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IN EASTERN CANADA
AMNEC
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DANS L'EST CANADIEN

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MAGNEC '89
Annual Report

Rapport annuel de
l'AMNEC 1989

Editors:

J.A. Heginbottom
Geological Survey of Canada

and

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Commission de contrôle
de l'énergie atomique

Ottawa
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Ottawa
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PREFACE

This is the second annual report of MAGNEC, the Multi-Agency Group for Neotectonics in Eastern Canada. The principal intent of the report is to provide information on the plans for the upcoming fiscal year and, by virtue of the short reports, to summarize the progress made in the previous year. In addition, the report includes the program and abstracts from a special session on "Intraplate Deformation, Neotectonics, Seismicity and the State of Stress in Eastern North America" held at the 1989 annual meeting of the Geological Association of Canada/Mineralogical Association of Canada (in Section 2), and copies of two newspaper reports of MAGNEC meetings and of research related to the MAGNEC program (in Section 6).

The editors thank Ms. Connie Morris and Mrs. Jeanne Barr, of the Geological Survey of Canada, who typed the report. In addition, the editors thank the editors of The Picton (Ontario) Gazette, Mr. Ed Reeves, and the Quotidien de Chicoutimi, Mr. Bertrand Genest, and also the Chairman, Publications Committee, GAC/MAC, Dr. R. Baragar, for permission to reproduce the articles and abstracts mentioned above.

PREFACE

Voici le deuxième rapport annuel d'AMNEC, l'Association Multipartite pour la Néotectonique dans l'Est Canadien. Son but principal est de fournir des propos pour la prochaine année financière et, en vertu des mini-articles, de signaler les progrès de l'année précédente. De plus, ce rapport englobe les sommaires d'une séance spéciale intitulée "Intraplate Deformation, Neotectonics, Seismicity and the State of Stress in Eastern North America", et qui a été convoquée à la réunion annuelle des Associations géologiques et minéralogiques du Canada (GAC/MAC) (Section 2). Deux activités de l'AMNEC ont été documentées dans les articles journalistiques qui sont reproduits ici (Section 6).

Les rédacteurs remercient les deux secrétaires qui ont dactylographié ce rapport, dont Miss Connie Morris et Mrs. Jeanne Barr de la Commission géologique du Canada. Ils remercient également des rédacteurs des journaux, soit The Picton (Ontario) Gazette, M. Ed Reeves, et Le Quotidien de Chicoutimi, M. Bertrand Genest, ainsi que le président du comité des publications de GAC/MAC, Dr. R. Baragar, pour la permission de reproduire les sommaires et les articles mentionnés ci-haut.

J.A. Heginbottom
J.L. Wallach

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STRESSES, BRITTLE STRUCTURES AND NEOTECTONICS

1. MAGNEC 1989 / L'AMNEC 1989

Report of MAGNEC Activities

The past year has proven to be a fulfilling one for MAGNEC. Among the activities was the organization, in conjunction with the Canadian Geophysical Union, of a special session of the annual Geological Association of Canada/Mineralogical Association of Canada (GAC-MAC) meeting entitled **"Intraplate Deformation, Neotectonics, Seismicity and the State of Stress in Eastern North America"**. Participants came from as far away as Arkansas and California and were among the contributors to the twenty-one papers and thirteen posters which comprised the all-day session. The talks were well attended with generally 80-100 people in the audience at any one time; the posters were on display throughout the entire day and also received considerable attention. The program listing (papers and posters) as well as the abstracts follow this report.

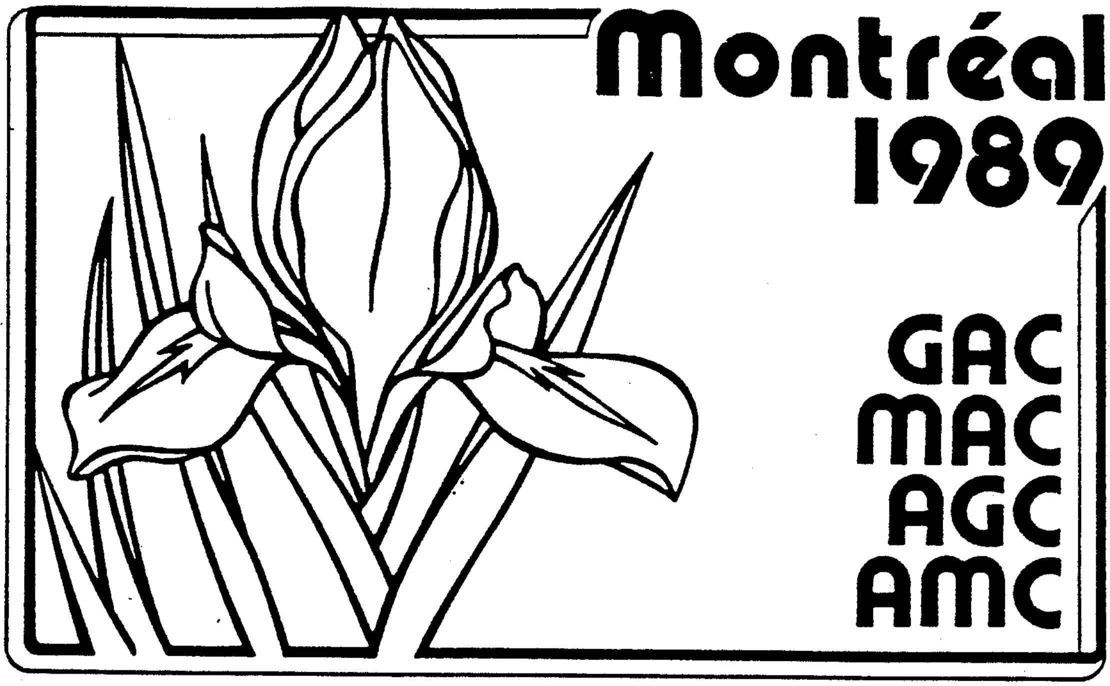
Two regularly scheduled meetings were convened in 1989, the first in Burlington, Ontario, February 22 and the second in Chicoutimi, Quebec, October 4. The technical sessions at both meetings were dominated by presentations on the M_{bLg}=6.5, Saguenay earthquake of November 25, 1988. The meeting in Chicoutimi was followed by a field trip, led by Gérard Woussen of the Université du Québec à Chicoutimi (UQAC), to outcrops of Precambrian rocks within the Saguenay Graben. Woussen also prepared a guide book which was a very welcome and appreciated addition to the trip.

The aftermath of the Saguenay earthquake continued to draw attention in the form of seismic monitoring (Du Berger, UQAC) and an evaluation of liquefaction features (Tuttle, Lamont-Doherty). Tectonic studies in Prince Edward County, Ontario (McFall, Ontario Geological Survey), Passamaquoddy Bay, New Brunswick (Burke, University of New Brunswick), and Lake Ontario (McQuest Marine), a compilation of LANDSAT-expressed lineaments and outcrop-scale fractures in southern Ontario and adjacent Quebec and New York State (Singhroy and Kenny, Ontario Centre for Remote Sensing; McFall, Ontario Geological Survey; Bowlby, Ontario Hydro) and reevaluations of seismicity on the Niagara Peninsula (Mohajer, Seismican) are among the other projects effected in 1989.

Results of the work in Prince Edward County show that, in addition to pop-ups, there are other tectonic structures which are suspected of having been produced by the current, ambient stress field. The marine work has revealed the presence of plumose structures, first recognized in Lake Ontario by Rich Thomas, Ken McMillan and Darren Keyes of McQuest Marine and by John Bowlby of Ontario Hydro. The origin of these structures is not yet known, but the aforementioned people suggest that they may be neotectonic indicators. Plumose structures have also been identified in sediments in the Bay of Fundy, along the seaward projection of a north-northwest-trending fault.

To date a considerable amount of new geologic and seismic information has emerged from the efforts of MAGNEC, though much more is needed in order to understand the relationship between geologic features and moderate to large earthquakes. Nonetheless, that which has accrued since the inception of MAGNEC should play a significant role in updating the National Building Code, due for release in 1995.

2. SPECIAL CONFERENCE SESSION SPONSORED BY MAGNEC/SESSION SPÉCIALE DE CONFÉRENCE PARRAINÉE PAR L'AMNEC (1989)



Montréal 1989

GAC
MAC
AGC
AMC

program

INTRAPLATE DEFORMATION, NEOTECTONICS, SEISMICITY AND THE STATE OF STRESS IN EASTERN NORTH AMERICA

Room 411 B
Organizers: J-C. Mareschal, J. Wallach and J. Bowlby
Sponsors: CGU and MAGNEC

ANNUAL MEETING, May 15 - 17, 1989
PALAIS DES CONGRÈS, MONTRÉAL
RÉUNION ANNUELLE, 15 - 17 mai, 1989

WITH THE PARTICIPATION OF THE CANADIAN GEOPHYSICAL UNION
AVEC LA PARTICIPATION DE L'UNION GÉOPHYSIQUE DU CANADA

WEDNESDAY, MAY 17

INTRAPLATE DEFORMATION, NEOTECTONICS, SEISMICITY AND THE STATE OF STRESS IN EASTERN NORTH AMERICA

Room 411B
Organizers: J-C. Mareschal, J. Wallach and J. Bowlby
Sponsors: Canadian Geophysical Union and Multi-Agency Group for Neotectonics in Eastern Canada (MAGNEC)

I. INTRAPLATE SEISMICITY AND CRUSTAL STRESSES

Chairperson: M.J. Berry

08:00 1. **J. Adams:** Seismicity, earthquake focal mechanisms, and crustal stresses in the Grenville Province, and their relation to the seismogenic rift structures of southeastern Canada.
08:20 2. **M. Lamontagne*, R.J. Wetmiller, P. Munro, I. Asudeh, R. Du Berger, R. Such, R. Busby, L. Seeber and J.G. Armbruster:** Field studies of the M6.0 Saguenay, Quebec, earthquake of November 25, 1988 and its foreshock and aftershocks.
08:40 3. **H.S. Hasegawa:** Seismotectonic environment of eastern and northern Canada earthquakes.
09:00 4. **A.A. Mohajer*, F. Kenny and V. Singhroy:** Seismotectonic framework of western Quebec.
09:20 5. **K. Fujita* and N.H. Sleep:** The seismicity of Michigan: earthquakes, explosions and other phenomena.
09:40 6. **J-C. Mareschal*, L.T. Long and J. Kuang:** Intraplate seismicity and stress in the southeastern United States.
10:00 BREAK

Chairperson: D.A. McKay

10:20 7. **P. Talwani* and K. Rajendran:** The intersection model for intraplate earthquakes.
10:40 8. **M. Ouellet:** Luminous phenomena in relation to the November earthquakes of the Saguenay region, Quebec.
11:00 9. **R.B. VanArsdale* and E.S. Schweig:** Geology of an intraplate earthquake swarm: Enola, Arkansas, 1982.
11:20 10. **I.L. Meglis* and T. Engelder:** Laboratory analysis of Moodus, CT and Kent Cliffs, NY cores and their relationship to *in situ* stress.
11:40 11. **A. Brown* and C.D. Kamineni:** *In situ* stress compared to structures at Lac du Bonnet batholith, Manitoba.

II. APPLICATIONS OF REMOTE SENSING AND GEOPHYSICS

Chairperson: V.H. Singhroy

14:00 1. **V. Singhroy* and F. Kenny:** Guidelines for the selection and use of remote sensing data in neotectonic studies over drift-covered terrains.
14:20 2. **P.D. Lowman Jr.:** Lineaments on the Canadian Shield: studies with Landsat and side-looking radar.
14:40 3. **J.B. Parrish:** The seismicity of Ohio and its relationship to potential field and remote sensing lineaments.
15:00 4. **J.E. Jones* and H.A. Pohn:** Appalachian neotectonic studies by the U.S. Geological Survey using airborne radar.
15:20 5. **R.L. Thomas*, K. McMillan, D.L. Keyes and A.A. Mohajer:** Surface sedimentary signatures of neotectonism as determined by side scan sonar in western Lake Ontario.
15:40 BREAK

III. GEOLOGICALLY YOUNG DEFORMATION

Chairperson: J.Y. Chagnon

16:20 6. **J.Y. Chagnon*, M. LaRoche et J. Locat:** Une structure majeure résultant de la liquéfaction dans la région de Charlevoix, Québec, Canada.
16:40 7. **F.H. Swan:** Preliminary results of paleoseismic investigations along the Meers Valley Fault, southwestern Oklahoma.
17:00 8. **J. Shaw* and G.A. Gorrell:** Deformation structures in glacial sediments.
17:20 9. **B.E. Broster:** Glacigenic deformation structures in rock and sediment.
17:40 10. **G.H. McFall*, A. Allam and O.L. White:** Detailed investigations of neotectonic features in Prince Edward County, southern Ontario.

POSTER SESSION III

Room 407B

All posters will be on display from 09:00 until 17:30. Those presenting the posters will be present at least during the morning and afternoon breaks and during the first twenty minutes of the lunch break.

INTRAPLATE DEFORMATION, NEOTECTONICS, SEISMICITY AND THE STATE OF STRESS IN EASTERN NORTH AMERICA (POSTERS)

9. **W.J. Nelson* and R.A. Bauer:** Rock deformation in contemporary stress field, Illinois Basin, USA.
10. **J.K. Costain*, G.A. Bollinger and S.A. Setterquist:** Correlations between streamflow and intraplate seismicity in the central Virginia, U.S.A., seismic zone.
11. **N.H. Dawers* and L. Seeber:** Results of bedrock geologic investigations of two intraplate epicentral areas in New York State.
12. **P-D. Zhu* and J-C. Mareschal:** Tectonic implications of the seismicity in the Central Metasedimentary Belt of the Grenville Province.
13. **R. Quittmeyer:** Seismic source zone interpretation for northeastern US and southeastern Canada based on tectonic and seismic data.
14. **L.T. Long* and K-H. Zelt:** A local shallowing of the brittle-ductile transition can explain some intraplate seismic zones.
15. **G.H. McFall, O.L. White and J.R. Bowlby:** Indicators of contemporary stress regimes in southern Ontario.
16. **M. Lodin and K.B.S. Burke:** Remote sensing and geophysical evidence for neotectonic features in the epicentral region of the 1982 Miramichi earthquake, New Brunswick.
17. **T.R. Stokes and J.D. Keppie:** Neotectonic and paleoseismic phenomena along the north shore of the Minas Basin, Nova Scotia.
18. **M. Ouellet:** Holocene seismicity sedimentary indicators in Lake Matamek, Quebec North-Shore.
19. **M. Ouellet:** Possible neotectonism in seismic subbottom sedimentary profiles of Lake St. Jean, Quebec.
20. **R. Doig:** 2,500-year history of seismicity from silting events in Lac Tadoussac, Charlevoix area, Quebec.
21. **M.K. Séguin* and E. Blais:** 2-D space prediction of earthquakes: Charlevoix area, Quebec.
22. **M.P. Tuttle*, L. Seeber and R. Such:** Ground failure triggered by the November 25, 1988 Saguenay Earthquake.

INTRAPLATE DEFORMATION, NEOTECTONICS, SEISMICITY AND THE STATE OF STRESS IN EASTERN NORTH AMERICA I

INTRAPLATE SEISMICITY AND CRUSTAL STRESSES

SEISMICITY, EARTHQUAKE FOCAL MECHANISMS, AND CRUSTAL STRESSES IN THE GRENVILLE PROVINCE, AND THEIR RELATION TO THE SEISMOGENIC RIFT STRUCTURES OF SOUTHEASTERN CANADA

ADAMS, John Geophysics Division, Geological Survey of Canada, 1 Observatory Crescent, OTTAWA K1A 0Y3, CANADA.

Recent detailed studies of seismicity in three zones in southeastern Canada - Timiskaming, Charlevoix, and Lower St. Lawrence - have revealed that many earthquakes occur in small, tightly confined clusters. Focal mechanisms from these clusters (and from other scattered earthquakes across the region) show most earthquakes represent thrust or thrust/strike-slip faulting and that a NE- to ENE- directed regional stress field dominates, at least in the upper 10 km. The spatial distribution of earthquakes, and the strikes of the nodal planes deduced from the focal mechanisms suggest a causal relationship between the earthquakes and faults that broke the integrity of the North American craton and were active in the Silurian or more recently. In particular, Adams and Basham (1989) have shown that reactivation of the crustal-scale normal faults along the the ancient rifted margin of the Iapetus Ocean (now along the St. Lawrence river) and on a failed rift (Ottawa Graben) accounts for much of the seismicity occurring within the Grenville basement.

A second graben along the Saguenay Fiord was neglected in the above analysis because the level of contemporary seismicity was very low. In November 1988, the M_S 6 Saguenay Earthquake occurred on the south side of the Saguenay Graben and might have involved thrusting on a fault striking within 30° of the graben, or on a plane parallel to the rift faults under the St. Lawrence (90 km to the east). Retrospectively, it is obvious that the Saguenay Graben should have been included in the rift model to be used for seismic hazard estimates. However, one wonders how many other such features will be evident only after they experience a future large earthquake.

FIELD STUDIES OF THE M6.0 SAGUENAY, QUEBEC EARTHQUAKE OF NOVEMBER 25, 1988 AND ITS FORESHOCK AND AFTERSHOCKS

LAMONTAGNE, M., WETMILLER, R.J., MUNRO, P. Geophysics Division, Geological Survey of Canada, OTTAWA, Canada K1A 0Y3; ASUDEH, I. Lithospheric and Canadian Shield Division, Geological Survey of Canada, OTTAWA, Canada K1A 0Y3; DU BERGER, R. Universite du Quebec a Chicoutimi, Chicoutimi, Quebec G7H 2B1; SUCH, R., BUSBY, R., SEEBER, L. and ARMBRUSTER, J.G. Lamont-Doherty Geological Observatory, Palisades, New York 10964, USA.

Special seismic monitoring of the epicentral area of the November 25th Saguenay earthquake with portable recorders began on November 24 (one day after the foreshock and one day prior to the mainshock) and has continued to date (January 10) without interruption but with varying levels of effort and coverage through a cooperative effort by the authors' agencies. The mainshock was recorded by the 3 MEQ-800 'smoker' seismographs installed the previous day by the GSC within 10 km of the epicentre of the eventual start of the mainshock's rupture. Data from these recorders showed that there was no small magnitude activity ($M>1$) in the 24 hours preceeding the mainshock and, combined with data from permanent stations of the Canadian Seismograph Network (all beyond 90 km), allowed the hypocentre of the mainshock (23:46:04.50 UT, 48.117 N, 71.184 W, and 29 km depth) to be determined with confidence. In the 2 weeks following the mainshock, additional portable recorders were deployed at 23 different sites throughout the epicentral area. The instruments consisted of MEQ-800 single-component seismographs and PRS1 single-component continuously recording digital seismographs. Less than 60 aftershocks, M 0-4.1, were recorded by the field network in this period and approximately 40 could be well located. After December 10 the field network was reduced to 4 MEQ-800 seismographs and one new station, DAQ, of the Eastern Canada Telemetred Network, supplemented by an array of strong-motion accelerographs consisting of 5 SMA-1 1g or ½g photographic recorders and 3 SSA-1 digital recorders. To date no strong aftershocks have taken place and the smaller events have occurred only infrequently.

SEISMOTECTONIC ENVIRONMENT OF EASTERN AND NORTHERN CANADA EARTHQUAKES

H.S. Hasegawa, Geological Survey of Canada, Canada

Although analyses of the larger eastern and northern Canada earthquakes indicate some common features, the respective seismotectonic environment can be quite different. Most earthquakes in this intraplate (midplate) region occur in a predominantly thrust-fault environment, but there are exceptions. Along the northeast coast of Baffin Island, earthquakes are occurring in a normal-fault regime; the superposition of extensional stresses due to mountains, crust-mantle transition and postglacial rebound are able to neutralize the ambient compressive plate tectonic component. Along the northwest passive margin, one Beaufort Sea earthquake manifests deviatoric extensional stress normal to the margin whereas a Labrador Sea earthquake manifests compression normal to the margin. In the former case the spreading ridge (Nansen-Gakkel) stress is parallel to the margin whereas in the latter, perpendicular to the margin and is able to overcome extensional stresses in this direction due to local features. At the mouth of the Laurentian Channel one (1975) earthquake fits the usual double-couple interpretation but another (1929 Grand Banks) event, the only seismic event along the passive margins of Canada that is known to have generated a destructive tsunami, is best interpreted as a slump (single force) mechanism. In the Miramichi region of New Brunswick, an earthquake sequence that commenced in 1982 occurred along conjugate faults within an intrusion. Most of the larger earthquakes that have occurred on land in eastern Canada have epicentres along the St. Lawrence Valley and interconnecting graben systems. However, there are a few notable exceptions that are not fully understood.

SEISMOTECTONIC FRAMEWORK OF WESTERN QUEBEC

Mohajer, A.A., Seismican, 239 Dunview Ave., North York, Ontario, M2N 4J3; Kenny, F., and Singhroy, V., Ontario Centre for Remote Sensing, 90 Sheppard Ave. East, North York, Ontario, M2N 3A1.

Known seismic activity in eastern Canada has occurred in areas where no obvious or simple association with surface geological features can be established. Although reactivation of a Paleozoic rift fault system along the Ottawa and St. Lawrence Rivers has been suggested in recent years, there are many other events which cannot simply be linked to geologically known seismic sources. Typical examples are the western Quebec, apparently dispersed activity, and the recent Chicoutimi earthquake of 25 November 1988.

In an attempt to further improve the location of recomputed hypocentres, original seismographic records of events which occurred prior to 1960 were examined in the National Archive Centre of Canada. 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 locations of the older events are related to biases in the geometrical spread of the seismographic stations and the time base corrections. Consistency in phase identification has some bearing on data improvement, but is usually masked by other sources of error in hypocentre computations.

A detailed study of the recomputed locations of the earthquakes in western Quebec, together with lineaments identified from Thematic Mapper multispectral satellite images and geological maps, revealed several active linear features in this region. Two conspicuous NW and NE seismic linears coincide, respectively, with the Baskatong Reservoir structural lineament and the western boundary of the Central Metasedimentary Belt.

THE SEISMICITY OF MICHIGAN: EARTHQUAKES, EXPLOSIONS AND OTHER PHENOMENA

Fujita, Kazuya, Department of Geological Sciences, Michigan State University, East Lansing, Michigan, 48824, and Sleep, Norman H., Department of Geophysics, Stanford University, Stanford, California, 94305.

Although nearly 60 seismic events have been reported as occurring within the state of Michigan, examination of historical newspaper records indicate that the large majority of these events are not tectonic earthquakes. Most events in the western upper peninsula are related to mining associated with copper deposits which align along the Keweenaw fault; even the largest events have a very small felt area indicative of a near surface focus. In the rest of the state, at least three events are atmospheric shock waves, one is an explosion, many are cryoseisms, and several are misattributions of events occurring elsewhere. The 1872 event reported from Wenona is confirmed to have been at Bay City, but was smaller than reported and may have been a cryoseism. Some of the events in the Detroit area are also smaller than have been reported. The 1876 events in Adrian and Detroit are erroneous; they occurred near Monroe and were probably related to blasting. The 1938 Amherstburg events remain difficult to explain. While they resulted in explosive noises and the rattling of windows, at least one of them was instrumentally recorded and no explosions or mine collapses can be identified. Definite tectonic earthquakes have occurred in Coldwater (1947), near Kalamazoo (1982), and in western Lake Erie (1976 and 1980). From a tectonic viewpoint, Michigan is thus considerably less seismic than indicated in earthquake catalogues.

INTRAPLATE SEISMICITY AND STRESS IN THE SOUTHEASTERN UNITED STATES

Mareschal, Jean-Claude, Dept des Sciences de la Terre and GEOTOP, Université du Québec à Montréal, Box 8888 sta A, Montréal, QC H3C3P8.
Long, L.T., and Kuang, Jian, School of Geophysical Sciences, Georgia Tech, Atlanta, GA 30332, USA.

The stress induced by the topography and the density heterogeneities in the lithosphere was computed for two seismically active regions in the southeastern United States: the southern Appalachians and the South Carolina Coastal Plain (Charleston region). The stress was calculated with the assumption that: (1) the lithosphere behaves as a layered elastic slab overlying an inviscid fluid, and (2) the loads are concentrated at the surface or on horizontal planes within the lithosphere. The density distribution was constrained by gravity and seismic refraction data, or was directly determined by downward continuation of the gravity field. The calculations indicate that the local stress is of the same order as the tectonic stress (10-100MPa). The comparison between principal stress differences, principal stress orientations, and the distribution and focal mechanisms of the earthquakes suggest contradictory conclusions. In the southern Appalachians, the seismicity correlates well with the maximum stress difference and the observed focal mechanisms agree with the focal mechanisms suggested by the principal stress direction. In the South Carolina Coastal Plain, the superposition of regional and local stress could perhaps explain the pattern of focal mechanisms but does not predict any stress concentration near Charleston. Other factors must thus be invoked to explain the Charleston seismicity.

THE INTERSECTION MODEL FOR INTRAPLATE EARTHQUAKES

Talwani, Pradeep, and Rajendran, Kusala, Department of Geological Sciences, University of South Carolina, Columbia, SC 29208

The tectonic cause of intraplate earthquakes has remained enigmatic. As newer geophysical and seismological data became available, several common features were apparent for intraplate earthquakes occurring in a wide variety of geologic terranes. These have been incorporated in the intersection model: Seismicity occurs near the intersection of, and by the reactivation of, preexisting zones of weakness. The intersections are the foci of anomalous stress buildup in response to the ambient stress field due to plate tectonic and other superimposed local forces. This anomalous stress buildup is relieved by strike slip motion (in most cases) on a suitably oriented faults and by kinematic adjustment by horizontal or vertical movement on the intersecting fault. For a wide variety of cases the main fault was found to be oriented at about 20 - 45° to S_{Hmax} and the angle between the faults ranged between 90° and 120°. The intersections were also found to be associated with increased microearthquake activity in some cases. No systematic correlation was found between the fault dimensions and the maximum magnitude of the earthquakes.

LUMINOUS PHENOMENA IN RELATION TO THE NOVEMBER EARTHQUAKES OF THE SAGUENAY REGION, QUEBEC.

Ouellet, M.,INRS-Eau (Univ. du Québec), Sainte-Foy, Québec, G1V 4C7

Although the association of luminous phenomena with the 1663 New France earthquakes was a fortuitous world premier description, no canadian researcher has yet dared to really look at this "grey" literature which is probably the darkest area of our national seismology. Some scientists have recently contributed to the shifting of the investigations of earthquake lights into the laboratory where it is now progressing rapidly. During the days following the earthquakes of the 23rd and 25th of November, I received over 30 reports relative to luminous phenomena which were mostly observed within the Lake-Saint-Jean-Saguenay-Region. Sightings came as far as Ungava and Pennsylvania (USGS, Denver). A certain extra number of reports originated from the Québec City Region. The temporal span of the sightings began as early as the 31st of October, a few Km from the focuses, to the 24 of December. The great majority of the luminous phenomena was observed between the 21st and the 26 of November with distinctive peaks the day of the two major shocks. Witnesses of various ages and occupations gave descriptions that were also quite heterogeneous. Some sightings were described as fire balls rapidly coming out of the ground a few m. to km. from the observers, some were stationary or moving vertically or horizontally in the sky, others illuminated the whole horizon for up to an hour. According to recent studies these lights appear to be associated with tectonic strain in active seismic areas and tend to accompany increases in earthquakes. More formal works should be carried in Canada on these phenomena in order to tentatively establish their earthquake predictive potential.

GEOLOGY OF AN INTRAPLATE EARTHQUAKE SWARM: ENOLA, ARKANSAS, 1982

VanArsdale, Roy B., Department of Geology, University of Arkansas, Fayetteville, AR., and Schweig, Eugene S., Center for Earthquake Research and Information, Memphis State University, Memphis, TN.

The 1982 Enola earthquake swarm was centered approximately 3 km southwest of the town of Enola, Arkansas, in the eastern portion of the Arkoma Basin. This is the largest earthquake swarm ever recorded in the central or eastern United States and occurred in a stable intraplate setting previously considered aseismic.

The epicentral area overlies an anticline in the Pennsylvanian Atoka section that appears to have formed by reactivation and uplift of a deep Paleozoic graben. Hypocenter depths range from 4 to 7 km, which corresponds stratigraphically to the Cambrian-Ordovician strata and Precambrian basement granite. Seismic reflection data reveal a steep, north-dipping fault striking east-northeast and discontinuous reflectors within the hypocentral zone. Immediately to the north is a parallel fault that dips steeply southward. Between the faults is a graben approximately 1.6 km wide with 150 m of normal displacement.

A third order level survey of the elevation difference between a benchmark on the anticline near the center of the epicentral area and one on the perimeter of the epicentral area revealed 14.3 cm of relative uplift of the benchmark on the anticline since 1961. We believe that the Enola earthquake swarm is due to movement on the Enola fault and perhaps renewed uplift of the deep Paleozoic graben.

LABORATORY ANALYSIS OF MOODUS, CT AND KENT CLIFFS, NY CORES AND THE RELATIONSHIP TO IN SITU STRESS

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Core samples from two boreholes in the northeastern U.S. (Kent Cliffs, NY and Moodus, CT) were examined as part of comprehensive crustal stress studies. Measurements of linear strain and ultrasonic velocity were made on the two core suites as a function of confining pressure. Both the compressibility and velocity properties are dominated by a microcrack porosity which increases with increasing initial sample depth. These cracks close at low pressures (less than 60 MPa) and are interpreted as forming on relief of in situ stresses by drilling. The apparent increase in porosity with depth reflects the increasing magnitude of mean stresses relieved. Both the microcrack porosities and closure pressures reflect qualitatively the mean stresses in the boreholes, though gneissic foliations in both suites influenced the crack orientations. Cores recovered from fractured zones in both holes show low crack porosity, reflecting local relief of deviatoric stresses in situ. Direct comparison with sonic logs is difficult, as the cracks controlling the core properties are not pervasive in situ. Above crack closure pressures, the core velocities are essentially equivalent to those found in the logs. Three main implications of this study are as follows. First, the laboratory properties of core specimens reflect qualitatively the in situ stress regime, through the effects of stress relief. Second, these effects must be accounted for before laboratory measurements of core properties can be used to interpret in situ measurements. And finally, stress relief occurs not only in core samples but also at the borehole wall. Thus, the properties of the rock near the cavity may be significantly different from those at a distance, and the interaction of stress relief cracks with the stress field at the borehole wall may be a factor in the formation of wellbore breakouts.

IN SITU STRESS COMPARED TO STRUCTURES AT LAC DU BONNET BATHOLITH, MANITOBA

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Assessment of the present-day in situ stress field orientations at Lac du Bonnet Batholith, Manitoba, both at surface and underground, are compared to the interpretation of the stress field orientation history up to the present day from structural mapping. Stress field data from local quarrying, surface pop-ups, borehole hydraulic fracturing, and overcoring techniques both at surface and underground have been used. Mapped structural elements are large- and small-scale foliations, dykes and large- and small-scale fracturing, including faulting with repeated movement and dated infillings.

Recovery on overcores is, in part, related to the granite fabric, as some hydraulic fractures. Some modern movement appears to be related to the in situ stress field but initiated by glacial rebound or the topographic relief.

INTRAPLATE DEFORMATION, NEOTECTONICS, SEISMICITY AND THE STATE OF STRESS IN EASTERN NORTH AMERICA II

II. APPLICATIONS OF REMOTE SENSING AND GEOPHYSICS

GUIDELINES FOR THE SELECTION AND USE OF REMOTE SENSING DATA IN NEOTECTONIC STUDIES OVER DRIFT-COVERED TERRAINS

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On the basis of recent studies carried out by the Ontario Centre for Remote Sensing for the Multi-Agency Group for Neotectonics in Eastern Canada (MAGNEC), guidelines are proposed for the selection and use of remote sensing imagery in the mapping of lineaments in drift-covered terrains.

Lineaments were mapped in the thin drift covered areas of the western Grenville province and in areas of variable drift which cover the low-lying Paleozoic rocks of eastern and southern Ontario.

Enhanced LANDSAT Thematic Mapper (TM) and multispectral scanner (MSS) imagery, SEASAT synthetic aperture radar (SAR) imagery and Shuttle Imaging Radar (SIR-B) imagery were used to produce a regional compilation of lineaments mapped at scales of 1:250,000 and 1:100,000. A SPOT image and airborne C and X-band radar imagery were used to trace lineaments at a scale of 1:50,000. Airborne thermal imagery and colour infrared and black and white aerial photography, recorded in early spring, provided adequate resolution for lineament mapping at a scale of 1:10,000. Colour infrared spring photography was taken at a scale of 1:2,000 for identifying joints in areas of thin drift.

LINEAMENTS ON THE CANADIAN SHIELD: STUDIES WITH LANDSAT AND SIDE-LOOKING RADAR

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This paper reports photogeologic mapping of lineaments on the Shield as a whole using 60 Landsat images, in the southern Slave Province using Seasat data, and north of the Subury Basin using airborne radar imagery. "Lineaments" are defined according to O'leary et al. (1976); broad composite regional features such as the Jemez Lineament are excluded. For the Shield collectively, the following conclusions have been reached: (1) The majority of mapped lineaments are extensional fractures or diabase dykes following and parallel to such fractures, (2) Azimuthal lineament maxima in the Bear, Slave, Churchill, and Superior Provinces can be identified with mapped dyke swarms; one maximum in the SW Grenville Province parallels dykes following the Ottawa-Bonnechere Graben, (3) Dyke-parallel lineaments, with radio-metric dates ranging from 2600 to 575 Ma, express regional uplift and extension related to mantle plumes, with the exception of those in the SW Grenville Province, (4) No one tectonic mechanism can account for all the fracture directions, which do not form the the continent-wide simple system implied by the regmatic shear theory. Local studies in the Yellowknife area of the Slave Province indicate that many lineaments are conjugate shears related to the Proterozoic tectonism of the Wopmay Orogen, some of which have localized Aphebian or Helikian dykes. In contrast, lineaments north of the Sudbury Basin show no such relationships, tending to rule out tectonic deformation as the cause of the elliptical outline of the North Range. In summary, remote sensing data have been found to be extremely valuable in understanding the distribution and origin of lineaments on the Shield.

THE SEISMICITY OF OHIO AND ITS RELATIONSHIP TO POTENTIAL FIELD AND REMOTE SENSING LINEAMENTS

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A total of 117 earthquakes which occurred from 1776 to 1988 were located on a base map of Ohio. The region of greatest concentration is Anna, Ohio. A secondary high is located near Cleveland, Ohio. The recurrence rate of earthquakes is discussed for the entire state of Ohio and for selected locations of high frequency.

The historic seismic data are compared with LANDSAT lineaments, oil field lineaments, and gravity and magnetic features. An interpretation was made of digitally processed shaded relief images (with intensity shown as color) of both magnetic and gravity data for the region. Previous workers have noted a relationship between mapped locations of epicenters and lineaments from potential field data, suggesting basement control of faulting.

Interpretation of LANDSAT, MSS and TM imagery show that potential field and satellite image-derived lineaments have similar azimuths and locations. Structural lineaments defining producing oil fields in the entire state of Ohio are coincident with known epicenters, suggesting that the lineaments are probably faults.

APPALACHIAN NEOTECTONIC STUDIES BY THE U.S. GEOLOGICAL SURVEY USING AIRBORNE RADAR

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Since 1980 the U.S. Geological Survey has conducted a Side-Looking Airborne Radar (SLAR) program that has acquired data of more than one-third of the United States in support of research and applications studies. This presentation describes three of the Geological Survey's ongoing combined field and SLAR studies in the Appalachians that have neotectonic applications.

In one study, fold wavelength and frequency changes in the central and southern Appalachians have been identified that indicate the presence of lateral ramps in the subsurface. Neotectonic activity in this region is supported by the fact that more than 50 percent of the historical seismicity occurs coincidental with lateral ramps.

In another study, giant landslides have been identified where blocks as great as a billion cubic meters have broken away from ridgetops and slid downslope by either catastrophic event or by slower creep. Although the age of these landslides is still uncertain, the process is apparently still active as indicated by the fact that rockslides are found in a continuum of failure stages, and in the spring of 1985, a landslide buried part of a major highway in central Virginia. These landslides have occurred either on or between closely spaced pairs of lateral ramps.

Another ongoing effort is a multifrequency\look SLAR study of faults, fracture patterns, and other geological structures of test sites in northern New York and Prince Edward County, Ontario, which is being coordinated with the Multi-Agency Group for Neotectonics in Eastern Canada.

SURFACE SEDIMENTARY SIGNATURES OF NEOTECTONISM AS DETERMINED BY SIDE SCAN SONAR IN WESTERN LAKE ONTARIO

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A number of previously undescribed surface sedimentary features were observed during side scan sonar surveys in western Lake Ontario. The first area, approximately 6 kilometers south of Toronto Island, revealed a large number of linear features oriented approximately NNE-SSW with a second set predominantly NW-SE resulting in intercepts, offsets and a number of triple junction type features. The structures were up to 15 meters in width, elevated up to 2 meters above the local substrate and extending, in some instances, over 1 kilometer in length. The features occurred in a glacio-lacustrine clay substrate and are interpreted as being a response to pop-up stress structures in the underlying bedrock. The second survey area was located 6 kilometers to the south of Bronte. This area revealed the occurrence of delicate plumose structures etched into the surface of the recent silty clay sediment of the area. In addition dark linear features appeared on the side scan records comprising continuous dark traces and alignments of individual dark spots. All these features were aligned predominantly WSW-ENE and extended to maximum lengths of close to 3 kilometers. Individual dark spots similar to gas seeps were also observed in this area. The plumose features are believed to be due to minor surface subsidence responding to stress release below the modern sediment. The dark linear features could be due either to sonar response to dewatering of sediment or more likely to intrusion of coarse sediment into the surface silty clays. The two areas fall in an alignment conforming to those revealed by aeromagnetic surveys.

III. GEOLOGICALLY YOUNG DEFORMATION

UNE STRUCTURE MAJEURE RESULTANT DE LA LIQUEFACTION DANS LA REGION DE CHARLEVOIX, QUEBEC, CANADA

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Une étude de la vallée de la rivière Du Gouffre, au nord de Baie St-Paul, en vue d'identifier dans les dépôts meubles des structures de déformation résultant de l'activité sismique, a permis de découvrir divers types de telles structures. Certaines, comme les dykes et les volcans de sable, ont déjà été décrites par les auteurs.

A environ 10 km au nord de Baie St-Paul, là où la vallée devient étroite, une structure circulaire d'un diamètre de 300 mètres est observée sur la rive sud de la rivière. Elle n'est pas très évidente sur le terrain à cause de son faible relief, de l'ordre de 3 à 4 mètres, mais elle se distingue facilement sur photographie aérienne à cause des contrastes de tonalité entre les dépressions humides concentriques alternant avec des crêtes de sable sec. A cet endroit le terrain n'est pas en culture et est couvert de broussailles. Environ 15 volcans de sable sont localisés sur la bordure nord de cette structure auquelle ils sont probablement reliés.

Une étude détaillée du site, réalisée en 1988 et comprenant une cartographie de terrain, des levés de sismique-réflexion et de sismique-réfraction selon une coupe perpendiculaire à la vallée et passant par la structure, des forages avec échantillonnage et des mesures au piézocône, indique que les déformations visibles en surface résultent de la liquéfaction d'une couche de sable saturé en profondeur, probablement lors d'un séisme.

PRELIMINARY RESULTS OF PALEOSEISMIC INVESTIGATIONS ALONG THE MEERS VALLEY FAULT, SOUTHWESTERN OKLAHOMA

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The Meers Valley fault is part of the northwest-trending Wichita frontal fault system. Southwest-facing fault scarps indicative of late Quaternary faulting extend along a 26-km segment of the fault. Lineaments along the southeastern projection of this trace suggest the total length of late Quaternary faulting could be as much as 36 km. It is one of the few faults in the United States east of the Rocky Mountains that has been identified as having had tectonic displacement during the late Quaternary. Southwestern Oklahoma has had very little historical earthquake activity and there is no seismicity associated with the fault.

Detailed geologic mapping and trenching at three sites along the northwestern part of the active trace indicate left-lateral oblique slip(down-to-the-southwest) on a steeply northeast-dipping to nearly vertical fault with about a 3:1 ratio of lateral to vertical displacement. About half of the cumulative vertical displacement of a Holocene valley fill (3.5 ± 0.2m) is due to warping in a zone extending about 20 m on both sides of the fault. Evidence for two late Holocene surface faulting events was identified at all three sites. Preliminary radiocarbon dates on twelve samples from two of the sites suggest that both events occurred within about the past 2,000 years. A third earlier Holocene or latest Pleistocene event was identified at one site. At each of the three sites, the average net slip per event (measured in the plane of the fault) ranged between 0.9 m and 3.1 m. These displacement values do not include deformation due to warping adjacent to the fault. Clearly, there have been repeated late Holocene surface-faulting events on the Meers Valley fault. It is reasonable to infer that these events were associated with moderate- to large-magnitude earthquakes.

DEFORMATION STRUCTURES IN GLACIAL SEDIMENTS

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Deformation structures in glacial sediments may result from a variety of causes: underconsolidation related to high rates of deposition, thaw consolidation in melt-out tills, diapirism related to glacial overburden, directly applied glacial shear stresses, melting of buried or supporting ice, post-depositional slumping in areas of fluvial or wave-cut cliff erosion and neotectonic seismic shocks. The actual deformation structures resulting from these various processes may look identical or very similar and it is only through careful consideration of the sedimentary context of the deformation structures and their geomorphic associations that the probable cause can be established. Examples are given of deformation structures identified by this sedimentological and geomorphological approach. By use of such techniques, the likelihood of erroneous conclusions regarding earthquakes and neotectonics may be reduced, and attention may be focussed on seismically significant structures.

GLACIGENIC DEFORMATION STRUCTURES IN ROCK AND SEDIMENT

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The study of deformation structures increases in complexity in glaciated areas. Studies have shown that glacitectonic structures are produced in underlying materials as a consequence of stress, applied or relaxed, during glacial activity. This may be as a result of direct load (vertical or horizontal), push or thrusting at the ice margin, shear at the ice-substrate interface, basal freezing and/or incorporation, injection into underlying materials, or altered pore pressures in adjacent materials. Similar but distinct "static glacigenic structures" can form by penecontemporaneous deformation accompanying sediment loading, or loss of support to the sediment pile from melting of underlying or adjacent ice. The formation and structural orientation of glacitectonic structures are commonly found to be correlative with early glacial advance into an area. The structures produced are often the product of an interrelationship of several factors, including; glacial dynamics, engineering properties of the glacial bed material, subglacial relief, and the variation between compressive and extending flow. Variations in style and structure can usually be attributed to changes in these factors. Conversely, the formation and structural orientation of static glacigenic structures are commonly found to be related to glacial retreat, particularly direction and rate of ice decay, climatic conditions and stability, orientation, slope and other conditions related to the environment of deposition.

Structures produced by these processes include faults, joints, folds, boudinage, clastic dikes and sills (simple fracture fillings and injections), diapirs, load and slump structures, and rafted portions of underlying materials. Sediments are sometimes found that display contrasting styles of deformation involving liquifaction, as well as brittle and ductile deformation. Bedrock is commonly found with brittle fracture, décollements and injection wedges. In the above, a glacigenic origin was deduced on the basis of; structural orientations consistent with glacial history, infillings of glacially-derived sediment and an association with adjacent glacial deposits. However, problems arise when structures are produced by tectonic activity that itself is glacigenic (i.e. postglacial rebound, reactivation of residual stress) or when glacial movement has been controlled by tectonically-active landforms

DETAILED INVESTIGATIONS OF NEOTECTONIC FEATURES IN PRINCE EDWARD COUNTY, SOUTHERN ONTARIO.

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Detailed investigations of possible neotectonic features in Prince Edward County, southern Ontario, are being conducted by the Ontario Geological Survey as part of an ongoing series of integrated geological and geophysical studies by the Multi-Agency Group for Neotectonics in Eastern Canada.

Activities conducted in the study area include: ground identification of unusual patterns and lineaments identified on false-colour infra-red air photographs, field examination of bedrock exposures, a limited drilling programme, and geophysical surveys.

The regional structural setting includes a northeasterly trending lineament that joins the Clarendon-Linden fault of northern New York State to the Salmon River fault and possibly the Picton fault systems of Ontario.

Examination of the bedrock exposures yeilded a variety of bedrock structural features. These include: joints, faults, open crevaces, buckles and pop-ups. Many of these bedrock structures are obscured by surficial deposits. Geophysical investigations using refraction seismic and resistivity exploration techniques were conducted on a number of structures.

Preliminary investigations indicate that the geological processes have produced a complex interrelationship of bedrock structures and Quaternary deposits. The structural features described above are the result of rejuvenation and modification of older zones of weakness by glacial, post-glacial and ongoing geological processes.

INTRAPLATE DEFORMATION, NEOTECTONICS, SEISMICITY AND THE STATE OF STRESS IN EASTERN NORTH AMERICA (POSTERS)

ROCK DEFORMATION IN CONTEMPORARY STRESS FIELD, ILLINOIS BASIN, USA

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Small thrust faults, a strike-slip fault, jointing, and compressive failure of coal mine roof rocks in the Illinois Basin (Illinois, SW Indiana, and W Kentucky) are interpreted to be the result of regional contemporary tectonic stress. Evidence indicates that these features developed between the Late Cretaceous, when the present tectonic stress regime was established, and the Quaternary. The stress regime in the Illinois Basin is consistent with that reported by other workers in most of eastern North America and is attributed to forces related to continental plate movement. To date none of the features have been found to disturb Quaternary deposits (absent where thrust faults have been found).

Orientation of stress is known from overcoring/undercoring studies, borehole breakouts, hydrofracturing, and earthquake focal-plane solutions. The major principal stress is E-W to N. 60° E., and up to 3 times the minor principal stress, which is vertical. Numerous N-trending thrust faults, having a few centimeters to 3 meters of net slip, displace coal-bearing rocks in the southern part of the basin. Also, a left-lateral fault at least 5 kilometers long, mapped in a coal mine in central Illinois, is consistent with this stress field. Unlike pre-Cretaceous faults in the region, these faults lack mineral fillings. Joints in mine roofs dominantly trend parallel to major principal stress. In some cases joints widen after mining. Post-mining compressive "kink zones" (small-scale thrust faults and crushing in the roof) develop normal to major principal stress in entries which are normal to the stress. Their effect on ground stability is severe enough that several operators have re-oriented their mine headings.

CORRELATIONS BETWEEN STREAMFLOW AND INTRAPLATE SEISMICITY IN THE CENTRAL VIRGINIA, U.S.A., SEISMIC ZONE

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In the Hydroseismicity hypothesis, long-period changes in rainfall play an important role in the generation of intraplate seismicity by diffusion of pore pressure transients from recharge areas of groundwater basins to depths as deep as the brittle-ductile transition. The basis for the hypothesis is a spatial correlation in the southeastern U. S. between 1) seismogenic crustal volumes, 2) large gravity-driven groundwater basins that can provide an adequate supply of water to the upper- and mid-crust, and 3) a fractured and permeable crust that is stressed close to failure. Streamflow, $f(t)$, and earthquake strain, $s(t)$, for a 60-year sample from 1925-1985 in the central Virginia seismic zone were cumulated, and a least-squares straight-line fit was subtracted to obtain residuals. From spectral analyses, we observed common cyclicities with periods of 10-20 years between residual streamflow, $F(t)$, and residual strain, $S(t)$. Solving the 1-dimensional diffusion equation, $\partial^2 h/\partial\psi^2 = 1/D\,\partial h/\partial t$, where h is hydraulic head and D is hydraulic diffusivity, we determined the impulse responses at depths, ψ, in a diffusive crust caused by an impulsive change in fluid pressure in the surface recharge area of a groundwater basin. These impulse responses, $h(\psi,t)$, were then convolved with streamflow residuals, $F(t)$, and, because of results from reservoir-induced seismicity, derivatives of streamflow residuals, $F'(t)$. Root-mean-square values of the convolutions, $h(\psi,t)*f(t)$, were computed for $\psi = 5, 10, 15,$ and 20 km. For central Virginia, the number of earthquakes, N, over a depth interval, $\Delta\psi$, that straddles a depth, ψ, is approximately proportional to the rms value of $h(\psi,t)*f(t)$ over $\Delta\psi$, suggesting that the number of intraplate earthquakes per km of crust is proportional to the rms changes in fluid pore pressure over that depth interval. That is, the larger the fluctuations in pore pressure over a crustal interval, the greater is the number of earthquakes over that interval. In addition, group delay analyses, and crosscorrelation of $h(\psi,t)*F'(t)$ with $S(t)$, and $h(\psi,t)*F(t)$ with $S(t)$, lead to lag times (6 to 12 months) for pore pressure diffusion and correlation maxima that are consistent with crustal diffusivity values of $D = 5 - 200$ km^2 year ($0.2 - 6$ m^2/ sec). These values are in the range of those expected for the crust above the brittle-ductile transition.

RESULTS OF BEDROCK GEOLOGIC INVESTIGATIONS OF TWO INTRAPLATE EPICENTRAL AREAS IN NEW YORK STATE

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We have conducted bedrock geologic studies of the 1983 Goodnow and the 1985 Ardsley epicentral areas, both are in seismically active areas of New York state. Since the orientation and the approximate size of rupture are known from detailed aftershock studies of each event, these areas offer unique opportunities to compare bedrock fracture characteristics to intraplate earthquake data.

The Ms=5.1 Goodnow event, in the central Adirondack Mountains, was a reverse fault rupture striking NNW and dipping steeply W. The surface extrapolation of the ~7.5km deep event coincides with a 12-15km long NNW-trending topographic lineament. Mapping along the lineament shows that it is fracture-controlled and, near the 1983 epicenters, slickensided fractures are present that are subparallel and orthogonal to the lineament. Also present in outcrops near the 1983 epicenters are anomalous microfractures that are remarkably similar to microstructures of the 1982 Miramichi, NB epicentral area, which have been proposed by Mawer and Williams (*Geology*, 1985) to be indicative of paleoseismicity. However, no evidence of a *major* fault was found.

The Mb=4.0 Ardsley event in southeastern New York, in the Manhattan Prong, was a left-lateral rupture of a WNW-trending vertical fault. The ~5km rupture was subparallel to and along strike from the NW-trending Dobbs Ferry fracture zone (DFFZ), which had been previously recognized (Hall, in press). Mapping shows that the DFFZ continues through the epicentral area and is defined by (1) NW-trending valleys and (2) concentrations of slickensided joints and discontinuous faults. Left-lateral faults strike NW parallel to the overall trend of the DFFZ. WNW-trending slickensided joints form *en echelon* patterns along the DFFZ, and E-W trending fractures often show right-lateral offset.

In both cases, brittle structures exposed in surface outcrops can be related to the earthquake ruptures, however, lithologic units do not appear to be substantially offset across these structures. The correlation between the rupture plane of each event with a dominant fracture (joint) set is consistent with outcrop scale field studies and laboratory experiments of fault zone formation in crystalline rocks.

TECTONIC IMPLICATIONS OF THE SEISMICITY IN THE CENTRAL METASEDIMENTARY BELT OF THE GRENVILLE PROVINCE.

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The distribution of seismicity was summarized for the earthquakes that occured in Western Québec and vicinity (45°N-48°N and 73°W-79°W) between 1 January 1970 and 1 July 1986. The study shows that most earthquakes in this region occur in the basement within the central metasedimentary belt (CMB); this region is characterized by a complex Bouguer gravity anomaly. The maximum P to S wave amplitude ratio can be used to determine source parameters with an accuracy better than 10° for the dip and strike and 20° for the slip, provided that data are available from at least four stations with adequate azimuthal coverage. Focal mechanisms from 32 microearthquakes ($M < 3.2$) indicate a dominantly compressive state of stress in this region. The orientation of the axis of maximum horizontal stress varies considerably within the CMB but it corresponds to the direction of maximum gradient of the gravity anomaly. This correlation could indicate that the pattern of seismicity is affected by small scale density heterogeneities within the lithosphere beneath the CMB.

SEISMIC SOURCE ZONE INTERPRETATION FOR NORTHEASTERN US AND SOUTHEASTERN CANADA BASED ON TECTONIC AND SEISMIC DATA

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As part of a seismic hazard study sponsored by the Electric Power Research Institute, source zones were defined for the northeastern United States and southeastern Canada. Geologic, tectonic and geophysical data formed the primary basis for most zones. The resulting source zone framework is designed to represent the occurrence of earthquakes of magnitude 5 and greater. Each zone has an associated probability of activity that is assessed from its spatial association with historical seismicity, its orientation in the tectonic stress field, and its expression in the deeper crust. This last criterion attempts to give more significance to well-developed features that extend through a larger portion of the crust than to shallow, superficial features. Taking a fairly skeptical view of our current ability to identify active features, we derive probabilities of activity that are generally less than 0.50. In some areas, "none of the above" zones are defined to represent a belief that earthquakes will occur, but for which the tectonic basis has not yet been identified or understood. Background zones are also defined because our current understanding of the cause of intraplate earthquakes is insufficient to rule out completely the occurrence of significant earthquakes at any site. The source zone interpreation can be used along with estimates of seismicity parameters and ground motion/attenuation relations to estimate probabilistically the seismic hazard at any given site.

A LOCAL SHALLOWING OF THE BRITTLE-DUCTILE TRANSITION CAN EXPLAIN SOME INTRAPLATE SEISMIC ZONES

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A local decrease in the strength of the crust, which would accompany a shallowing of the brittle-ductile transition, could concentrate crustal deformation through viscous or dislocation creep in response to existing regional plate stress. Two-dimensional finite element models, which include a regional plate stress and various shapes of a local decrease in crustal strength, show concentrations of stress at the brittle-ductile transition surrounding the local decrease in strength. The deformation and stress of the model suggest that strike slip faulting should dominate in the central local area of decrease in crustal strength. Outside the central area, the deformation of the crust in the vicinity of the brittle-ductile transition predicts that the dominant strike slip faulting should exhibit components of normal and reverse faulting, and that these components should be more pronounced above the brittle-ductile transition. In southeastern Tennessee the seismicity is diffused over a narrow elliptical zone trending northeast with the greatest concentration of activity near the center. Focal mechanism solutions (43 in total) agree with the predictions of the finite element model within the confidence levels of the solutions. The central zone is characterized by deep strike slip focal mechanisms and events surrounding the central zone exhibit higher proportions of reverse or normal fault movements.

INDICATORS OF CONTEMPORY STRESS REGIMES IN SOUTHERN ONTARIO

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Many evidences of high, horizontal in situ stresses have been observed in various rock formations in southern Ontario. Pop-ups and offset boreholes are indicators of anisotropic stress relief. High, horizontally-directed compressive stresses cause pop-ups to form naturally by rock failure, probably along pre-existing, sub-vertical planes of weakness. These failures result in chevron or antiform configurations which appear as positive, linear structures at the rock surface and may disrupt any overlying soils. Bedding slip dislocations of borehole walls also provide evidence for rock movements.

Man-made excavations such as quarries, roadcuts and tunnels, may locally disturb regional stress conditions, resulting in "rock-squeeze phenomena". Floor buckles are a stress relief response similar to the formation of pop-ups. At one roadcut location, pre-split boreholes drilled for construction in 1984 now exhibit offsets on thin shale beds, predominantly parallel to the roadway and in an updip sense. A natural analogue for the quarry floor process is erosion by and ablation of a glacial ice sheet. A stress regime within a rock mass may also be perturbed by other natural occurrences such as seismic events.

The locations, orientations and scales of these geological features provide direct indications of the directions of the causitive rock stress regimes for both regional and locally anomalous conditions. Collectively, such features may indicate areas where larger-scale crustal instabilities could possibly occur and may thereby contribute to geological hazard assessment.

The observations included in this poster presentation have been contributed by members of the Multi-Agency Group for Neotectonics in Eastern Canada (MAGNEC).

REMOTE SENSING AND GEOPHYSICAL EVIDENCE FOR NEOTECTONIC FEATURES IN THE EPICENTRAL REGION OF THE 1982 MIRAMICHI EARTHQUAKE, NEW BRUNSWICK.

Michal Lodin, Geodat Information Services Ltd., 301 Woodstock Road, Fredericton, N.B., E3B 2H9 and Kenneth B.S. Burke, Department of Geology, University of New Brunswick, Fredericton, N.B., E3B 5A3.

Digital processing of satellite and airbourne imagery, complemented by digitized geophysical, topographical and geological data, has defined patterns possibly related to neotectonic features in the epicentral region of the 1982 Miramichi earthquake in central New Brunswick. Detailed lineament analysis of NOAA AVHRR, LANDSAT MSS, LANDSAT TM and airbourne MSS imagery revealed a regional lineament close to the epicentre of the main 1982 event (NOAA data) and five generally north-south trending linements in the region of aftershock activity (LANDSAT data). The most dominant, NNW trending lineament is also evident on a regional scale. Ground VLF surveys showed conductors to be present over three of the lineaments. The trace of a previously mapped WNW-ESE trending shear zone was also extended by the analysis.

Hypocentres obtained in a 1985 microearthquake survey were plotted on a series of east-west cross sections and various interpolation algorithms were used to estimate a best fitting 'fault plane.' Good correlation between the surface position of this 'fault plane' and the mapped lineaments was found in the northern part of the epicentral region. A similar correlation was found for linear features in the interpolated aeromagnetic data.

In summary, integration of data from several sources support the existence of lineaments in the epicentral region. Five different sets of data correlate with a NNW trending, overburden-covered lineament, which may reflect the surface expression of a structure responsible for the current seismicity in the region.

NEOTECTONIC AND PALEOSEISMIC PHENOMENA ALONG THE NORTH SHORE OF THE MINAS BASIN, NOVA SCOTIA.

Stokes, T.R., Prospect Bay Consulting Services, 143
Brennans Rd., P.O.Box 25, RR#4, Armdale, Nova Scotia,
B3L 4J4, and Keppie J.D., Department of Mines and
Energy, P.O.Box 1087, Halifax, Nova Scotia.

Structures affecting Late Wisconsinan sediments were found at 34 locations along the north shore of the Minas Basin: 29 in glacial outwash deltas of Saints Rest (SR) glacio-fluvial sediments and Advocate Harbour (AH) glacio-marine sediments, and 5 in Eatonville till. The most important structures are: (1) at Finney Brook where conjugate normal faults, which downthrow a 15-20m wide block of AH forset sands by c. 1-2m, are the probable result of a reactivated NE-SW bedrock fault; (2) at Lower Five Islands metre scale folds and associated faults, restricted to a horizon of AH bottomset muds, appear related to extension during delta slumping or bedrock movement; and (3) at Economy Point, major chaotic folds in AH bottomset muds, which occur beneath a thin (1-3m) undisturbed SR gravel layer, may be attributed to delta slumping or seismically induced liquidization. It is not possible to uniquely determine the origin of these structures: whether they be neotectonic, related to glacial processes or to glacial rebound. However, most are probably associated with paleoseismicity. Reflection seismic profiles (which indicate that NE-SW listric normal faults and E-W flower structures affect Mesozoic strata and the Cenozoic sea-bottom sediments), the present day NE-SW compressional stress regime and recent earthquake activity support the interpretation that the structures observed are possibly the result of neotectonic and paleoseismic activity associated with the genesis of Bay of Fundy.

HOLOCENE SEISMICITY SEDIMENTARY INDICATORS IN LAKE MATAMEK, QUEBEC NORTH-SHORE

Ouellet, M.,INRS-Eau (Univ. du Québec), Sainte-Foy, Quebec, G1V 4C7

A ten meter long core taken from Lake Matamek (100 m) ice cover has revealed an exceptional fine (1 mm) organic (40%) laminated sequence along the 9 to 3 m stratigraphic interval. This sequence was unevenly interrupted by 13 grey clay-silty strata reaching thickness up to 11 cm. Sub-bottom profiling with a low frequency (3 kHz) continuous seismic refection system clearly shown, within the deepest part of the lacustrine basin, the wide and uniform spreading of these sedimentary units. Some sediment avalanchings were evident only at the base of steep slooping lake bottom sections. Under water mass slumpings are very common in all the deep lake of the Charlevoix Region but absent in Lake Memphremagog. The absence of any old landslide scar along the upstream Matamek River banks has eliminated such possible original sources for the inorganic material. These peculiar layers were probably generated by important earthquakes which triggered the resuspension of the material within the fluvial system. Subsequently, these suspensions were largely transported downstream by the hydro-dynamic forces where, under special morphological and physical conditions, they would pile-up discretly over the preexisting autochtonous sediments. Other paleoseismicity lacustrine sites will be investigated within the Charlevoix-Saguenay Region.

POSSIBLE NEOTECTONISM IN SEISMIC SUB-BOTTOM SEDIMENTARY PROFILES OF LAKE ST.JEAN, QUEBEC

Ouellet, M.,INRS-Eau (Univ. du Québec), Sainte-Foy, Quebec, G1V 4C7

The Saguenay-Lake-Saint-Jean hydrographic system comprises a vast region (85,000 km^2) located, largely on the Canadian Precambrian Shield, within the South-Central part of the Québec Province. The lake (1 053 km^2), in which the water level (100.4 m asl) has been artificially maintained at its maximum natural spring flooding line since 1926, acts as the central main reservoir of the catchment (1 [illegible] m^3/s). Unlike about all large Québec man-made reservoirs, thick Postglacial marine sediments are found within its basin. Liquifaction of the Postglacial marine clay cliffs of the south shore exposed to the dominant north-westerly winds is often at the origin of catastrophic landslides. From the lake 40.6 km fetch as well as its relative shallow (11.3 m) mean water depth and weak thermal stratification at the end of the summer period, we would expect an important bottom shifting of sediments. Unexpectedly, a 30 km long low frequency (3 kHz) seismic reflexion profile from the mouth of the Métabetchouane River to Pointe Taillon has revealed numerous sedimentary structural anomalies in the Holocene sediments. The presence of surface deep (5 m) V-shaped valleys as well as continuous (bendings) and discontinuous deformations ("faultings") of the sedimentary structures (40 m) do not support the levelling effect of the bottom sediment resuspensions during the homeothermic periods of this large dimictic lake. It is difficult to attribute these anomalies to the bedrock topography as well as the fluvioglacial and till deposits or to a giant lateral post-depositional compression. Unexplained neotectonic activities are probably at the origin of some of these unexpected bottom lacustrine structures.

2,500-YEAR HISTORY OF SEISMICITY FROM SILTING EVENTS IN LAC TADOUSSAC, CHARLEVOIX AREA, QUEBEC

Doig, Ronald, Department of Geological Sciences, McGill University,
3450 University St., Montréal, Québec H3A 2A7.

Silt layers in organic-rich lake sediments in the epicentral region of Charlevoix have been interpreted to represent the earthquakes of 1663, 1791, 1360 + 1370 and possibly 1925. This was based on the relative depths of the layers, and very approximate dating using the ^{137}Cs fallout horizon from testing of nuclear weapons (Doig 1986, C.J.E.S. 23, 930-937). Conventional ^{14}C dating is not useful because of the presence of old carbon in these sediments.

A new series of six longer cores has been obtained from Lac Tadoussac. These preserve a very fine and reproducible mm-scale stratigraphy that includes two new layers in the upper parts of the cores that correlate well with the remaining large historical earthquakes of 1535 and 1638. One core contained the first significant artifact recovered, a 3 x 40 mm twig, at a depth of 48 cm. An age of

910 ± 250 years has been determined using the accelerator-^{14}C (AMS) method, confirming the correlation of the silt layers with known earthquakes of magnitude six or greater.

The cores contain up to 20 silt layers of thickness 1 to 45 mm over a depth equivalent to about 2,500 years. The thickness of a layer probably does not directly reflect the magnitude of an event, but there is likely to be some correlation. On this basis there would be four events of magnitude greater than 7, in 1663 and 1250 A.D., and 250 and 515 B.C. The 16 other layers could correspond to earthquakes of magnitude 6 to 7.

There seems to be a different, but regular spacing of layers within each of three time periods. These are an average spacing of 125 years (standard deviation of 35 years) from 550 B.C. to 700 A.D., 270 (SD 115) years from 700 to 1535 A.D., and just 75 (SD 40) years from 1535 to the present. Age assignments beyond 1,000 years depend on the assumption of a constant sedimentation rate.

2-D SPACE PREDICTION OF EARTHQUAKES: CHARLEVOIX AREA, QUEBEC. Seguin, M K. and Blais, E., Groupe de Recherche en Géochimie et Géophysique Appliquées, Département de Géologie, Université Laval, Québec, G1K 7P4, Canada.

The objective of this study is the application of methods predicting the occurrence of earthquakes in the space domain. Their space distribution appears unrelated to the position of the Charlevoix meteoritic impact. The hypocenters are mainly located at the ends of the Charlevoix Seismic Zone (CSZ) and along northeast trending fault planes. The three methods used were

1) Gaps of the first kind: Gaps of the first kind are areas without epicenters of earthquakes larger than a preselected magnitude ($M > 4.0$). This method confirms such earthquakes will probably be located near Ile aux Coudres and Ile aux Lièvres (extremities of the CSZ). With this method, we found that 7 2 is the maximum possible magnitude in the CSZ

2) Gaps of the second kind: A gap of the second kind is a zone without earthquakes but circled by microseisms occurring in a time interval smaller than 2 or 3 years. This method allows short-term prediction but is unreliable because it yields too many gaps. Selection criteria and constraints (filters) used are: a) Steady area of the gap with depth, b) Formation time interval, c) Location and size of the gap. If it is too big, it is not a gap, d) The circular shape of the gap. No irregularities are allowed.

3) Gaps of the second kind along fault planes: This is a modified version of the former method, adapted to an intraplate seismic zone with subnormal faults. The gaps are drawn in a vertical plane. It yields few gaps and a better resolution of the positioning, of the areal extent and of the maximum predicted latitude. Conclusion: The last method is the most reliable of the three. To improve the space prediction, one should use 3-D location of hypocenters to get the real volume of the gaps and to ease the relocation from x-z to x-y coordinates.

GROUND FAILURE TRIGGERED BY THE NOVEMBER 25, 1988 SAGUENAY EARTHQUAKE

Tuttle, Martitia, P., Seeber, Leonardo, and Such, Russell, Lamont-Doherty Geological Observatory, Palisades, New York 10964

Settlements of houses in liquefied glaciolacustrine sands, translational slides in fluvial sands and gravels, and flow failures in marine clays occurred in response to the November 25th, 1988 Saguenay earthquake (m_b=5.9). Slope failures were widely distributed across the region; whereas, manifestations of liquefaction were concentrated in the Ferland-Boilleau valley. This perception may be biased by the small percentage of the land area actually surveyed during the 2-week time period following the event. In addition, many features were covered by snow that fell soon after the earthquake and so we depended on the observations of residents for locating earthquake-induced features. Liquefaction was a more significant mode of ground failure than slope failure in contributing to structural damages of buildings because most buildings in the Saguenay region occur away from slopes and on fairly flat land which may be underlain by liquefiable sediments.

Fine-grained glaciomarine and glaciolacustrine sediments in northeastern U.S. and southeastern Canada have liquefied during moderate historic earthquakes as well as the m_b=5.9 Saguenay earthquake, suggesting that these deposits may be especially prone to liquefaction. This modern example of earthquake-induced liquefaction provides the opportunity to study (1) the geologic factors (sedimentological properties and stratigraphy as a function of specific depositional environments, and ground water conditions) that contributed to the susceptibility of the sediments in Ferland and Boilleau to liquefy during ground shaking, (2) the characteristics of earthquake-induced liquefaction features in glacial deposits, and (3) the geologic record for evidence of previous (historic and prehistoric) earthquakes. All three lines of inquiry could significantly contribute to seismic hazard assessments not only in southeastern Canada but also in the northeastern United States.

3. PROGRAM 1989-1990 /

LE PROGRAMME DE 1989-1990

The 1989/90 program consists of the following projects:

MARITIME PROVINCES

1. The deployment of a ship in Passamaquoddy Bay equipped with side-scan sonar, deep tow, seismic reflection equipment to attempt to determine if there is postglacial faulting, and magnetic equipment to detect offset diabase dikes, if any.

2. A continuation of structural mapping, both on land and in Passamaquoddy Bay, to determine whether or not diabase dikes have been displaced, at least laterally, across the Oak Bay Fault as well as across other structures in Passamaquoddy Bay.

   Note: Field work for these projects was completed successfully in 1988-89. Activities in 1989-90 will comprise analysis and interpretation of the field data.

CHARLEVOIX AND SAGUENAY REGIONS, QUEBEC

1. Seismic monitoring in the area of the Saguenay earthquake.

2. Detailed documentation of liquefaction features in the Ferland-Boileau Valley, east of the epicentral area of the Saguenay earthquake.

SOUTHERN ONTARIO & WESTERN QUEBEC

1. Continued documentation and evaluation of outcrop-scale, bedrock structures, including pop-ups, kink bands, fractures and faults and macroscopic structures such as the Salmon River and Picton Faults in Prince Edward County, Ontario.

2. A re-assessment of the locations of historic (pre-instrumented) earthquakes on the Niagara Peninsula and in the West Quebec Seismic Zone.

3. The deployment of side-scan sonar and echo sounders in the Great Lakes.

4. Continuation of the compilation of a satellite lineament map, at a scale of 1:1,000,000, for all of southern Ontario in order to identify faults and fractures across the province. Some of these may have characteristics suggestive of neotectonic activity, in which case they may be singled out for more detailed field work (ground-truthing).

PARTICIPATING AGENCIES IN 1989

Federal Government

Atomic Energy Control Board (AECB)
Ottawa, Ontario

Geological Survey of Canada (GSC)
Ottawa, Ontario

Province of Ontario

Ontario Center for Remote Sensing (OCRS)
North York, Ontario

Ontario Geological Survey (OGS)
Toronto, Ontario

Ontario Hydro (OH)
Toronto, Ontario

Universities

Université du Québec
Chicoutimi, Quebec

Université Laval (UL)
Quebec City, Quebec

University of New Brunswick (UNB)
Fredericton, New Brunswick

Independent Consultants

Seismican Consulting Services (CSC)
North York, Ontario

McQuest Marine Research and Development
Burlington, Ontario

American Agencies

Lamont-Doherty Geological Observatory (LDGO)
Palisades, New York

United States Geological Survey (USGS)
Reston, Virginia and Ithaca, New York

National Center for Earthquake Engineering Research (NCEER)
Buffalo, New York

4. REPORTS AND ABSTRACTS/
RAPPORTS ET RÉSUMÉS

4.1 SOME RESULTS FROM THE NOVEMBER 25, 1988 SAGUENAY (QUEBEC) EARTHQUAKE

Maurice Lamontagne*, Robert Wetmiller*, R. Du Berger**

*Geological Survey of Canada
**Université du Québec à Chicoutimi

On November 25, 1988 the Saguenay earthquake, the largest earthquake to take place in Eastern North America in over 50 years, occurred in the Laurentide Fauna Reserve, some 35 km to the south of the city of Chicoutimi, Quebec and 100 km north of Quebec City. This event has provided a large amount of new information for seismic hazard estimation in Eastern North America, previously based largely on questionable data from earthquakes which took place early this century. The location of the Saguenay event in a hitherto relatively aseismic region, its depth in the lower crust, its large component of high-frequency seismic waves, its remarkably mild aftershock activity and the difficulty in defining the reactivated structure, pose several problems for existing models of seismic zoning and hazard assessment for eastern North America.

The Saguenay earthquake had a teleseismic magnitude of m_b 5.9 but produced unexpectedly large amounts of high frequency seismic energy, as evidenced by the value of the local magnitude m_{bLg} 6.5 and high accelerations observed at distances ranging from 40 to 800 km.

The felt area exceeded 3.5 million km^2 (maximum intensity VII) and closely approached that of the larger 1925 Charlevoix earthquake which had a magnitude of 6.7. The earthquake caused isolated cases of property damage in the Saguenay region and in the metropolitan areas of Quebec City and Montreal. The damage often consisted of cracked or collapsed masonry walls and in some cases was obviously as much due to the unstable foundation of the damaged structure as to the initial strength of the ground shaking. Hydro-Quebec suffered some significant damage at one of their transformer stations. In all, the total expense for damage caused by the earthquake in the province of Quebec has been estimated to be a few tens of million dollars.

Focal mechanisms for the foreshock, main shock and two aftershocks all indicate thrust faulting with some strike slip movement which is quite consistent with the idea of reactivation of existing faults by the regional stress field presently active in eastern Canada.

The Saguenay event was preceded 62 hours earlier by a foreshock (m_b 4.4) which allowed the GSC to deploy field equipment in the epicentral area before the unexpected main shock. The depth of the main shock could thus be well determined at 29 km which is deeper than 95% of all the other activity in eastern Canada. One area where seismic activity does occur at comparable depth is the Charlevoix seismic zone where a small percentage of the activity occurs below 25 km. However, while almost all earthquakes in stable continental areas around the world are shallow, similar or greater depths have been reported for occasional earthquakes in Brazil and Fennoscandia, indicating that deep crustal events are a rare but very real seismic phenomena. The seismic hazard implications for such events in stable continental areas have never been fully appreciated.

The field network showed that no small magnitude activity occurred in the epicentral area in the 24 hours prior to the mainshock. The absence of continuous low-level activity preceding the main shock may represent a characteristic of these deep events.

Nearly all of the aftershock activity was located above the main shock which would seem to indicate that the rupture propagated upwards. The aftershock activity spread out over a wide area, more than 10 km from the main shock, but we feel that much of this spread-out activity was caused by secondary stress/strain adjustments and does not represent the true dimensions of the rupture. Three dimension analysis of the hypocentres has not yielded any unequivocal orientation that unambiguously indicates the main shock rupture plane but a clustering of very small events around the main shock hypocentre could represent a rupture plane with dimension of a few km which is more consistent with the results of modelling of the teleseismic waveforms.

The Saguenay main shock was followed by over 85 aftershocks (as of August 31), of which only two have been larger than magnitude 3. Since the main shock, the activity has been monitored by a network of two Geological Survey of Canada stations (one telemetered to Ottawa and one to the Université du Québec in Chicoutimi) and four field stations operated by the Université du Québec à Chicoutimi. These stations are located within 50 km of the epicentre of the main shock, giving a detection threshold of approximately magnitude 0.5. The aftershock activity has decreased very rapidly, much more so than in two other recent Canadian earthquake sequences, Miramichi in 1982 and Nahanni in 1985 and is currently very mild, with only three shocks of magnitude 2 or greater since the end of January. For zoning purposes, it is very difficult to delineate and define the Saguenay source zone from the present level of aftershock activity, even though it is less than a year since the event. By contrast the source zones of the Miramichi and Nahanni events are still clearly identifiable by their continuing aftershock activity. The greater depth of the Saguenay activity may be the factor controlling its unusual quiescence.

Seismotectonically, the epicentral region lies between the Saguenay Graben and the St. Lawrence valley and is some 75 km from the outer boundary of the Charlevoix seismic zone which has been a source of several large (magnitude up to 7) earthquakes over the last three hundred years, most recently in 1925. The Saguenay region was not previously considered to be particularly seismically active as only a few small events of magnitude smaller than 3 had been located within 50 km of the November 1988 epicentre during the last ten years and there were no historical accounts of large events in the last 150 years. It is thought that any recent earthquake exceeding magnitude 2 should have been seen on the permanent seismograph station LMQ, at about 100 km to the south-east. Interestingly, a reexamination of these earthquakes has shown

that a magnitude 2.7 had occurred 10 months prior to the November shock at less than 15 km from
its epicentre. However, this small shock can not be considered exceptional since small earthquakes in this magnitude range are recorded from time to time throughout the Grenville province outside the most active regions.

The Saguenay earthquake occurred some 20 km to the south of the most southerly of the mapped faults considered to be associated with the Saguenay Graben and there has been considerable controversy about the possibility that the earthquake was associated with the Graben in some manner. Any seismotectonic interpretation of the situation will have to consider the depth of the earthquake which makes a correlation with surface geology difficult to establish. However, as a first step towards a better understanding of the region, efforts have been made to better define the geological characteristics of the area. A synthesis of previous geological works in respect to the earthquake has been prepared (Du Berger et al.), various velocity models for the crust have been tested, and in June 1989, a RADARSAT airborne survey has been conducted over the epicentral region.

Although many lineaments can be seen on LANDSAT, RADARSAT and air photographs, no prominent faults could be correlated with certainty with the main shock. A LITHOPROBE survey in the area would certainly constitute the best way of defining the crustal structure at depth in the epicentral region.

Reference:

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1989: The Saguenay (Quebec) earthquake of November 25, 1988: Seismological data and Geological Setting, Submitted to Tectonophysics.

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4.2 CANADIAN STRONG-MOTION DATA FOR SAGUENAY, QUEBEC, EARTHQUAKE, 25 NOVEMBER 1988

P.S. Monro and A.E. Stevens

Geological Survey of Canada

Earthquake Engineering Research Institute Special Earthquake Report,
EERI Newsletter Vol. 23, No. 5, May 1989

The eastern Canadian strong-motion seismograph network, maintained by the federal government, is designed to measure free-field ground motion, not structural or soil response. Most of the 19 accelerographs are located along or near the St. Lawrence River in Quebec to monitor the active Charlevoix-Kamouraska seismic zone (see Figure 4.2.1). In addition, Hydro-Quebec has installed accelerograph arrays on three of its large dams (Manic-3, Manic-5 and Outardes-2) on the Manicouagan and Outardes rivers in northeastern Quebec. All instruments are analogue SMA-1s.

Accelerographs at 15 of the 22 sites triggered on the main shock of 25 November 1988. No stations triggered on either the foreshock of 23 November nor on any of the aftershocks. During the field project, five additional SMA-1s were installed in the epicentral region. To mid-August 1989, none of these have triggered on aftershocks, although they lie within 20 km epicentral distance of the active area.

In Figure 4.2.1, difference symbols denote triggered and un-triggered sites; the triggered sites are labelled with their maximum horizontal acceleration in g (Munro and Weichert, 1989). Three of the un-triggered sites are labelled by name. At the Hydro-Quebec sites (upper right corner) peak free-field accelerations were less than 0.01g. All 13 stations within 200 km epicentral distance triggered, with one exception, as noted on Figure 4.2.1. One instrument malfunctioned after triggering. Seven of the 10 triggered bedrock sites were free-field sites. The remaining three accelerographs were sited on concrete basement floor slabs on bedrock in one- or three-storey buildings.

Examples of ground motion and pseudo-velocity response spectra are presented in Figures 4.2.2 and 4.2.3 for St-André, Quebec, the site exhibiting the largest horizontal bedrock acceleration (plotted as 0.156 in Figure 4.2.1). None of the accelerograms at any of the sites shows strong spikes. Digital strong-motion data recorded at United States sites are referenced by Munro and Weichert (1989).

Reference

Munro, P.S. and Weichert, D.
1989: The Saguenay Earthquake of November 25, 1988 -- Processed Strong-Motion Records; Geological Survey of Canada, Open File Report No. 1996, 150 pp.

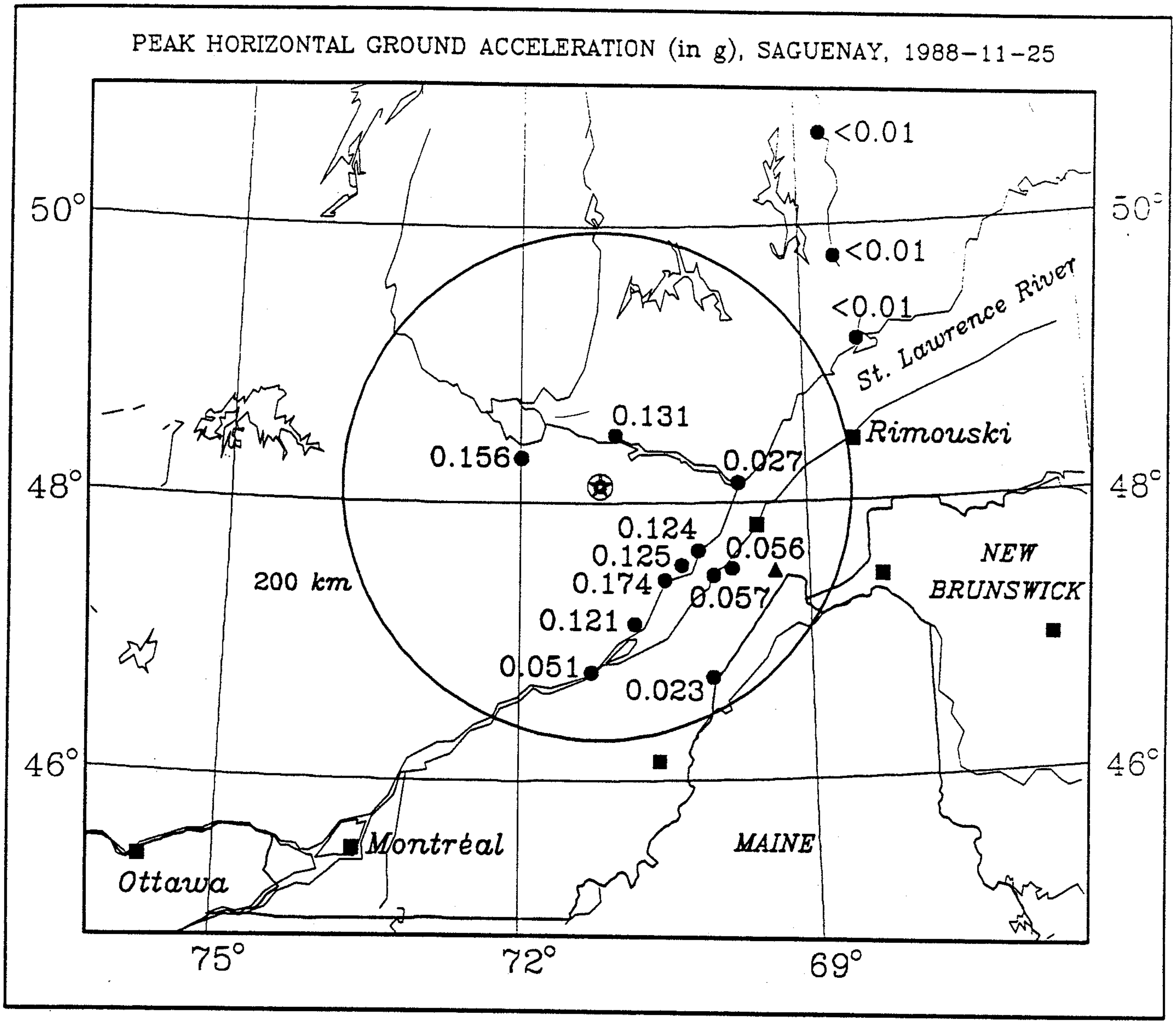

Figure: 4.2.1. Maximum horizontal acceleration (in g), from Table of 2 Munro and Weichert (1989). All instruments on bedrock, except Baie-St-Paul on alluvium (0.174 on map). Symbols: encircled star - epicentre; solid circles - triggered; solid square - not triggered; solid triangle - triggered but equipment malfunctioned; large circle has a radius of 200 km.

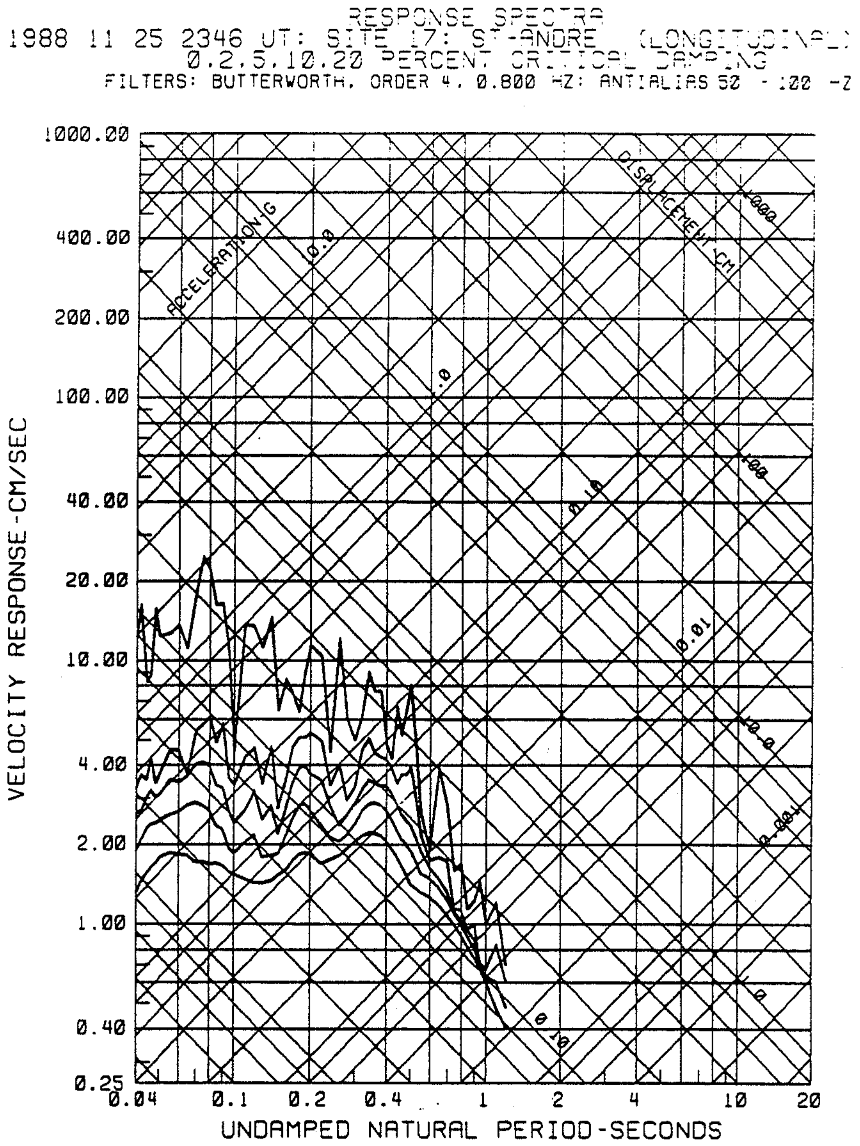

Figure 4.2.2. Corrected acceleration, velocity and displacement of north-south horizontal component at St. André (Québec; azimuth from epicentre is 291 degrees, epicentral distance is 64 km.

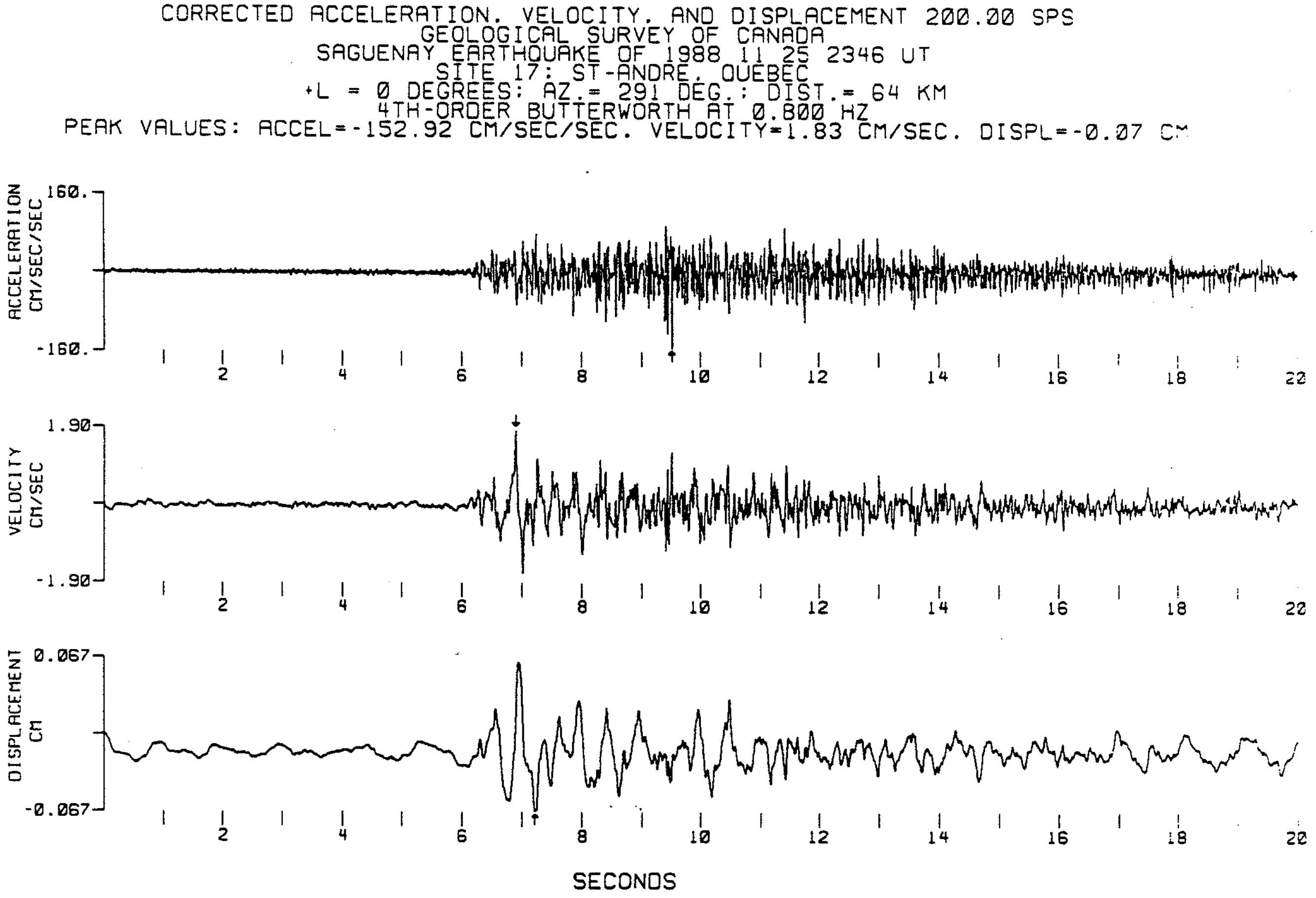

Figure 4.2.3. Pseudo-velocity response spectra for north-south horizontal component at St. André (Québec) for 0, 2, 5, 10 and 20% damping; azimuth from epicentre is 291 degrees, epicentral distance is 64 km.

4.3 THE 1988 SAGUENAY EARTHQUAKE - STRONG MOTION, INTENSITY AND MAGNITUDES.

North, R.G., Monroe, P.S.,and Cajka, M.G.

Geological Survey of Canada

The absence of well recorded strong earthquakes in eastern North America has resulted in the development of a number of models for ground motion from such earthquakes based on various assumptions for historical earthquakes and extrapolations for small events in the east or larger events in different tectonic environments. The Saguenay event provides an opportunity to test these assumptions; in particular those involving relationships between the various magnitude scales employed and between magnitude and intensity. The available strong ground motion data will be presented and compared with the predictions of the various models proposed. The earthquake took place slightly over 100 km for the Charlevoix seismic zone and thus useful comparisons can be made of the far field seismic data and intensity distributions for the 1988 Saguenay event and the 1925 Charlevoix event. Although postulated teleseismic magnitude for the 1925 event are larger than those measured for the 1988 event, felt area and regional magnitudes for the two events appear to be quite similar. The effects of the 30 km depth of the 1988 event upon magnitude, strong motion and intensity will be discussed.

4.4 FOCAL MECHANISMS AND AFTERSHOCK DISTRIBUTION OF THE 1988 SAGUENAY, QUEBEC EARTHQUAKE SEQUENCE

Wetmiller, R.J., Adams, J., Anglin, F.A., Lamontagne, M. and Drysdale, J.

Geological Survey of Canada

Focal mechanisms of the Saguenay earthquake mainshock, foreshock and largest aftershock were determined from short-period P-wave first motions recorded at seismograph stations beyond 90 km as follows:

	Date	Time	Mag	Nodal Plane #1			Nodal Plane #2		
				str	dip	rake	str	dip	rake
Foreshock:	Nov. 23	09:11	4.7	358	44	060	216	53	115
to:				322	57	066	181	40	122
Mainshock:	Nov. 25	23:46	6.0	325	67	054	208	41	145
Aftershock:	Nov. 26	03:38	4.1	335	48	098	143	42	081

All the solutions were consistent with thrust events on primarily north-to-northwest-trending, intermediate-dipping planes. The mainshock solution was very tightly constrained by its data set while the solutions for the aftershock was less well constrained and the data for the foreshock allowed a range of solutions. No existing faults have as yet been identified in the epicentral region to resolve which of the nodal planes represented the mainshock's fault plane. By January, 1989 thirty-two events (M>0.1) in the four days following the mainshock have been located, including the foreshock, mainshock and all the larger (M>1) aftershocks. The hypocentres were calculated using information from the field stations and selected permanent stations within 100 km assuming 6.2 km/s as an average crustal velocity; the estimated location errors were generally smaller, <1 km. The activity as a whole was scattered over an area approximately 40 km square, but more than one-half of events including the mainshock were clustered in a smaller NS-trending zone approximately 20 km long by 15 km wide centred near 48.06 N, 71.15 W with their depths ranging from 20 to 30 km. The mainshock epicentre was located near the northern end at the bottom of this zone suggesting that the rupture generally expanded upwards and to the south from its start through all or part of the zone.

4.5 FIELD STUDIES OF THE M6.0 SAGUENAY, QUEBEC EARTHQUAKE OF NOVEMBER, 25 1988 AND ITS FORESHOCK AND AFTERSHOCKS

Wetmiller, R.J.*, Lamontagne, M.*, Monroe, P.*, Asudeh, I.*,
Du Berger, R.**, Such, R.***, Busby, R.***, Seeber, L.***, and
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Seismological Research Letters, v. 60, p. 18-19

Special seismic monitoring of the epicentral area of the November 25 Saguenay earthquake with portable recorders began on November 24 (one day after the foreshock and one day prior to the mainshock) and has continued to date (January 10) without interruption but with varying levels of effort and coverage through a cooperative effort by the authors' agencies. The mainshock was recorded by the 3 MEQ-800 `smoker' seismographs installed the previous day by the GSC within 10 km of the epicentre of the eventual start of the mainshock's rapture. Data from these recorders showed that there was no small magnitude activity (M>1) in the 24 hours preceding the mainshock and, combined with data from permanent stations of the Canadian Seismograph Network (all beyond 90 km), allowed the hypocentre of the mainshock (23:45:04.50 UT, 48.117 N, 71.184 W, and 29 km depth) to be determined with confidence. In the 2 weeks following the mainshock, additional portable recorders were deployed at 23 different sites throughout the epicentral area. The instruments consisted of MEQ-800 single-component seismographs and PRS1 single-component continuously recording digital seismographs. Less than 60 aftershocks, M 0-4.1, were recorded by the field network in this period and approximately 40 could be well located. After December 10 the field network was reduced to 4 MEQ-800 seismographs and one new station, DAQ, of the Eastern Canada Telemetred Network, supplemented by an array of strong-motion accelographs consisting of 5 SMA-1 g or 0.5 g photographic recorders and 3 SSA-1 digital recorders. To date no strong aftershocks have taken place and the smaller events have occurred only infrequently.

4.6 EARTHQUAKE-INDUCED LIQUEFACTION FEATURES IN FERLAND, QUEBEC

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Water and sands were extruded at several localities in Ferland-Boileau, Quebec, in association with the November 25, 1988 earthquake. Sand boils in Ferland were observed and documented in a cursory way a few days following the event, but were studied in detail in three excavations at two sites in August 1989. They are characterized by aprons deposited on the ground surface and by dikes, sills and conduits emplaced within glacial sediments and modern soils. In addition to these 1988 liquefaction features, other structures were revealed in the excavations that are suggestive of two earlier liquefaction events.

The 1988 sand aprons range from 1 to 10 m in diameter and up to 22 cm in thickness. The largest body of extruded sand is composed of at least 4 coalesced aprons. The fans of the aprons are composed of laminated and graded, grey, fine sand; silty, very fine sand and very fine sand, silt. The events of the aprons are characterized by steep truncation of sub-horizontal laminae and by normally graded, fine to coarse sand. Clasts of soil occur locally within both the fan and vent deposits.

Sand conduits, dikes and sill produced by the 1988 earthquake occur within near-surface materials below the sand boils. The conduits are typically 5 to 15 cm in diameter and the dikes and sills range from 1 to 30 cm in width. Dikes are best developed at depths greater than 1 m. At Site 1, in the two excavations, which are located near slope breaks, dikes are sub-parallel to the topographic contour. In the excavation at Site 2, which is also located near a slope bread and within 8 m of the creek, known as Bras Hamel, dikes emerge from below boulders at a depth of 1 m. Sills occur below soil or organic-rich horizons and sand conduits occur within these horizons. Sills and conduits are best developed where the soil is at least 0.3 m thick. In addition to these structures, lenses of sand are present below and around stones, boulders and large pieces of wood which had been in the pathway of escaping sand.

In the excavation located close to a house at Site 1, a well developed system of dikes and faults is related to a small 1988 sand boil. The main dike is sub-vertical and is well defined below 1 m. Above this depth, the dike splits into a family of thin and discontinuous dikes. However, these dikes can be followed along a linear zone just below the modern soil for a distance of 4 m. Several subsidiary dikes branch upward from the main dikes and occur along faults exhibiting centimetres of displacement. Two of the normal faults and one of the thrust faults offset a 27 year old layer of fill by 1.5 to 3 cm. Displacements up to 11 cm of depositional contacts are greater than the displacements of the fill suggesting that these faults are older than the fill, were reactivated during the 1988 event, and experienced at least one pre-1988 displacement.

Several of the subsidiary dikes injected along normal faults terminate 1 m below the surface at the contact between silty, very fine sand and medium sand. Sedimentation within the dikes varies with depth. Below 1.5 m, the dikes exhibit vertical grading and are finer-grained near their edges; above this depth, dikes exhibit horizontal grading. In dikes dipping less than 40 degrees, sediments also exhibit normal grading.

Dikes are the primary pathway for liquefied sands as it moves upwards from its source. Textural variations within 1988 dikes suggest that the pore pressure of escaping liquefied sand is significantly affected by the permeability of host sediments. Therefore, the permeability of near-surface sediments, among other physical characteristics such as relative density, may play an important role in determining the types of structures formed in liquefaction events. If the permeability of the near-surface sediments is high, then the pore pressure of the liquefied sand is reduced and structures either terminate or are only weakly developed. On the other hand, if pore pressures are extremely high, then more explosive structures may form at the surface such as sand-blow craters. If the permeability of the host sediments is low, which is the case for thick soil or organic-rich layer, then sills and conduits may form as secondary pathways. Furthermore, boulders or other impermeable objects can obstruct the movement of liquefied sand, creating lenses of sand below the obstacles and possibly deflecting the course of the sand dikes.

The occurrence of several 1988 sand boils near slope breaks suggest that topography may exert influence on the localization of ground failure. Furthermore, the orientation of the sand dikes and related faults parallel to the topographic contour suggests that lateral spreading resulting from ground shaking is the principal mode of ground failure. The relationship of normal faults to a well developed system of 1988 sand dikes supports this hypothesis. Once a subsurface layer has liquefied, overlying material begins to move downslope. This can lead to tension in the sediments which can be accommodated by either tension fractures and/or normal faults both of which would be perpendicular to the movement direction. Liquefied sand would fill the fractures and possibly drive fracture propagation towards the surface. Downslope movement of subsurface materials and evacuation of the liquefied sand would create an unstable boundary situation leading to normal faulting of adjacent sediments towards the fracture.

In every excavation, there are weathered dikes and sills similar in texture and morphology to 1988 structures which are likely to be paleo-liquefaction features. Several of the weathered dikes at Site 1 are associated with both the normal and reverse faults mentioned above and are intruded or cross-cut by 1988 dikes. At Site 2, weathered dikes cross-cut a charcoal layer which may be related to a fire that burned much of the region in 1870. Structures even older than the weathered dikes have been recognized form cross-cutting relationships and degree of weathering, primarily iron-staining and cementation. These older structures tend to be larger than the more recent dikes and sills. At Site 1, one of these structures is comprised of a weathered sand dike at depth and an iron-stained and cemented sand crater near the surface. Organic material lines the base of the crater and clasts of host the surface. Organic material lines the base of the crater and clasts of host sediment are contained within the crater. Reverse faults with up to 20 cm of displacement occur within 0.5 m of the carter and root in the associated sand dike. This structure is quite different from the 1988 structures and exhibits characteristics of sand-blows described near Charleston, South Carolina (Obermeier et al., 1986). The relationship of the reverse faults to the sand dike is not clear. The reverse faults do not cut the dike and therefore may pre-date it. Like the normal faults exposed in the same trench, the reverse fault may have controlled the replacement of the dike. At Site 2, older deformation structures include sand lenses located below boulders and 30 cm wide dikes and diapirs. Overlying organic-rich sediment and soil are deformed by these structures. The degree of iron-staining of the sand in the lenses, dikes and diapirs is similar to that of the sand filling the crater at the other site, suggesting that older deformation at both sites may be contemporaneous. A bearing-load failure due to liquefaction is one plausible mechanism for the formation of these structures.

Evidence for an earlier liquefaction event similar to the 1988 event suggests that the Ferland area has been subjected to moderate ground shaking in the recent past. If the charcoal layer that is cut by weathered dikes does date back to the 1870 fire, then these structures would post-date the fire. Perhaps these structures are induced by the large 1925 earthquake. In two of the excavations, there is also a suggestion of an even earlier liquefaction event. The size and nature of the structures suggest that pore pressures were much higher during this event and that the earthquake may have been either larger than the 1988 earthquake or closer to Ferland. A much broader area must be surveyed in order to determine the size or location of these earthquakes.

4.7 IMPLICATIONS OF THE 1988 SAGUENAY EARTHQUAKE FOR FOR SEISMIC HAZARD ZONING OF SOUTHEASTERN CANADA

Adams, J. and Basham, P.W.

Geological Survey of Canada

The current seismic zoning for Canada (1985 National Building Code of Canada) defines zones of intense, moderate, and background seismicity in the southern craton. To generalise from the pattern of contemporary seismicity (which taken over a few hundred years might have missed potentially active seismic zones), we adapted the seismogenic rift framework proposed by Johnston (1989) to eastern Canada. Most large earthquakes have occurred near Palaeozoic or younger rift structures that surround or break the integrity of the North American Craton. In particular, reactivation of a Palaeozoic normal faults along the ancient rifted margin of the Iapetus Ocean (now along the St. Lawrence river) and on a failed rift (Ottawa Graben) accounts for much of the seismicity occurring within the Grenville basement. A second graben along the Saguenay Fiord was neglected in our analysis because the level of contemporary seismicity was very low. In November 1988, the M_w 6 Saguenay Earthquake occurred on the south side of the Saguenay Graben and from the focal mechanism might have involved thrusting on a fault striking within 30° of the graben, or on a plane parallel to the rift faults under the St. Lawrence (90 km to the east). Retrospectively, we believe that the Saguenay graben should have been included in the rift model for seismotectonics. However, we wonder how many other such features will be evident only after they experience a future large earthquake. Quite apart from its location and implications for seismic zones, the Saguenay earthquake has interesting hazard implications with regard to (i) unusually great depth, (ii) relatively high stress drop, (iii) paucity of aftershocks, and (iv) its instrumental record of strong ground motions.

References:

Johnston, A.C.
1989: The seismicity of 'Stable continent interiors'; in Earthquakes at North Atlantic Passive Margins: Neotectonics and Postglacial Rebound; S. Gregersen and P.W. Basham (ed.); Kluwer Academic Publishers, Dordrecht, p. 299-327.

4.8 THE NOVEMBER 1 1935, M 6.2 TIMISKAMING EARTHQUAKE, ITS AFTERSHOCKS AND SUBSEQUENT SEISMICITY, AND SOME COMPARISONS WITH THE 1988 SAGUENAY EARTHQUAKE

John Adams and Andrew Vonk

Geological Survey of Canada,

Seismological Research Letters, v. 60, p. 19, 1989

ABSTRACT

The November 1, 1935 Timiskaming earthquake, m_b=6.2 was felt over an area of 1.3 million km^2 and was the first recorded from the Timiskaming area. A new epicentre at 46.885°N 79.004°W has been determined for the mainshock using local phases. Seven new aftershocks that were reported in the national press are documented along with the twelve already known. The largest aftershock (m_{bN} 4.9) lies 30 km northeast of the mainshock. Relocation of the subsequent earthquakes suggests that most of the earthquakes lie in a northwest-southeast trending band approximately 10 km wide and 55 km long under Lac Kipawa (Fig. 4.8.1), here called the Kipawa Seismic Zone. Recurrence rates (B-9.2; M_o=2.0) calculated for the zone have an extremely low B value and imply $M \geq 5.0$ earthquakes once every 48 years. Available data provide poorly-constrained focal mechanisms for the zone. The best choice suggests thrusting on planes striking northwest and dipping about 45°, probably related to Lower Palaeozoic rift faults that extend from the Ottawa Valley to Lake Timiskaming.

The 1935 Timiskaming earthquake is the previous largest earthquake to the 1988 Saguenay earthquake and the aftershock sequence, historical seismicity, focal mechanism, and seismotectonics provide an interesting contrast.

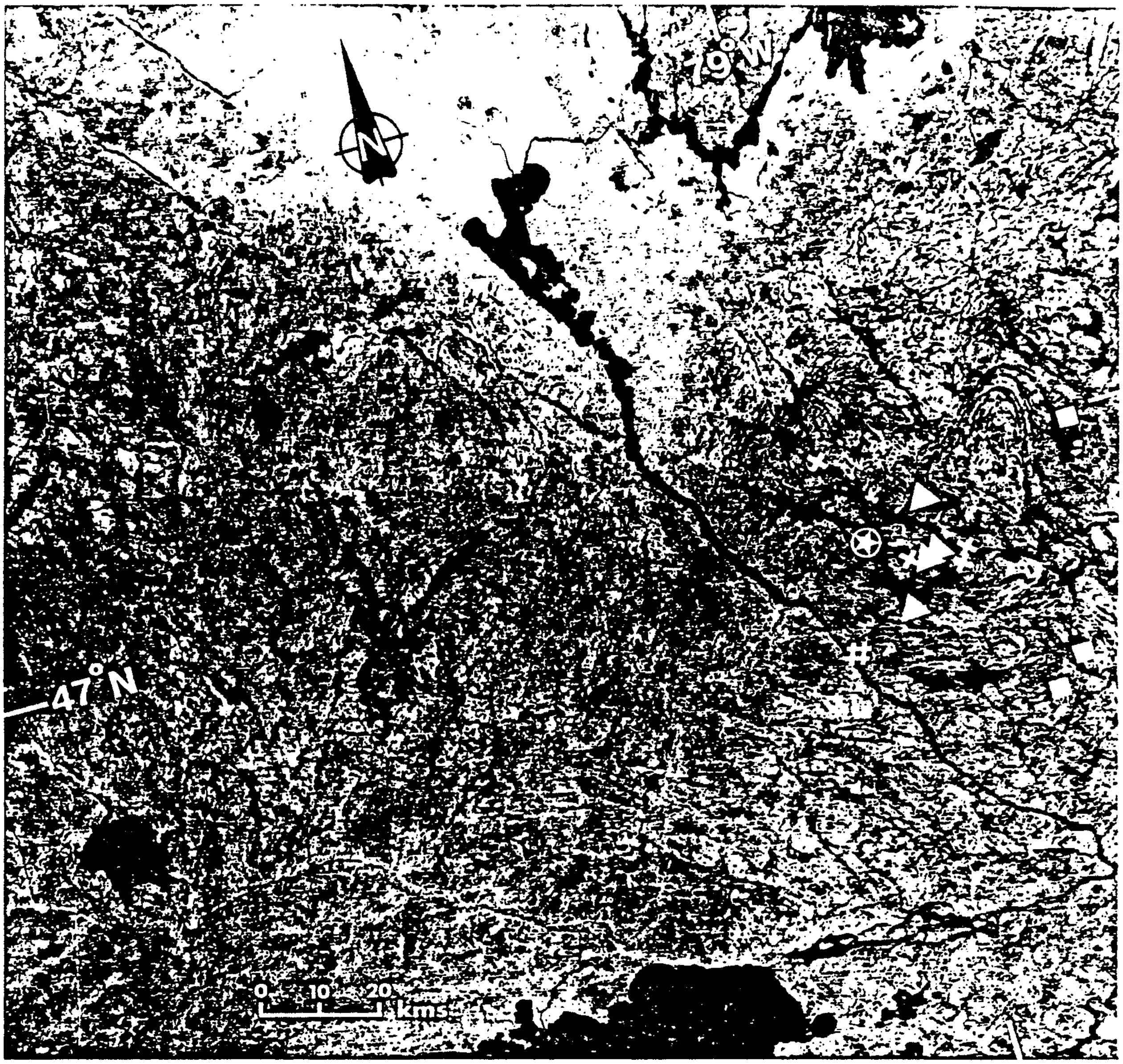

Figure 4.8.1. Revised Kipawa Seismic Zone earthquakes superimposed on LANDSAT photograph. Note the intersection of the northwest-and north-northwest-trending lineaments at Lac Kipawa (Taken from a GSC Open File in preparation).

4.9 COMMUNICATION ASPECTS AFTER AN UNEXPECTED MAJOR EVENT: EXPERIENCE WITH THE M6 SAGUENAY EARTHQUAKE

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*Geological Survey of Canada
**Université Québec à Chicoutimi

The magnitude 6 earthquake of November 25, 1988, was the first large event to be strongly felt along the Saguenay and St. Lawrence River Valleys since 1925. The cumulative effects of the force of the strong ground shaking, the coincident electrical blackout and the general lack of earthquake experience and preparedness of the population at large resulted in a widespread, deep and lasting psychological trauma. The relevance of seismologists' communications to the public was consequently not only scientific but also social and considerable effort was made to decrease the psychological impact of the event. Scientific information was provided to de-mystify the earthquake process, to reinforce the successful aspects of surviving such an event and about the individual measures possible to reduce the effects of future such occurrences. The difficult challenges arose in trying to instill some sense of reality and confidence in the "not so exact" science of Seismology, to explain why prediction is still not a dependable science and to temper the effects of some of the less dependable statements of astrologers and of other newly-found "experts". The foremost lessons to be learned are that one must always think carefully about communications directed at a shocked population, with particular attention being paid to the very first information provided, that one should keep in close contact with the local media and that one should be very honest about the limitations of Seismology and the Earth Sciences.

4.10 SEISMICITY AND SEISMOTECTONICS OF SOUTHEASTERN CANADA

John Adams

Geological Survey of Canada

Earthquake Hazards and the Design of Constructed Facilities in the Eastern United States, Annals of the New York Academy of Sciences, v. 558, p. 40-53, 1989.

SUMMARY

Eastern Canada - Canada east of the Rockies, and extending north from the United States border to the Arctic Ocean - comprises about two-thirds of the stable craton of the North American plate. Much of this large area appears to be substantially aseismic, however it contains several zones of intense seismicity. Earthquakes in eastern Canada appear to be occurring within a stress field dominated by northeast to east compression, and most large earthquakes have occurred near palaeozoic or younger rifts or rifted continental margins, i.e. places where the continent has been most recently weakened.

Large or damaging earthquakes in eastern Canada during the first half of the century (1925 M7.0 Charlevoix, 1929 M7.2 Grand Banks, 1933 M7.3 Baffin Bay, 1935 M6.2 Timiskaming, 1944 M5.6 Cornwall) provide a recent history that is a useful complement to the absence of such experience in the eastern United States. Much is now being learned about the seismic zones and the nature of the seismicity through the intensive study of recent smaller earthquakes. However, seismological studies, earthquake engineering practice and emergency preparedness planning are all hampered by the lack of large earthquakes during the memory of most people in the eastern United States and Canada.

SEISMIC HAZARD AND SEISMIC RISK IMPLICATIONS

It is now 40 years since the last large, damaging earthquake in southeastern Canada (Cornwall, 1944, M5.6, damage $15,000,000 dollars in 1987). In recent times, the 1982 Miramichi earthquakes (largest shock M5.7) have provided many seismological "surprises" (notably the swarm-like nature of the four M5 mainshocks, the large number of aftershocks, and the 1/2 g accelerations recorded at very high frequencies), but were not really large enough to produce substantial surface faulting or to allow a definitive relationship to geological observations. Neither, fortunately, did they occur near enough to any large towns to cause any significant damage. It is clear, however, that had they occurred close to a metropolitan area there would have been considerable superficial damage (cracked plaster, etc.) and the possibility of some structural failure or collapse of older masonry buildings in poor condition, with attendant fatalities.

The Miramichi earthquakes were too small and too remote to have had much affect on the popular perception of earthquake rise in Canada. There is still a feeling in the general public that earthquakes are confined to western Canada (or, indeed, to California). In fact, eastern Canadian earthquakes exceed M7, shake a much larger area because of the lower attenuation in the east, and affect many more people because of the higher population density. Figure 4.10.1 shows a crude attempt to place earthquake *risk* in Canada into perspective. The model used multiplies the annual probability of potentially-damaging ground motion (taken from the current National Building Code of Canada model for seismic hazard estimation and so including the effects of weaker eastern attenuation) by the population affected (as na alias for value of structures and potential for injury) and expresses the product at each place as a percentage of the Canadian total. The pie chart shows graphically what the historical record of earthquakes has demonstrated: life in the east has an associated earthquake risk. It would be naive to suppose that the 40-year absence of damaging earthquakes in southeastern Canada is what we should expect for the next few decades.

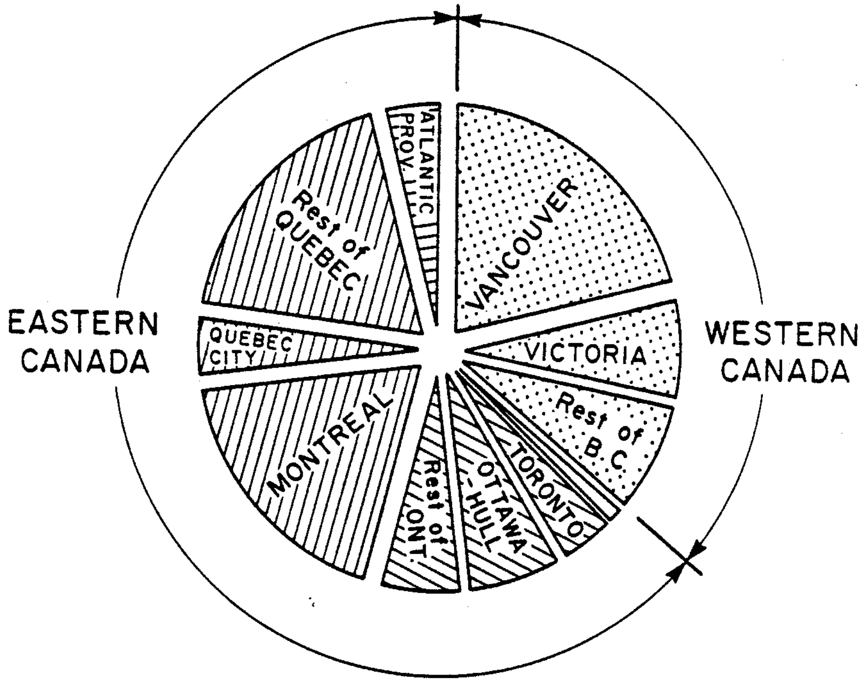

Figure 4.10.1. Pie chart showing relative levels of seismic risk in eastern and western Canada (Pittman and Adams, unpublished work, 1987).

4.11 SEISMICITY, EARTHQUAKE FOCAL MECHANISMS, AND CRUSTAL STRESSES IN THE GRENVILLE PROVINCE, AND THEIR RELATION TO THE SEISMOGENIC RIFT STRUCTURES OF SOUTHEASTERN CANADA

John Adams

Geological Survey of Canada

Program and Abstracts, 16th Annual General Meeting of the Canadian Geophysical Union, Montreal May 17-19, 1989 p. 18, 1989.

Recent detailed studies of seismicity in three zones in southeastern Canada - Timiskaming, Charlevoix, and Lower St. Lawrence - have revealed that many earthquakes occur in small, tightly confined clusters. Focal mechanisms form these clusters, Figure 4.11.1, (and from other scattered earthquakes across the region) show most earthquakes represent thrust or thrust/strike-slip faulting and that the NE-to ENE- directed regional stress field dominates, at least in the upper 10 km. The spatial distribution of earthquakes, and the strikes of the nodal planes deduced from the focal mechanisms suggest a casual relationship between the earthquakes and faults that broke the integrity of the North American craton and were active in the Silurian or more recently. In particular, Adams and Basham, 1989) have shown that reactivation of the crustal-scale normal faults along the ancient rifted margin of the Iapetus Ocean (now along the St. Lawrence river) and on a failed rift (Ottawa Graben) accounts for much of the seismicity occurring within the Grenville basement.

A second graben along the Saguenay Fiord was neglected in the above analysis because the level of contemporary seismicity was very low. In November 1988, the M_w 6 Saguenay Earthquake occurred on the south side of the Saguenay Graben and might have involved thrusting on a fault striking within 30° of the graben, or on a plane parallel to the rift faults under the St. Lawrence (90 km to the east). Retrospectively, it is obvious that the Saguenay Graben should have been included in the rift model to be used for seismic hazard estimates. However, one wonders how many other such features will be evident only after they experience a future large earthquake.

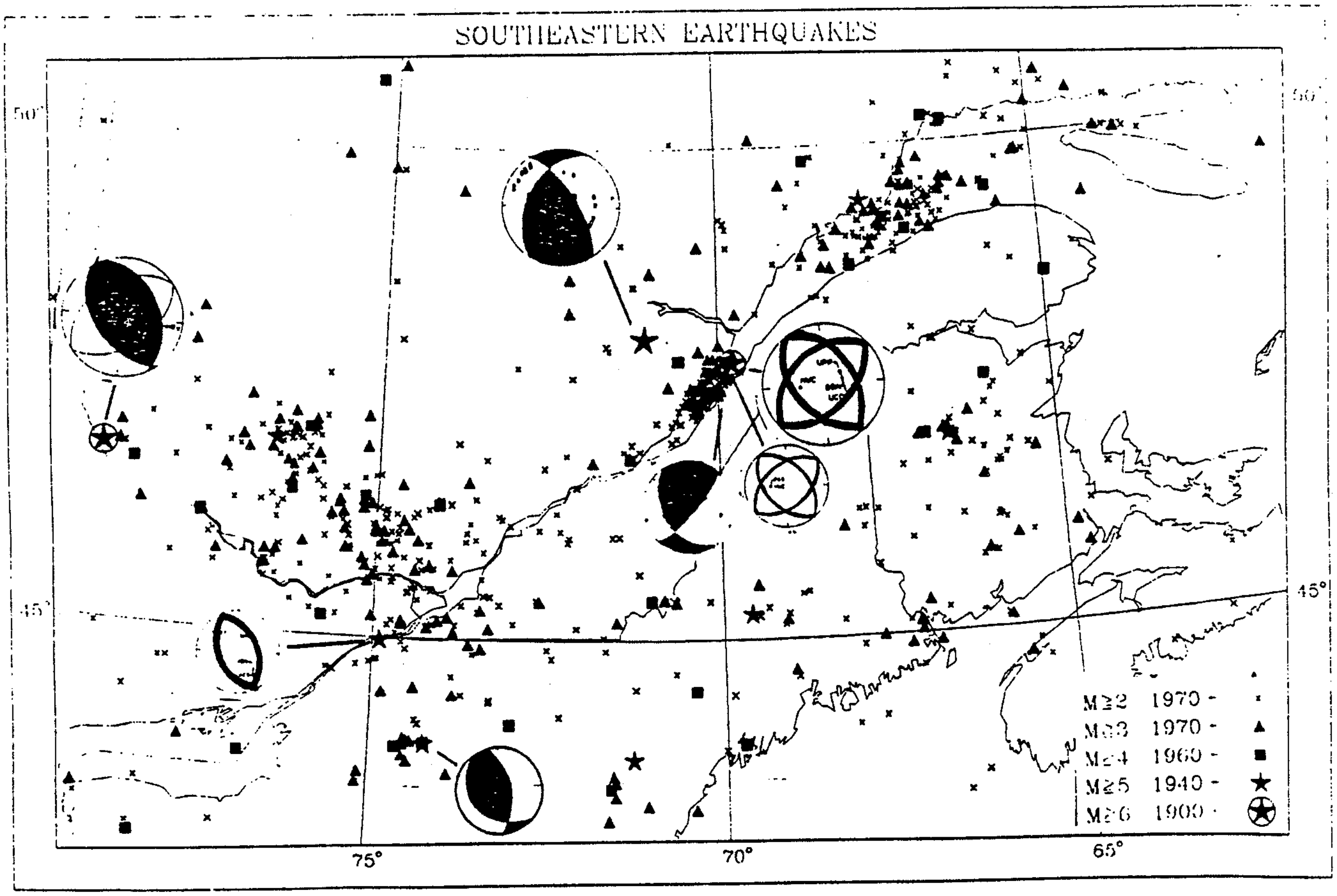

Figure 4.11.1. Available focal mechanisms for large M>5 earthquakes in the Grenville Province. From west to east they are: Timiskaming; 1935, Cornwall, 1944; Goodnow, 1983; Saguenay, 1988; Charlevoix, 1979, 1939, and 1925. Lack of shading denotes uncertainty in the orientation of the focal planes. All these earthquakes involve a large component of thrust faulting.

4.12 REVISED EPICENTRES FOR EARTHQUAKES IN THE LOWER ST. LAWRENCE SEISMIC ZONE, 1928-1968

John Adams, Jennifer Sharp and Kimberly Connors

Geological Survey of Canada

Geological Survey of Canada Open File 2072,
82 pp. 11 figures, April, 1989

ABSTRACT

Phase arrival times of 46 Lower St. Lawrence earthquakes (m_N 2.2 to 4.8). between 1928 and 1968 were re-examined to test the hypothesis that many of the early epicentres previously placed on land were mislocations of earthquakes that had actually occurred beneath the St. Lawrence River within the active zone defined by recent, better-located earthquakes. The magnitudes of the earthquakes were also revised.

Where possible, the original seismograms were re-read and new data added. Difficulties encountered when relocating these earthquakes included weak signals due to low seismograph gain, incompletely annotated seismograms, uncertain time corrections, and poor station distribution with respect to the seismic zone.

Of the 46 earthquakes, one was found to be a mislocated New Brunswick event, one a mislocated Quebec City event, four remained on the Gaspé Peninsula, six remained associated with the Manic-2 reservoir, six lie at least 10 km inland from the north shore, and 29 were found to lie under or within 10 km of the St. Lawrence River (Fig. 4.12.1). The median distance moved was 35 km and many of the earthquakes moved along the northwest-southeast axis because of the poor station control in this direction. Increasing the Lg velocity to 3.62 km/s removed a 10 km bias form some of the early epicentres. The study confirmed the hypothesis that most earthquakes in the Lower St. Lawrence lie under the river, that both north and south shores have lower levels of seismicity, and that the boundaries of the seismic source zone for the Lower St. Lawrence should be redefined.

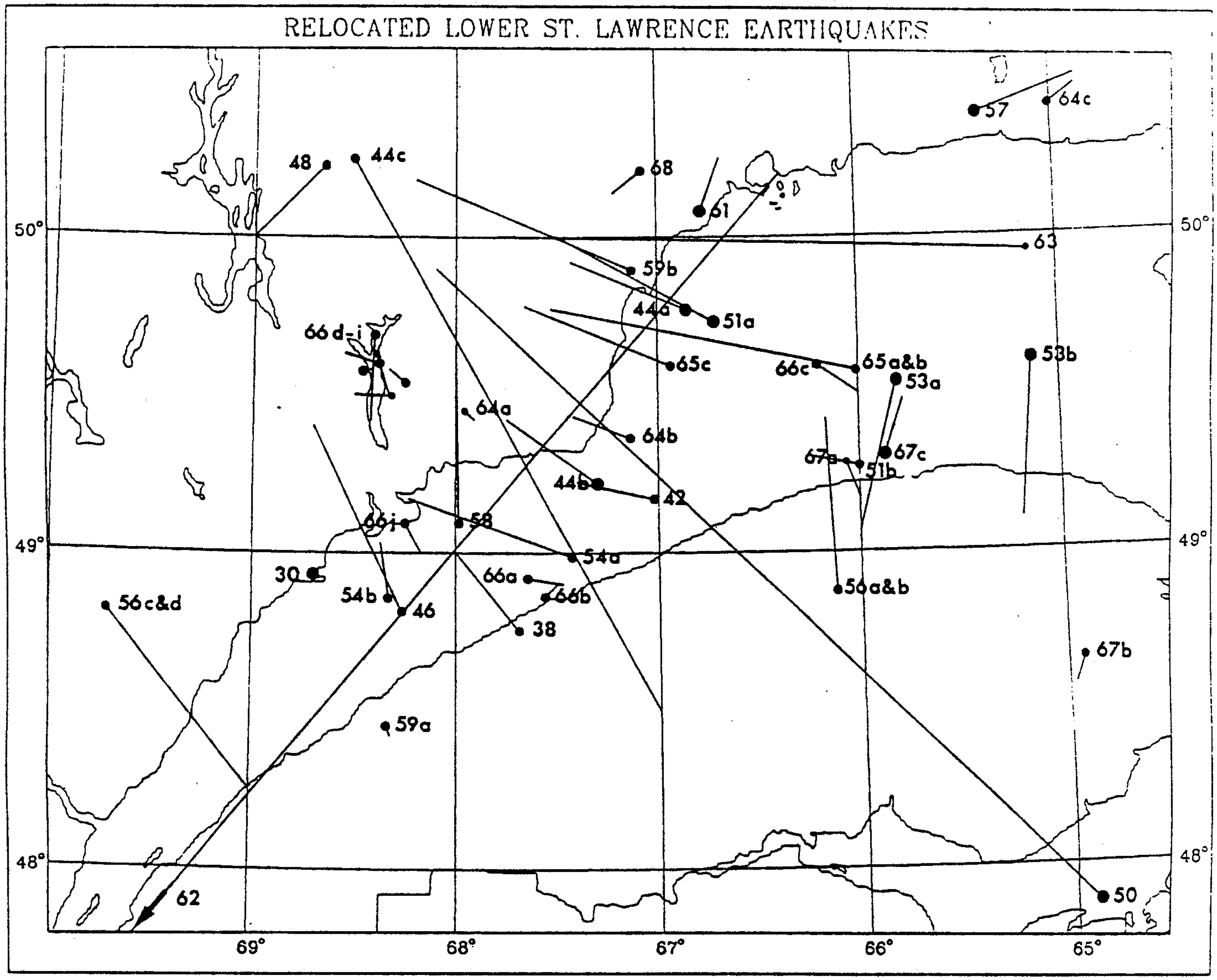

Figure 4.12.1. Revised seismicity of the Lower St. Lawrence, 1928-1968. Dots mark the new epicentres computed in this report, while the "tails" point back to the original epicentre. Year-letter combinations denote the individual events.

4.13 NEW FOCAL MECHANISMS FOR SOUTHEASTERN CANADIAN EARTHQUAKES - VOLUME II

John Adams, Andrew Vonk(1), Darren Pittman(2), and Howard Vatcher(2)

Geological Survey of Canada

Geological Survey of Canada Open File 1995, 97 p., January 1989

ABSTRACT

Using P-wave polarities, Sv/P amplitude ratios, and the program FOCMEC, we have determined the focal mechanisms of 19 recent earthquakes in southeastern Canada. (Fig. 4.13.1.). The mechanisms show thrust or thrust/strike-slip faulting is dominant in eastern Canada and is in response to nearly-horizontal compression. Local differences in the direction of compression can be used to identify small areas of anomalous stresses. In addition, the strike of the fault planes provides valuable insights into the seismotectonics of the western Quebec, Charlevoix, Lower St. Lawrence, and northern Appalachian regions.

Reference:

Basham, P.W., Weichert, D.H., Anglin, F.M. and Berry, M.J.
1982: New probabilistic strong seismic ground motion maps of Canada: a compilation of earthquake source zones, methods and results; Energy Mines and Resources Canada, Earth Physics Branch Open File Report 82-33, 202 pp.

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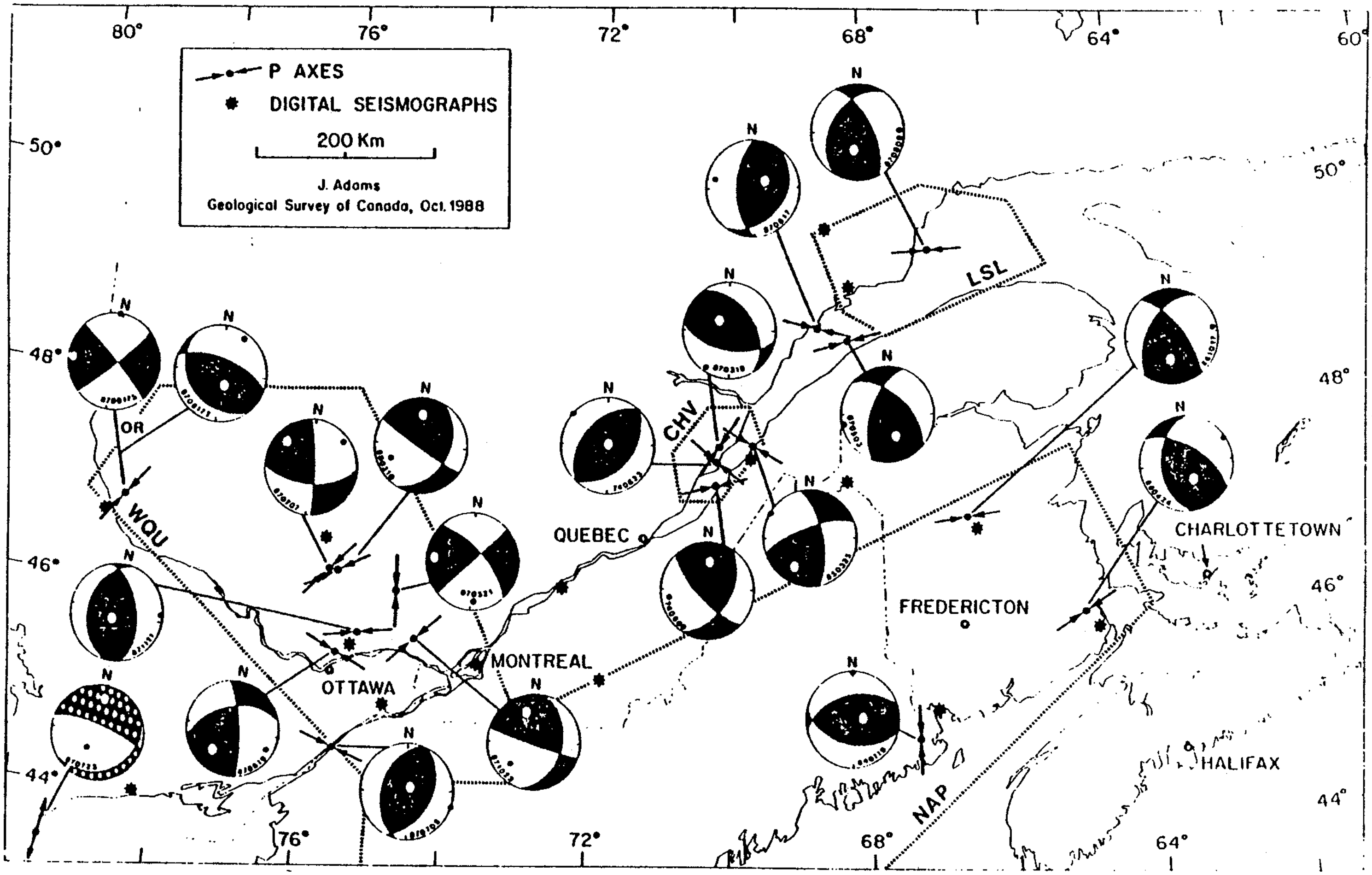

Figure 4.13.1. New focal mechanisms for southeastern Canada derived in this report . Shown are equal-area lower-hemisphere projections of the focal mechanism with compressional quadrants shaded. Black and white dots represent the P and T axes respectively. Pairs of inward-pointing arrows on the map represent the direction of maximum horizontal compression taken from earthquake P-axes. Dotted lines enclose the seismic zones of Basham et al. (1982). The mechanism for #870723, marked by white polka-dots, is poorly constrained by the data and should not be considered as reliable as the other solutions.

4.14 SOUTHEASTERN CANADIAN EARTHQUAKE ACTIVITY
JULY 1, 1988 TO JUNE 30, 1989

Janet Drysdale and Robert Wetmiller

Geological Survey of Canada

During the period July 1, 1988 to June 30, 1989, 312 earthquakes in southeastern Canada were analyzed for location and magnitude (Figure 4.14.1). Thirty-nine earthquakes were magnitude 3.0 or greater, the largest being the magnitude 6.0 Saguenay, Quebec earthquake on November 25, 1988. Fourteen earthquakes were reported felt in southeastern Canada. Figure 1 shows that, aside from the Saguenay earthquake, the pattern of activity continued to be similar to that of previous years, occurring primarily in the recognized seismic zones of West Quebec; Charlevoix, Quebec; Lower/St. Lawrence, Quebec; Miramichi, N.B.; and the Laurentian Slope.

There were several notable earthquakes recorded during the report period:

- A M4.7 foreshock to the Saguenay earthquake occurred on Wednesday, November 23 at 04:11 EST near 48.13°N, 71.20°W in the Laurentide provincial park of Quebec. It was strongly felt in the Chicoutimi area and was felt significantly in Quebec City. A few people in Montréal and Ottawa also reported the tremor. The Geophysics Division (GD) dispatched a field team to the epicentral area that day and had recorders set up at three sites close to the epicentre of the foreshock by the following afternoon.

- On Friday, November 25, 62 hours after the foreshock, the M6.0 Saguenay earthquake took place in the same epicentral area. Its epicentre was only a few km from that of the foreshock and still within 10 km of the portable recorders deployed by the GD field crew. The local recorders allowed the depth of the start of the rupture to be calculated accurately and confirmed that the event occurred unusually deep in the crust at a depth of 29 km. No seismic activity with magnitude grater that 1.0 had been detected by the portable recorders in the 24 hours prior to the mainshock. The Saguenay earthquake was felt with maximum intensity VII in the Chicoutimi-Jonquière-La Baie area, was felt strongly by most people within 500 km, felt by many within 1000 km and was perceptible by some people in special circumstances beyond 1000 km. The earthquake was felt south of Washington, D.C., north to Poste-de-la-Baleine, east to Goose Bay and Halifax, and west to Thunder Bay and Detroit. The total felt area appears to exceed 3 million square km. The GD sent over 2000 questionnaires to rural postmasters in Quebec, Ontario, the Maritime provinces and Newfoundland in order to determine the isoseismal distribution of the tremor. The Canadian data has been combined with similar data collected by the National Earthquake Information Centre in the U.S. to produce an intensity distribution map.

- Two M4 events in the Charlevoix-Kamouraska zone on March 9 and 11 were an earthquake doublet. The events had very similar relative times and waveforms on the Charlevoix Local Telemetered Network (CLTN) stations. Their hypocentre lay under the St. Lawrence river at a depth of 10 km at the northeast end of the seismic zone in the same area where the last large earthquake of March 01, 1925 began. Earthquake doublets of any size in the Charlevoix-Kamouraska seismic zone have been extremely rare events since detailed monitoring began in the zone in 1977. A doublet of this magnitude has probably not occurred in the seismic zone at any time previously since 1925. The GD will be monitoring Charlevoix-Kamouraska seismicity closely with CLTN in the future looking for more unusual features.

- The January-March 1989 period included one of the most unusual flurries of seismic activity experienced in eastern Canada in recent years. Starting with the Saguenay Earthquake on November 25, 1988 and continuing for approximately 4 months, exceptional earthquakes occurred in the Saguenay region, the lower St. Lawrence valley, the Atlantic margin, Charlevoix region, the Labrador Sea, the Ungava region and the Labrador margin. The regions are widely separate and no obvious relationship could be seen between the activity in the different regions. The sequence of these events was as follows:

#	Area	Mag.	Days After	Comments
1	Saguenay	6.0	0	largest in 53 years
2	Lower St. Lawrence	4.3	36	largest locally in 20 years
3	Atlantic Margin	4.7	68	largest locally in 15 years
4	Lower St. Lawrence	4.1	76	
5	Charlevoix	4.3	103	largest locally in 10 years
6	Charlevoix	4.3	105	repeated event
7	Labrador Sea	5.3	108	largest locally in 20 years
8	Ungava	5.7	110	largest locally in 30-50 years
9	Labrador Margin	4.1	120	

- Another significant event, possibly another member of the flurry noted above, occurred near Sundridge, Ontario on February 13, 1989. It was magnitude 3.5 and was felt with maximum intensity IV by local residents. The event took place in an area of historically low seismicity in northern Ontario, outside bounds of the West Quebec Seismic Zone, and was the largest event in the region in the last 44 years. Even more unusually it was preceded by a magnitude 2.2 foreshock and followed by a magnitude 2.6 aftershock.

- On September 9, 1988 the first earthquake ever located in Prince Edward County on the northeastern shore of Lake Ontario was recorded. It was only magnitude 2.2, but is considered significant because Prince Edward County is crossed by some of the possible extensions of the Clarendon-Linden lineament from northern New York State into Canada and the area has been recently selected as a study area for the enhanced multi-agency neotectonic investigations (MAGNEC). The event was thoroughly investigated by the GD and no source of blasting could be identified to explain it.

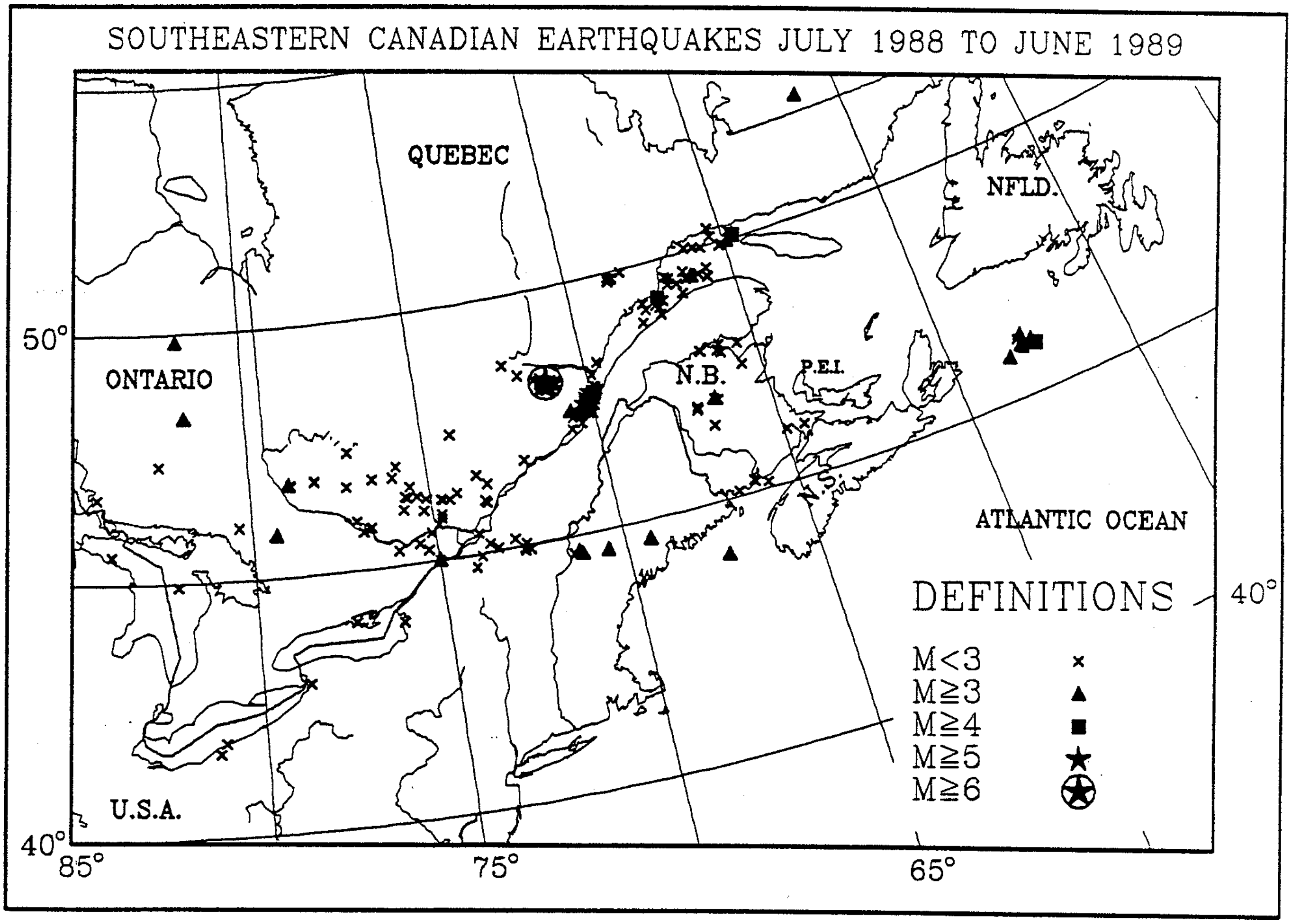

Figure 4.14.1. Southeastern Canadian earthquakes, July 1988 to June 1989.

4.15 SEISMIC ACTIVITY IN NORTHERN ONTARIO, 1988

R.J. Wetmiller and Mary Cajka

Geological Survey of Canada

This report summarizes seismic activity in northern Ontario and adjacent areas from January to December 1988. These events were located largely as a result of the additional facilities provided by Atomic Energy of Canada (AECL) to Geological Survey of Canada (GSC) in its task of monitoring seismicity in the northern Ontario portion of the Precambrian Shield.

EARTHQUAKES

There were 11 earthquakes located in the area under study during 1988. These are plotted in Figure 4.15.1 and summarized in Table 4.15.1. Five of the located events occurred just east of EEO near Témiskaming, Quebec, an area of continuing earthquake activity within the larger Western Quebec Zone.

Three events occurred near mining areas (east of Sudbury and between Sudbury and Timmins) but a thorough investigation has revealed no blasting activity and the events are considered to be earthquakes.

Of the three remaining events, one occurred in Ontario west of James Bay, the second occurred in Quebec east of James Bay and is probably an induced earthquake associated with the James Bay power project, and the third occurred near Atikokan, Ontario.

A full discussion of recent seismic activity in northern Ontario (up to mid-1987) is included in Wetmiller and Cajka (1989).

ROCKBURSTS

Rockburst activity continued throughout 1988 with almost 200 events being recorded in Canada. There were 11 events of magnitude 2.5 or larger that occurred in northeastern Ontario.

STATION OPERATION

A combination of equipment problems and operator replacement produced an overall efficiency for the network of 94.2% (slightly less than the minimum 95% generally expected).

Reference:

Wetmiller, R.J. and Cajka, M.G.
1989: Tectonic implications of seismic activity recorded by the northern Ontario seismograph network; Canadian Journal of Earth Sciences, v. 26, p. , February 1989.

TABLE 4.15.1
Located Local Earthquakes
January-December 1988
Northern Ontario

DATE	TIME (UT)	LAT. (°N)	LONG. (°W)	MAG.	COMMENT
Feb. 06	04:47	51.86	82.87	3.0	west of James Bay
Feb. 09	11:14	53.67	76.76	2.2	east of James Bay
Feb. 17	11:27	46.67	78.86	2.1	Temiskaming area
Mar. 11	18:13	46.51	80.34	1.8	east of Sudbury
Aug. 22	22:24	46.83	78.83	2.3	Temiskaming area
Sept.	12:15	48.28	81.74	3.0	south of
02	16:46	46.82	78.91	3.1	Kapuskasing
Sept.	18:24	46.80	78.83	2.6	Temiskaming area
29	01:55	46.81	78.84	1.2	Temiskaming area
Oct. 11	07:24	48.89	92.27	2.3	Temiskaming area
Oct. 15	01:04	47.34	82.52	2.4	near Atikonan
Dec. 03					north of Elliot
Dec. 25					Lake

TABLE 4.15.2
Recorded Rockbursts Magnitude 2.5 and Over
January-December 1988
Northern Ontario

DATE	MINE	LOCATION	MAGNITUDE
Feb. 03	Copper Cliff N	Sudbury	2.6
Mar. 10	Lockerby	Sudbury	2.6
Mar. 18	unconfirmed	Kirkland	2.5
June 19	Strathcona	Lake	2.7
June 21	Strathcona	Sudbury	2.7 (01:44UT)
June 21	Strathcona	Sudbury	2.7 (05:07UT)
Aug. 30	Creghton	Sudbury	2.5
Sept. 13	Strathcona	Sudbury	2.6
Sept. 27	Creighton	Sudbury	2.7
Nov. 07	Frood-Stobie	Sudbury	2.7
Dec. 31	Copper Cliff N	Sudbury	3.3
		Sudbury	

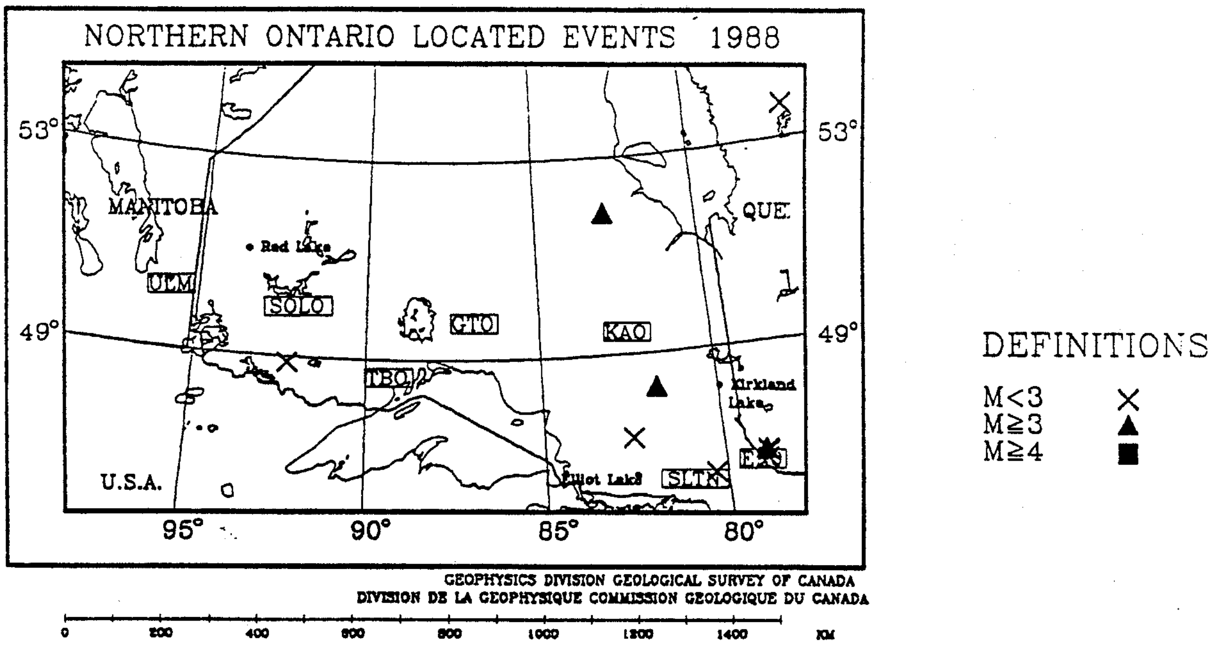

Figure 4.15.1 Located seismic events in Northern Ontario in 1988.

4.16 THE SEISMOGRAPHIC NETWORK OF THE CANADA CENTRE FOR MINERAL AND ENERGY TECHNOLOGY

M. Plouffe

Canada Centre for Mineral and Energy Technology
Elliot Lake, Ontario

Since 2985, the Canada Centre for Mineral and Energy Technology (CANMET) has contributed to the Canada/Ontario/Industry Rockburst Research Project, by analyzing data recorded by seismic networks around mining camps in northern Ontario.

Through northern Ontario, CANMET operates four seismographic stations located at Red Lake, Kirkland Lake, and Elliot Lake (2). The Elliot Lake stations began to operate in 1985, the Red Lake station in 1986 and finally the Kirkland Lake station in 1989. All these stations are comparable to the regional stations operated by the Geological Survey throughout Canada. Their main purpose is to record local mining-induced and natural seismicity.

Besides these regional stations, CANMET operates five macroseismic systems located in mines at Sudbury, Elliot Lake, Kirkland Lake and Red Lake. These systems record whole waveforms and are used to determine seismic parameters from rockbursts.

4.17 PREPARATION OF A BEDROCK STRUCTURAL MAP FOR SEISMICITY ASSESSMENT IN SOUTHWESTERN NEW BRUNSWICK

Kenneth S. Burke and Peter Stringer

University of New Brunswick

An outline geological map of the northern part of Passamaquoddy Bay, showing NW-trending faults, was produced at a scale of 1:50,000. This map is based on an atlas of geological maps of areas containing NW-trending faults prepared at a scale of approximately 1:7500 scale, compiled from published maps and reports and unpublished thesis, together with our own unpublished fieldwork in a few localities. All know outcrops are plotted on the 1:7500 scale maps.

The position of several of the NW-trending faults are uncertain and where the position is known, the nature of the displacement may be unclear or even contradictory. For example, over the 8 km known length of the fault at Berry Point, there is geological evidence for right lateral displacement, left lateral displacement, downthrow northeast and downthrow southwest at different points along its length. Actual exposures of the traces of NW-trending faults are rare throughout the region and no evidence of post-glacial displacement has been found.

A marine geophysical survey was conducted in Passamaquoddy Bay by the Atlantic Geoscience Centre during the summer of 1988 and interpretation of the high resolution seismic profiles and magnetic data is in progress. Preliminary interpretation of the magnetic data confirms the continuity of the Lower Jurassic Minister Island dyke across the Oak Bay fault, but supports the offset of the dyke to the east of Minister Island. The line of offset coincides with a linear distribution of pockmarks identified by Fader (1989) and also 'plumose structures', which may reflect active faulting in this zone. However, no displacement of the Quaternary sediments that overlie the bedrock has been detected in the seismic profiles over the possible fault zone.

Reference:

Fader, G.B.J.
1989: Cruise Report 88-018 (C), Phase 4, 88-018 (C), Phase 5 M.V. Navicula Passamaquoddy Bay and Bay of Fundy. Atlantic Geoscience Centre, GSC, Bedford Institute of Oceanography, P.O. Box 1006, Dartmouth, N.S. 22 p.

4.18 SUBBOTTOM PROFILING OF QUEBEC APPALACHIAN LAKES AND ITS POTENTIAL APPLICATION TO ASSESSING SEISMIC HAZARD

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*Geological Survey of Canada,
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Current Research, Part B, Geological Survey of Canada,
Paper 89-1B, p. 143-154, 1989.

ABSTRACT

Subbottom acoustic profiling was carried out on four Quebec Appalachian lakes located within 100 km of major seismic zones in St. Lawrence Valley and Miramichi Highlands of New Brunswick. Two of these lakes, Lac Témiscouata (Fig. 4.18.1) and Grand Lac Squatec, are thought to have been damaged by earthquakes because:

1. Bottom disturbance is widespread in both lakes and appears to be multicyclic;

2. The hummocky appearance of both resedimented and erode sediments is similar to features found in lakes observed to be damaged during historical earthquakes;

3. The geographical relationship between these lakes and the Charlevoix seismic zone provides a plausible mechanism for dislodging sediment from slopes beneath the surface of the lakes.

RESUME

Au Quebec, on a réalisé des profils acoustiques du fond de quatre lacs de la région appalachienne, situés dans un rayon de 100 km à partir des grandes zones sismiques de la vallée du Saint-Laurent et des hautes terres de Miramichi au Nouveau-Brunswick. On estime que deux de ces lacs, le lac Témicouata et le Grand Lac Squatec, ont été endommagés par des séismes, puisque:

1. les perturbations du fond couvrent une grande surface des deux lacs et semblent être multicycliques;

2. l'apparence bosselée des dépôts resédimentés et érodés rappelle des structures découvertes dans des lacs ayant subi des dommages observés durant les séismes de la période historique; et,

3. la relation géographique entre ces lacs et la zone sismique de Charlevoix peut agir à titre de mécanisme plausible responsable du décollement des sédiments de pentes situées au-dessous de la surface des lacs.

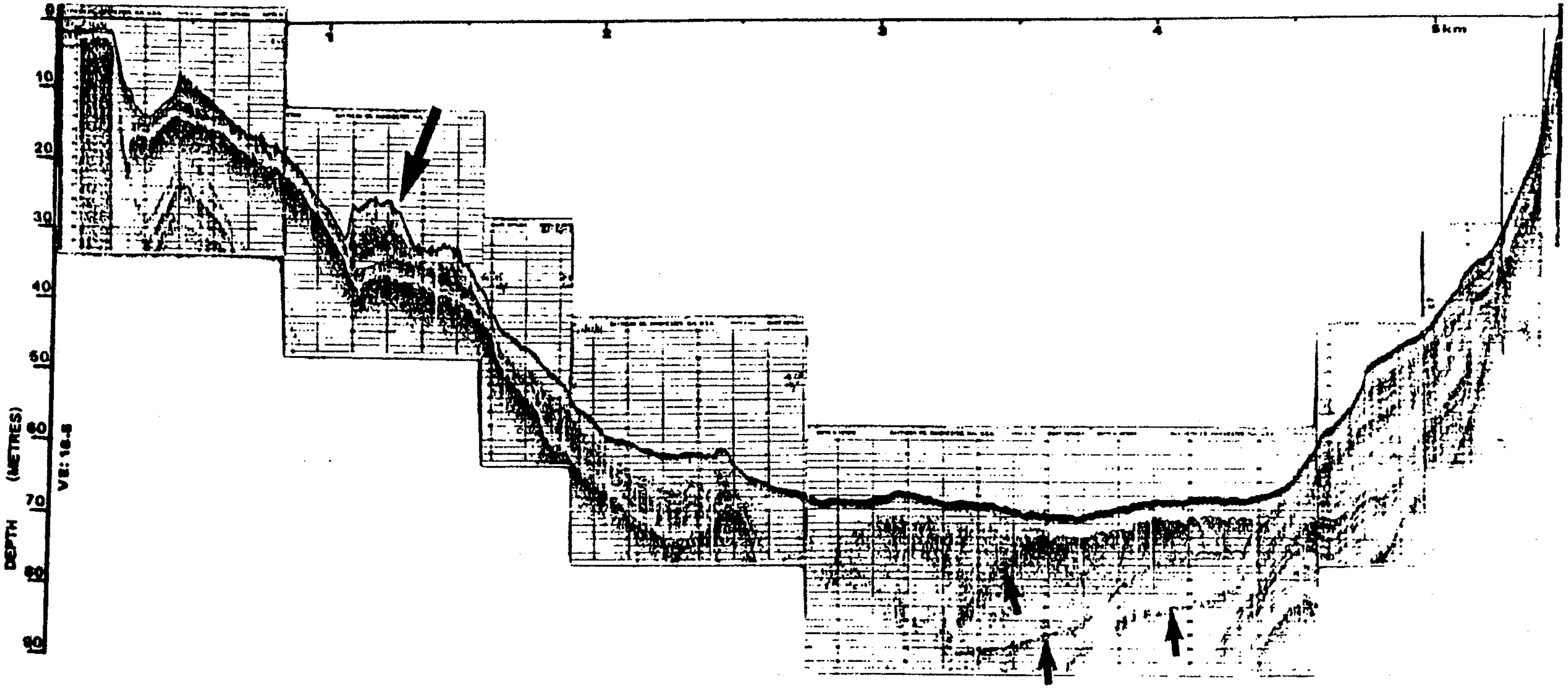

Figure 4.18.1 Profile showing typical hummocky bottom in central Lac Témiscouata. Small arrows point to buried hummocky erosional or depositional surfaces that may mark tops of old, seismically induced, slumped deposits. Large arrow points to disturbed (erode or slumped), acoustically laminated sediment.

4.19 A STUDY OF THE SEISMICITY OF OHIO USING GEOPHYSICAL, STRUCTURAL, AND HISTORIC SEISMIC DATA.

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**Pollution Control Systems, Inc.

Earthquakes are relatively rare events in Ohio with only 117 having occurred between 1776 to 1988. Although damage from these events was limited, the potential for damage in the region is enhanced by the poor attenuation of seismic waves and inadequate preparation for damaging earthquakes. Earthquakes in the western U.S. are felt over relatively small areas whereas midwestern quakes can be felt over larger areas so that even a minor earthquake has the potential to affect a large population. Without the large number of events to raise the civil interest there are relatively few communities in Ohio which have earthquake response plans in place, and there is little public education on seismic hazards.

When assessing the seismic risk of an area, it is possible to assume that the likelihood of future occurrences can be predicted from the history of past seismicity (Howell and Schultz, 1975). An historic epicentre map was compiled using data from the Earthquake Data Centre in Golden, Colorado, and histograms of frequency and intensity distribution were generated.

Ohio is noted for two main seismic zones. One the Anna region, has experienced 32 earthquakes since 1776, and the second, northeastern Ohio region near Cleveland has had a recent upsurge in activity, perhaps in part due to well injection (Monastersky, 1986). The distribution of events near Cleveland, Cincinnati, and Toledo may be a function of population concentration. In particular, the earthquakes described during the 1800's are highly biased by settlement patterns. This may be seen in data distribution for the Anna seismic zone. The majority of seismic events were of Mercalli intensity III, with very few either above or below.

It is difficult to locate and define active faults in Ohio. Glacial till covers approximately half of the state, although some fault-related features are visible through the use of satellite imagery. Historic seismic data were compared with LANDSAT Thematic Mapper (TM) lineaments, some of which are spatially related to oil fields and gravity and magnetic lineaments. Geophysical data include residual total intensity aeromagnetic anomaly and Bouguer gravity maps which were processed by GeoSpectra Corp. of Ann Arbor, Michigan). The potential field images were illuminated to enhance lineaments. The illuminated data were presented as a grey scale over a colour intensity image. It was noted that there is a relationship between mapped locations of epicentres and lineaments from potential field data, suggesting basement control of faulting. Interpretations of a LANDSAT TM image for northwest Ohio shows that potential field and satellite image-derived lineaments have similar azimuths and locations.

Structural lineaments were derived from wells which reach the Trenton Formation (Van Wagner, 1986). Those which define producing oil fields throughout the entire state of Ohio are coincident with known epicentres, suggesting that the lineaments are probably faults. The resulting distribution of mapped faults and epicentres is consistent with the model put forth in Sandford et al., (1985), regarding basement faulting.

In conclusion:

1. There is a variation in seismicity with time which may be biased by population distribution;

2. There is a variation in reported intensity, throughout the state;

3. Epicentres are related to limits of oil production, LANDSAT TM lineaments, and gravity and magnetic lineaments, indicating basement involvement in historic faulting.

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4.20 AN UPDATE ON THE SEISMICITY OF NORTHEAST OHIO

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The increased interest in the seismicity of northeast Ohio is the result of the magnitude 5 Leroy earthquake which occurred on January 31, 1986. This event was consistent with the historical seismicity of the region. Nonetheless, because of its proximity (10 miles) from the Perry Nuclear Power Plant and its timing (just few months before starting of low power testing operation), an environmental group expressed some concern about the safety of the plant. The US Nuclear Regulatory Commission requested Cleveland Electric Illuminating Company to engage in several studies to substantiate that the maximum earthquake potential chose to establish the safe shutdown earthquake design response spectrum was still adequate. It was a fact that high frequency peak acceleration had exceeded the design spectrum at frequencies greater than 14 hz; these excedences, however, had caused no damage or resulted in any problem whatsoever at the plant. Two seismic networks had to be installed for monitoring the regional activity and the immediate area around two deep injection wells suspected to have induced the earthquake. Dynamic analysis of some plant structural components, geological field surveys, detailed aeromagnetic and gravity surveys were also conducted prior to the final licensing of the plant.

At present, a low rate of microseismicity is observed (about one event per month with M_c less than 1.0); the seismicity pattern does not confirm the existence of a single, large scale capable fault coinciding with the Akron Magnetic Boundary. Some small microearthquakes in the vicinity of the injection wells could be related to them, but such a relationship is not yet demonstrated. Re-evaluation of some historical events used to support the hypothesis of an active major tectionic structure supposedly revealed by the AMB suggests that such a scenario is highly speculative.

In summary, a call is made for a clearer distinction between highly speculative tectonic models and those which are truly supported by high quality data from observational seismology, field geology, modelling and interpretation of geophysical data.

4.21 THE ONSET OF THE CURRENT STRESS FIELD IN EASTERN NORTH AMERICA

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Stress measurements made in recent years (e.g. McKay, 1986) show that the greatest principal horizontal compressive stress (σ_1) in eastern North America is generally, but not exclusively, in the northeast quadrant. Results of the direct measurements have been corroborated by well-constrained focal mechanisms, consequent upon earthquake activity, and observations of surfically expressed deformation, such as pop-ups (in open fields and on quarry floors) and offset boreholes. The focal mechanisms generally reveal either north-northwest to northwest oriented reverse faults, as in the case of the 1988, M_{bLg}=6.5 Saguenay earthquake (North, et al, in press), or north-northeast striking wrench faults, as exemplified by the 1986 M_b=5.0 Leroy earthquake in Ohio (Weston Geophysical, 1986). Pop-ups normally trend west-northwest to northwest and boreholes area displaced in a reverse sense, commonly toward the east-northeast or west-southwest. All of these phenomena, whether at depth or on the surface, are the result of stress accumulation and release of stored strain energy and all are kinematically congruent (McKay and others, 1986).

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, in preparation). 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. Nonetheless, the relative ages of the two kinds of structures are generally difficult to determine. 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, compressional structures indicating that the bounding normal faults are older. Sub-horizontal slickenside 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, to date, where a relative age relationship can be established unequivocally between tensional and compressional structures the latter are always shown to be

younger. Following the crustal compression caused by continental collision during the Paleozoic, crustal extension dominated much of the Mesozoic. It lasted at least through the Jurassic Period, if not into the Lower Cretaceous when the alkaline rocks, which make up the Monteregian Hills of Quebec and the White Mountains of New Hampshire, USA, were emplaced. The Monteregian Hills, which formed about 124±1 my ago (Foland and others, 1986), define an east-west to west-northwest line. The eastern end of this line appears to be fairly close to the northward projection of the north-south oriented White Mountains, which were emplaced approximately 120 my ago (Foland and Faul, 1977).

Fractures parallel to normal faults in and around Montreal, and dipping 50°-70°, were identified in the gabbro on Mount Royal one of the plugs of the Monteregian suite. These fractures are interpreted as incipient normal faults which post-date crystallization, though no displacement was recognized along them. If this interpretation is correct, it implies that tensile stresses were active following crystallization of the gabbro. Despite speculation about the origin of the fractures, the overall picture seems to support the model put forth by Kay (1942), who proposed that the intrusion of the Monteregians was related to crustal extension. It also appears to be suited to the concept of a hot spot.

The coarse-grained igneous rocks of the Monteregian Hills, which in the Montreal area rise some 200-300 metres above the present-day surface, indicate that there had to be a relatively thick supracrustal suite into which these plutons were intruded. The confining pressures exerted by this suite upon the rocks currently exposed at the surface may have been sufficient in Cretaceous time, and perhaps for some time thereafter, to permit permanent deformation by bending.

The similarity of the current stress field to that inferred from the 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 Monteregian Hills, suggests that the current stress field may have evolved as far back as Cretaceous time.

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Weston Geophysical Corporation
1986: Investigations of confirmatory seismological and geological issues, northeastern Ohio earthquake of January 31, 1986; 70 p. plus diagrams.

4.22 BEDROCK EXPRESSIONS OF INTRAPLATE SEISMOGENIC FAULTS

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Studies of brittle structures in the epicentral areas of the 1983 Goodnow (mb=5.1) and the 1985 Ardsley (mL=4.0) earthquakes in New York State indicate that intraplate seismogenic faults have subtle, but recognizable, expressions in the exposed crystalline bedrock. The 1983 Goodnow rupture and the 1985 Ardsley rupture are correlated with the Catlin Lake fault zone (CLFZ) and the Dobbs Ferry fault zone (DFFZ), respectively, though both ruptures are totally confined to the subsurface. The structures had been recognized as brittle features prior to these earthquakes (Isachsen and McKendree, 1977; Hall, in press), but neither had been mapped as a fault because lithologic markers are not substantially offset by them. We interpret these structures as the surface expressions of seismogenic faults because of the following observations: (1) the spatial correlation of the extrapolated rupture plane, as defined by aftershock hypocentres, with a prominent fracture-controlled topographic lineament; (2) occurrences of increased joint density, zones of anomalous fracturing, slickenside joints, and faults along these lineaments; and (3) kinematic agreement between mesoscopic fault zones with the seismic source mechanisms.

The CLFZ, in the central Adirondacks, is interpreted as a 12-15 km long, 2 km wide brittle structure composed of NW to N-S and ENEN to E-W striking fracture sets. Bedrock mapping indicates that his feature is structurally much more complex than other fracture-controlled lineaments in this region which are primarily N-S trending. In addition to mesoscopic faulting associated with the CLFZ, a suite of microfractures proposed by Mawer and Williams (1985) to be indicative of paleoseismicity is found along an E-W striking marble/gneiss contact where the CLFZ transects it. Pseudotachylite-filled microfractures are present at the western terminus of this marble belt, about 2 km north of the mainshock epicentre.

Well-exposed mesoscopic faults located about 4 km northeast of the Goodnow mainshock exhibit a geometry similar to that inferred for the CLFZ. The Goodnow rupture plane was oriented 345°±10°, 60°±10°W; slip during the event was reverse with a small right-lateral strike-slip component. Eight faults have been identified in this outcrop and all have strikes between 313° and 355° and dips between 50°W and 89°E; five of these are oriented 332°-355°m 63°-69°W. A NNW striking joint set at this locality implies that these faults were initially joints. The only fault that has distinct markers along it has a 5 cm right-lateral strike-slip component; only a map view is available, so that any dip-slip motion, if it exits, can not be directly observed. On two fault surfaces striking 355° dip-slip slickenside are present. A fault with a 2-3 cm wide cataclastic zone has a set of NE striking splay fractures that swing into parallelism with a prominent set of ENE striking joints in this outcrop. This is consistent with a ENE compression direction, similar to the 1983 Goodnow P-axis.

The DFFZ is one of several northwest striking faults in the Manhattan Prong of probable Mesozoic age. The DFFZ is comprised of NW striking, subvertical left-lateral faults., WNW striking joints and faults, and locally occurring E-W fractures that tend to have right-lateral offsets. At one locality, pseudotachylite is associated with the E-W striking faults. Superimposed slickenside on some northwest striking faults suggest an earlier dip-slip phase of movement on these surfaces. Patterns of subsidiary fractures and offset markers indicate that this earlier phase down-dropped southwestern blocks and had a right -lateral component. We interpret the later left-lateral phase to have reactivated older faults, and perhaps as a result of stress concentration near these surfaces, activated joints as small left-lateral faults. Fracture geometries and offsets associated with northwest striking left-lateral fault zones are consistent with a compression direction close to E-W.

The 1985 Ardsley event was a west-northwest striking left-lateral rupture; mechanisms of the mainshock and two aftershocks suggest approximately E-W compression, consistent with the kinematics of bedrock faults.

Several aspects of these studies are topics of ongoing and future research. The occurrence of pseudotachylite is of particular interest. Pseudotachylite occurs locally in both areas, about 2 km form the mainshock epicentre, as injection veins and vein networks. The veins are up to 1 mm wide and have spherulitic textures characteristic of devitrified glass. We have not yet identified a major generation surface and, therefore, cannot unequivocally relate pseudotachylite generation to neotectonic seismic activity. Nevertheless, its presence and spatial relationship to the microfracture suite in the Goodnow area are of interest.

Because both fault zones evolved largely from preexisting joints, determinations of ages of regional joint sets in both study areas would put an approximate limit on the age of the faults. Fault zone segmentation is believed to be related to local variations in strikes of preexisting joints; this, in turn, seems to be lithologically related. In both areas marble/gneiss contact regions appear to be areas of more widely distributed brittle deformation. The DFFZ is inferred to be segmented with bends of the fault zone correlating with crossings of marble. A better understanding of fault zone structure and segmentation is important because magnitude estimates for ruptures of individual fault segments could be made (i.e. applying the concept of a characteristic earthquake to an intraplate structure).

Comparisons should also be made of faults in the Adirondacks and Manhattan Prong that are similar to the CLFZ and the DFFZ, respectively. Literature reviews of local seismicity and brittle bedrock structure suggest that other events in these areas may be related to similar structures.

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4.23 INDICATORS OF RECURRING STRUCTURAL INSTABILITIES IN PRINCE EDWARD COUNTY, SOUTHERN ONTARIO

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Detailed investigations of probable neotectonic features have been confined to an area of approximately 100 square kilometres in the southern part of Prince Edward County, Ontario. The topography is generally flat to very gently undulating and the relatively continuous bedrock exposure along the shoreline of Lake Ontario consists of predominantly fault-lying to gently dipping bedding plane surfaces with little or no exposure of the strata in cross-section. Cross-sectional exposures of the bedrock are limited to a few road cuts and localized cliff exposures in the western part of the study area. Observations of the bedrock geology have therefore largely been restricted to the plan view which has led to uncertainties regarding the third dimension of some bedrock structures. To gain a better understanding of these structures at depth, investigations outside of the study area have focused on cross-sections of the strata exposed in the Picton and Mountainview quarries, in the northeastern and central parts of the county, and in the shoreline cliffs along the south side of Prince Edward Bay at the southeastern tip of the peninsula. Mesoscopic scale faults were identified in the Picton Quarry and in the Prince Edward Bay area.

The Picton Quarry, 4 kilometres north-northeast of Picton, is located adjacent to Long Reach which is the topographic expression of the Picton Fault. Up to 55 metres of the Lindsay and Veralum Formations are exposed in vertical section. The central part of the quarry is cut by a 40 metre wide zone that includes an ultra-mafic dyke, several faults, many calcite veins, and closely spaced fractures. On either side of this zone, the fractures are well developed but more widely spaced. The dominant fracture orientation is 085° dipping 77° with 229° dipping 88° and 028° dipping 87° being less common. The ultramafic dyke is up to 32 centimetres wide, intrudes a 1.25 metre wide zone of intensely fractured limestone, and trends 090° dipping 76° to the south. Horizontal slickenside were observed both on the dyke and on the fracture faces of the adjacent country rock. A large fault trending 238° dipping78° appears to transect the dyke. Sub-horizontal slickenside on these fault surfaces suggest strike-slip movement but it is not known whether the dyke or the fault is displaced as their intersection is not exposed.

Barnett et al. (1984) conducted palaeomagnetic and K-Ar age-dating studies on the dyke. They concluded that intrusion occurred in the Jurassic (173 Ma) during which time rejuvenated basement structures probably served as conduits for deep seated magmatism. They suggest that rejuvenation may have been a distal expression of continental rifting prior to the opening of the North Atlantic. The presence of horizontal slickenside on the dyke suggests that strike-slip motion occurred along fracture zone sometime after the Jurassic emplacement of the dike. This in turn implies two periods of instability: one marked by the intrusion of the dyke during the Jurassic; and another, indicated by the slickenside, occurring at a later time.

The Mountainview Quarry, located 17 kilometres to the northwest of Picton, exposes an 8 to 10 metres vertical section of the Lindsay Formation. Fractures are widely spaced and generally not well developed. The dominant fracture orientation is 247° dipping 88°, with 282° dipping 86° and 071° dipping 88° also being common. Brittle deformation is exhibited by a gentle concentric fold trending 335°, and a "kink-band" trending 169° dipping 70°.

Several faults were observed in the cliff exposures, accessible only by boat, along he south side of Prince Edward Bay.

(i) A normal faults that is well exposed on the beach at Point Traverse trends 120°, dipping 80° to the southwest and with the Hangingwall displaced downwards 40 centimetres relative to the footwall. The fault zone is weathered with no apparent infilling material. Slickenside are not common but when observed are vertical. Ductile deformation of the adjacent strata has occurred on both sides of the fault plane for a distance of about 20 centimetres.

(ii) A conjugate pair of low-angle faults, striking 315° and dipping 17° and striking 144° and dipping 19° respectively, were observed where a prominent lineament observed on the aerial photographs intersects the cliff about 3 kilometres west of Point Traverse. Slickenside perpendicular to the strike of the fault were observed. Reverse movement of about 2.25 metres, or more, on the fault is possible, but the amount of movement is difficult to establish as marker horizons in the unit are poor. Gentle warping of the otherwise flat-lying beds over 30 to 40 metres adjacent to the fault is probably due to ductile deformation. The occurrence of low-angle reverse faults sub-parallel to the observed normal faults prompts questions about their relative ages which at present is not known. The faults however imply the possibility that two periods of stress, one compressional and one extensional, have acted upon the rocks.

(iii) Strike-slip faults occur in two closely spaced and intensely fractured zones trending 273°. The faults are marked by calcite veins and the strike-slip motion is suggested by the presence of sub-horizontal slickenside on the fault surfaces. The faults are partially infilled with calcite which is generally euhedral with well developed crystal terminations. This suggest that deposition of the calcite occurred after the strike-slip motion, perhaps during a later period of extension.

The presence of sub-parallel faults with apparently opposite senses of movement, faults with evidence of two or possibly more periods of movement, and the observation of both ductile and brittle deformation structures suggest that the tectonic history of Prince Edward County is more complex than previously believed and that the area has been subjected to several periods of deformational stresses. The field observations reported here indicate that periodic rejuvenations of the structures probably occurred between the late Ordovician to some time after the Jurassic but the presence elsewhere in the county of neotectonic features (McFall el al., 1988) suggests a more recent period of instability. Ongoing stress relief is indicated by the presence of earthquake activity related to some of the major structures which transect Prince Edward County (McFall et al., in preparation). There is a potential for future movement as many of the observed structures are apparently not yet "healed".

The presence of periodically rejuvenated structures and neotectonic features in southern Ontario has important implications for the construction of major engineering structures. A clear understanding of these geological features, the stresses which formed them and how they may act in the future is a necessary component of proper site evaluation and suitable construction design.

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4.24 RECENTLY DISCOVERED GEOLOGICAL FEATURES AND THEIR POTENTIAL IMPACT ON THE NUCLEAR POWER PLANTS AT DARLINGTON AND PICKERING, ONTARIO

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Atomic Energy Control Board
Internal Assessment Report

ABSTRACT

A prominent north-northeast oriented aeromagnetic lineament has been identified on a map published recently by the Geological Survey of Canada (Aeromagnetic Total Field Map 7334G, 1987). This lineament extends from the Niagara Oeninsula across Lake Ontario and northward to at least the latitude of Lake Simcoe, a distance of more than 150 km. In addition to the lineament, east-northeast trending linear patterns in young sediments on the bottom of Lake Ontario and diversely oriented pop-ups (?) which cut those sediments, were discovered in the Toronto-Burlington area within the last two years by Thomas and others (personal communication).

The magnetic lineament appears to line up with the Central Metasedimentary Belt Zone, passes practically beneath the Pickering Nuclear Generating Station and lies about 30 km west of the Darlington Nuclear Generating Station. Under Lake Ontario, it is superimposed on a linear Bouguer gravity anomaly. Since it is composed of at least two different geophysical signatures (though dominated by the magnetics) and extends from the Niagara Peninsula through Pickering, it is referred to as the Niagara-Pickering Linear Zone (NPLZ). Magnetic data suggest that the NPLZ may be the signature of a fault; geological data lend support to this hypothesis and one 19th century earthquake on the Niagara Peninsula occurred very close to it. The linear patterns in the lake bottom sediments may be, and the pop-ups (?) most likely are, tectonic in origin.

A series of aligned, but discontinuous, north-northwest trending linear Bouguer gravity anomalies crosses western Lake Ontario, also in the vicinity of both the Darlington and Pickering Nuclear Generating Stations, and extends from North York State into Georgian Bay. A magnetic lineament parallels this series of Bouguer anomalies in its traverse from north of the Niagara-Pickering Linear Zone into, and along side the east coast of, Georgian Bay. From Lake Simcoe to the northeastern corner of Georgian Bay, a topographic lineament is superimposed on both the gravity and magnetic lineaments. The topographic lineament may also extend south-southeastward into New York State. The spatial relationships of the differently expressed lineaments to each other implies that each represents a different signature of the same major crustal structure or structural zone, referred to here as the Georgian Bay Linear Zone (GBLZ).

A north-northwest trending belt of earthquake epicentres, which includes the Lockport, N.Y. earthquake (est M=5.0) and the Attica, N.Y. earthquake (M-5.8), lies just east of, and parallels, the entire length of Georgian Bay en route to Attica, New York. The proximity and parallelism of the Georgian Bay Linear Zone to this belt of earthquake epicentres implies that the Georgian Bay Linear Zone may be tectonically active.

The Niagara-Pickering and Georgian Bay Linear Zones appear to intersect very near Pickering and within about 30 km from Darlington. This, combined with the presence of high horizontal stresses in the area, previous occurrences of moderate to large earthquakes, evidence of brittle faulting along the northward projection of the NPLZ and the implication that at least the GBLZ may be seismically active , suggests that many of the ingredients necessary for an earthquake of at least M=5.0 to M-6.25 exist near both Darlington and Pickering. Therefore, it is necessary that the region encompassing the Niagara-Pickering and Georgian Bay Linear Zones, as well as the other newly discovered structural features, be properly evaluated in order to determine whether or not the current Design Basis Seismic Ground Motions (DBSGM) for Darlington and Pickering are adequate.

4.25 DRILL TARGETS IN THE CENTRAL METASEDIMENTARY BELT, GRENVILLE PROVINCE OF ONTARIO

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Scientific Drilling: Southern Ontario Algonquin Arch Transect;
Canadian Continental Drilling Program Report 89-2, p. 24-28, 1989

The Central Metasedimentary Belt (CMB) of eastern Ontario is the best understood of any part of the Grenville Province, being almost completely covered by 1:50,000 geological mapping. A new compilation of aeromagnetic and gravity data at 1:1,000,000 (Forsyth et al., in press) displays improved resolution of Grenvillian structural features beneath the extensive Paleozoic cover in the region. It allows many of the lithotectonic units observed in outcrop to be traced northeasterly into Quebec and southwesterly under the Great Lakes and into the northern United States. The compilation also reveals several terranes that are not continuous with known terraces in the exposed Shield.

Figure 4.25.1 shows the main features of the regional gravity field and their relation to terrane boundaries proposed by Brock and Moore (1983) and Davidson (1986). Figure 4.25.2 is a shaded relief aeromagnetic map superimposed on the same base. The Clarendon-Linden high, a regional gravity feature, coincides approximately with the boundary between the Elzevir terrane and Frontenac-New York Lowlands terrane, which are geologically distinct and possess characteristic aeromagnetic patterns. South of Lake Ontario this zone is seismogenic and appears to be associated with normal faulting (Forsyth et al, in press).

The CMB Boundary Zone is also marked by a significant change in the aeromagnetic field pattern, but both aeromagnetic and gravity signatures are less conspicuous along strike (Forsyth et al, in press). In the vicinity of Toronto and projection of this zone meets a terrane with an entirely different aeromagnetic signature that continues to the south beneath Lake Erie.

Scientific drilling in general may be justified by one or more objectives:

1. to obtain an unweathered, continuous sample of intermittently exposed and poorly preserved rocks;
2. to test the continuity of bedrock features at surface;
3. to identify and calibrate the nature of key geophysical anomalies that correspond to poorly exposed or unexposed geological structures;
4. to measure and monitor physical properties at depth.

In the shield of eastern Ontario, exposure is generally of sufficient quality that the first objective does not apply. The other three are, however, valid for this region.

Continuity of bedrock features

Exposed geological subdivisions of the CMB have distinctive geophysical signatures that continue beneath Paleozoic cover. The Elzevir Terrane, for example (3, Fig. 4.25.2) is characterized by a relatively low-amplitude magnetic pattern truncated by subcircular highs, that reflect, in the region of the exposed shield, late mafic and alkalic intrusive bodies. Some of these have associated contact-metasomatic ore deposits e.g. iron at Marmora (Fig. 4.25.2) and gold at nearby Deloro. This pattern continues southward and is particularly prominent both north and south of Lake Ontario. Near Port Hope there is also a prominent magnetic lineament that appears to project from a thick (rift-related?) basaltic lava succession. Whether these features can simply be correlated with their exposed counterparts will not be known without coring.

Identification of unexposed structures

The southward continuation of the CMB Boundary Zone and adjacent Bancroft Terrane (1 and 2, Fig. 4.25.1) is unclear. The nature of this zone, which is a regional tectonic contact between Aphebian basement rocks and the underlying allochthonous (?) Grenville Supergroup, is important to tectonic models of the Grenville Province. It also has tectonic significance because of its association with rare-element minerals in the Bancroft area. Just west of Oshawa, the aeromagnetic pattern suggests that the above divisions terminate and, farther south, their places are taken by new terraces, with different signatures, that underlie the northwest shore of Lake Ontario and are nowhere exposed at surface.

Recently proposed tectonic models for the CMB (see Moore, 1986) allow the possibility that the entire region is an allochthon that lies on the Central Gneiss Belt to the northwest along the CMB Boundary Zone and is bounded by the Adirondack Highlands segment of the Central Granulite Terrane to the southeast (Carthage-Colton-Labelle mylonite zone, nos. 5-6, Fig. 4.25.1). Gravity modelling in the CMB (Real and Thomas, 1987) suggests that surface features do not extend below about 5 km, thus a décollement may exist at that depth, within reach of drilling prominent both north and south of Lake Ontario. Near Port Hope there is also a continuation of a prominent magnetic lineament that appears to project from a thick (rift-related?) basaltic lava succession. Whether these features can be simply correlated with their exposed counterparts will not be known without coring.

Measurement and monitoring of physical properties at depth

Upper crustal intraplate earthquake activity is prominent in the region underlain by the CMB and its thin Paleozoic cover, from the West Quebec seismic zone to the north (Forsyth, 1981) south to the Clarendon-Linden structure in New York State and eastern Ohio (Pomeroy et al., 1978). A better understanding of intraplate stresses and rock physical properties in this region is of growing importance in the light of the high population density, strategic installations (such as nuclear power stations) and known record of large magnitude seismic events.

Throughout the region, the Precambrian is accessible at depths no greater than 2 km and the deepest holes to investigate any of the above-mentioned problems would not exceed ca. 5 km. The high quality geological and geophysical database that is available minimizes the amount of prepatory work that would be required to precede a drilling project. The Central Metasedimentary Belt should therefore not be neglected as a promising site in planning both LITHOPROBE seismic investigations and subsequent scientific drilling.

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Figure 4.25.1. Simplified Bouguer gravity anomaly map of the Central Sedimentary Belt (CMB). 1. CMB Boundary Zone, 2. Bancroft Terrane; 3. Elzevir Terrane; 4. Frontenac and New York Lowlands Terrane; 5,6. Carthage-Colton-Labelle mylonite zone. Dash-dot: CMB boundaries; dashed: structural trends from mapped geology and aeromagnetic data; dots: outline of Paleozoic sedimentary cover.

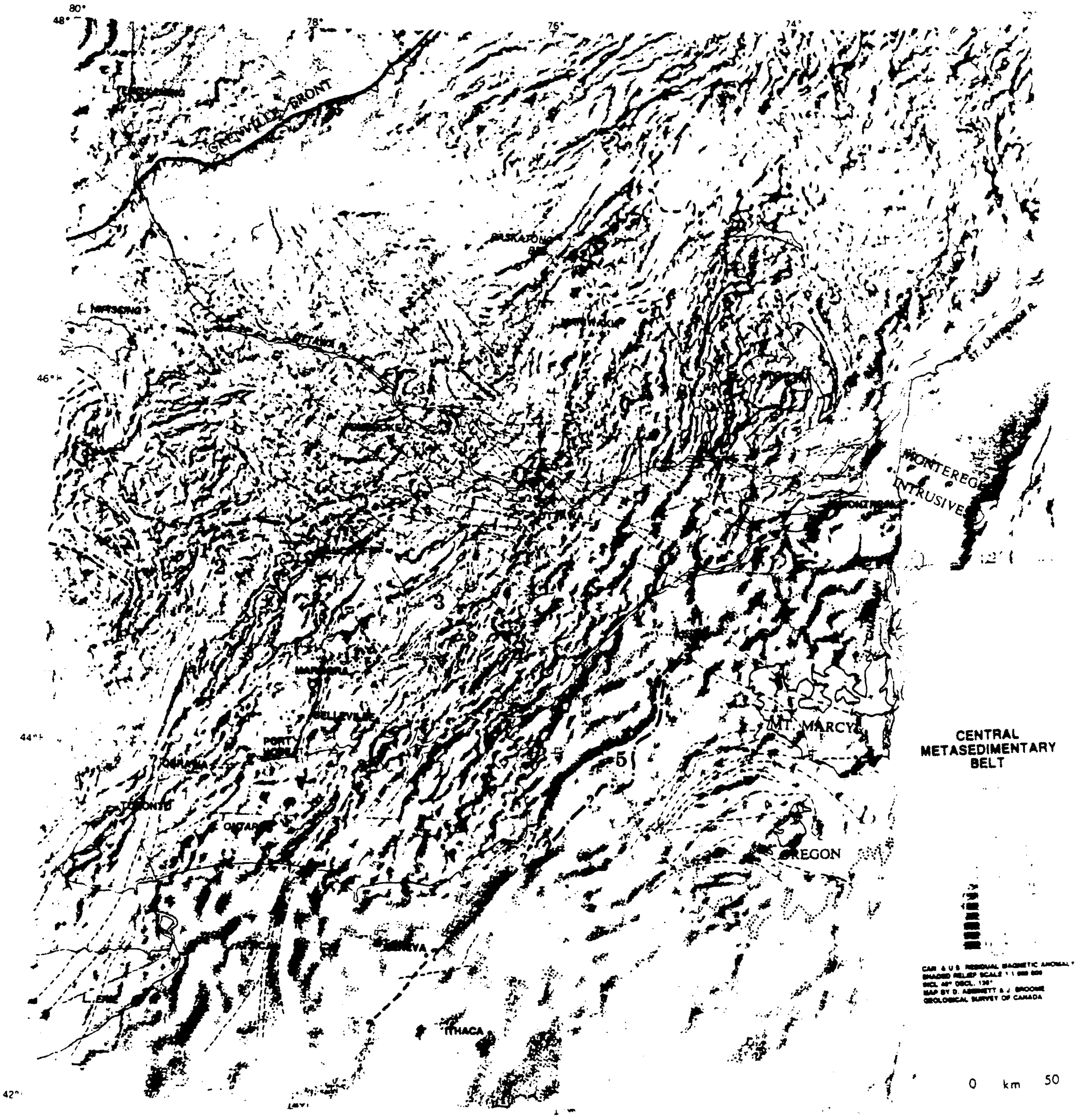

Figure 4.25.2. Shaded relief aeromagnetic anomaly map of the CMB. Grey scale units are reflectance values from the apparent light source. Symbols as on Figure 4.25.1.

4.26 THE IMPLICATIONS OF BRITTLE DEFORMATION WITHIN THE CENTRAL METASEDIMENTARY BELT BOUNDARY ZONE

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The Central Metasedimentary Belt Boundary Zone (CMBBZ) separates the Central Metasedimentary Belt from the Central Gneiss Belt, two subprovinces in the Grenville Province. Hanmer (1988) indicated that the CMBBZ is marked by northwest overthrusting and concluded that it formed as a ductile fault zone about 1,060 ma ago. Minor structures all along the zone reflect both the kinematics and the ductile conditions existing during its formation (Hanmer and others, 1984).

A well-defined aeromagnetic lineament, one of the signatures of what is named the Niagara-Pickering Linear Zone (Wallach, 1989) crosses Lake Ontario from the Niagara Peninsula, passes virtually beneath the nuclear power plant at Pickering and continues to the north-northeast where it joins the CMBBZ. Contrasting magnetic properties across this lineament, first recognized and described by Forsyth, and others (in press), fostered an interest for evidence of brittle faulting. Bedrock exposures are rare to non-existent near Pickering, but are more numerous just south of, and on, the Canadian Sheild. Outcrops of Middle Ordovician limestone and Precambrian geneissic granite, marble and quartz-feldspar-biotite gneiss were examined within, and adjacent to, the Central Metasedimentary Belt Boundary Zone in the area from Coboconk to Miners Bay, Ontario.

Some exposures of Precambrian rocks reveal evidence of brittle faulting. The faulting is manifested by: (1) dip-slip slickenside on northeast striking (035°), gently southeast and northwest dipping, fractures that are subparallel to the strike of the CMBBZ, (2) north-northeast oriented vertical fractures with horizontal slickenside, and (3) northwest trending tectonic breccia zones, also with horizontal slickenside. No shearing was seen in the limestone. However, an obvious north-northeast trending fracture zone, which is about 2 m wide, >100 m long and parallel to the CMBBZ, cuts across the entire length of the floor of a quarry which is located in the CMBBZ. One hundred measurements in the limestone at Coboconk show major concentrations of vertical fractures striking 024°, again parallel to the CMBBZ.

The age of the faulting is not known, but it is clearly younger than the ductile thrusting which formed the CMBBZ. Slickenside on the parallel striking, gently, and oppositely, dipping fracture surfaces suggest that those fractures may be small-scale, conjugate reverse faults. If so, this could represent a continued application of the stresses responsible for the ductile thrusting, but which occurred following cooling of the rocks below the ductile-brittle threshold consequent upon the Grenvillian orogeny. Alternatively the postulated thrusting may have taken place furring Paleozoic crustal compression. The northwest-oriented breccia zones may have formed at

the same time as the inferred thrusts, but the geometry and kinematics of the north-northeast trending, vertical
fractures with horizontal slickenside probably formed at a different time. As in the case of the faults, the precise age of the fractures in the limestone is not known, though it clearly is Middle Ordovician or younger.

Small-scale structures are generally reliable indicators of the nature of much larger structures. Thus, the existence of the outcrop-scale faults implies that the CMBBZ itself, though formed as a ductile fault was probably reactivated as a brittle fault. The observations and interpretations are preliminary, they suggest that the CMBBZ may be a zone of prolonged, and even possibly recurrent, tectonism. More work is required to sort this out, but if the CMBBZ has been rejuvenated in the past then it may be a zone of current stress concentration. Stress concentration on the CMBBZ could have adverse implications for the nuclear, and perhaps other critical, facilities located along, or near, it.

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4.27 SURFICIAL POP-UPS: ARE THEY GEOLOGICAL INDICATORS OF MAJOR SEISMICITY IN EASTERN NORTH AMERICA?

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Large-scale earthquakes have occurred in areas where they have not been anticipated, due to a lack of either felt reports or instrumented records of major tremors in historical or recent times. Examples include the 1976 Tangshan, China (M7.8) earthquake and the 1968 Meckering, Australia (M7.2) event. There have also been several in Canada, among which are the 1935 Timiskaming (M6.25) and the 1944 Cornwall-Massena (M5.7) earthquakes in the east and the 1985 Nahanni (M6.8) earthquake in the west.

The science of earthquake prediction in eastern North America is not yet well advanced. Nevertheless, valuable information for improving estimates of seismic hazard has emerged. Geological features have been discovered in some areas of eastern North America, known for major, historical earthquakes which suggest that those areas have experienced significant, pre-historic events as well. However, what about areas in which there have been neither felt reports nor instrumental recordings of large-scale seismicity? Are these areas to be considered, a priori, unlikely to experience a large earthquake and, consequently, to be assigned a lower level of seismic hazard than is justified?

Pop-ups, or rock buckles, may provide a visual means of detecting areas potentially subject to sizable earthquakes. These structures result from the release of stored elastic-strain energy consequent upon the application of high horizontal stress and are recognized in many areas where earthquakes of magnitude 5.0, or greater, have occurred. In the northeastern United States, pop-ups have been identified in the vicinity of the 1929 Attica, New York (M5.8) earthquake, the 1944 Cornwall-Massena (M5.7) earthquake, which was virtually centred on the Canadian-American border, and the 1986 Leroy, Ohio (M5.0) earthquake. In eastern Canada pop-ups have been documented around western Lake Ontario, in and around Ottawa, along the St. Lawrence River near Cornwall, in Quebec City and in the Miramichi region of New Brunswick all seismically active areas. As well as occurring in proximity to areas of known, large-scale seismicity, pop-ups have also been identified in areas somewhat remote from such events. Because of their spatial association with some of the largest earthquakes in eastern North America, their presence in regions considered to be relatively aseismic signals the need to search for, and carefully evaluate, other relevant geologic evidence within those regions before concluding an estimate of seismic hazard in a risk analysis.

4.28 COMPILATION OF REMOTE SENSING LINEAMENTS IN SOUTHERN ONTARIO AND ADJACENT AREAS

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Recent studies of neotectonic settings in eastern Canada have increased the need to have current information on regional fracture systems. Spaceborne and airborne remote sensing images are primary sources of visual data that provide information about surficial lineaments. The Ontario Centre for Remote Sensing, in collaboration with the Ontario Geological Survey and Ontario Hydro, have undertaken a compilation of lineaments in southern Ontario and adjacent areas.

Lineament segments with more than 2 km length were traced from multiseasonal LANDSAT MSS and TM images to 1:250 000 scale intermediate maps. These lineament maps were then transferred to an existing 1:1 000 000 scale regional base map. Other lineaments were compiled from Trevail and Singhroy (1984); Sanford, Thompson and McFall (1985); Harris et al. (1987); Lowman et al. (1987), and Ontario Geological Survey and Petroleum Resources maps.

Observed lineaments are being compiled into a digital data base for a GIS format spatial information application study and for subsequent statistical evaluation. Rose diagrams show the relative variabilities of orientation between different areas in the region. Three-dimensional stereographic plots of bedrock fracture data obtained from site-specific ground validation studies are presented for comparison. A bibliography is included with the map. Inspection copies of the map are to be available before the 1990 field season.

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4.29 JOINTING WITHIN SOUTH-CENTRAL ONTARIO

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There is mounting pressure to find suitable disposal sites for both household and industrial waste within south-central Ontario as a solution to Metro Toronto's growing "garbage crisis". Until recently, site investigation studies carried out by hydrogeologists have considered the surficial units of the region an impermeable system suitable for the siting of waste disposal pits. Their assumption was that by placing the garbage within this 'tight' material, there would be no need for a barrier between the garbage and the aquifer below. However, new data indicate that sediments deposited in south-central Ontario during the late Wisconsinan are penetrated by extensive fracture systems. Fracture systems increase the permeability of the till considerably and may render it unsuitable for refuse disposal. Unfortunately, basic information regarding the regional character, extent, orientation and origin of fracture systems in southern Ontario is not available, although comprehensive studies of similar features have been carried out within the surficial tills of Saskatchewan and Wisconsin (Penner, 1986; Connell, 1983).

In an attempt to discern the regional character of jointing within the surficial units and related bedrock, extensive field work was carried out during the summer of 1989. Study sites were selected within a belt stretching around Lake Ontario from Pickering through Hamilton to Niagara (Figure 4.29.1). The sites were most commonly located either in active quarries and pits or along Lake Ontario and its tributaries where a bluff had been exposed by erosion. At each site, the bedrock or sedimentological characteristics were described and the orientation (strike and dip) and quality (staining and extent) of each joint was determined.

Published data show that fractures in bedrock, within south-central Ontario and northern New York State, are mostly vertical to nearly vertical and trend predominantly northeast and northwest. Fracture characteristics in the unconsolidated sediments are similar. Data analysis is currently underway, thus interpretations of the results have not yet been completed.

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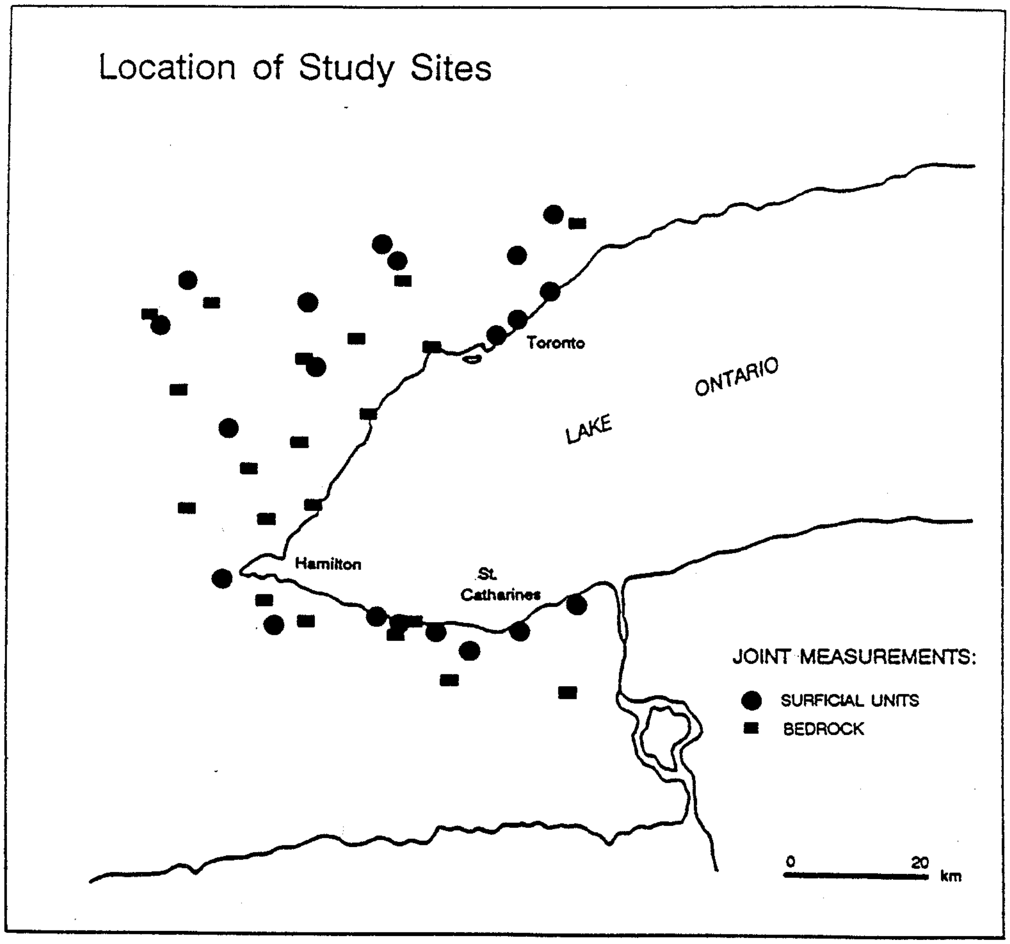

Figure 4.29.1. Location of study sites.

4.30 POSTGLACIAL FAULTING IN EASTERN CANADA: NATURE, ORIGIN AND SEISMIC HAZARD IMPLICATIONS

John Adams

Geological Survey of Canada

Tectonophysics, vol. 163, pp. 321-331, 1989

ABSTRACT

At more than 70 locations in southeastern Canada and the adjacent United States tiny bedrock faults displace glacial striations that are about 10 000 years old. These reverse faults, mostly of small displacement, occur in a broad arc from western Ontario and Newfoundland. The faults lie near the margin of the Laurentian ice sheet, strike generally tangential to it, and imply compression nearly normal to the ENE-directed contemporary regional stress (Fig. 4.30.1). These observations and some age relationships suggest that the faults formed very soon after deglaciation, perhaps in the first few thousand years after ice melting in each place, and probably represent the release of stresses caused by flexural deformation of the upper crust. Although the individual offsets are small, the faults are believed to be pervasive, and individual outcrops reflect amounts of stress-relief consistent with stresses implied by the postglacial tilt of nearby lake shorelines.

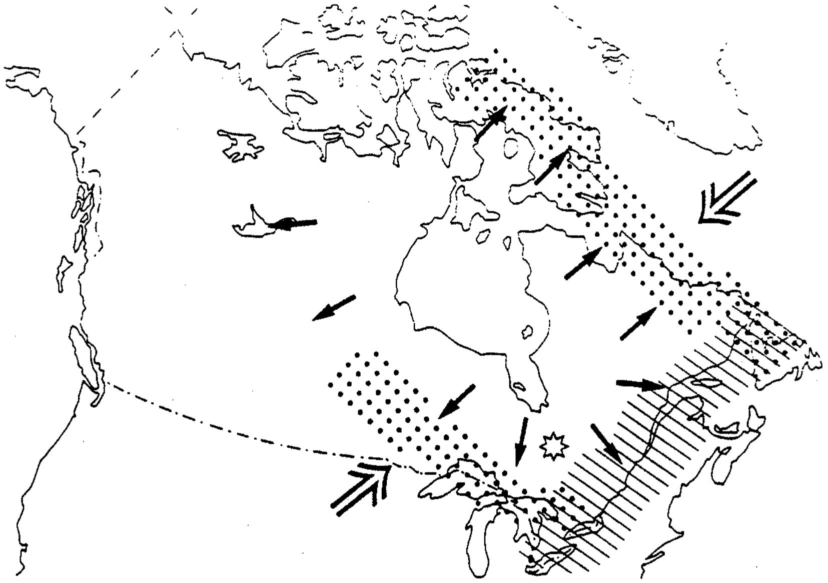

Figure 4.30.1 Regions where the glacially-induced flexural stresses (small, radial arrows) are superposed on the regional tectonic field (pair of large arrows) at a high angle and are able to change the direction of maximum compression (stripes), and where the regional field and the flexural stresses act in the same direction and reinforce each other (stipple), and may cause large-scale postglacial faults. Open star marks site of lake Barlow-Ojibway.

5. REPORTS SUBMITTED TO MAGNEC/
RAPPORTS SOUMIS A L'AMNEC

5.2 NEOTECTONIC INVESTIGATIONS IN SOUTHERN ONTARIO: PRINCE EDWARD COUNTY - PHASE 1; G.H. McFall and A. Allam, Ontario Geological Survey; Prepared for Safety and Safeguards Section, Atomic Energy Control Board, March 31, 1989, 67 pp. plus appendix (MAGNEC Contribution 89-02)

ABSTRACT

This report summarizes the preliminary results of geological and geophysical investigations of possible neotectonic features in Prince Edward County, southern Ontario, made by the Ontario Geological Survey during 1988. Low magnitude seismic events indicative of contemporary stress relief occurred during 1987/88 near Salmon Point and Consecon (M 2.2). These events were located proximal to a major regional fault system crossing Lake Ontario and consisting of the Clarendon-Linden Fault System in New York State and the Salmon River-Picton fault systems in Ontario.

Detailed observations were made of regional jointing orientations (predominantly 060° and 125°), erosion of surficial deposits adjacent to open fracture, lineaments, a local fault displacement (post-glacially), dome structures located at Point Petre, and dissolution/karst terrains in the eastern part of the study area.

Excavations of four pop-up structures indicate that three are "classical" pop-ups and one is atypical in structure. Level transects were conducted across complex structures in the eastern part of the study area.

Detailed refraction seismic and resistivity surveys were conducted on pop-up and fault features. Preliminary results indicate that the Picton Fault is a complex zone of fractures with differing bedrock on each side. The central zone of the "East Duck Pond" pop-up is fractured and may contain variable amounts of water.

Overturned and upright folds in the Consecon Quarry located outside of the primary research area were documented and found to be trending in a west-northwest to northwest direction. This fold orientation is compatible both with a glacial shove origin and with the present stress field orientations. Although glacial shove can produce overturned folds, it cannot form upright folds. A regional, tectonic deformation oriented northeasterly is therefore suggested as the causative mechanism.

5.1 **A DOCUMENTATION OF STRUCTURES IN UNCONSOLIDATED SEDIMENTS ALONG THE NORTH SHORE OF THE MINAS BASIN, NOVA SCOTIA: A RECONNAISSANCE NEOTECTONIC SURVEY**; by T.R. Stokes, Prospect Bay (Geological) Consulting Services, Armdale, Nova Scotia; prepared for the Safety and Safeguards Section, Atomic Energy Control Board, December 30, 1988, 15 pp. plus Appendix. (MAGNEC Contribution 89-01).

ABSTRACT

During the summer of 1987 the north shore of the Minas Basin, Nova Scotia was examined for evidence of structures in unconsolidated sediments. This shoreline exposes the eastern extension of the Cobequid-Chedabucto fault system, which was active from the Devonian until at least the Permian, and possibly into the Mesozoic. The primary aim of the study was to document, measure and record any structures in unconsolidated sediments. In all, thirty-four structure locations were found, of these twenty-nine were in glacial outwash deltas, the result of the Late Wisconsinan ice retreat. The most important structures include: (1) conjugate normal faults in Advocate Harbour sands and mud at East Finney Brook; (2) associated faults and folds in the Advocate Harbour bottomset mud at Lower Five Islands and (3) major convolutions in Advocate Harbour bottomset mud at Economy Point. The convolutions are the result of seismic "shaking" which either post dated delta formation or triggered syn-sedimentary slumping. The faults and folds at Lower Five Islands were formed by extension related to either delta slumping or possible bedrock movement. The conjugate fault set at East Finney Brook is the result of an extensional event probably caused by late NE-SW normal fault reactivation. It is unclear whether this reactivation is the result of glacial rebound or neotectonic movement.

6. OTHER REPORTS ON MAGNEC ACTIVITIES/
AUTRES RAPPORTS DES ACTIVITÉS DE L'AMNEC

6.1 SCIENTISTS EXAMINE GEOLOGICAL STRUCTURES IN SEARCH OF ANCIENT EARTHQUAKES IN AREA

Anthea Weese
Picton Gazette
16 August 1989

For the third consecutive summer, a crew of geologists and geophysicists from the provincial Ministry of Northern Development and Mines is poking around the fields, conservation areas and shorelines of southern Prince Edward County.

By mapping the bedrock with its geological structures -- faults, crevasses, fractures and sink holes -- they are increasing the scientific knowledge for the public record. But they also have a special mission, party chief Gail McFall, a geologist, said.

"We're identifying areas that have been structurally unstable. This information, with information from other field parties in other areas, will be considered when revisions to the National Building Code (NBC) come up for review in 1992. When an engineer is designing a building the NBC gives guidelines as to the designs and materials -- specifically for withstanding earthquakes".

Why are they here in Prince Edward County? Are we in a high risk area?

No, McFall said. One of the reasons the county was chosen is because the seismic activity here is so low. Three test sights are being studied in eastern Canada, chosen for their relative seismic activity: Charlebois (sic), Quebec -- with high activity; Maramichi, New Brunswick-with intermediate activity; and Prince Edward County -- with low seismic activity.

McFall says some low-level activity is good -- "it's a constant relief of stress". Earthquakes recorded in this area have not been above 2.5 on the Richter Scale, a level that isn't even felt. "One was recorded at Consecon last fall. We didn't hear anything from the population so it probably was not noticeable".

"Geology has progressed a lot in the past decade sine the NBC was last reviewed", McFall said. "There's the possibility of discovering past earthquakes through examining the geological record, in areas where earthquakes were not thought possible before".

McFall said the study conditions in the county are optimum -- it's an ideal "working laboratory" for several reasons:

- The Quaternary cover (topsoil and glacial deposits) is thin, allowing the scientists to see the bedrock and how it interacts with the cover.

- The area contains a large fault -- the Picton Fault. One arm starts at Point Petre at the picnic area and runs up through Cherry Valley, Picton and Long Reach. "That's probably why Long Reach is where it is," McFall said. Another arm comes up from Salmon Point and joins the first at Cherry Valley. A 1961 Geological Survey of Canada study revealed a 30- meter displacement along the fault line.

- There has been good aerial photo coverage of the area dating from 1927, allowing a look at human intervention on the land, and developments over the past six decades. "To get the early pictures they must have hung off the wings of a biplane", McFall said.

- The areas of interest are easily accessible by road, making it easier for the scientists and their visiting colleagues to reach.

"We're trying to determine if there has been any recent ground motion in the past 12,000 years ("a blink of the eye geologically" in the 450-500 million-year-old limestone rock of the country) since the last retreat of ice from the Prince Edward County area", McFall said
"We don't have any firm evidence but we do have a number of features that suggest something has happened during that period".

One of the best indications of recent activity is the presence of "pop-ups", McFall said. Pop-ups are created when flat lying rock is pushed together horizontally. When the breaking point is reached, the rock is pushed up in an inverted V-structure. Nine pop-ups have been discovered in the area so far. One in the Consecon area is 1.8 meters high, McFall said.

The crew is also examining open crevasses in the bedrock. "Farmers throw garbage, logs and rock in them to fill them up so their animals don't fall in", McFall said. "What we're doing is getting an idea of when they formed. It will give a geological history of the area. We're trying to figure out which structures are associated with which geological events, for example, the colliding of the North American and European continents".

The crew has received a lot of assistance from local farmers, McFall said. "They come out in the field with us and give us ideas of where to look for these features. They're very helpful and some are knowledgeable. They know the land. Crevasses contain deeper topsoil so crops growing over them are taller and mature faster".

This summer the field crew arrived in mid-June and will be in the county until the end of August.

6.2 Tremblement de terre du 25 novembre
LA RÉGION FAIT FIGURE DE "MOUTON NOIR"

Yvon Bernier
Le Quotidien
5 octobre 1989

CHICOUTIMI (YB) - Le tremblement de terre de magnitude 6.5 (L.G.) survenu le vendredi 25 novembre 1988, à 18h46 dans la région de Chicoutimi fait figure, en quelque sorte de "mouton noir" comparativement à la série de séismes survenus dans la région de Charlevoix, puisque dans ce cas-ci il a été généré dans un système de failles indépendant ou si l'on veut dans une zone qui n'était pas du tout connue pour sa sismicité.

De l'avis du séismologue américain, Gabriel A. Leblanc, qui a étudié pendant une bonne vingtaine d'années le territoire qui s'étend de Québec à Tadoussac, la région de La Malbaie demeure définitivement l'un des endroits les plus actifs en Amérique du Nord, au plan sismologique s'entend.

Contrairement à ce que prétend l'un de ses collègues québécois, le séismologue américain dit ne pas être d'avis que certains tremblements de terre importants aient eu par le passé leur origine au Saguenay, car il n'existe pas à toutes fins utiles de données valabes pour étayer cette hypothèse. "Le tremblement de terre du 25 novembre, tout comme celui observé au Témiscamingue en 1935 sont à mon avis des cas isolés."

Causes possibles

Appelé à identifier les causes du séisme qui s'est produit au Saguenay, le professeur Reynald Du Berger de l'UQAC rappelle que l'ensemble des mesures et observations scientifiques effectuées jusqu'à maintenant relativement aux séismes antécédents tendent à démontrer que la partie Est de l'Amérique du Nord subit une formidable compression horizontale de la croûte océanique.

D'autre part, ajoute-t-il, ce même phénomène peut dans une certaine mesure être attribué au déplacement (relèvement isostatique) du bloc tectonique Jacques Cartier qui est limité par le Graben du Saguenay (axe de la rivière Saguenay), par le rift du Saint-Laurent (axe du fleuve Saint-Laurent) et par l'alignement du Saint-Maurice (axe de la rivière Saint-Maurice).

Principales caractéristiques

Le professeur Du Berger fait observer que le tremblement de terre du Saguenay est remarquable tant par sa durée que par son intensité: 6.5 (L.G.), par la profondeur de son épicentre (29 kilomètres), par le faible nombre de répliques (86) compte tenu de l'intensité du séisme, ainsi que par des accélérations horizontales sur roc égales à 16 pour cent de l'accélération gravitationnelle (G).

Il indique également que les chercheurs poursuivent leurs efforts pour améliorer les méthodes d'estimation du péril sismique tout en sachant que dans la région du Saguenay-Lac-Saint-Jean le prochain tremblement de terre de cette importance n'est pas pour demain.

La plupart des communications présentées hier à l'Université du Québec à Chicoutimi dans le cadre de la réunion annuelle des membres de l'Association multipartite pour la néotectonique dans l'Est du Canada (MAGNEC) ont porté entre autres sur le contexte, la portée, les effets séismologiques, tectoniques et psycho-sociaux de même que sur la signification de l'événement survenu.

Des ingénieurs à l'emploi d'Hydro-Québec ont fait part des dommages occasionnés à diverses installations du réseau hydroélectrique québécois ainsi que démontré d'autre part que les barrages majeurs n'ont pas été touchés par le séisme. Les mêmes intervenants ont indiqué de plus que la société Hydro-Québec entend tirer une leçon de l'événement survenu et apporter des modifications notamment au niveau des instruments de détection et d'observation.

Des spécialistes américains et canadiens ont communiqué de leur côté les résultats de recherches réalisées à la suite de tremblements de terre survenus dans leur région ou Etat respectif.