

Post-glacial induced earthquakes – a review

Patrick Wu & Holger Steffen
University of Calgary

Joint DynaQlim/GGOS Workshop
Espoo, Finland
23/06 – 26/06/2009



Content

- Introduction
- Brief overview of physics
- Review of investigations and results
 - Works from Wu et al., Hampel et al., Lund et al.
 - 2D and 3D modeling
 - Studies on virtual faults
 - General studies on faults
 - Stress modeling in Fennoscandia and North America
- Nuclear waste management, just briefly
- Summary

Introduction



- We talk about intraplate earthquakes, while...
- ...Plate tectonics only explain earthquakes that occur on plate boundaries (e.g. subduction, transform faults and spreading ridges), but...
- ...What causes the intraplate earthquakes in Eastern Canada and Northern Europe or the New Madrid earthquake in Mid-U.S.A. 1811/12?
- Can it be post-glacial rebound?
or
Other mid-plate tectonics?

Pressure ridge as surface expression



1989 Ungava fault rupture



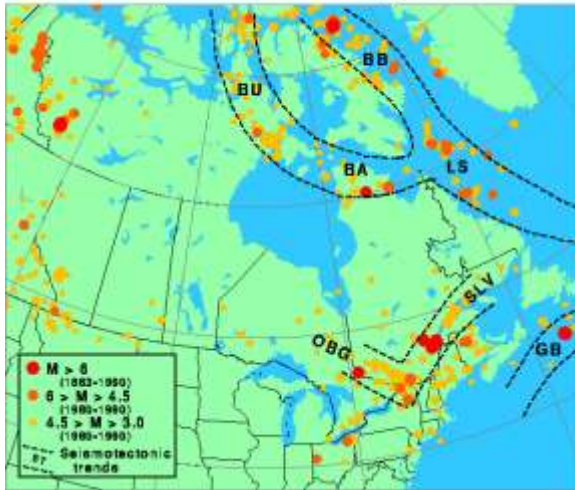
(Photo: NASA)



(Photo: Adams 1996, JGR, Fig. 2)

Earthquakes in Eastern Canada

Earthquake location and magnitude



Most seismic activity in Eastern Canada along the 3 tectonic trends or pre-weakened zones:

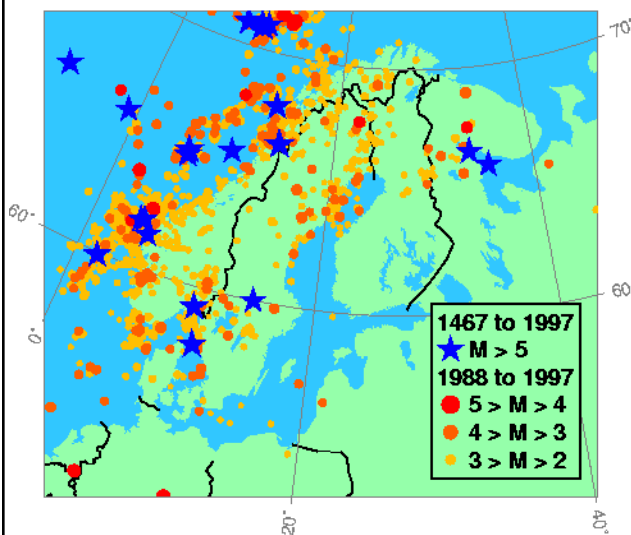
- 1) BB-LS-GB Mesozoic rift margin
- 2) BU-BA reactivated Paleozoic structures
- 3) SLV-OBG Paleozoic rifts

BA - Bell Arch; BB - Baffin Bay; BU - Boothia Uplift; GB - Grand Banks; LS - Labrador Sea; OBG - Ottawa Bonnechere Graben. SLV - St. Lawrence Valley;

(Wu & Hasegawa 1996, GJI)

Earthquakes in Northern Europe

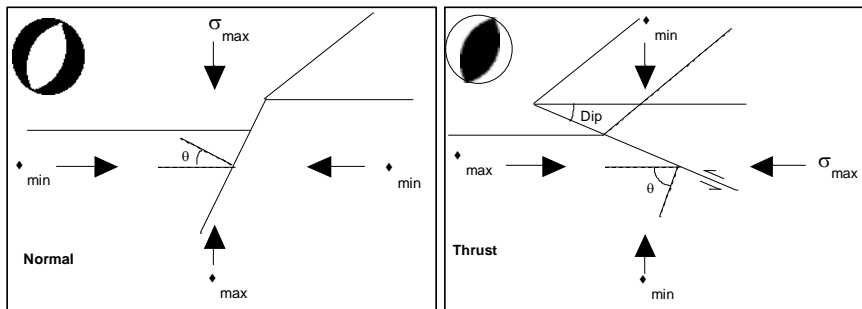
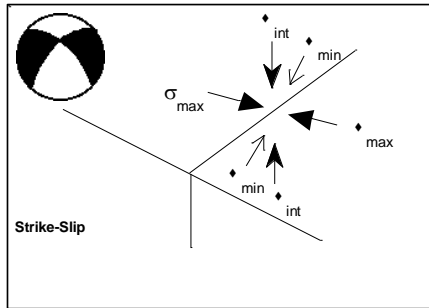
Earthquake location and magnitude



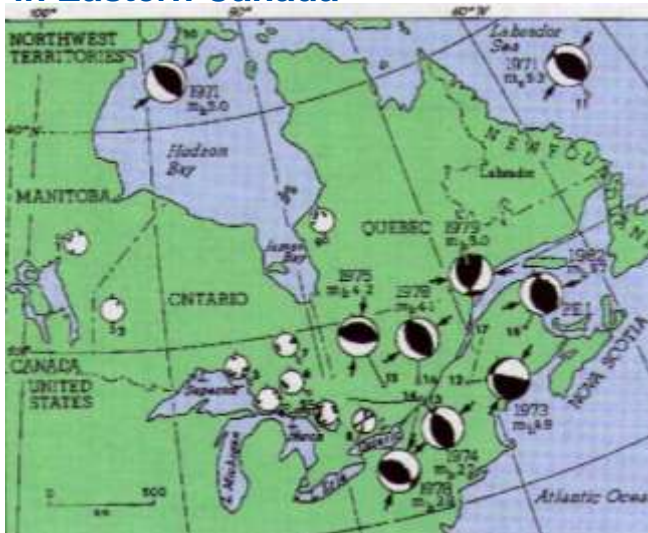
Most seismic activity offshore Norway and Bothnian Gulf (oil and ore extraction)

(Wu et al. 1999, GJI)

Fault mechanisms



Fault mechanism in Eastern Canada

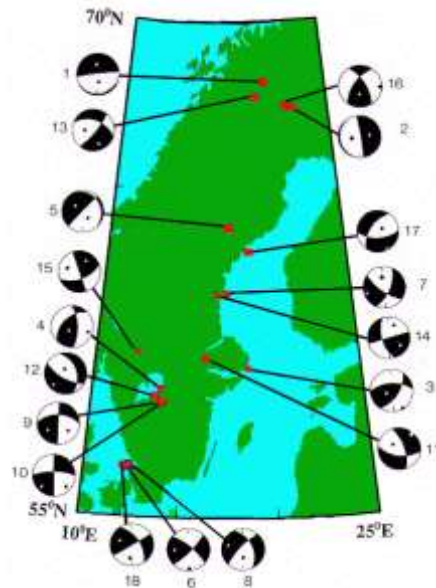


Mode of failure mostly thrust, except in NE Baffin Island

(Hasegawa et al. 1985, JGR)

Fault mechanism in Northern Europe

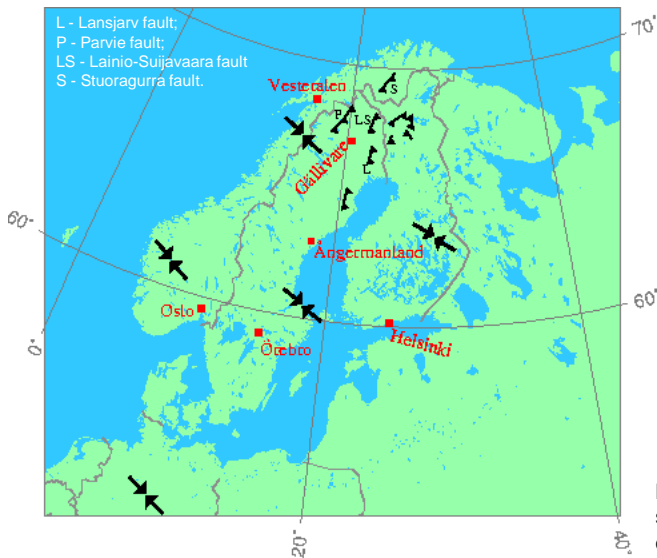
Mode of failure mixture of strike-slip, normal and thrust faulting



(Arvidsson & Kulhanek 1994, GJI)

Fault mechanism in Northern Europe

L - Lansjarv fault;
P - Parvie fault;
LS - Lainio-Suijjavaara fault
S - Stuoragurra fault.



Location and orientation of post-glacial faults in Fennoscandia

Bold inward pointing arrows show orientation of 1st order stress field at present.

(Wu et al. 1999, GJI)

Fault mechanism in Northern Europe

Arial view of the Pärvie fault
(outlined by snow at the footwall)



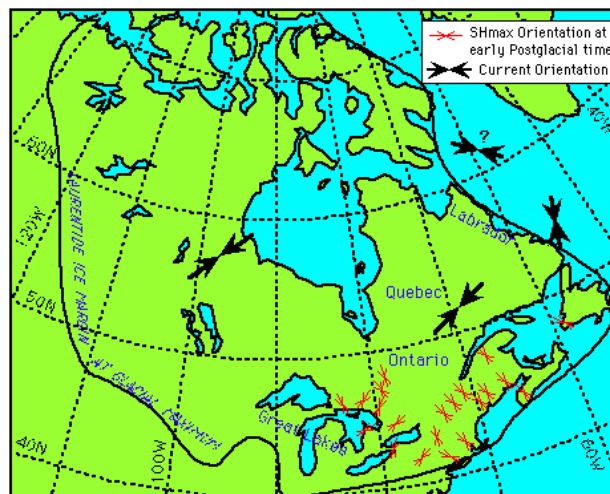
(Johnston 1996, Science)

Close view of the Fault Scarp. The average throw of these postglacial thrust faults is 15 m.

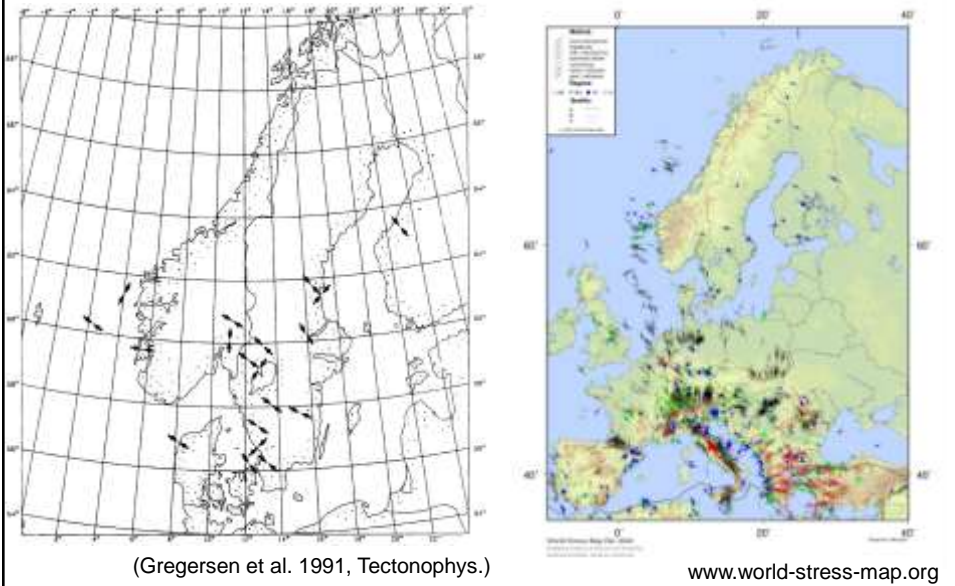


(Johnston 1996, Science)

Current and paleo-stress orientations in Eastern Canada



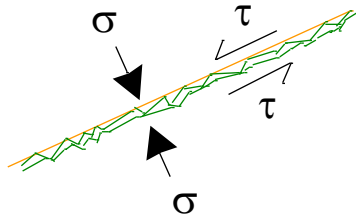
Current stress orientations in Northern Europe



Observations

- Spatial distribution of current earthquakes:
 - Eastern Canada: along weak zones
 - Northern Europe: mainly along coastline
- Focal mechanism of current events:
 - Eastern Canada: mainly thrusting inside ice margin
 - Northern Europe: mixed thrusting/Strike-slip/Normal
- Post-glacial thrust faults:
 - Eastern Canada: formed 7-9 ka BP, throw ~ 5 m
 - Northern Europe: formed 9-8 ka BP, throw ~ 15 m
- Present state of stress has SH_{max} in direction of Mid-Atlantic Ridge spreading

Mohr-Coulomb failure criterion



$$\tau = \tau_0 + \mu_f \sigma$$

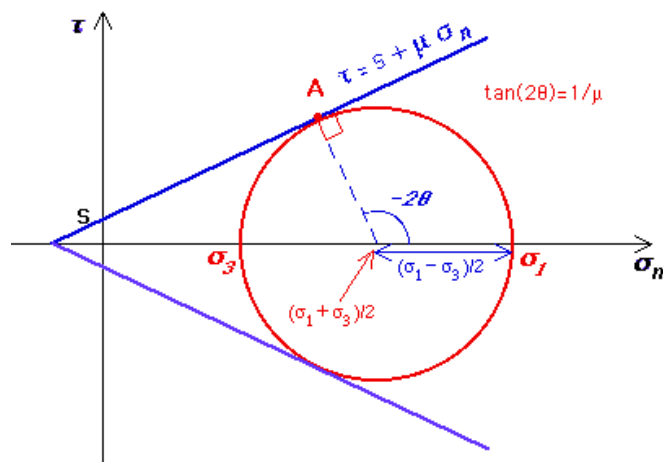
Shear Strength τ_0

Internal friction μ_f

Mechanical strength is controlled by the sliding of one fracture surface on the other - due to the shear stress τ

On the other hand, the normal stress σ presses the fracture surfaces together, increasing the friction and prevent sliding.

Mohr-Coulomb failure criterion

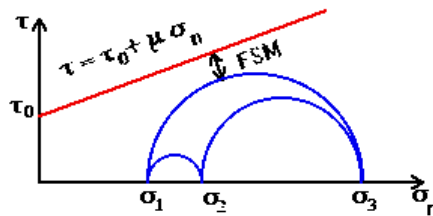


Fault stability margin (FSM)



$$FSM = \beta [\mu (\sigma_1 + \sigma_3) + 2 \tau_0] - \frac{1}{2} (\sigma_3 - \sigma_1)$$

$$\beta = \frac{\sin(\arctan(\mu))}{2\mu}$$



Normal Faulting:	horiz	horiz	vert
Thrust Faulting:	vert	horiz	horiz
Strike Slip :	horiz	vert	horiz

Change in Fault Stability Margin:

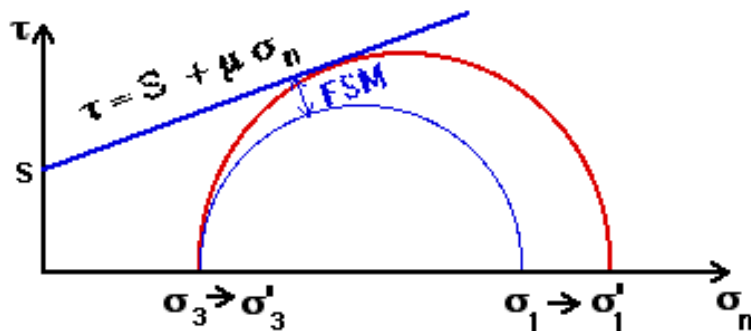
$$dFSM(t) = FSM(t) - FSM(t_0)$$

(Wu & Hasegawa 1996, GJI)

Fault stability variations

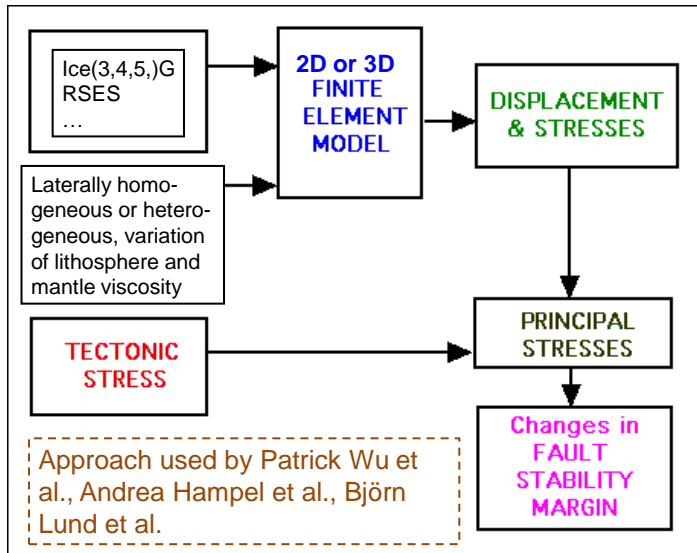


b) Fault Stability Margin decreases after deglaciation in Thrust Regime

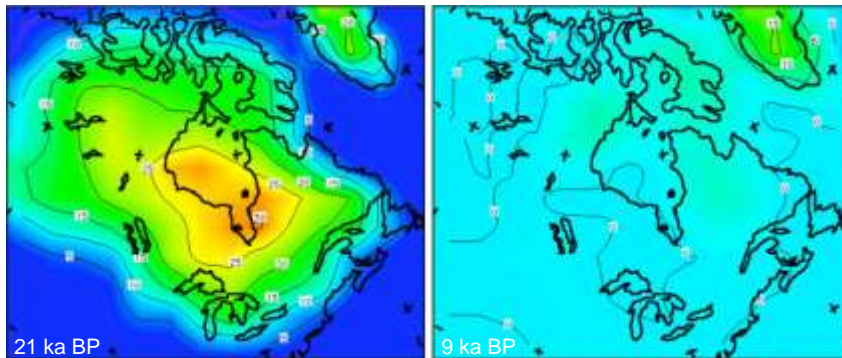


(Wu & Hasegawa 1996, GJI)

Modeling approach

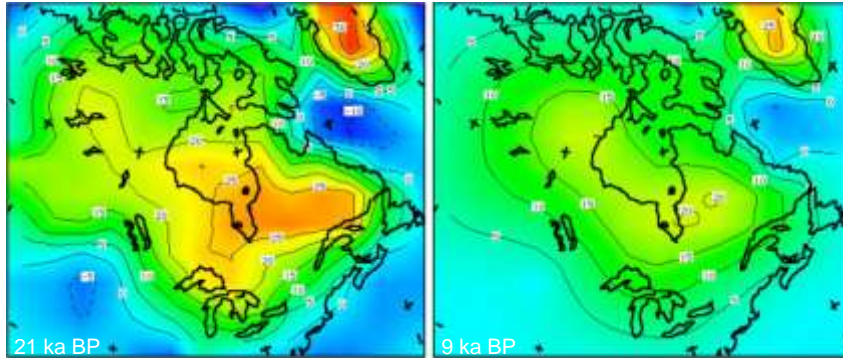


3D model results



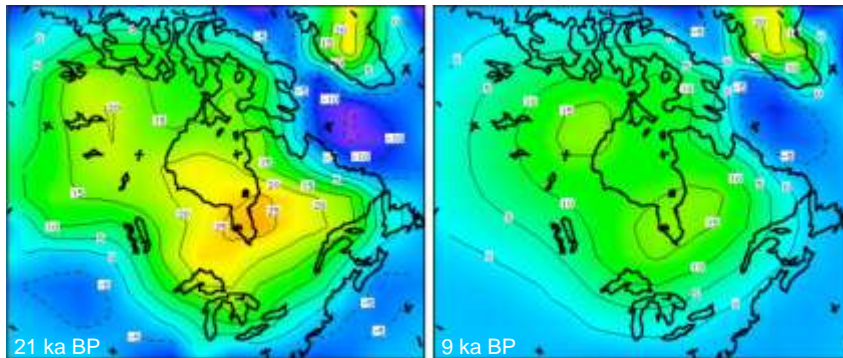
Typical magnitude of near surface SV [MPa] induced by ICE-4G glacial loading/unloading.

3D model results



Typical magnitude of near surface SH_{\max} [MPa] induced by ICE-4G glacial loading/unloading.

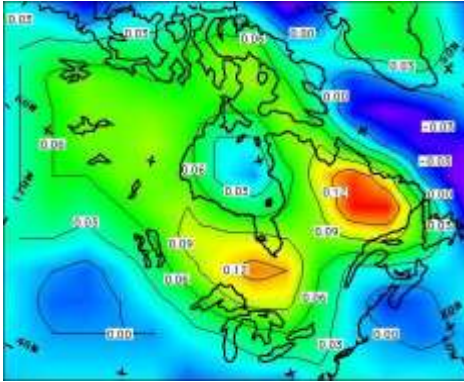
3D model results



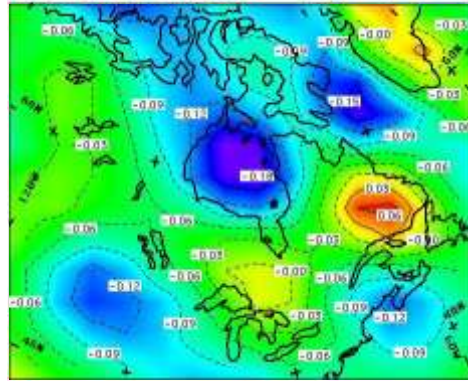
Typical magnitude of near surface SH_{\min} [MPa] induced by ICE-4G glacial loading/unloading.

3D model results

Present rate of change of Fault Stability Margin
for a uniform $1E21$ Pa-s Mantle

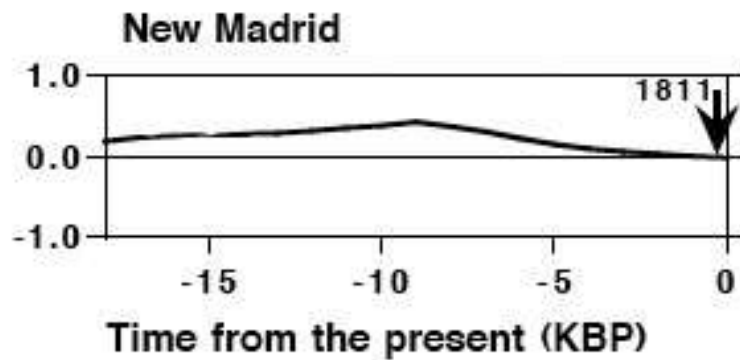


Present rate of change of Fault Stability Margin
for a high viscosity ($1E23$ Pa-s) lower Mantle



(Wu 1998, Can. J. Earth Sci.)

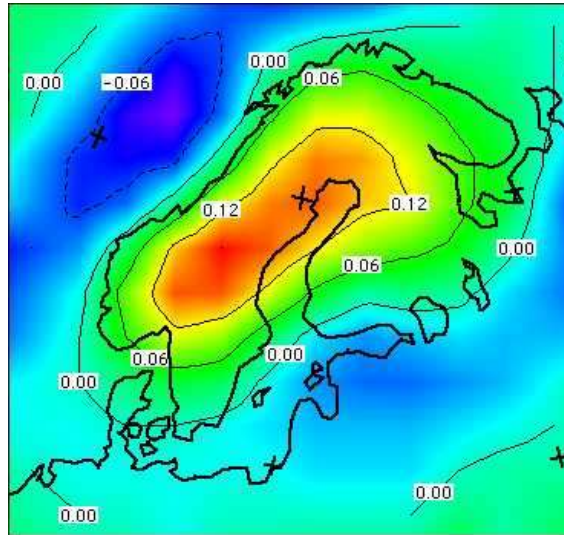
3D model results



(Wu and Johnston 2000, GRL)

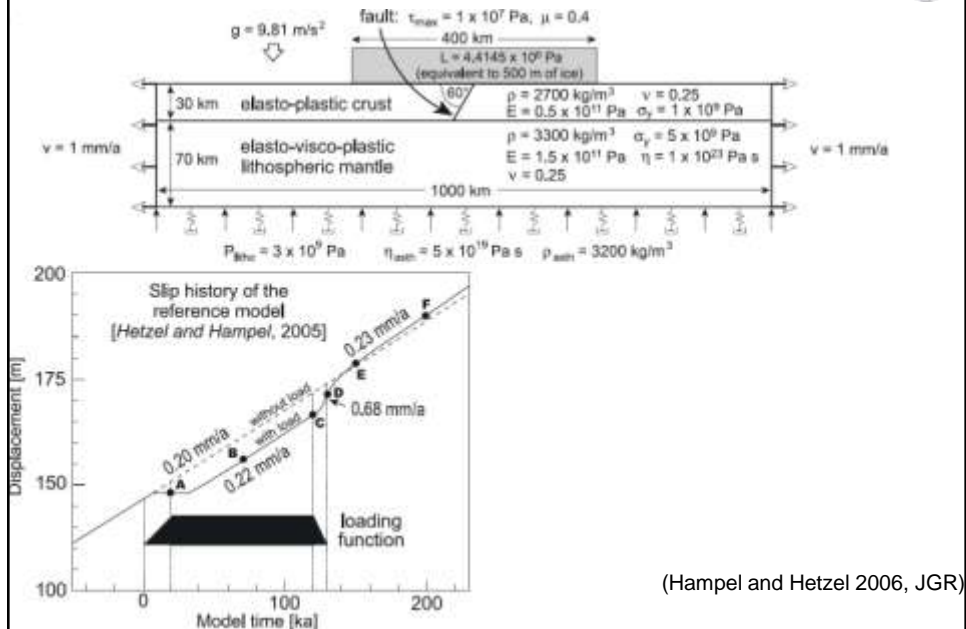
3D model results

Present rate of change of Fault Stability Margin
for a uniform $1E21$ Pa-s Mantle



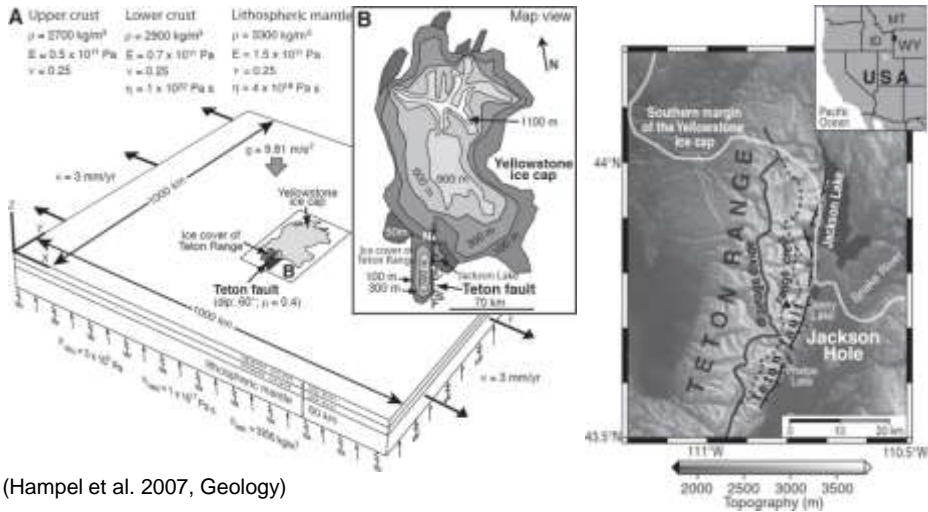
(Wu et al. 1999, GJI)

2D model experiments

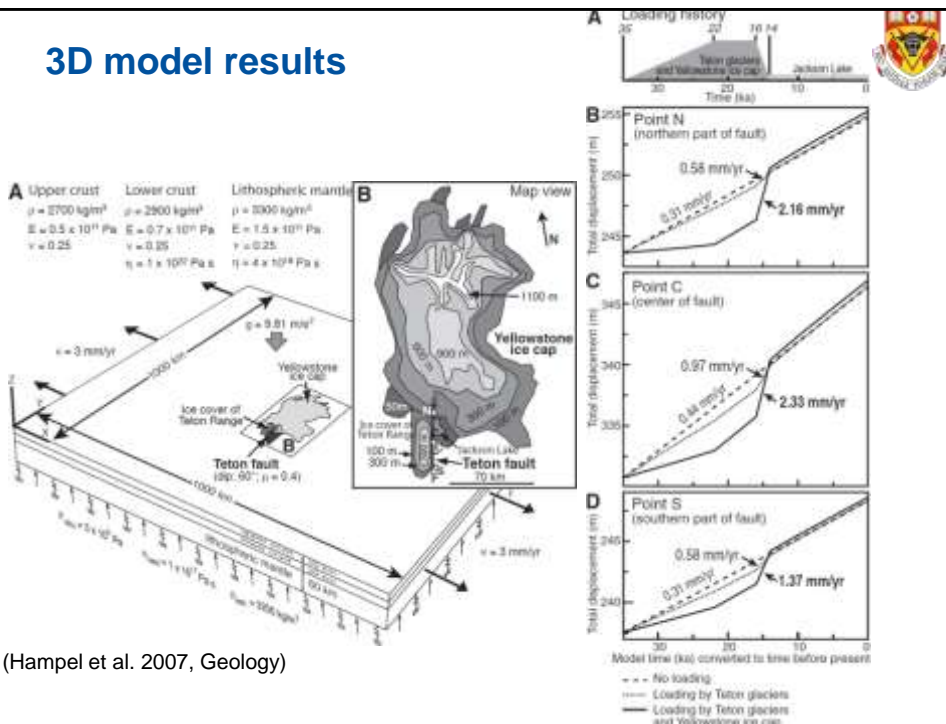


(Hampel and Hetzel 2006, JGR)

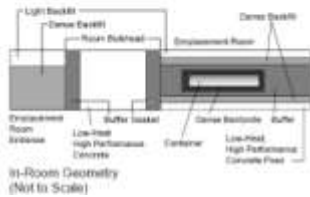
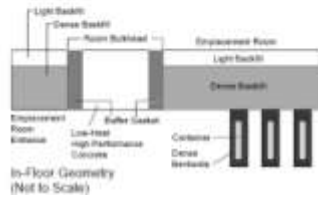
3D model test



3D model results



Nuclear waste management



(NWMO 2007 Ann. Tech Report)

Nuclear waste management



Canadian Nuclear Facilities



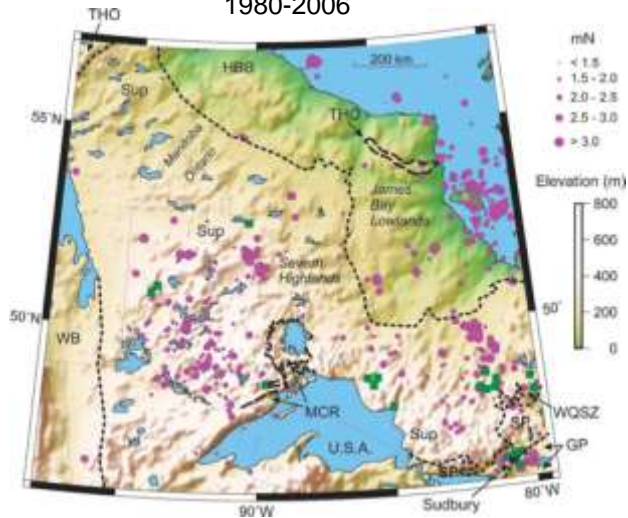
(NWMO 2007 Annual Report E)

FACILITY	LOCATION	STORED BUNDLES
1. Point Lepreau	New Brunswick	118,070
2. Gently-2	Québec	107,237
3. Bruce A	Ontario	388,730
4. Bruce B	Ontario	464,856
5. Pickering	Ontario	571,406
6. Darlington	Ontario	322,757
7. Douglas Point	Ontario	22,256
8. AECL - Gently-1	Québec	3,213
9. AECL - Whiteshell Laboratory	Manitoba	360
10. AECL - Chalk River Laboratory	Ontario	4,853
Total		2,001,738

Earthquakes in Eastern Canada

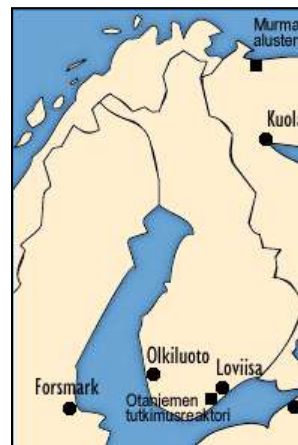


Seismic events in Northern Ontario
1980-2006



(Ma et al. 2008, BSSA)

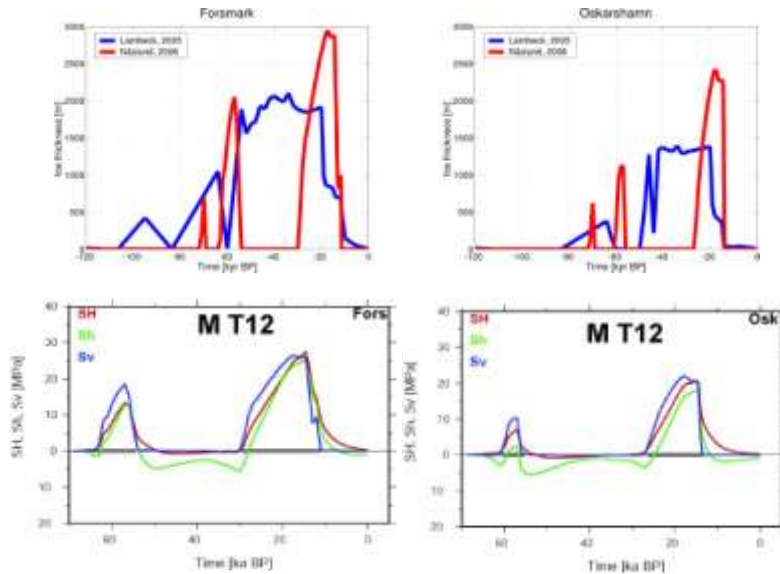
Nuclear waste management



www.ssi.se

www.stuk.fi

Nuclear waste management



(Lund et al. 2009, Report)

Summary

- Deglaciation can trigger post-glacial faults and earthquakes
- Current 'Rebound' stresses large enough to trigger earthquakes
- GIA can explain spatial distribution of current earthquakes in Eastern Canada if initial dFSM > 3 MPa except at pre-weakened zones
- Size of ice sheet and the ice sheet history has large effects on onset timing and the amplitude of dFSM:
 - Presence of large ice sheets (e.g. Laurentide) suppress earthquakes (Johnston 1996, Science) and removal of ice sheets can induce fault instability (Wu & Hasegawa 1996a,b, GJI)
 - For smaller ice sheets (e.g. Fennoscandia, Scotland), stress amplification and earthquakes can occur about 2,000 years before the end of deglaciation (Johnston et al. 1998, GJI)
- Ongoing research regarding Nuclear Waste Management in Eastern Canada and Fennoscandia