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Lasting mantle lithosphere scars lead to perennial plate tectonics

Phil Heron

Geodynamics Group, Department of Earth Sciences

University of Toronto

Russell Pysklywec (*University of Toronto*)

Randell Stephenson (*University of Aberdeen*)

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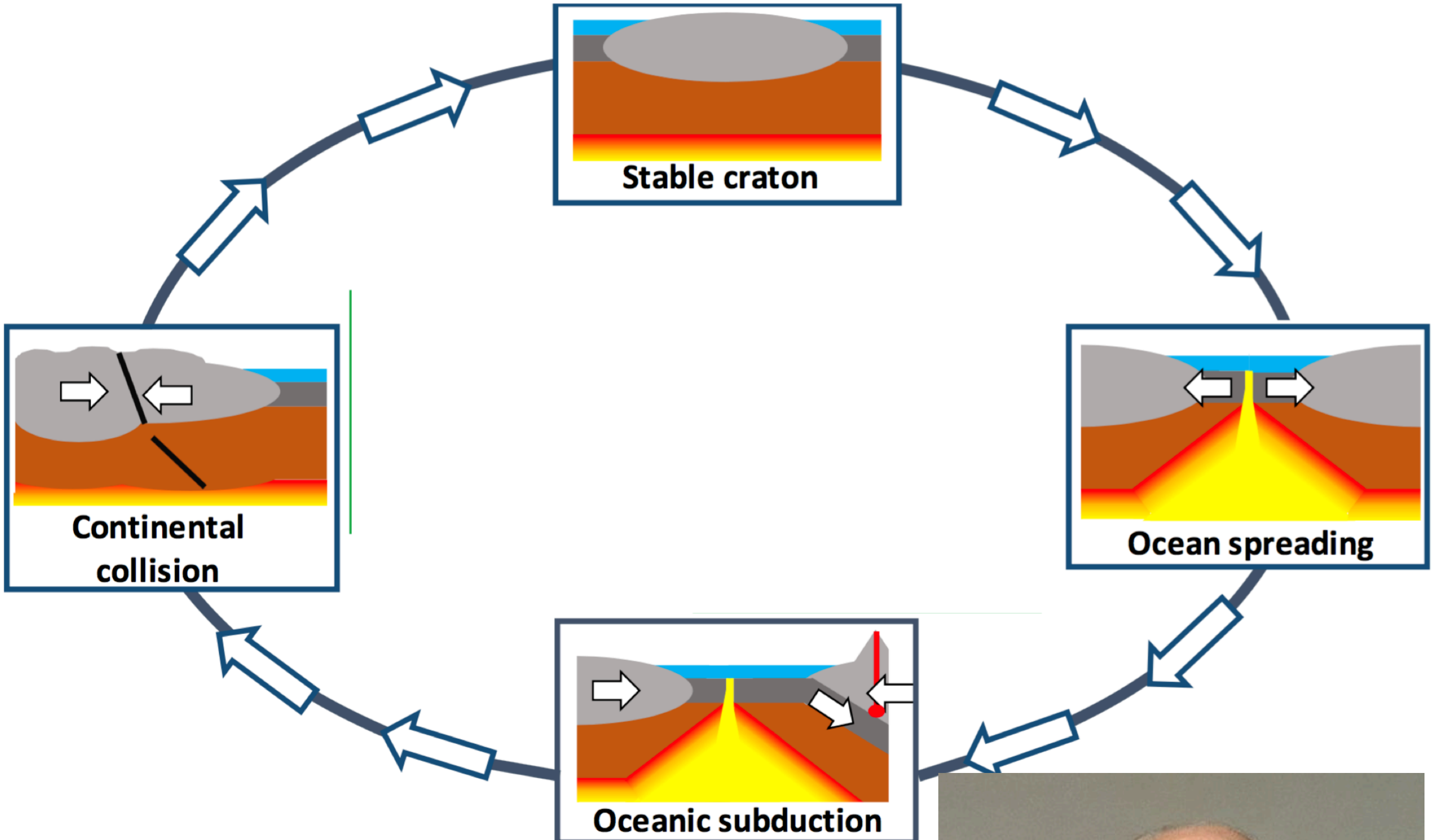
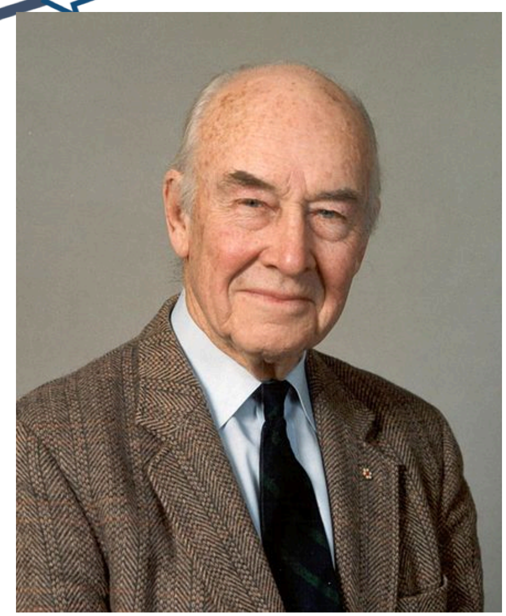
CLASSIC PLATE TECTONICS

PLATE BOUNDARIES

- SUBDUCTION
- MID-OCEAN RIDGE
- CONTINENT COLLISION
- TRANSFORM FAULT





PHIL HERON

CLASSIC PLATE TECTONICS

BEYOND PLATE BOUNDARIES

PLATE BOUNDARIES

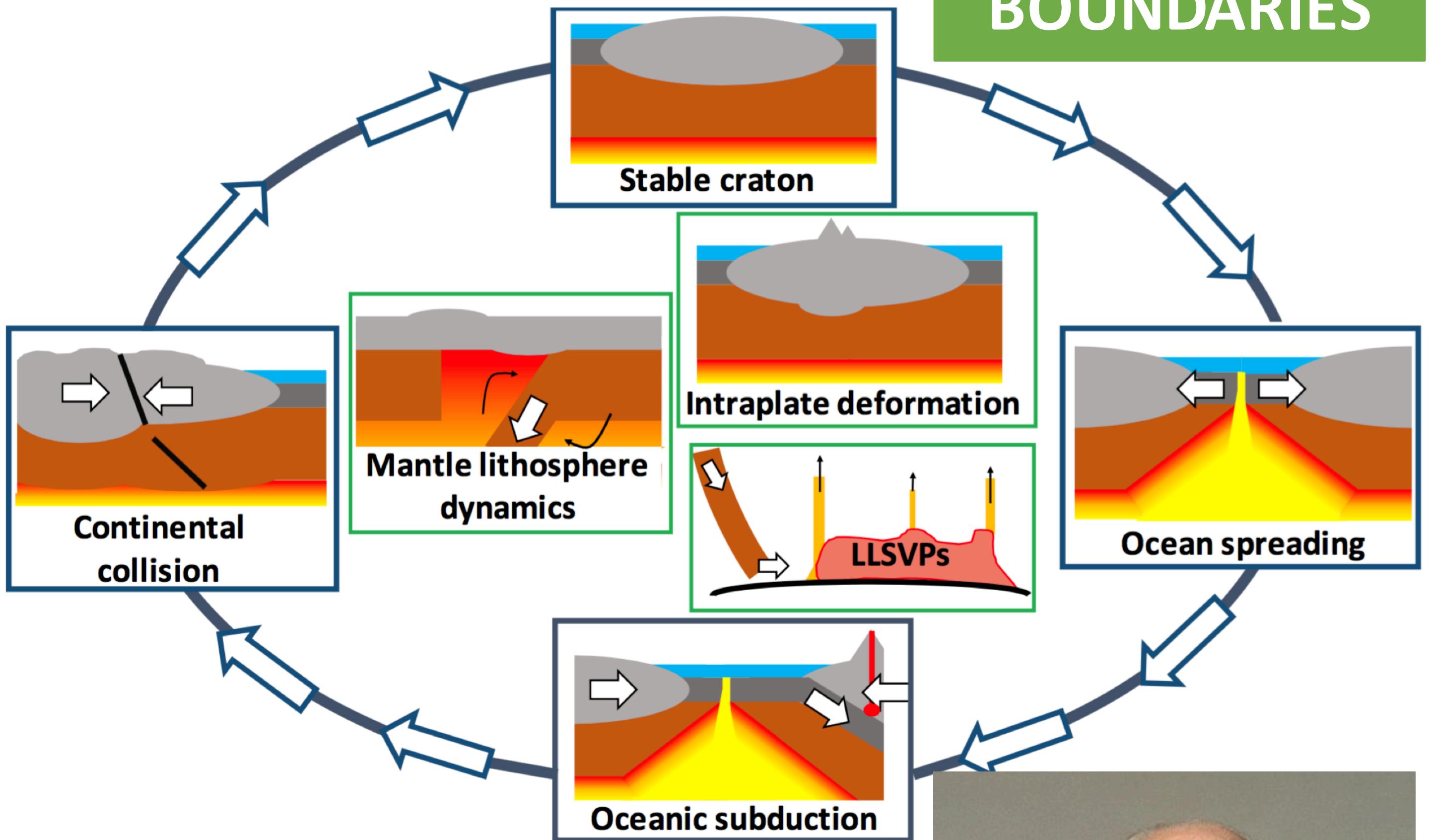
SUBDUCTION

MID-OCEAN RIDGE

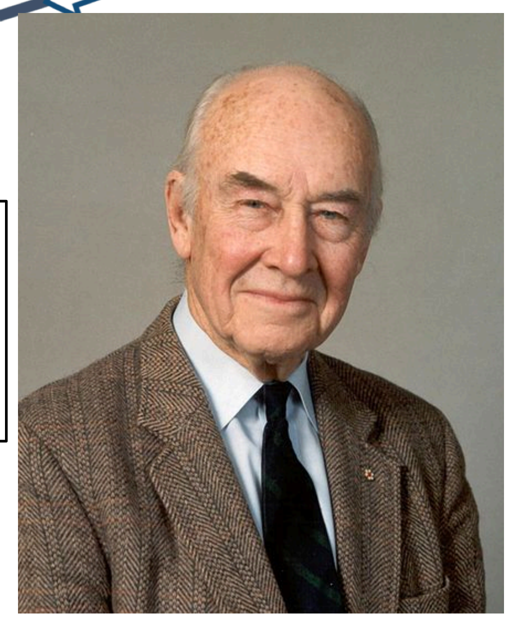
CONTINENT COLLISION

TRANSFORM FAULT

INTRAPLATE DEFORMATION



What processes could be involved in intraplate orogenesis, seismisicty, and/or deformation?



BEYOND PLATE BOUNDARIES → **INTRAPLATE DEFORMATION** → **CRUSTAL INHERITANCE**

What processes could be involved in intraplate orogenesis, seismisicty, and/or deformation?

BEYOND PLATE BOUNDARIES → INTRAPLATE DEFORMATION → CRUSTAL INHERITANCE

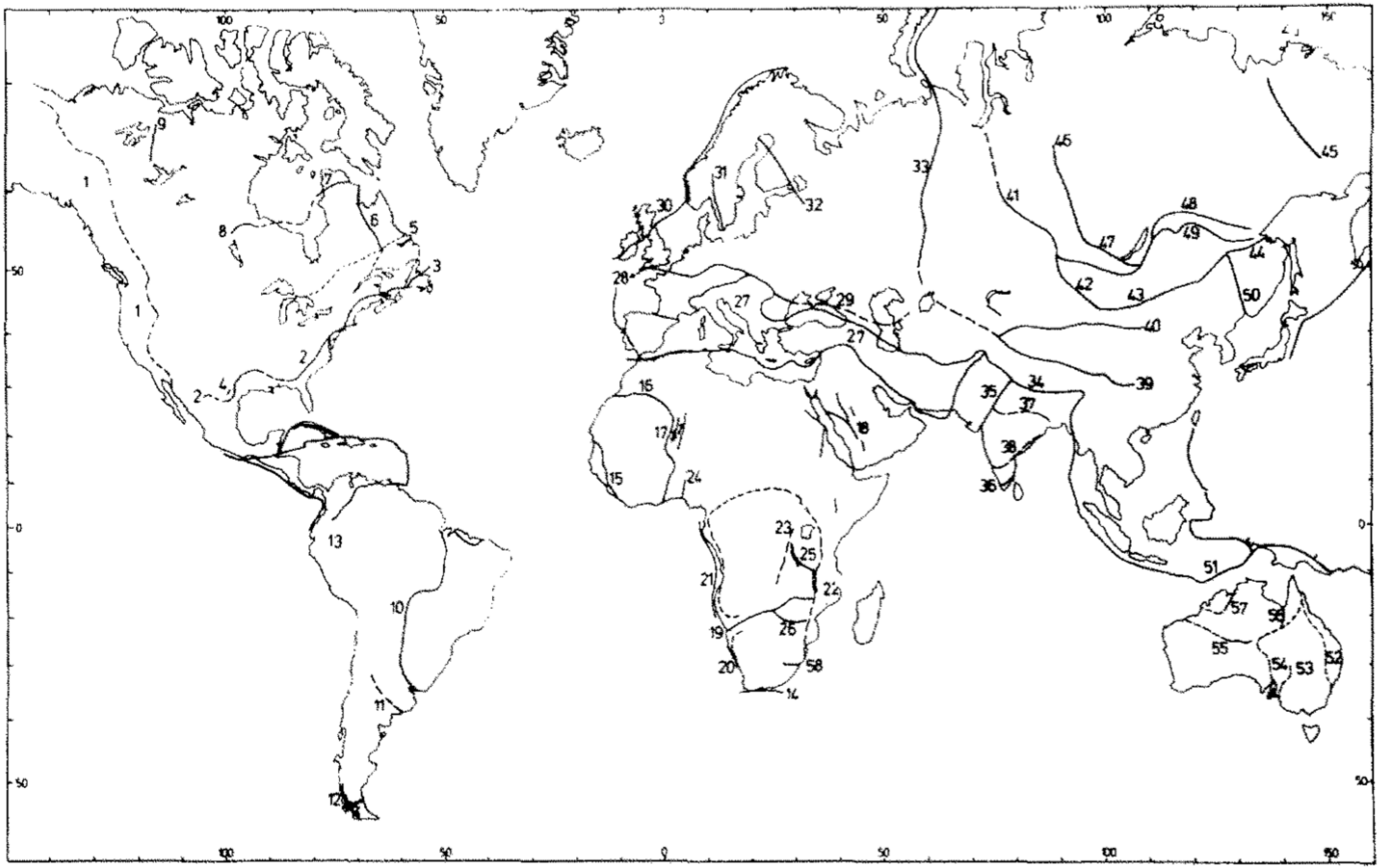


Fig. 1. World map showing distribution of major Phanerozoic and Proterozoic suture zones.

[Burke, Dewey and Kidd, Tectonophysics, 1977]

BEYOND PLATE BOUNDARIES → INTRAPLATE DEFORMATION → CRUSTAL INHERITANCE

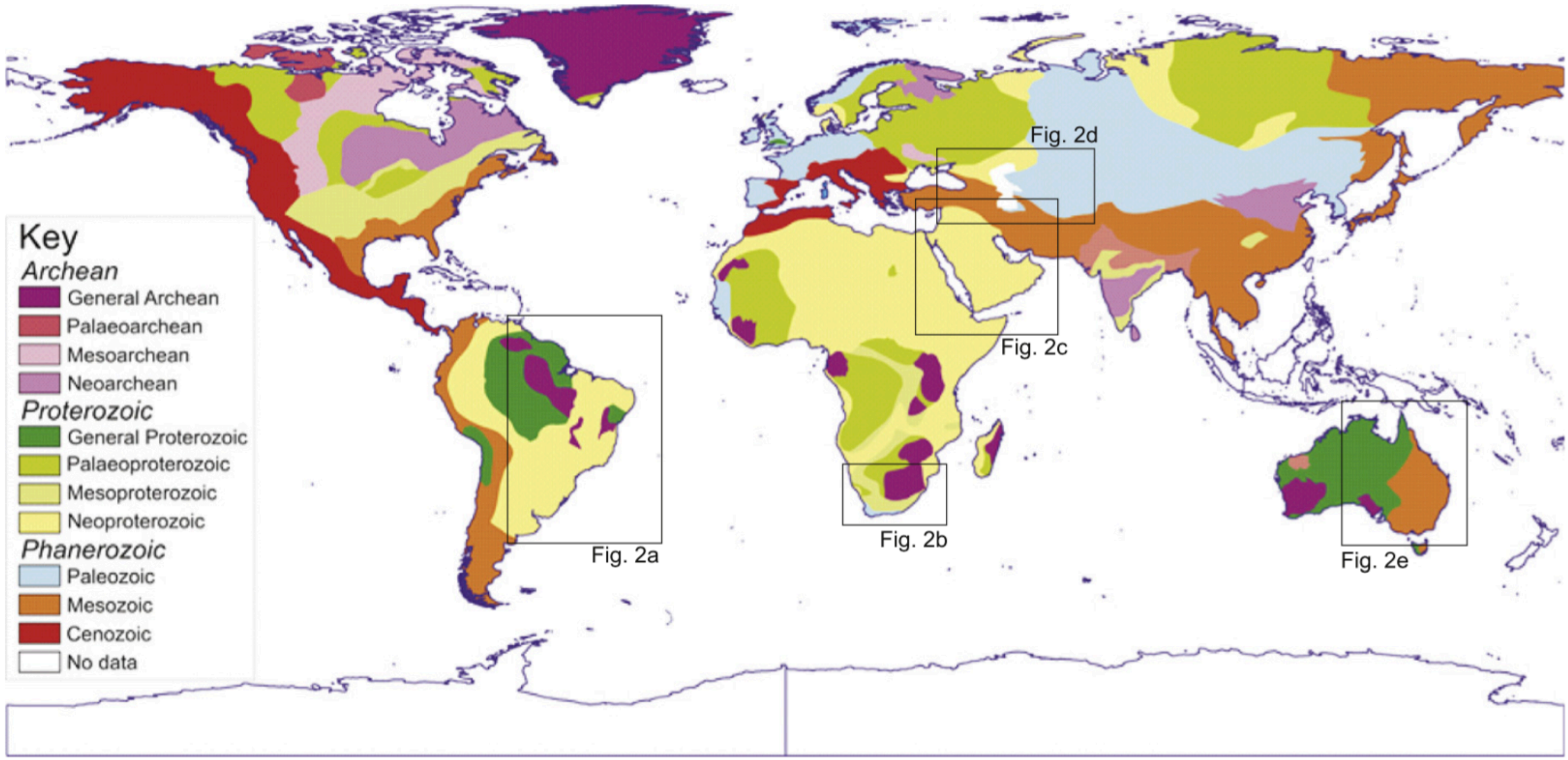
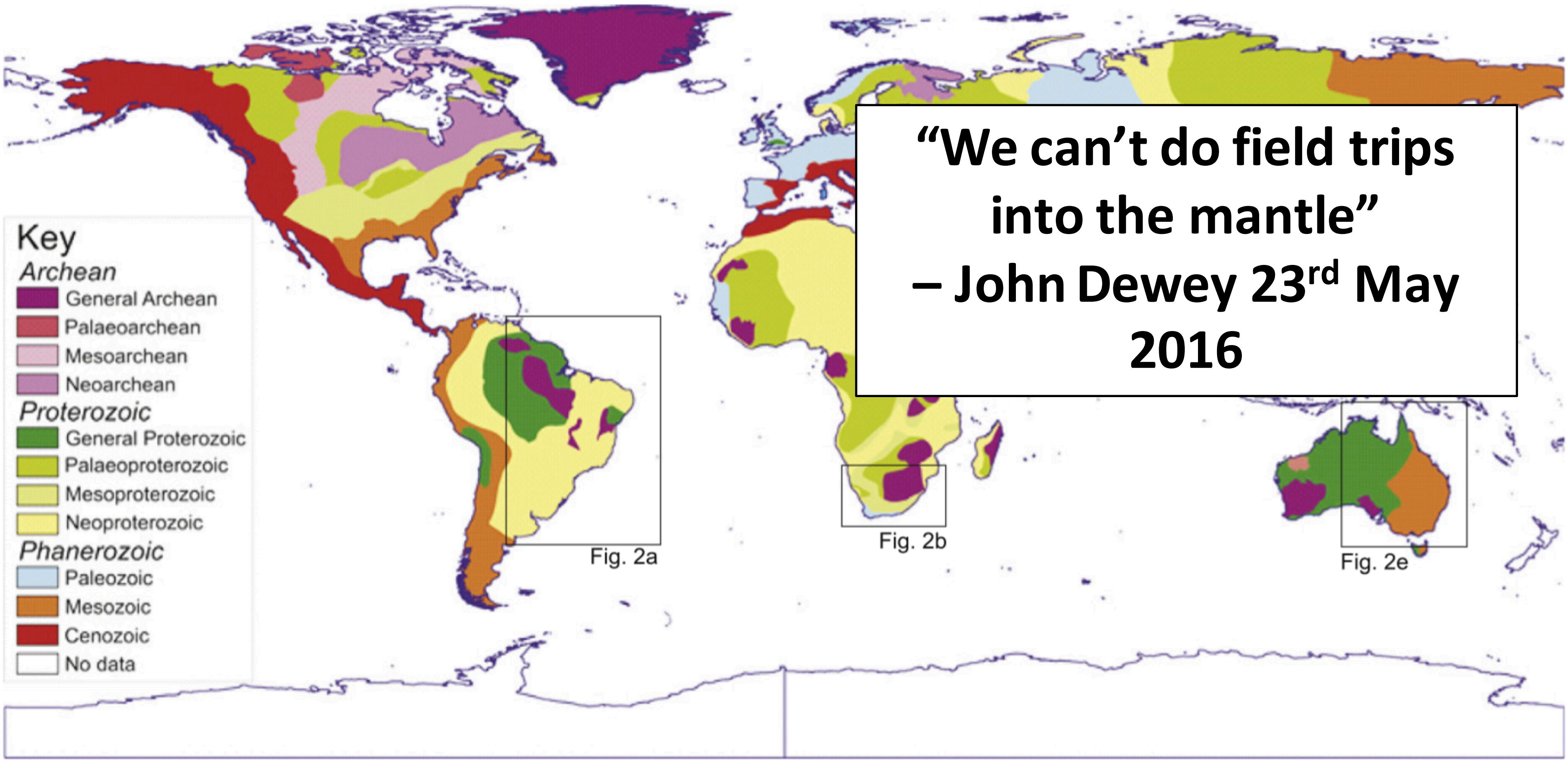


Fig. 1. Age of assembly of continental crust. This is not necessarily the age of the units within each area, but the age at which that region of crust was assembled as a unit. This is a compilation of data from numerous publications covering South America (Almeida et al., 2000; Milani and De Wit, 2008), North America (Canil, 2008; Williams et al., 1991), Europe (Gee and Stephenson, 2006), Africa and Arabia (Begg et al., 2009; Van Hinsbergen et al., 2011), Asia (Şengör and Natal'in, 1996) and Australia (Debayle and Kennett, 2003).

[Holt et al., Tectonophysics, 2015]

BEYOND PLATE BOUNDARIES → **INTRAPLATE DEFORMATION** → **CRUSTAL INHERITANCE**

P.J. Holt et al. / Tectonophysics 639 (2015) 132–143 133



"We can't do field trips into the mantle" – John Dewey 23rd May 2016

Fig. 1. Age of assembly of continental crust. This is not necessarily the age of the units within each area, but the age at which that region of crust was assembled as a unit. This is a compilation of data from numerous publications covering South America (Almeida et al., 2000; Milani and De Wit, 2008), North America (Canil, 2008; Williams et al., 1991), Europe (Gee and Stephenson, 2006), Africa and Arabia (Begg et al., 2009; Van Hinsbergen et al., 2011), Asia (Şengör and Natal'in, 1996) and Australia (Debayle and Kennett, 2003).

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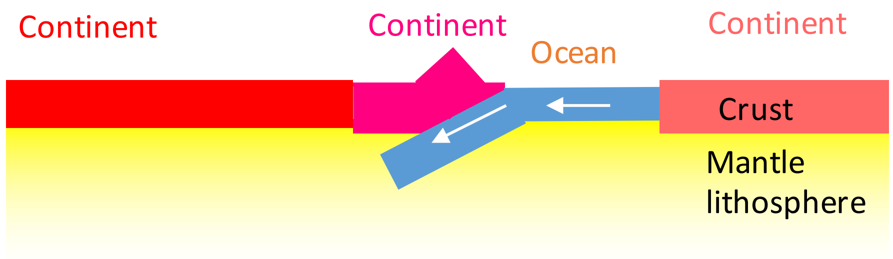
PLATE BOUNDARIES

SUBDUCTION

(1) Assemblage of continental fragments



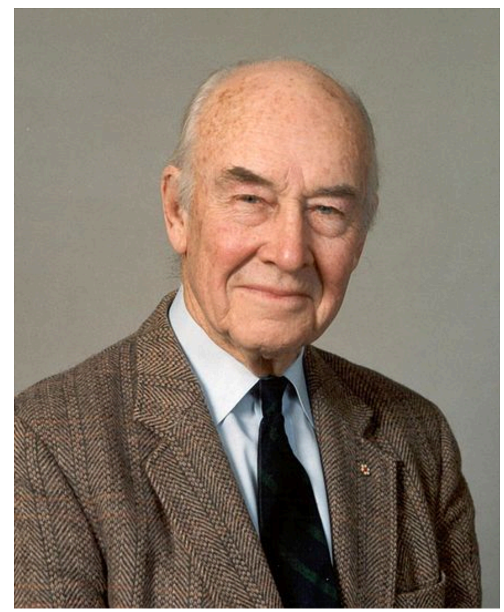
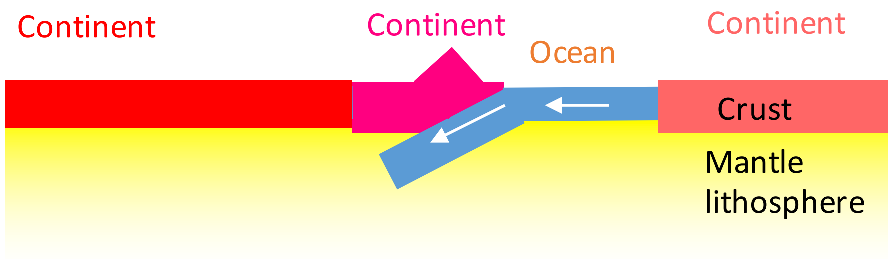


PLATE BOUNDARIES

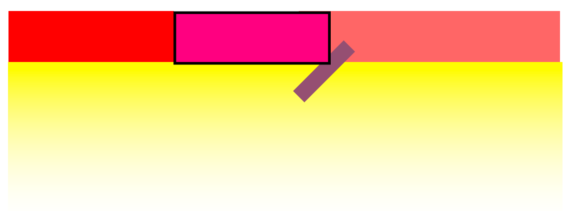
SUBDUCTION

SUB-CRUSTAL INHERITANCE

(1) Assemblage of continental fragments



(2) Mantle lithosphere deformation due to amalgamation



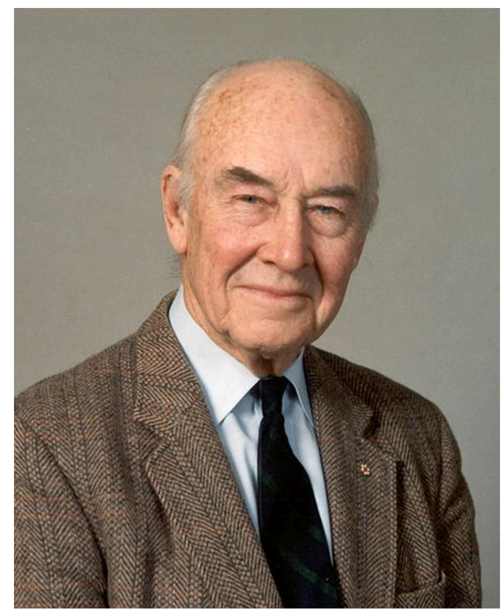


PLATE BOUNDARIES

SUBDUCTION

SUB-CRUSTAL INHERITANCE

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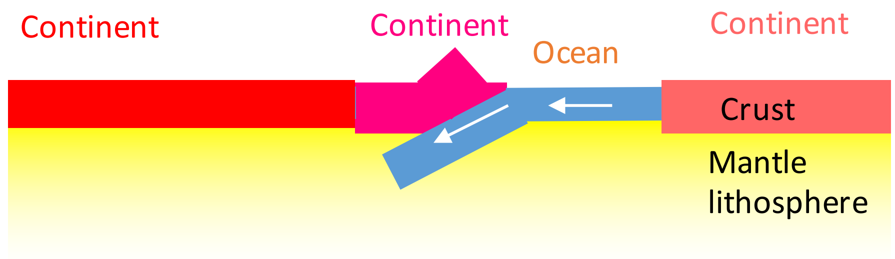

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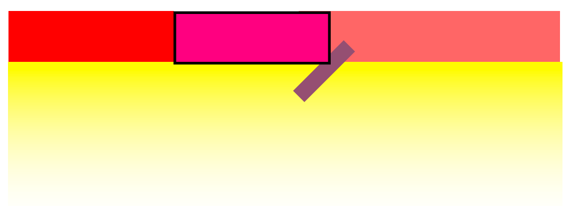

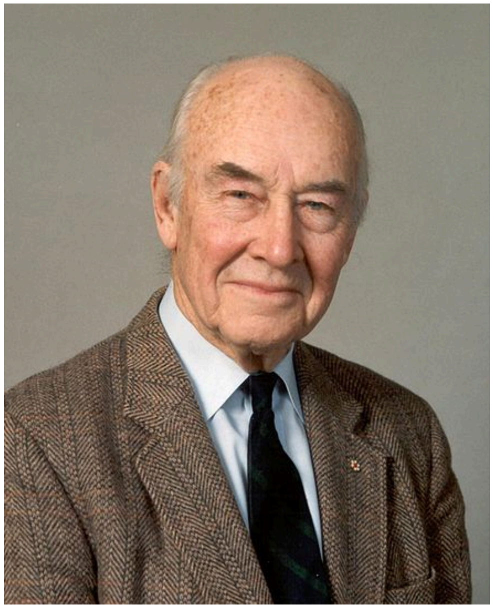

Could the mantle lithosphere retain ancient structures over long timescales?

Archaean subduction inferred from seismic images of a mantle suture in the Superior Province

A. J. Calvert*, E. W. Sawyer†, W. J. Davis‡§ & J. N. Ludden‖§

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† Département des Sciences Appliquées, Université du Québec à Chicoutimi, Chicoutimi, Québec G7H 2B1, Canada
‡ GEOTOP, Université du Québec à Montréal, CP 6888, succ. centre-ville, Montréal, Québec H3C 3P8, Canada
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PLATE tectonics provides the basis for the interpretation of most current terrestrial tectonic activity, and is widely accepted as having been active over much of the Earth's history[1]. Yet the timing of initiation of this process is subject to debate[2–9]. So far, the earliest seismic evidence for plate tectonics has come from a fossil mantle suture in the Svecofennian orogen (1.89 Gyr ago)[10] and

§ Present addresses: Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario K1A 0E8, Canada (W.J.D.); Centre de Recherches Pétrographiques et Géochimiques, 15 Rue Notre Dame des Pauvres, 54401 Vandoeuvre-les-Nancy, BP 20 Cedex, France (J.N.L.).

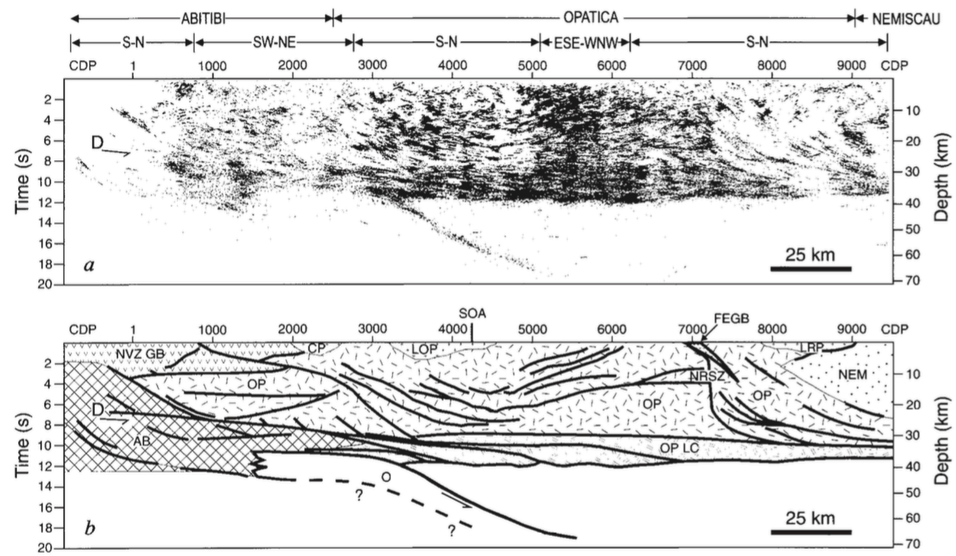


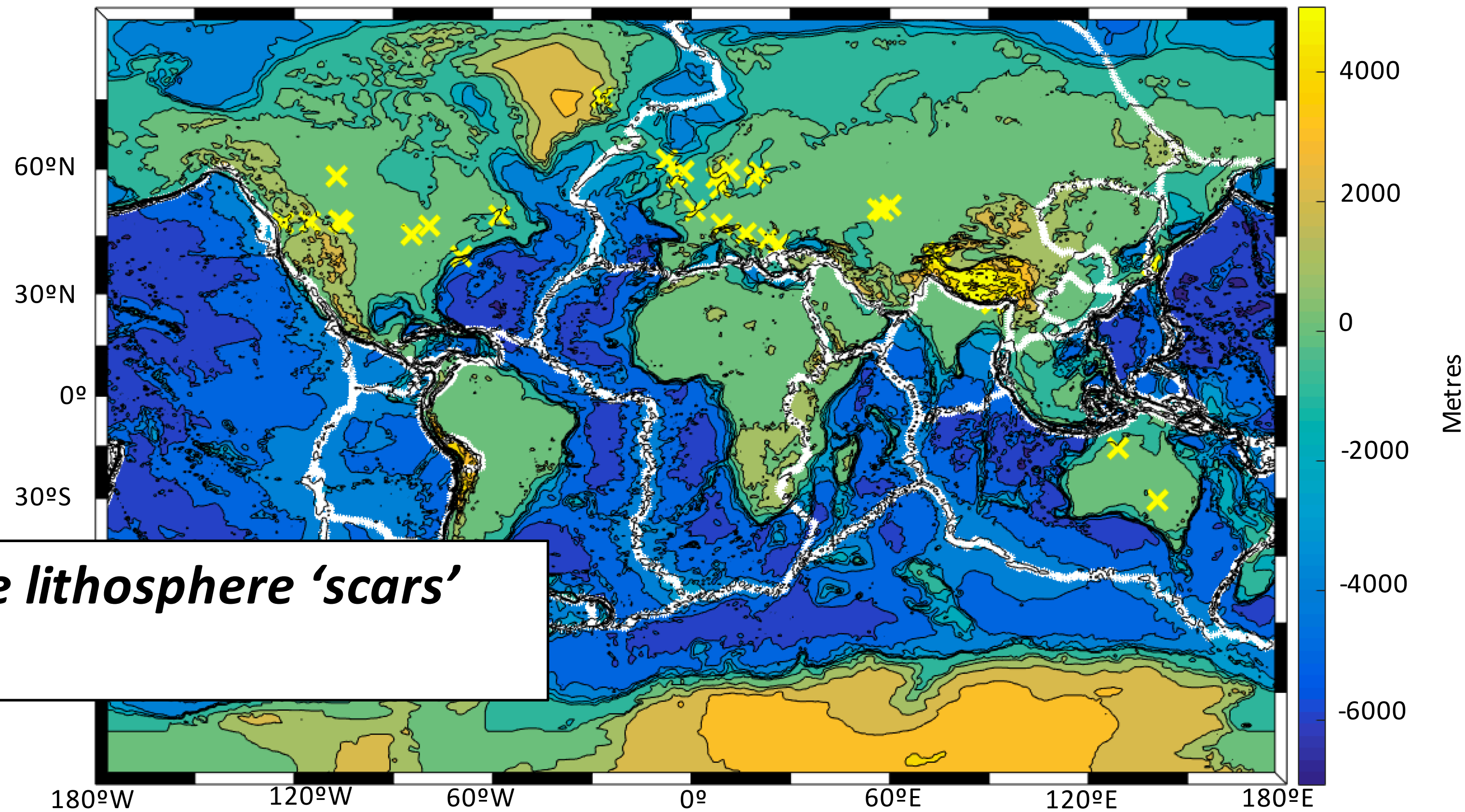
FIG. 4 *a*, Line migration of line 48 displayed at true scale (1:1) derived by migrating the stack at 6,500 m s^{-1} using apparent local dips estimated over a 21-trace window; this method avoids artefacts associated with wave-equation migration and provides a better image in the mantle. The most prominent feature of the data is the band of mantle reflections that dip in a north to northwest direction beneath the Opatica belt. The mantle reflections intersect the Moho beneath the Abitibi–Opatica boundary mapped at the surface. In the Abitibi belt to the south, a comparatively non-reflective upper crust down to 3.0 s (but with the notable exception of the Bell River igneous complex near CDP 600) overlies a moderately reflective middle crust. The lower crust exhibits diffuse reflectivity that continues to 13.5 s in places before dying out. In marked contrast, the lower crust of the Opatica belt contains well defined, high-amplitude subhorizontal seismic layering and a sharp reflection Moho. The upper and middle Opatica crust contains a broad zone of high-amplitude reflectivity with reflections of opposing dips between CDP 2,500 and 6,000 that extend down to 9 s. We infer the presence of a lower-crustal decollement (D) corresponding to shallowly north-dipping reflections between CDP 1 at 7 s and CDP 5,000 at 12 s, because more steeply dipping overlying reflections sole out at this level. The major changes in orientation of the seismic line are indicated. *b*, Interpretation of the seismic section in *a* displayed at true scale (1:1) along the seismic line. The major crustal units are indicated: OP, Opatica crust; OP LC, Opatica lower crust consisting of strong subhorizontal reflectors; AB, Abitibi (sub-greenstone) crust interpreted partly by correlation with earlier seismic data[15,25]; NVZ GB, greenstone rocks that form part of the Abitibi northern volcanic zone; NEM, Nemiscau (metasedimentary) crust; O, subcrustal unit, tentatively identified as a relict Archaean oceanic slab. CP, LOP, LRP, SOA, NRSZ, FEGB, as in Fig. 2. D as in *a*. Unmigrated stack, F-K migration and line migration sections (*a*) were all employed in making the interpretation.

[Calvert et al., Nature, 1995]

Could the mantle lithosphere retain ancient structures over long timescales? - Yes!

Orogenic inheritance and continental breakup: Wilson Cycle-control on rift and passive margin evolution Christian Schiffer

Lasting Mantle Lithosphere Scar Map



Could mantle lithosphere 'scars' be weak?

Plate boundaries:
Bird [G-cubed, 2003]
Mantle lithosphere scars:
Schiffer et al. [Geology, 2015]; Steer et al. [Tectonophysics, 1998]

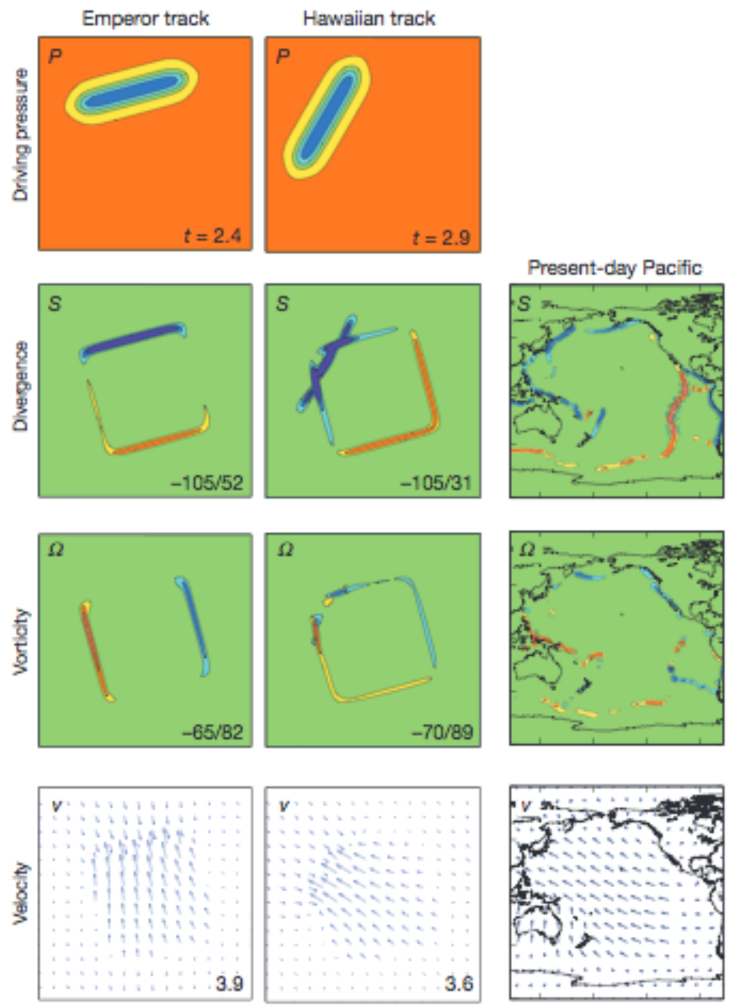
LETTER

doi:10.1038/nature13072

Plate tectonics, damage and inheritance

David Bercovici[1] & Yanick Ricard[2]

Could mantle lithosphere 'scars' be weak? - Yes!



[Bercovici and Ricard, Nature, 2014]

Structural reactivation in plate tectonics: the roles of rheological heterogeneity and anisotropy in the mantle Andréa Tommasi

LETTER

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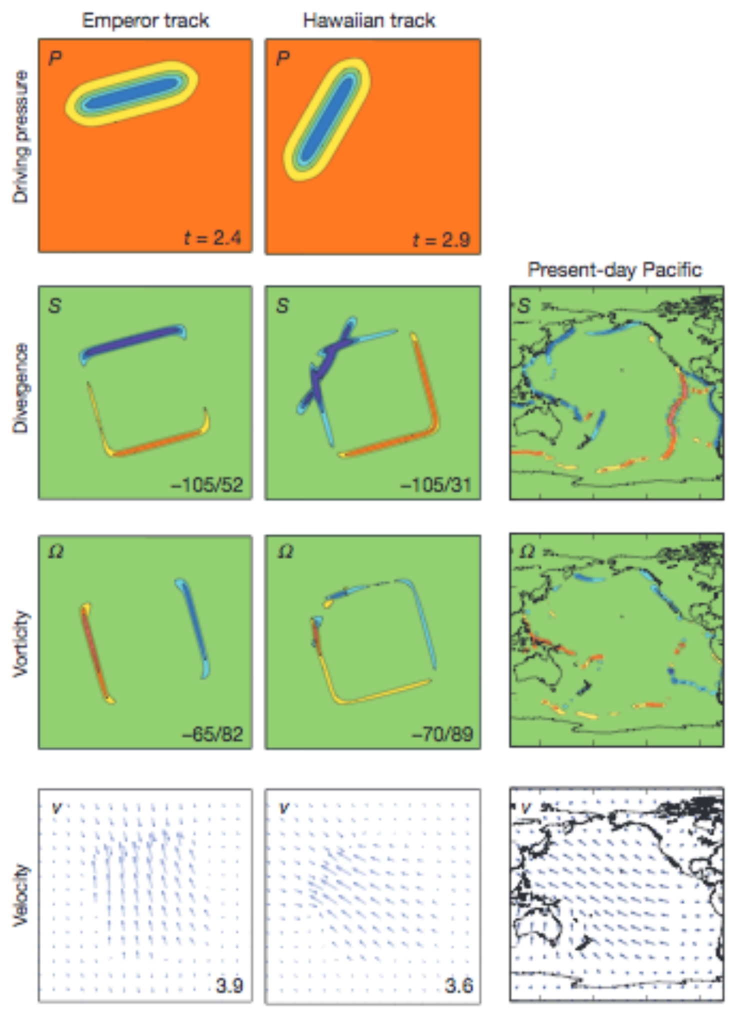

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Plate tectonics, damage and inheritance

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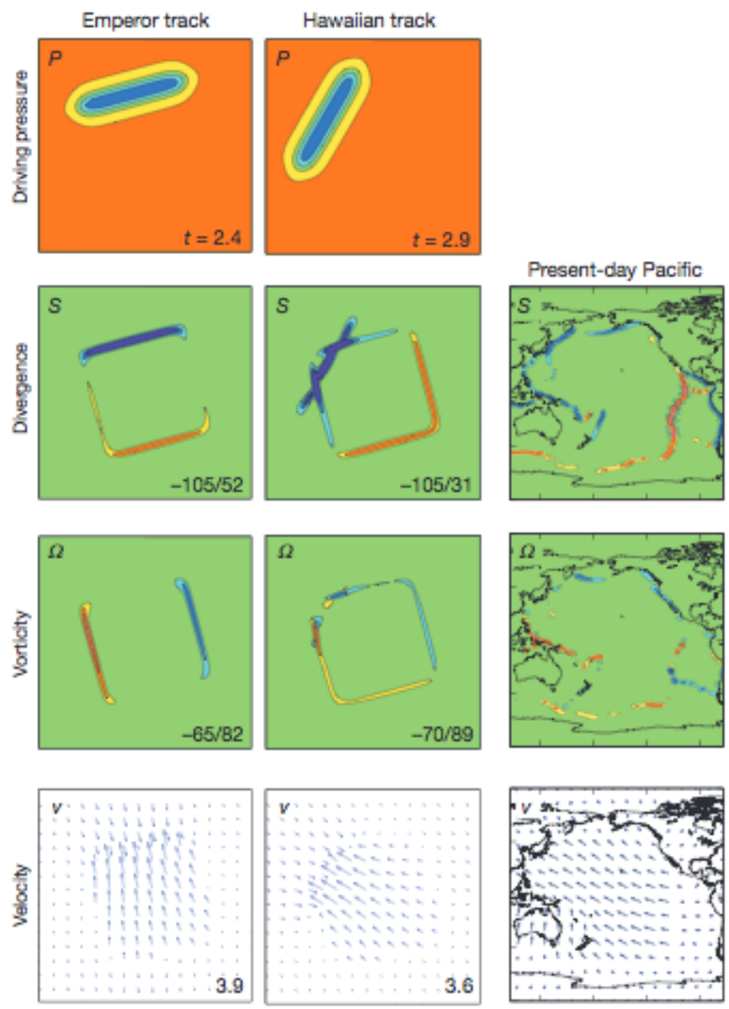

Could mantle lithosphere 'scars' be weak? - yes?

Could mantle lithosphere 'scars' have a large scale impact on tectonics?

[Bercovici and Ricard, Nature, 2014]

What processes could be involved in intraplate orogenesis, seismisicty, and/or deformation?

Could the mantle lithosphere retain ancient structures over long timescales?

Could mantle lithosphere 'scars' be weak?

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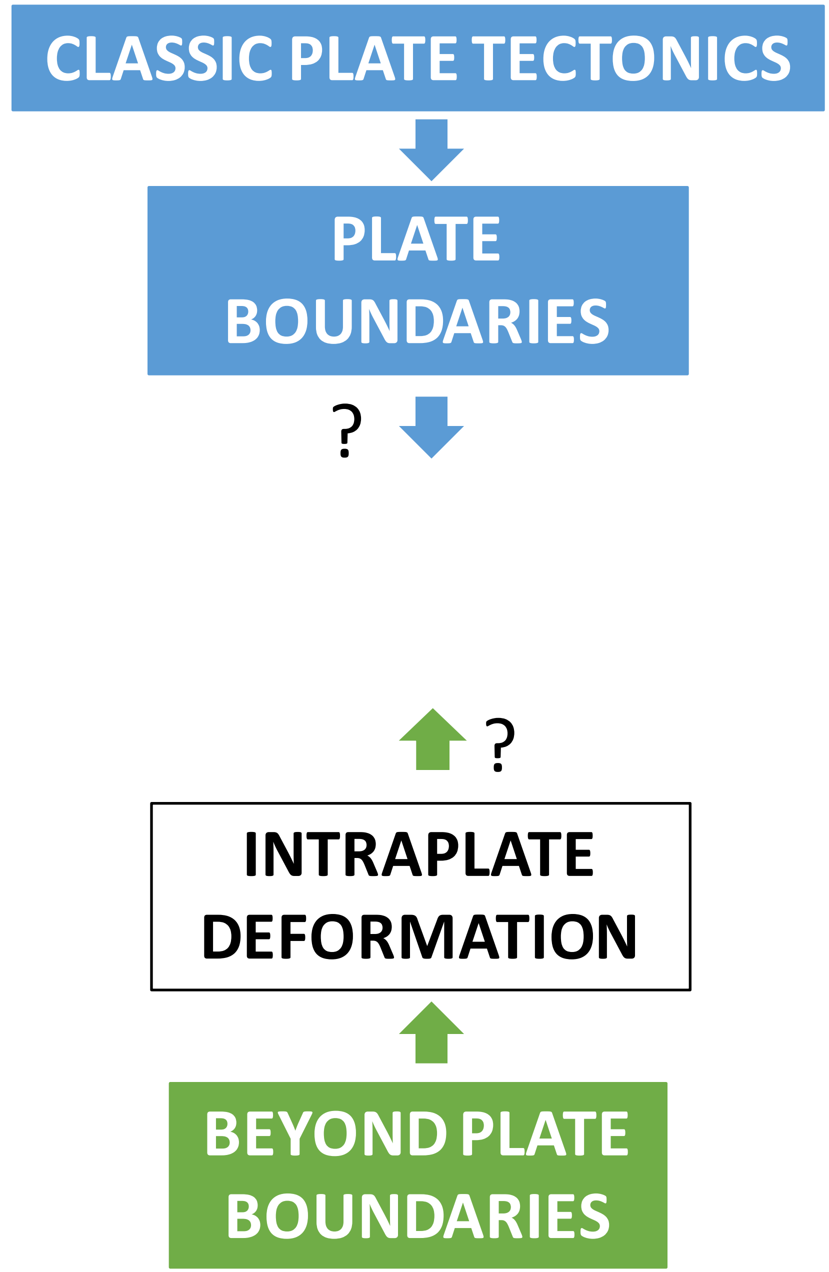

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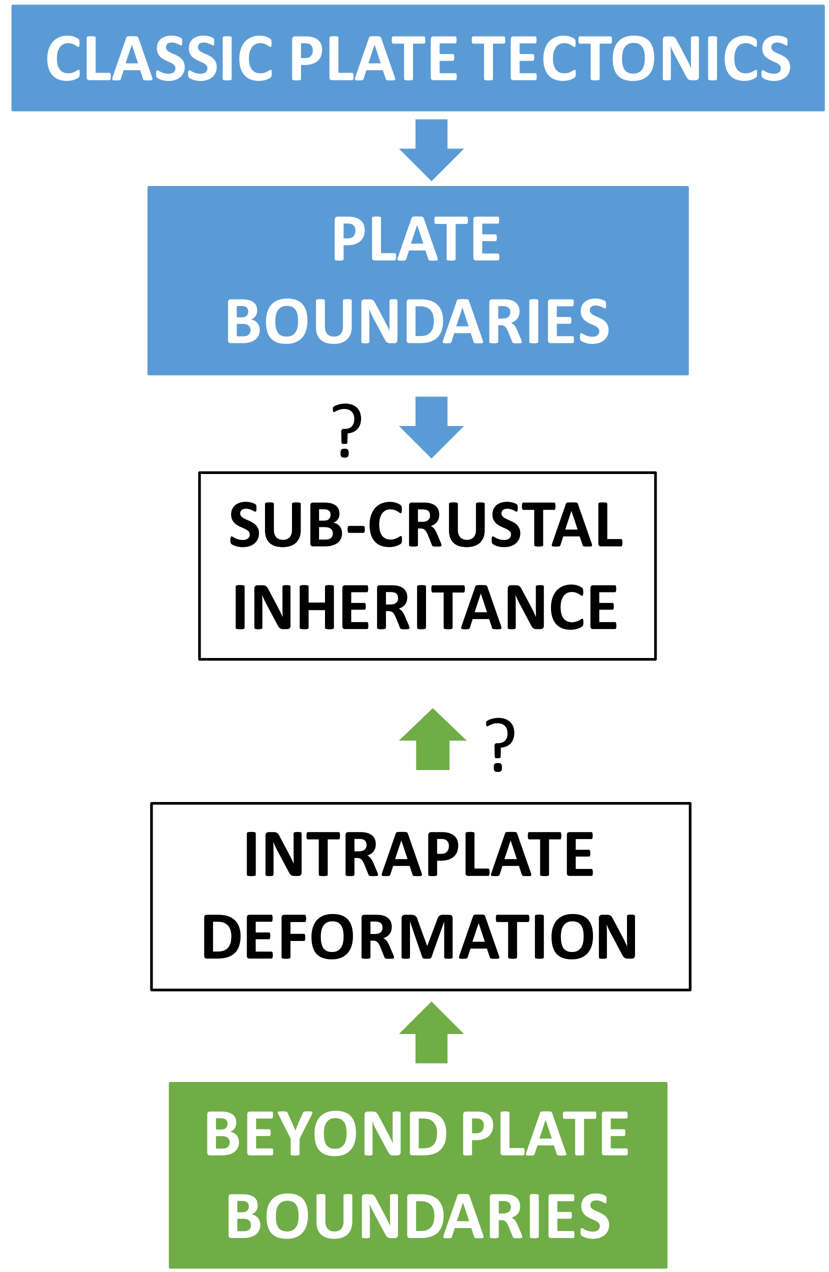


NUMERICAL MODELLING

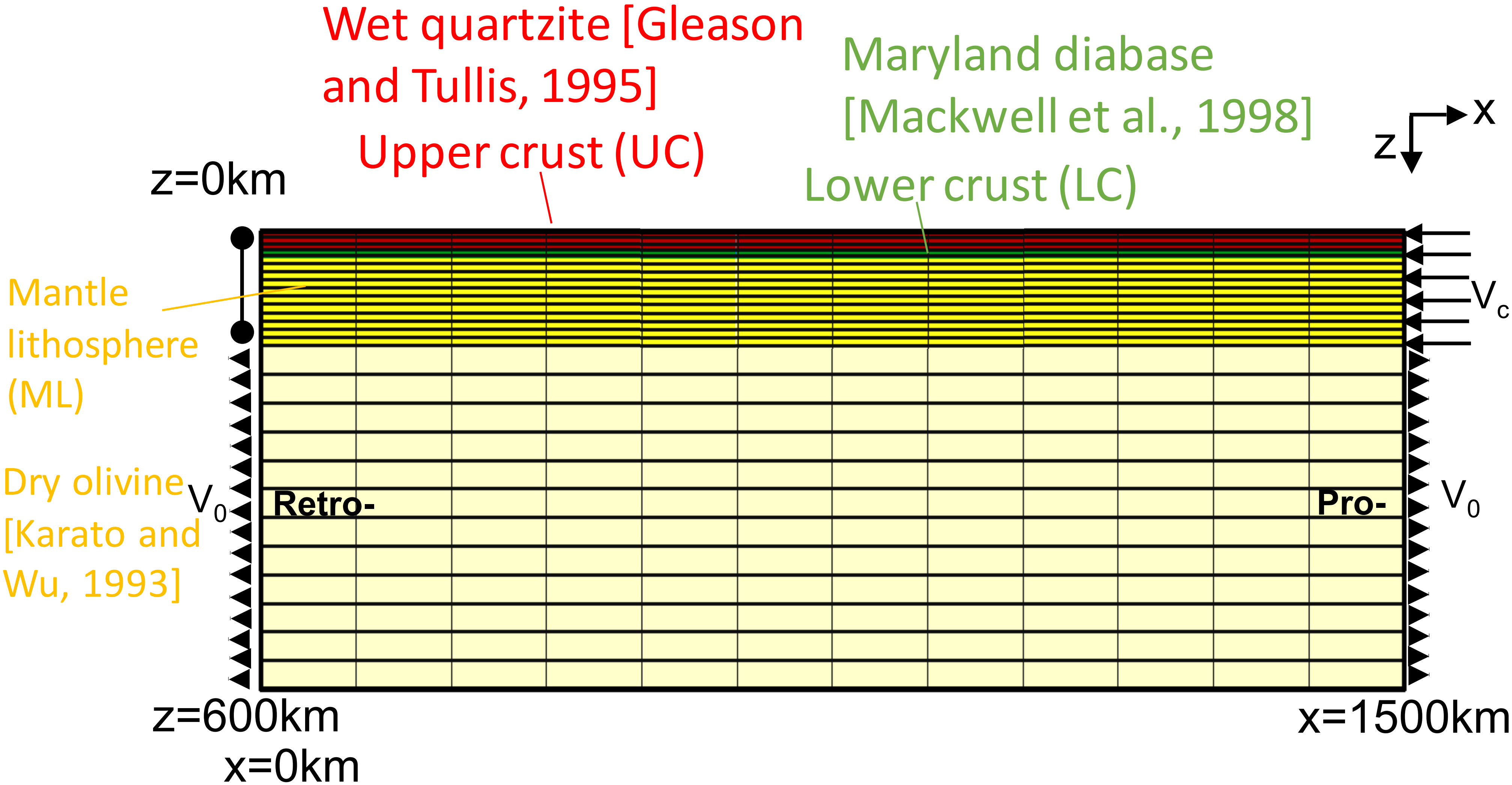
SUB-CRUSTAL INHERITANCE V **CRUSTAL INHERITANCE**

- Thermal-mechanical finite element numerical code [Fullsack, 1995]

- Implements an Arbitrary Lagrangian Eulerian (ALE) method

- Solves for the deformation of high Prandtl number incompressible viscous-plastic media

- All materials have a viscous-plastic rheology



Upper crust thickness: 24km

Lower crust thickness: 12km

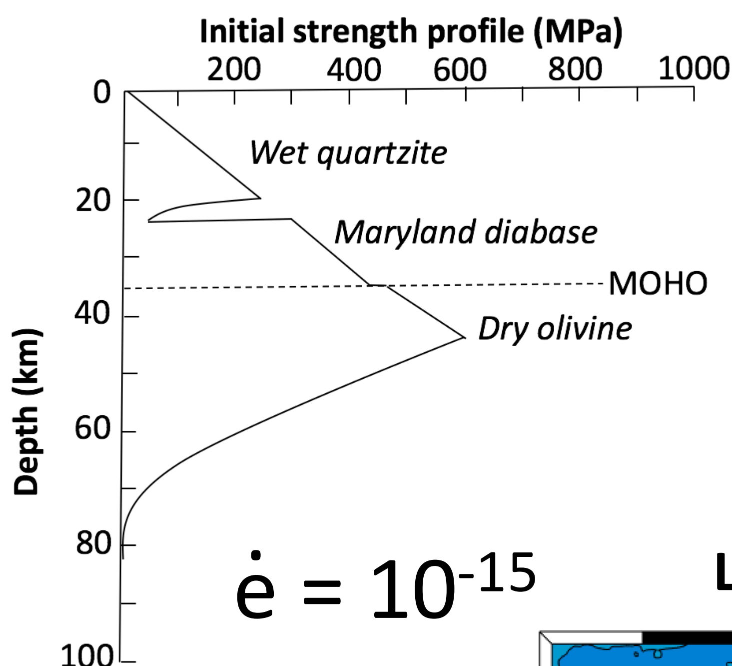
Mantle lithosphere thickness: 114km

Lagrangian grid: 801x649

Eulerian grid: 401x217

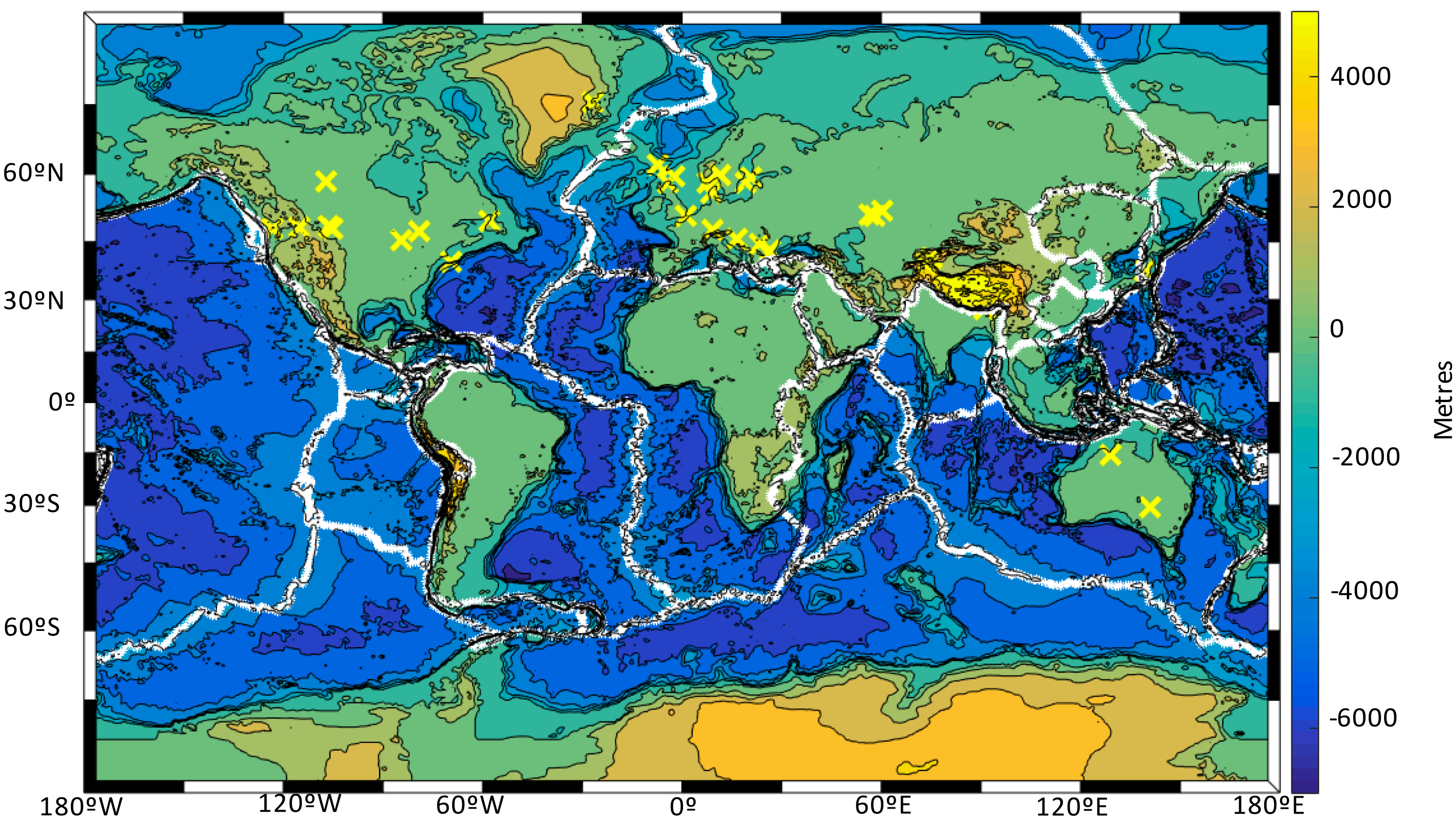
Temperatures

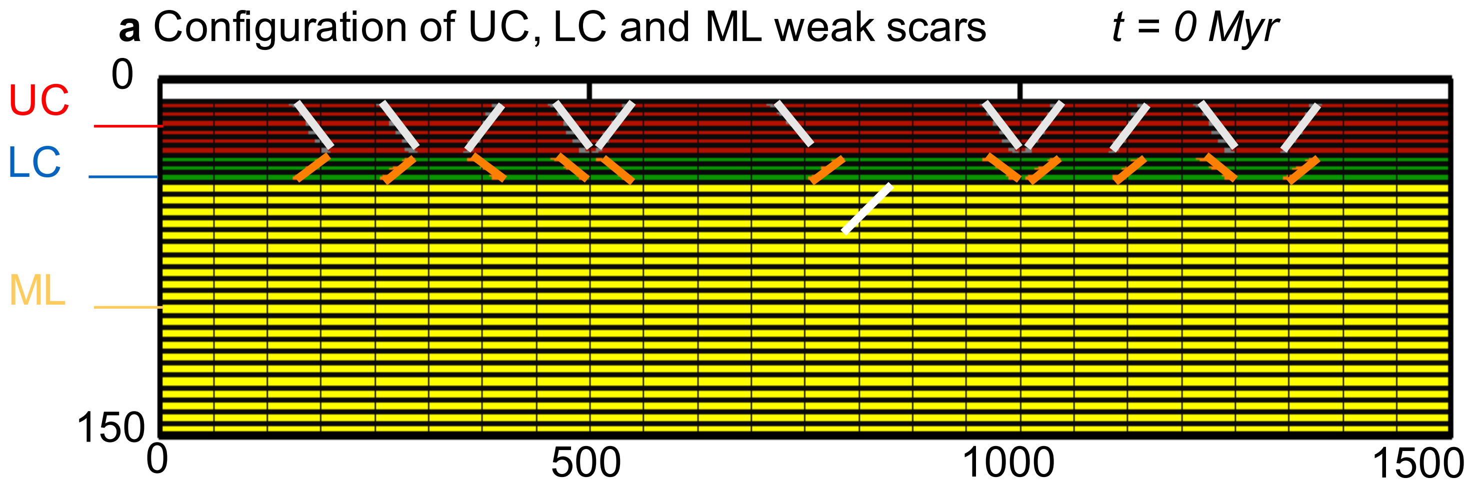
Surface: 20℃; MOHO: 550℃; Base lithosphere: 1350℃; Base model: 1570℃.



$\dot{e} = 10^{-15}$

Lasting Mantle Lithosphere Scar Map



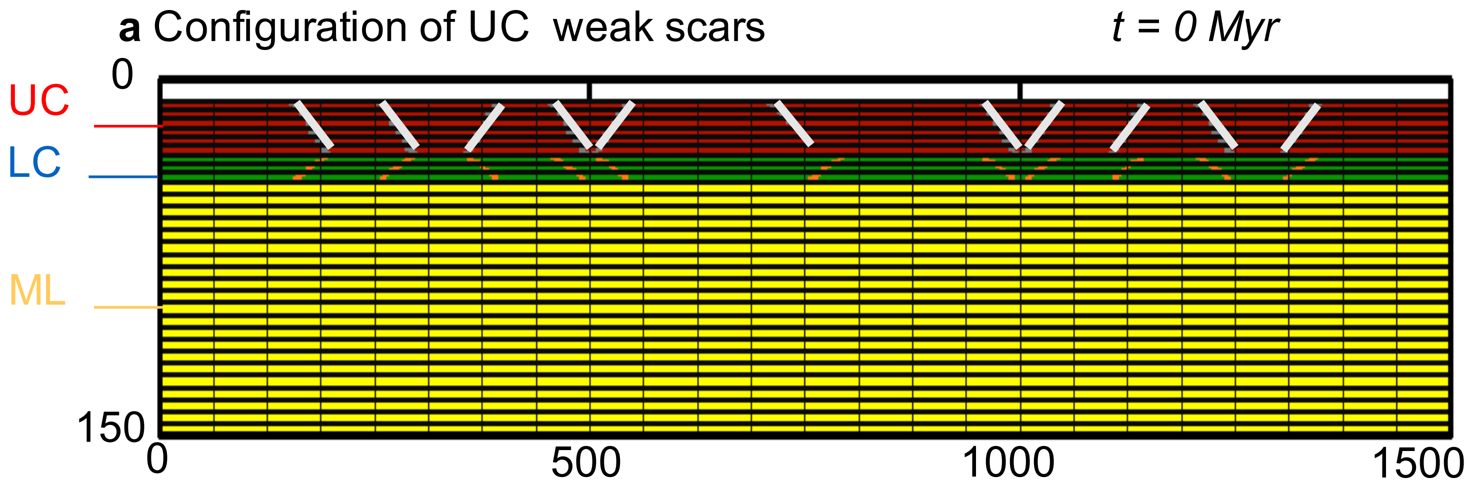


Could mantle lithosphere 'scars' have a large scale impact on tectonics?

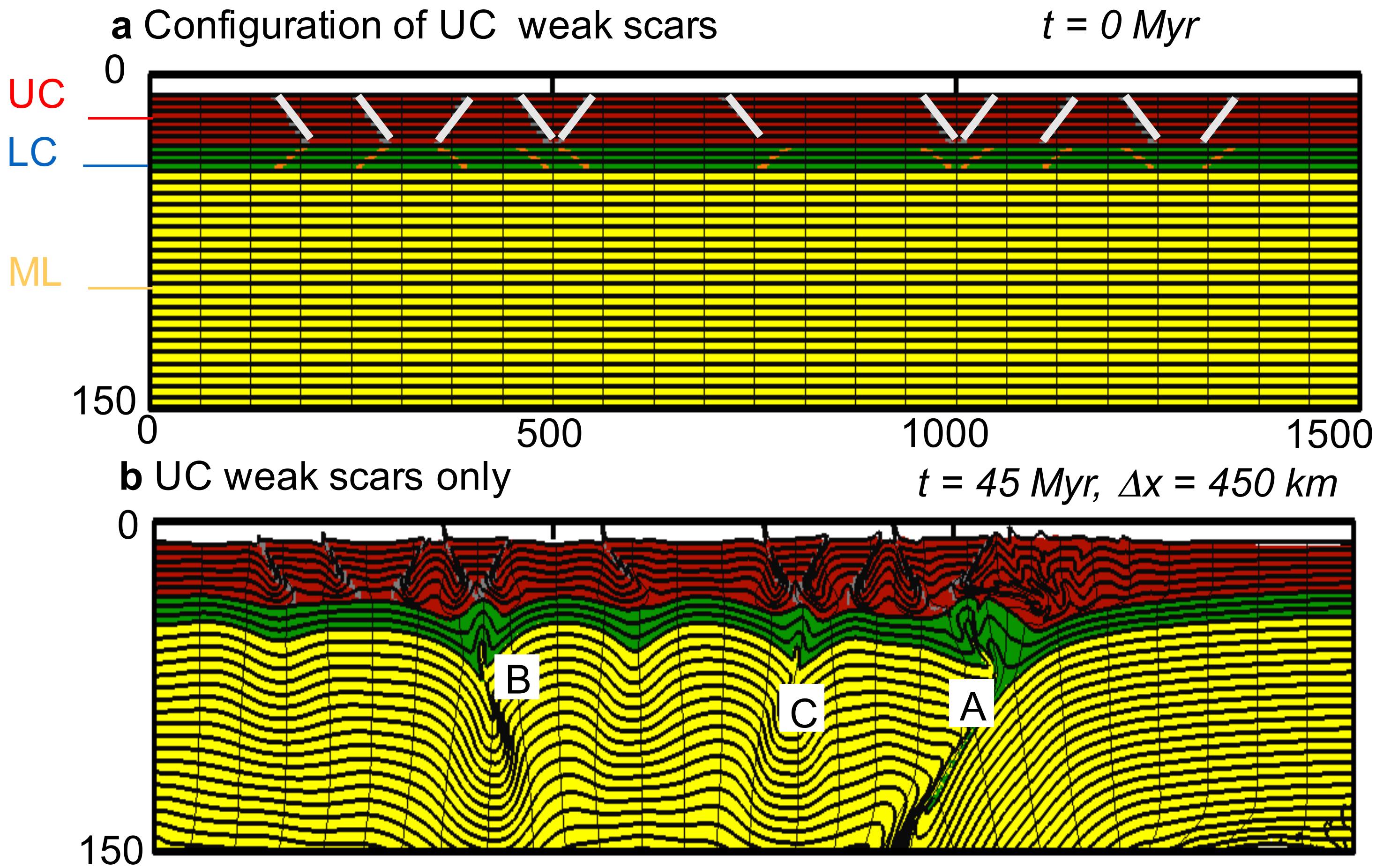
Effective angle of friction = 0º.

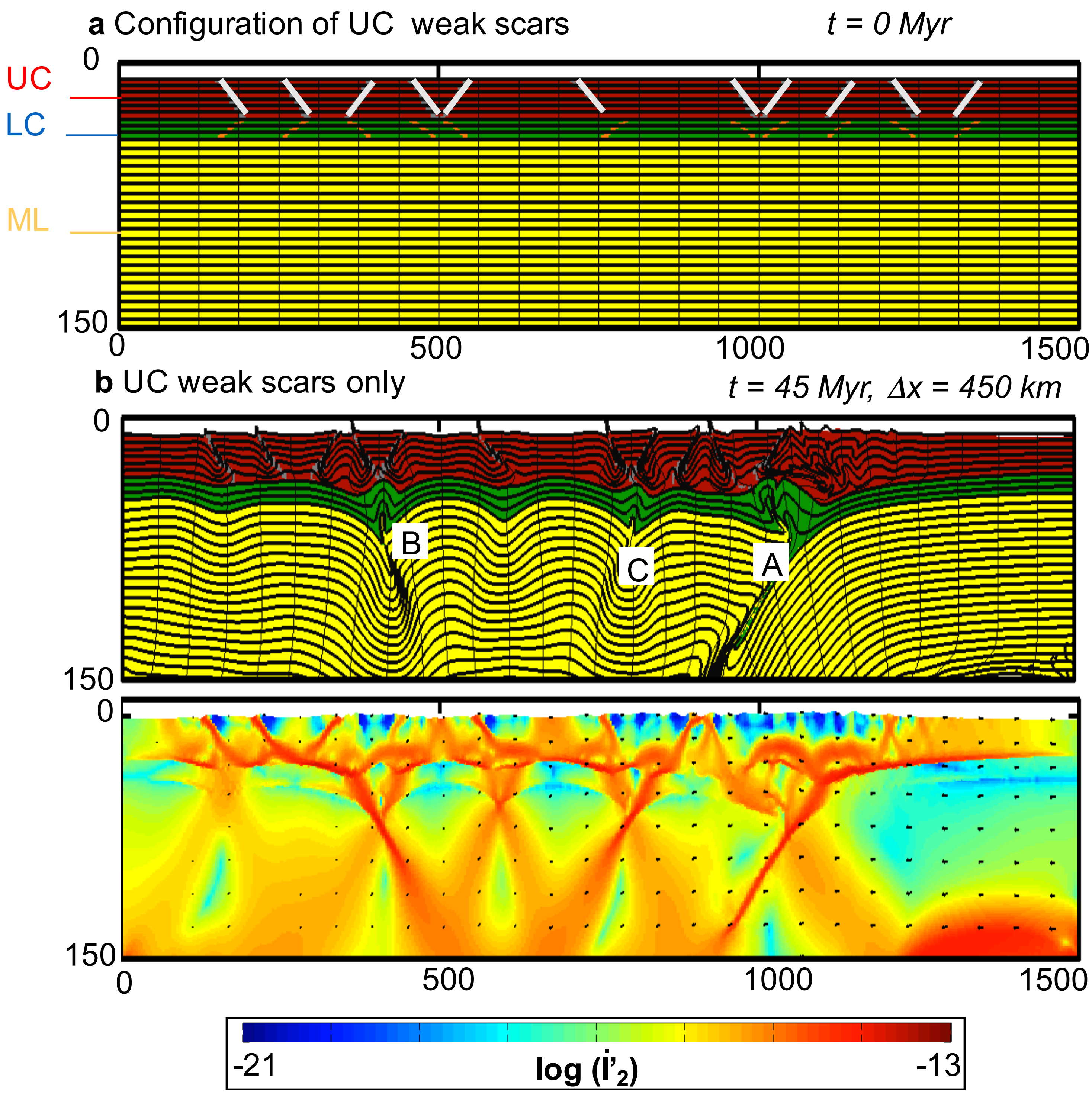
All weak zones equally primed for failure.

SUB-CRUSTAL INHERITANCE **V** **CRUSTAL INHERITANCE**

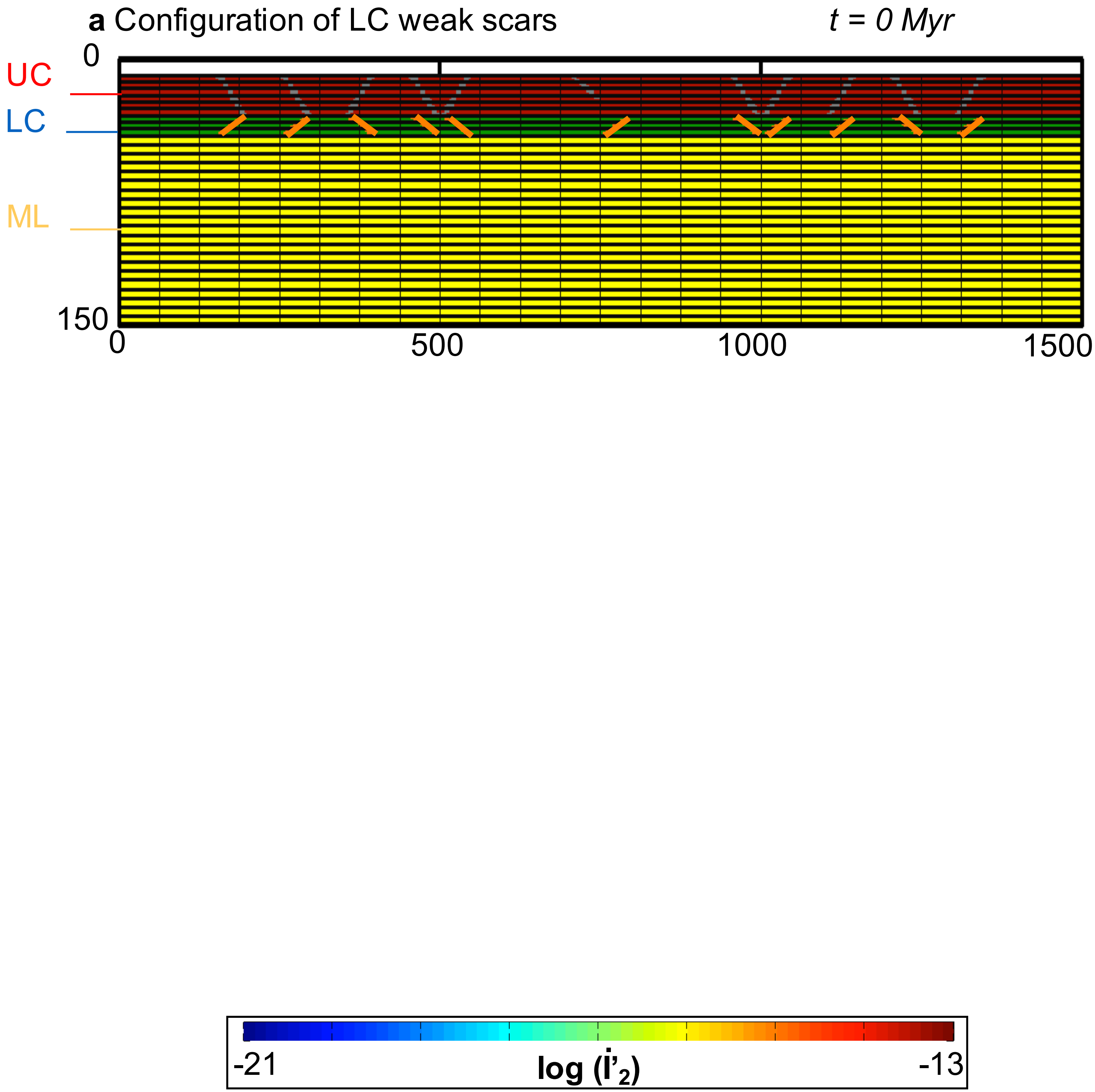


a Configuration of UC weak scars
t = 0 Myr
UC
LC
ML
0
150
0
500
1000
1500

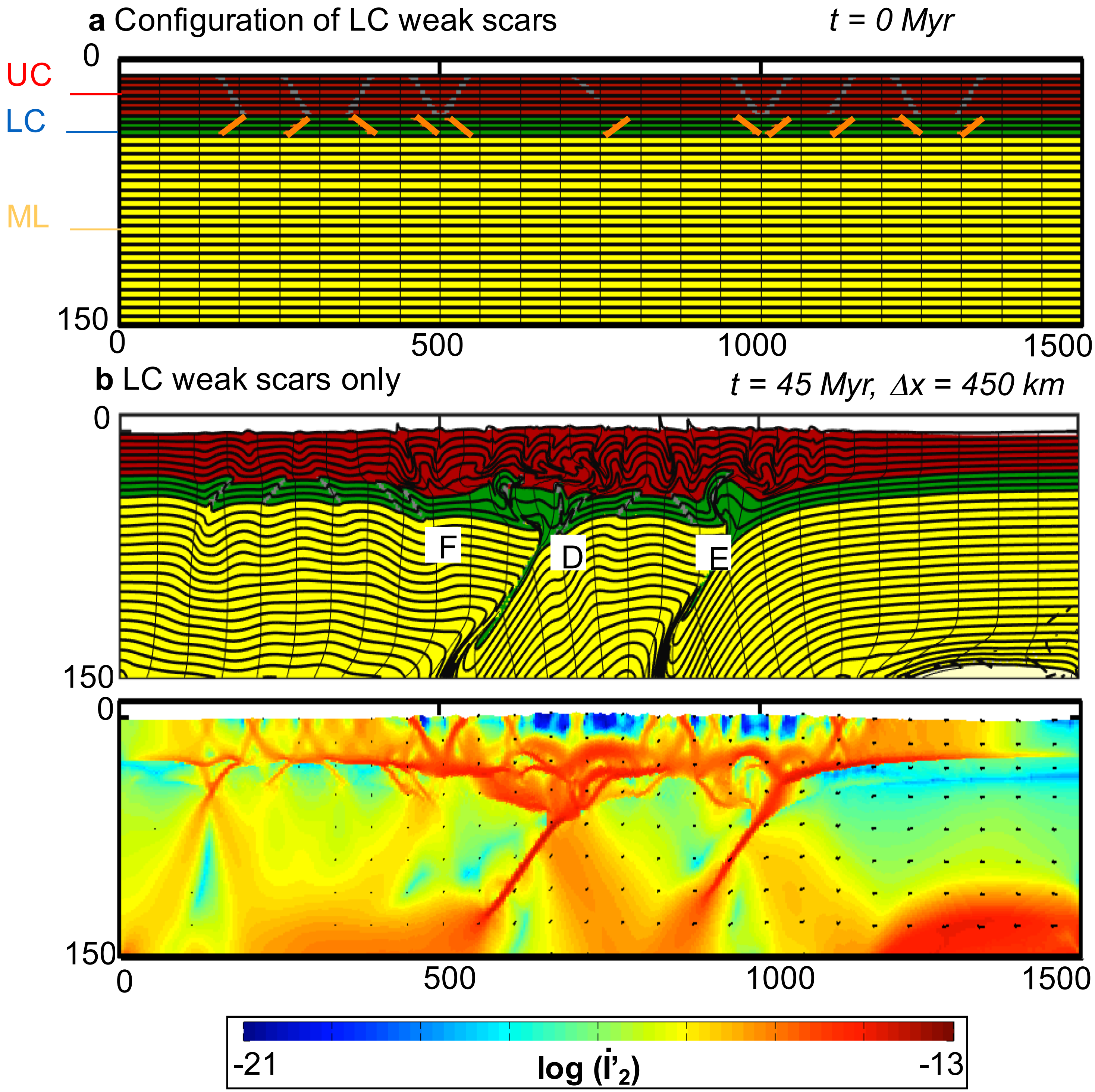

a Configuration of UC weak scars
t = 0 Myr
UC
LC
ML
0
150
0
500
1000
1500
b UC weak scars only
t = 45 Myr, Δx = 450 km
0
150
B
C
A



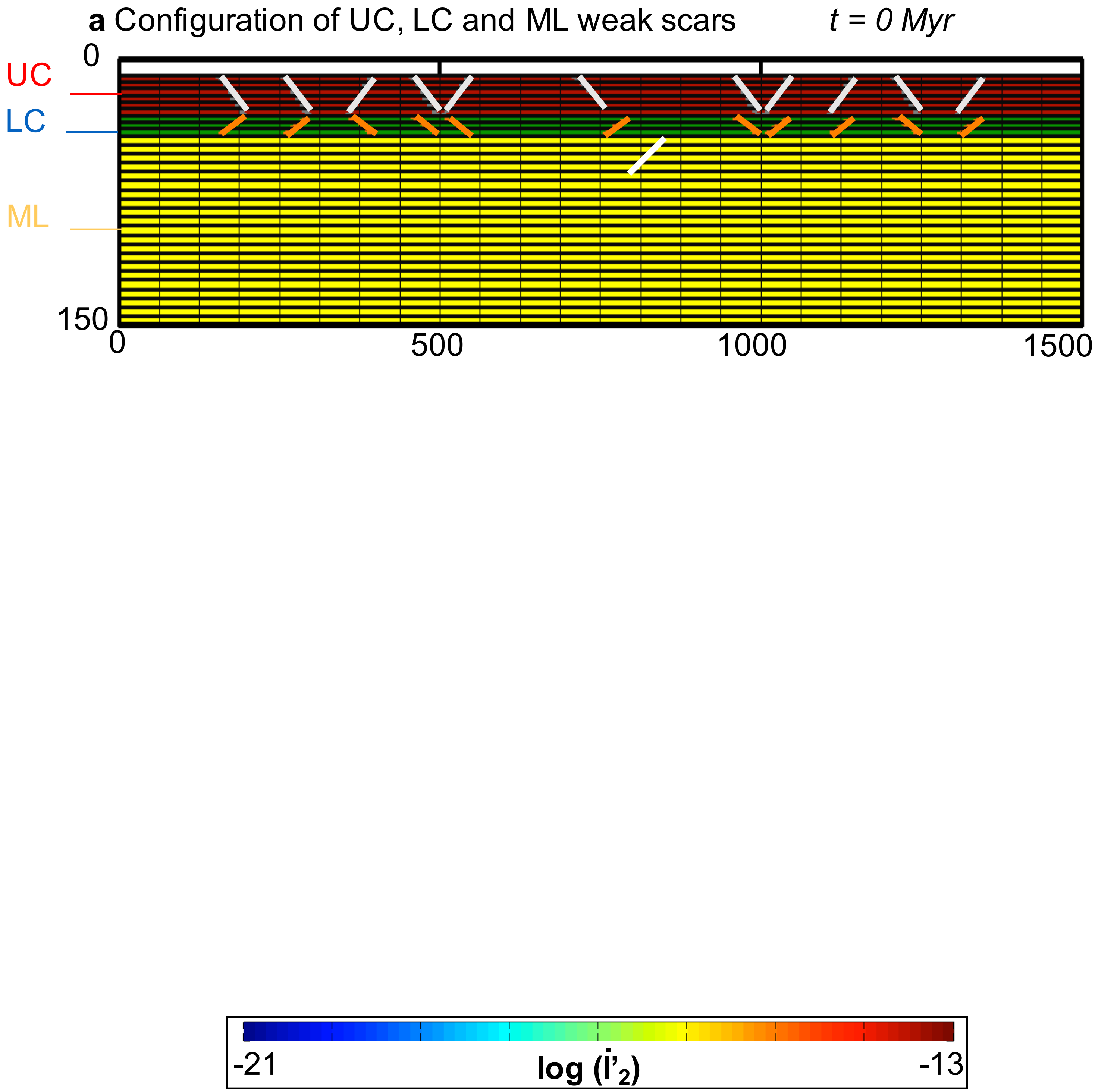
a Configuration of UC weak scars
t = 0 Myr
UC
LC
ML
0
150
0
500
1000
1500
b UC weak scars only
t = 45 Myr, Δx = 450 km
0
150
B
C
A
0
150
0
500
1000
1500
-21
log (İ'2)
-13



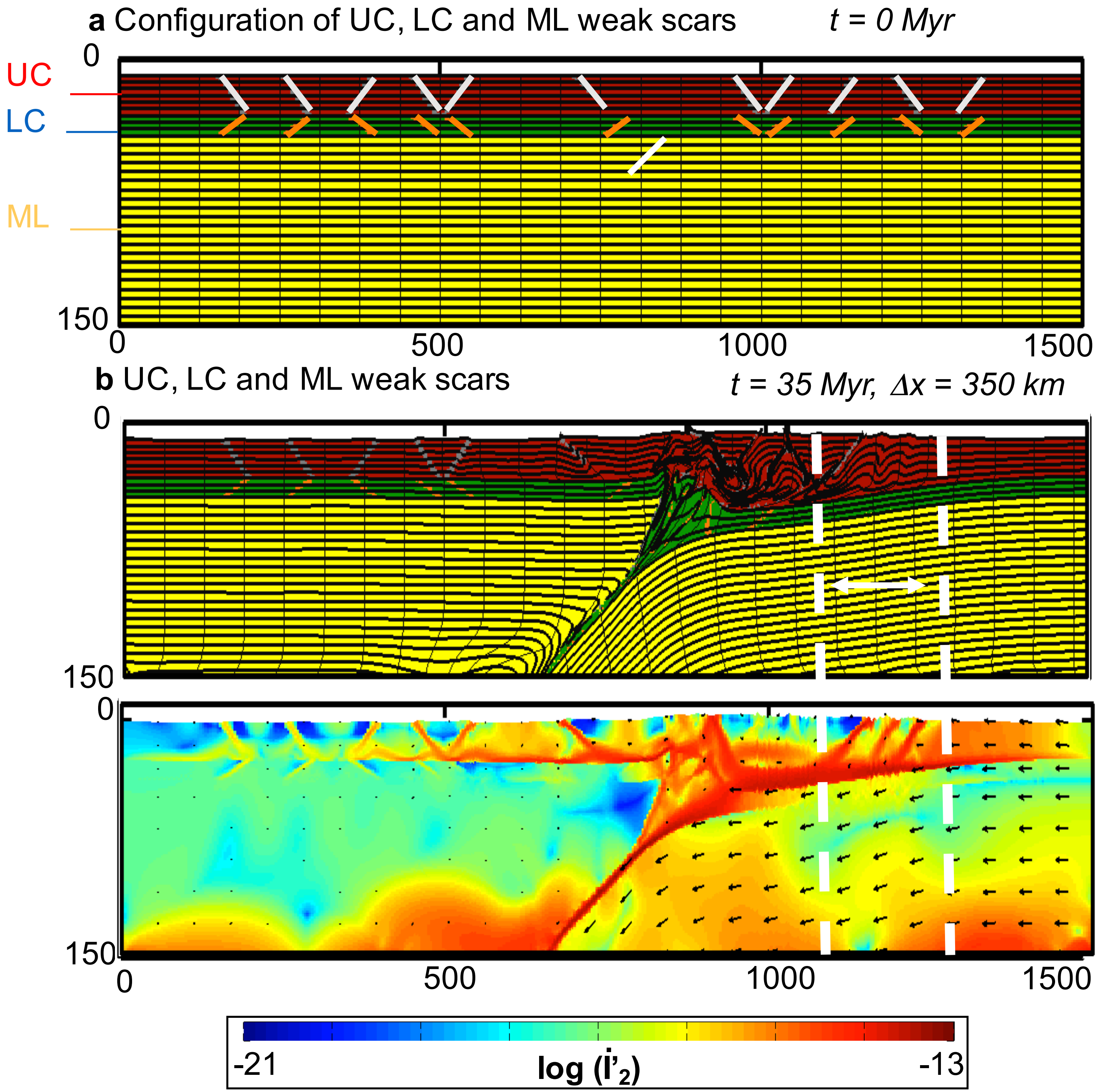
a Configuration of LC weak scars
t = 0 Myr
0
UC
LC
ML
150
0
500
1000
1500
-21
log (İ'2)
-13



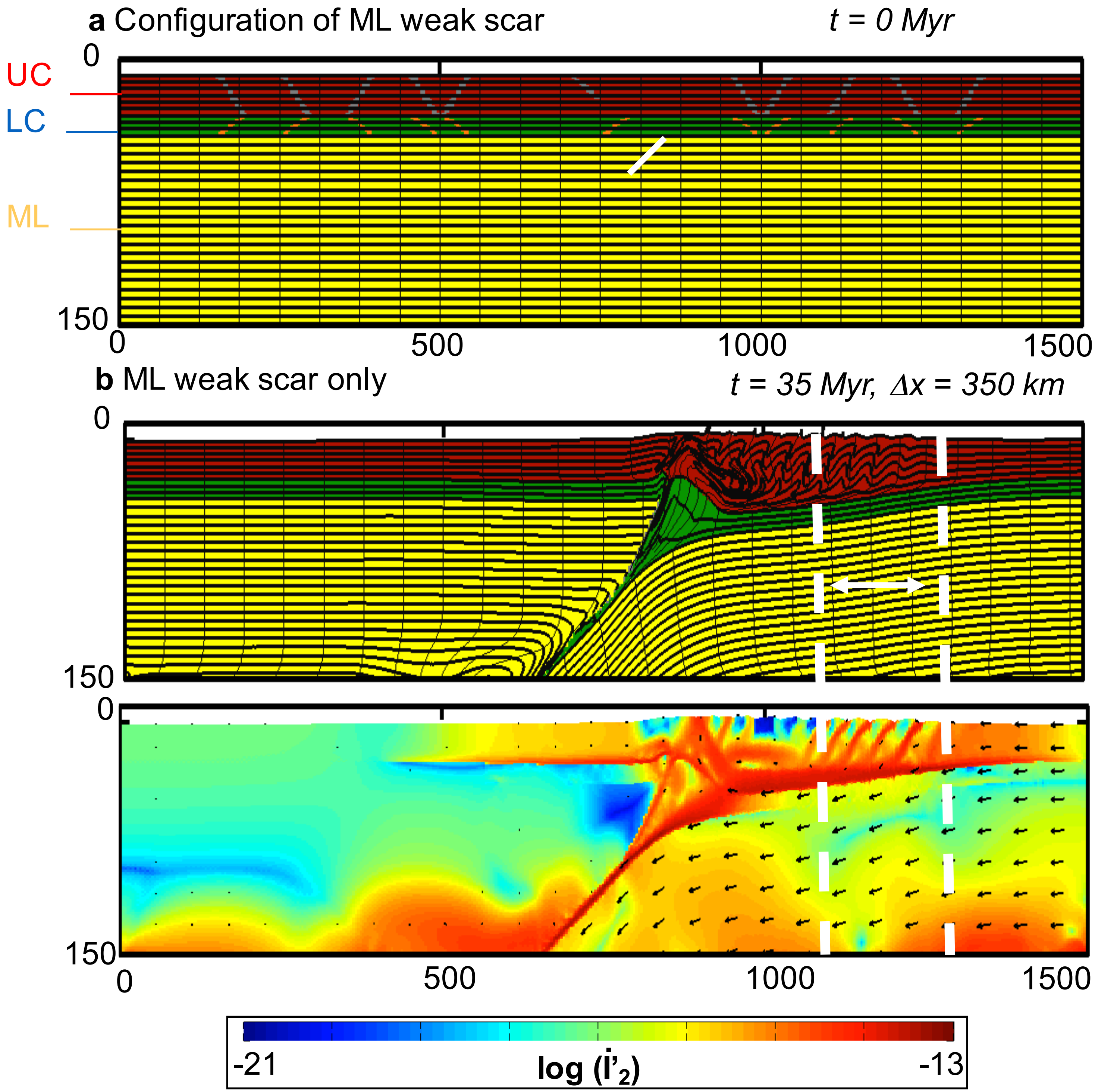
a Configuration of LC weak scars
t = 0 Myr
UC
LC
ML
0
150
0
500
1000
1500
b LC weak scars only
t = 45 Myr, Δx = 450 km
0
150
F
D
E
0
150
0
500
1000
1500
-21
log (İ'2)
-13



a Configuration of UC, LC and ML weak scars
t = 0 Myr
UC
LC
ML
0
150
0
500
1000
1500
-21
log (İ'2)
-13



a Configuration of UC, LC and ML weak scars
t = 0 Myr
UC
LC
ML
0
150
0
500
1000
1500
b UC, LC and ML weak scars
t = 35 Myr, Δx = 350 km
0
150
0
150
0
500
1000
1500
-21
log (İ'2)
-13


a Configuration of ML weak scar
t = 0 Myr
UC
LC
ML
0
150
0
500
1000
1500
b ML weak scar only
t = 35 Myr, Δx = 350 km
0
150
0
150
0
500
1000
1500
-21
log (İ'2)
-13

What processes could be involved in intraplate orogenesis, seismisicty, and/or deformation?

Could the mantle lithosphere retain ancient structures over long timescales?

Could mantle lithosphere 'scars' be weak?

SUB-CRUSTAL INHERITANCE V **CRUSTAL INHERITANCE**

Could mantle lithosphere 'scars' have a large scale impact on tectonics? - Yes!

Mantle lithosphere scars dominate shallow geological features in activating tectonics in plate interiors

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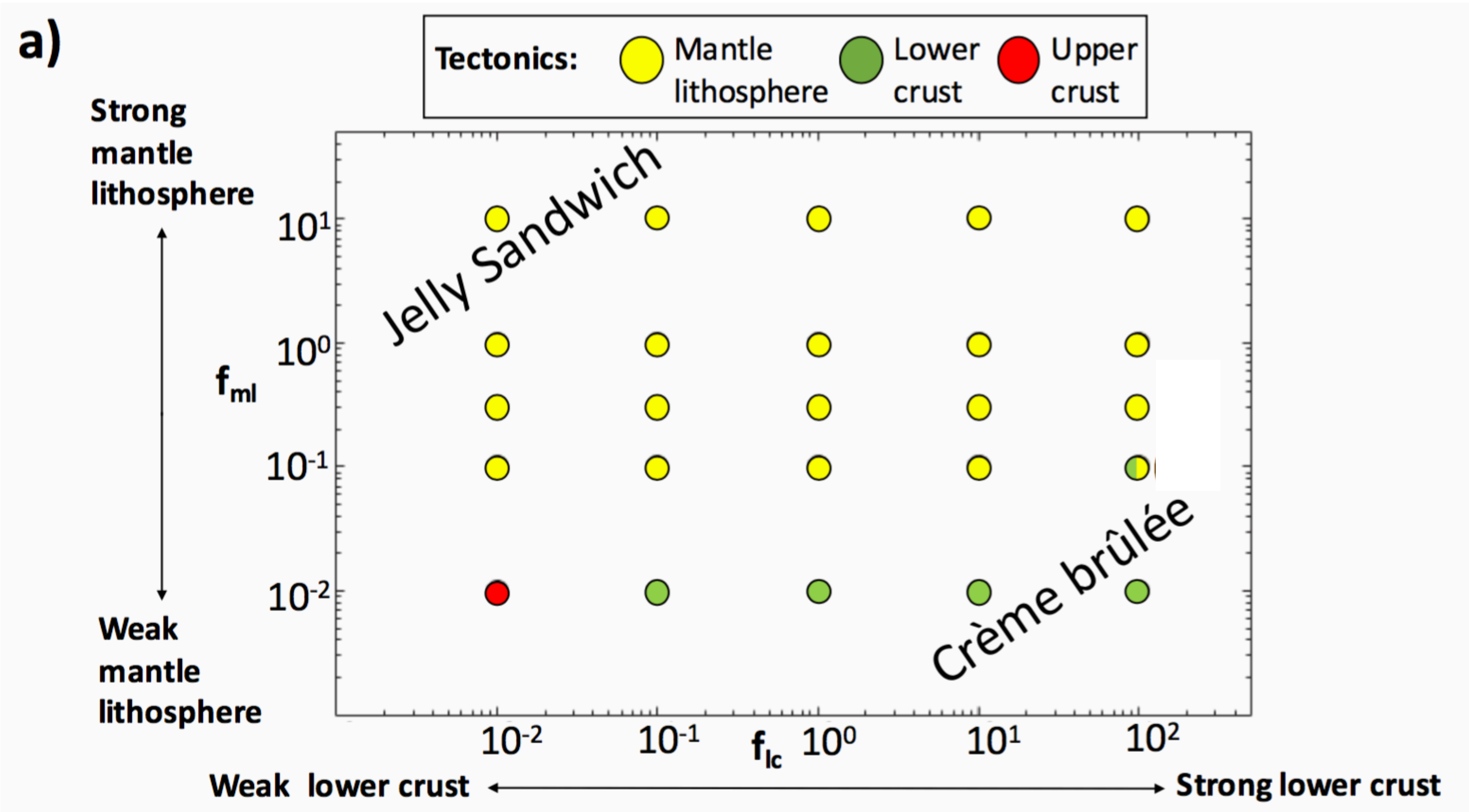
→ **Limits and applicability**

SUB-CRUSTAL INHERITANCE V **CRUSTAL INHERITANCE**



Limits:

HOT MOHO

WEAK ML

Crème Brulee

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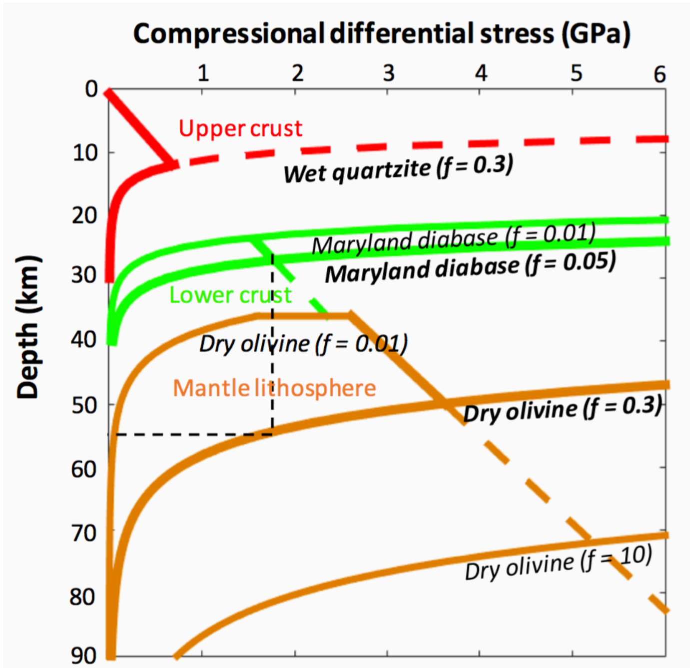
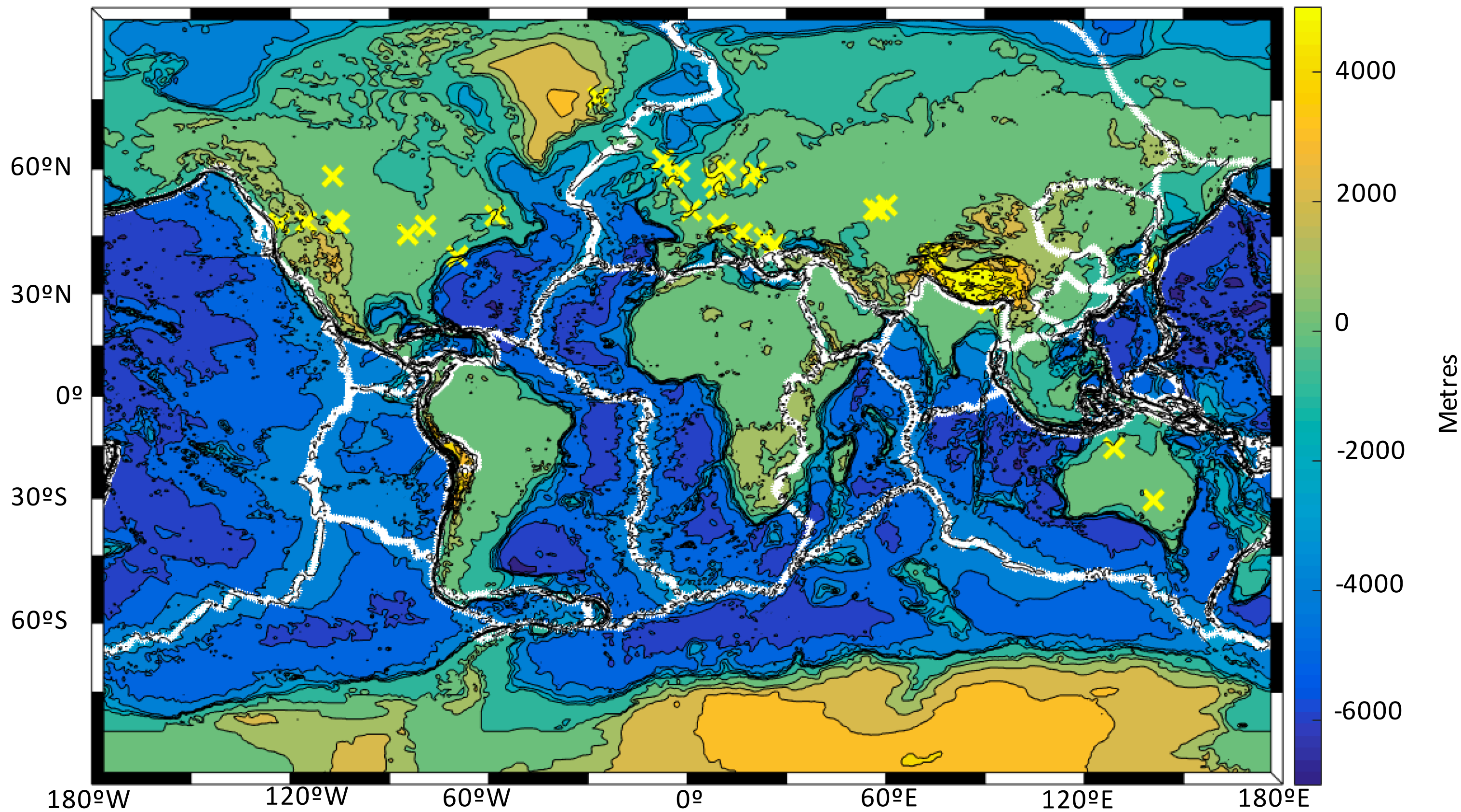


Lasting Mantle Lithosphere Scar Map



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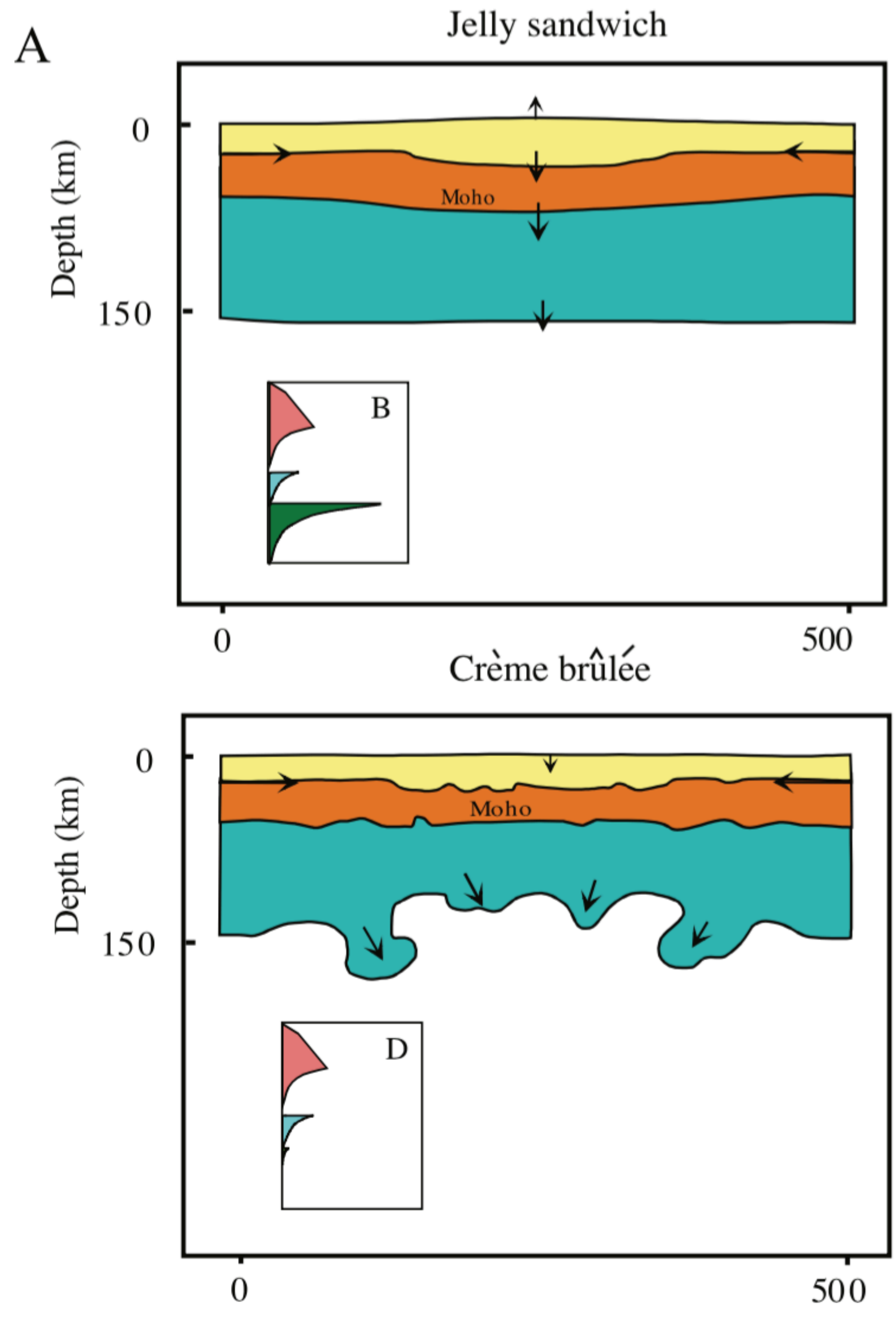
Mantle lithosphere scars:
Schiffer et al. [Geology, 2015]; Steer et al. [Tectonophysics, 1998]

The long-term strength of continental lithosphere: "jelly sandwich" or "crème brûlée"?

E.B. Burov, *Laboratoire de Tectonique, University of Paris 6, 4 Place Jussieu, 75252 Paris Cedex 05, France, evgenii.burov@lgs.jussieu.fr, and* **A.B. Watts,** *Department of Earth Sciences, University of Oxford, Parks Road, Oxford OX1 3PR, UK, tony.watts@earth.ox.ac.uk*



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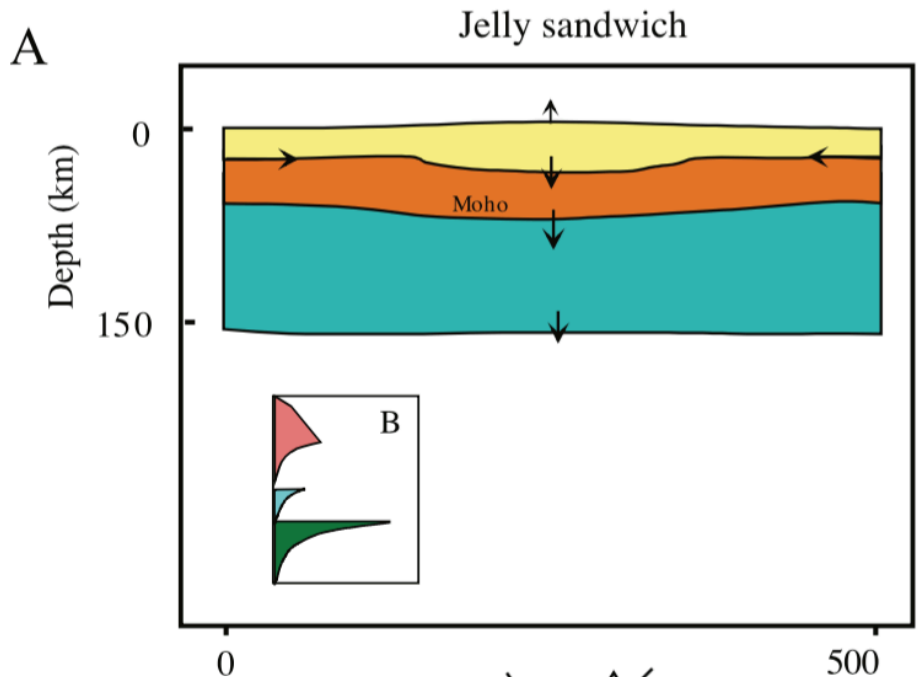
E.B. Burov, *Laboratoire de Tectonique, University of Paris 6, 4 Place Jussieu, 75252 Paris Cedex 05, France, evgenii.burov@lgs.jussieu.fr,* and **A.B. Watts,** *Department of Earth Sciences, University of Oxford, Parks Road, Oxford OX1 3PR, UK, tony.watts@earth.ox.ac.uk*



Earth and Planetary Science Letters 391 (2014) 224–233

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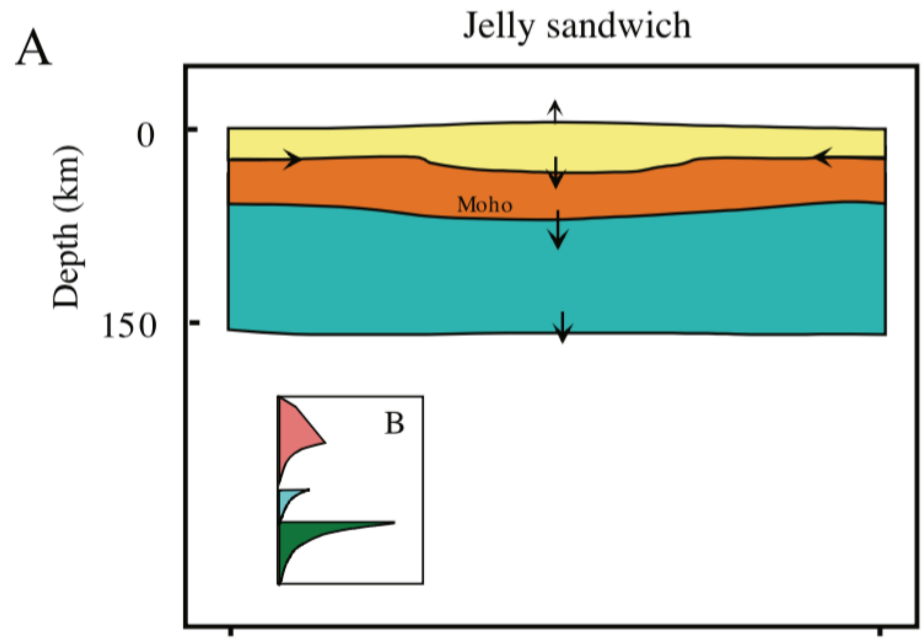
Craton stability and longevity: The roles of composition-dependent rheology and buoyancy

Hongliang Wang [a,*], Jeroen van Hunen [a], D. Graham Pearson [b], Mark B. Allen [a]

[a] *Department of Earth Sciences, Durham University, Durham, UK*
[b] *Department of Earth & Atmospheric Sciences, University of Alberta, Edmonton, Canada*

The long-term strength of continental lithosphere: "jelly sandwich" or "crème brûlée"?

E.B. Burov, *Laboratoire de Tectonique, University of Paris 6, 4 Place Jussieu, 75252 Paris Cedex 05, France, evgenii.burov@lgs.jussieu.fr, and* **A.B. Watts,** *Department of Earth Sciences, University of Oxford, Parks Road, Oxford OX1 3PR, UK, tony.watts@earth.ox.ac.uk*



"Cancel the crème brulee" – John Dewey 23rd May 2016

Earth and Planetary Science Letters 391 (2014)

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Craton stability and longevity: The roles of composition-dependent rheology and buoyancy

CrossMark

Hongliang Wang [a,*], Jeroen van Hunen [a], D. Graham Pearson [b], Mark B. Allen [a]

[a] *Department of Earth Sciences, Durham University, Durham, UK*
[b] *Department of Earth & Atmospheric Sciences, University of Alberta, Edmonton, Canada*

What processes could be involved in intraplate orogenesis, seismisicty, and/or deformation?

Could the mantle lithosphere retain ancient structures over long timescales?

Could mantle lithosphere 'scars' be weak?

Could mantle lithosphere 'scars' have a large scale impact on tectonics?

Limits:

HOT MOHO

WEAK ML

Crème Brulee

Application:

Rheologically strong mantle lithosphere

Far-field compressional forcing

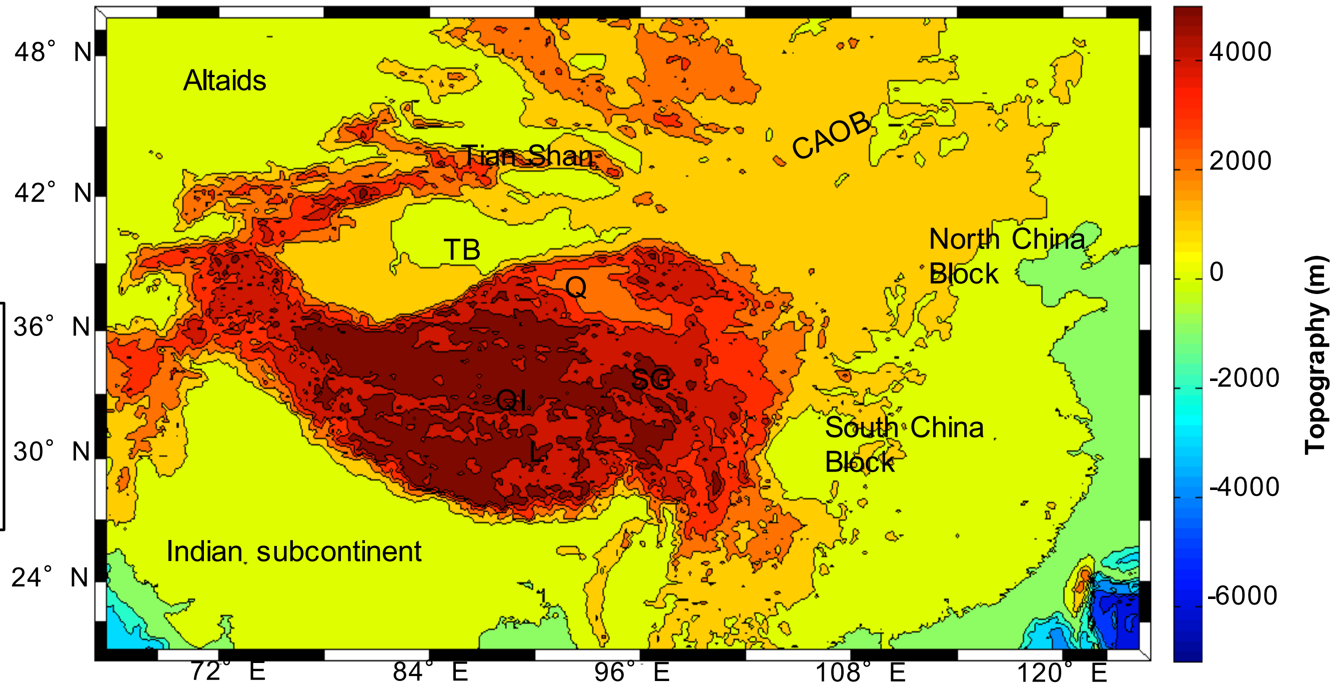
Suture zones

Mantle lithosphere scars

Localized and/or periodic deformation

Far-field compressional forcing

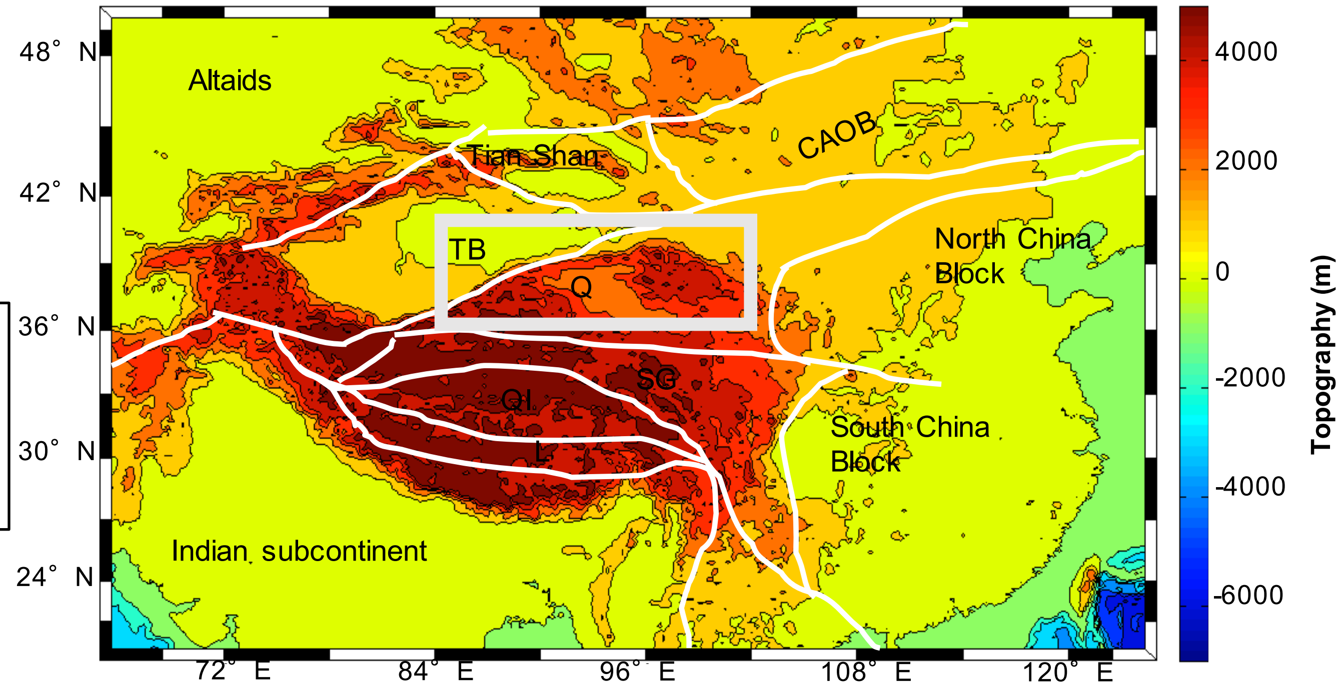
a India and Eurasia collision zone and ancient suture zones



a India and Eurasia collision zone and ancient suture zones

Far-field compressional forcing

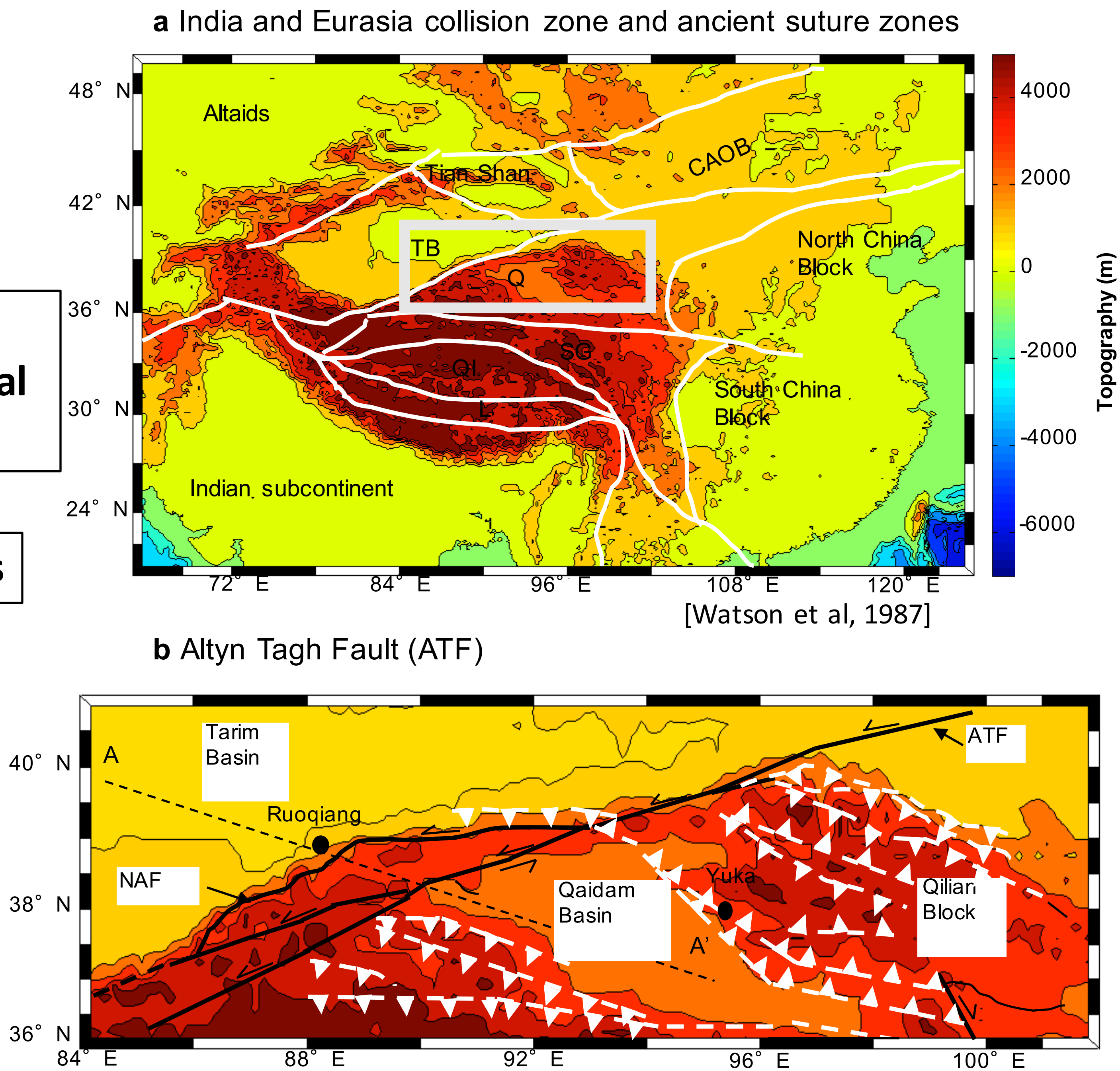
Suture zones



[Watson et al, 1987]

Far-field compressional forcing

Suture zones

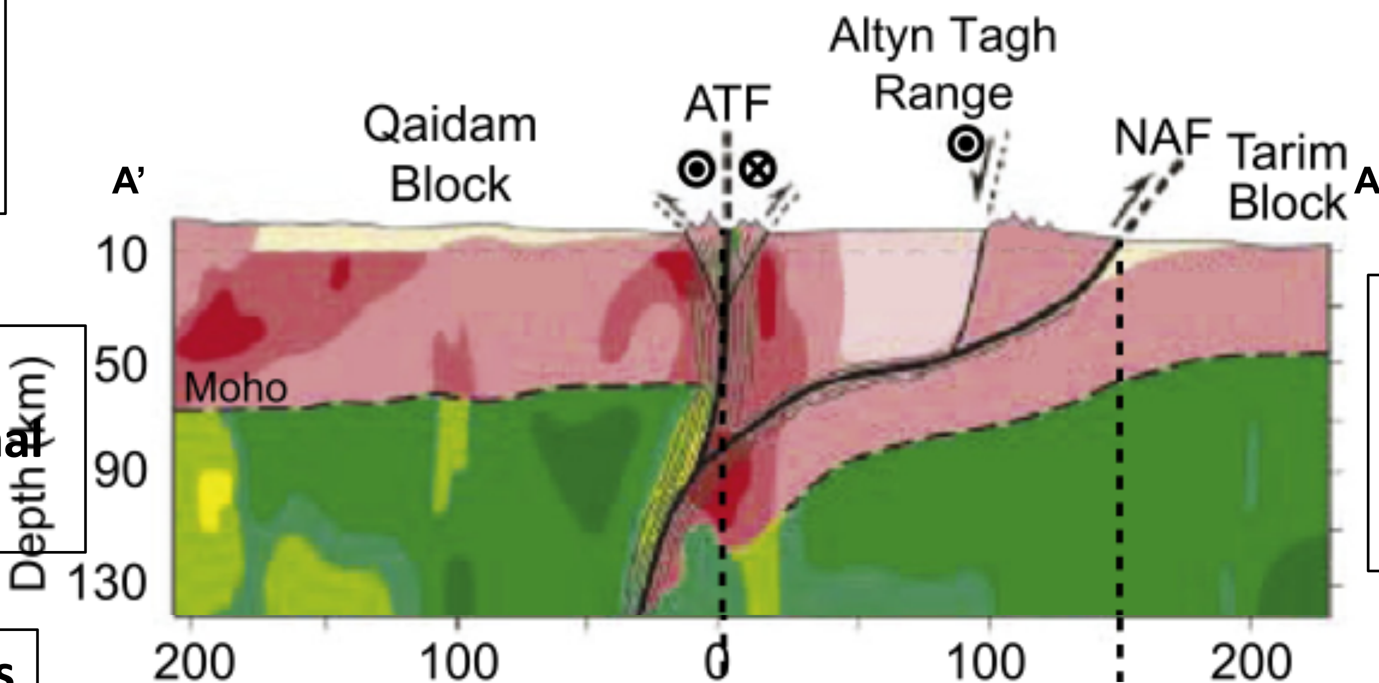


Mantle lithosphere scars

Far-field compressional forcing

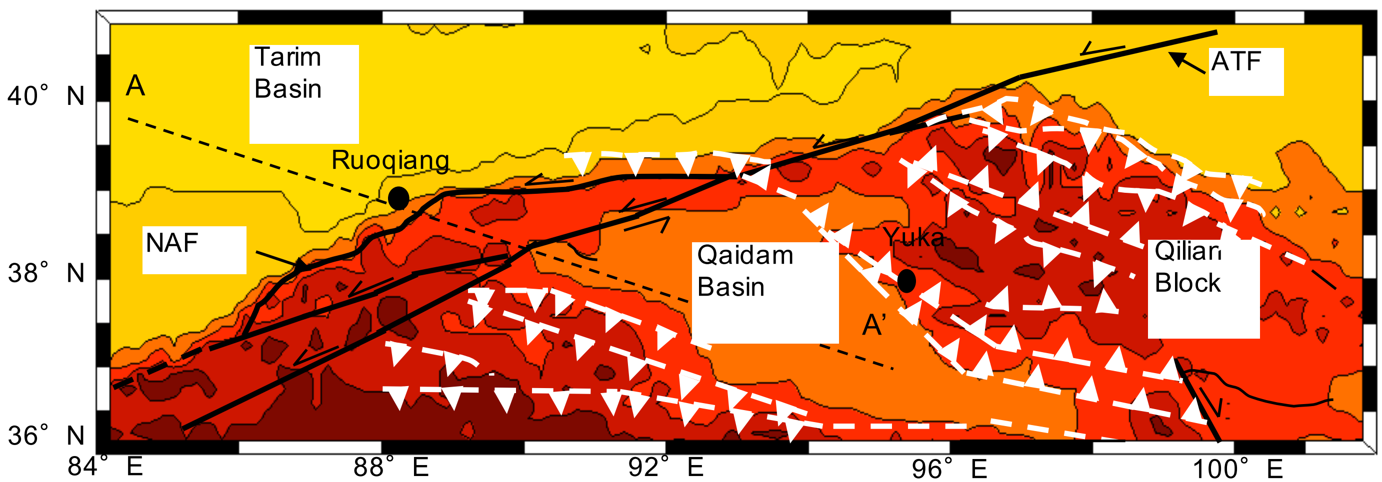
Suture zones

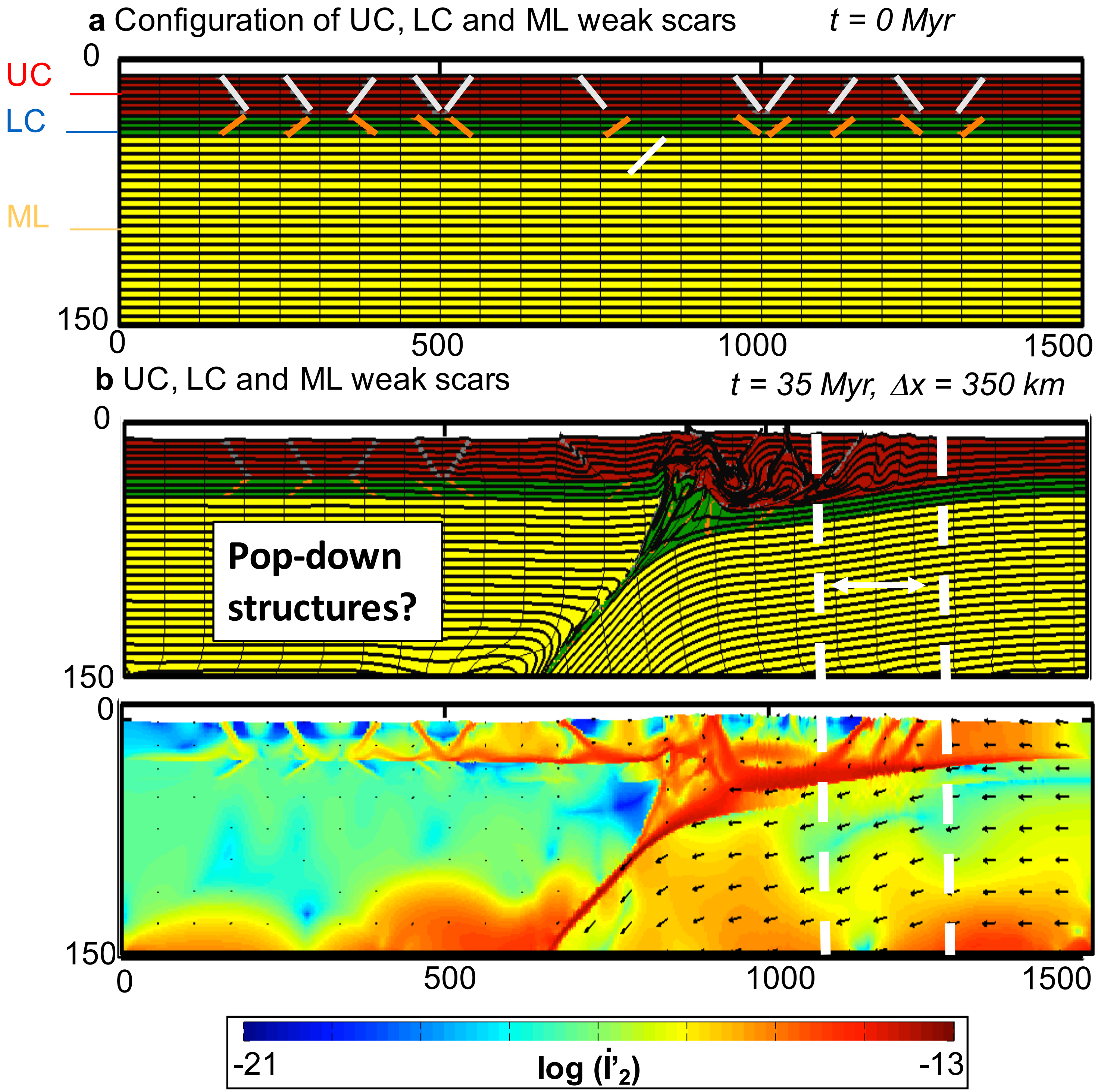
c Seismic imaging of ATF (Wittlinger et al., 1998)



Localized and/or periodic deformation

b Altyn Tagh Fault (ATF)





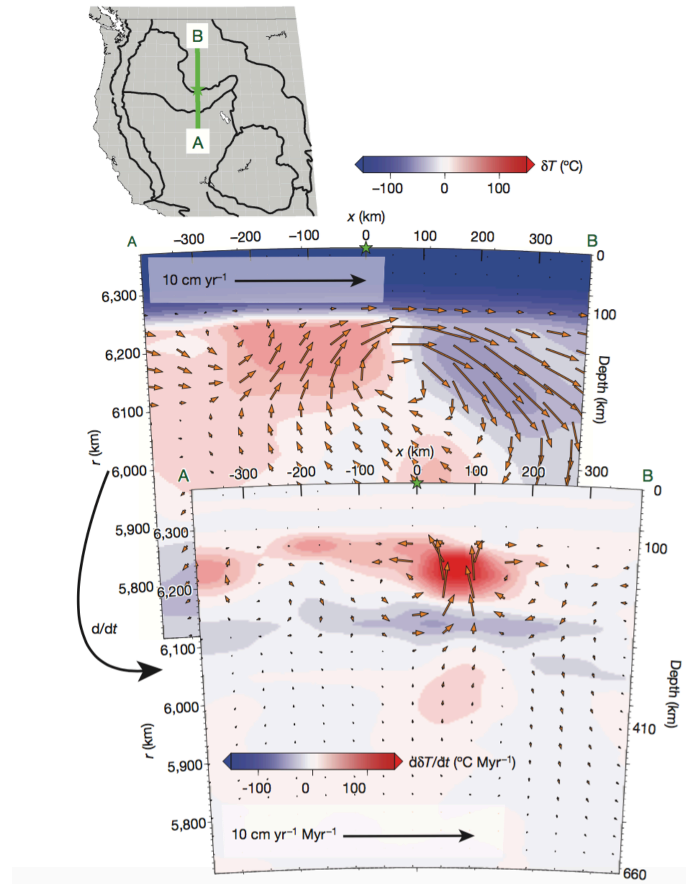
a Configuration of UC, LC and ML weak scars
t = 0 Myr
UC
LC
ML
0
150
0
500
1000
1500
b UC, LC and ML weak scars
t = 35 Myr, Δx = 350 km
0
150
Pop-down structures?
0
150
0
500
1000
1500
-21
log (İ'2)
-13

LETTER

doi:10.1038/nature14867

Western US intermountain seismicity caused by changes in upper mantle flow

Thorsten W. Becker[1], Anthony R. Lowry[2], Claudio Faccenna[3], Brandon Schmandt[4], Adrian Borsa[5] & Chunquan Yu[6]



[Becker et al., Nature, 2015]

SUB-CRUSTAL SCARS

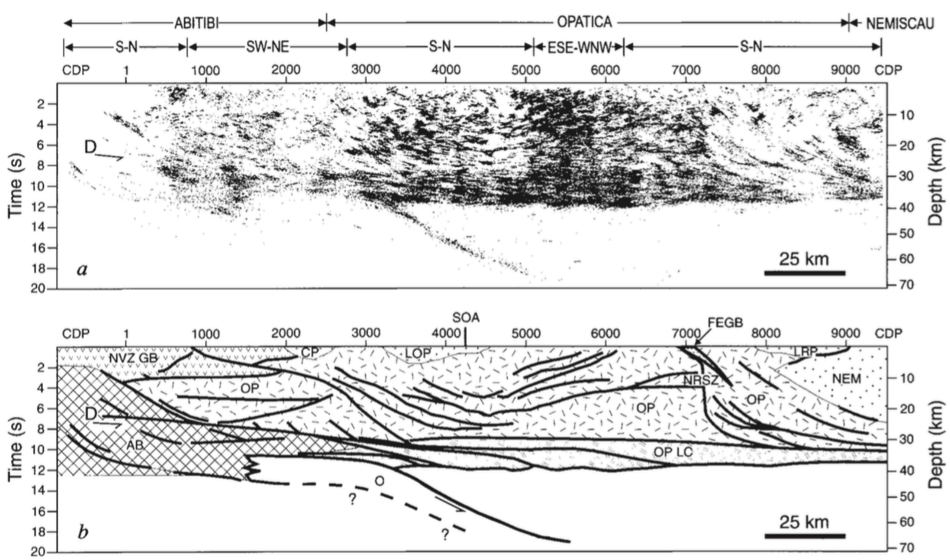
BEYOND PLATE BOUNDARIES

Archaean subduction inferred from seismic images of a mantle suture in the Superior Province

A. J. Calvert*, E. W. Sawyer†, W. J. Davis‡§ & J. N. Ludden‖§

SUBDUCTION

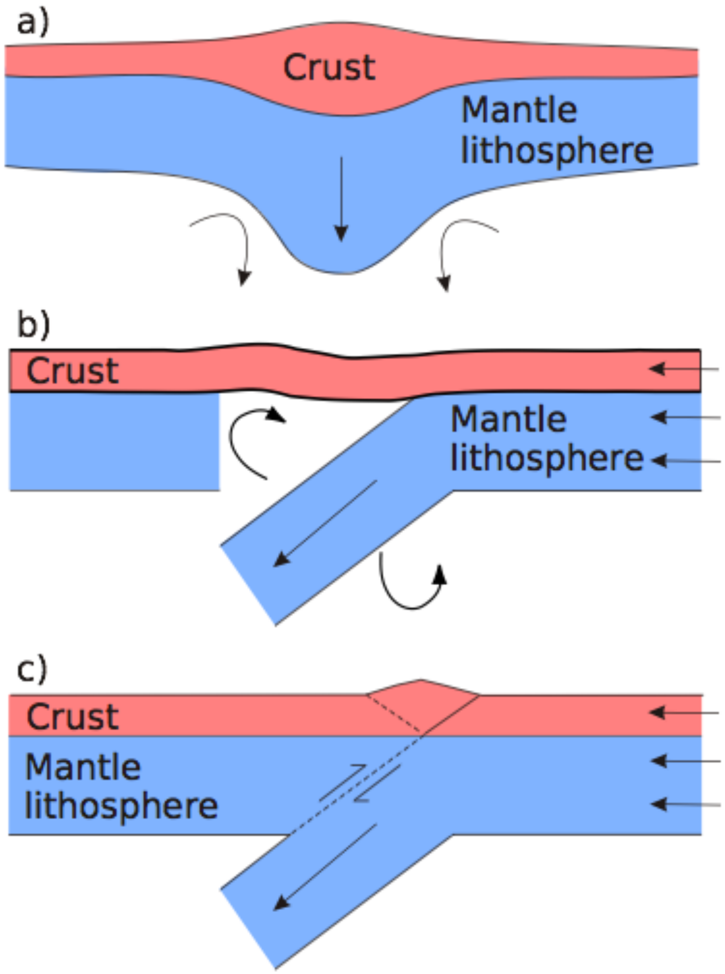
LETTERS TO NATURE



[Calvert et al., Nature, 1995]

SUB-CRUSTAL SCARS

BEYOND PLATE BOUNDARIES



[Pysklywec et al., JGR, 2002]

PLATE BOUNDARIES

- **SUBDUCTION**
- **MID-OCEAN RIDGE**
- **CONTINENT COLLISION**
- **TRANSFORM FAULT**

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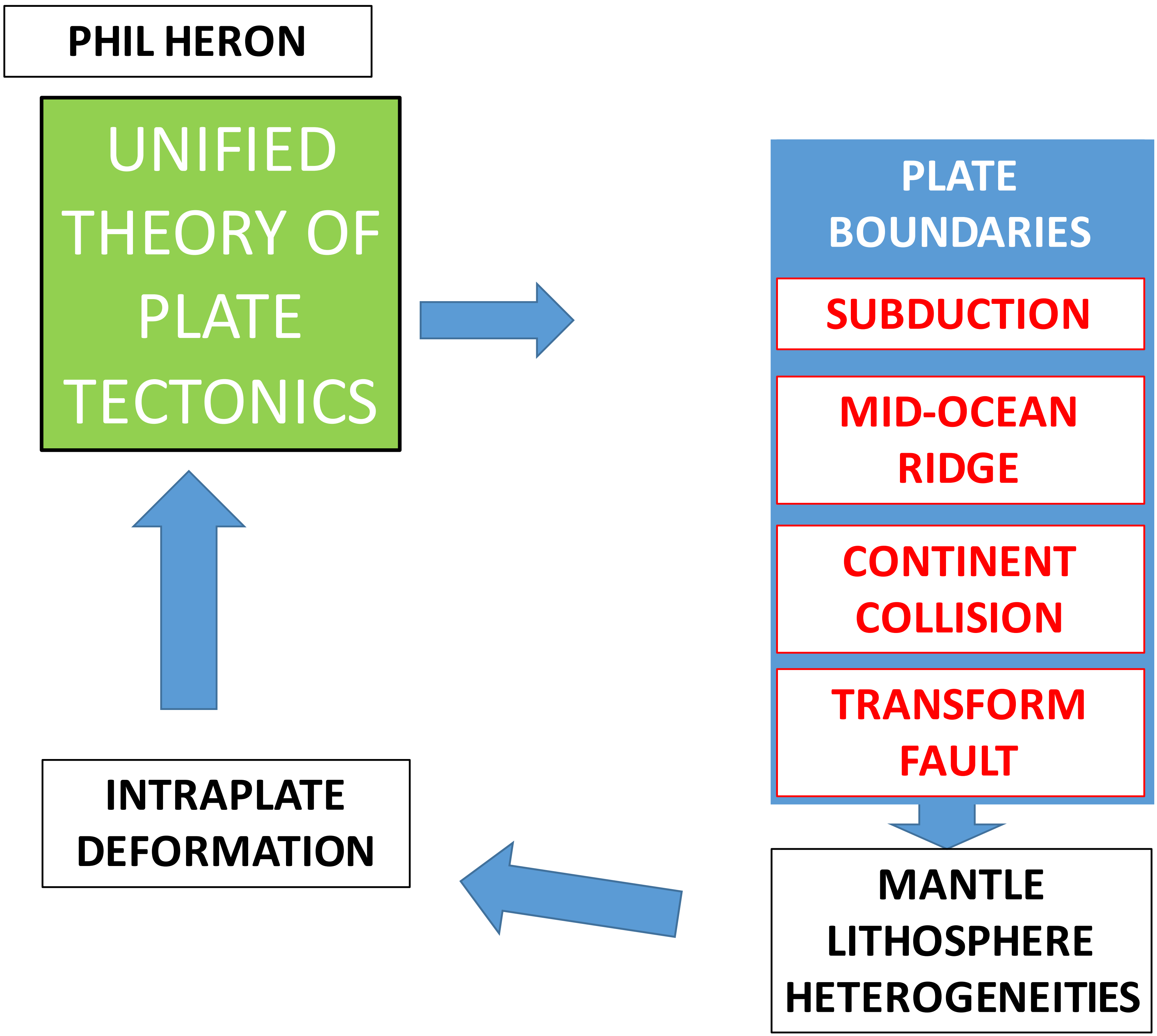
PLATE TECTONICS

PLATE BOUNDARIES

- SUBDUCTION
- MID-OCEAN RIDGE
- CONTINENT COLLISION
- TRANSFORM FAULT

INTRAPLATE DEFORMATION

??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UNIFIED THEORY OF PLATE TECTONICS
PLATE BOUNDARIES
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UNIFIED THEORY OF PLATE TECTONICS

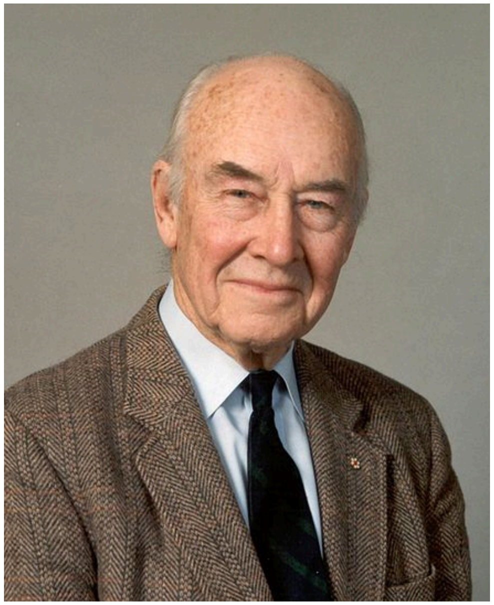

PLATE BOUNDARIES

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MANTLE LITHOSPHERE HETEROGENEITIES

INTRAPLATE DEFORMATION

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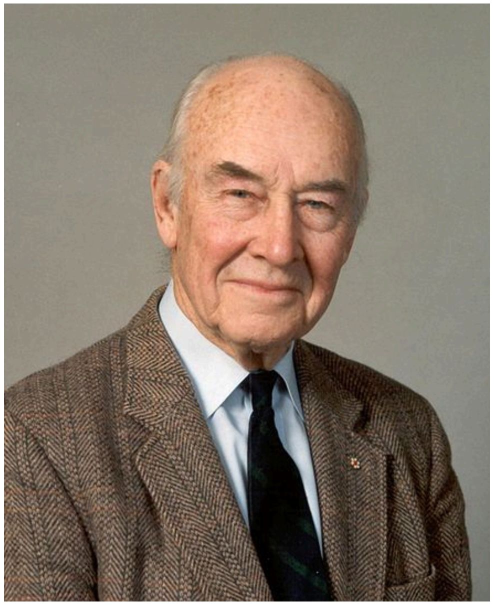
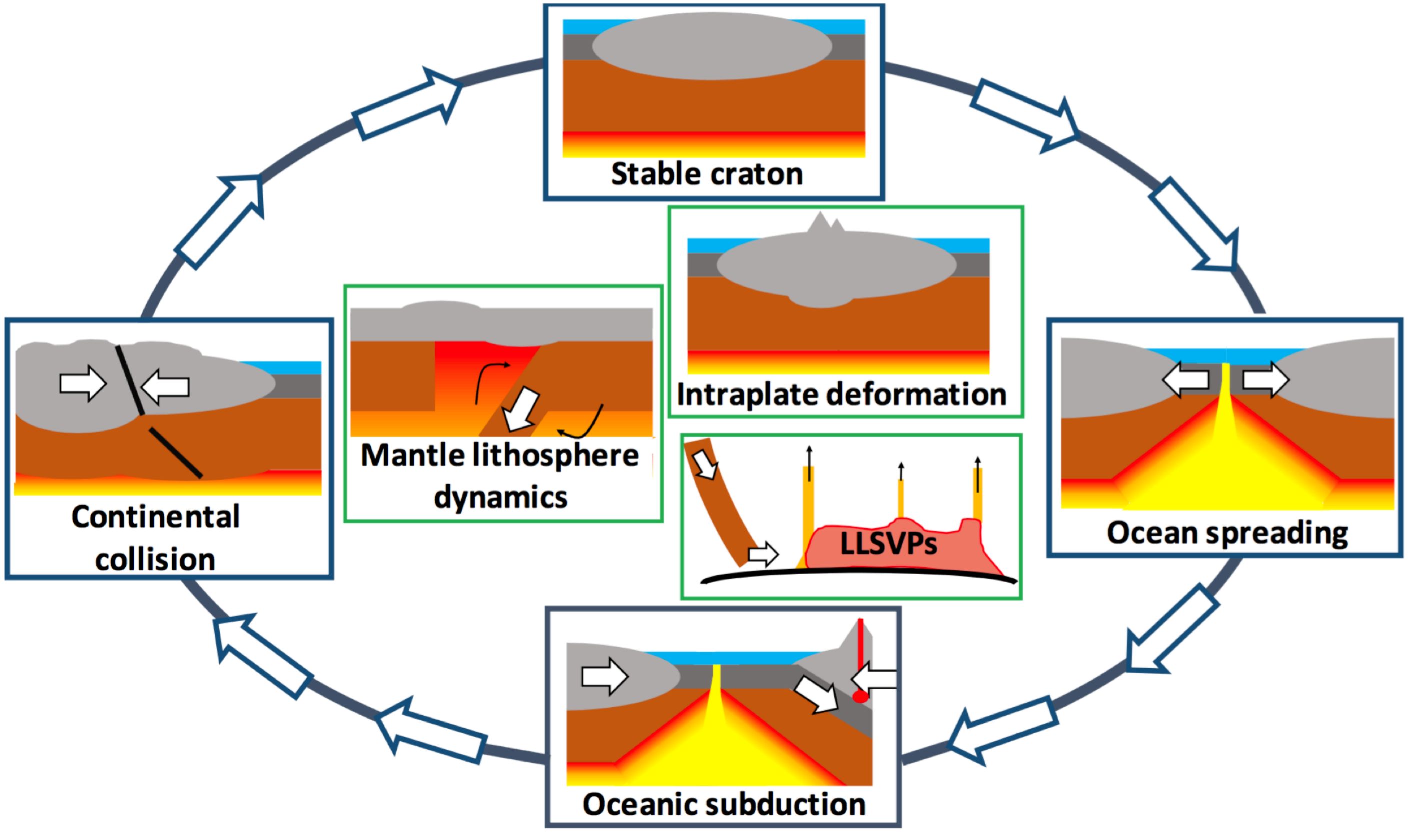
UNIFIED THEORY OF PLATE TECTONICS





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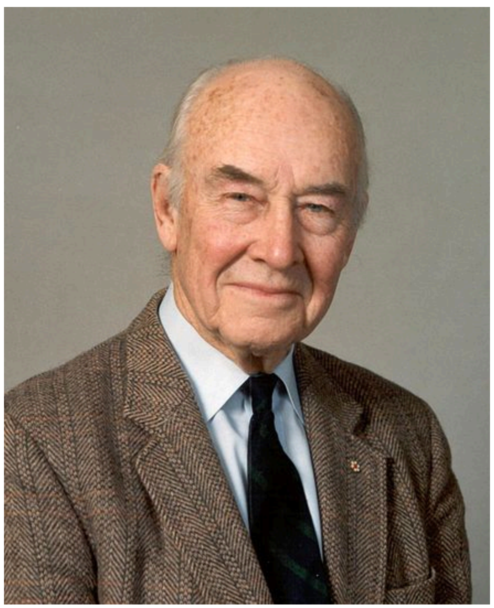

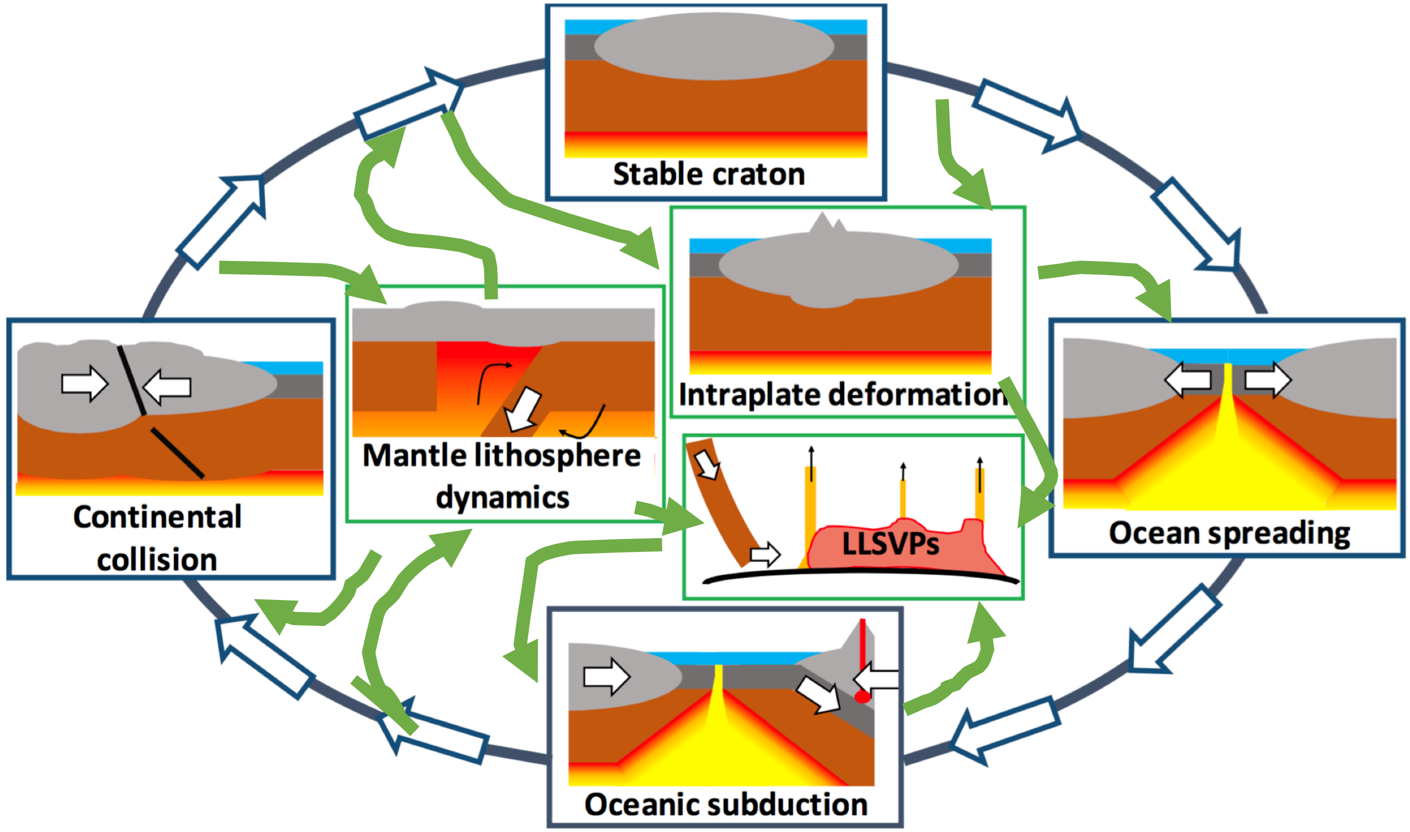

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AGU FALL MEETING

San Francisco | 12–16 December 2016

Session proposal

Exploring the theory of plate tectonics: the nature and role of the mantle lithosphere

CONVENORS

PHIL HERON

FIONA DARBYSHIRE

VADIM LEVIN

RUSS PYSKLYWEC

INDEX

GEODYNAMICS

GEOCHEMISTRY

GEODESY

SEISMOLOGY

TECTONICS

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PHIL HERON

Heron et al. (2016) *Nature Communications*.

Summary of work in relation to

Arthur Holmes Meeting 2016 - The Wilson Cycle: Plate Tectonics and Structural Inheritance During Continental Deformation

- The role of the mantle lithosphere is understudied
- A number of tectonic processes could leave lasting mantle lithosphere scars, not just subduction
- Mantle lithosphere structures could dominate shallower features in generating continental tectonics
- Reactivation of deep scars related to ancient plate boundary processes may mean that plate boundaries never go away

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Heron et al. (2016) ***Nature Communications*****.**

Plate Tectonic Map

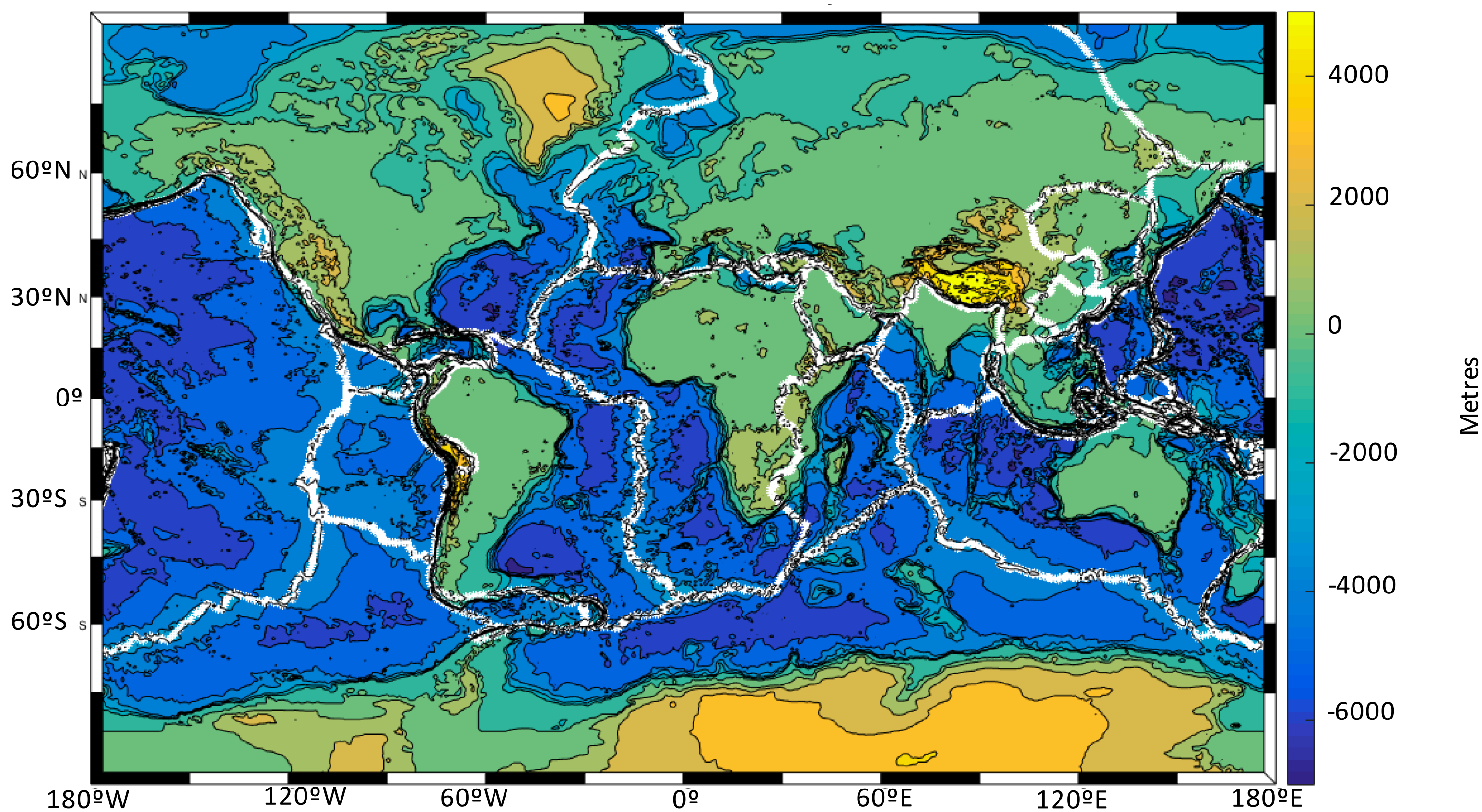

plate tectonics

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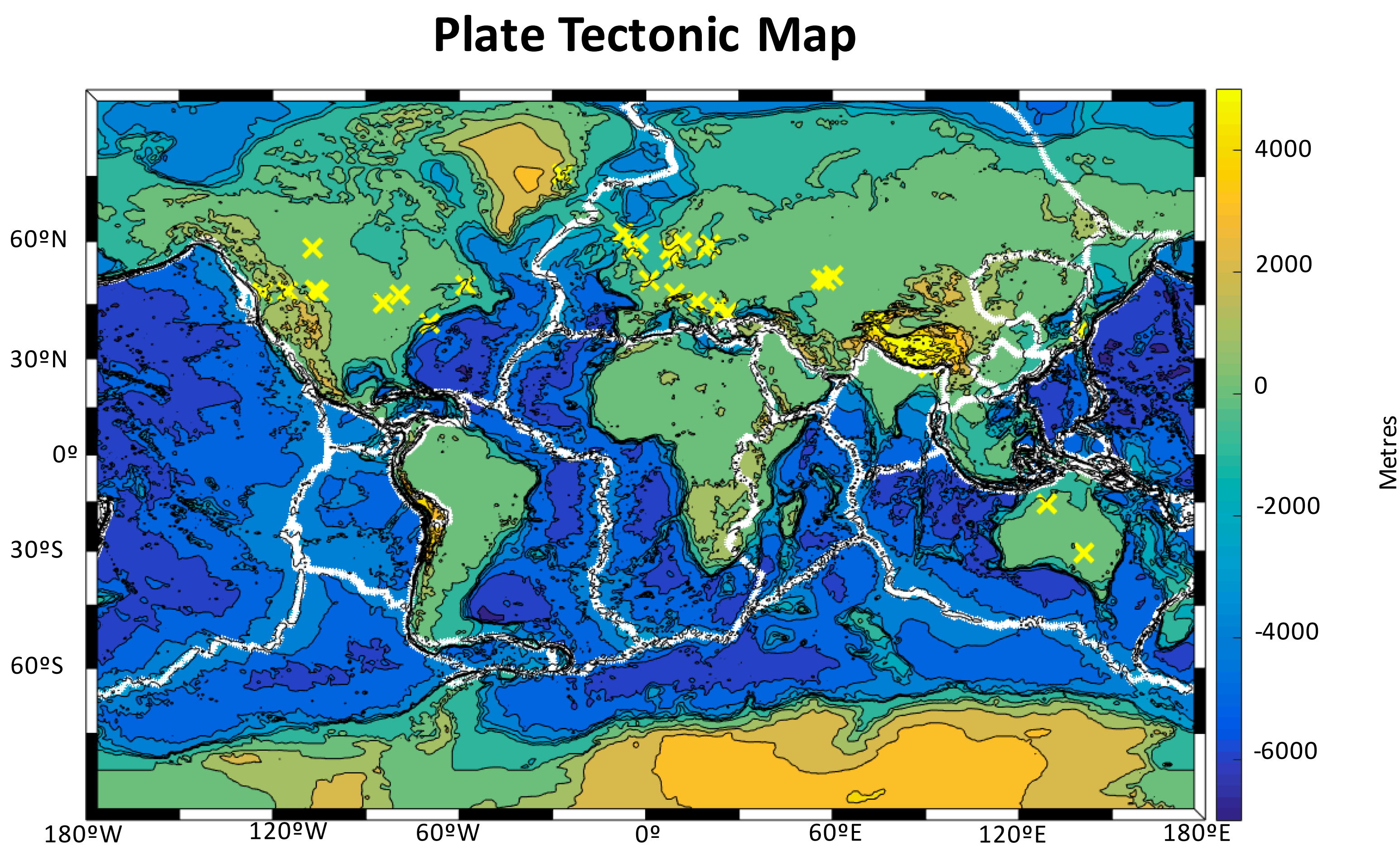
Heron et al. (2016) *Nature Communications*.



Lasting mantle lithosphere scars plate tectonics

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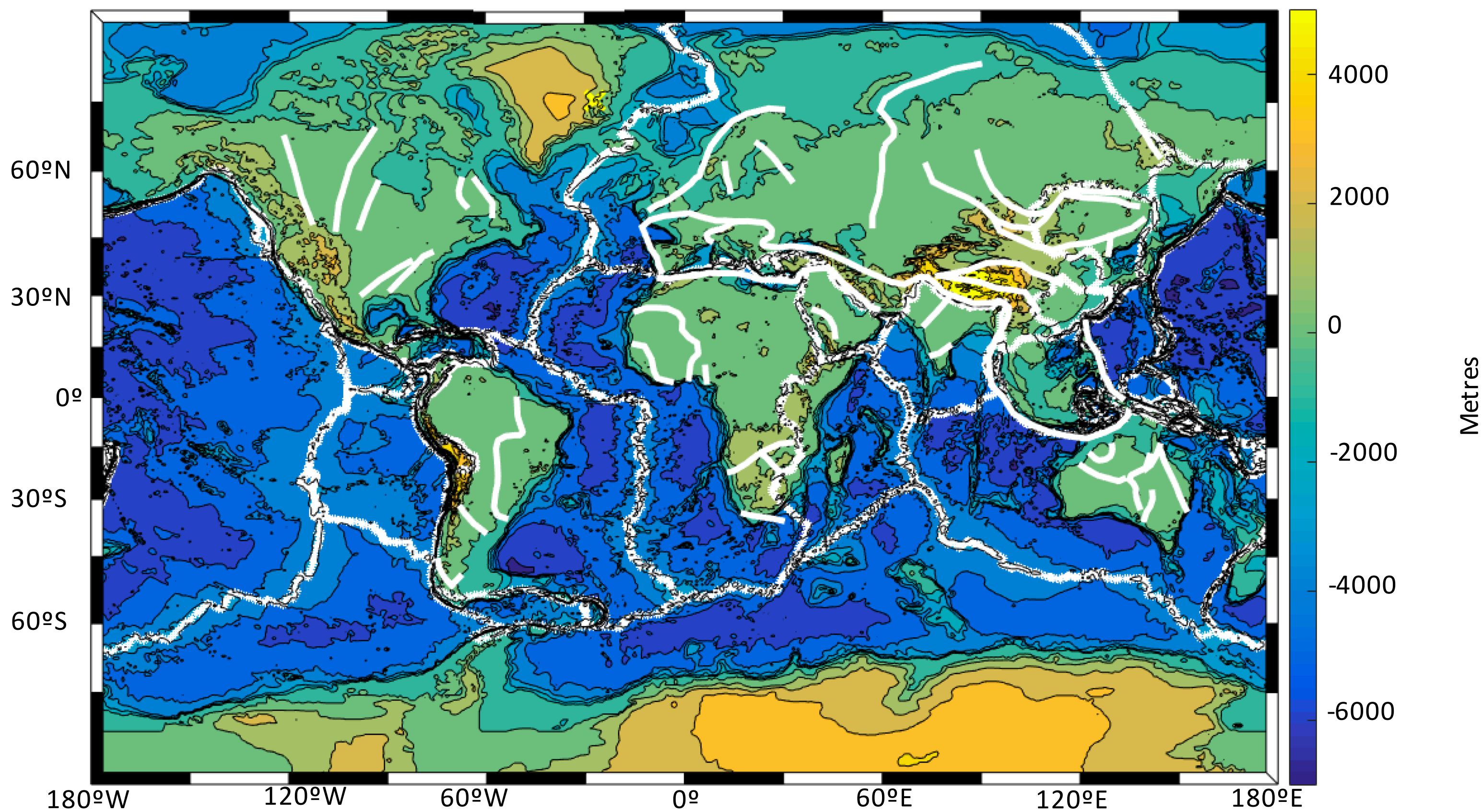
Heron et al. (2016) *Nature Communications.*

Timeless Plate Tectonic Map
Perennial Plate Tectonic Map



Lasting mantle lithosphere scars lead to perennial plate tectonics

PHIL HERON

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Lasting mantle lithosphere scars lead to perennial plate tectonics

PHIL HERON

Heron et al. (2016) *Nature Communications*.

What processes could be involved in intraplate orogenesis, seismisicty, and/or deformation?

Ongoing discussion – mantle lithosphere understudied

Could the mantle lithosphere retain ancient structures over long timescales?

Yes – there are many examples of scars possibly related to ancient tectonic structures

Could mantle lithosphere 'scars' be weak?

Yes - damage theory indicates scarring could mean weakness

Could mantle lithosphere 'scars' have a large scale impact on tectonics?

Yes - if crust and mantle are coupled, the mantle scars could dominant tectonics