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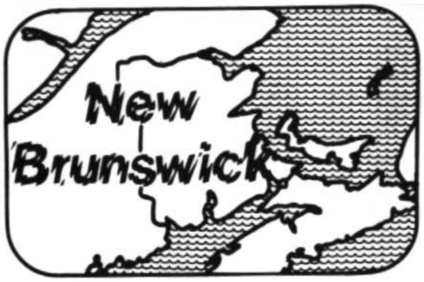

The Miramichi, New Brunswick Earthquakes: Near-Surface Thrust Faulting in the Northern Appalachians

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Introduction

On January 9, 1982, in the unpopulated Miramichi Highlands of north-central New Brunswick, the largest earthquake in eastern Canada in thirty-eight years occurred. The recordings of this earthquake and its subsequent large aftershocks by modern global seismographs and accompanying field investigations have provided the most extensive data set ever captured for a potentially damaging eastern North American earthquake. This article will describe the sequence of earthquakes, summarize the results of investigations achieved to date by the Earth Physics Branch and by other Canadian and U.S. workers, and speculate on possible geological interpretations of the activity.

Earthquake History of New Brunswick

The decade of seismicity in the New Brunswick region (1970-1981) prior to January, 1982 is shown as an epicentre map in Figure 1, superimposed on the regional geology (adapted from Williams, 1978). None of these earthquakes exceeded a magnitude of 4. No obvious correlations can be seen between the epicentral patterns and the mapped geology and faults. Indeed, the pattern of epicentres in the western two thirds of New Brunswick and eastern Maine appears to be random. The cluster of activity in the top left corner of the map is associated with the active Charlevoix zone in the St. Lawrence Valley (Anglin, 1984). Only the earthquakes in this zone with epicentres on the south shore are shown. A small concentration of epicentres near the southern New Brunswick-Maine border may be associated with the Oak Bay Fault (Rast *et al.*, 1979) or with the local downwarp in the regional postglacial uplift that has been identified in the region of Passamaquody Bay (Barosh, 1981).

The largest earthquakes known in New Brunswick prior to 1982 occurred in 1855, 1869, 1904, 1922 and 1937 (Fig. 1). Isolated minor damage was reported for each of these earthquakes. The epicentres have been estimated from an analysis of reported effects and are uncertain by at least 50 km (the radius of the circles in Fig. 1). Magnitudes of approximately 5 for 1869 and 1904, and 4.5 for 1855, 1922 and 1937 have been inferred from estimates of the total felt area (A.E. Stevens, unpublished report, 1975). The magnitude of the 1937 event is supported by available instrumental data and the approximate location is a recent revision (A.E. Stevens, personal communication, 1983) of the location near Saint John published by Smith (1966). Thus the 1982 Miramichi mainshock, magnitude 5.7, is the largest earthquake in New Brunswick in historical times.

However, all or most of the province has been shaken by many other large eastern North American earthquakes, notably the Charlevoix earthquakes in 1663, 1860, 1870, 1925 and 1939, the Cape Ann, Massachusetts earthquake in 1755 and the Grand Banks earthquake in 1929. The last earthquake in eastern Canada with a magnitude similar to the Miramichi mainshock was the Cornwall-Massena earthquake of 1944. This event caused damage amounting to about $1,000,000 (1944 dollars) in each of the two cities on either side of the St. Lawrence River, but was felt only mildly in New Brunswick (see also Stevens, 1977).

The Miramichi Earthquake Sequence

The mainshock of magnitude 5.7 occurred at 08:53 AST on January 9 near 47.0N 66.6W. It was followed three and a half hours later by an aftershock of magnitude 5.1, and two and a half days later (January 11, 17:41 AST) by an aftershock (or second mainshock) of magnitude 5.4.

The intensity distribution of the main shock is shown in Figure 2. The inner isoseismal contour defines the general extent of Modified Mercalli V intensities; the outer, that of intensities III and IV. Intensity V is defined as "felt indoors by practically all, outdoors by many; many awakened; small or unstable objects overturned or moved; hanging objects, doors swing considerably". Intensity III is defined as "felt indoors by several; motion usually rapid vibration; duration estimated in some cases; vibration like that due to passing light truck; hanging objects may swing slightly; movements may be appreciable on upper levels of tall structures" (Wood and Neumann, 1931).

In the furnished, but unoccupied, cabins and cottages in the epicentral zone no evidence of displaced objects was found, although there was one unverified report that a stovepipe, lampshade and dishes had fallen to the floor. This apparently modest level of strong shaking in the immediate epicentral area might have occurred if the vertical component of ground motion was dominant and the horizontal

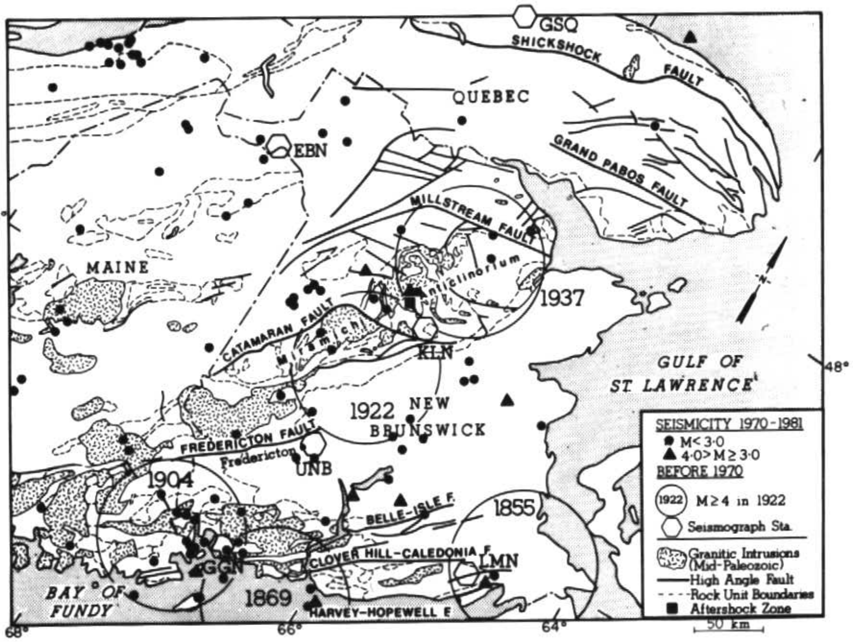

Figure 1 *Seismicity of New Brunswick and adjacent areas prior to the 1982 earthquake activity. Seismograph stations operated by the Earth Physics Branch. Major faults and granitic intrusions adapted from Williams (1978). Figure adapted from Wetmiller* et al. *(1984)*

forces were insufficient to topple small objects. There was no structural damage anywhere, although earthquake-induced hairline cracks were confirmed in a few buildings in Chatham, Newcastle, Bathurst and Perth-Andover up to about 100 km from the epicentre (Pernica and Maurenbrecher, 1982).

The outer contour in Figure 2 is the outer limit of the area over which the earthquake was generally perceptible at ground level (Intensity III). This area is well defined by the questionnaire surveys conducted by the Earth Physics Branch in Canada and the U.S. Geological Survey in the U.S. (Stevens and Cajka, 1984). The earthquake caused perceptible swaying in highrise buildings in Ottawa (750 km) and New York City (950 km), but it was not felt at ground level at these distances.

The magnitude 5.1 aftershock on January 9 was felt over most of New Brunswick with intensities of III to IV. The principal aftershock of magnitude 5.4 on January 11 was felt in all of New Brunswick, in parts of Nova Scotia, Prince Edward Island, the Gaspé and eastern Maine, with scattered reports from elsewhere in New England. The maximum intensities for this event might have reached V in some communities, but it is unlikely that intensity V was experienced over a significant area because most communities reported lower intensities than on January 9.

The numbers of aftershocks per hour during January, as detected at the nearest permanent seismograph at Edmundston (EBN in Fig. 1) are shown in Figure 3. Some additional aftershocks from mid-January to late-March were reported felt; then, on March 31 a magnitude 5.0 aftershock was felt over most of New Brunswick, the western half of Prince Edward Island and along the New Brunswick-Maine border. The largest recent aftershock was magnitude 4.1 in May, 1983. Events larger than magnitude 2.0 are still occurring weekly at the time of writing (March, 1984), more than two years after the main shock.

Aftershock Field Studies

On the afternoon of January 9 an Earth Physics Branch field party with portable seismographs flew to New Brunswick. By the afternoon of January 10 three instruments were in operation along Highway 108 about 25 km south of the epicentre, as close as the team could get in the severe winter conditions. Arrangements were made with the New Brunswick Department of Highways to plough open logging roads into the epicentral area that are normally passable only in summer. With much additional assistance from the New Brunswick Forest Service and Emergency Measures Organization, a total of 24 analogue and digital seismographs were eventually put into operation in the epicentral region. The Branch was assisted in this field program by teams and equipment from the Atlantic Geoscience Centre, the U.S. Geological Survey, three U.S. universities, two U.S. consulting companies and the U.S. Nuclear Regulatory Commission. Although there were many instrumental malfunctions due to the low temperatures, sufficient aftershock data were collected by January 22 that most of the field instruments were removed.

On January 28 a new outstation, as part of the Eastern Canadian Telemetered Network, was put into operation at Mt. McKendrick (KLN in Fig. 1) about 25 km southeast of the epicentral region, as close as the line-of-sight radio link would allow. This station has since provided a continuous monitor for the lower magnitude aftershock activity, although these aftershocks cannot be accurately placed within the active zone.

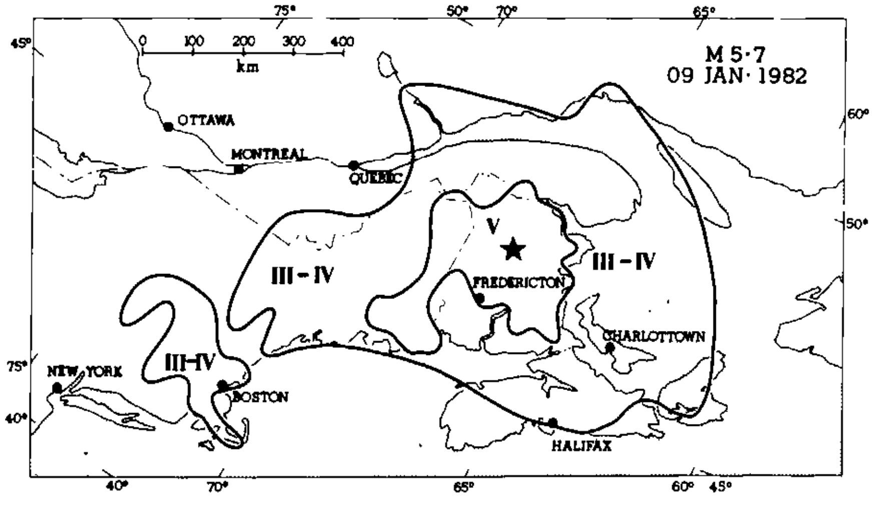

Figure 2 *Isoseismal contours of January 9 mainshock showing extent of Modified Mercalli intensity V and III. Adapted from Stevens and Cajka (1984)*

The rare opportunity to record strong seismic ground motion of engineering significance from a large aftershock led to a joint project with the U.S. Nuclear Regulatory Commission under which seven strong motion seismographs were installed in the epicentral region by February 6. These instruments were triggered by the March 31, magnitude 5.0 aftershock and a number of smaller events, including the May 1983, magnitude 4.1 aftershock. An analysis of the 1982 strong motion data has been presented by Weichert *et al.* (1982), and these data are receiving considerable attention from the earthquake engineering community because of their implications for the effects of future similar earthquakes on critical facilities in eastern North America.

The March 31 aftershock was of sufficient size to warrant another field deployment, and the Branch operated four seismographs in the epicentral region April 2-7. These data (as discussed below) played a significant part in the overall understanding of the earthquake sequence. On June 16 an earthquake of magnitude 4.7 occurred 30 km west of the January and March events. Because of the new location, a third field survey was conducted in the epicentral region of this event June 17-23. Although the focal depth and mechanism of the June 16 event were similar to those of the Miramichi sequence (Wetmiller *et al.*, 1984), there is no evidence to causally connect them. The June 16 earthquake is, therefore, assumed to be an independent event and is not discussed further here.

Searching for the Fault Break

The Miramichi epicentral zone lies on the axis of the Miramichi Anticlinorium that forms the central highlands of New Brunswick and that consists of a series of large granite plutons of Devonian age intruding Ordovician and older metasediments and granites. Faulting is known to affect some of the rock units of the anticlinorium, the Catamaran Fault in Figure 1 being a prominent example. It is a right-lateral, strike-slip fault that offsets the Early Carboniferous granite pluton south of the epicentral area (Fyffe, 1982a). However, no evidence for faulting younger than Paleozoic has yet been found on the Catamaran Fault, or for others like it, and it was not a causative factor in the 1982 earthquakes.

The earthquakes occurred within a massive Devonian granite pluton remarkably free of any surface evidence of previous deformation (see Fig. 4). A subsequent gravity survey (Burke and Chandra, 1983) has shown that the pre-Devonian deformed granites and metasediments represent only a thin cover (0-1 km) to the main granite pluton and that the granite pluton is probably 8 km thick. Hence, most of the aftershocks probably occurred entirely within the granite pluton. The gravity data suggest that the dioritic bodies within the pluton are more extensive than as mapped on Figure 4, but that they are probably thin (0.5 – 1 km) tabular bodies.

At the request of the Earth Physics Branch, the Canada Centre for Remote Sensing scheduled a flight over the epicentral area on January 13. However, aircraft problems and bad weather delayed the flight until January 19, by which time 0.5 m of fresh snow had fallen, effectively masking any subtle earthquake effects that might have been visible earlier. A careful search of stereoscopic air photos of the epicentral region revealed no earthquake-related features. A lineament map which shows a dominant trend of linears in a WNW direction was prepared from the photos (Adams, 1982). Many of these linears are now thought to be concealed shear zones like the two WNW trending shears mapped by Fyffe (1982b) and shown in Figure 4.

In May, 1982, after the snow had melted, a geological field survey was conducted in the epicentral area. Although the large size, shallow depth and thrust mechanism of the mainshock suggested that a primary surface rupture might have occurred, no significant fault break was found. Assuming a rupture area of 20-25 km², as indicated by the aftershock distribution, the average slip on the fault was 25-35 cm (Wetmiller *et al.*, 1984). Vertical thrust displacement as small as 100 mm across any of the dirt roads in the area would not have been missed; but off the roads much larger displacements could have gone undetected. Although a 100 mm or larger displacement would certainly have been seen had it occurred in one place, it is possible that the bedrock displacement at shallow depths occurred as a number of individual displacements on parallel splay faults that cumulated to the total slip.

In the southeast corner of the aftershock zone glacially-smoothed bedrock was discovered to be displaced by very recent small-scale thrusting on a pre-existing joint (Fig. 5). The joint belongs to a minor orthogonal set that trends 000 and 090 and that may have been produced by a more recent (post-Triassic) stress field than the one responsible for the majority of the jointing (Lajtai and Stringer, 1981). The thrust joint could be traced 3 m across the outcrop and involved 25 mm of thrust displacement, west side up, along a joint trending N5E that dipped at 40° to the west. Additional field work in the area of the thrust joint is described below.

Aftershock Distribution and Speculative Fault Planes

The epicentral distribution of the January and April activity (Fig. 4) is defined by those aftershocks judged sufficiently well located. Considering the uncertainties in the crustal velocity model and the distribution of temporary seismograph stations, the absolute uncertainties in the epicentral locations are not likely to be smaller than ±1 km. Uncertainties in estimates of focal depth are not likely to be smaller than ±2 km. The January activity was diffuse, but confined principally to a volume 6 km on a side, with the deepest events at about 7 km. In cross section the least scatter is produced when the hypocentres are projected onto an east-west plane (Fig. 6a). Most of the January activity was concentrated in the southwest portion of the active volume. The April epicentres are concentrated in the northeast portion of the January activity and the depths are generally shallower. In Figure 6a the distribution of after-shocks suggests a north trending conjugate "V" pattern.

P-wave first-motion and surface-wave analyses of the magnitude 5.7 mainshock using data from Canadian seismograph stations suggest thrust faulting on a north-striking plane dipping about 50° (to either the east or west), the causative stress being east-west compression (Wetmiller *et al.*, 1984).

If the aftershocks on Figure 6 are divided into four groups, shallow and deep, west and east, the composite P-nodal solutions (i.e., solutions using the combined results from a group of aftershocks) for each group suggest steeper dips at shallower depths. The western groups of January events show dips of about 47° at depth and 63° near the surface; the eastern groups of April events show dips of about 42° at depth and 78° near the surface. Thus, the dip of the mainshock plane seems to be representative of the rupture at depth. The aftershock analysis further suggests that both east- and west-dipping rupture planes steepen toward the surface. From an analysis of broadband displacement and velocity records of P-waves at teleseismic distances, Choy *et al.* (1983) suggested that the mainshock ruptured up dip on a west-dipping plane.

Figure 3 shows that the magnitude 5.4 event on January 11 had the most intense aftershock sequence. Therefore, most of the January aftershocks in Figure 6a are associated with this earthquake, and their locations suggest that the earthquake ruptured the east-dipping plane. At the present time there is no other independent evidence to specifically associate the magnitude 5.4 with this plane.

The following hypothesis has emerged (Fig. 6b): The January 9 mainshock occurred as a thrust with rupture up dip on a west-dipping plane. The exact location

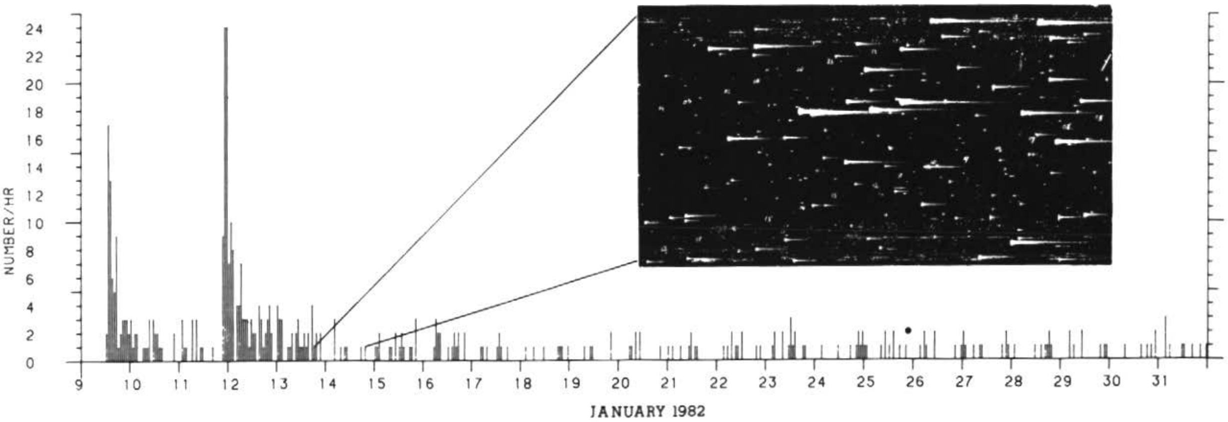

Figure 3 *Number of Miramichi earthquakes per hour detected at EBN seismograph station (Fig. 1). Inset shows field recording of 237 aftershocks in a 25-hour period, January 13-14*

of the magnitude 5.1 aftershock three and a half hours later is not known independently, but on sparse evidence given by Choy *et al.* (1983) it has been assigned to the lower northern portion of this same plane. Then, on January 11 the magnitude 5.4 event ruptured (probably up dip) a conjugate east-dipping plane and was followed by an intense sequence of smaller aftershocks. Finally, the March 31, magnitude 5.0 aftershock occurred as a repeat rupture in the upper northern portion of the west-dipping plane. In this description each of the two principal ruptures is assumed to be on a single plane, with the additional evidence, described above, that these planes steepen toward the surface. Another possibility is that the shallower aftershocks are associated with steeply dipping splay faults coming off a more shallowly dipping principal fault at depth. Three speculative alternatives are illustrated for the west-dipping plane in the lower portion of Figure 6. These alternatives illustrate the uncertainty as to where the principal rupture planes may lie relative to the aftershocks. In (c) it is assumed that the up-thrown wedge has become unstressed and the aftershocks are occurring beneath the main rupture planes; in (d) the aftershocks (with their recognized location uncertainties) are clustering about the main rupture planes; in (e) most of the aftershocks are in the up-thrown wedge. Which of these possibilities, or some other, is correct cannot be determined from available information.

Examination of the literature gives few examples of the accurate location of thrust fault planes relative to their aftershocks. Aftershocks associated with the southwestern half of the rupture zone of the 1980 El Asnam thrust earthquake are, clearly, mainly in the footwall, with relatively little activity on the fault plane (Figs. 7-9 in Ouyed *et al.*, 1983). However, in the northeastern part the aftershocks appear to lie mainly in the hanging wall (Fig. 10, Ouyed *et al.*, 1983), behaviour thought anomalous by Ouyed *et al.* Jackson *et al.* (1982) note that aftershocks on shallow dip-slip faults often concentrate in the hanging-wall block and attribute this to internal deformation resulting from either curvature of the fault plane or from non-uniform slip on it. One possible example is the induced seismicity at Nurek reservoir, U.S.S.R. (Leith *et al.*, 1981), which is almost entirely confined to the hanging-wall block above a major thrust plane that steepens towards the surface.

We suggest that the number, location and nature of aftershocks near a shallow thrust fault is probably controlled by the geometry of the thrust plane. A thrust plane that becomes less steep as it approaches the surface will apply less compressive stress to the hanging-wall block, so fewer aftershocks will occur there relative to the footwall which is still stressed. Very shallow aftershocks that occur above a gently-dipping thrust might exhibit secondary, normal focal mechanisms. At El Asnam normal faulting occurred on the ground surface of the hanging-wall block, although this localized extension in a compressional environment could be due to uneven fault slippage (more fault slip at depth; King and Brewer, 1983) or termination of the rupture at a bend, rather than to a change in dip of the thrust fault.

In contrast, a fault plane that steepens near the surface – as we believe do the Miramichi fault planes – will apply additional compressional stress to the hanging-wall block, which will thus become the locus of most of the aftershocks. These will still occur in a compressional environment, and so will have thrust mechanisms similar to those of the main shock. A concentration of aftershocks above the main rupture plane could also result from slip increasing towards the surface on a planar fault, although fault slip that increased towards the surface would make the absence of a surface rupture even more puzzling. For this reason, and because the Miramichi composite fault plane solutions show the steepening of the fault planes directly, we consider that uneven fault slippage provides a poor explanation for the Miramichi observations.

East-West Horizontal Stress

In September, 1983, as a cooperative project among the Atomic Energy Control Board, the Geological Survey of Canada and the New Brunswick Department of Natural Resources, the bedrock in the region of the thrust joint (Fig. 5) was cleaned off over an area 100 by 30 m (Fyffe, 1983). The observed thrust displacement of 25 mm was found to die out to zero, 1 m to the north of the original outcrop. To the south of the original outcrop the bedrock surface drops 150 mm across an east-west vertical joint, and on the lower block the thrusting decreases to 5 mm and then dies out completely. It is clear from field observations that the thrusting does not continue to any significant depth and probably dies out along sub-horizontal sheeting fractures. Although the orientation and nature of the thrusting are very similar to the deduced focal mechanisms, we interpret the thrust joint to represent the relief of surficial stresses that were released by the earthquake shaking, rather than a primary rupture.

In addition to the thrust joint, a small stress-relief buckle occurred in the bedrock overnight between two examinations of the outcrop (Fig. 7). A slab of diorite about 3 m long, 1 m wide and 50-100 mm thick buckled up 55 mm from the underlying bedrock along a sub-horizontal fracture. The separation has since increased to 80 mm. The slab was in contact with the intact bedrock at either end, but in the centre had cracked along a general trend of 010, i.e., more or less parallel to the thrust joint and to the strike of the fault planes determined from the composite focal mechanisms. A further incipient buckle – a diorite slab separated vertically from the underlying rock by a few mm on a sub-horizontal fracture – was also seen. As less than 1 m of overburden had been removed, the confining pressure that previously prevented the buckle was not great, suggesting that the rock was already close

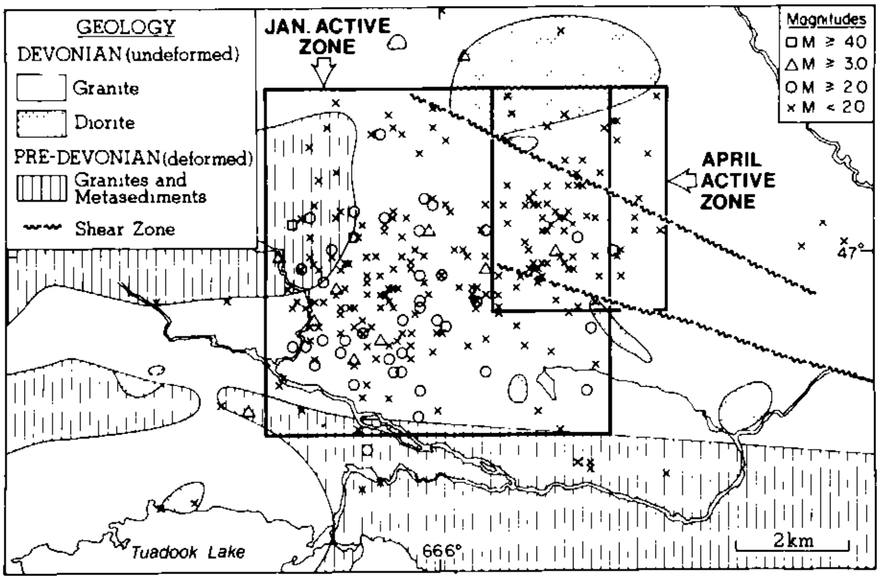

Figure 4 *Epicentres of January and April aftershocks superimposed on the geology of the epicentral region, from Fyffe (1982b). After Wetmiller* et al. *(1984)*

to failure. The size of the buckle provides a crude estimate (by calculating the probable strain change and estimating a Young's modulus) of 5 MPa for the horizontal surface stress relieved.

The stress-relief phenomena on the cleaned-off outcrop (buckle and thrust joint) indicate both high horizontal stresses and east-west compression. Further, the eight composite focal mechanisms for the Miramichi aftershocks and the independent Trousers Lake earthquake all have nearly horizontal east-west directed P-axes (Wetmiller *et al.,* 1984) and hence are consistent with E-W compression. Some oil well breakout data from the Gaspé and the Maritime Provinces (Cox, 1983) indicate regional E-W to NE-SW compression, although some other measurements close to the Miramichi – in southern New Brunswick and Prince Edward Island – have varied stress directions within the same well. Direct measurements of stress have been made by Golder Associates for Brunswick Mining and Smelting in their Bathurst Mine, 75 km north of the Miramichi epicentral area (C. Pagel, personal communication, 1983). At 1 km depth the ESE-WNW horizontal stress is about 55 MPa, the NNE-SSW stress is 33 MPa, and the vertical is 23 MPa.

The general consistency of regional stress orientations and their specific agreement with the local stresses confirm that New Brunswick is subject to horizontal compression with the maximum horizontal component in an E-W direction. The challenge in the next few years will be to determine the present state of stress in the epicentral area, to discover how the earthquakes modified the initial stress field and to understand why the stresses were concentrated and released within the pluton.

Implications for Seismic Risk Estimation

The Earth Physics Branch has recently prepared new seismic zoning maps for the 1985 edition of the National Building Code (Basham *et al.,* 1982). This work was essentially complete prior to the Miramichi earthquakes. The method used in deriving these maps requires a model of earthquake source zones for all seismically active regions of the country. New Brunswick is part of a Northern Appalachians source zone in which a random distribution of future earthquakes is assumed throughout the southern three quarters of the province and the northern New England states. The assumption of random occurrence throughout an arbitrarily defined zone was required because it was not possible to identify regional geological features that controlled the distribution of seismicity (as noted above with respect to Fig. 1).

The risk calculations also require esti-

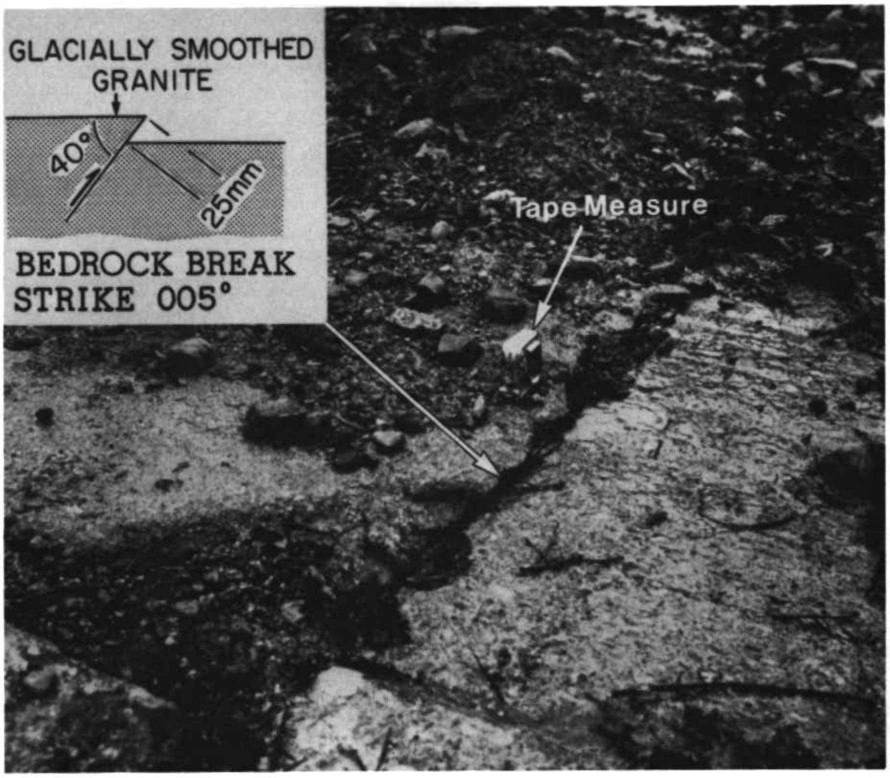

Figure 5 *The observed ground break with an east-west cross section showing the relative displacment. The location of the break in an east-west section of aftershock hypocentres in shown in Figure 6a. After Wetmiller* et al. *(1984)*

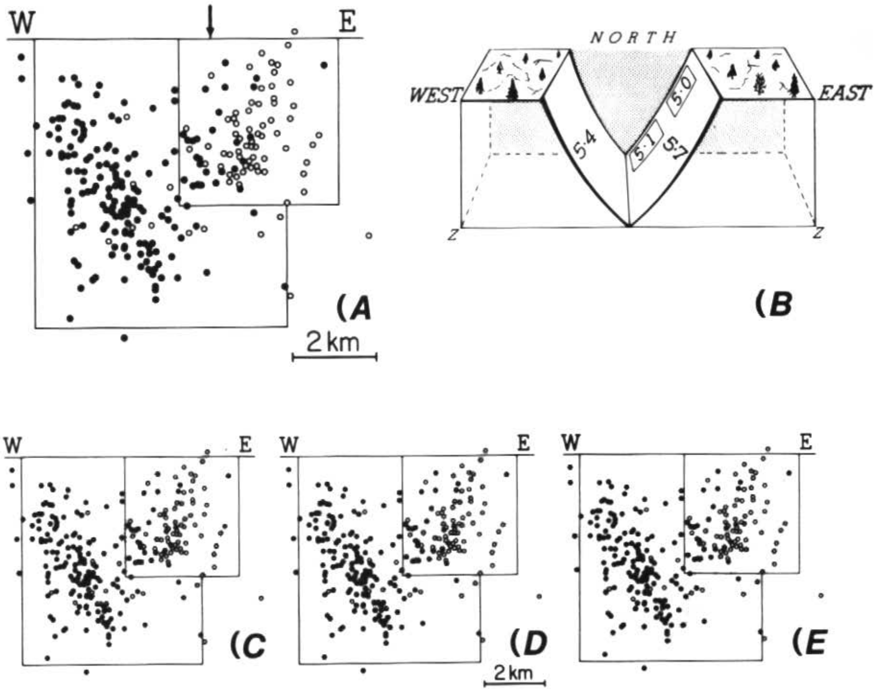

Figure 6 *(a) East-west cross section of January (solid circles) and April (open circles) aftershock hypocentres. (b) Possible Miramichi rupture planes. View is from the south looking north, and number on each plane identifies the magnitude of the earthquakes. (c,d,e) Three alternative sets of speculative rupture planes superimposed on aftershock distribution from (a). The relative location of the bedrock crack (Fig. 5) is shown by the arrow. Horizontal and vertical scales are equal*

mates of earthquake rates as a function of magnitude (determined from historical and recent seismicity), and an upper bound magnitude. For the Northern Appalachians source zone, the upper bound magnitude was set as 6.0, an arbitrary value selected as being somewhat larger than the then known largest historical event. Lack of neotectonic constraints (e.g., dimensions of potentially active faults) prevented determination of the relevant value. The Miramichi mainshock came close to, but did not exceed, this upper bound.

A recalculation of the seismic ground motion with the Miramichi earthquakes added to the Northern Appalachian model has shown that the zoning maps would not change significantly. The computed ground motion would increase by about 5 percent of its value, which is well within the uncertainty in the original calculations.

The current understanding of the focal parameters and inferred faulting of the Miramichi earthquakes (as summarized above) is much better than for any equivalent magnitude earthquakes anywhere in eastern North America. However, in spite of this, we are not yet much closer than before to having a general understanding of the types of geological features or structures on which similar earthquakes will occur in the future, i.e., the random earthquake model still provides our best estimates. Further work in Miramichi may provide additional clues.

Work in Progress

Three field projects in addition to the bedrock cleanoff project described above were conducted in the Miramichi epicentral zone in the summer of 1983. A number of sites were occupied by analogue and digital seismographs to record continuing aftershocks, and two calibration explosions were detonated in shallow holes to determine more accurate local crustal velocities. The aftershock survey was designed to determine accurate hypocentres of continuing activity in the shallow portion of the eastern aftershock cluster (Fig. 6). The data are now being analyzed and it is hoped that the results will more clearly define the near surface faults on which the aftershocks are occurring and, thereby, provide better target areas for a further search for the surface expression of the faults.

A magnetotelluric (MT) survey was conducted using both tensor MT and scalar audiomagnetotelluric (AMT) techniques. Tensor MT soundings were made at eleven locations inside and on the edges of the epicentral region to establish the conductivity structure throughout the crust. Scalar AMT measurements were made at seventy-six locations along an E-W profile in the east-central portion of the zone. These measurements were designed to look for a conductivity signature of one or more postulated shallow rupture planes. Both sets of data are now being analyzed and any positive results will also aid in determining the nature and location of the rupture planes.

A NW-SE trending electromagnetic anomaly was located near Indian Lake, in the SE corner of the epicentral zone, by the New Brunswick Department of Natural Resources (J. Chandra, personal communication, 1984). Two trenches were cut across the anomaly and revealed an apparent gouge, or mylonite zone, separating unweathered and strongly weathered granites of different lithology, the lithology difference probably being sufficient to account for the weathering difference. There was no firm evidence for young displacement on the gouge zone, although gouge material appeared to have been dragged up into the till along the direction of ice movement.

Future Work

Our investigations of the epicentral area are by no means concluded. In 1984 a multi-agency project led by Ontario Hydro intends to make direct measurements of horizontal stresses at four or five sites within and outside the epicentral area. The measurements will be made by overcoring in 15 m-deep holes, and should provide valuable data about regional and local post-earthquake stresses. Also in 1984, the Earth Physics Branch will lead a second multi-agency project to expose bedrock along a narrow strip across the expected surface outcrop of the west-dipping rupture plane. The search for a surface rupture – which if found will be the first to be associated with a historical earthquake in northeastern North America – is important: comparisons will be made with our seismic estimates of rupture displacements at depth, and it will enable us to test models that seek to explain the lack of such ground breakage during previous earthquakes in eastern North America.

Looking still further into the future, we hope that it will be possible to fund a high resolution seismic reflection survey to attempt to map in detail the fault planes at depth and to determine the degree to which the faulting has altered the integrity of the rock mass. If such mapping is successful, it may be possible to "see" the faults directly and improve our understanding of the events and processes during this remarkable earthquake sequence.

Acknowledgements

We are grateful to our colleagues at the Earth Physics Branch, R.J. Wetmiller, A.E. Stevens, F.M. Anglin and H.S. Hasegawa, from whose work we have drawn liberally for this article. J. Wallach of the Atomic Energy Control Board was instrumental in arranging the 1983 bedrock clean-off operation in New Brunswick. We also acknowledge the excellent cooperation and timely geophysical and geological mapping provided by J. Chandra and L. Fyffe of the New Brunswick Department of Natural Resources.

Figure 7 *View of pop-up induced by removing till overburden. Note axial crack, gap under buckled slab, and dirt piled up against former position of slab. Compass provides scale and points north*

References

Adams, J., 1982, Miramichi earthquake – epicentral geology, lineaments and field plans: *in* A.E. Stevens, ed., Preliminary Report of the Miramichi, New Brunswick, Canada Earthquake Sequence of 1982, Earth Physics Branch Open File Report 82-24, p. 50-52.

Anglin, F.M., 1984, Seismicity and faulting in the Charlevoix zone of the St. Lawrence Valley: Bulletin of the Seismological Society of America, v. 74, No. 2, p. 595-603.

Barosh, P.J., 1981, Seismicity and tectonics of the Passamaquoddy Bay area, Maine and New Brunswick (abstract): Geological Society of America, Abstracts with program, v. 13, p. 122.

Basham, P.W., D.H. Weichert, F.M. Anglin and M.J. Berry, 1982, New probabilistic strong seismic ground motion maps of Canada: a compilation of earthquake source zones, methods and results: Earth Physics Branch Open File Report 82-33, 205 p.

Burke, K.B.S. and J.J. Chandra, 1983, Gravity survey of the epicentral area of the main sequence of 1982 Miramichi earthquakes: New Brunswick Department of Natural Resources Open File Report 83-3, 27 p.

Choy, G.L., J. Boatwright, J.W. Dewey and S.A. Sipkin, 1983, A teleseismic analysis of the New Brunswick earthquake of January 9, 1982: Journal of Geophysical Research, v. 88, p. 2199-2212.

Cox, J.W., 1983, Long axis orientation in elongated boreholes and its correlation with rock stress data: Transactions 24th Annual Logging Symposium, Calgary, Alberta, Canada, June 27-30, 1983, Society of Professional Well Log Analysts, v. 1, 17 p.

Fyffe, L.R., 1982a, Geology in the vicinity of the 1982 Miramichi earthquake: *in* A.E. Stevens, ed., Preliminary Report of the Miramichi, New Brunswick, Canada Earthquake Sequence of 1982, Earth Physics Branch Open File Report 82-24, p. 44-46.

Fyffe, L.R., 1982b, Geology in the vicinity of the 1982 Miramichi earthquake Northumberland County, New Brunswick: New Brunswick Department of Natural Resources, Open File Report, 82-27, 37 p.

Fyffe, L.R., 1983, Joint patterns within the epicentral area of the 1982 Miramichi Earthquake: New Brunswick Department of Natural Resources, Open File Report 83-13, 19 p.

Jackson, J.A., G. King and C. Vita-Finzi, 1982, The neotectonics of the Aegean: an alternative view: Earth and Planetary Science Letters, v. 61, p. 303-318.

King, G. and J. Brewer, 1983, Fault related folding near the Wind River thrust, Wyoming, U.S.A.: Nature, v. 306, p 147-150.

Lajtai, E.Z. and P. Stringer, 1981, Joints, tensile strength and preferred fracture orientation in sandstone, New Brunswick and Prince Edward Island, Canada: Maritime Sediments and Atlantic Geology, v. 17, p. 70-77.

Leith, W., D.W. Simpson and W. Alvarez, 1981, Structure and permeability: Geologic controls on induced seismicity at Nurek reservoir, Tadjikistan, USSR: Geology, v. 9, p. 440-444.

Ouyed, M., G. Yielding, D. Hatzveld and G.C.P. King, 1983, An aftershock study of the El Asnam (Algeria) earthquake of 1980 October 10: Geophysical Journal of the Royal Astronomical Society, v. 73, p. 605-639.

Pernica, G. and A.H.P. Maurenbrecher, 1982, Survey of building damage in New Brunswick caused by the 1982 New Brunswick earthquake: *in* A.E. Stevens, ed., Preliminary Report of the Miramichi, New Brunswick, Canada Earthquake Sequence of 1982, Earth Physics Branch Open File Report 82-24, p. 56-70.

Rast, N., K.B.S. Burke and D.E. Rast, 1979, The earthquakes of Atlantic Canada and their relationship to structure: Geoscience Canada, v. 6, p. 173-180.

Smith, W.E.T., 1966, Earthquakes of eastern Canada and adjacent areas 1928-1959: Publications of the Dominion Observatory, v. 32, p. 87-121.

Stevens, A.E., 1977, Some twentieth century Canadian earthquakes: Geoscience Canada, v. 4, p. 41-45.

Stevens, A.E. and M.G. Cajka, 1984, Intensity distributions of some 1982 Miramichi, New Brunswick, Canada, earthquakes: in preparation.

Weichert, D.H., P.W. Pomeroy, P.S. Munro and P.N. Mork, 1982, Strong Motion records from Miramichi, New Brunswick, 1982 aftershocks: Earth Physics Branch Open File Report 82-31, 94 p.

Wetmiller, R.J., J. Adams, F.M. Anglin, H.S. Hasegawa and A.E. Stevens, 1984, Aftershock sequence of the 1982 Miramichi, New Brunswick earthquakes: Bulletin of the Seismological Society of America, v. 74, p. 621-653.

Williams, H., 1978, Tectonic lithofacies map of the Appalachian Orogen: Map No. 19, Memorial University of Newfoundland.

Wood, H.O. and F. Neumann, 1931, Modified Mercalli intensity scale of 1931: Bulletin of the Seismological Society of America, v. 21, p. 277-283.

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