Géosciences Montpellier

Géodynamique et aléa sismique en domaine continental stable: Exemple de l'Est Américain

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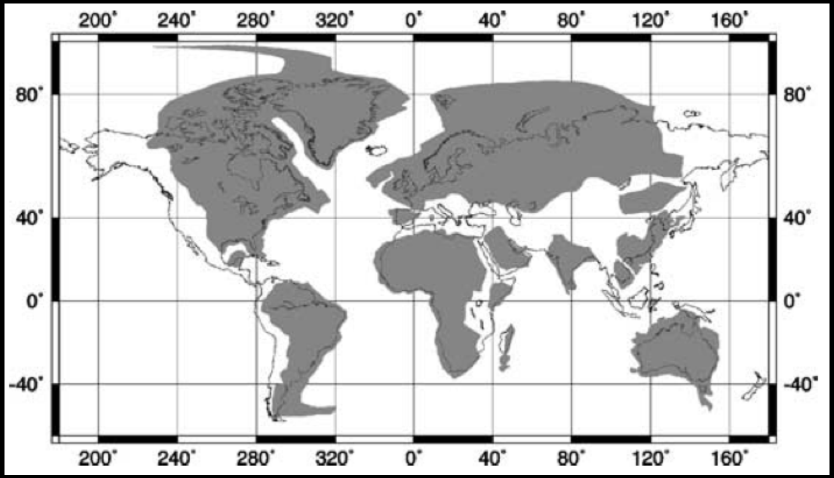
Géodynamique et aléa sismique en domaine continental stable

Domaines continentaux stable (intra-plaque) = 2/3 de la surface des continents

Zones stables, se déformant pas / peu



Géodynamique et aléa sismique en domaine continental stable

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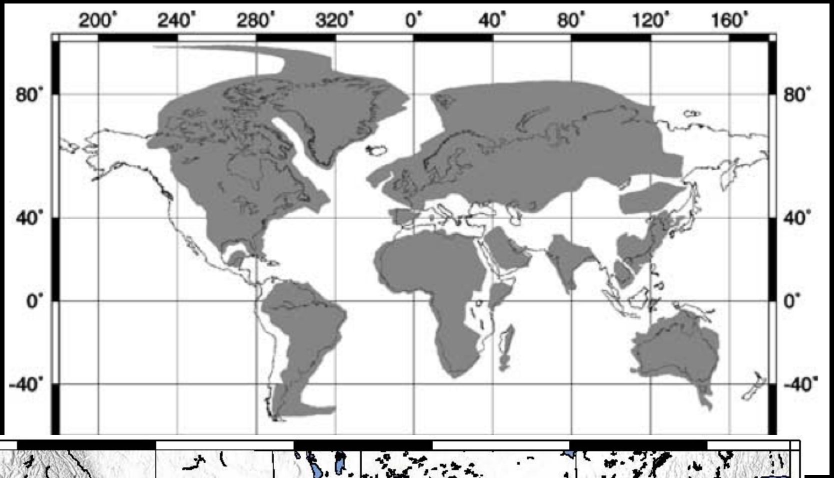
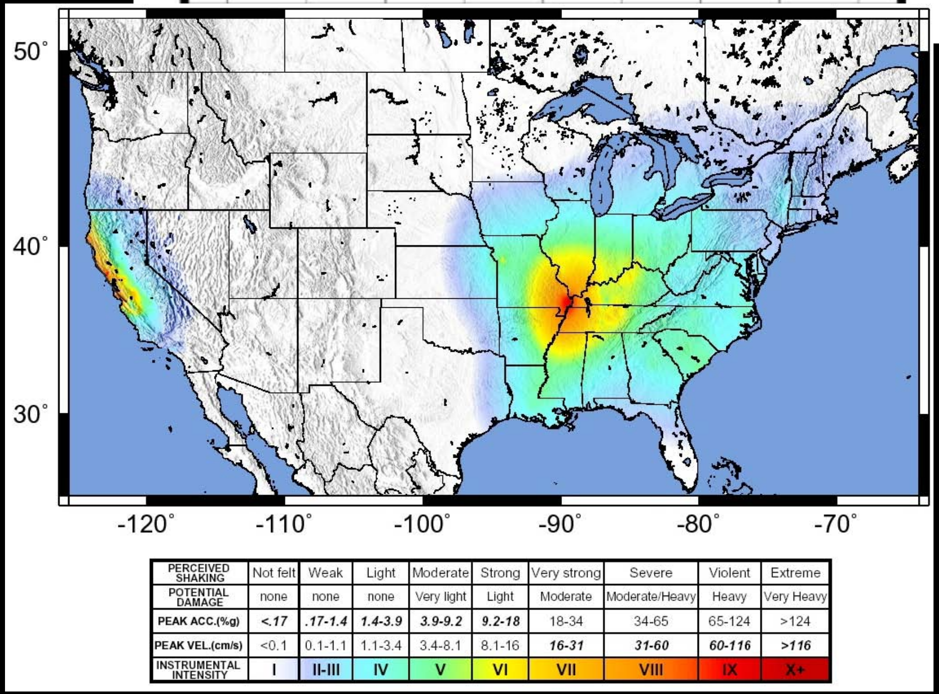
Zones stables, se déformant pas / peu

Mais, sismicité & aléa sismique potentiellement fort



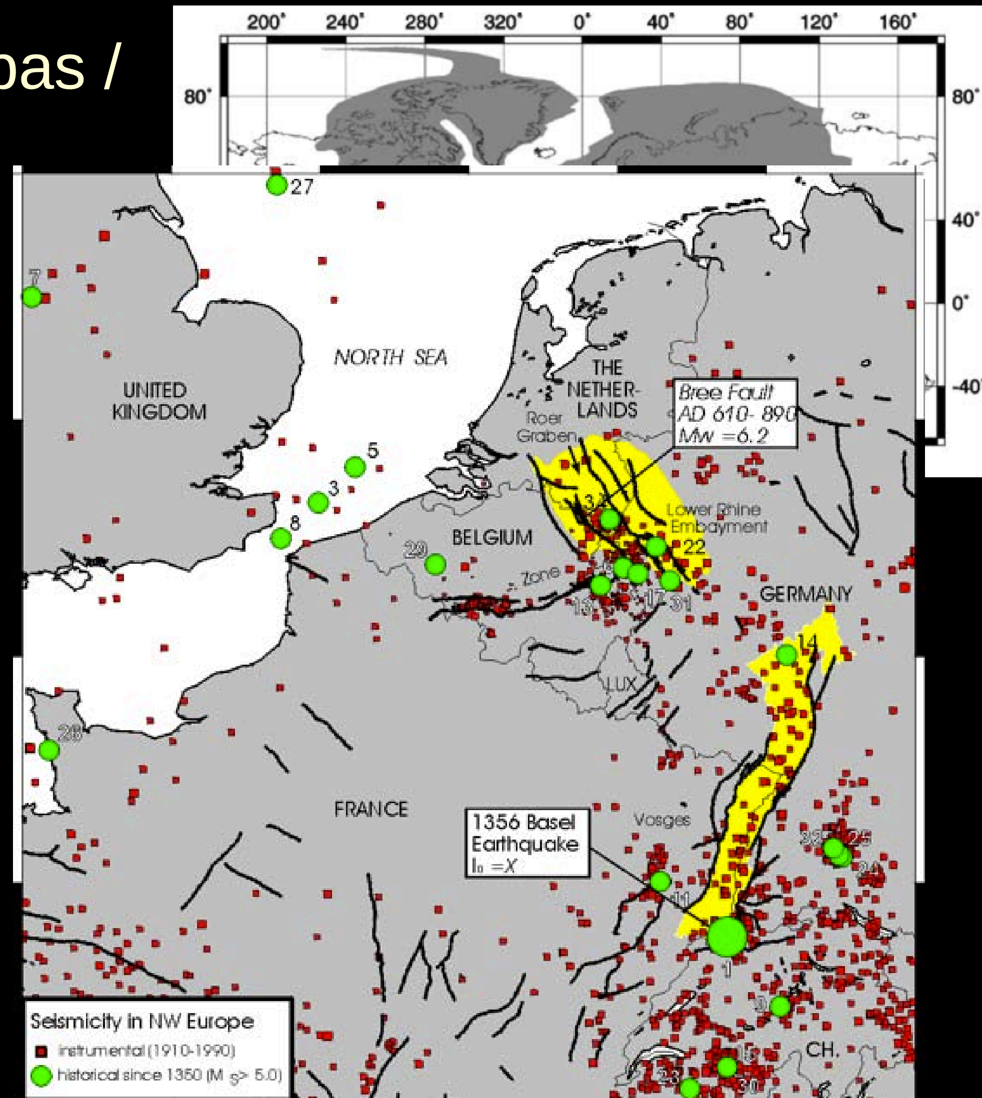


Géodynamique et aléa sismique en domaine continental stable

Zones stables, se déformant pas / peu

Mais, sismicité & aléa sismique potentiellement fort

e.g., Graben du Rhin



Géodynamique et aléa sismique en domaine continental stable

Problématique fondamentale:

Quels facteurs contrôlent la distribution et l'amplitude de la déformation en domaines intra-plaque?

- Rôle de l'héritage structurale?

- Etat de contrainte et bilan de forces?

- Taux de déformation et de sismicité à court et long terme?

- Aléa sismique?

Géodynamique et aléa sismique en domaine continental stable

Exemple de l'Est Américain

1) Sismicité et géodynamique de l'Est Américain

2) Etat de contraintes
=> Mécanismes au foyer
=> Rotations de contraintes en zones sismiques
=> Implications géodynamiques

3) Taux de déformation
=> Mesures GPS – Vallée du St. Laurent
=> Est Américain
=> Relations contraintes – déformation

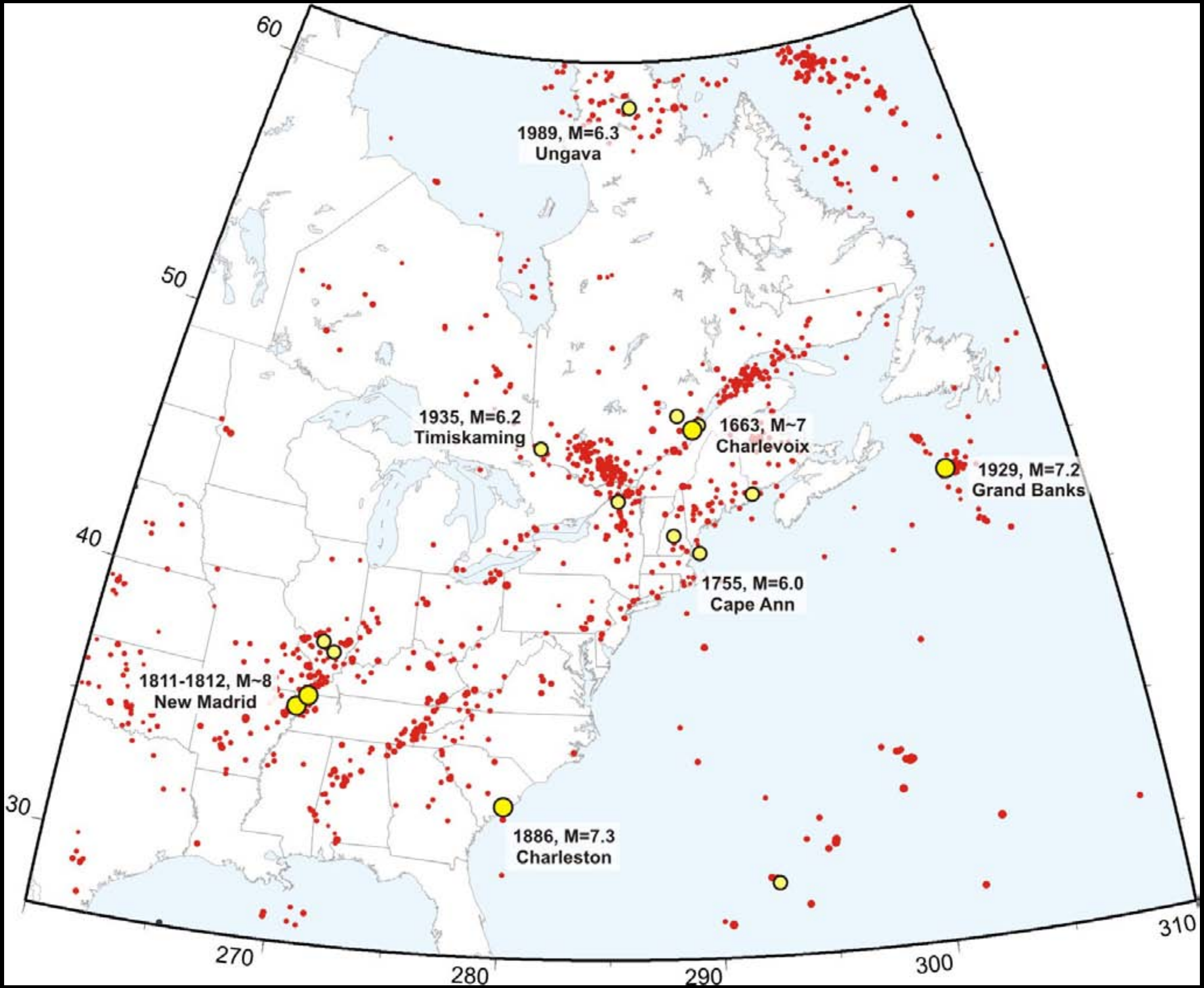
Background Seismicity and Large Earthquakes

18 M ≥ 6 since ~1600

Concentrations in “hot spots”, e.g.

* New Madrid (3 M ≥ 7 in 1811-1812)

* Charlevoix (5 M ≥ 6 since 1650)

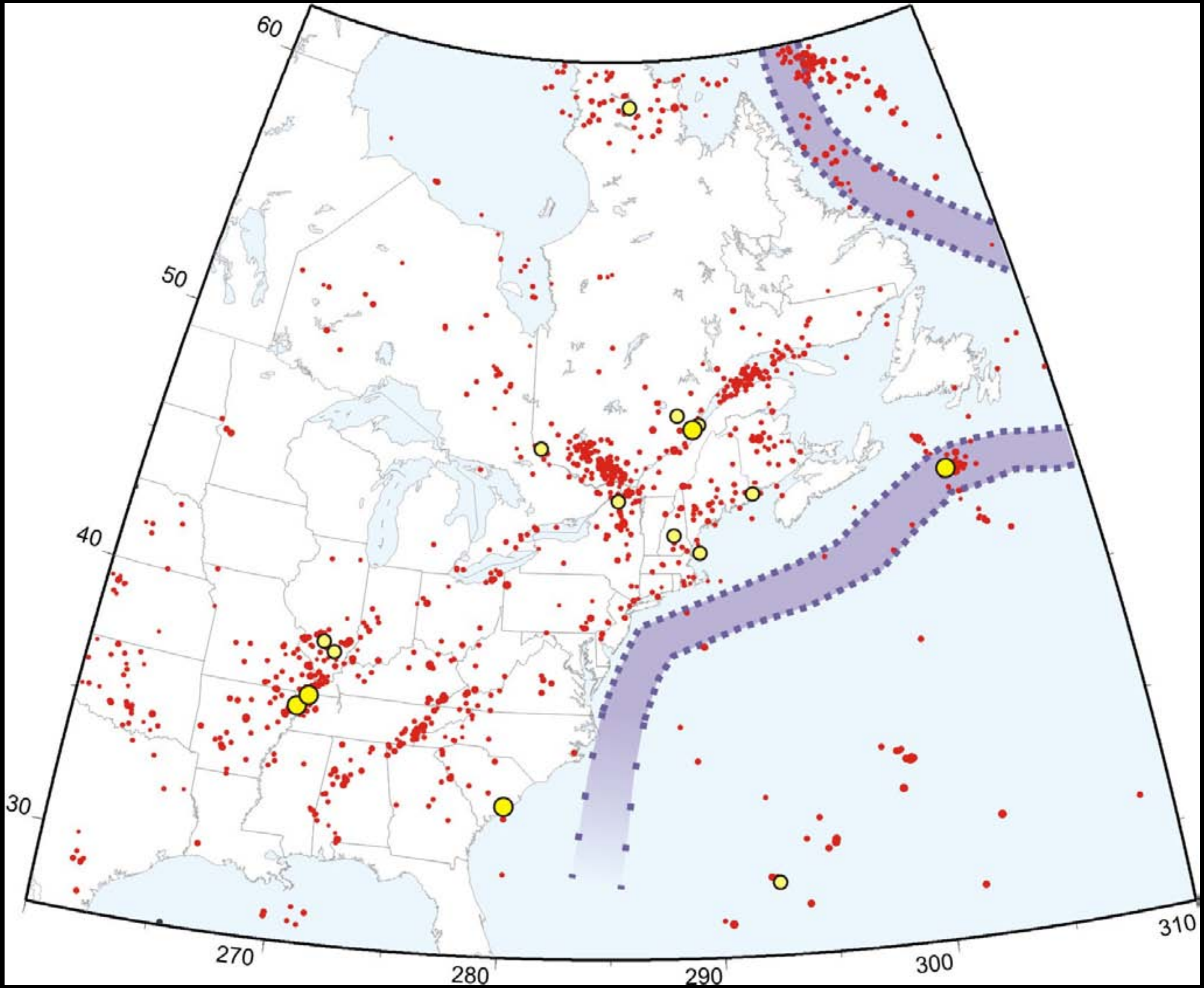


Mazzotti, 2007, GSA Special Paper 425

Relation to Geological Heritage

Seismic activity clusters along paleo-tectonic zones:

* Atlantic rifted margin (~180 Ma)

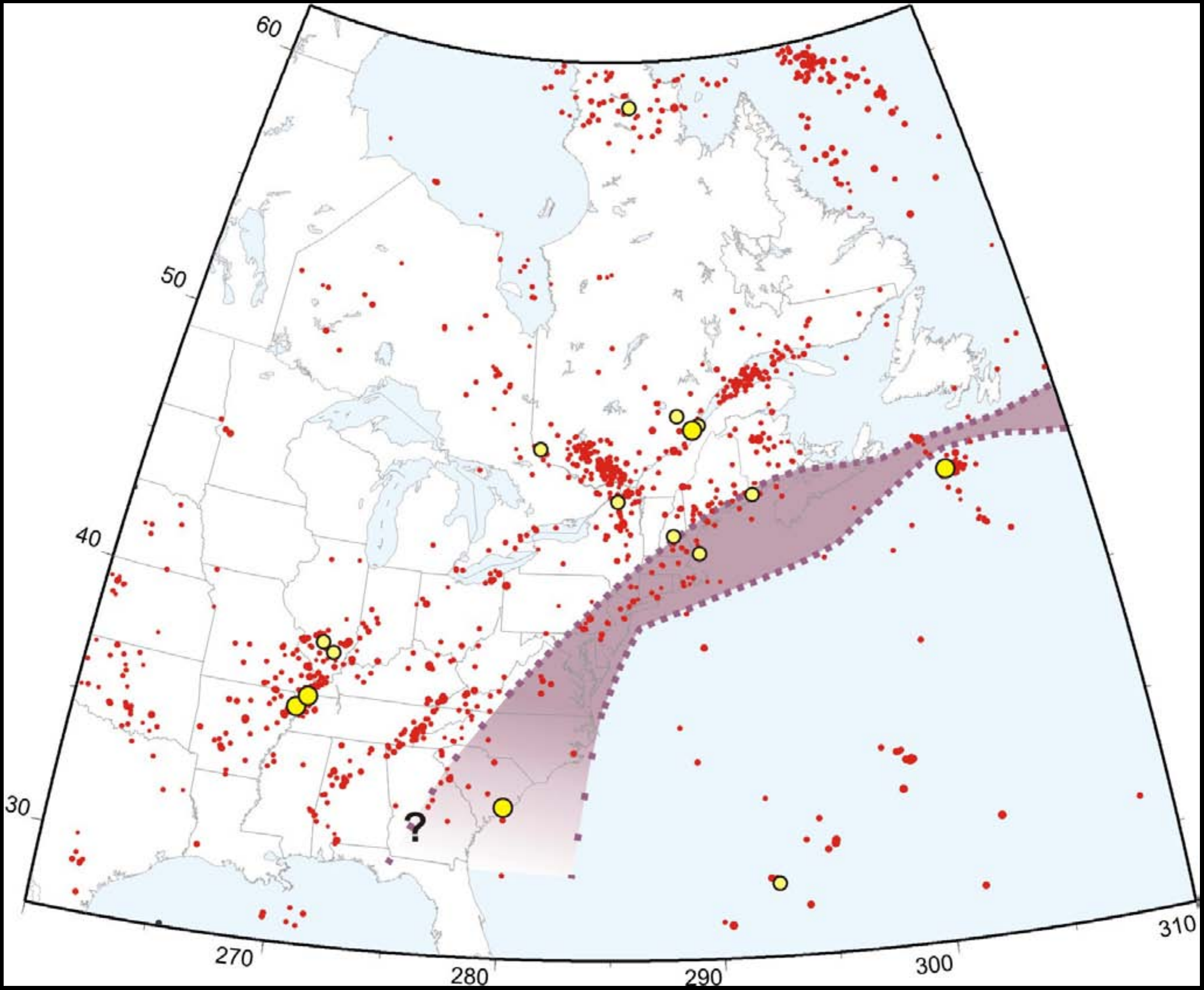


Mazzotti, 2007, GSA Special Paper 425

Relation to Geological Heritage

Seismic activity clusters along paleo-tectonic zones:

* Mesozoic rift / extension basins (~200 Ma)

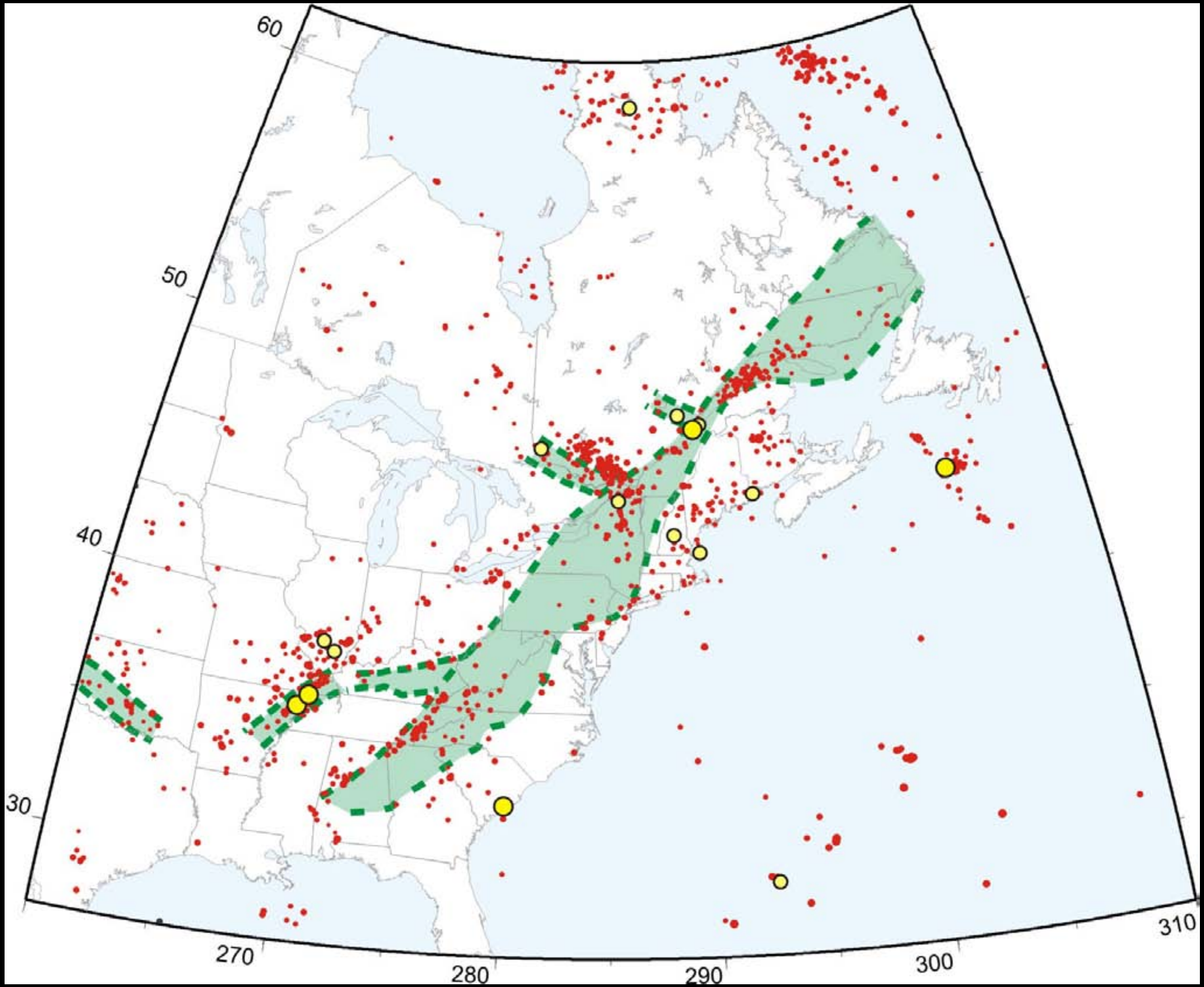


Mazzotti, 2007, GSA Special Paper 425

Relation to Geological Heritage

Seismic activity clusters along paleo-tectonic zones:

* Iapetus rift structures (~600 Ma)



Mazzotti, 2007, GSA Special Paper 425

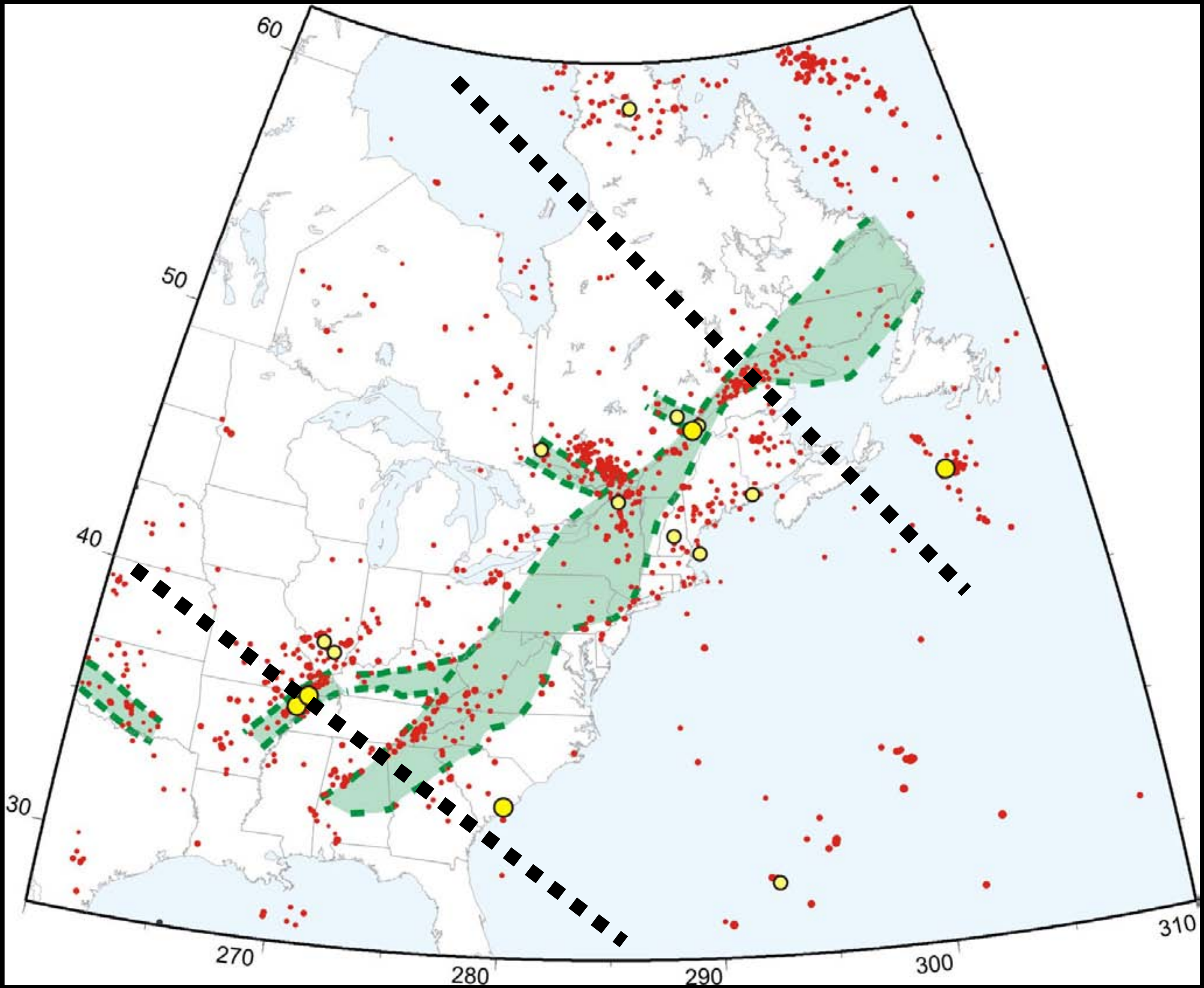
Relation to Geological Heritage

Seismic activity clusters along paleo-tectonic zones:

Recurrence of $M \geq 6.0$

$T \approx 10$ yr in paleo-tectonic zones

$T \approx 2500$ yr in craton



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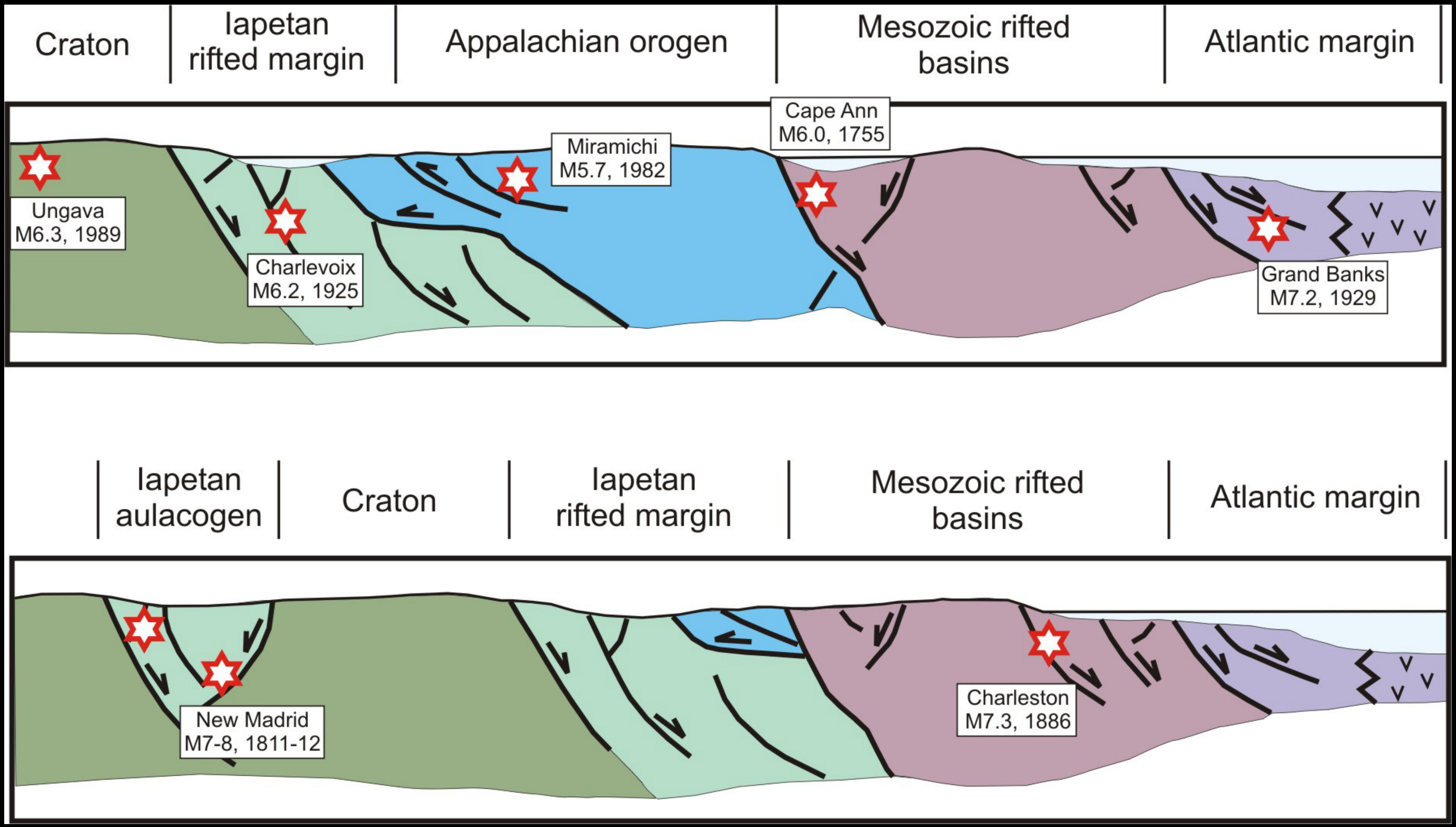
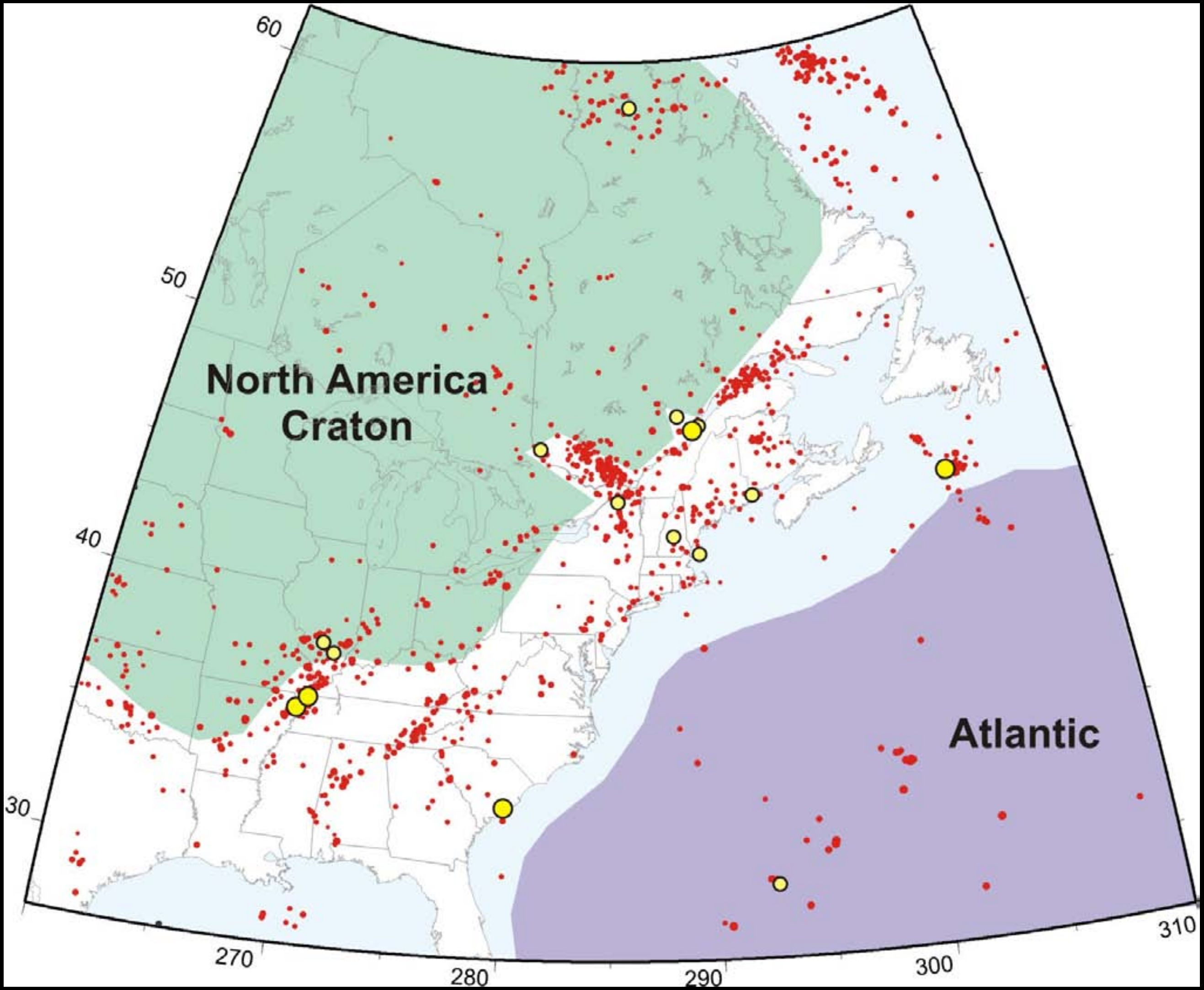


Mazzotti, 2007, GSA Special Paper 425

Relation to Geological Heritage

Seismic activity clusters along paleo-tectonic zones:

"Weak" deforming zone between two "rigid" blocks



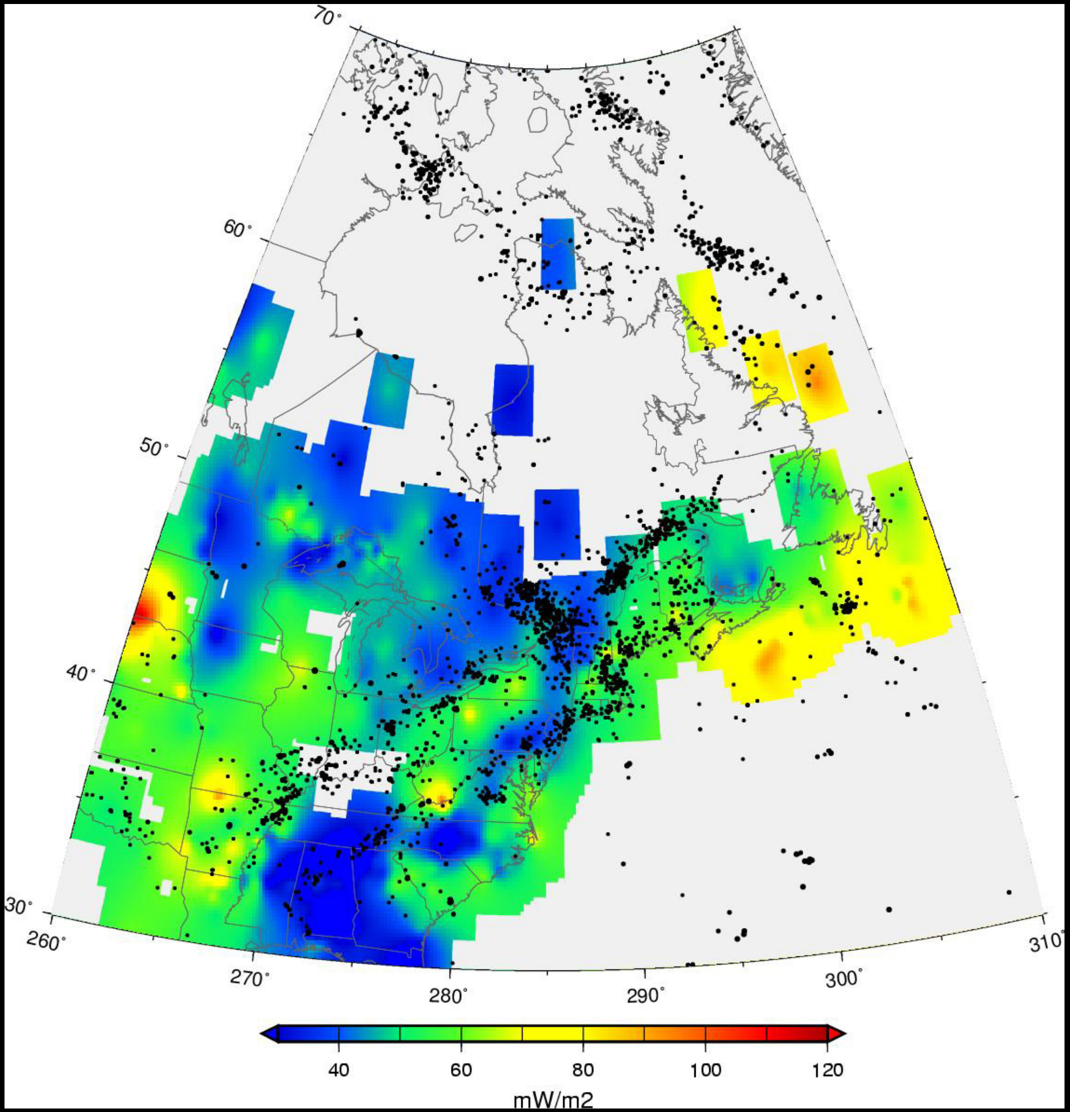
Mazzotti, 2007, GSA Special Paper 425

Relation to Lithosphere Strength

Thermal state of the lithosphere (heat flow as a proxy for crustal / upper mantle “weakness”)

Limited data coverage / limited resolution

No obvious relationship to seismicity



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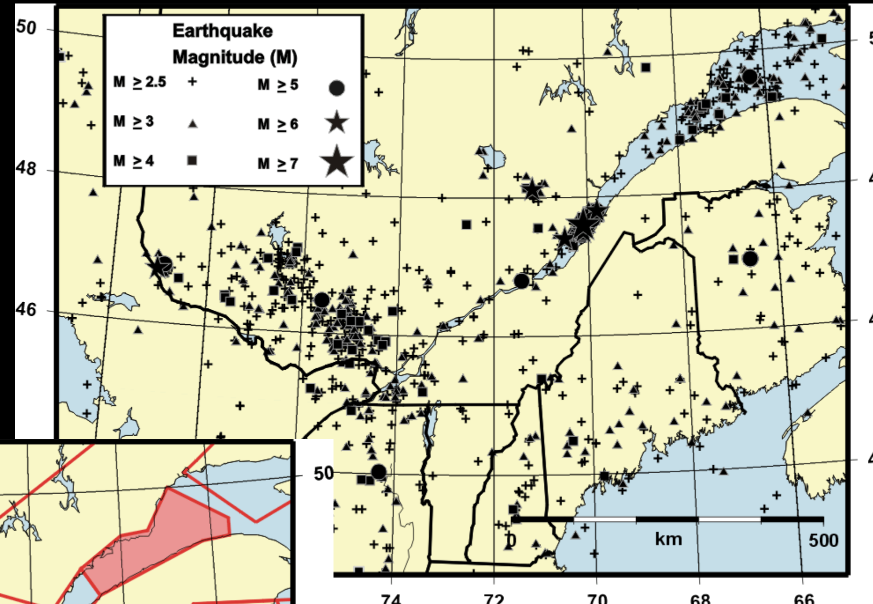
Seismic Hazard Impact

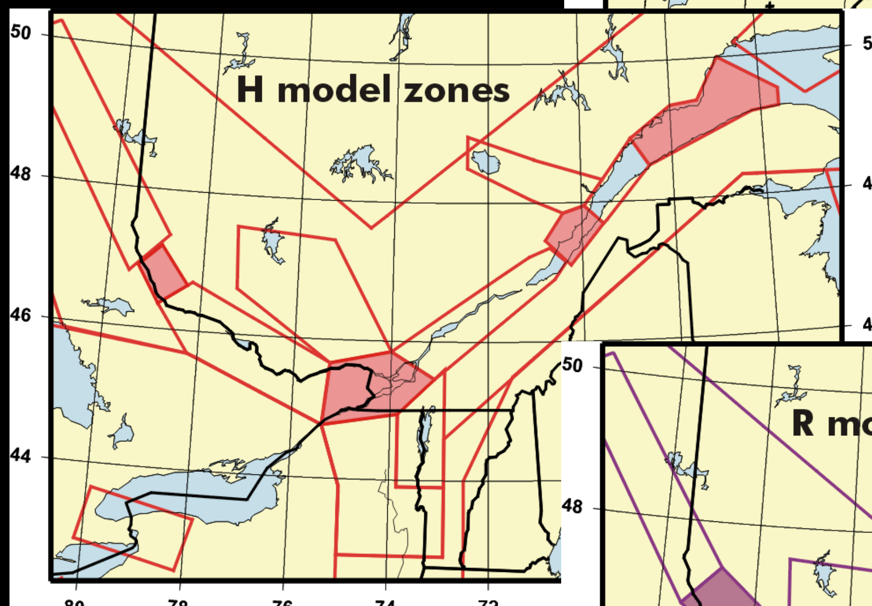
e.g., St. Lawrence – Ottawa valleys

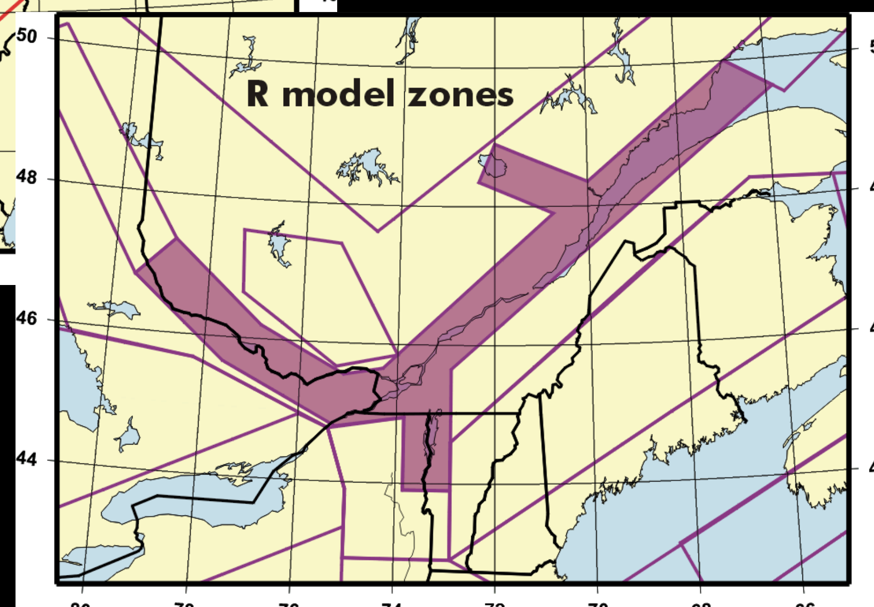
2 models:

- H = historical seismicity clusters

- R = tectonic structure of Iapetus rift







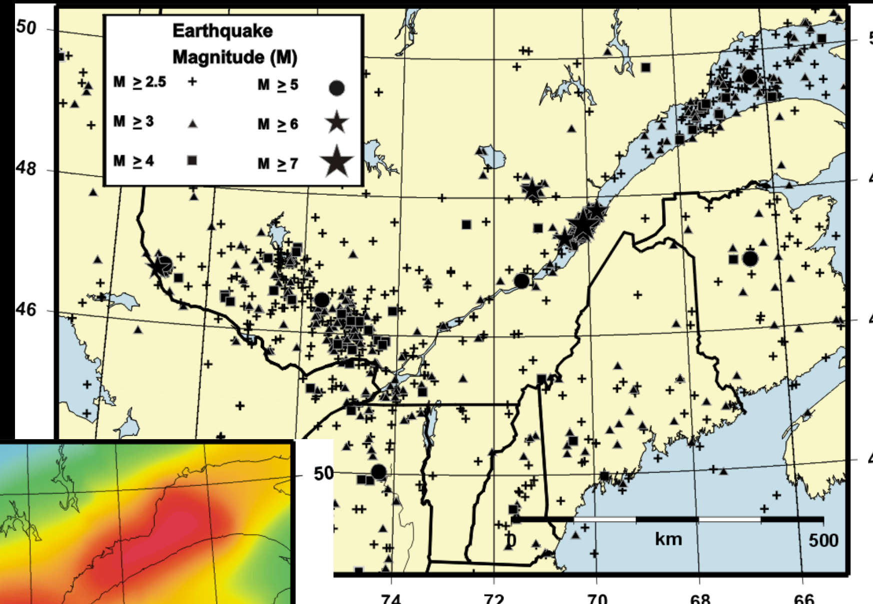
Adams and Halchuk, 2001

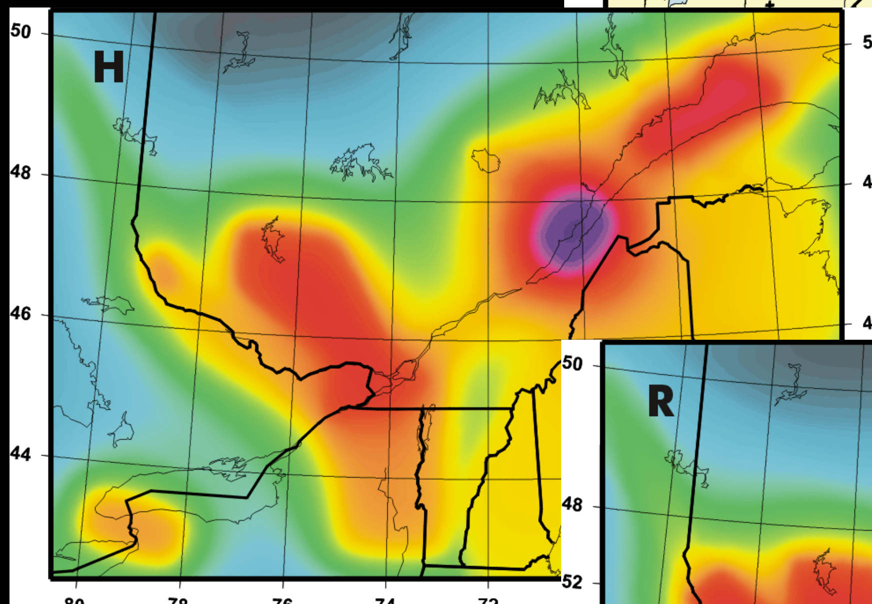
Seismic Hazard Impact

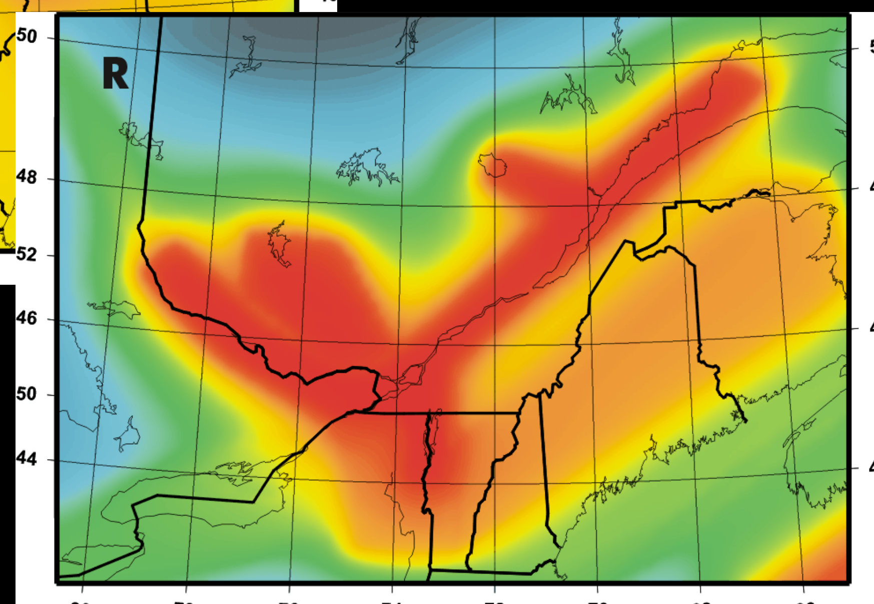
e.g., St. Lawrence – Ottawa valleys

2 models:

PGA varies by factors of 0.5 – 2.5







Adams and Halchuk, 2001

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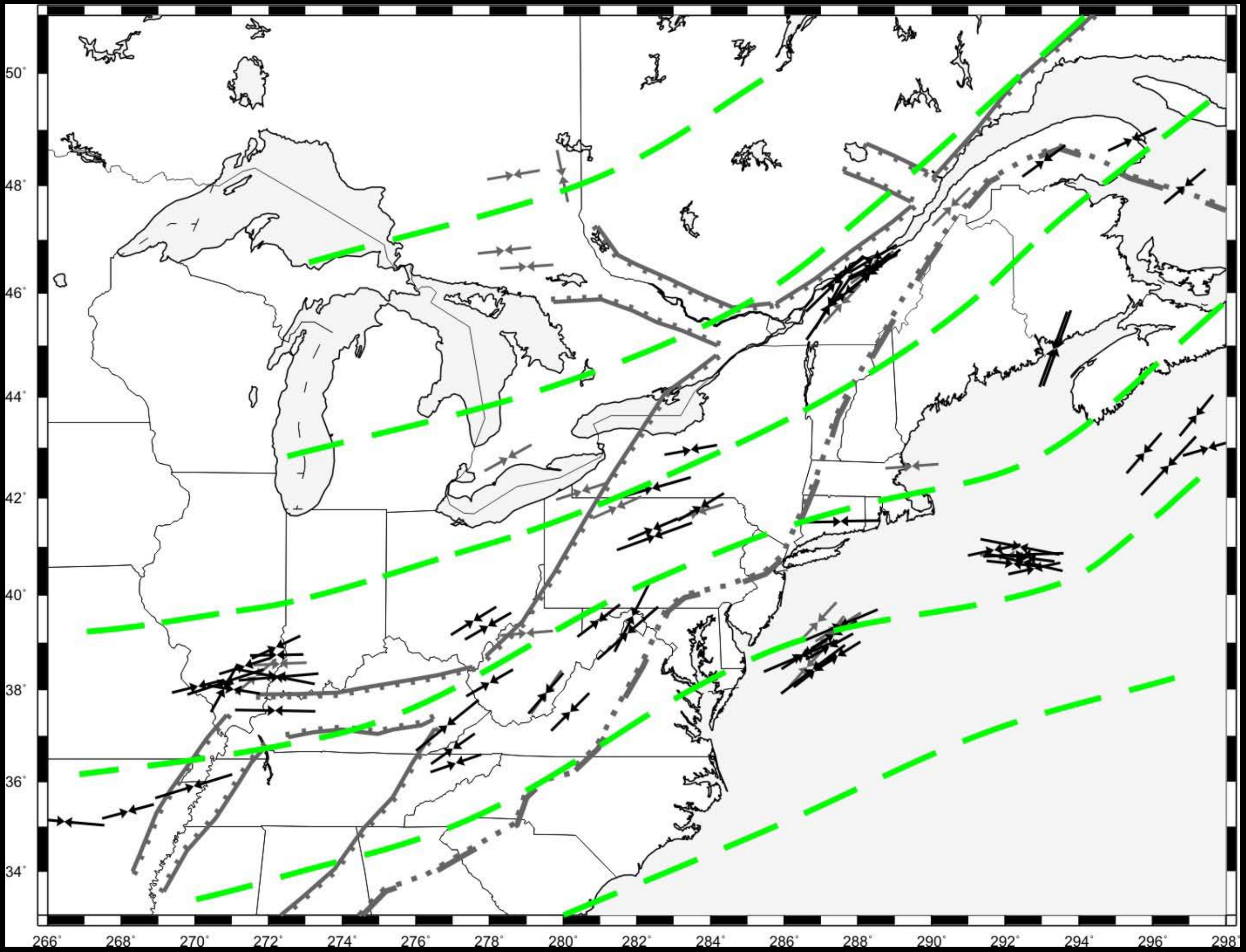
Borehole Stress Measurements

WSM borehole max. horiz. compr. Stress orientation (σ_H) ~ NE-SW

Related to tectonic driving forces

Parallel to rift in St. Lawrence, oblique in central U.S.



Mazzotti and Townend, 2010, Lithosphere

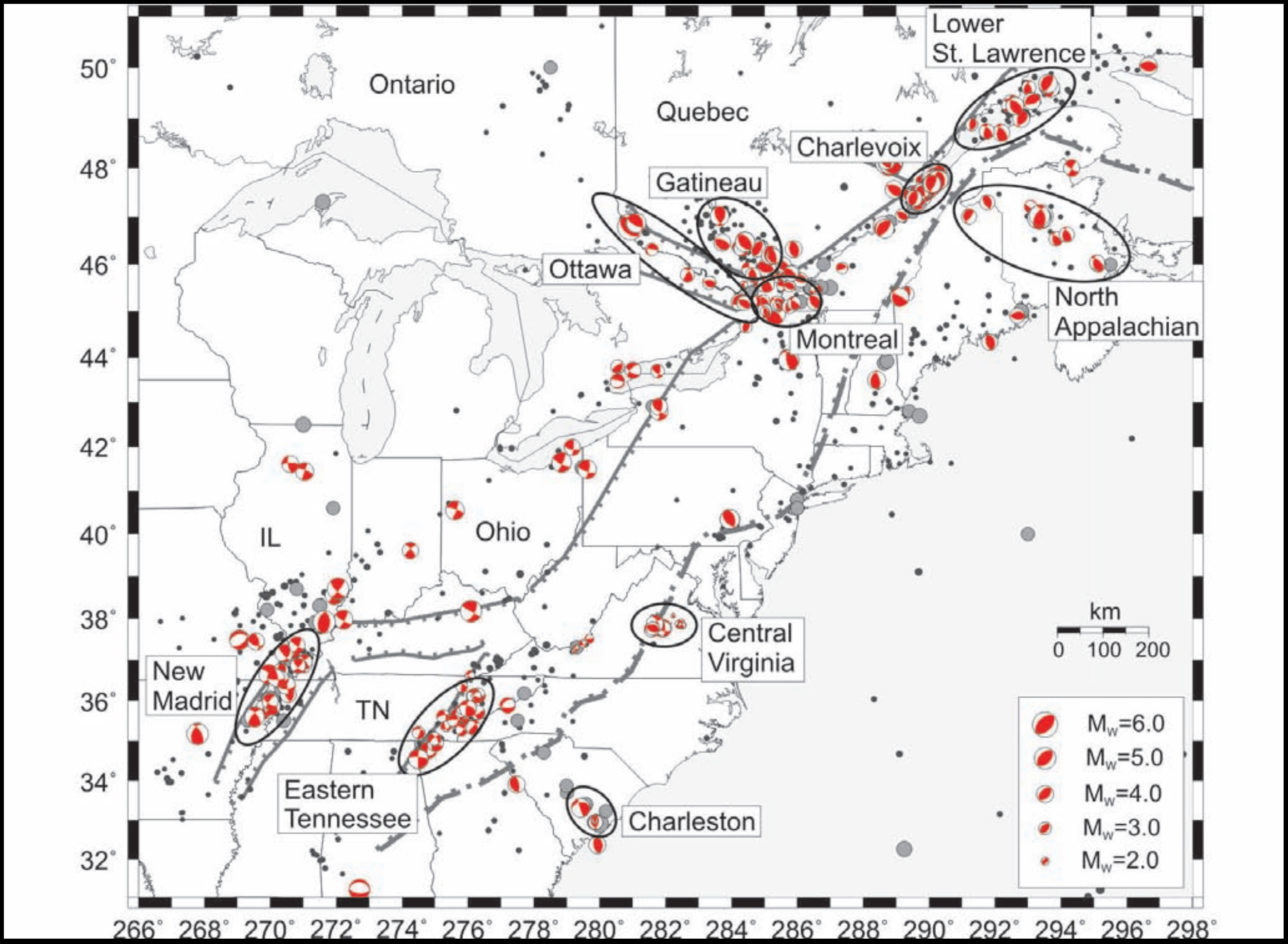
Earthquake Focal Mechanisms

Compilation of 300+ focal mechanisms

10 major seismic zones

- 6 inside Iapetus Rift

- 4 outside



Mazzotti and Townend, 2010, Lithosphere

Seismological Stress

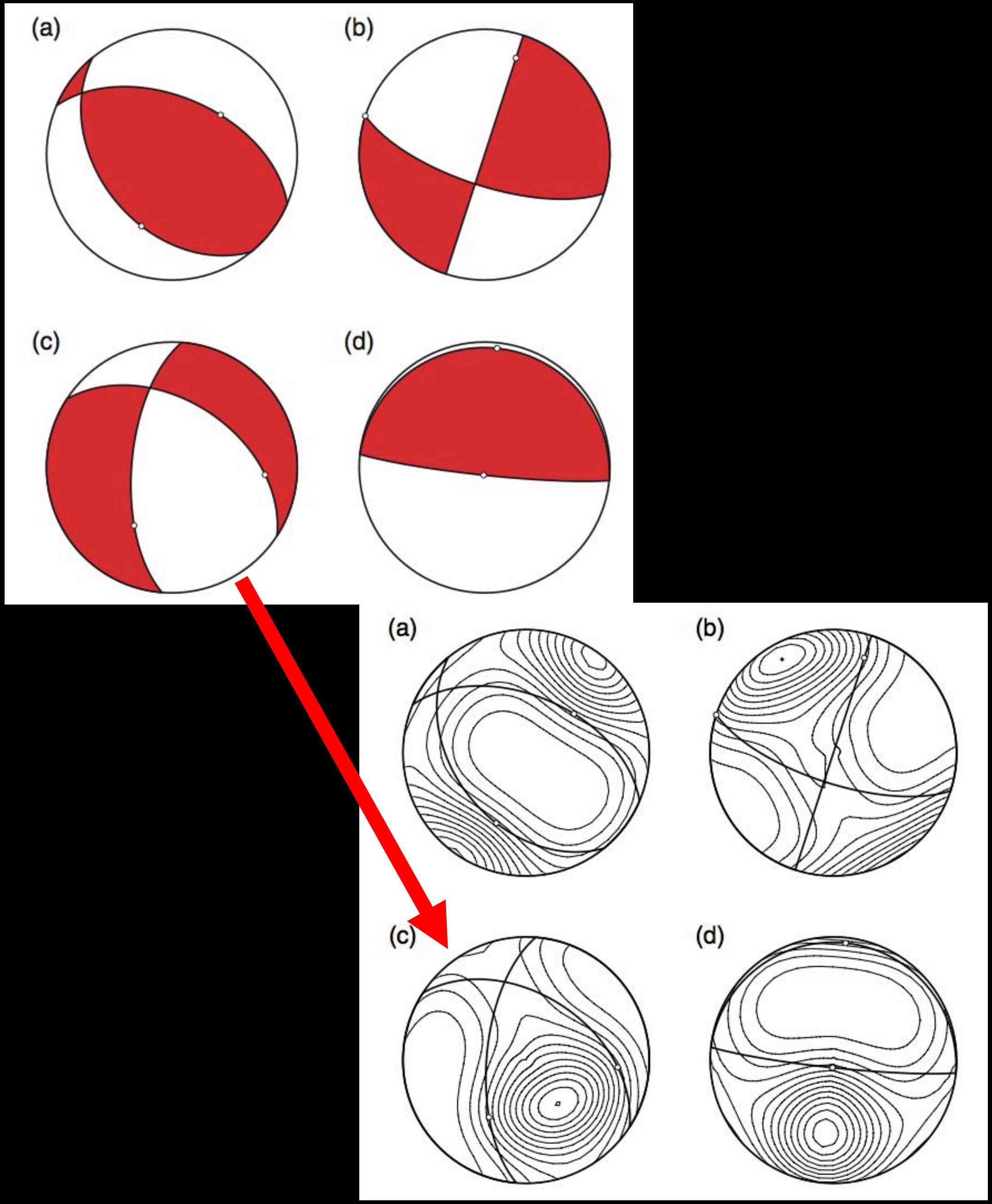
Bayesian inversion of focal mechanisms

Allows statistical integration of:

- Fault / auxiliary uncertainty

- FM limited constraint on stress

- FM error (eg. 20°)



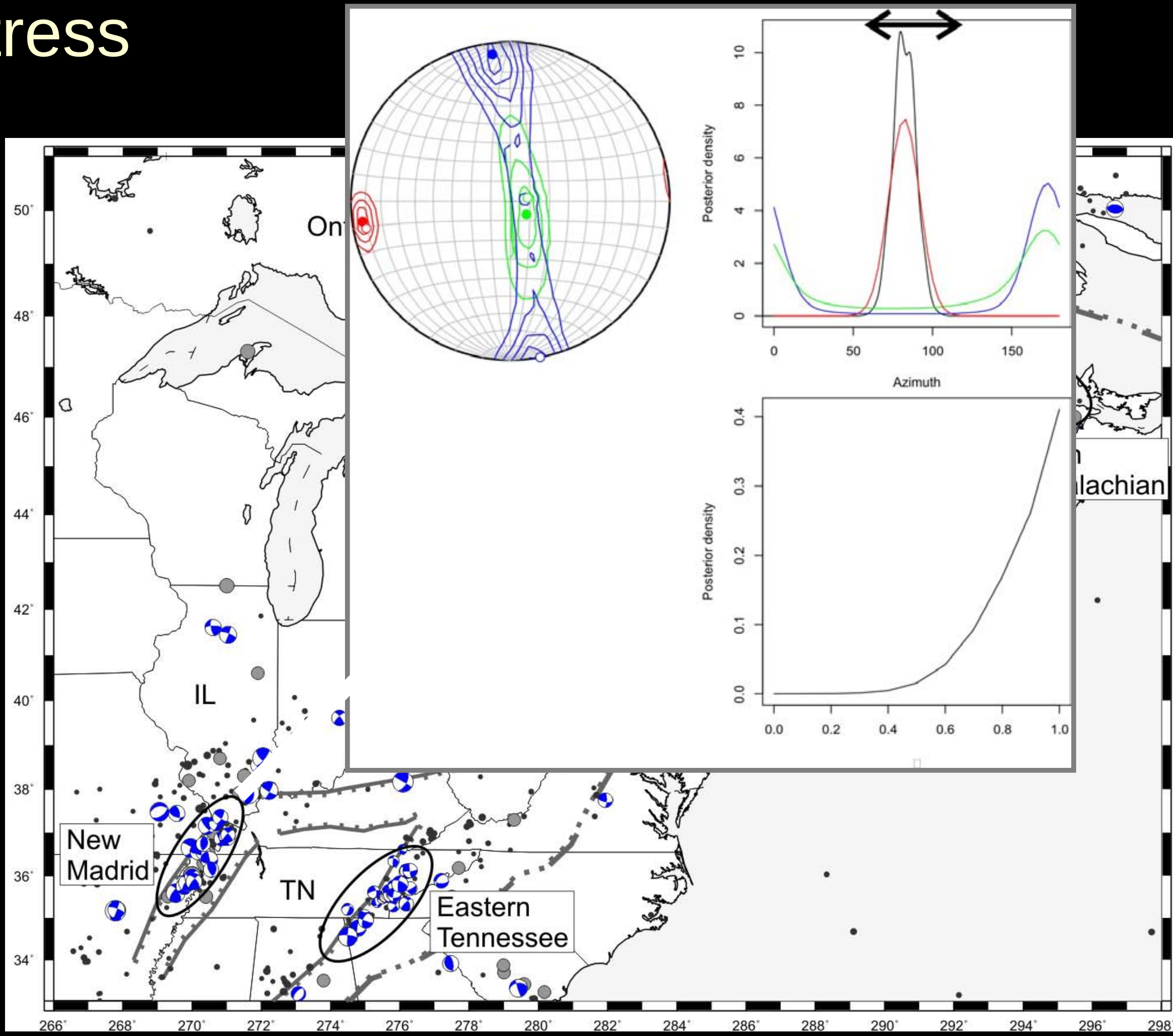
Arnold and Townend, 2007, GJI

Seismological Stress

Bayesian inversion of foc. mech.

Probability density functions of σ_1, σ_2, σ_3, R, and σ_H

=> Allows comparison with borehole σ_H



Mazzotti and Townend, 2010, Lithosphere

Seismological Stress

Borehole data:

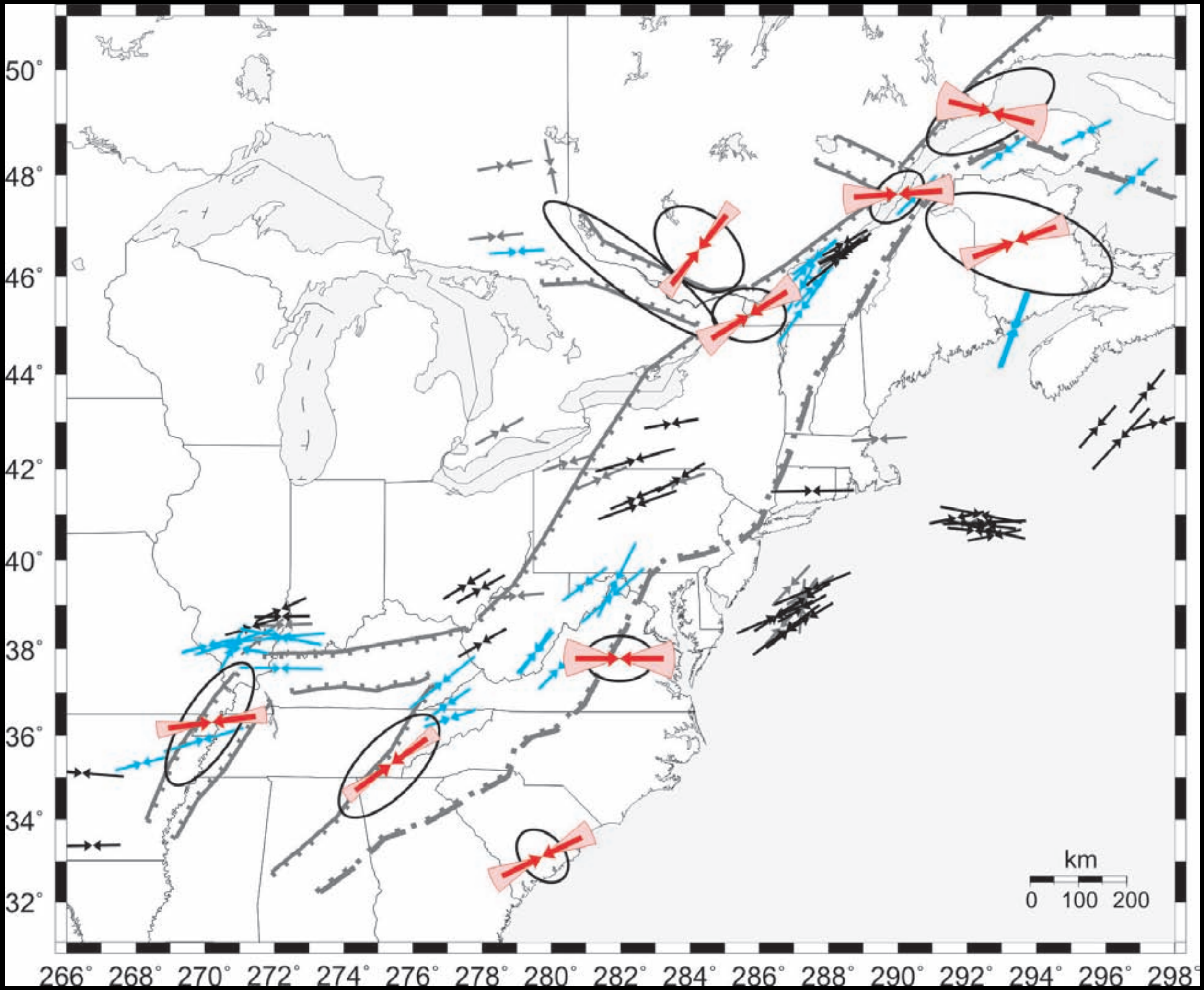
- Blue (near seismic zone)

- Black (not used)

FM stress results:

- Red = median

- Pink = 90% CI

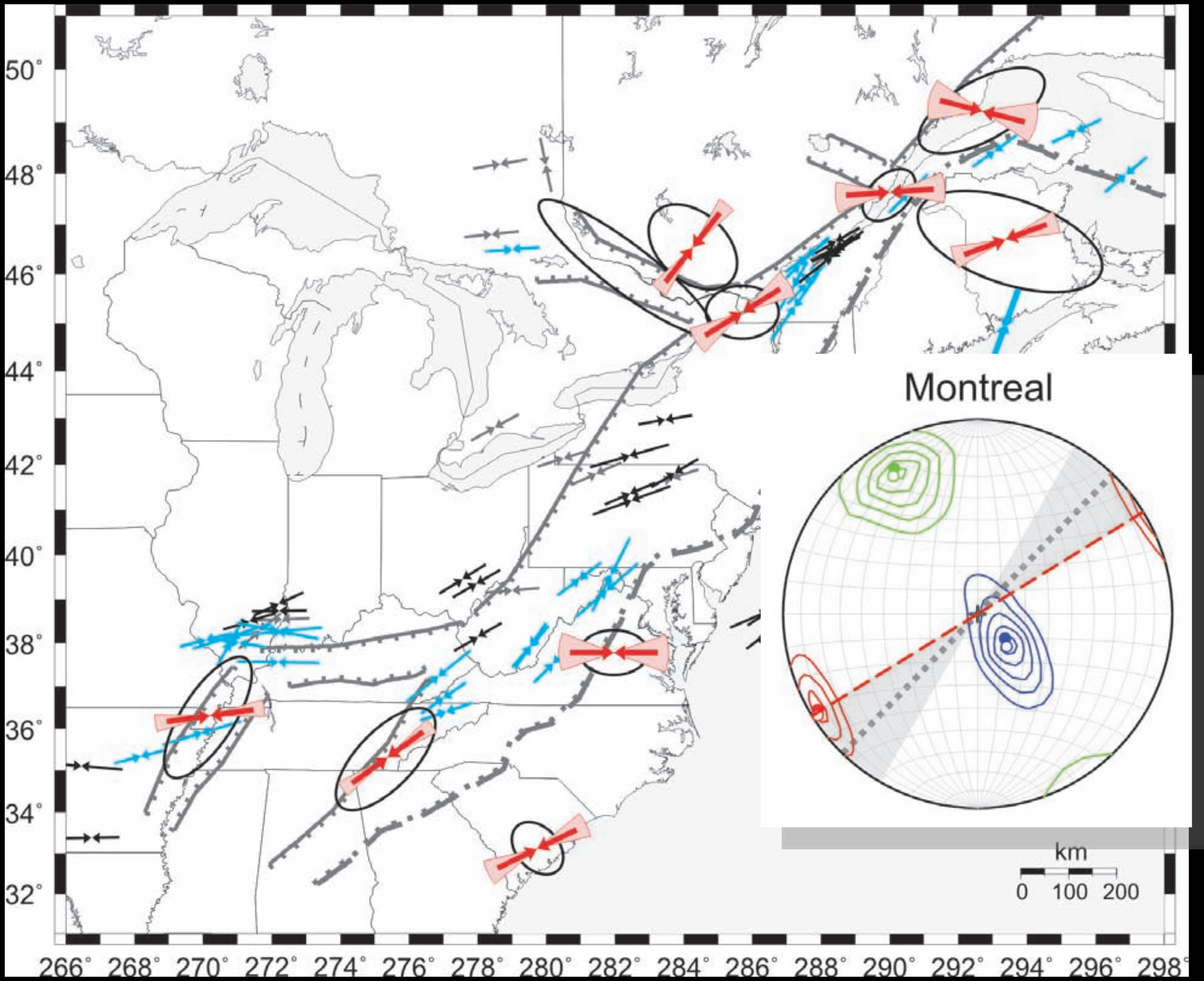


Mazzotti and Townend, 2010, Lithosphere

Seismological Stress

4 (maybe 6) zones: seismological σ_H sub-parallel to borehole σ_H

Collinear within 90% confidence interval (10-20˚)



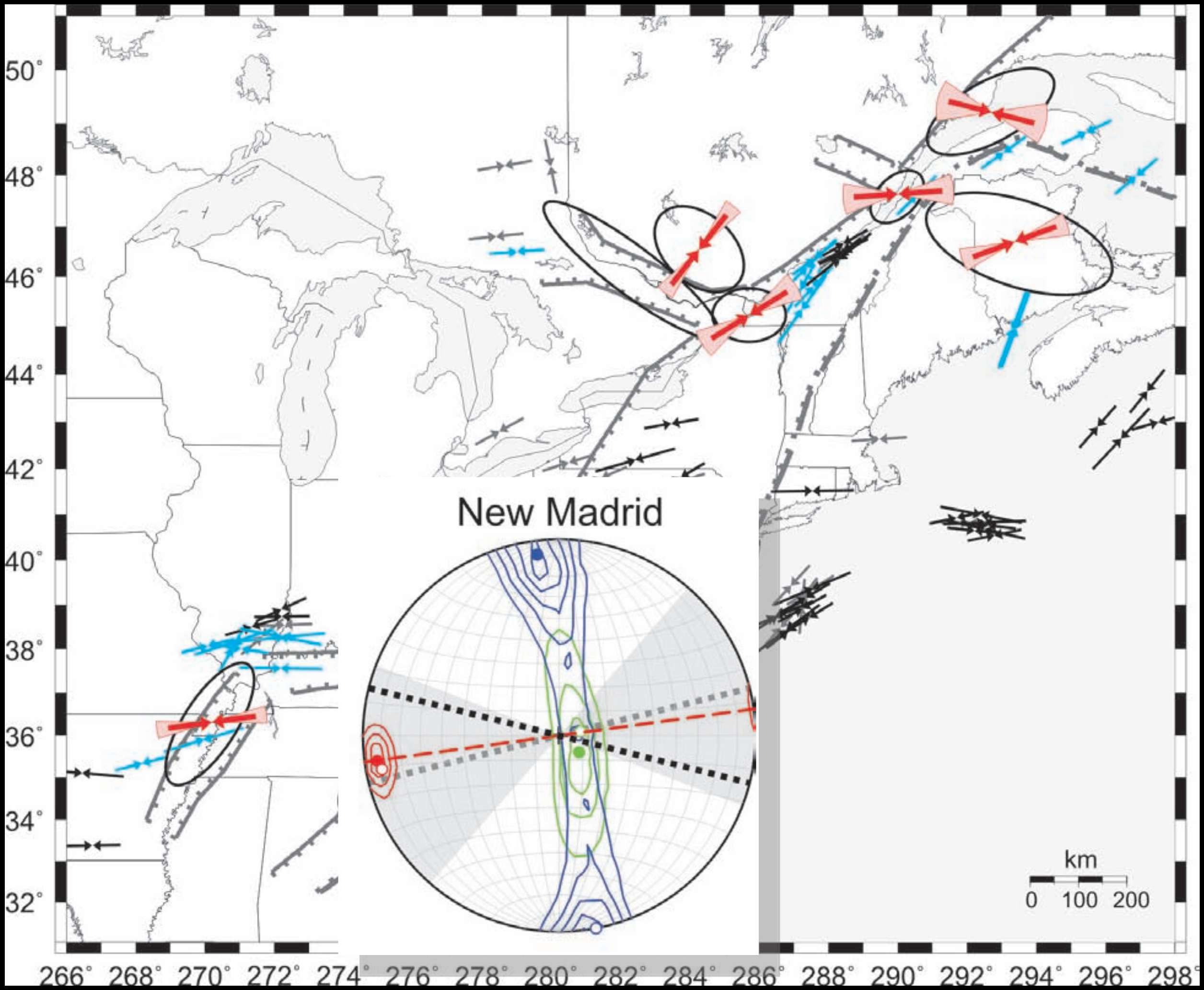
Mazzotti and Townend, 2010, Lithosphere

Seismological Stress

4 (maybe 6) zones: seismological σ_H sub-parallel to borehole σ_H

New Madrid:

Interesting case of 2003 Bardwell sequence (Horton et al., 2005)



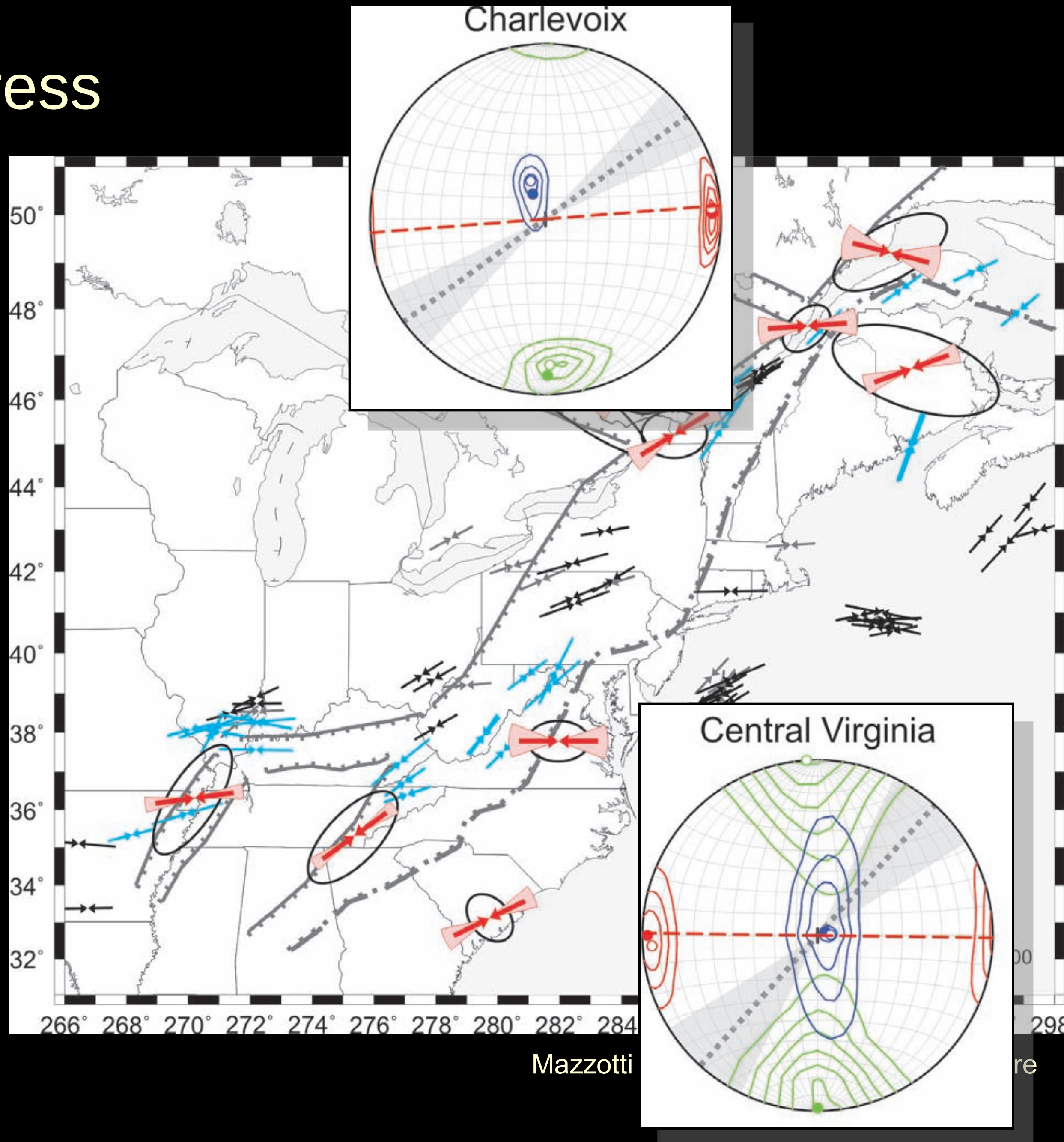
Mazzotti and Townend, 2010, Lithosphere

Seismological Stress

3 zones:

* Low St. Lawrence
* Charlevoix
* Central Virginia

Seismological σ_H rotated 30-40° clockwise relative to nearby borehole σ_H



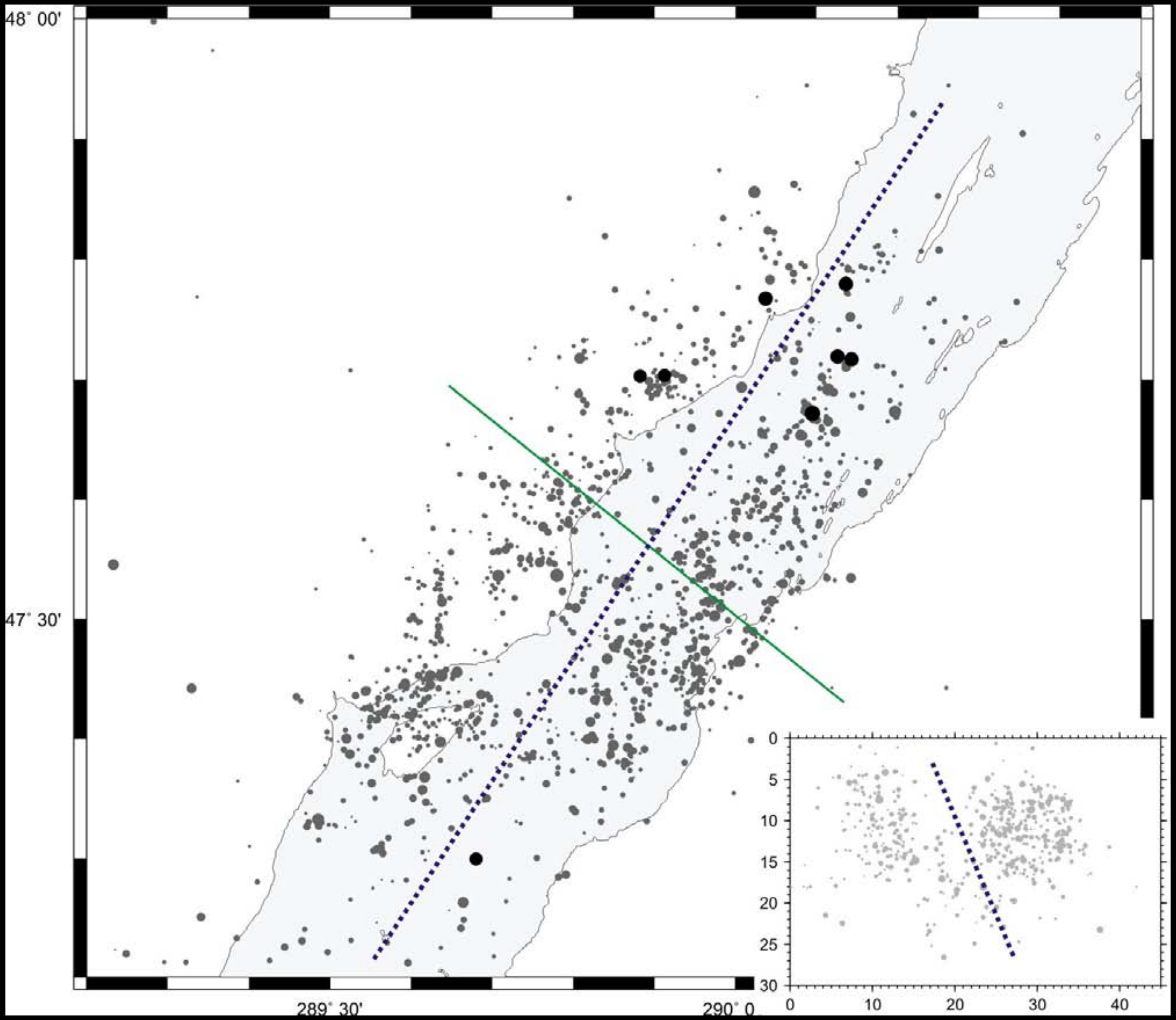
Mazzotti ... re

Charlevoix Seismic Zone

50x100 km along Iapetus Rift

Two main earthquake clusters (NW and SE)

60+ foc. mech.



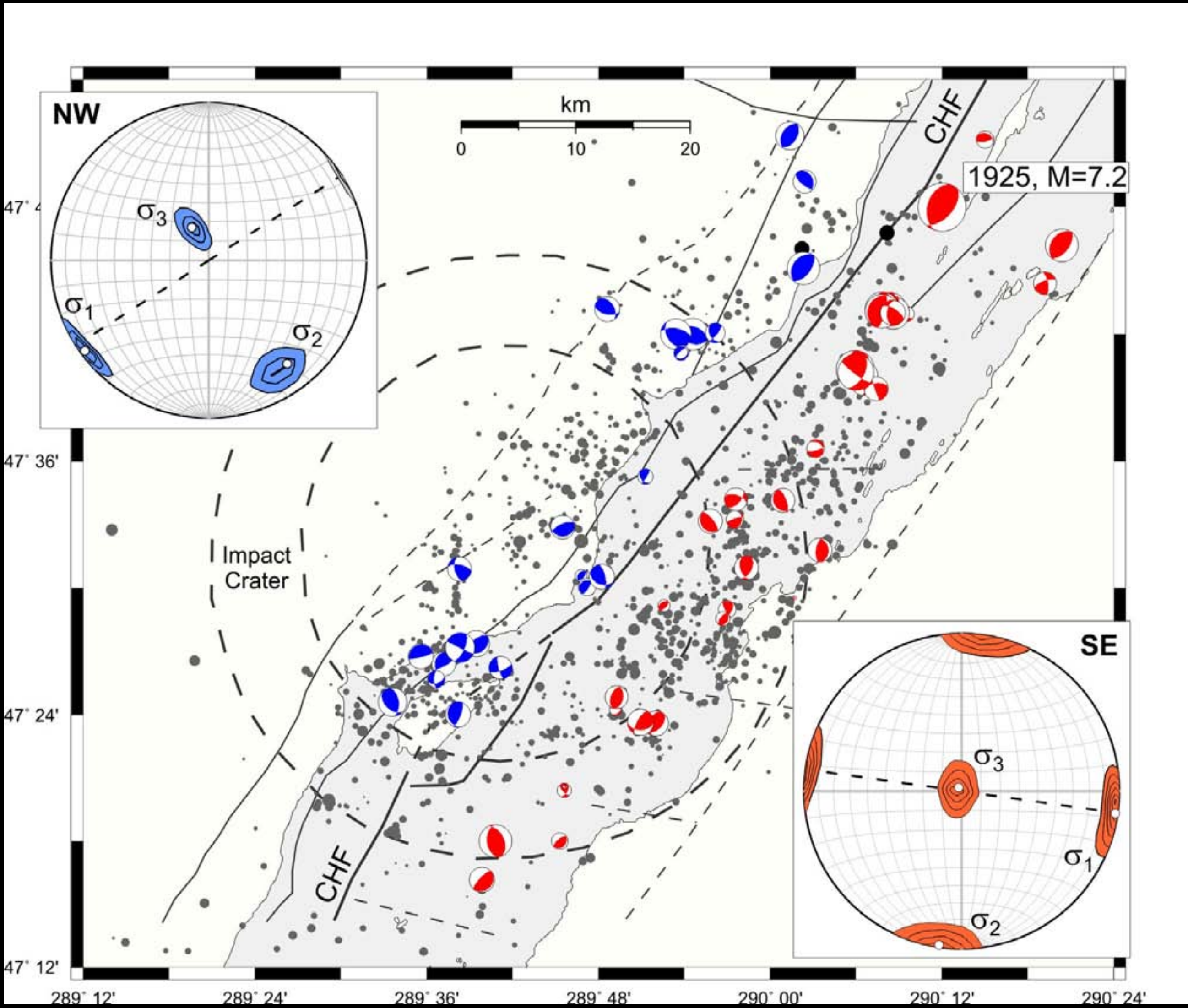
Charlevoix Seismic Zone

NW cluster:

Seismological σ_H parallel to borehole σ_H

SE cluster:

Seismological σ_H rotated 45° ckw.

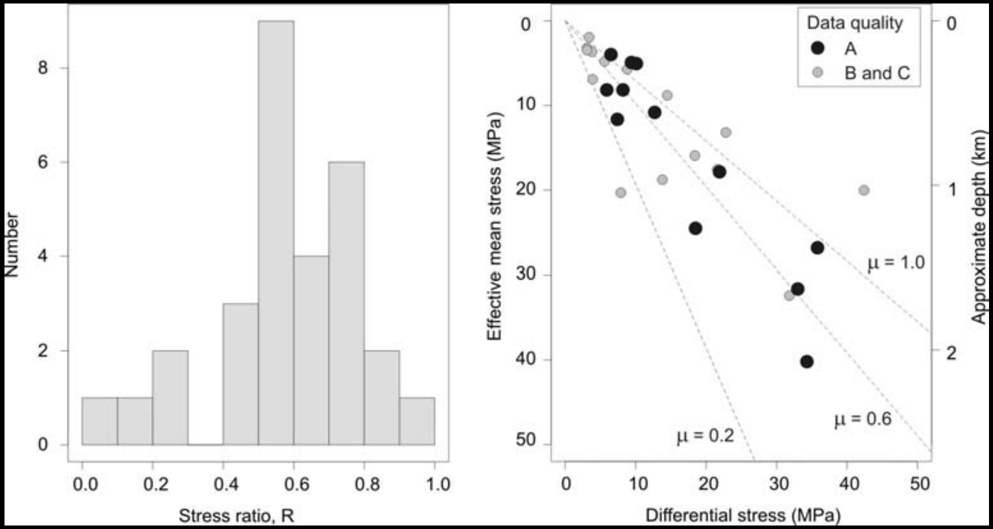


Potential Causes of Stress Rotation in Seismic Zones:

Implications of systematic rotations on stress level in the crust and in seismic zones

* σ_H rotation of 30-50° requires a stress perturbation 80-110% of regional diff. stress (cf. Zoback, 1992)

* Borehole stress measurements indicate incipient frictional failure with μ > 0.6 and near hydrostatic Pf



>> Stress perturbation of 160 – 250 MPa at mid-crustal depth

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Implications of systematic rotations on stress level in the crust and in seismic zones

* stress perturbation 80-110% of regional diff. stress
* Borehole μ > 0.6 and near hydrostatic Pf

>> Stress perturbation of 160 – 250 MPa at mid-crustal depth

What mechanisms can cause ~200 MPa stress perturbations?

- over 30 – 50 km distances (Charlevoix)
- over distances of 1000 – 1500 km (Eastern US)

Potential Causes of Stress Rotation in Seismic Zones:

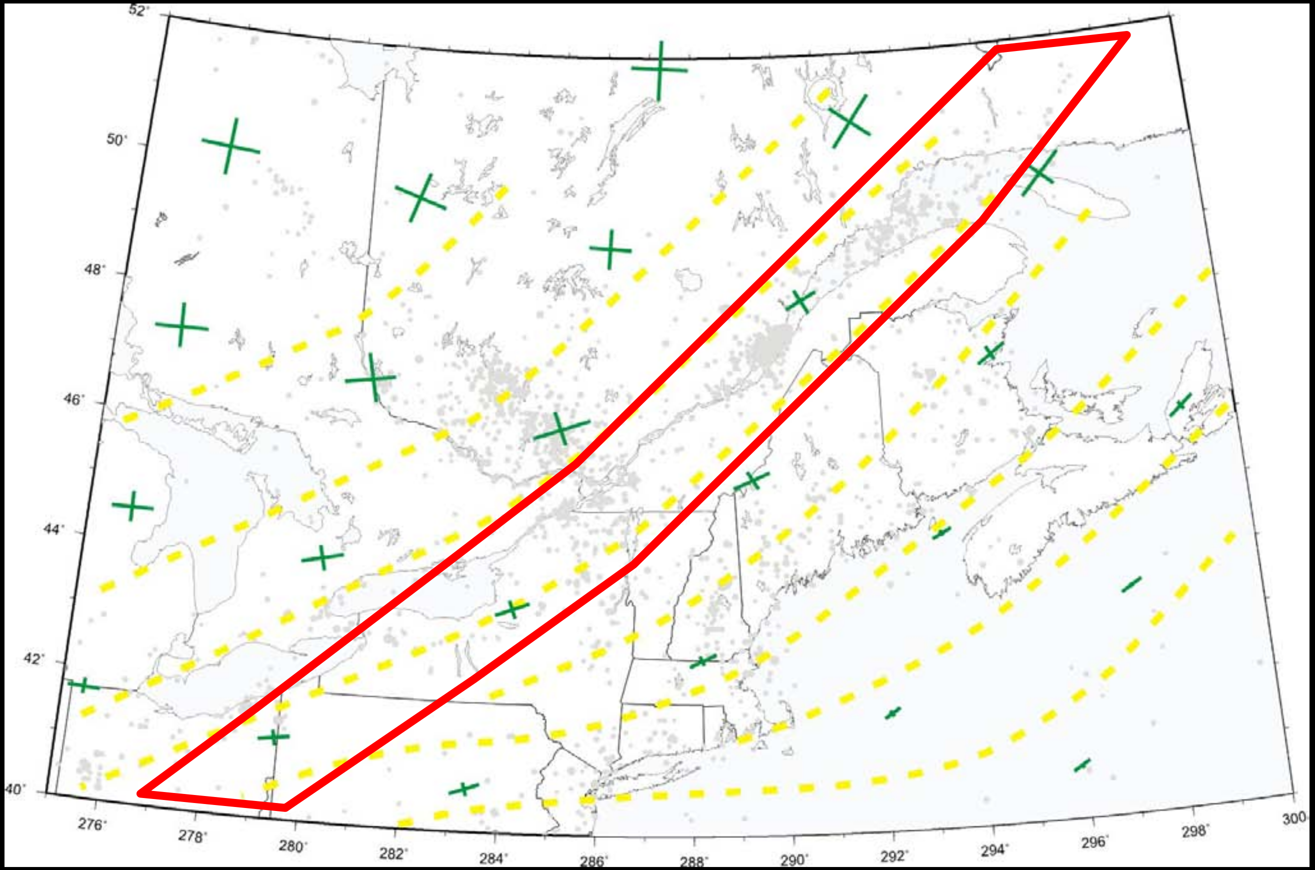
Postglacial Rebound & Weak Lithosphere

Reference PGR Model:

$\sigma_H \sim \sigma_h$

sub-parallel to tectonic stress (NE-SW)

Introduce a weak (lower viscosity) upper mantle



Wu and Mazzotti, 2007, GSA Special Paper 425

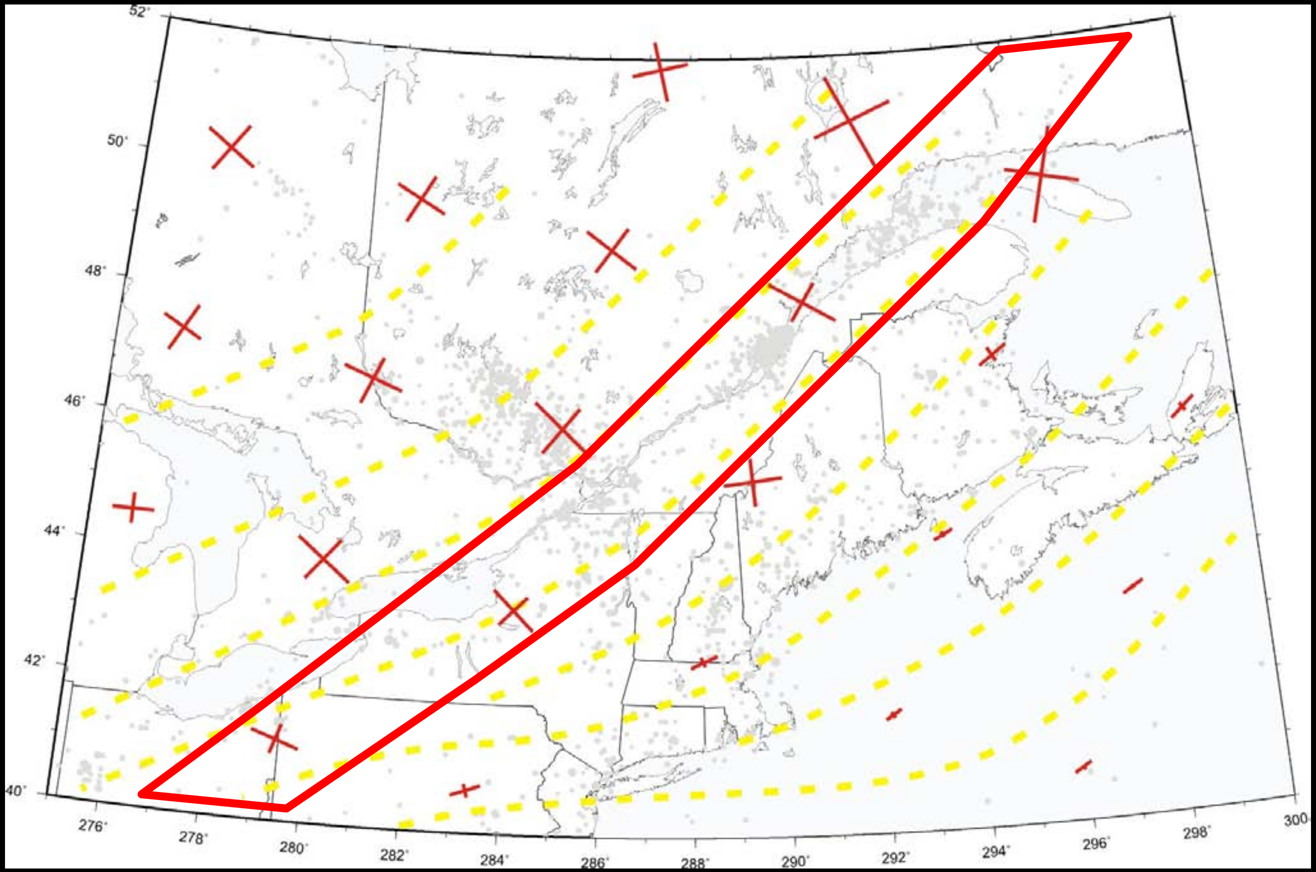
Potential Causes of Stress Rotation in Seismic Zones:

Postglacial Rebound & Weak Lithosphere

Weak Zone PGR Model:

>> Stress concentration

>> 40-60° ckw. rotation of σ_H



Wu and Mazzotti, 2007, GSA Special Paper 425

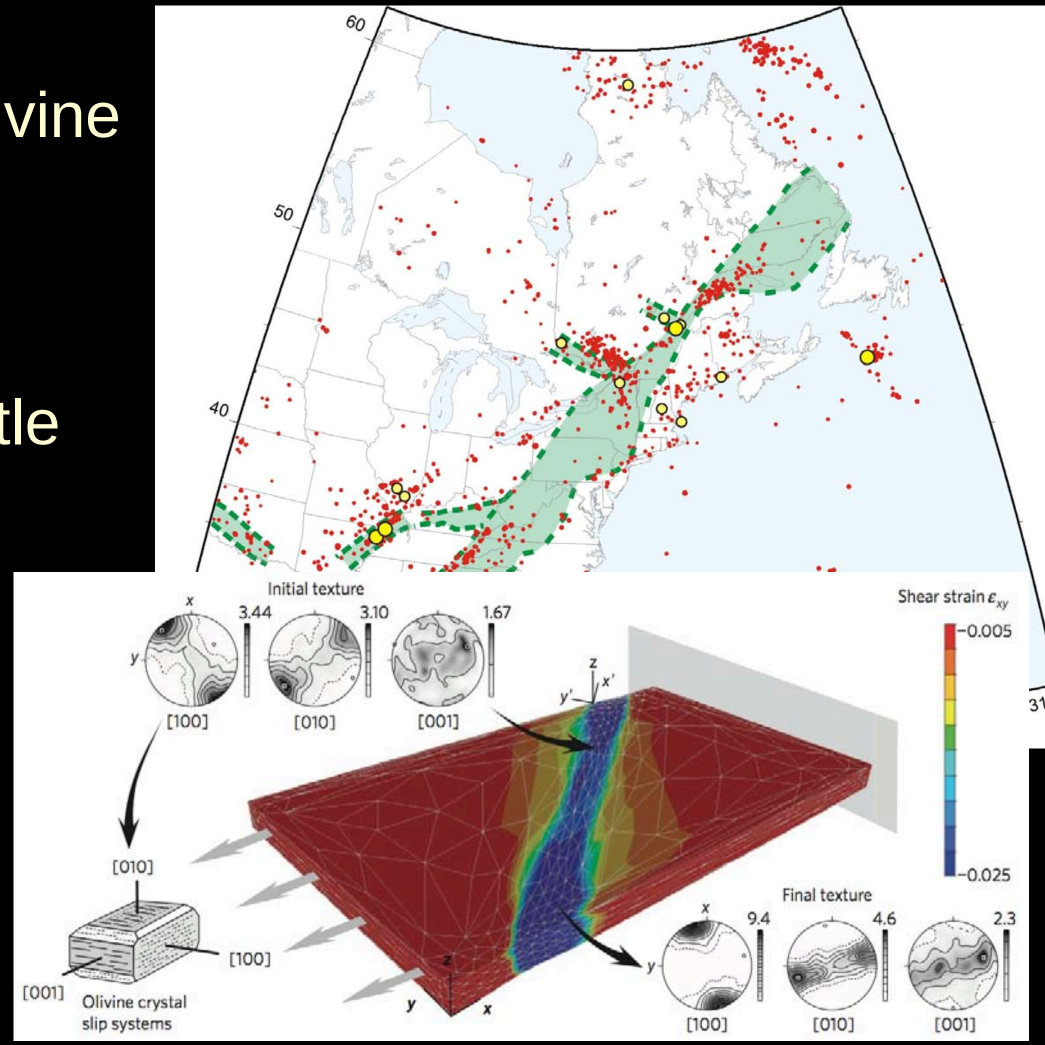
Potential Causes of Stress Rotation in Seismic Zones:

Weak Lithosphere

Preferential orientation of olivine crystals in zone of high deformation

>> Anisotropy of upper mantle viscosity

>> Concentration of stress and strain



Tomassi et al., 2009

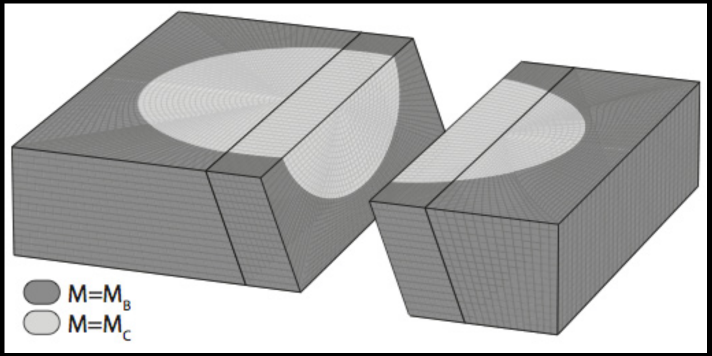
Potential Causes of Stress Rotation in Seismic Zones:

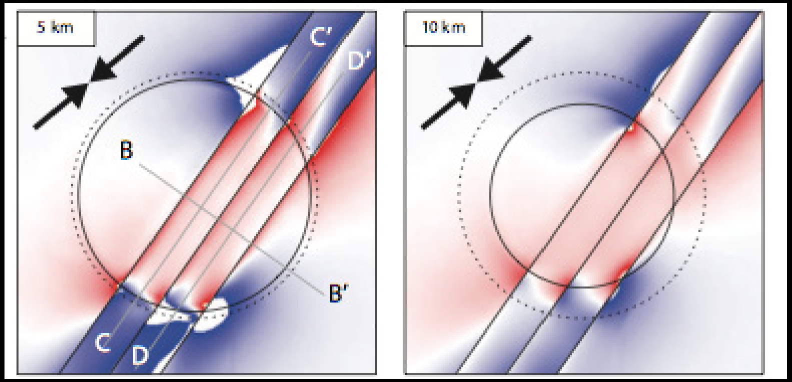
Guiding Faults with Low Effective Friction

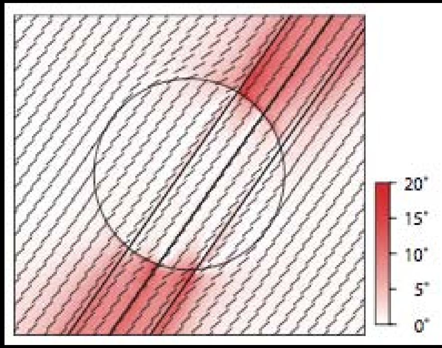
Mechanical model of stress channeling between weak ($\mu_{eff} < 0.1$) rift faults around impact crater ($M_C = \frac{1}{4} M_B$)

>> Stress (and seismicity) concentration + 10 – 20%

>> 15 – 20° ckw. rotation of σ_H







A. Baird, 2010, Ph.D. thesis, Queens University

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* stress perturbation 80-110% of regional diff. stress
* Borehole $\mu > 0.6$ and near hydrostatic P_f

>> Stress perturbation of 160 – 250 MPa at mid-crustal depth

What mechanisms can cause ~200 MPa stress perturbations?

- over 30 – 50 km distances (Charlevoix)
- over distances of 1000 – 1500 km (Eastern US)

>> Require "weak" upper mantle and / or upper crustal faults

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Exemple de l'Est Américain

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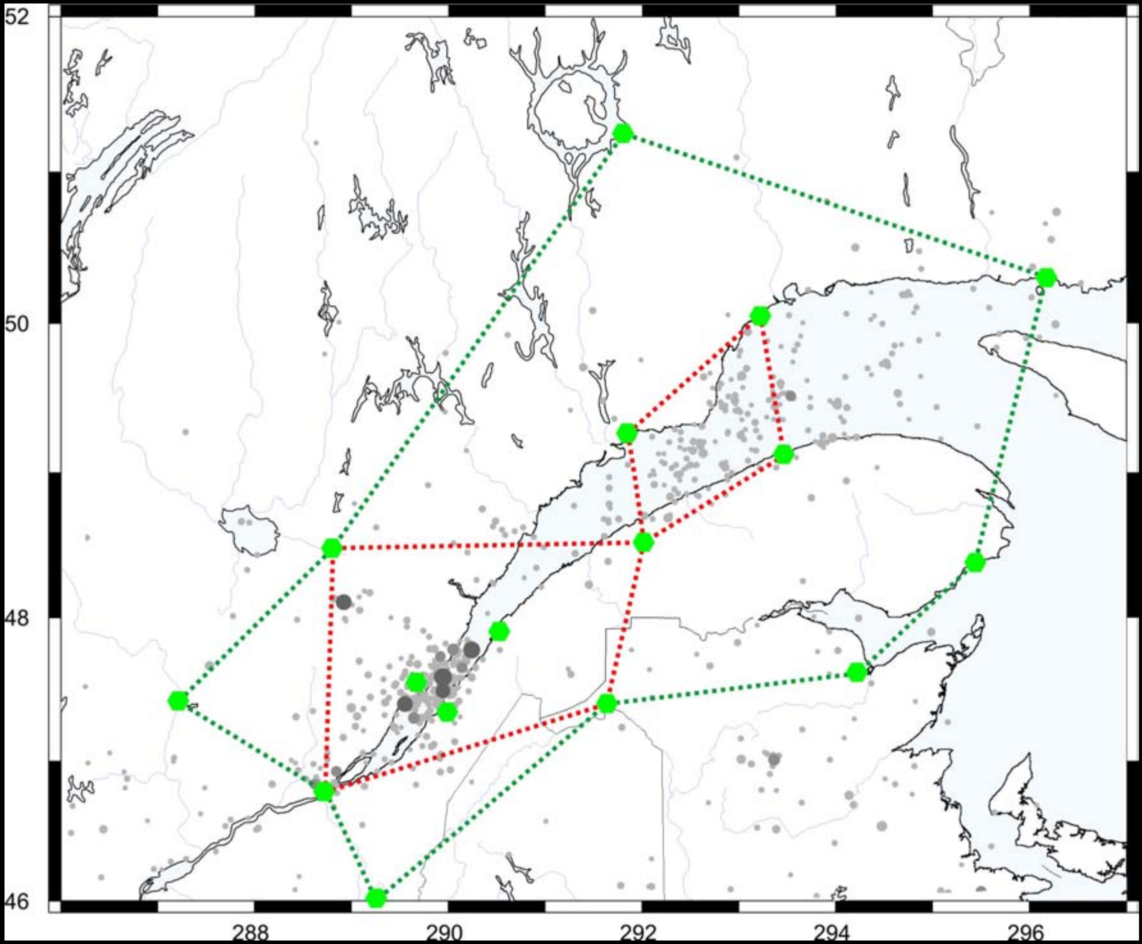
St. Lawrence Seismic Zone Strain Rates

16 campaign sites (Canadian Base Network)

4 – 5 occupations over 7 – 11 years (1994/1996 – 2005)

Good geometry for crustal strain
- Regional
- Local (CHV & BSL)



Mazzotti et al., JRG 2005

St. Lawrence Seismic Zone Strain Rates

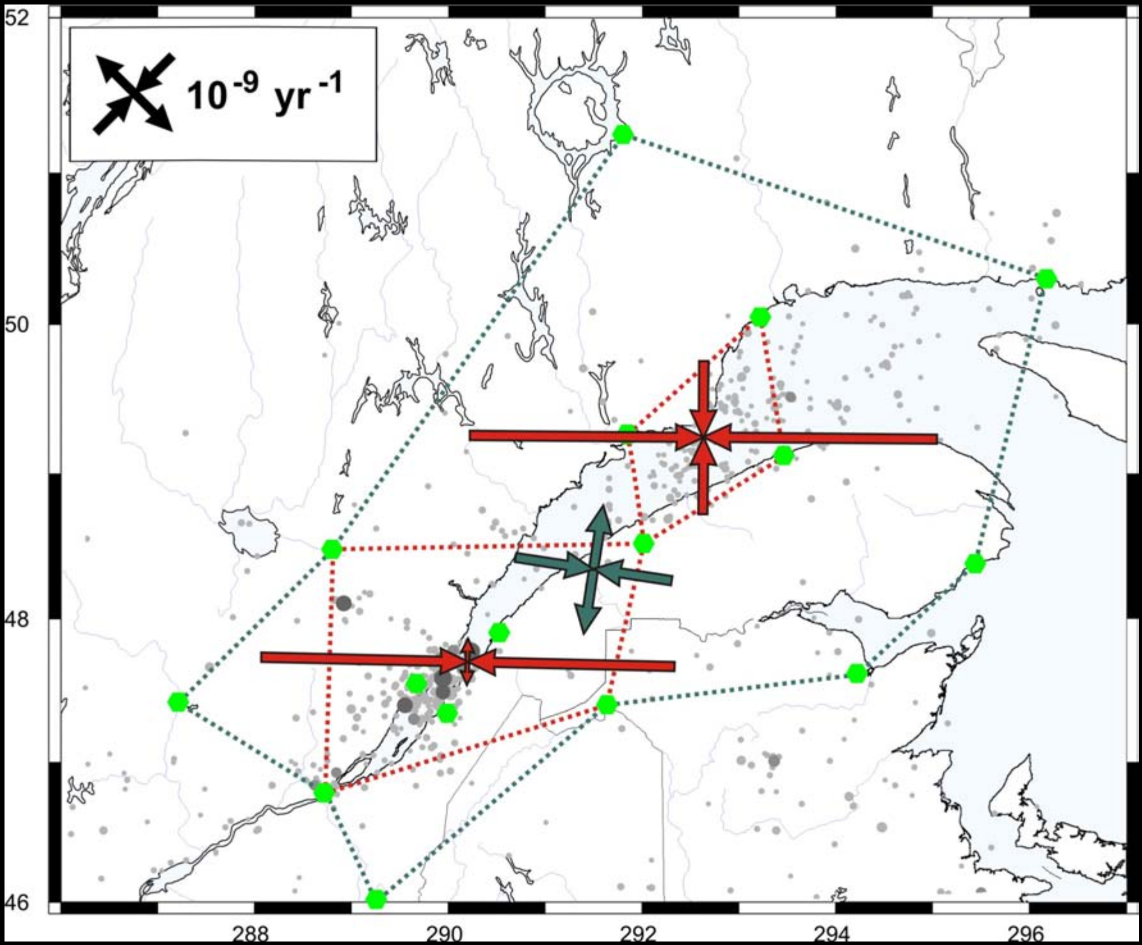
Regional strain =
E-W shortening

Agrees with FM stress
(BSL & SE cluster)

Resolved at 1 sigma,
e.g. Charlevoix:

$3.8 \pm 2.3 \times 10^{-9}$ yr^{-1}

0.7 ± 0.4 mm/yr



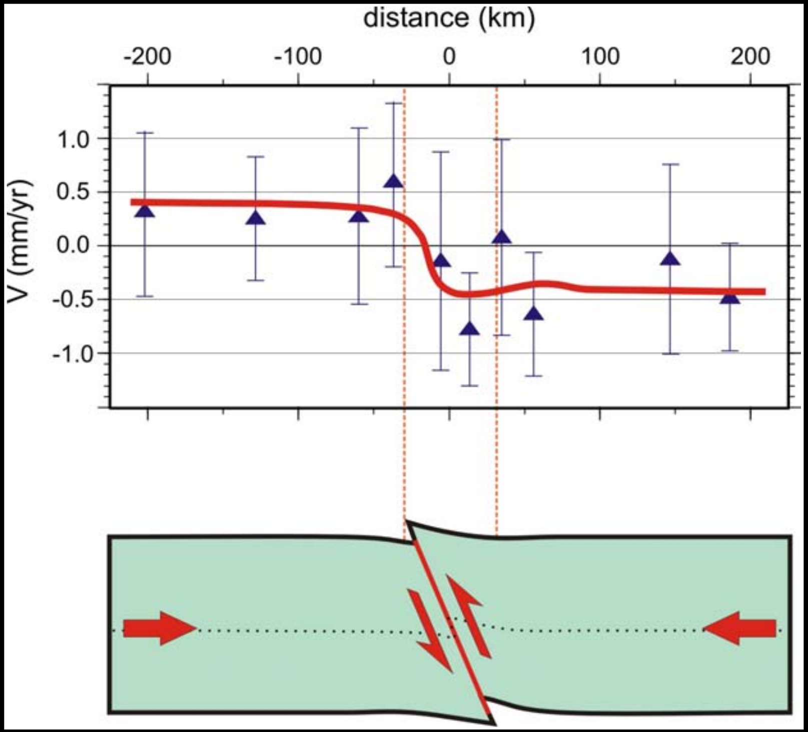
Mazzotti et al., JRG 2005

St. Lawrence Seismic Zone Strain Rates

Resolution ~1 mm/yr at 95%

Cannot discriminate models:

- Localized strain, e.g. elastic loading of locked thrust from far-field



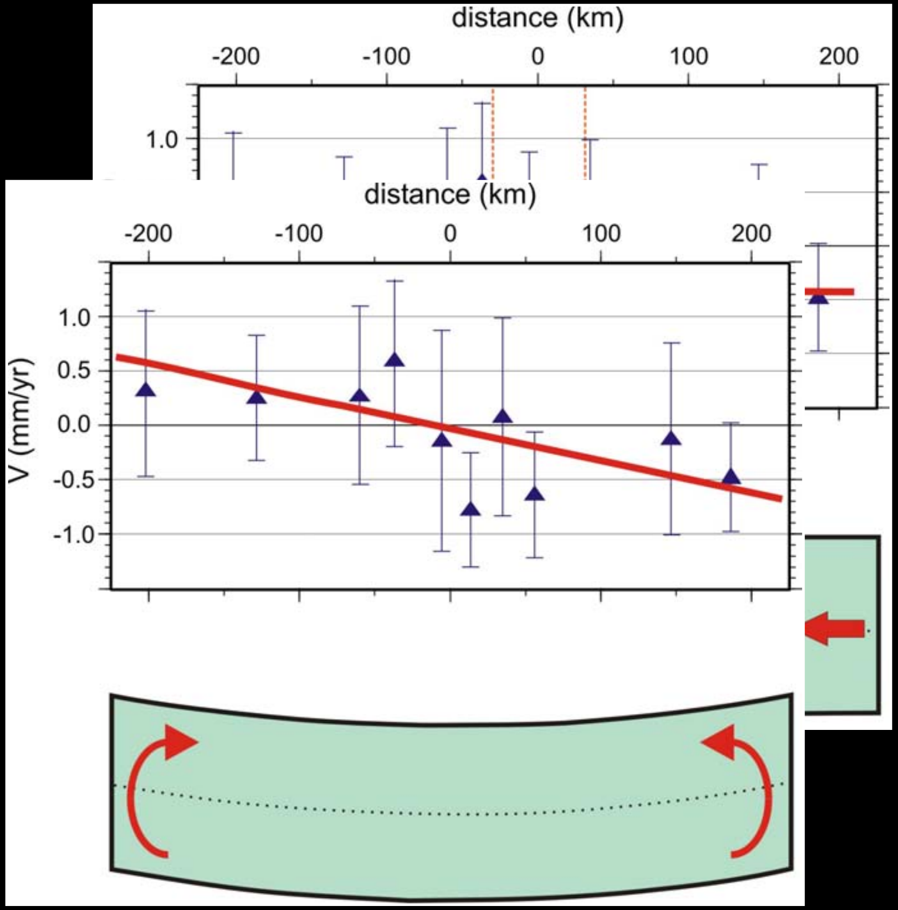
St. Lawrence Seismic Zone Strain Rates

Resolution ~1 mm/yr at 95%

Cannot discriminate models:

- Localized strain, e.g., elastic loading of locked thrust from far-field

- Distributed aseismic strain



St. Lawrence Seismic Zone Strain Rates

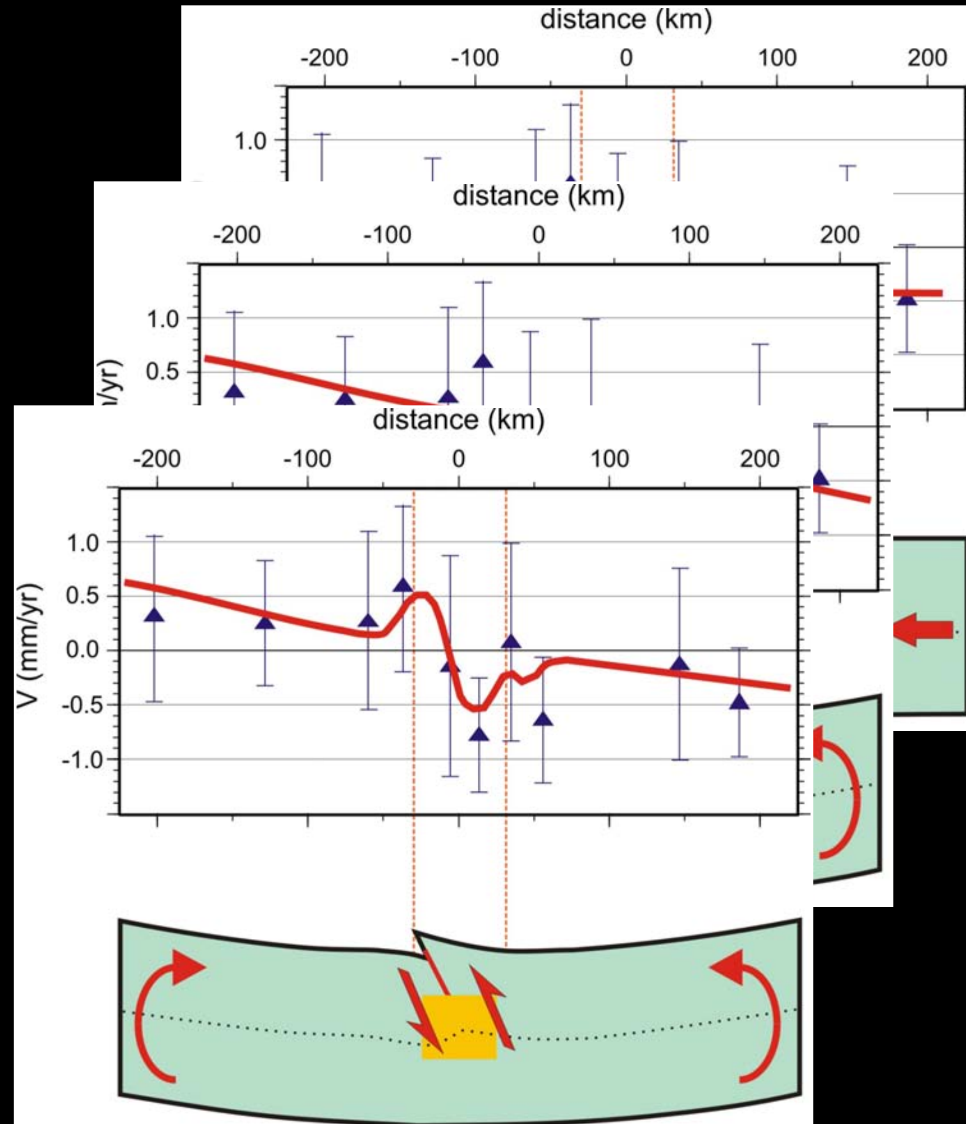
Resolution ~1 mm/yr at 95%

Cannot discriminate models:

- Localized strain, e.g. elastic loading of locked thrust from far-field

- Distributed aseismic strain

- Localized strain, e.g. elastic loading of locked thrust from large-scale bending



St. Lawrence Seismic Zone Strain Rates

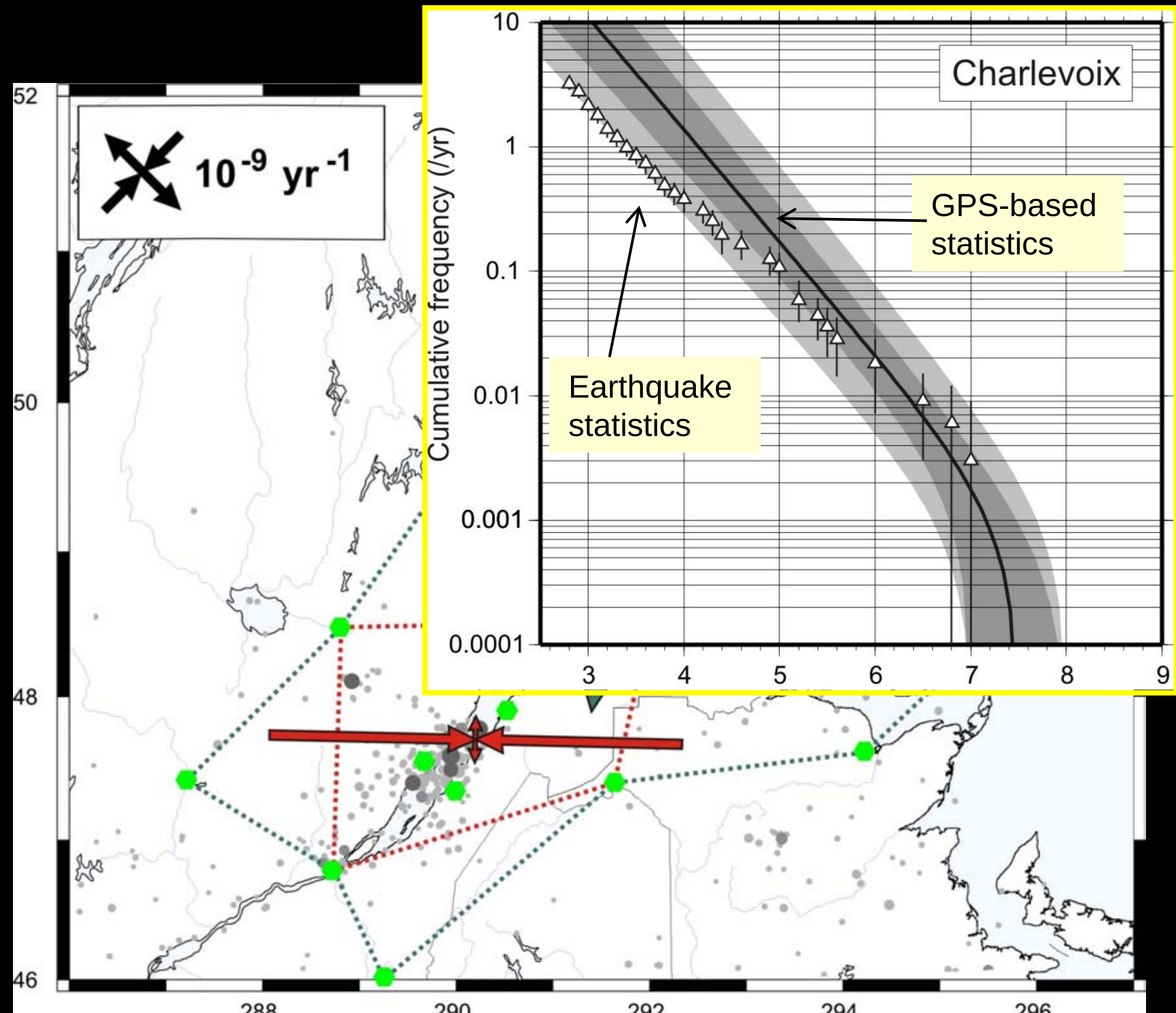
Charlevoix GPS vs. seismicity rates

$3.8 \pm 2.3 \times 10^{-9}\ yr^{-1}$

0.7 ± 0.4 mm/yr

>> GPS-based and catalog statistics agree for M ≥ 6

>> Potential integration of GPS data in seismic hazard



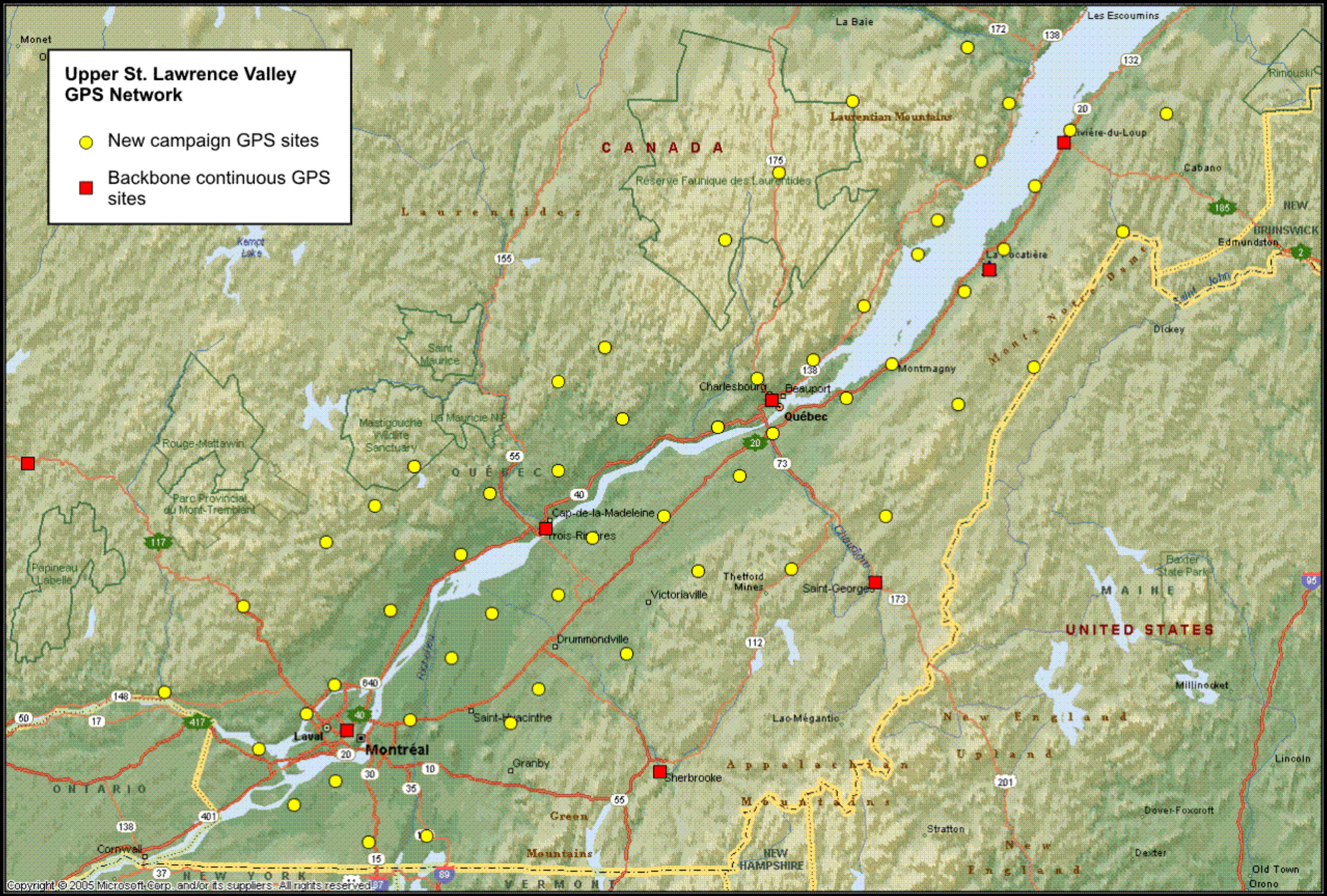
Mazzotti et al., JRG 2005

St. Lawrence Seismic Zone Strain Rates

Denser permanent & campaign GPS network from Charlevoix to Montreal

- 9 perm. sites

- 55 camp. sites



St. Lawrence Seismic Zone Strain Rates

55 camp. Sites

* 35 bedrock – chained mast

* 6 bedrock / concrete – tripod

* 14 soil – tripod

2-3 surveys so far

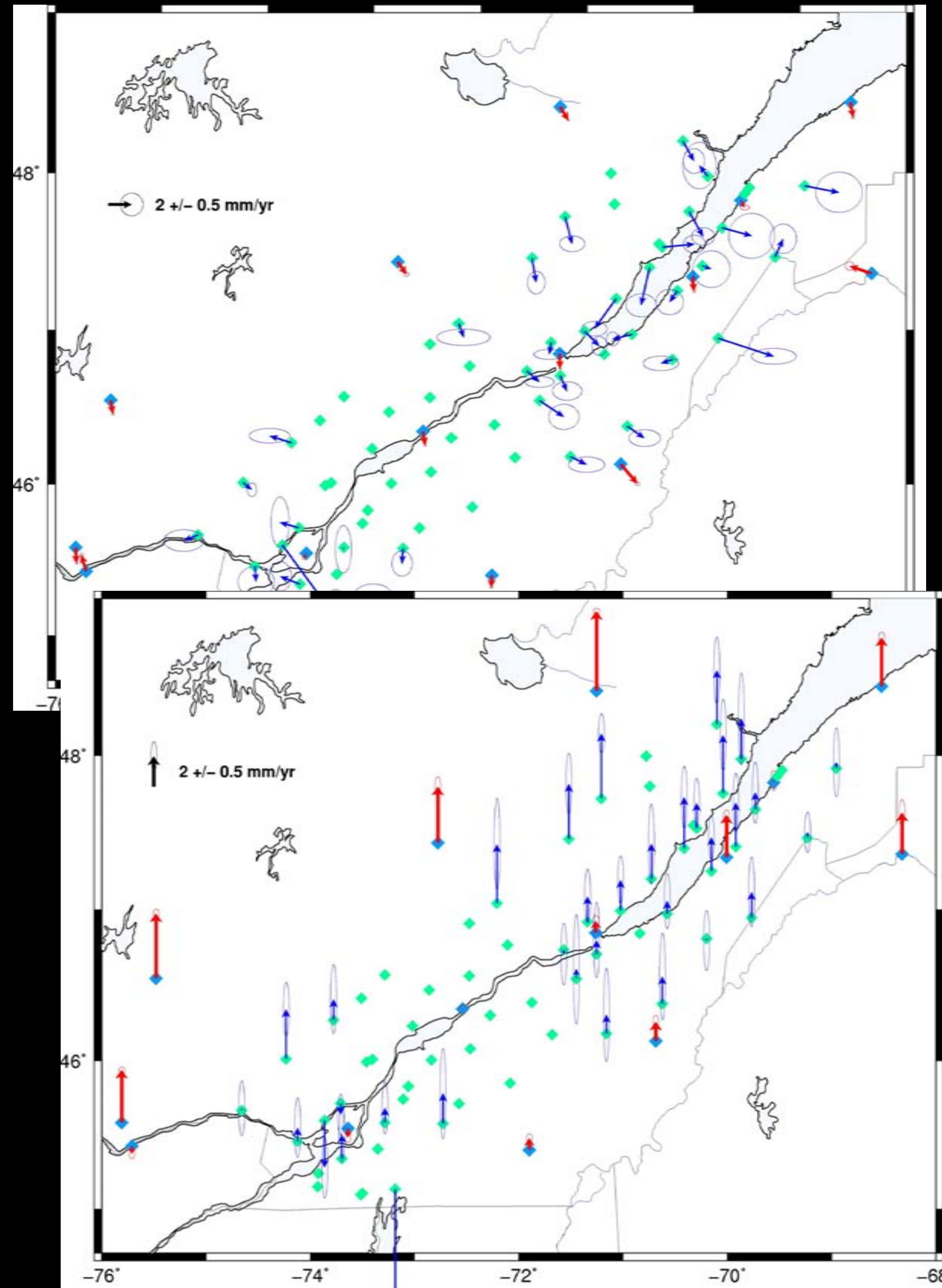
St. Lawrence Seismic Zone Strain Rates

PPP solution

Velocities coherent with regional continuous stations at ~1.0 mm/yr level

Both in Hz and Vt

Not bad for 3 surveys over 4 years!



St. Lawrence Seismic Zone Strain Rates

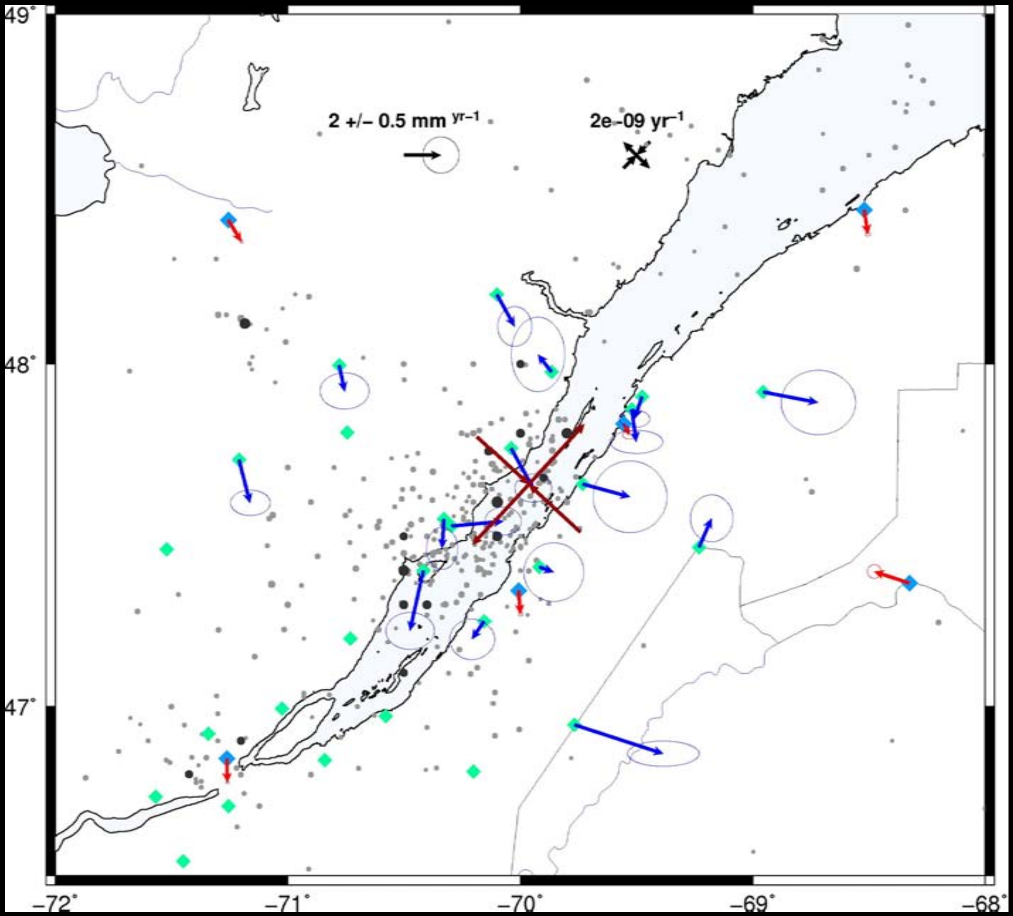
Charlevoix sub-network

NW-SE shortening rate
$7.5 \pm 3.0 \times 10^{-9}$ yr^{-1}
~0.4 ± 0.2 mm/yr

Consistent with previous sparse measurements

Consistent with seismicity

NE-SW extension rate ?



St. Lawrence Seismic Zone Strain Rates

Quebec sub-network

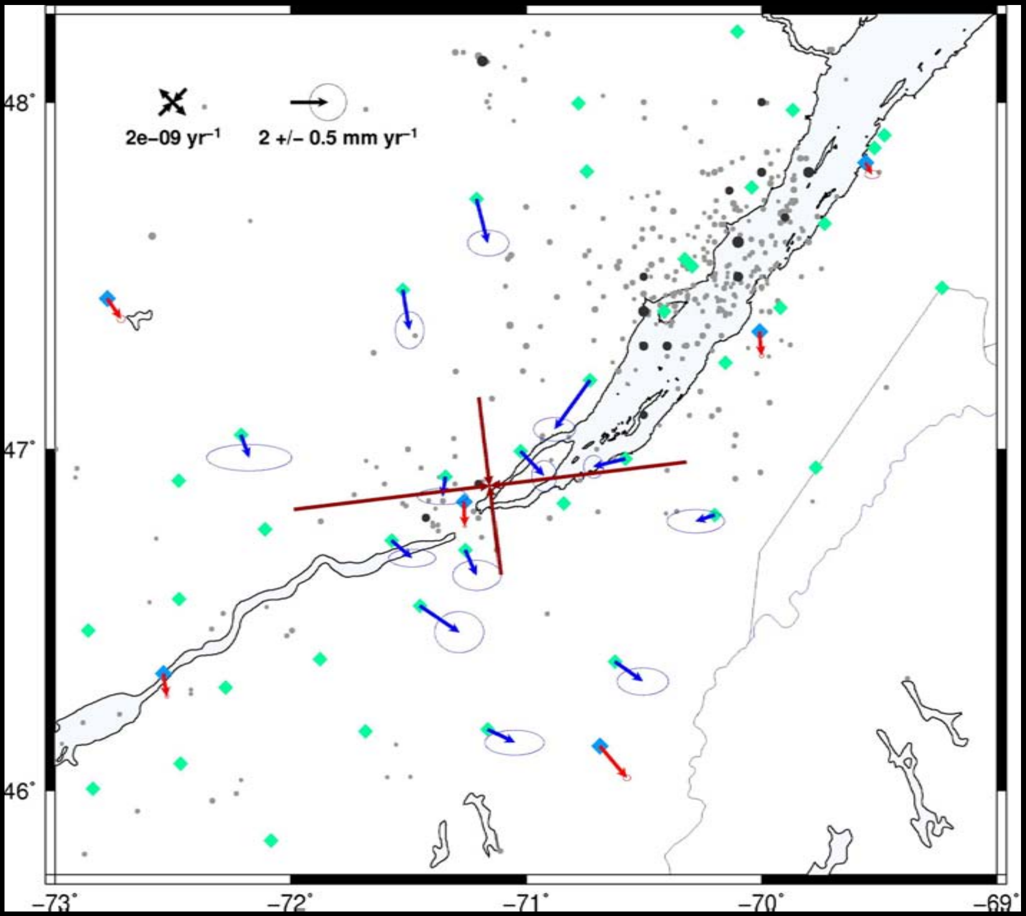
E-W shortening rate

$20.1 \pm 4.8 \times 10^{-9}\ yr^{-1}$

$\sim 1.0 \pm 0.3$ mm/yr

Artifact of short measurement period?

Not consistent with seismicity !



TO BE CONTINUED

Continental Intraplate Strain Rates

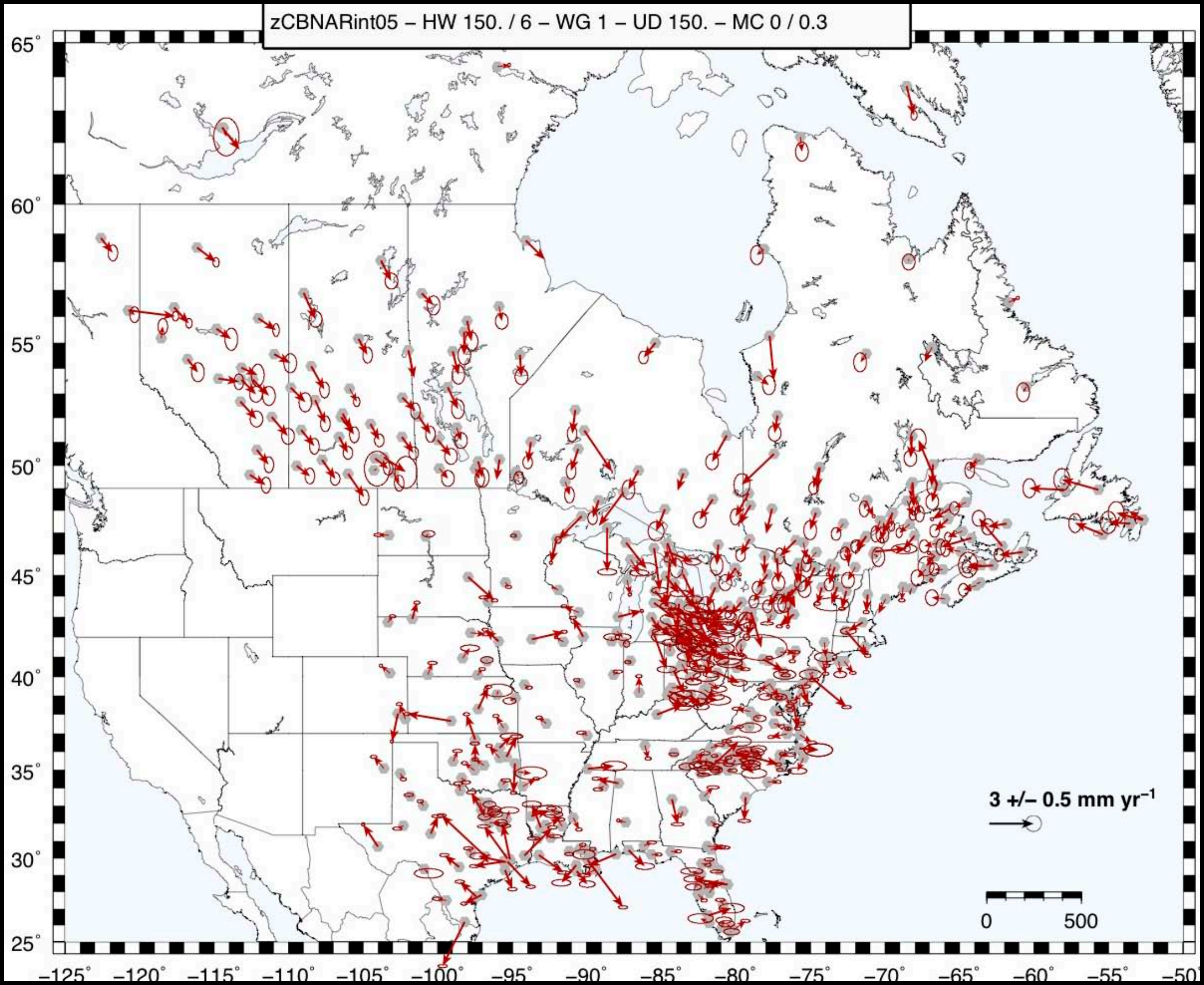
NAREF 2005 solution

477 GPS velocities

- Perm. geodetic RF stations

- Perm. 2nd-order stations

- Camp. CBN network



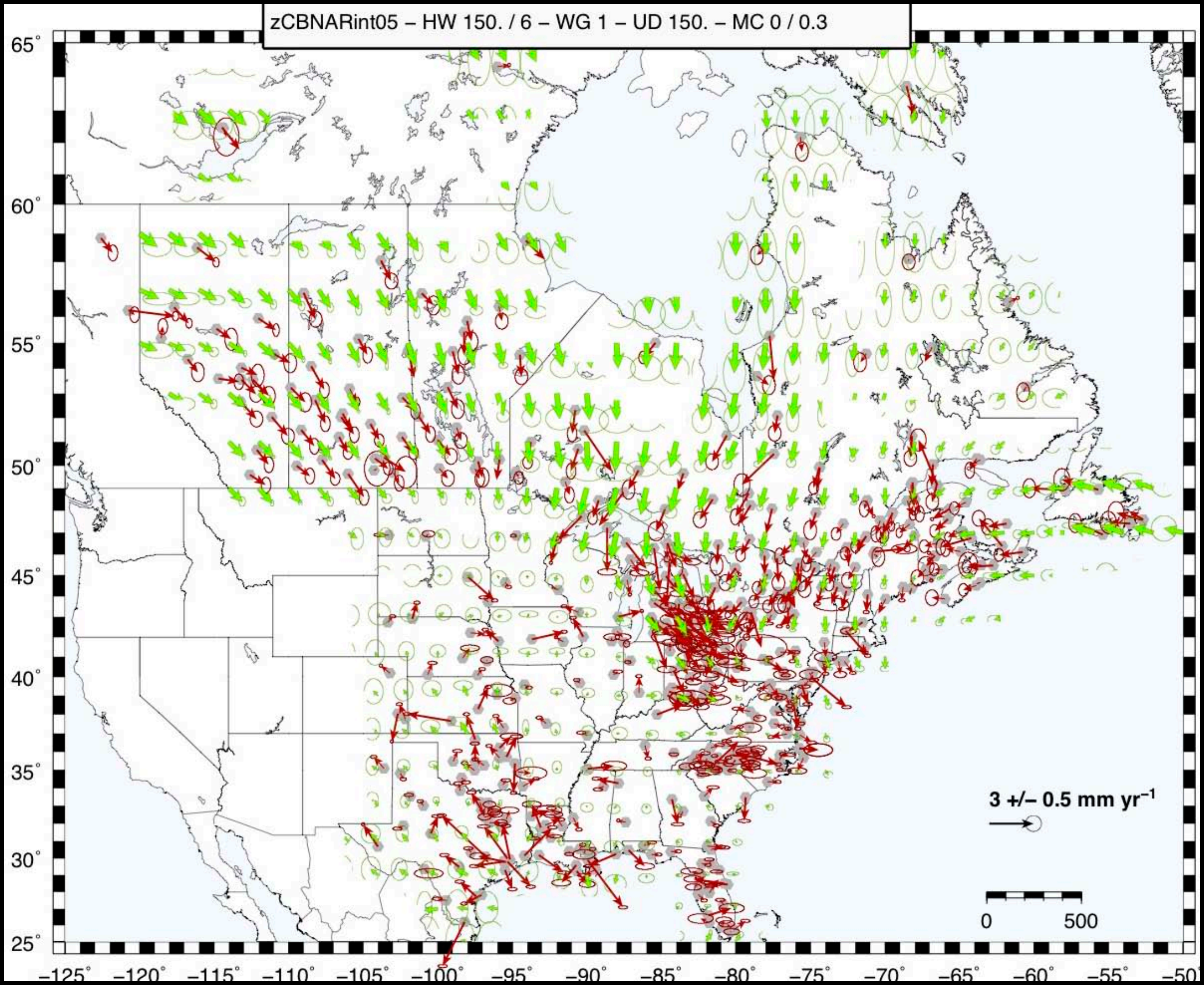
Continental Intraplate Strain Rates

Step 1

Smoothed interpolated velocity field

(adaptive gaussian filter)

Efficient at extracting long-wavelength signals



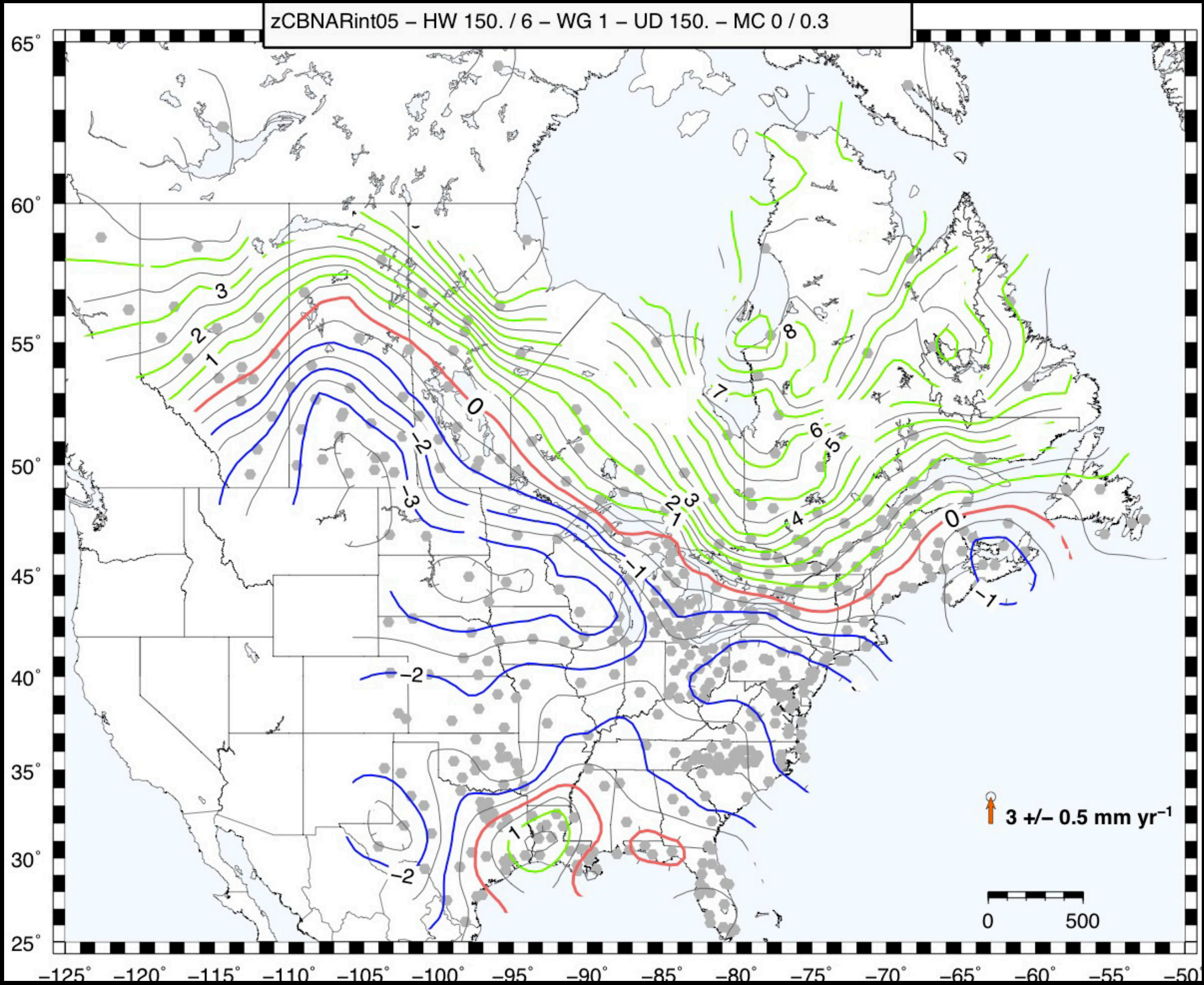
Continental Intraplate Strain Rates

Step 1

Smoothed interpolated velocity field

Vertical velocity field shows clear postglacial rebound features

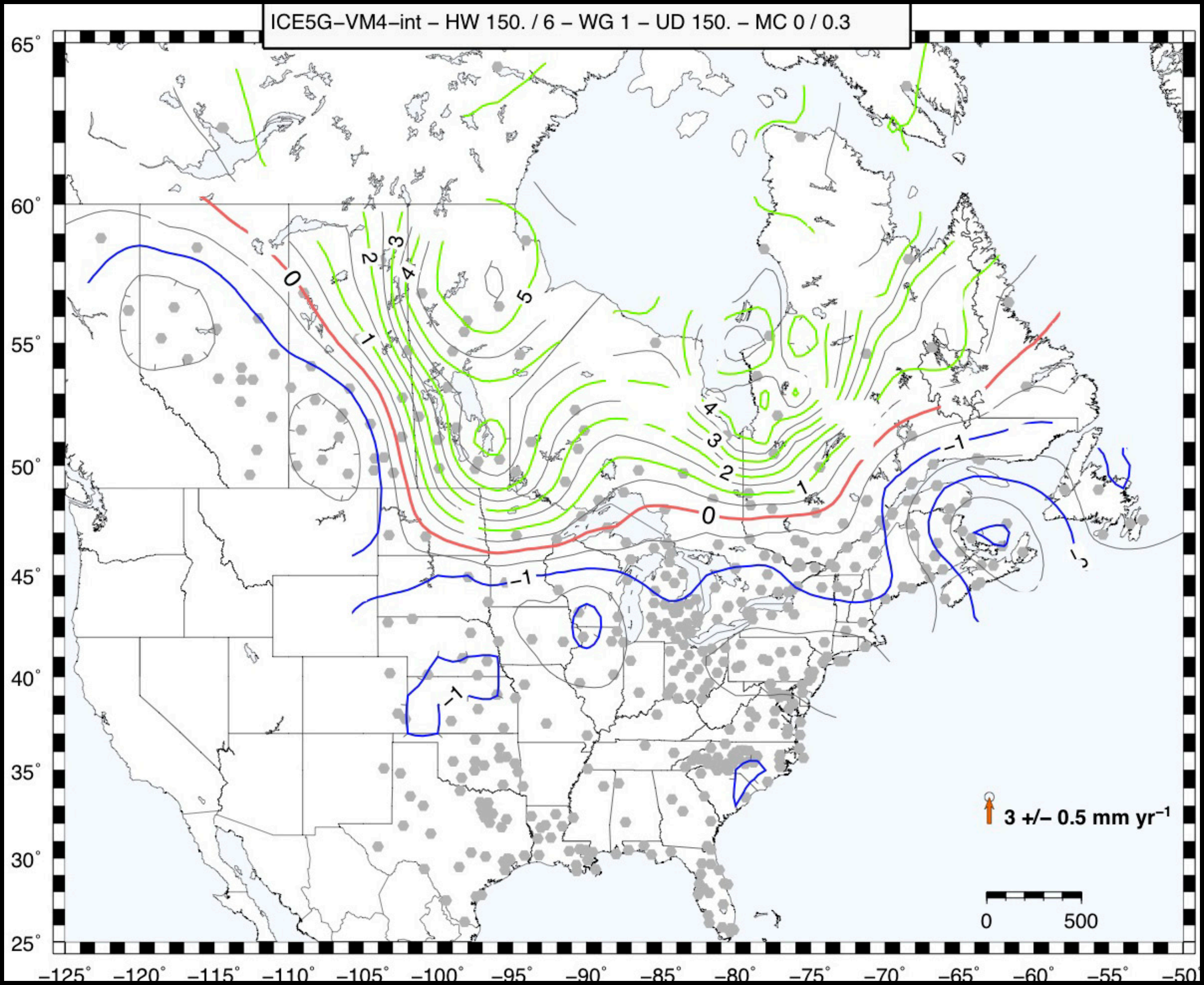
+ other local signals



Continental Intraplate Strain Rates

Vertical velocity field from ICE5-G, VM2 model

Still some work to do… especially in northern US



Continental Intraplate Strain Rates

<u>Step 2</u>

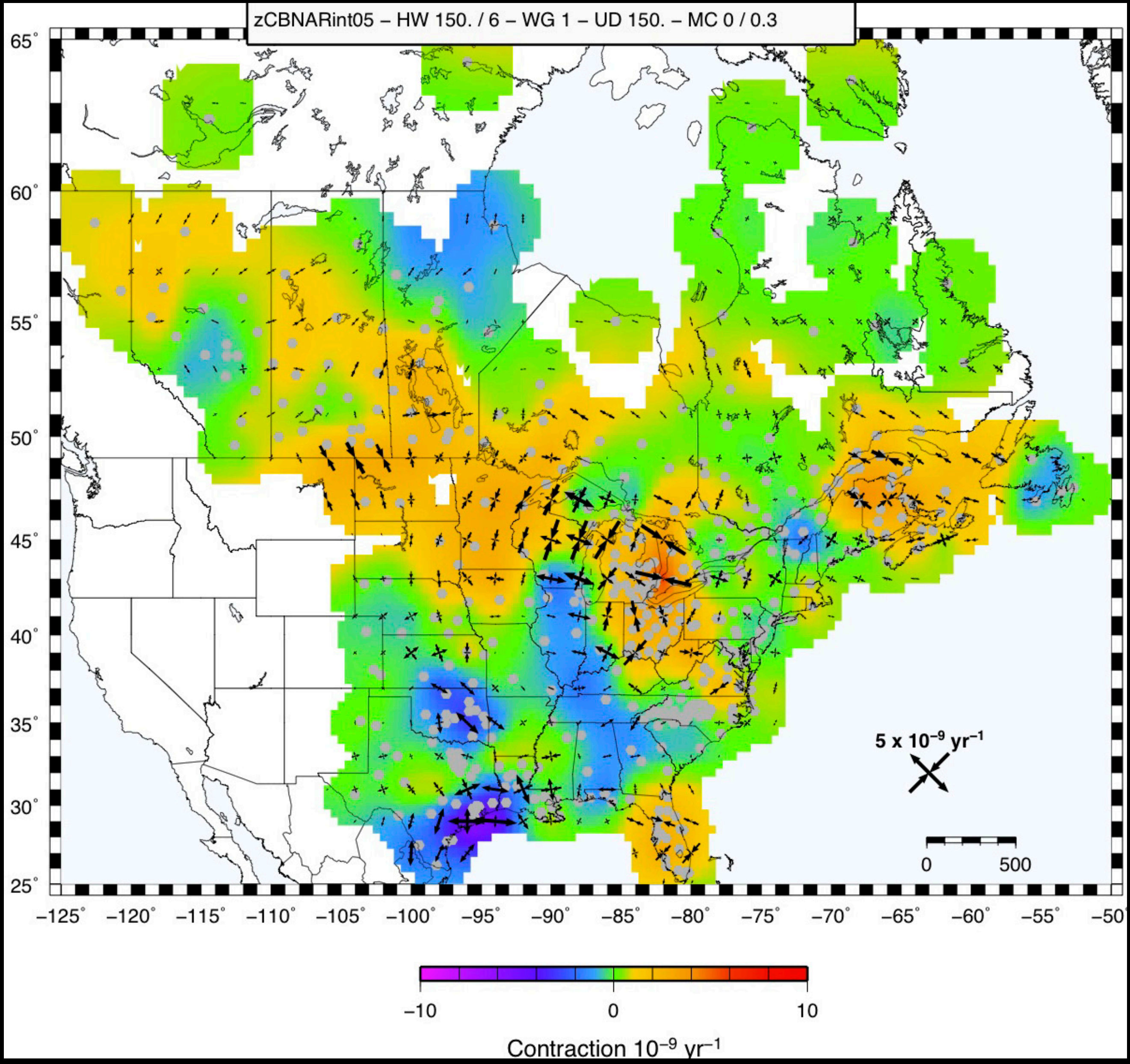
Spatial derivative

>> Full strain rate tensor

- Radial shortening at paleo ice margin

- E-W extension in Midwest

- Local features (e.g. S Texas)

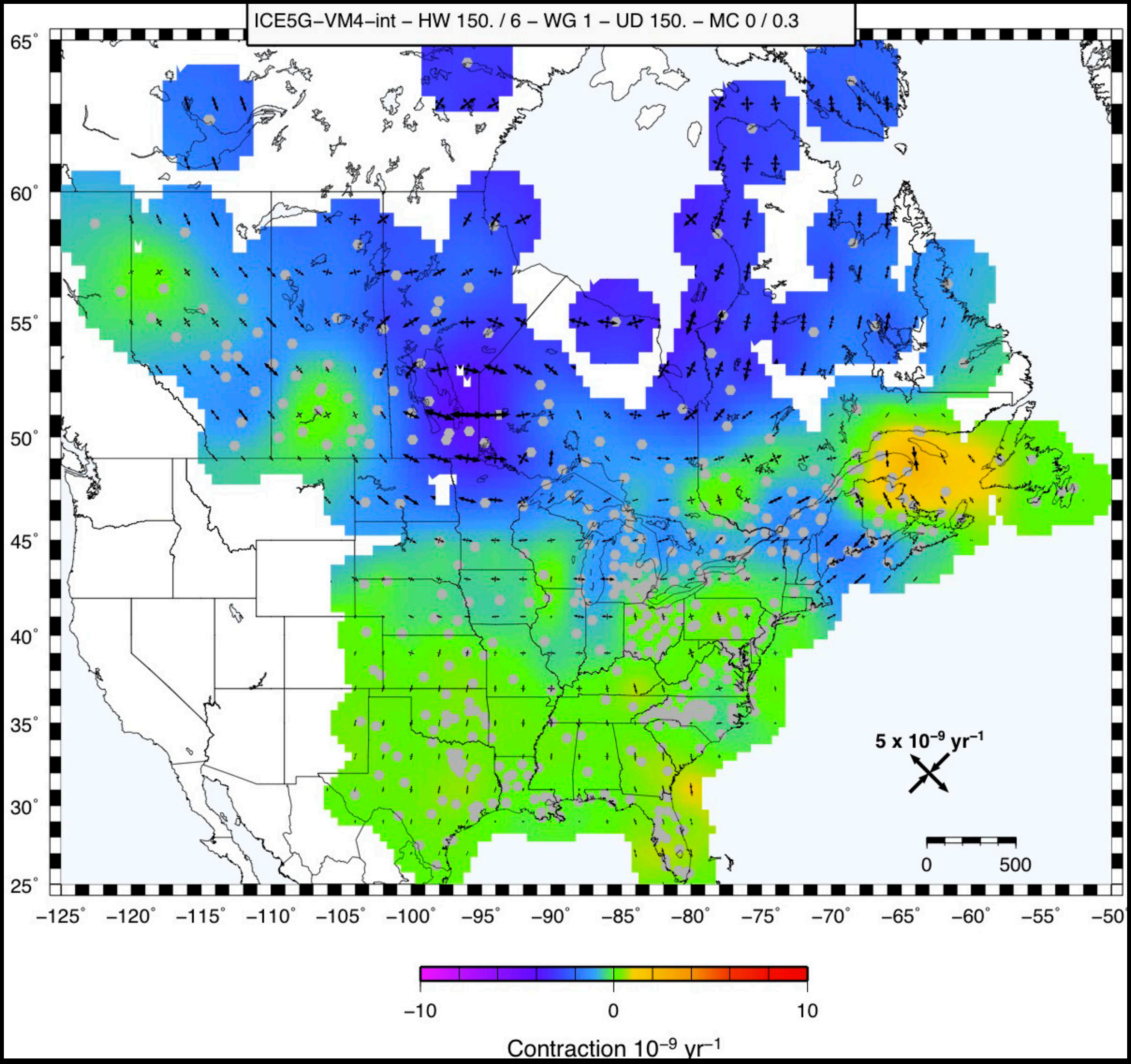


Continental Intraplate Strain Rates

Strain rate field from ICE5-G, VM2 model

Poor match in central Canada and US

Fair agreement in Maritimes – NE US



Continental Intraplate Strain Rates

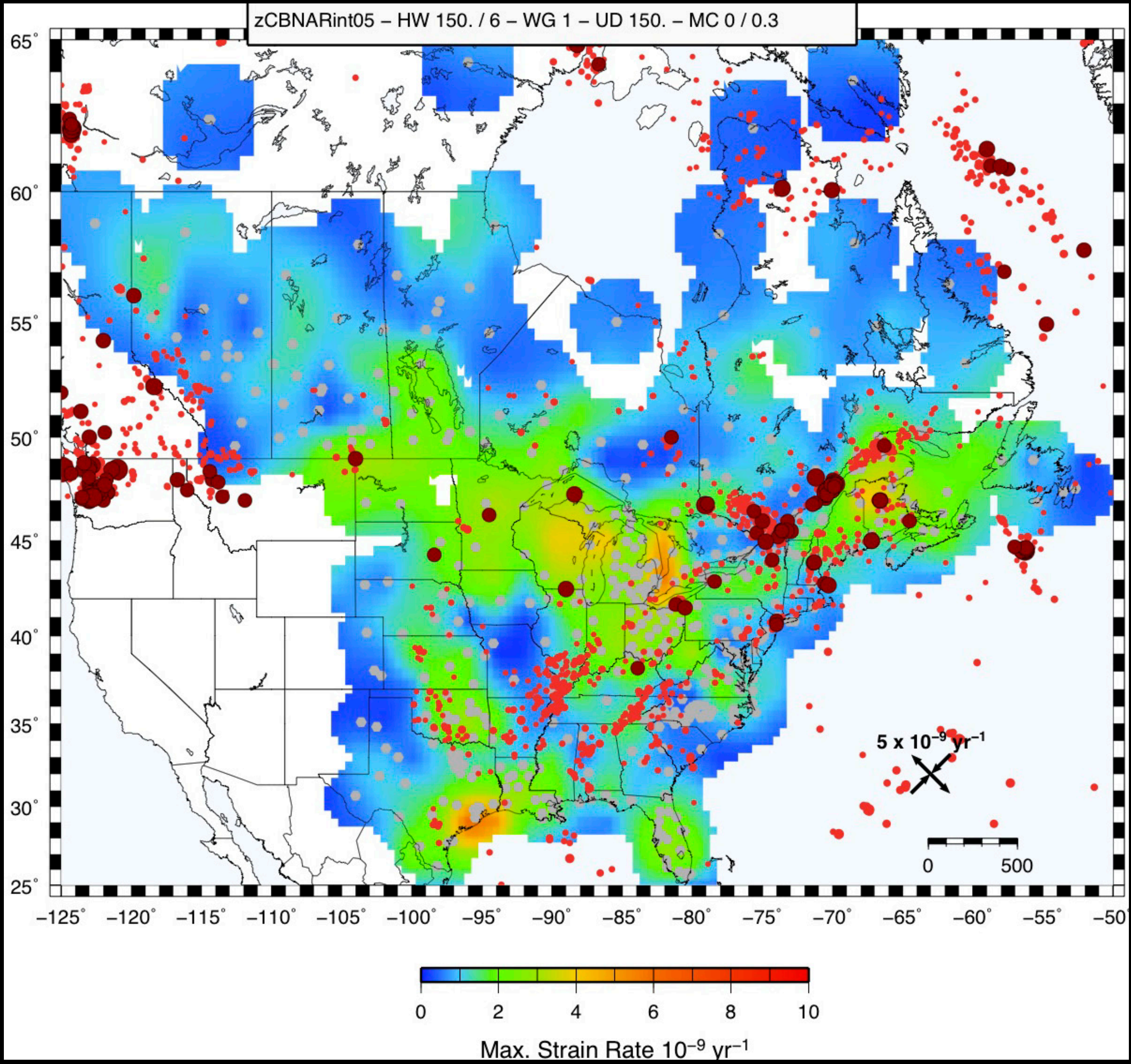
Step 2

Spatial derivative

>> Full strain rate tensor

Max. strain rate
= max (e1, e2, e1+e2)

Little to no correlation with seismicity



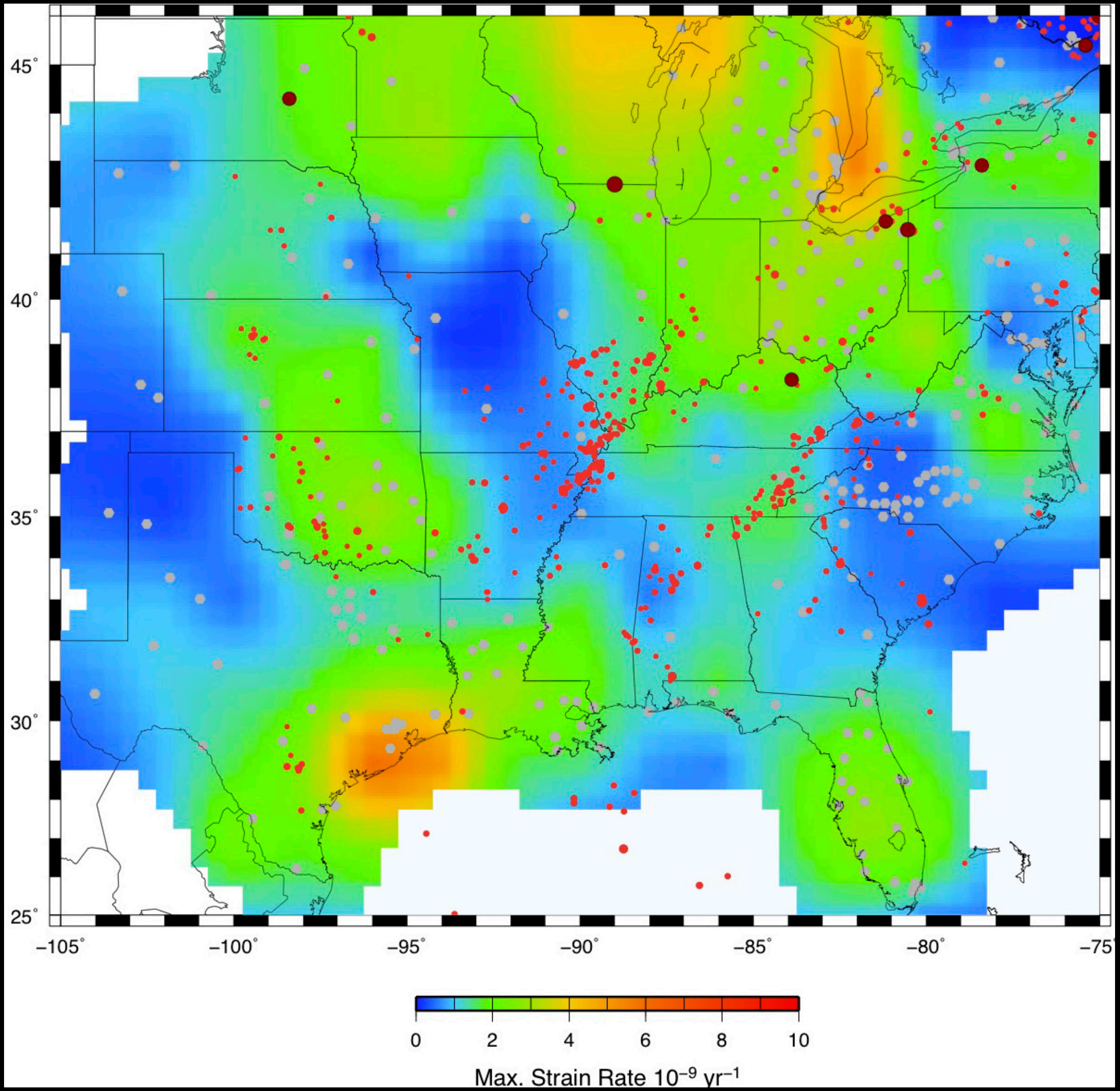
US Intraplate Strain Rates

Low Emax in New Madrid, Eastern Tennessee, Charleston

But:

- Method tuned for long-wavelength signals (> 100 km)

- Poor local site coverage



Continental Intraplate Strain Rates / Stress

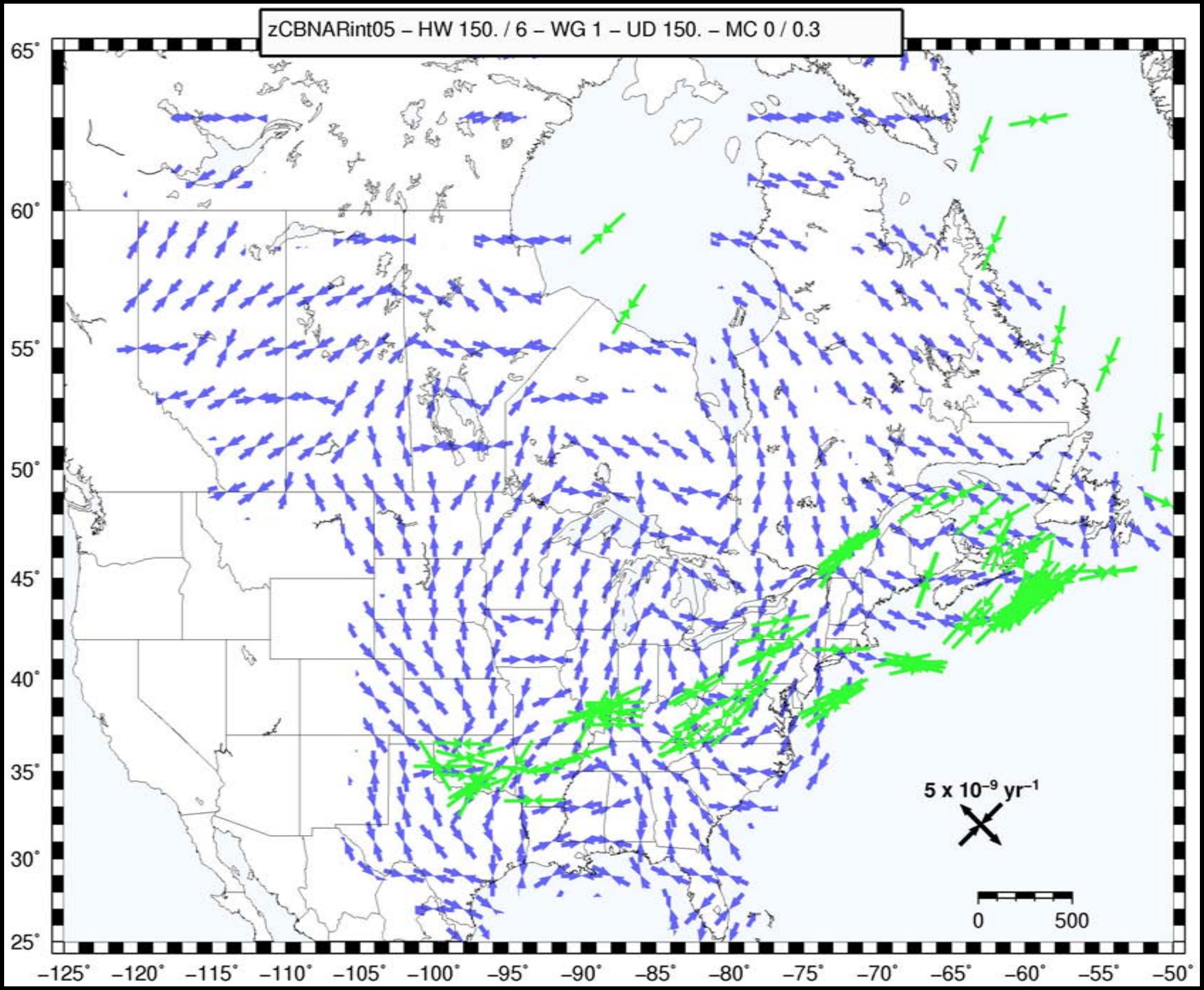
GPS max horiz. shortening (blue)

>> mainly radial to paleo icesheet

vs.

Borehole max. horiz. compression (green)

>> mainly E-W to NE-SW



US Intraplate Strain Rates / Stress

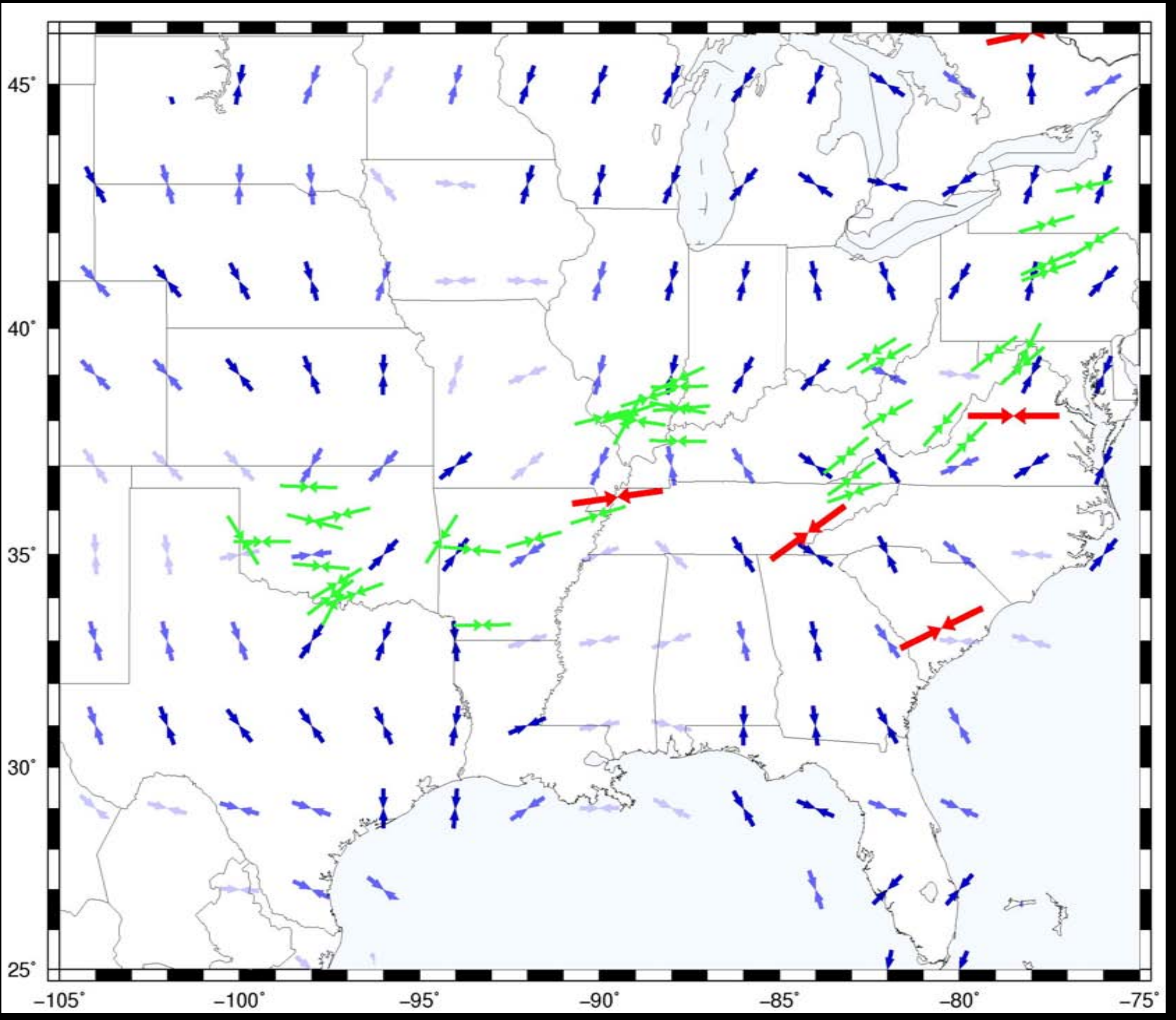
GPS max horiz. shortening (blue)

vs.

Borehole max. horiz. compression (green)

>> Present-day strain rate mostly elastic

>> Link to seismicity?



Conclusions (1) Etat de contrainte en domaine continental stable

* S_H en zones sismiques colinéaire ou tourné de 30 – 50 ° (horaire) relatif au S_H régional

* Rotation de contrainte a lieu sur de faible distances (20 – 50 km), mais cohérente à grande échelle (+1000 km)

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>> Mécanismes de perturbation des contraintes en zones sismiques ?

- GIA, héritage structural

- Requière une résistance (friction) faible ?

Conclusions (2) Taux de déformations

* Bon accord des taux de déformation GPS et sismique dans les zones les plus actives (Charlevoix et Bas St. Laurent)

* Pas de corrélation générale
entre taux de déformation GPS
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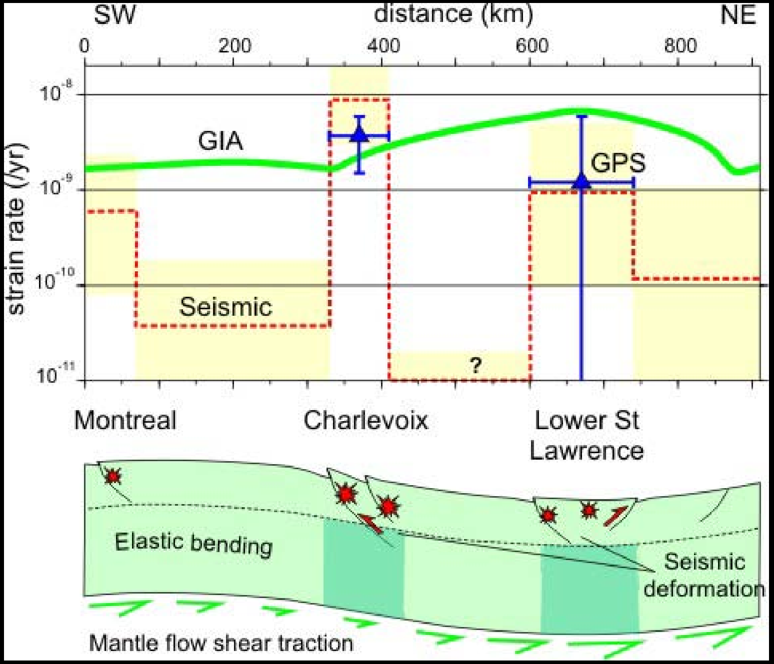

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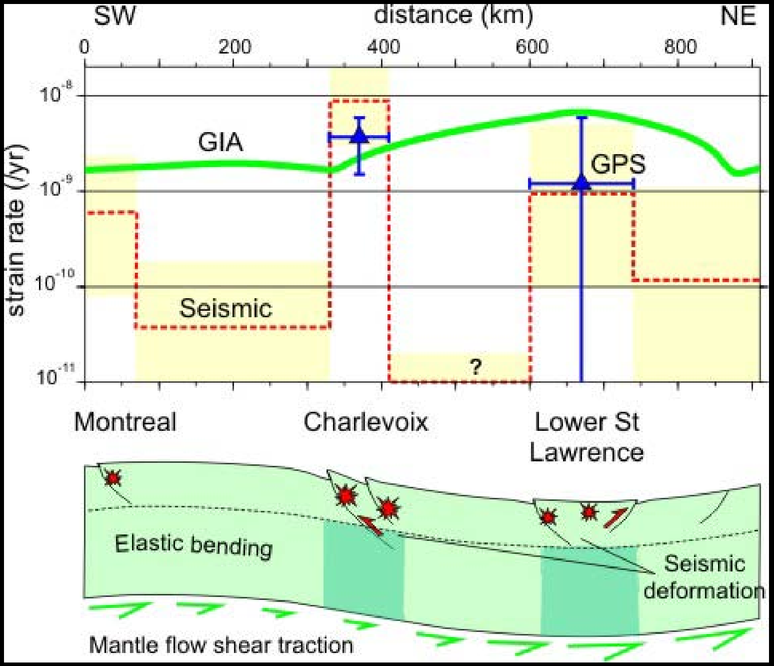

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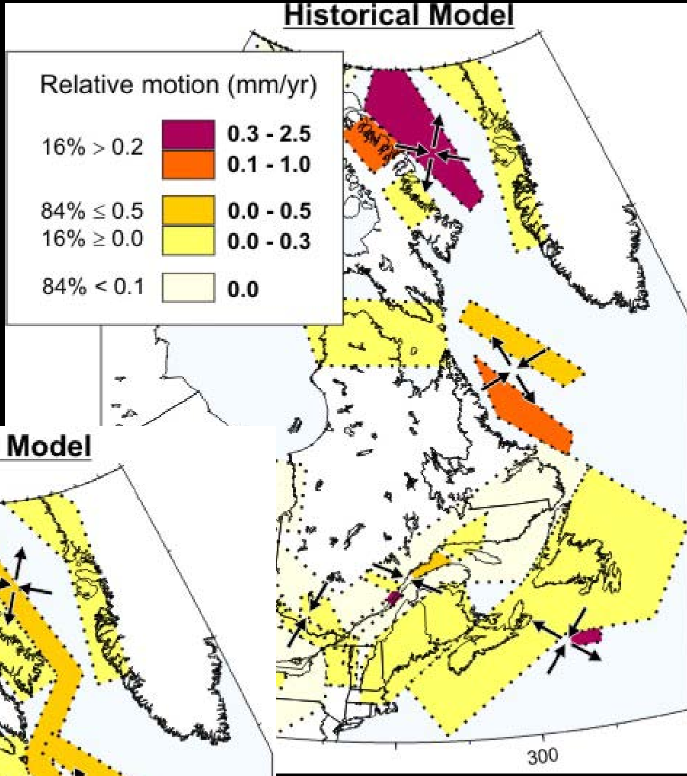
?? Modèle physique pour expliquer les concentrations et taux de déformation et sismicité ??

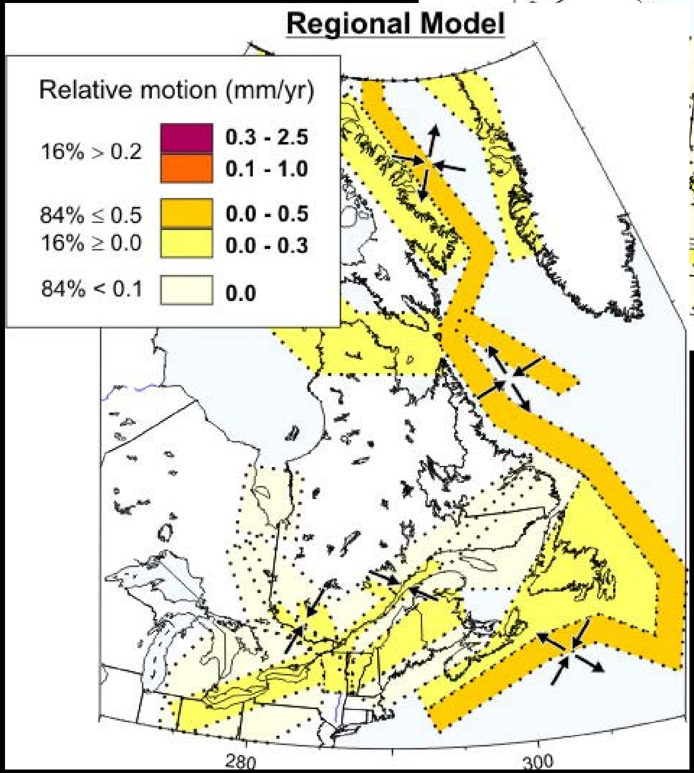
1) Seismicity & Seismic Source Zones

<u>Seismic moment and deformation rates</u>
based on earthquake statistics in
historical vs. geological source zones

Historical source zones:
- very heterogeneous
- few high strain zones
- 0.0 – 2.5 mm/yr

Geological source zones:
- homogeneous
- no high strain zone
- 0.0 – 0.5 mm/yr





Mazzotti & Adams, JRG 2005