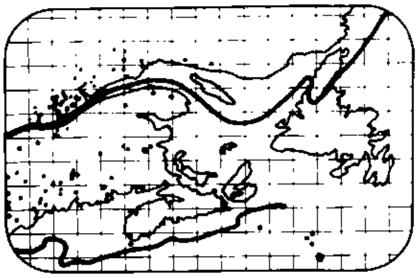


The Earthquakes of Atlantic Canada and Their Relationship to Structure

N. Rast*, K. B. S. Burke
and D. E. Rast*
Department of Geology
University of New Brunswick
Fredericton, N.B. E3B 5A3

**Present address:*
Bowman Hall
Department of Geology
University of Kentucky
Lexington, Kentucky 40506

Abstract

Earthquakes are common in Atlantic Canada, but instrumentally determined magnitudes have rarely exceeded 5 on the Richter scale. One exception is the Grand Banks earthquake of 1929 which had a magnitude of 7.2. However, it is probable that the Richter scale overestimates earthquake magnitude in Atlantic Canada. A recalculation of magnitudes for many of the non-instrumentally recorded earthquakes, using the various empirical relationships between felt area and magnitude, rather than maximum intensity and magnitude, shows a reduction in magnitudes for historically reported earthquakes.

Because of the paucity of available instrumentation - there has been only one three-component seismograph in the region for a part of the time - the detailed pattern of epicentres and focal depths is poorly known in Atlantic Canada. Attempts to correlate epicentres with known geological features have generally failed because of the uncertainty in the epicentral positions. Nevertheless, several hypotheses have been advanced to explain the earthquake pattern in Atlantic Canada: 1) movement on faults, 2) glacial rebound, 3) association with igneous intrusions.

An analysis of these explanations, shows that the five major known episodes of faulting all happened between Precambrian and early Tertiary times and are not at present active. Furthermore, glacial rebound in detail cannot be related to the distribution of earthquakes. Association with igneous intrusions is a working hypothesis, but recent evidence from Quebec and New England suggest a mid-crustal focal depth for those earthquakes for which a good solution is available. It is therefore suggested that earthquakes are not associated with the intrusions as such, but possibly only with deep channels that led the magma to the upper crust. The repeated motion on these deep magmatic conduits is provisionally attributed to the cooling of the existing thermal high that underlies New England and Atlantic Canada.

Introduction

The seismic activity on the eastern American seaboard is well known, both historically and at the present time. The large majority of shocks were and are very small, seldom exceeding magnitude 5, but there have been several nearly catastrophic events. In Atlantic Canada and the northeastern U.S.A. a majority of these earthquakes have occurred either along the St. Lawrence Valley or in southern New England. A comparatively large number of small earthquakes occur sporadically throughout the Canadian Maritimes. In a few cases the earthquakes can be related to specific faults in terms of concentration (for example the Oak Bay Fault, Fig. 1). Nevertheless, the vast majority of these earthquakes are not obviously related to surface faults, but may be related to deeper structures. The fact that correlation with surface faults is difficult has been commented upon by Poole *et al.* (1970) and prior to that by Smith (1967). An alternative suggestion has been that earthquakes in New England can be related to gabbroic intrusions (Rand, 1977; Simmons, 1978). This line of reasoning (i.e., association with igneous intrusion) has also been applied more widely in the U.S.A. (Kane, 1976; McKeown, 1978).

Difficulties regarding the monitoring and recording of earthquakes are encountered both with regard to the precise determination of their position and also their magnitude. For instance, in New Brunswick the position of the earthquakes can be determined only within limits of error that make the correlation with specific structures very difficult.

Position and Depth of Earthquakes in Atlantic Canada

The position of historical earthquakes has been determined mostly on conjectures based on somewhat assumed intensities (Smith, 1962, 1966). Since 1959, instrumentally determined earthquakes have been compiled and listed by the

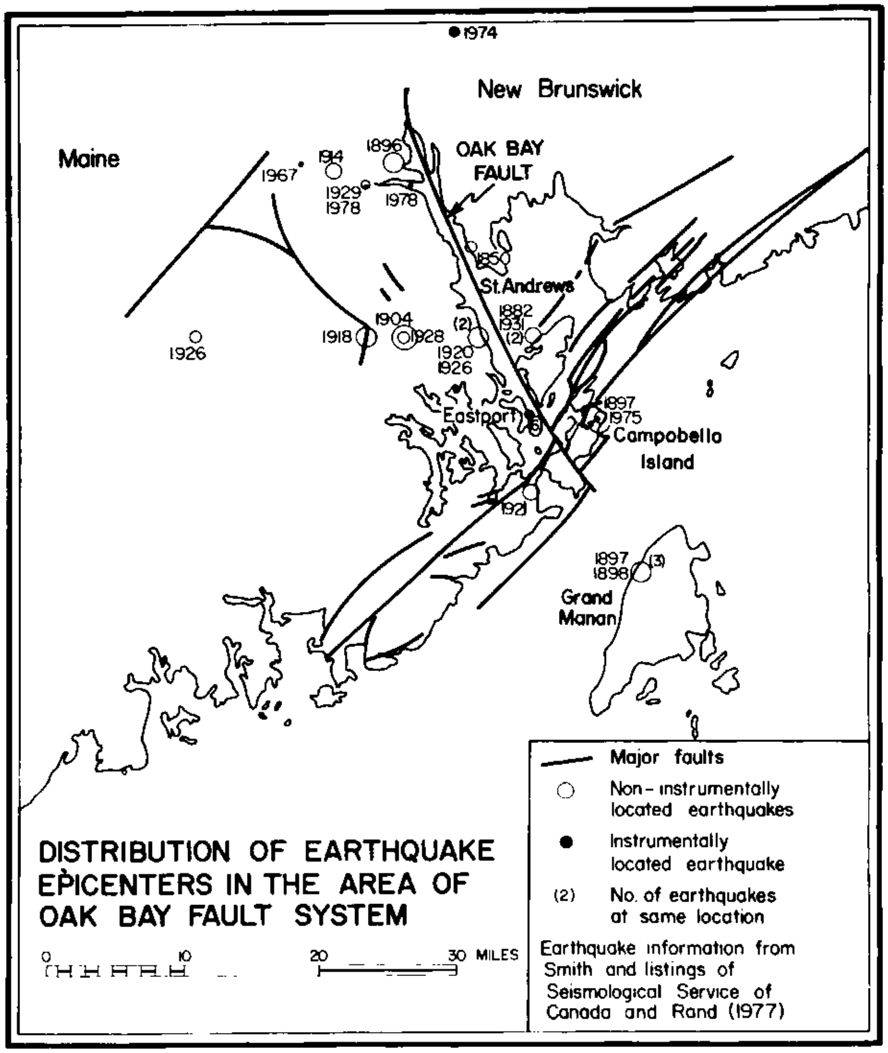


Figure 1
Distribution of earthquake epicentres in the vicinity of Oak Bay Fault system

Seismological Service of Canada in a series of bimonthly and annual publications of Energy, Mines and Resources Canada. In Atlantic Canada at the present time there are three seismic recording stations; in Fredericton, N.B., Halifax, N.S. and St. John's, Newfoundland. Only the last is a three component standard station, the other two being simple vertical component seismographs, serving as regional stations.

Most of the early events listed by Smith in 1962 were not recorded instrumentally and estimates of positions and magnitudes are mainly based on historical records and contemporary accounts given by untrained observers. During this period (1534-1927 A.D.), because of the sparseness of population, the record for smaller earthquakes (magnitude less than 4) is probably incomplete. Epicentres for the majority of these earthquakes are defined by the central point of the area over which the earthquake was reportedly felt. This procedure implies a great uncertainty in positioning epicentres.

The instrumental earthquakes listed by Smith in 1966 constitute a large proportion of post-1927 seismic activity recorded in Atlantic Canada. These earthquakes were estimated mainly from records of more than one station, but a few were recorded at one station only. Thus, the location of epicentres in most instances is fairly reliable, being generally less than 20′ of arc (about 37 km).

Focal depths have been reported in E.M.R. catalogues for some of the earthquakes in Atlantic Canada, most of the depths being in the range 15 to 30 km. However, the uncertainty involved in these depth determinations (±10 km) led Stevens *et al.* (1972) to advise that such values should only be taken as indicating upper, middle or lower crustal positions. The evidence therefore points to a middle to lower crustal focal depth for the earthquakes in Atlantic Canada.

As support for this generalization, it is possible to cite the evidence of a more intensive study of one earthquake sequence in Quebec, where a study by Horner *et al.* (1978) of the 1975 Maniwaki earthquake and its aftershocks yields a focal depth of 17 ± 2 km. Activity associated with the main earthquake and the aftershocks was confined to a volume of 1 km diameter, centred at the hypocentre. If this earthquake is typical of other earthquakes in the eastern region of North America, the search for a causative mechanism should be focussed on the middle to lower crust.

Magnitudes of Atlantic Earthquakes

Magnitudes suggested by Smith (1962) for historical earthquakes are in the main related to epicentral intensities determined for particular earthquakes by using the empirical relationship $M = 1 + 2I_{max}/3$ (Gutenberg and Richter, 1956), where M is the estimated magnitude (Richter scale) and I_{max} is the maximum intensity on the modified Mercalli Scale.

More reliable estimates for historically reported earthquakes can be made if the assignment of magnitude is based on the area over which the earthquake is felt, or alternatively, the area within the MM intensity IV isoseismal (Nuttli and Zollweg, 1974; Street and Lacroix, 1979).

In Table I, nine earthquakes in Atlantic Canada, for which there is information on the felt area in the listings, have been re-evaluated using the magnitude-felt area relationships of the above workers, i.e. $m_b = 2.65 + 0.098f + 0.054f^2$ (Nuttli and Zollweg, 1974), $f \leq 6$, where: f is the logarithm to

DATE OF EARTHQUAKE	LATITUDE °N	LONGITUDE °W	MAGNITUDE BASED ON EPICENTRAL INTENSITY M_I	MAGNITUDES BASED ON FELT AREAS	
				m_b NUTTLI AND ZÖLLWEG (1974)	m_{bLg} STREET AND LACROIX (1979)
FEB. 3TH, 1855	46.0	64.5	5.7	4.7	4.8
OCT. 22ND, 1869	45.0	66.2	6.3	5.0	5.3
FEB. 8TH, 1870	44.1	67.1	5.0	4.2	4.2
MAR. 17TH, 1870	45.5	66.5	3.7	3.7	3.5
DEC. 31ST, 1882	45.0	67.0	5.0	4.7	4.8
JUNE , 1885	45.1	66.1	3.7	3.5	3.3
MAR. 22ND, 1896	45.2	67.2	4.3	4.1	4.0
MAR. 21ST, 1904	45.0	67.2	5.7	4.9	5.1
JULY 2ND, 1922	46.5	66.6	5.0	4.4	4.3

Table I
Magnitude estimates for 9 earthquakes in Atlantic Canada.

base 10 of the felt area in km², and m_b is the magnitude estimate $m_{bLg} = 2.77 - 0.147f + 0.100f^2$ (Street and Lacroix, 1979), $f \leq 6.5$, where: m_{bLg} is the logarithm to base 10 of the felt area in km².

Also listed in Table I for comparison purposes are the magnitude values for the earthquakes based on epicentral intensity (M_I). It is seen from the listed values that magnitudes based on felt area are consistently smaller than those based on epicentral intensity. This reduction in size is particularly noteworthy for M_I greater than 5. Thus, it is suggested that the magnitude of historically reported earthquakes in the region, have been, in the past, overestimated.

Magnitude values in the listings, for instrumentally determined earthquakes for the years until 1968 were calculated by means of Richter's (1935) M_L scale for epicentral distances of up to 600' kms and by extrapolation to 1500 km. Gutenberg and Richter's (1936) M_s magnitude scale was also used for those earthquakes that generated surface waves at teleseismic distances. It was pointed out by Stevens *et al.* (1973) that the application of the M_L scale in the eastern region of Canada gave rise to magnitude values that were ½ to 1 unit higher than the M_s and m_b magnitudes assigned for teleseismic data. Magnitudes using Nuttli's Scale based on L_g waves of about one second period have been used wherever possible in the listings published since 1973 and recorded as m_N. Because a vast majority of earthquakes in Atlantic Canada are small, the more reliable method of measuring magnitudes based on the spectral characteristics of the L_g phase (Street and Turcotte, 1977) has normally not been employed in Canada, except for the very large earthquakes (Basham *et al.*, 1978) in the St. Lawrence Valley region.

With the exception of the Grand Banks earthquake of 1929, all instrumentally determined earthquakes in Atlantic Canada have had magnitudes less than 5.2. A magnitude M_s of 7.2 was assigned to the Grand Banks earthquake by Gutenberg and Richter (1954) and has since been confirmed by Street and Turcotte (1977). It is thus seen that the one *large* earthquake whose occurrence can be confirmed in the region still requires a detailed investigation to arrive at a convincing explanation. This is beyond the scope of the present paper. In general, however, the vast majority of earthquakes in Atlantic Canada are moderate in size, which coupled with the focal depth information, suggests a small volume source in the middle to lower crust.

Faulting in Atlantic Canada

Faulting in Atlantic Canada has been investigated by many authors (e.g., Webb, 1963, 1969; Eisbacher, 1970; Garnet and Brown, 1973) and large scale faults of pre-Carboniferous and post-Carboniferous ages are recognised. Altogether five episodes of major faulting have been detected (Fig. 2).

1) *Precambrian faults.* Very large shear zones are recorded in the Precambrian (Rast and Currie, 1976).

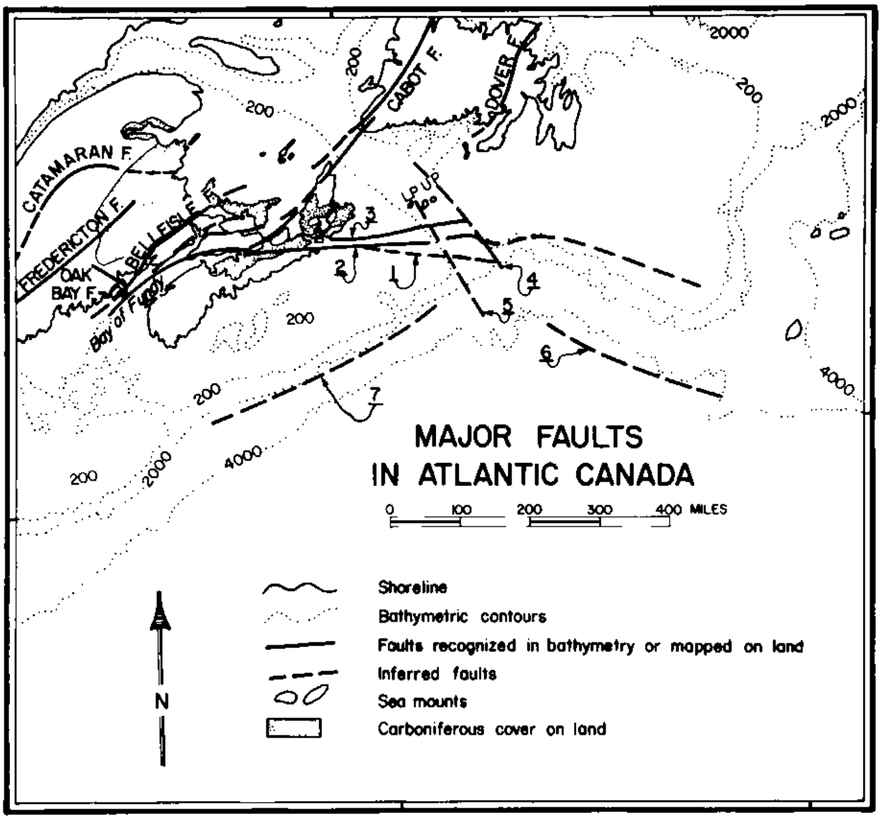


Figure 2
Major faults in Atlantic Canada. Faults 1, 2 and 3 are branches of the Chedabucto system; faults 4, 5, 6 and 7 are inferred distensional faults in the Cabot Strait and Atlantic Ocean.

Faults of this age are characterised by extensive recrystallized mylonite zones and correlation across them is at present impossible. Although one would expect the recrudescence of movement on such faults, a detailed investigation of the Pocologan zone conducted by N. Rast and W. L. Dickson, failed to indicate appreciable post-Precambrian movement.

2) *Lower-Middle Paleozoic faults.* Very large Paleozoic faults are detected everywhere in New Brunswick. Some, such as the Catameran fault of central New Brunswick, are somewhat sinuous and parts of their traces are covered by Carboniferous rocks, implying that no post-Carboniferous movements affected this fracture. Others, such as the Belleisle fault (Garnett and Brown, 1973), are straight and show a considerable post-Carboniferous component. The latter fault at the surface dies out under Prince Edward Island rocks of Permian age and therefore it evidently lacks a component of post-Paleozoic deformation. The Fredericton fault is also of this type.

3) *Late Carboniferous faults.* In southern New Brunswick, large scale, possibly late Westphalian, thrust faulting has been widely recorded (Rast and Grant, 1973, 1977; Rast *et al.*, 1978) as the Variscan front, or as cataclastic zones (Ruitenberg *et al.*, 1973, 1977). There is no evidence for any post-Paleozoic movements along these faults.

4) *Triassic faults.* The Triassic of the Maritime provinces is extensively faulted with the faults in New Brunswick having two orientations (ENE-WSW and NW-SE). An example of the former is the New River Beach fault and of the latter the Lepreau fault (Rast *et al.*, 1978). In both cases the faults throw the Triassic against older rocks and there is some evidence that they may have been partly contemporaneous with the deposition of the Trias (Rodgers, 1970). The Triassic Lepreau fault is covered by undisturbed glaciogenic sediments therefore suggesting that there has been no post-Pleistocene regeneration of movements.

5) *Post-Triassic faults.* The evidence for post-Triassic, probably Cretaceous-Tertiary movements is sparse. Perhaps the most significant evidence comes from the submarine extension of the Cobequid-Chedabucto fault, which has been mapped to displace Cretaceous, but not Lower Tertiary sediments (King and McLean, 1974). On a small scale, vertical faults with the orientation of the Chedabucto fault are found in the Triassic rocks of the Bay of Fundy. The small faults have a strike-slip displacement suggesting a component of movement similar to that along the Chedabucto fault zone. These faults are overlain by undisturbed Pleistocene deposits and therefore appear to have been inactive for a long time. Furthermore, joints in the Triassic rocks in proximity of these faults are filled by undisturbed calcite, thus indicating that there has been no recent deformation.

In one instance (the Oak Bay fault), however, there is some evidence of the possibility of more recent movements. The fault principally affects Lower Paleozoic or Devonian rocks, but on Campobello Island (McLeod, 1979) it appears to cause a displacement in glacial deposits. The evidence is not absolutely conclusive, but the possibility of syn-Pleistocene or even post-Pleistocene displacement across the fault has to be considered (Fig. 1).

The plotting of historical or instrumentally recorded earthquakes in Atlantic Canada (Fig. 3) indicates that there is no definite association of these with known faults except with respect to the Oak Bay fault on land and a possible system of faults in the Cabot Straits channel. These faults have been partly inferred by us from the morphology of the channel and partly from the absence of the continuation of rock stratigraphy across the channel. At any rate, only in the cases of the Oak Bay fault and the Cabot Strait do we find concentrations of recent earthquake epicentres to lend credence to the hypothesis of association of surface faults and earthquakes in coastal Atlantic Canada, although in Quebec they may be rift related (Kumarapeli, 1979).

There is some direct evidence of the possible activity along the northeast-southwest trending faults in Maine. Rand (1977) reports a concentration of 12 epicentres near Orrington, Maine, that are situated along the continuation of the Fredericton fault, where it is known as the Norumbega Fault (Williams, 1978). Rand, incidentally, also notes 10 epicentres of recent and historical earthquakes at the Oak Bay fault.

At this stage one should discuss the evidence of displacement of glacial features by the apparently post-glacial faults. In New Brunswick this was first recorded by Matthew (1894). Thompson (1979) undertook a search for possible glacial displacements in Maine and reports a few very minor displacements (1.5 - 30.0 mm) of the glacially striated bedrock surface along northeast trending bedding-plane faults. In the Norumbega fault zone, four such readings were made, but none were associated with mapped fault traces. The small post-glacial faults extend only a few metres along the strike, thus they are not likely to have precipitated appreciable earthquakes or to have been associated with major fault movements, but as Oliver *et al.* (1970) points out, the surface postglacial faults can be associated either with glacial loading or unloading and therefore their mechanical significance is unknown. In any case

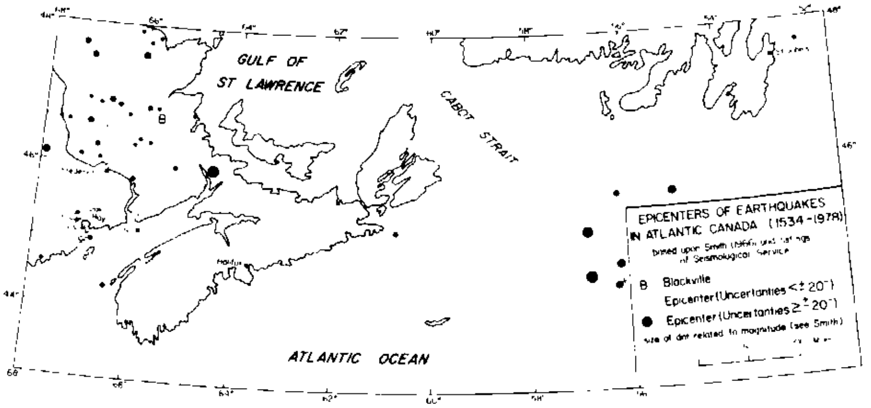


Figure 3
Earthquakes in Atlantic Canada

neither loading nor unloading is likely to be effective at depth (Coffman and von Hake, 1973). We therefore, at present, regard the influence of glaciation at best subsiduary.

The Relationship to Intrusive Bodies

A recently developed hypothesis is that of the relationship of earthquakes to mafic intrusives. Perhaps the most clear popular exposition of this hypothesis is that prepared by Simmons (1977). The hypothesis depends on the observed spatial correlation between earthquakes and mafic intrusions. In New England such a relationship is particularly clear at Cape Ann, north of Boston, and also in association with the intrusives of the White Mountains in New Hampshire. In the latter instance, the surface intrusion sometimes has acid affinities, but when as in the case of the Ossipee pluton, it is associated with a high gravity or magnetic anomaly, it is assumed that the intrusion is underlain by a cylindrical body of basic composition.

In this context it is important to notice that in New Brunswick one of the few clusters of recorded earthquake epicentres (Fig. 3, loc. B) is situated in the Blackville area. (In fact one of the largest instrumentally recorded earthquakes in New Brunswick ($M_L = 4.6$) belongs to the Blackville cluster). Here, although the surface rocks are Carboniferous sediments, the coincidince of a magnetic (Geol. Surv. Canada map 757G) and a gravity high (Earth Physics Branch Open File 77-4) suggests sub-Carboniferous mafic pluton.

There are some speculations put forward to explain the association of earthquakes and gabbroic bodies. Simmons (1977) envisages the gabbroic plugs to be stiffer than the surrounding rock and therefore acting as force concentrators. Similar hypotheses have been suggested by Long and Champion (1977) and McKeown (1978). Kane (1976) and Kane and Hildebrand (1976) suggest that the mafic material under external stress deforms by creep and therefore acts like a cavity that concentrates stress in the surrounding country rock. From our experience, the latter suggestion fits better with geological data, since gabbroic intrusions rarely show extensive internal shear zones, although they often have a very large number of small internal cracks. Seismologically, Kane's hypothesis is advantageous, since most earthquake epicentres fall outside the limits of the actual bodies.

Spatially, some of the gabbroic bodies with which the earthquakes are associated occur along fault zones. Thus, McKeown (1978) suggests that the New Madrid earthquake is spatially related both to a gabbro body and to a fault zone which may represent a reactivated rift. There has in fact been a suggestion by Woollard (1958) that the New Madrid epicentre was located on the rift structures continuous from the Saint Lawrence Valley into the east-central U.S.A. Similarly, Sbar and Sykes (1973) have pointed out the association of the White Mountain plutons of New Hampshire and the Monteregian Hills of Quebec with an earthquake belt and proposed that this belt is related to a postulated transform fault that also passes through the Kelvin Seamounts. The linear arrangements of the New Hampshire and Monteregian plutons certainly suggests a relationship to a lineament, but not to a surface fault.

Thus, there are three main associations of earthquakes with geological structures. First, one may mention the association with individual intrusions that bear no spatial relation to any detectable geological structures. An example of this is the Megantic Hill, Quebec, which although petrologically has affinity with the Monteregian intrusions, is not on trend with them. Secondly, gabbroic intrusions of the White Mountain Magma series in New Hampshire and Massachusetts are on a lineament, presumably a lower crustal fault, that does not affect the upper crust. Thirdly, there is the belt of earthquake activity associated with postulated rifts, as for instance in the St. Lawrence Valley or New Madrid. In these situations the earthquakes may or may not be related to identifiable gabbroic intrusions. In Atlantic Canada the earthquakes of the last type appear to be concentrated on a few NW-SE trending fractures. Any viable model must incorporate all these features and in addition it must explain why mafic bodies, rather than rigid granites, have earthquakes associated with them.

We would try to construct the model on the basis of plate tectonics. It seems reasonable to speculate that all the eastern seaboard earthquakes are in some way conditioned by the North Atlantic rifting and therefore their mechanism is related to the events associated with the continental fragmentation and the drifting of North America from Africa.

The model proposed involves three development stages (Fig. 4). The first stage, initiated in the late Triassic and Lower Jurassic time, was that of the rifting produced above an extensive magma chamber situated in the Upper Mantle. This chamber we refer to as an asthenolith (Belousov, 1966). As a result of consequent doming and fragmentation of the Pangean crust, tholeiitic magmas reached the surface as flows or consolidated below as dykes (King, 1969). The igneous activity at this stage was concentrated at the edge of nascent North America rather than Africa.

The decrease in the support of the domed continental North American crust then caused collapse of marginal fault blocks, squeezing and trapping a part of the asthenolith. Along penecontemporaneous 'transform' lower crustal faults, intrusion of basic magma occurred to produce the Kelvin Seamounts, the White Mountain complexes and the Monteregian Hills. The magmas of the Monteregian Hills, starting from lower mantle levels, were appreciably more alkaline than those of the White Mountains. During the collapse an apron of sediments accumulated on the ocean side forming the continental shelf.

The volcanic-intrusive activity during the second stage lasted throughout the rest of the Jurassic and Cretaceous. Although most of the activity took place along lower crustal faults, some occurred independently as local penetrative plumes.

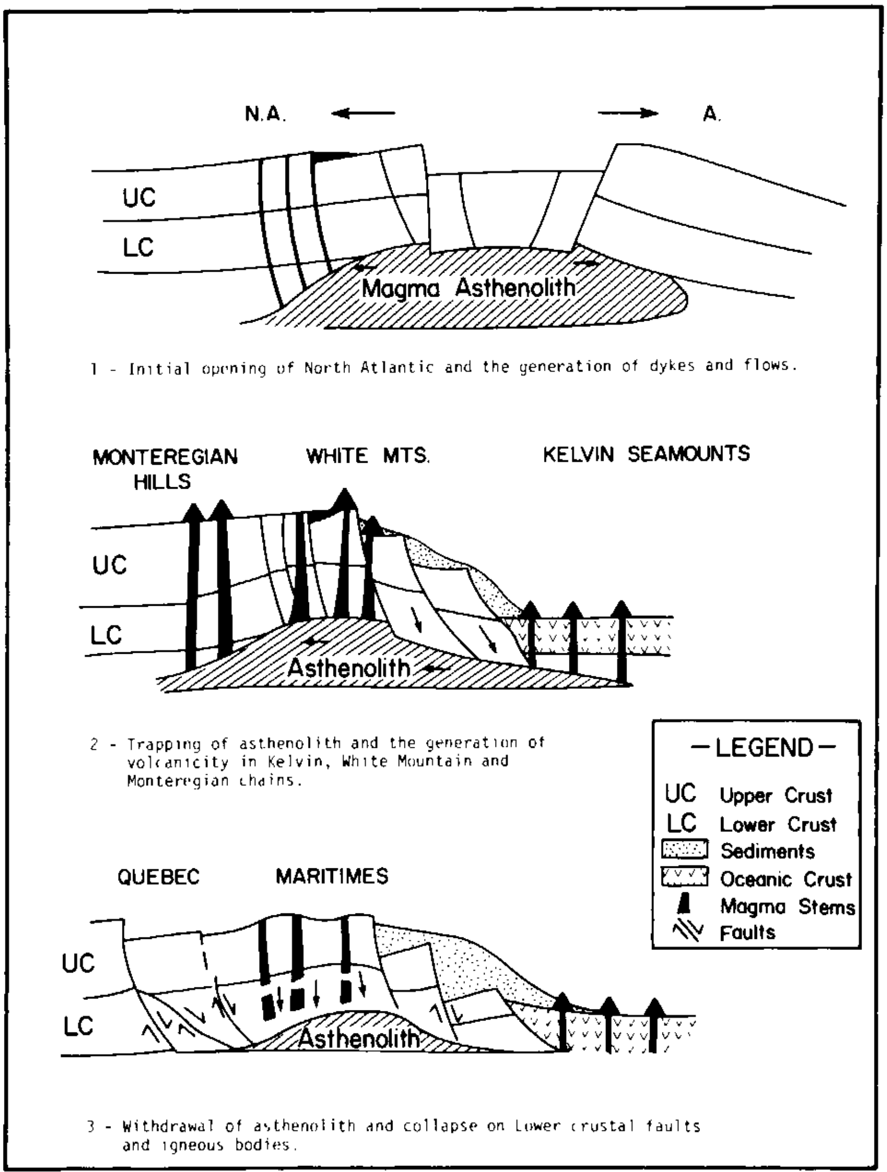
The Tertiary to Recent times involved the cooling of the asthenolith, which has still not entirely disappeared, because in New England and the Maritimes, a thermal high (Fig. 5) can be recognised that we propose represents the residual asthenolith. Although in eastern Canada a much more intensive gathering of heat flow data is desirable, it appears that the thermal high encompasses most of the area of coastal Maritime Canada where moderate to small earthquakes are common.

We suggest that the cooling of the asthenolith would lead to the withdrawal of support from the overlying crust, leading to the formation of faults in the lower crust and a collapse of the lower parts of mafic intrusions. At the surface and in the upper crust such a collapse, in many cases, would not be noticeable since the intrusions will be supported by rigid upper crustal rocks. In the lower crust, and perhaps Upper Mantle, the surrounding rocks would yield more easily and parts of the dense basic bodies would tend to move downwards generating earthquakes. Above the edge of the former asthenolith (Saint Lawrence Valley), a more general collapse on deep crustal faults can be expected. Lastly, the accumulation of the overlying sedimentary apron of the continental shelf would lead to more accelerated movements on faults giving rise to large earthquakes such as the Grand Banks shock in 1929. The gradual shrinkage of the asthenolith can also be expected to give rise to transverse fractures and earthquakes along them. We propose that the Oak Bay fault is one such fracture.

At present further details of the model are difficult to support by numerical data, since the heat flow data are not entirely adequate and the instrumental deficiencies and especially the sparse network of seismographs in Canada render local studies inconclusive. Yet the hypothesis is worth investigating.

Acknowledgements

The authors are grateful for the opportunity to participate in regional investigations in 1976 when N.R. and D.E.R. were financed by Boston and Edison Co. Ltd. Sandi Guptill typed the successive versions of the paper and Michael Oudemans has drawn the figures to all of whom we are grateful.



1 - Initial opening of North Atlantic and the generation of dykes and flows.

2 - Trapping of asthenolith and the generation of volcanicity in Kelvin, White Mountain and Monteregian chains.

3 - Withdrawal of asthenolith and collapse on Lower crustal faults and igneous bodies.

Figure 4

The evolution of the seismotectonic zone in Atlantic Canada and New England.

References

Basham, P. W., A. E. Stevens, F. M. Anglin and R. J. Wetmiller, 1978, The seismicity of eastern Canada: Program with Abstracts, Geol. Assoc. Canada/Mineral. Assoc. Canada, v. 3, p. 364.

Belousov, V. V., 1966, Modern concepts of the structure and development of the Earth's crust and the upper mantle of continents. Quart. Jour. Geol. Soc. London, no. 487, v. 122, Part 3, p. 293-314.

Coffman, J. L. and C. A. von Hake, 1973, Earthquake history of the United States. U.S. Dept. of Commerce Publication 41-1, 208 p.

Eisbacher, G. H., 1970, Deformation Mechanics of Mylonitic Rocks and Fractured Granites in Cobequid Mountains, Nova Scotia, Canada: Geol. Soc. Amer. Bull., v. 81, p. 2009-2020.

Garnett, J. A. and R. L. Brown, 1973, Fabric Variation in the Lubec-Belleisle Zone of Southern New Brunswick: Can. Jour. Earth Sci., v. 10, p. 1591-1599.

Gutenberg, B. and C. F. Richter, 1936, On seismic waves (third paper): Geol. Beitr. Geophys., v. 47, p. 73-131.

Gutenberg, B. and C. F. Richter, 1954, Seismicity of the earth and associated phenomena: Princeton Univ. Press.

Gutenberg, B. and C. F. Richter, 1956, Earthquake magnitude, intensity, energy, and acceleration: Seismol. Soc. Amer. Bull., v. 46, p. 105-145.

Horner, R. B., A. E. Stevens, H. S. Hasegawa and G. Leblanc, 1978, Focal parameters of the July 12, 1975, Maniwaki, Quebec, earthquake - an example of intraplate seismicity in eastern Canada: Seismol. Soc. Amer. Bull., v. 68, p. 619-640.

Jessop, A. M., M. A. Hobart, and J. G. Sclater, 1976, The World Heat Flow Data Collection - 1975: Geothermal Series n. 5, Earth Physics Branch, Energy, Mines and Resources, Canada, 125 p.

Kane, M. R., 1976, Spatial relations between mafic/ultramafic plutons and seismicity in the northern Mississippi embayment: Abst., EOS, Amer. Geophys. Union, v. 57, p. 963.

Kane, M. F. and T. G. Hildenbrand, 1976, Spatial relations between mafic/ultramafic plutons and seismicity in the northern Mississippi embayment. Abst., EOS, Amer. Geophys. Union, v. 57, p. 963.

King, P. B., 1970, Tectonics and geophysics of Eastern North America: *in* H. Johnson and B. L. Smith, eds., The Megatectonics of Continents and Oceans. Rutgers Univ. Press, New Brunswick, New Jersey, p. 74-112.

King, L. H. and B. MacLean, 1974, Geology of the Scotian Shelf and adjacent areas: Geol. Surv. Canada Map 812H.

Kumarapeli, P. S., 1979, Possible Relationships between Seismicity and Large Scale Tectonics of Eastern Canada: Program with Abstracts, Geol. Assoc. Canada/Mineral. Assoc. Canada, v. 4.

Long, L. T. and J. W. Champion, 1977, Bouguer gravity map of the Summerville-Charleston, South Carolina, epicentral zone and tectonic implications: U.S.G.S. Prof. Paper 1028K, p. 151-166.

Matthew, G. F., 1894, Post glacial faults at St. John, New Brunswick: Amer. Jour. Sci. Ser. 3, v. 48, p. 501-503.

McKeown, F. A., 1978, Hypothesis: Many earthquakes in the central and southeastern United States are causally related to mafic intrusive bodies. Jour. Research, U.S. Geol. Survey, v. 6, p. 41-50.

McLeod, M. J., 1979, The Geology of Campobello Island Southwestern New Brunswick: Unpubl. M.Sc. Thesis, Univ. New Brunswick, Fredericton.

Nuttli, O. W. and J. E. Zollweg, 1974, The relation between felt area and magnitude for central United States earthquakes. Seismol. Soc. Amer. Bull., v. 64, p. 73-85.

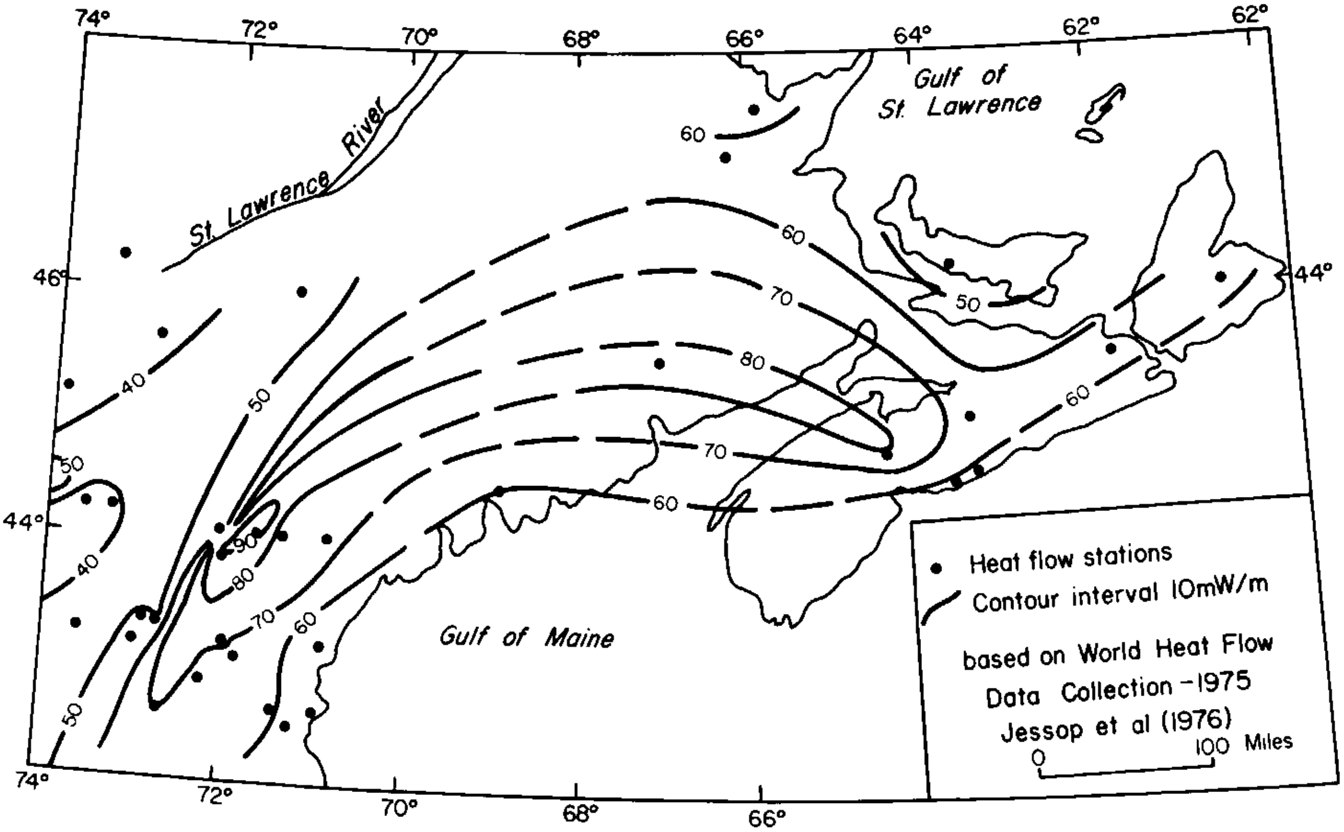


Figure 5
Heat flow in Atlantic Canada and New England.

Oliver, J., T. Johnson and J. Dorman, 1970, Post-glacial faulting and seismicity in New York and Quebec: Can. Jour. Earth Sci., v. 7, p. 579-590.

Poole, W. H., B. V. Sandford, H. Williams and D. G. Kelly, 1970, Geology of south-eastern Canada *in* R. J. W. Douglas, ed., Geology and Economic Minerals of Canada: Geol. Survey Canada, Econ. Geol. Rept. 1.

Rand, J. R., 1977, Historical earthquakes in Maine: The Maine Geologist, Geol. Soc. of Maine, v. 3, p. 3-6.

Rast, N. and K. L. Currie, 1976, On the position of the Variscan front in southern New Brunswick and its relation to Precambrian basement: Can. Jour. Earth Sci., v. 13, p. 194-196.

Rast, N. and R. Grant, 1973, Transatlantic Correlation of the Variscan-Appalachian Orogeny. Amer. Jour. Sci., v. 273, p. 572-579.

Rast, N. and R. Grant, 1977, Variscan Appalachian and Alleghenian Deformation in the Northern Appalachians: *in* La chaine varisque d'Europe moyenne et occidentale, Coll. Intern. CNRS, Rennes, no. 243, p. 583-586.

Rast, N., W. L. Dickson and R. H. Grant, 1978, Precambrian Basement in Southwestern New Brunswick: Guidebook for Field Trips in Southeastern Maine and Southwestern New Brunswick, Geol. Bull., no. 6.

Richter, C. F., 1935, An instrumental earthquake magnitude scale. Seismol. Soc. Amer. Bull., v. 25, p. 1-32.

Rodgers, J., 1970, The tectonics of the Appalachians: New York, John Wiley and Sons, 271 p.

Ruitenberg, A. A., D. V. Venugopal, and P. S. Giles, 1973, "Fundy Cataclastic Zone", New Brunswick: Evidence for post-Acadian penetrative deformation. Geol. Soc. Amer. Bull., v. 84, p. 3029-3044.

Ruitenberg, A. A., L. R. Fyffe, S. R. McCutcheon, C. J. St. Peter, R. R. Irinki and D. V. Venugopal, 1977, Evolution of Pre-Carboniferous Tectonostratigraphic Zones in the New Brunswick Appalachians: Geosci. Canada, v. 4, p. 171-181.

Sbar, M. L. and L. R. Sykes, 1973, Contemporary compressive stress and seismicity in eastern North America: an example of intra-plate tectonics: Geol. Soc. Amer. Bull., v. 84, p. 1861-1882.

Simmons, G., 1978, Our New England Earthquakes: Boston Edison Company Report reprinted by Western Geophysical, Westboro, Mass., 18 p.

Smith, W. E. T., 1962, Earthquakes of eastern Canada and adjacent areas: 1534-1927: Publ. Dom. Obs., v. XXI, no. 5, p. 271-301.

Smith, W. E. T., 1966, Earthquakes of eastern Canada and adjacent areas: 1928-1959: Publ. Dom. Obs., v. XXXII, no. 3, p. 87-121.

Smith, W. E. T., 1967, Basic seismology and seismicity of eastern Canada. Dom. Obs. Seismol. Ser., 1966-2, 43 p.

Stevens, A. E., W. G. Milne, R. J. Wetmiller and R. B. Horner, 1972, Canadian earthquakes - 1966, Seism. Series Earth Physics Branch, no. 62, 55 p.

Stevens, A. E., W. G. Milne, R. J. Wetmiller and G. LeBlanc, 1973, Canadian earthquakes - 1967. Seism. Series, Earth Physics Branch, no. 65, 65 p.

Street, R. L. and A. Lacroix, 1979, An empirical study of New England seismicity. 1727-1977. Bull. Seismol. Soc. Amer., v. 69, p. 159-175.

Street, R. L. and F. T. Turcotte, 1977, A study of northeastern North American spectral moments, magnitudes and intensities: Seismol. Soc. Amer. Bull., v. 67, p. 599-614.

Thompson, W. B., 1979, Postglacial faulting along the Norumbega fault zone: The Maine Geologist, Geol. Soc. Maine, v. 5, p. 6.

Webb, G. W., 1963, Occurrence and exploration significance of strike-slip faults in southern New Brunswick, Canada: Bull. Amer. Assoc. Petrol. Geol., v. 47, p. 1904-1927.

Webb, G. W., 1969, Paleozoic Wrench faults in Canadian Appalachians: *in* Marshall Kay, ed., North Atlantic Geology and Continental Drift, Amer. Soc. Pet. Geologists, Memoir 12, p. 754-791.

Williams, H., 1978, Tectonic-lithofacies map of the Appalachian orogen (1:1 000 000): Dept. of Geol., Memorial Univ. Newfoundland, St. John's, Map no. 1.

Wollard, G. P., 1958, Areas of tectonic activity in the United States as indicated by earthquake epicentres: Amer. Geophys. Union Trans., v. 39, p. 1135-1150.

Manuscript received July 3, 1979

Geological Association of Canada
Association Géologique du Canada

History of Concepts in Precambrian Geology

edited by W.O. Kupsch and W.A.S. Sarjeant
Geological Association of Canada Special Paper 19, 1979

This volume results from a symposium sponsored by the International Committee on the History of Geological Sciences (INHIGEO). It comprises a total of 18 papers dealing with the history of geological studies on Precambrian rocks in many parts of the world.

ISBN 0-919216-13-7

Obtainable from:
Geological Association of Canada
Publications
Business and Economic Services Ltd
11 Peter Street, Suite 509
Toronto, Ontario, Canada M5V 2H1

GAC Members $15.00, Non-Members $18.00
(Postage and handling included)

M&L

Testing Equipment Co. Ltd.

Quality Testing Equipment
(Destructive & Non-Destructive)
For Lab or Field Use

For
Soil – Concrete – Asphalt – Rock
Steel – Plastics – Rubber Etc.

Offices
Warehouses
Service

Montreal
Hamilton
Edmonton