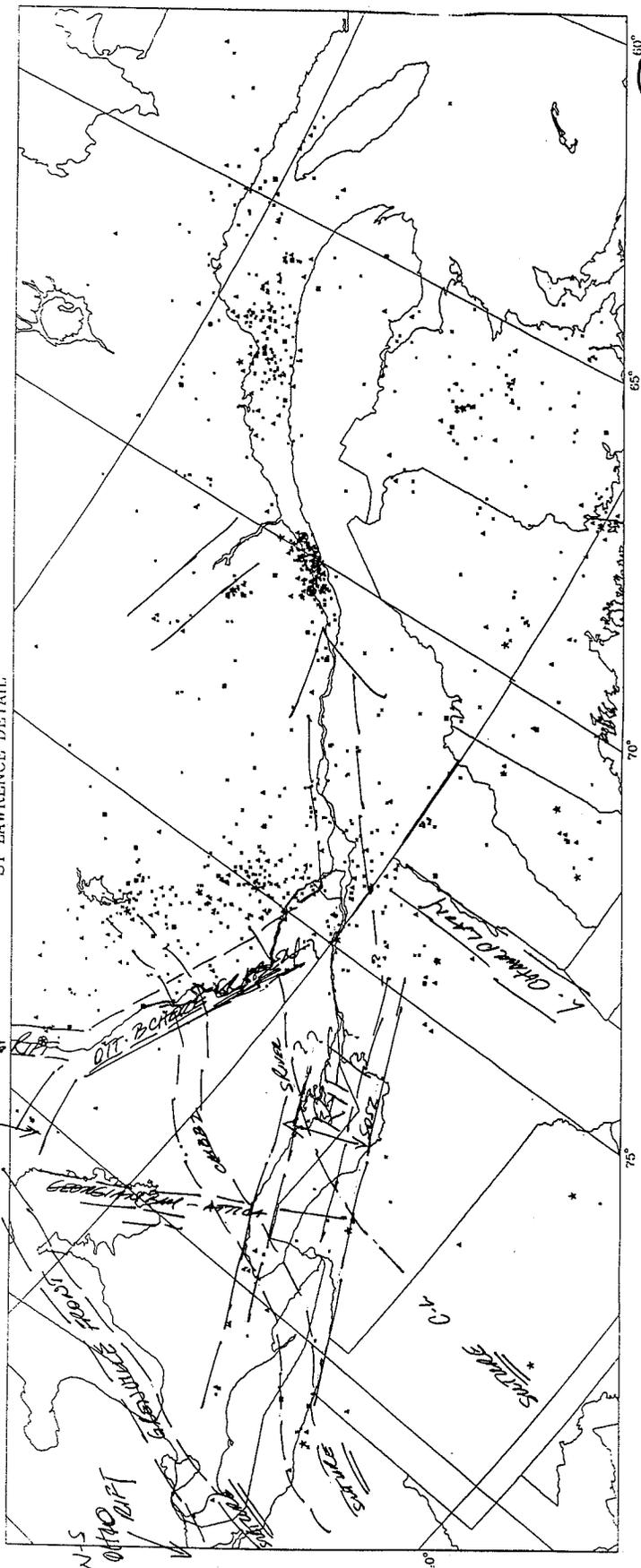


16
March 19, 1991

DEFINITIONS

- M ≥ 2.0 1980+ *
- M ≥ 3.0 1975+ *
- M ≥ 3.5 1968+ *
- M ≥ 4.0 1963+ *
- M ≥ 4.5 1937+ *
- M ≥ 5.0 1900+ *
- M ≥ 6.0 1870+ *

ST LAWRENCE DETAIL



2 1/2
MILE

BRIT. LAKES ZONE
(i.e. CHD, LUMBERG)

1. Set STRUCTURAL ELEMENTS
(faults, compressive belts, etc)

2. Define: 1. probable ~~type~~ associated with each structural element
2. cumulative beyond associated with each intersection
3. CONTRAST VALUES (i.e. harmonic (?) type accumulation)