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EARTHQUAKES ALONG THE PASSIVE MARGIN OF EASTERN CANADA

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Abstract. An active seismic zone extends along the passive margin of eastern North America from Baffin Island to the Grand Banks of Newfoundland. We have determined the focal mechanisms of several of the earthquakes, including the 1933 Ms 7.3 Baffin Bay earthquake, the largest event ever recorded along the eastern North American margin. The mechanisms show thrust faulting for earthquakes seaward of the 1000 m contour, and primarily normal faulting for earthquakes landward. We propose that these earthquakes are induced by the removal of the Pleistocene glacial loads which extended onto the continental shelf. The deglaciation reactivated basement faults remaining from rifting associated with the opening of the Labrador Sea, Baffin Bay and the Atlantic. A simple flexure calculation yields horizontal extension (normal faulting) in the previously glaciated region, and horizontal compression (thrust faulting) farther seaward, in good general agreement with the observed earthquake mechanisms. The magnitude of the stresses, 100 to 150 bars, is sufficient to reactivate preexisting basement faults. Large passive margin earthquakes may occur as far south along the coast as glaciation extended.

Introduction

In contrast to many other passive margins, the eastern seacoast of North America is active seismically. During this century, two earthquakes with magnitudes greater than seven have occurred along this coast. This is a major fraction of the largest earthquakes of eastern North America. In this paper we discuss the seismicity along the northernmost Atlantic coast from Baffin Island to Newfoundland.

The Labrador Sea and Baffin Bay formed by seafloor spreading, which separated Greenland from North America. In *Srivastava's* [1978] reconstruction, spreading began in the Labrador Sea about 75 mybp, and in Baffin Bay about 60 mybp. Spreading continued until about 40 mybp, when Greenland became part of the North American plate. The separation of Greenland from Canada began with continental rifting, as shown by the Tertiary basalts of Baffin Island and West Greenland [*Clarke and Upton*, 1971]. The rifting process involves thermal uplift followed by erosion [*Sleep*, 1971], thinning of the continental lithosphere [*Artemjev and Artyushkov*, 1971], and major faulting [*Dewey and Bird*, 1970]. Faults are preserved in the continental basement in Baffin Bay [*M. Keen et al.*, 1972] and the Labrador Sea [*Grant*, 1975]. The present location of the transition from continental to oceanic crust is the subject of considerable discussion. For our purposes, we will consider all crust landward of the 3000 m contour as rifted continental material.

The other tectonic process which concerns us is the Pleistocene glaciation, which occurred well seaward of the present coastline, as shown by glacial features on the continental shelf [*Holtedahl*, 1958]. Most, if not all, of the Baffin Island, Labrador, and Newfoundland shelves were glaciated [*McMillan*, 1973; *Loken*, 1973], as were the shelves off Nova Scotia, the Gulf of Maine, and the inner shelf as far south as New York.

Seismicity

The seismicity of the Canadian passive margin is shown in Figure 1. The data from the period 1900-1952 are from *Gutenberg and Richter* [1965]; later data are from the ISS, ISC or PDE, and include only earthquakes of magnitude four or greater. The earthquakes seem to cluster in three distinct groups. The northernmost, along Baffin Bay, is the largest both in number of events and magnitude – several events are greater than Ms 6, including the 1933 Ms 7.3 Baffin Bay earthquake. These earthquakes occur on land, on the continental shelf (the region of ocean depths less than a few hundred meters) and on the continental slope, which extends approximately out to the 3000 m isobath. *C. Keen et al.* [1972] observed highly deformed sediments on the shelf in this area, and suggested this was a result of seismic activity. The smaller earthquakes in the Labrador Sea generally occur beyond the 1000 m contour. The third seismic region, the Grand Banks, includes the 1929 Ms 7.2 earthquake as well as a smaller number of earthquakes on the continental slope.

As discussed below, we have determined three of the focal mechanisms shown in Figure 1; the other four are from published studies. *Hashizume* [1973] studied the 1970 and 1972 Baffin Island earthquakes using surface waves; the northern event showed normal faulting on an east-west plane; the southern event showed a combination of normal and strike slip faulting. Thrust faulting mechanisms were published for the 1971 [*Hashizume*, 1977] and 1969 [*Sykes and Sbar*, 1974] Labrador Sea earthquakes.

1933 Baffin Bay Earthquake

The November 20, 1933 Baffin Bay earthquake (Ms 7.3) is one of the largest intraplate events ever recorded, and probably the largest in eastern North America. Determining its mechanism is therefore essential to understanding the regional tectonics. We combined first motion data from historic seismograms and the International Seismological Summary (ISS), to constrain the south dipping nodal plane (Figure 2). To determine the second plane, we used the ratio of Love to Rayleigh waves on excellent long period records at DeBilt (Netherlands). We then varied the slip angle on the known plane to fit the observed Love to Rayleigh ratio. This technique is especially useful for historic earthquakes for which only a few records are available, and instruments were not standardized. The resulting slip angle (λ = 100) indicates almost pure thrust faulting. Using the DeBuilt, Ottowa (radial) and Berkeley (vertical) records, we found a seismic moment of 4×10^{27} dyn-cm. The EW strike of both fault planes accords with the locations of the major aftershocks [*Qamar*, 1974].

We determined the depth by calculating synthetic seismograms (Figure 3) for the P waves observed on the vertical Wiechert instrument at Berkeley. The best fit was obtained for a focal depth of 65 km; the times and amplitudes of P, pP and sP agree quite well with the data. This depth is surprisingly large, but is required to fit the record.

1963 and 1976 Earthquakes

Two conflicting mechanisms from first motion studies have been reported for the 1963 Baffin Island event (Ms = 6.2). *Sykes* [1970] reported pure normal faulting on an east-west plane for this event. (A similar mechanism with a focal depth of 7 km was presented by *Liu and Kanamori* [1978].) An alternative mechanism, involving a significant strike slip component was given by *Qamar* [1974]. Using the Rayleigh wave radiation pattern, as well as the body waves, we found almost pure dip-slip faulting, with nodal planes similar to Sykes (Figure 4). The two lobed Rayleigh wave radiation pattern clearly excludes Qamar's solution. (Thrusting cannot be ruled out if the nearly vertical nodal plane dips slightly to the north, but normal faulting seems more likely.)

The smaller (Ms 5.1) 1976 Baffin Bay event shows almost pure thrust: first motions shown are from short period records since the event is so small. No first motions were reported by the ISS for the 1929 Grand Banks earthquake; we have not studied this event.

Model for Passive Margin Earthquakes

The earthquakes in Figure 1 all occur landward of the 3000 meter contour and can be assumed to occur in the old rifted continental lithosphere. The inner group, the three Baffin Island events, are interpreted as extension perpendicular to the coast. In contrast, the Labrador Sea earthquakes, and the 1933 and 1976 Baffin Bay earthquakes, seaward of the shelf, show thrust faulting. The events showing extension occur in the forformerly glaciated area, and those beyond it show horizontal compression.

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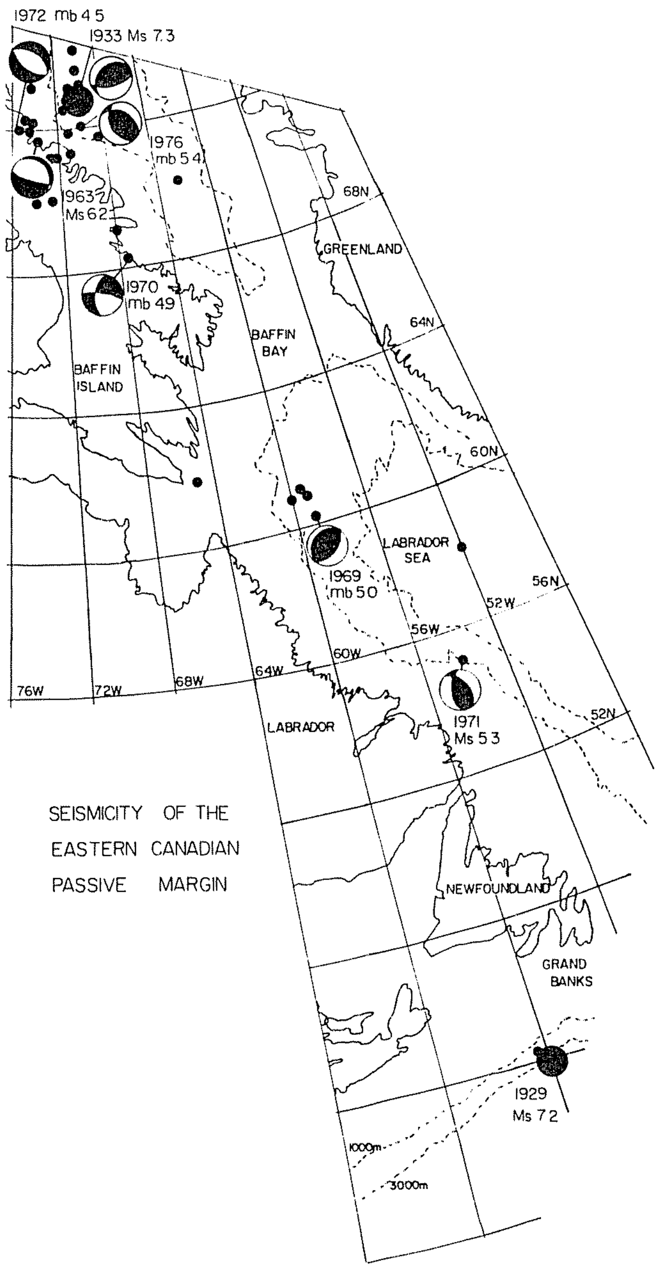

Fig. 1. Seismicity and focal mechanisms of the eastern Canadian margin. Earthquakes seaward of the 1000 m contour show thrust faulting; landward events show primarily normal faulting.

The large 1933 earthquake has a 65 km focal depth, but all the other events are very shallow. (33 km is a default depth.) We propose that these earthquakes are induced by the removal of the glacial load. This produces lithospheric flexure which causes extension in the upper portion of the lithosphere below the previously glaciated area, and compression seaward. These stresses then reactivate basement faults from the original rifting.

This model can be tested using a simple calculation, following *Walcott* [1970], for an elastic lithosphere over an asthenosphere of density ρ_a (Figure 6). The vertical displacement, w, for the ice load P(x), whose density is ρ_i satisfies

$$D \frac{d^4 w}{dx^4} + (\rho_a - \rho_i) wg = P(x)$$

The flexural rigidity, D, and the flexural parameter, α, are defined in terms of Young's modulus, E; Poisson's ratio, σ, and the plate thickness, T: $D = E\,T^3/(12(1 - \sigma^2))$ and $\alpha^4 = 4\,D/((\rho_a - \rho_i)g)$.

For deglaciation, we solve this problem for a negative load of height h for which $P(x) = -hg\rho_i$ for $x<0$ and $P(x) = 0$ for $x>0$.

The solution is

$$w = \begin{cases} \dfrac{-1}{2} \dfrac{\rho_i h}{(\rho_a - \rho_i)} \; e^{-x/\alpha} \cos(x/\alpha) & x>0 \\[2ex] \dfrac{-1}{2} \dfrac{\rho_i h}{(\rho_a - \rho_i)} \; (2 - e^{x/\alpha} \cos(x/\alpha)) & x<0 \end{cases}$$

Defining z, the vertical distance from the center of the lithosphere (positive down), the fiber stress is

$$\sigma_{xx} = -E\,z \frac{d^2 w}{dx^2} = \frac{E h \rho_i z}{\alpha^2 (\rho_a - \rho_i)} \sin\left(\frac{x}{\alpha}\right) e^{-|x|/\alpha}$$

The plane $z = 0$ is the neutral sheet, where the stress is zero. Above the neutral sheet, σ_{xx} is positive (extensional) for $x>0$, and is negative (compressive) for $x>0$. Thus the deglaciated region is under extension, and the unglaciated region is under compression (Figure 6), as suggested by the observed focal mechanisms. The region below the neutral sheet is not seismically active, perhaps due to the transition from stick-slip to stable sliding.

We estimate the stress using ρ_i = 1 g/cm^3, ρ_a = 3.3 g/cm^3, E = 6.5 x 10^{11} dynes/cm^2, σ = 1/4, h = 1 km. T = 140 km and α = 230 km. The maximum stress occurs when $|\tan(x/\alpha)| = 1$, or x = ±180 km. This stress is about 100 bars at a depth of 20 km, and 150 bars at the surface. Such stresses, though not enough to fracture previously unfaulted lithosphere, can induce faulting on the faults remaining from the rifting process, as they are comparable to earthquake stress drops [*Geller*, 1976]. The precise location of the neutral sheet depends on the variation of the elastic parameters of the lithosphere with depth, and on any possible overall horizontal compression in the lithosphere. The exact values used above are somewhat uncertain, but do not affect the overall conclusion. The focal depth of the 1933 Baffin Bay earthquake (65 km) suggests that the depth of the neutral sheet may be greater than 65 km.

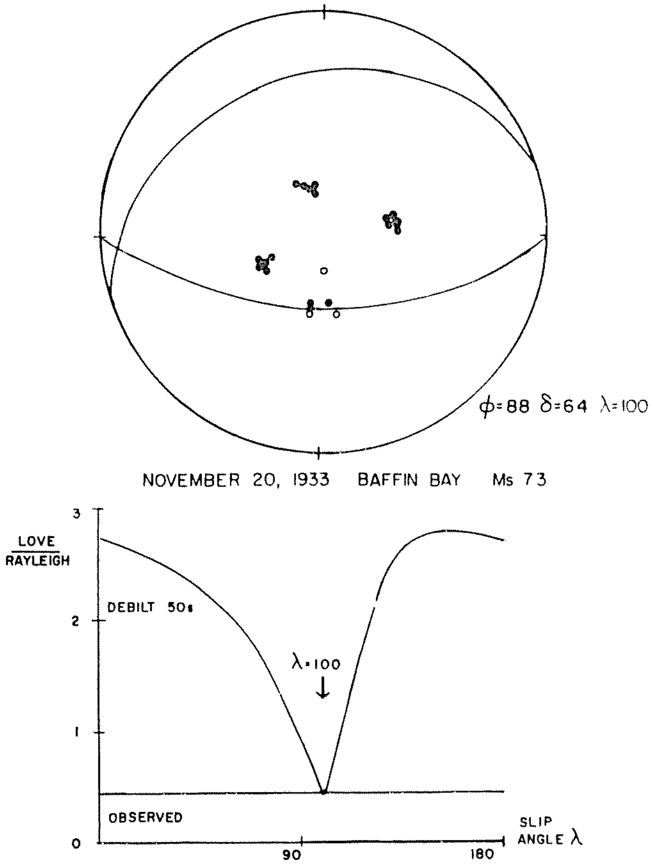

Fig. 2. Focal mechanism of the 1933 thrust fault earthquake. The south dipping E-W nodal plane is from first motions. The second plane was found using the slip angle (λ = 100) which matches the observed Love to Rayleigh wave ratio.

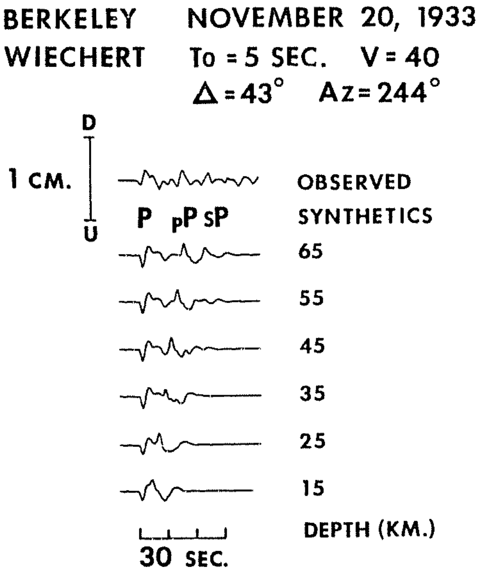

Fig. 3. Body wave record at Berkeley (vertical) clearly showing P, pP and sP. The synthetics (which include the water reverberations) indicate a focal depth of 65 km.

Our model assumes that the unstressed equilibrium state of the lithosphere is glaciated. This is valid because the time since deglaciation is much less than that required for irreversible strain to relax the present state. The stress system remains long after the rebound has occurred, until relaxation occurs. The fact that flexural stresses produce both normal and reverse faulting indicates that the intraplate stresses are less than the sum of the flexural stresses and those resulting from isostatic compensation of the continental lithosphere [*Artyushkov*, 1973]. As this stress is about 150 bars, the observation of both normal and reverse faulting indicates that intraplate stresses here are substantially less than one kilobar.

Discussion

This model combines two important processes: reactivation of preexisting faults, and glacial loading. Both have previously been suggested; *Gutenberg* [1933] and *Jacobs and La Fountain* [1975] proposed a relationship between seismicity and previously glaciated areas. The reactivation of preexisting faults or weak zones has been observed in the oceans and on land and has been proposed for the Baffin Bay area [*Wetmiller and Forsyth*, 1978]. For such earthquakes, the principal stress directions inferred from focal mechanisms are constrained to the appropriate quadrants, but may differ somewhat from the true stress field [*Stein*, 1979]. Our model, which predicts an outer region of compressional and an inner region of extensional earthquakes predicts the stress directions inferred from the focal mechanisms only approximately. The general agreement of predicted and inferred stress directions is thus quite acceptable, especially since the rifting geometry is not well known.

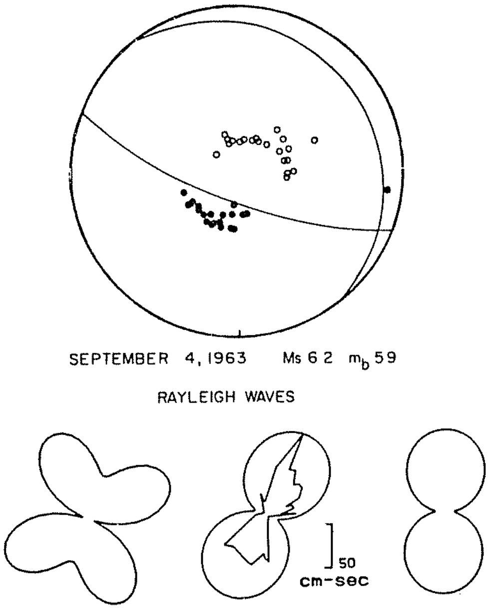

Fig. 4. Focal mechanism of the 1963 Baffin Island earthquake derived from body and surface waves, and surface wave radiation patterns for our mechanism and two previous mechanisms (Qamar's on left, Sykes' on right, ours, as shown in the first motion plot, in center). Observed data are in center.

Table 1. Earthquake Data

Date	Origin Time	Location	Depth	m_b	M_s
November 20, 1933	23:21:32	73.3N 70.7W	65 km	–	7.3
September 4, 1963	13:32:12	71.4N 73.3W	7 km	5.9	6.2
November 24, 1969	21:14:13	60.5N 58.7W	33 km	5.0	–
December 12, 1970	11:03:10	68.4N 67.3W	9 km	4.9	–
December 7, 1971	12:04:19	55.0N 54.3W	16 km	5.4	5.3
January 21, 1972	14:43:42	71.9N 74.7W	6 km	4.5	–
November 12, 1976	14:47:25	72.5N 70.2W	33 km	5.4	5.1

The loading effect of deglaciation may be reinforced by sediment loading during glacial retreat. *Vogt and Perry* [1978] suggested that extensive post-glacial sediment deposition may occur at the continental shelf edge, creating flexural stresses similar to those produced by deglaciation. The fact that recently glaciated margins are more seismically active than those which have not been glaciated suggests that sedimentation alone is generally inadequate to induce earthquakes. This is because the large sediment loads have generally been in place long enough that the stress has relaxed.

Our glacial loading model suggests that earthquakes may occur anywhere along the rifted margin which has been glaciated. The fact that seismicity along the margin is highest near Baffin Island, and generally decreases southward may be related to the time since glacial retreat.

Seismic activity can also be seen along other, recently glaciated, passive margins. The Greenland [*Sykes*, 1978] and Norwegian margins [*Husebye et al.*, 1975] are active seismic areas. Few focal mechanisms are available, but *Sykes and Sbar* [1974] found a normal fault mechanism for an earthquake (79.4 N, 17.7 W, mb 5.2) on the east Greenland coast, which may be similar to the Baffin Island events. Future analysis of other passive margin earthquakes can be used to test our model of the effect of deglaciation in causing such earthquakes.

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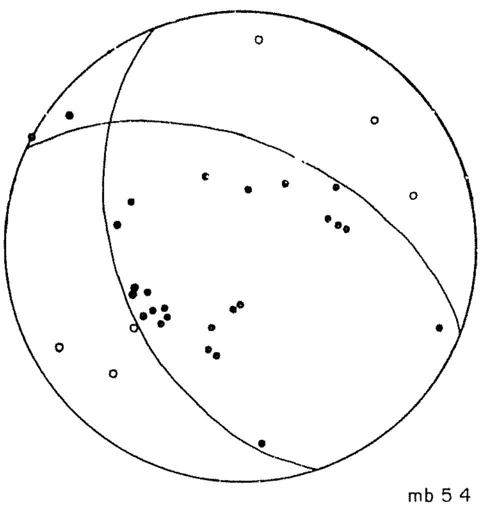

Fig. 5. Focal mechanism for the 1976 Baffin Bay thrust fault earthquake.

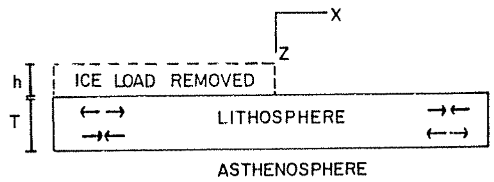

Fig. 6. Geometry of the lithospheric flexure induced by deglaciation, showing the induced stresses.

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