The Earthquakes of Atlantic Canada and Their Relationship to Structure

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Volume 6, numéro 4, december 1979

URI : https://id.erudit.org/iderudit/geocan6_4art01

Résumé de l'article

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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.
The Earthquakes of Atlantic Canada and Their Relationship to Structure

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Abstract
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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.

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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
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 $M = 1 + 2\log \Delta / 3$ (Gutenberg and Richter, 1956), where $M$ is the estimated magnitude (Richter scale) and $\Delta$ 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 (Nuttl 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. $m_s = 2.65 + 0.098f + 0.054f^2$ (Nuttl and Zollweg, 1974), where $f$ is the logarithm to.
<table>
<thead>
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<th>DATE OF EARTHQUAKE</th>
<th>LATITUDE 9N</th>
<th>LONGITUDE 9W</th>
<th>MAGNITUDE BASED ON EPICENTRAL INTENSITY RI</th>
<th>MAGNITUDES BASED ON FELT AREAS</th>
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<td></td>
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<td>MUTTLI AND ZOLLWERG (1979)</td>
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<td></td>
<td></td>
<td>STREET AND LACROIX (1979)</td>
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<td>69.5</td>
<td>5.7</td>
<td>4.7</td>
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<tr>
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<td>66.2</td>
<td>6.3</td>
<td>5.0</td>
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<tr>
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<td>67.1</td>
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<td>4.2</td>
</tr>
<tr>
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<td>66.5</td>
<td>3.7</td>
<td>3.7</td>
</tr>
<tr>
<td>Dec. 31st, 1882</td>
<td>45.0</td>
<td>67.0</td>
<td>5.0</td>
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</tr>
<tr>
<td>June, 1885</td>
<td>45.1</td>
<td>66.1</td>
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<td>3.5</td>
</tr>
<tr>
<td>Mar. 22nd, 1896</td>
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<td>67.2</td>
<td>4.3</td>
<td>4.1</td>
</tr>
<tr>
<td>Mar. 21st, 1904</td>
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<td>5.7</td>
<td>4.9</td>
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<tr>
<td>July 2nd, 1922</td>
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<td>66.6</td>
<td>5.0</td>
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</tr>
</tbody>
</table>

Table 1
Magnitude estimates for 9 earthquakes in Atlantic Canada.

M 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; Eibshuber, 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).

![Map of Major Faults in Atlantic Canada](image)

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 recrystallised 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 Cartersville 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 (Ruttenberg et al., 1973, 1977). There is no evidence for 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 Leprau 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 Triassic (Rodgers, 1970). The Triassic Leprau 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, and there are not likely to have precipitated appreciable earthquakes of 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 subsidiary.

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 Simons (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 epicenters (Fig. 3, loc. B) is situated in the Blackville area. (In fact one of the largest instrumentally recorded earth- quakes in New Brunswick (M, = 4.6) belongs to the Blackville cluster). Here, although the surface rocks are Carboniferous sediments, the coincidence 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. Simons (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 epicenters 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 is in fact been a suggestion by Woolard (1958) that the New Madrid epicenter was located on the rift structures continuous from the Saint Lawrence Valley into the 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 Magentic 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 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 ashenolith 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 ashenolith (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 ashenolith 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.

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**Figure 4**

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


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Figure 5
Heat flow in Atlantic Canada and New England.


Manuscript received July 3, 1979.

Geological Association of Canada
Association Géologique du Canada

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Edited by W. O. Kuppers and W. A. S. Sarraff
Geological Association of Canada Special Paper 13, 1979

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