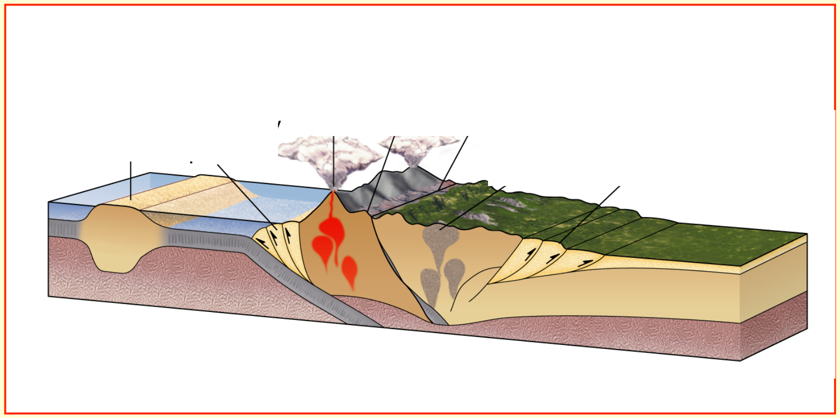
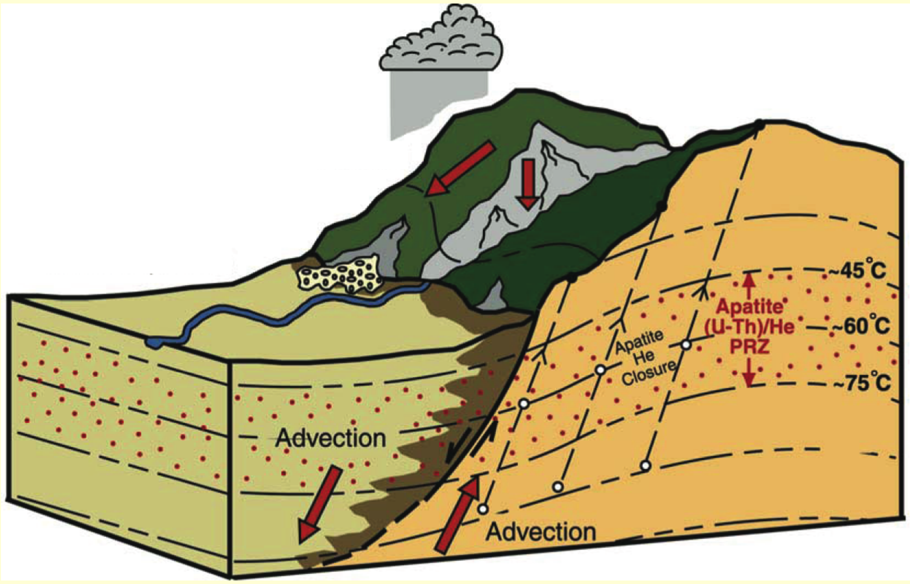
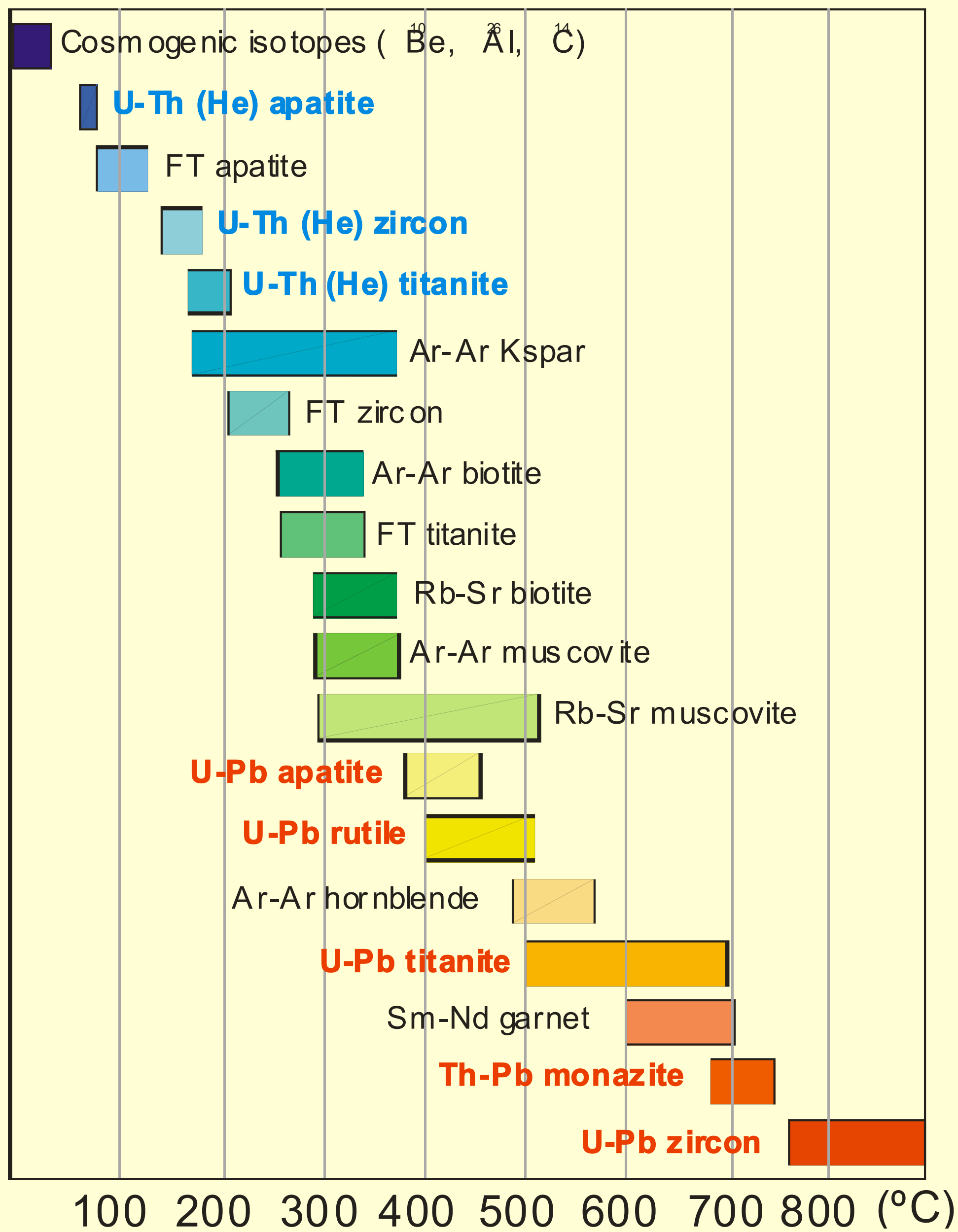
Thermochronology, thermal histories, and the stability of continents



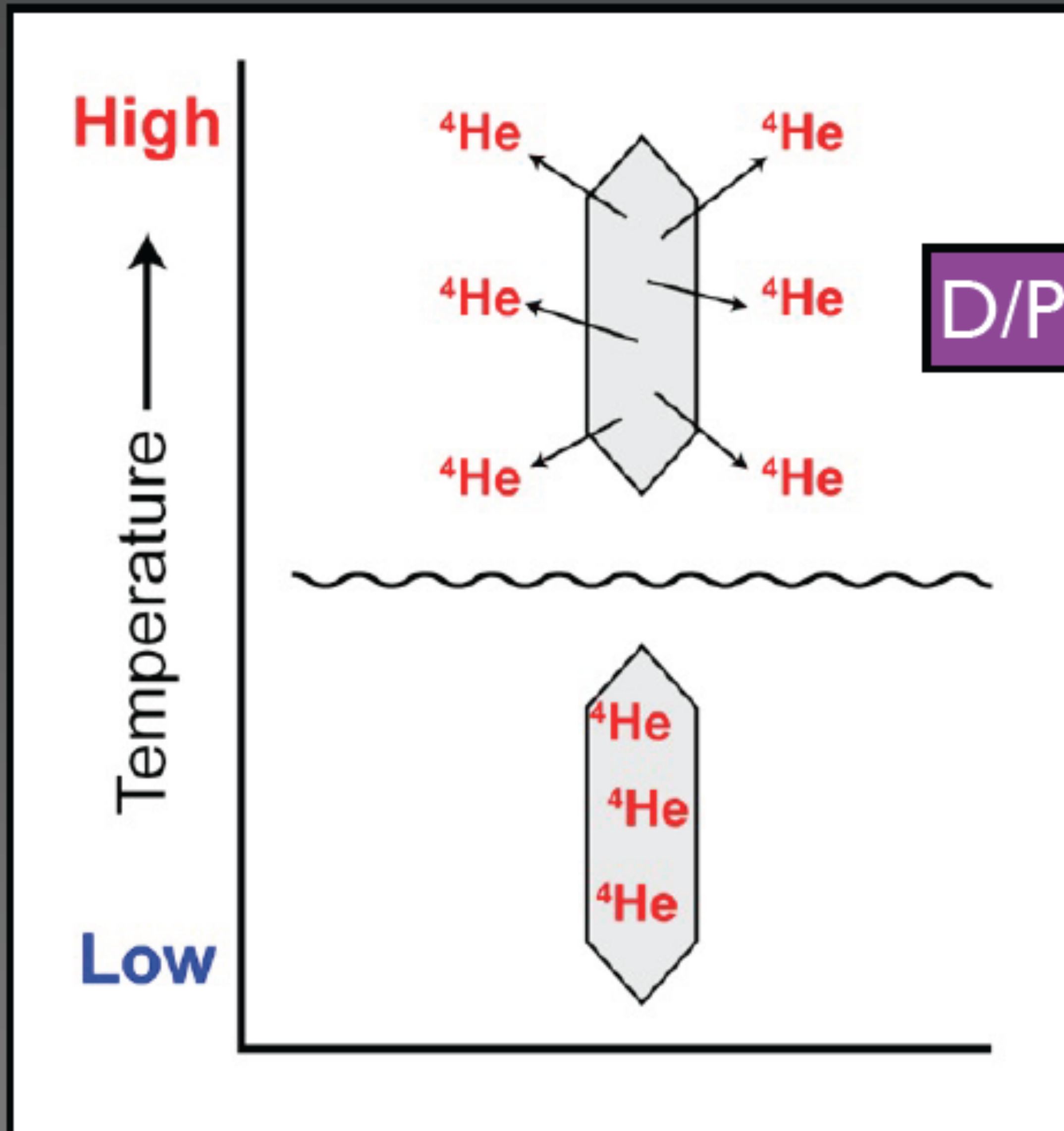



Cosmogenic isotopes (10Be, 26Al, 14C)
U-Th (He) apatite
FT apatite
U-Th (He) zircon
U-Th (He) titanite
Ar-Ar Kspar
FT zircon
Ar-Ar biotite
FT titanite
Rb-Sr biotite
Ar-Ar muscovite
Rb-Sr muscovite
U-Pb apatite
U-Pb rutile
Ar-Ar hornblende
U-Pb titanite
Sm-Nd garnet
Th-Pb monazite
U-Pb zircon
100
200
300
400
500
600
700
800
(°C)

Cartoon Thermochronology

$$t \propto \frac{D}{P}$$

$$t \propto \frac{He}{U + Th}$$

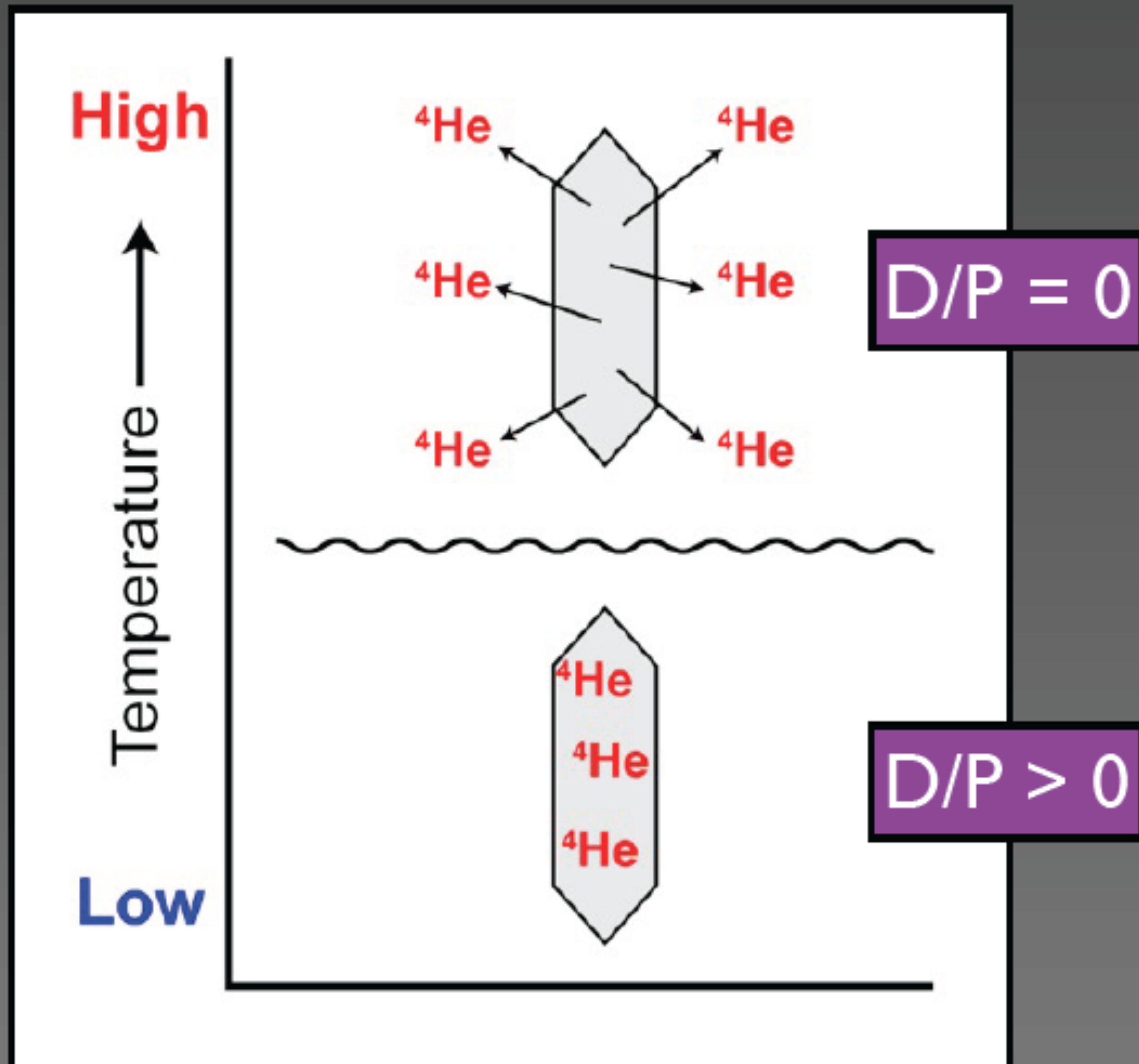


D/P = 0

Cartoon Thermochronology

$$t \propto \frac{D}{P}$$

$$t \propto \frac{He}{U + Th}$$



Cartoon Thermochronology

$$t \propto \frac{D}{P}$$

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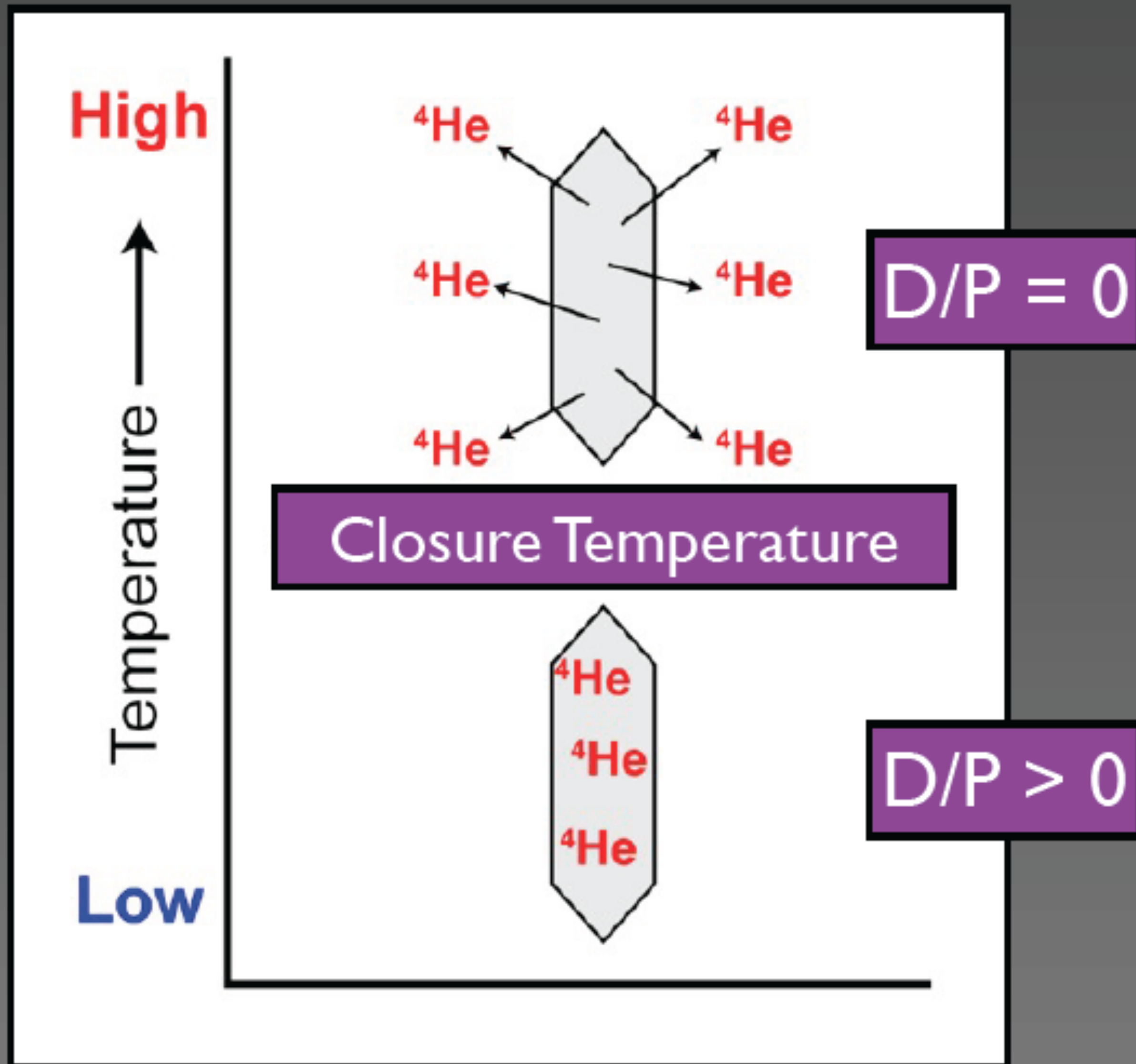
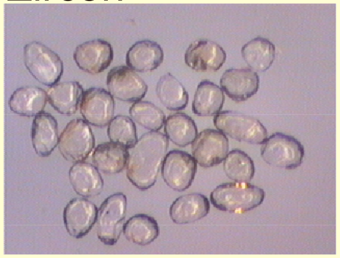


Geochronometers & Thermochronometers

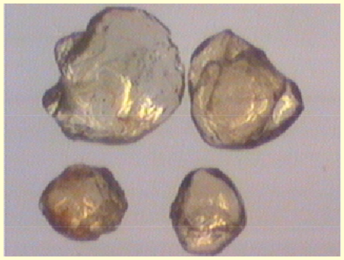
Geochronometer:
Mineral grows below closure temperature,
Date records crystallization

Thermochronometer:
Mineral grows above closure temperature,
Date records cooling

Zircon

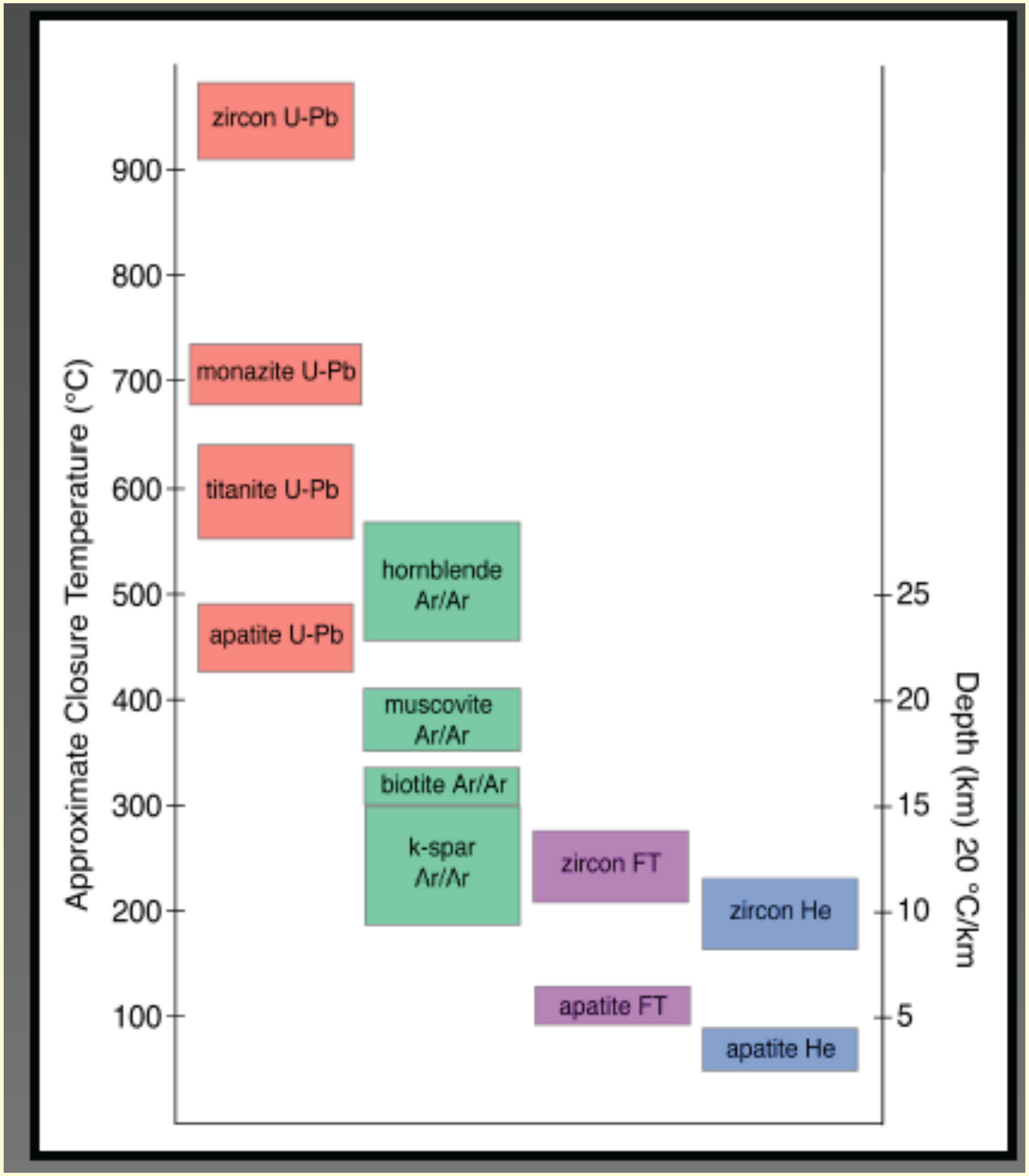


Titanite



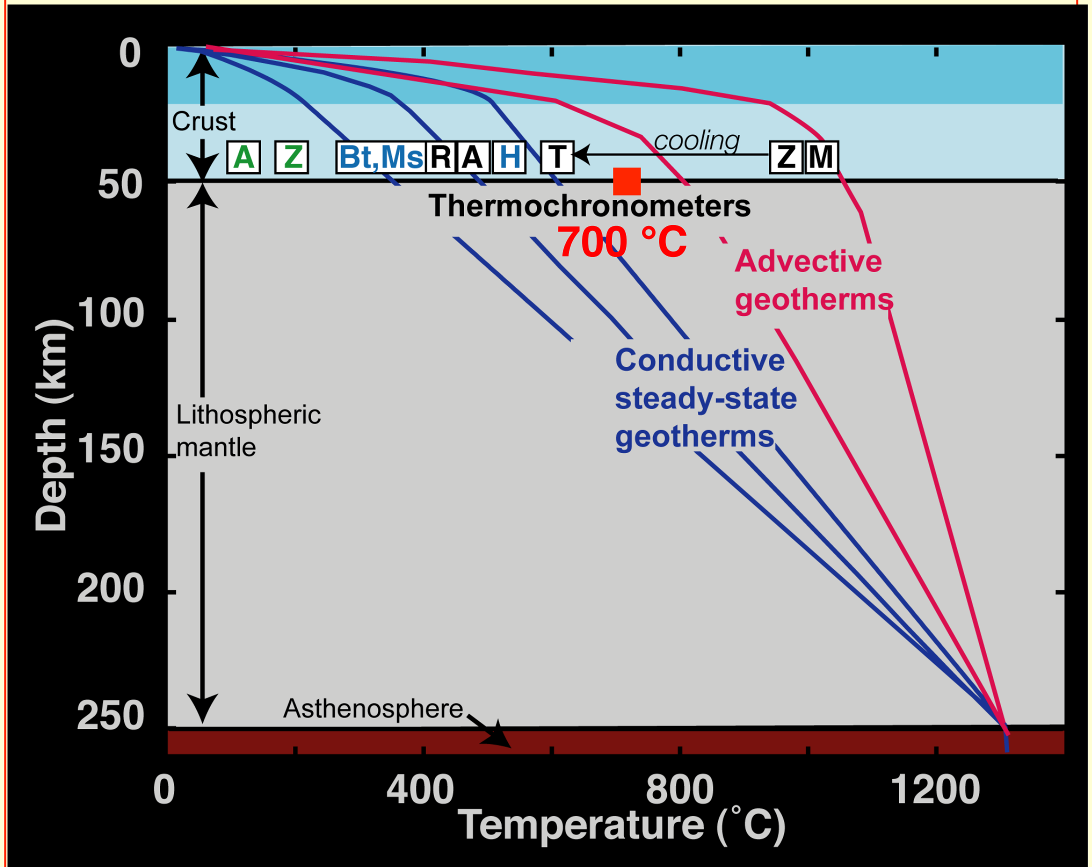
Rutile

Apatite

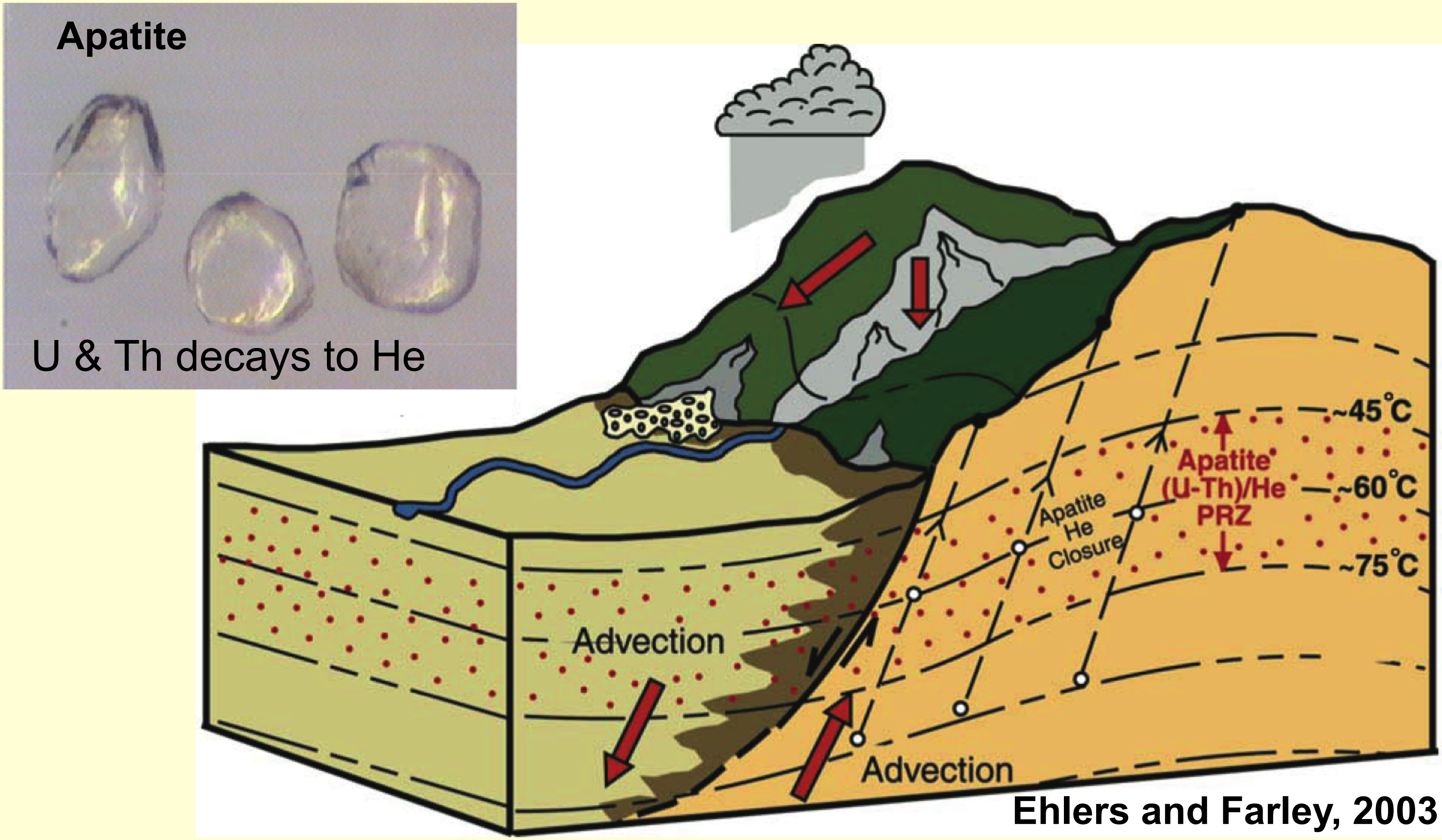


High to moderate temperature thermochronology

Lower crustal exposure, western Canadian Shield



Low Temperature Thermochronology: AFT & (U-Th)/He



- Use to decipher **thermal histories**
- Assumptions about geothermal gradient to constrain regional **unroofing**
- Lateral age variations can be used to detect **paleotopography**

Outline

1) Some thermochronology basics

(Some slides below from Kip Hodges and David Shuster
class lecture materials)

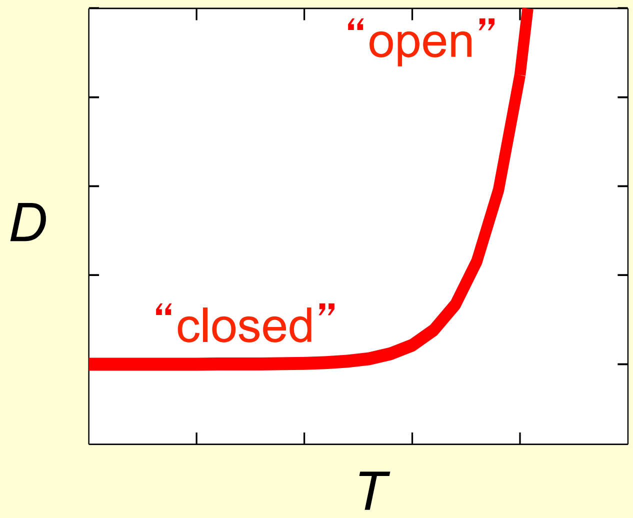
2) Fundamentals of (U-Th)/He thermochronology

3) How stable are continents?

- North American cratonic interior
- Southern African Plateau
- Colorado Plateau

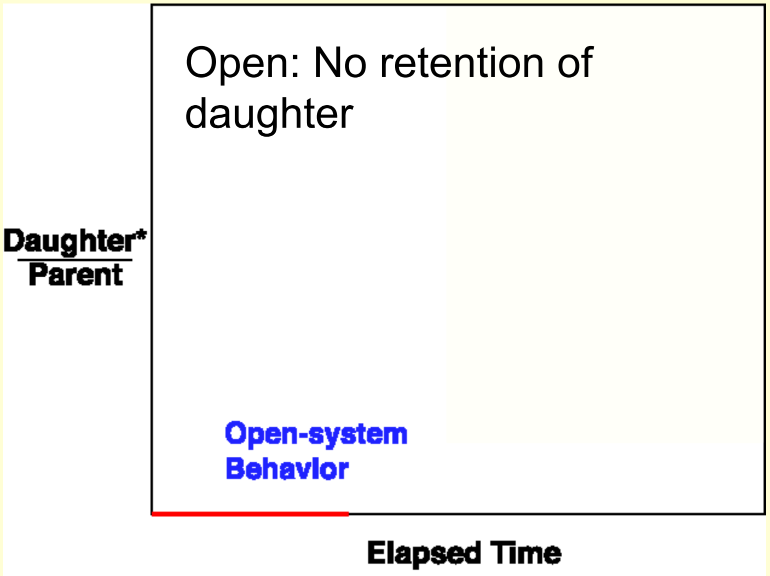
The Transition from Open- to Closed-System Behavior

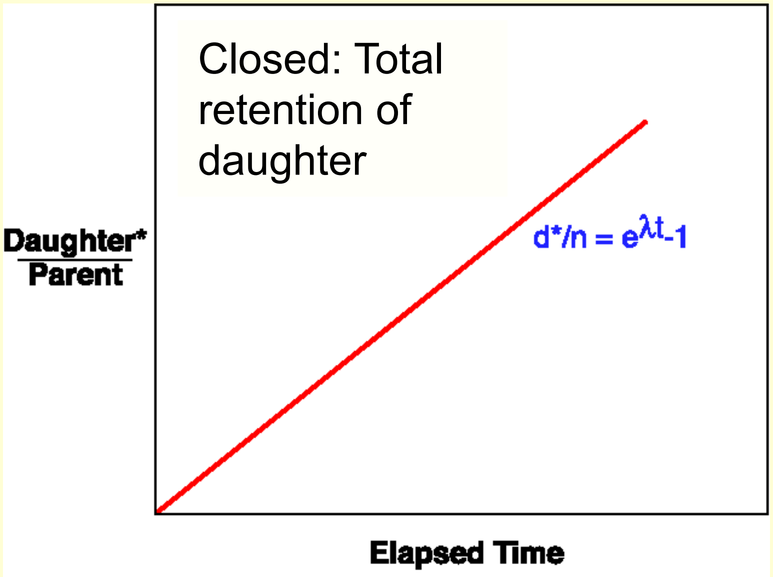
Dodson (1973)



Diffusion kinetics: D(T)

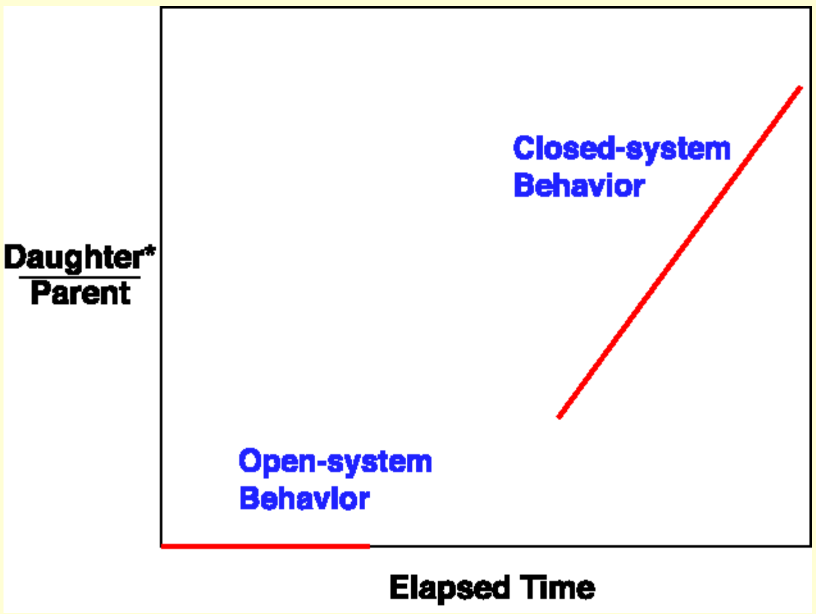
Simple diffusion scales exponentially with temperature





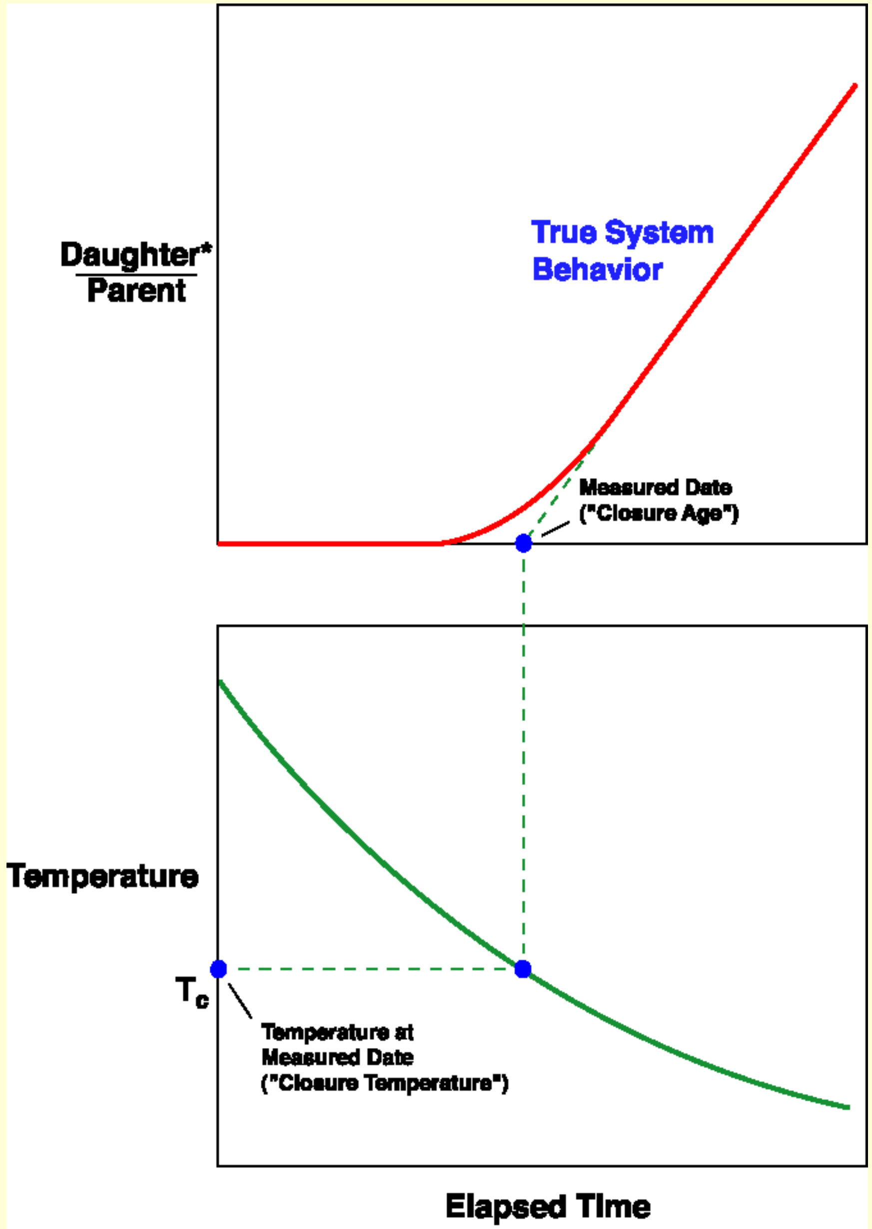
The Transition from Open- to Closed-System Behavior

As a system cools, we might expect it to have an early history of purely open-system behavior, and a later history of purely closed-system behavior:



Closure Temperature Concept

The “closure temperature” – T_c – was defined by Dodson as the temperature of a system at the time of its measured date.



Bulk Closure Temperature Equation

$$T_c = \frac{E}{R \ln\left[\frac{ART_c{}^2 D_0}{a^2 E(dT/dt)}\right]}$$

Where

T_c	=	closure temperature
D_0, E	=	diffusion parameters
R	=	gas constant
A	=	geometric term (55 for a sphere, 27 for a cylinder, 8.7 for a plane sheet)
a	=	effective diffusion dimension
dT/dt	=	cooling rate

Characterizing diffusion kinetics:

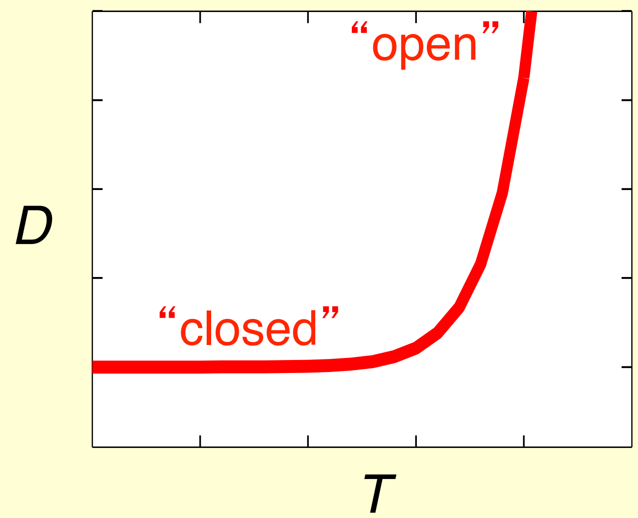
Our ability to accurately interpret thermochronology data fundamentally depends on our understanding of diffusion kinetics

Based on many experimental studies of natural systems, D has been found to depend exponentially temperature through the so-called "Arrhenius relationship":

Simplified: $$D = D_o e^{\frac{-E}{RT}}$$

Where

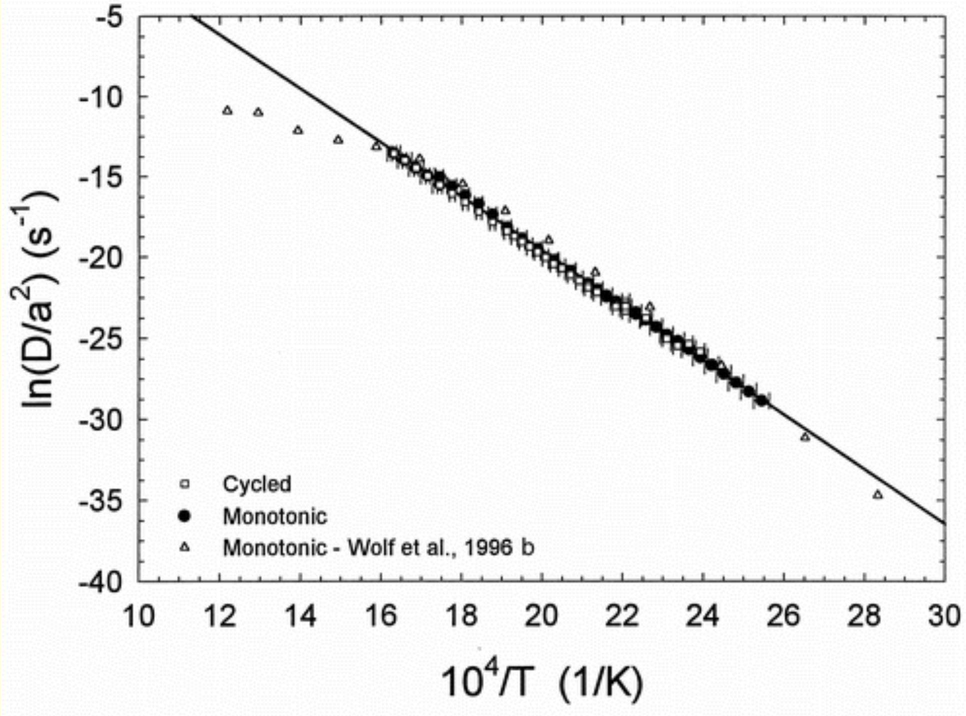
D	=	Diffusivity at conditions of interest
D_o	=	Pre-exponential constant
E	=	Activation energy
R	=	Gas constant
T	=	Temperature



Diffusion kinetics: D(T)

Experimental Diffusion Studies

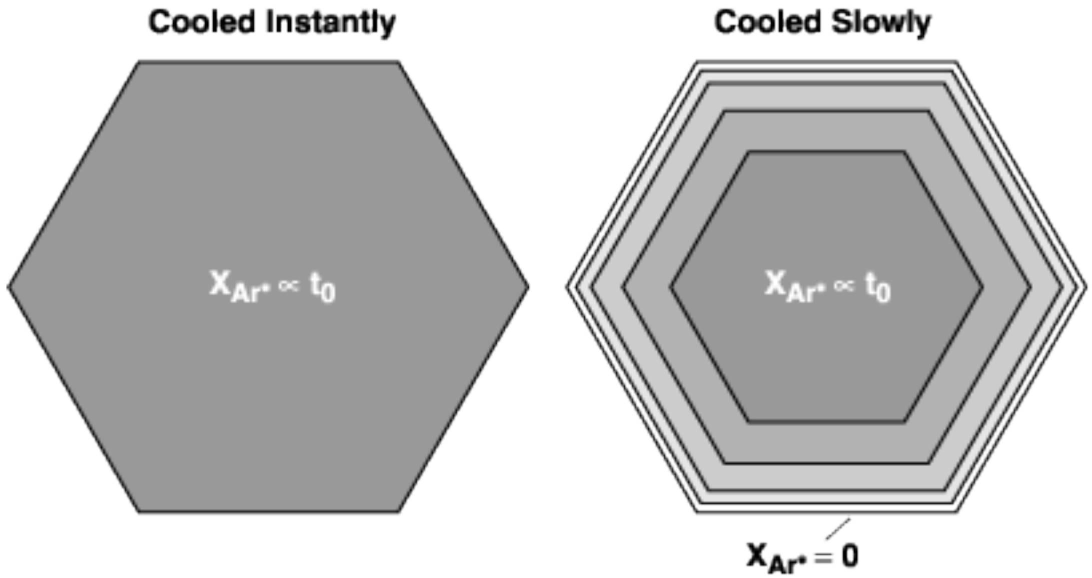
- Appropriate for gaseous species
- Involve controlled heating experiments
- Small amounts of gas liberated by heating for a certain time at a certain temperature, such that *D* can be determined as a function of fractional loss
- Calculate Arrhenius parameters from plots of ln*D* *vs.* 1/*T*



Farley, 2000

Effects of Slow Cooling

- Diffusion theory suggests that minerals become zoned in radiogenic daughter elements during cooling as a consequence of diffusive loss.

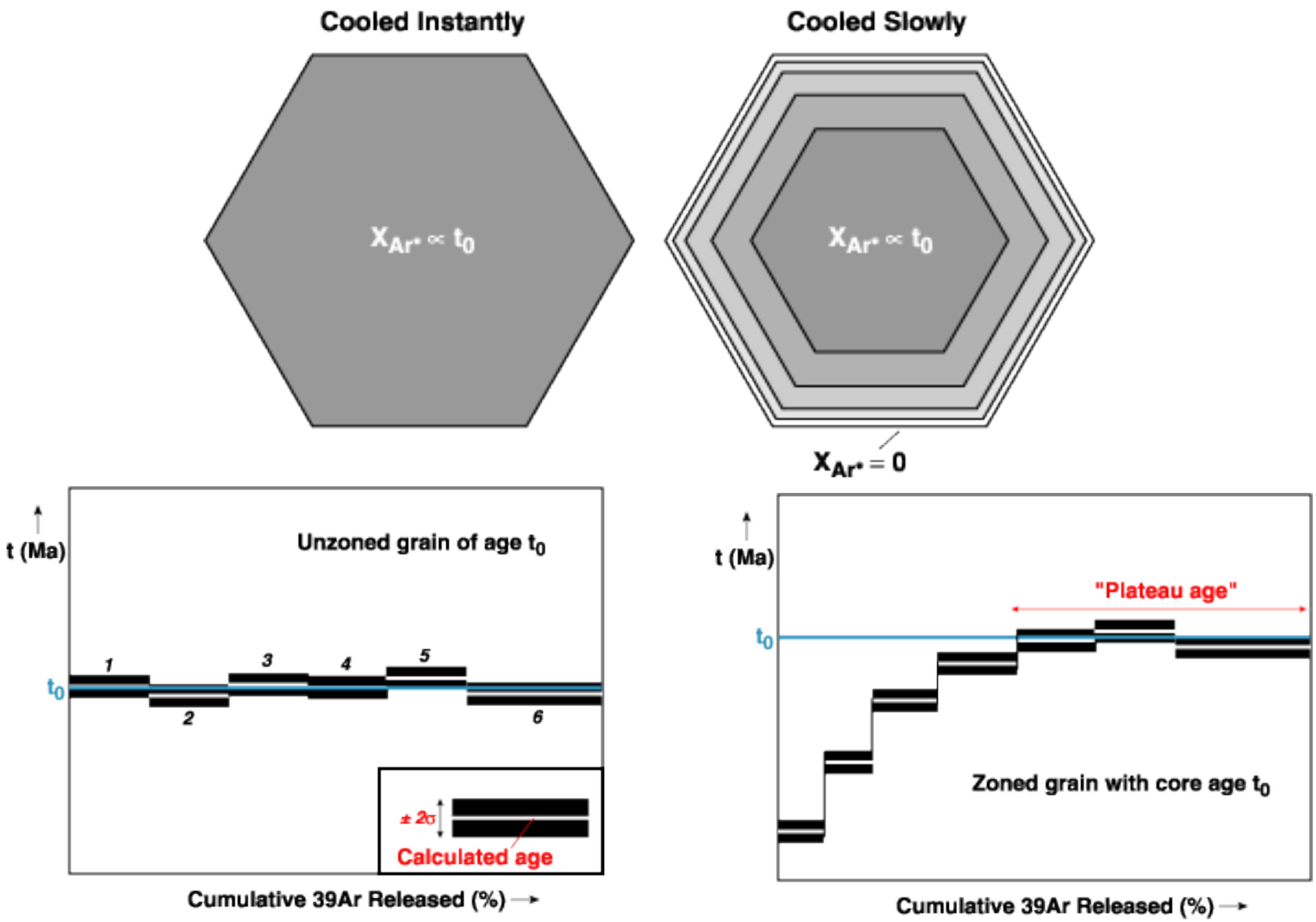


Characterizing gradients

1. Laser ablation techniques
2. Step-heating experiments

Characterizing gradients

- Diffusion theory suggests that minerals become zoned in radiogenic daughter elements during cooling as a consequence of diffusive loss.



Outline

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(Some slides below from Kip Hodges and David Shuster
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- North American cratonic interior
- Southern African Plateau
- Colorado Plateau

Actinium, Uranium, and Th Decay Series

Actinium series decay leads eventually to the production of stable ^{207}Pb and can be written as:

$$^{235}U \Rightarrow {}^{207}Pb + 7\,{}^{4}He + 4\beta^{-} + Q$$

Uranium series decay leads to the production of stable ^{206}Pb and can be written as:

$$^{238}U \Rightarrow {}^{206}Pb + 8\,{}^{4}He + 6\beta^{-} + Q$$

Thorium exists primarily in nature as ^{232}Th. For ^{232}Th, the scheme can be written:

$$^{232}Th \Rightarrow {}^{208}Pb + 6\,{}^{4}He + 4\beta^{-} + Q$$

^{4}He Production

The vast majority of ^{4}He is produced through the process:

$$^4He = 8\,^{238}U(e^{\lambda_{238}t} - 1) + 7\,^{235}U(e^{\lambda_{235}t} - 1) + 6\,^{232}Th(e^{\lambda_{232}t} - 1)$$

Where

λ_{238} = 1.55125×10^{-10} a^{-1}

λ_{235} = 9.8485×10^{-10} a^{-1}

λ_{232} = 4.9475×10^{-11} a^{-1}

History of (U-Th)/He Thermochronometry

Early days:

1. Rutherford first proposed U-He dating in 1905 (the first geochronometer)

2. Hurley, 1954 first tried applying the technique to date geologic materials

   Fundamental problems:

   - System yielded results that were unreasonably young (e.g., based on stratigraphy constraints)
   - some crystals gave “less unreasonable” ages

   The dating technique was abandoned for years…

History of (U-Th)/He Thermochronometry

Renewed interest:

1. Zeitler et al., 1987 proposed use of (U-Th)/He in apatite as a "thermochronometer"

2. Farley dealt with alpha particle emission from grain edges and carried out diffusion experiments to characterize apatite He diffusivity

3. Since then, hundreds of papers have been published

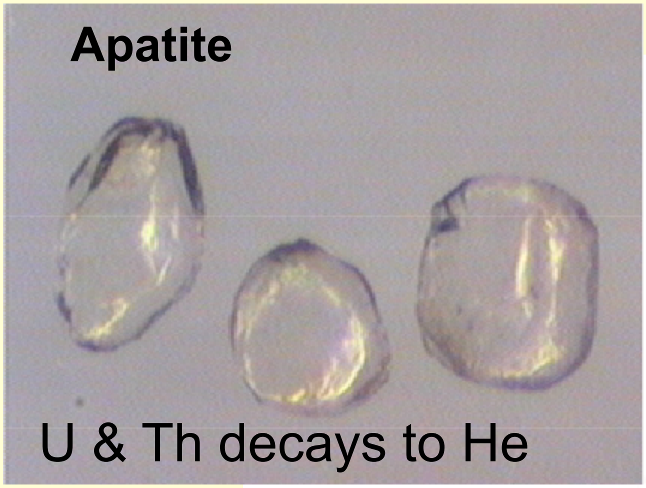
Minerals used for (U-Th)/He thermochronometry

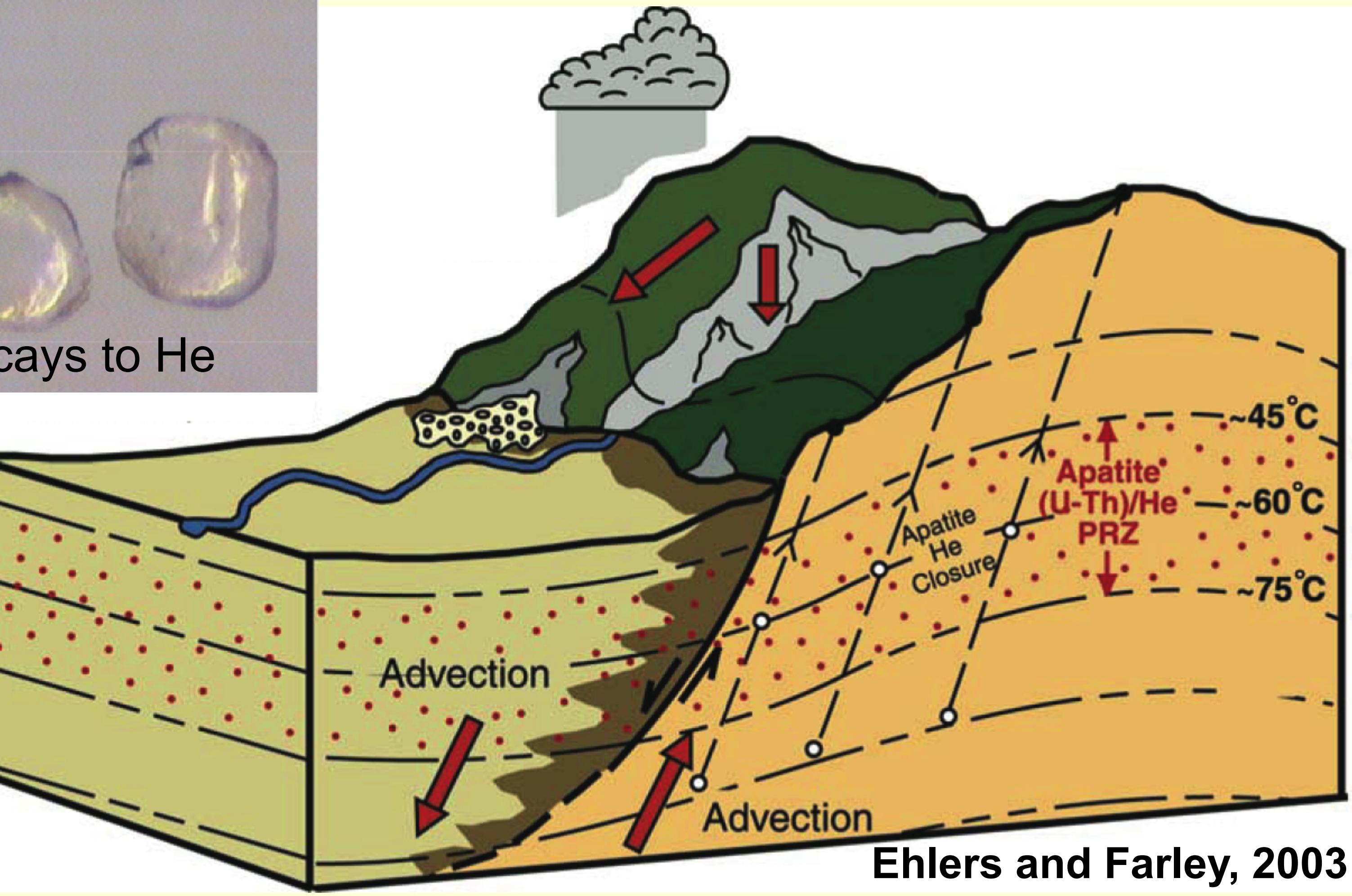
Most applications thus far have focused on apatite and zircon.

However, any U-Th bearing mineral can be dated.

Other possibilities on which some work has been or is being carried out include titanite, monazite, xenotime, rutile, magnetite, goethite, epidote, calcite, garnet and baddeleyite.

Low Temperature Thermochronology: AFT & (U-Th)/He



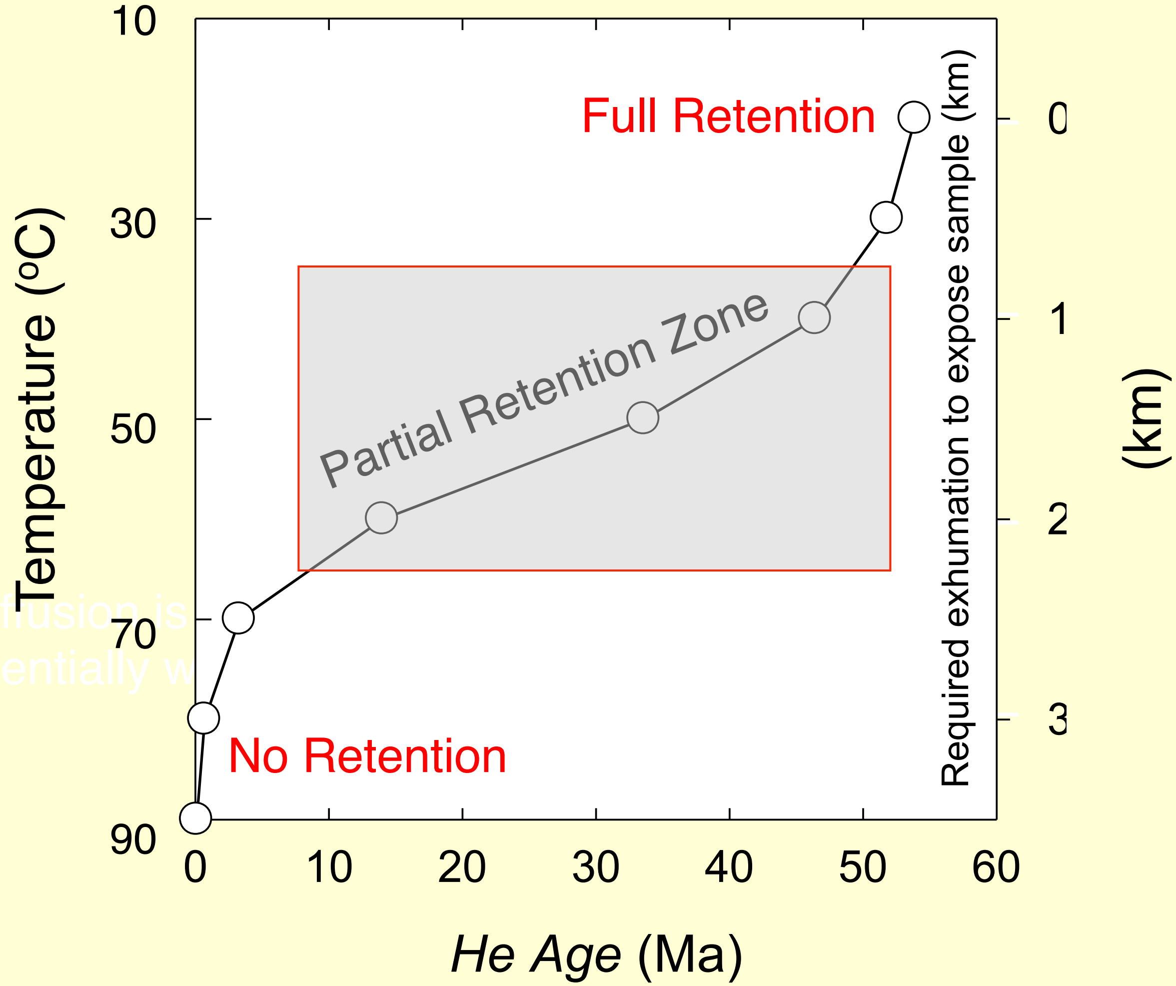


Ehlers and Farley, 2003

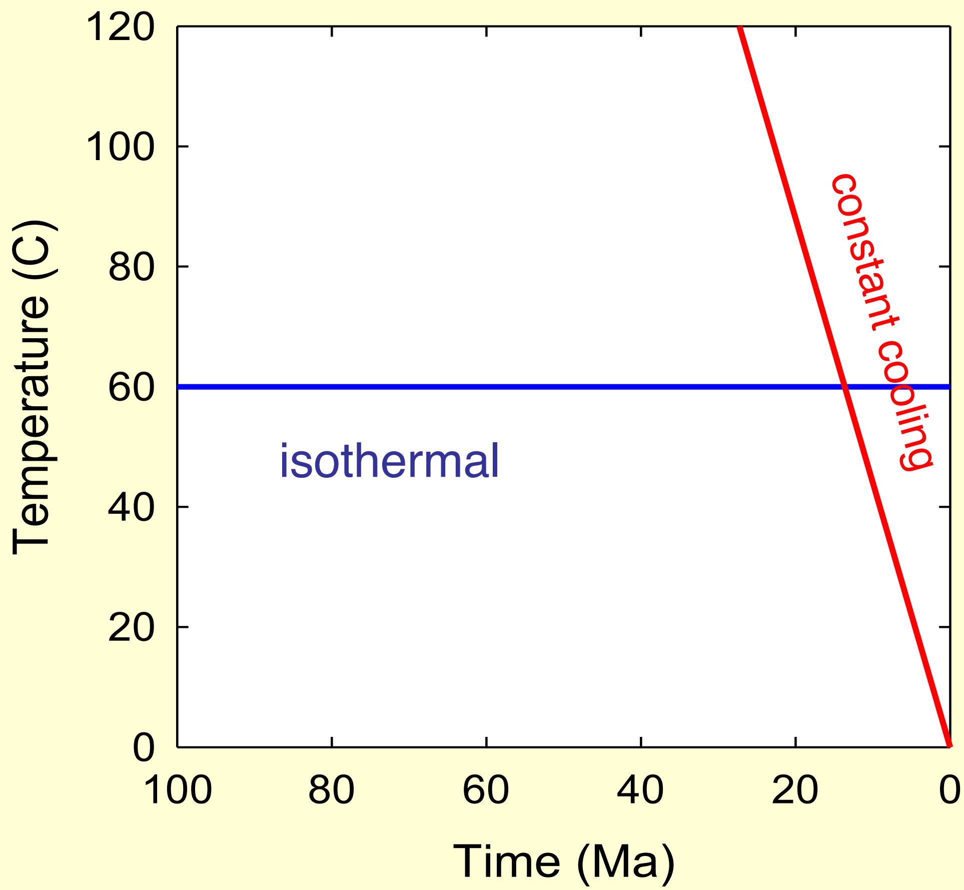
- Use to decipher **thermal histories**
- Assumptions about geothermal gradient to constrain regional **unroofing**
- Lateral age variations can be used to detect **paleotopography**

Some basic ideas: He Partial Retention Zone (HePRZ)

Isothermal development of HePRZ depth profile over 55 Myrs



Important point: A thermochronological date need not and usually does not date an event, or even the time at which the closure isotherm was crossed

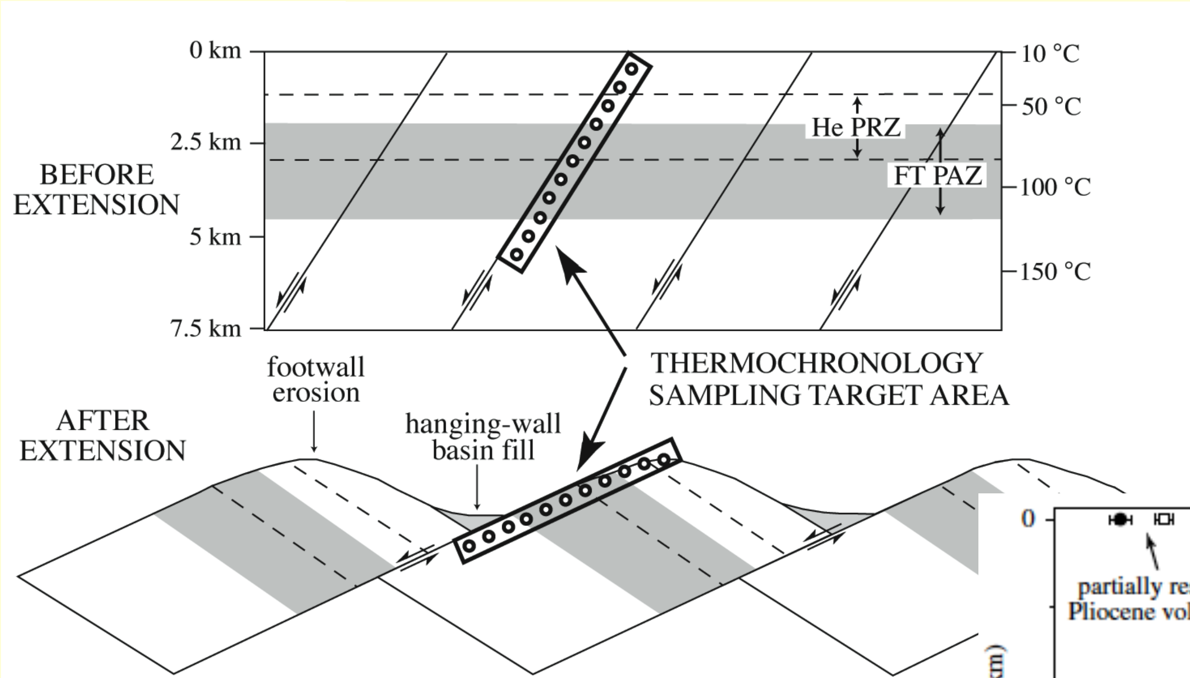


→These two histories predict an apatite He date of 15 Ma

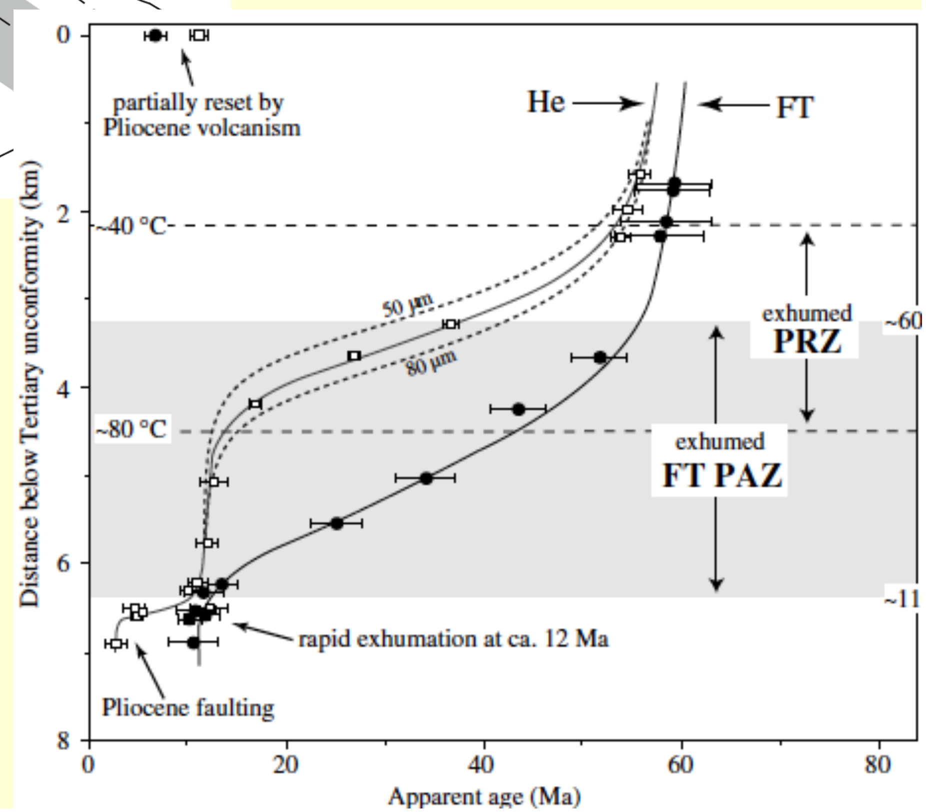
Tectonic problems
Vertical profiles: He date vs. elevation

Some styles of faulting move rocks relative to isotherms

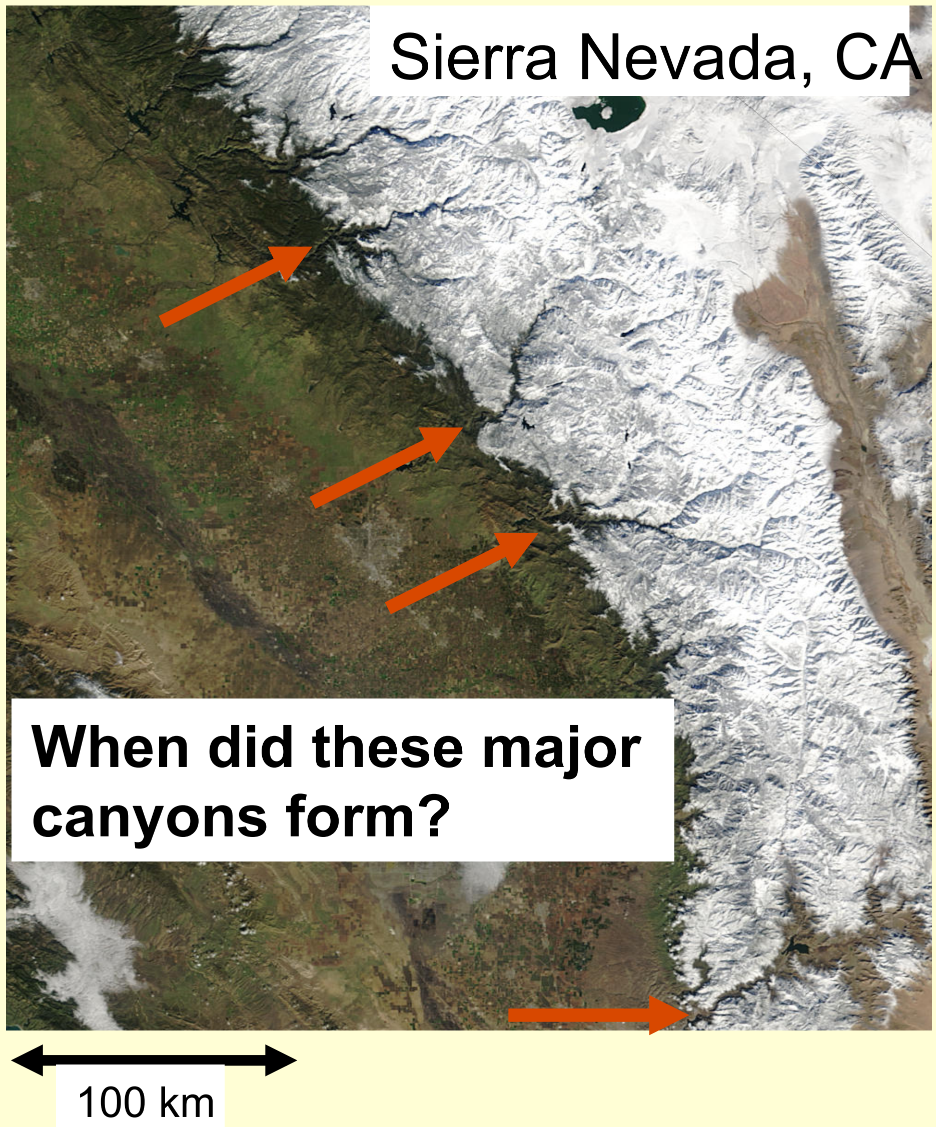
Vertical profiles: He date vs. elevation



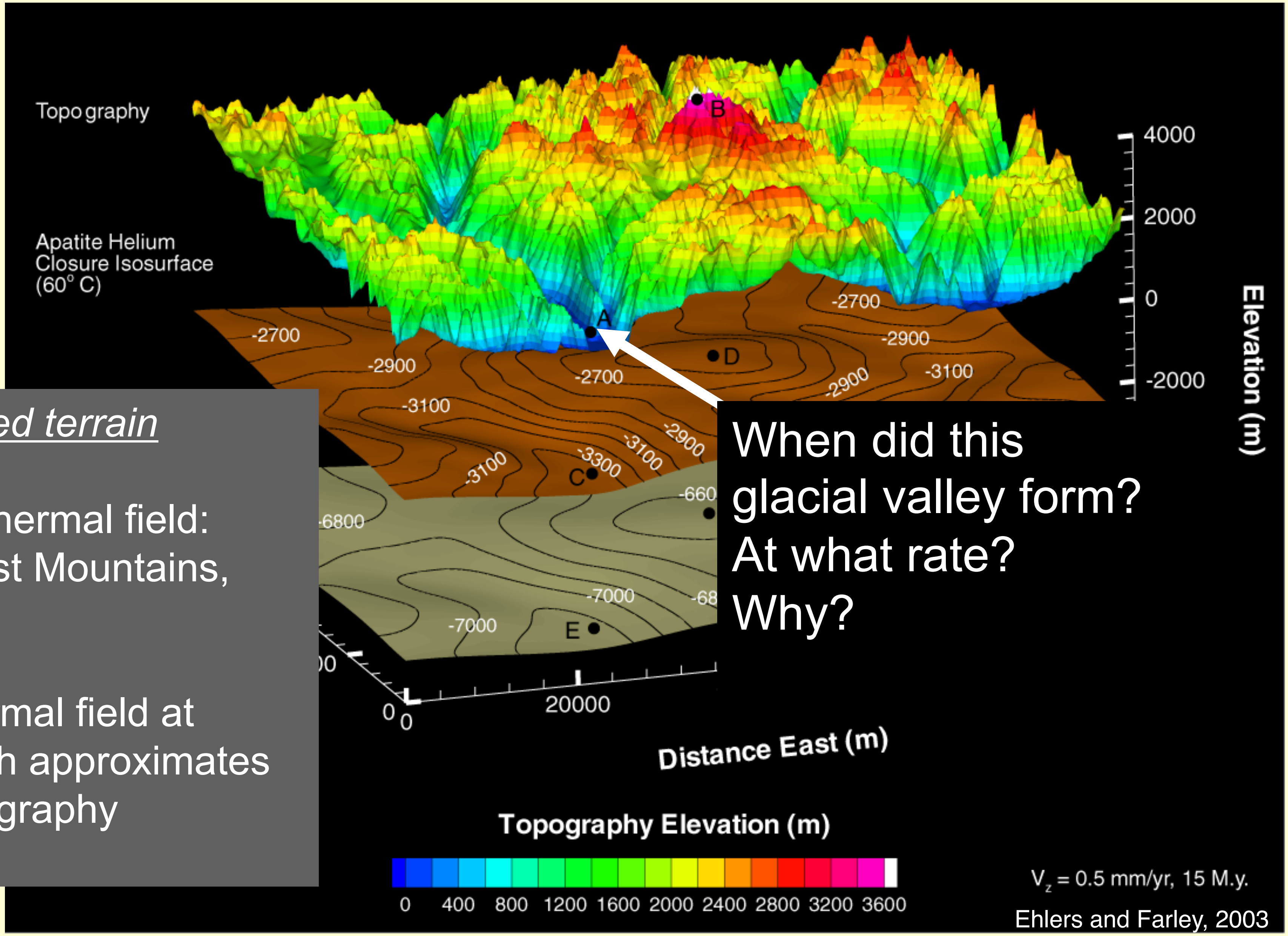
Stockli et al., 2000 - White Mountains



Paleotopography



Erosion rates and histories



When did this glacial valley form? At what rate? Why?

Glaciated terrain

- 3D thermal field: Coast Mountains, B.C.
- Thermal field at depth approximates topography

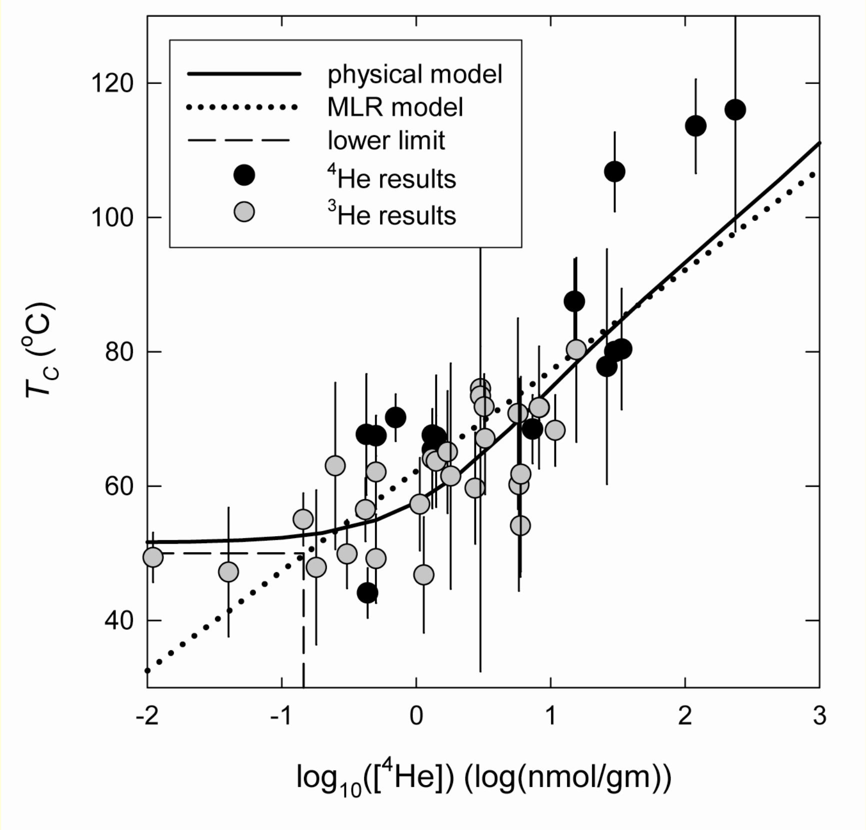
Radiation damage control on He diffusion kinetics

Problematic: Protracted cooling histories

Example: Cratonic settings

- Commonly yielded scattered, inexplicable results

- Sometimes yielded dates older than expected



Shuster et al., 2006

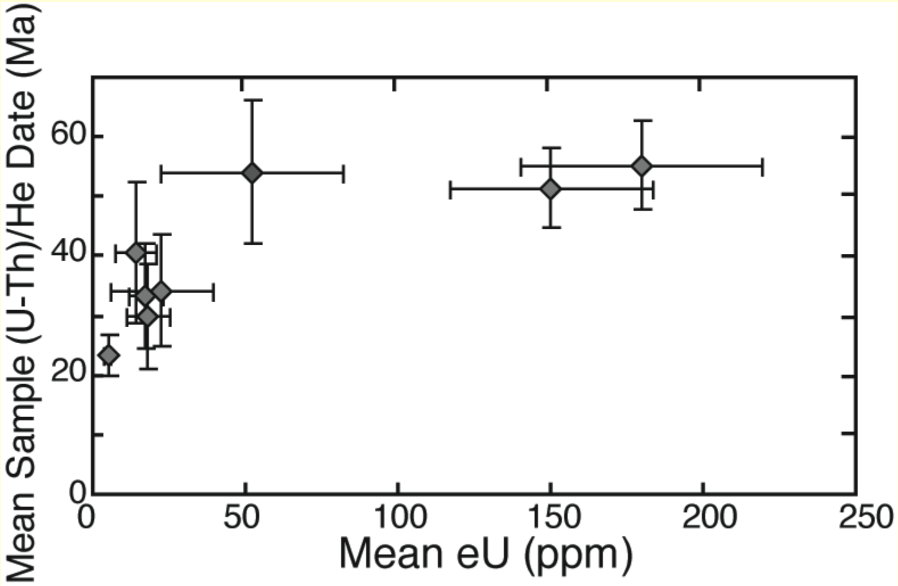
RDAAM – Flowers et al., 2009

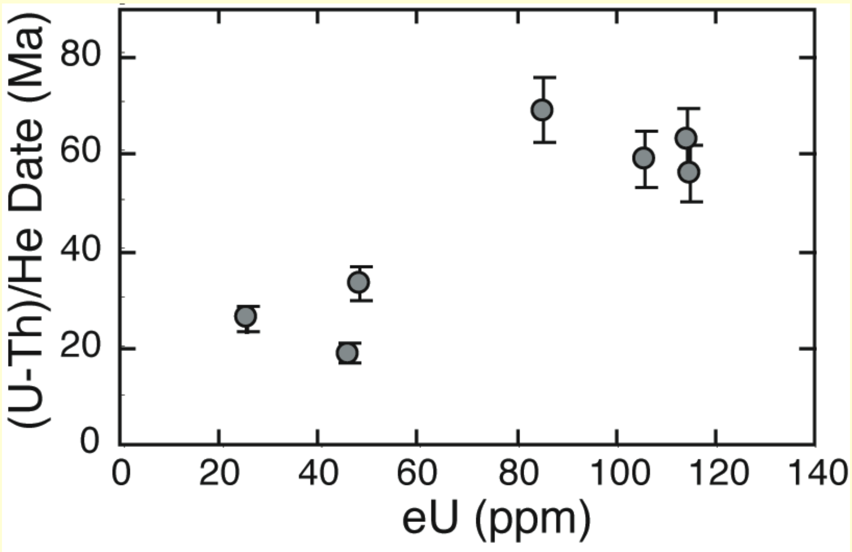
Radiation damage control on He diffusion kinetics

• Predicts diagnostic date-eU correlations that are very sensitive to the thermal history

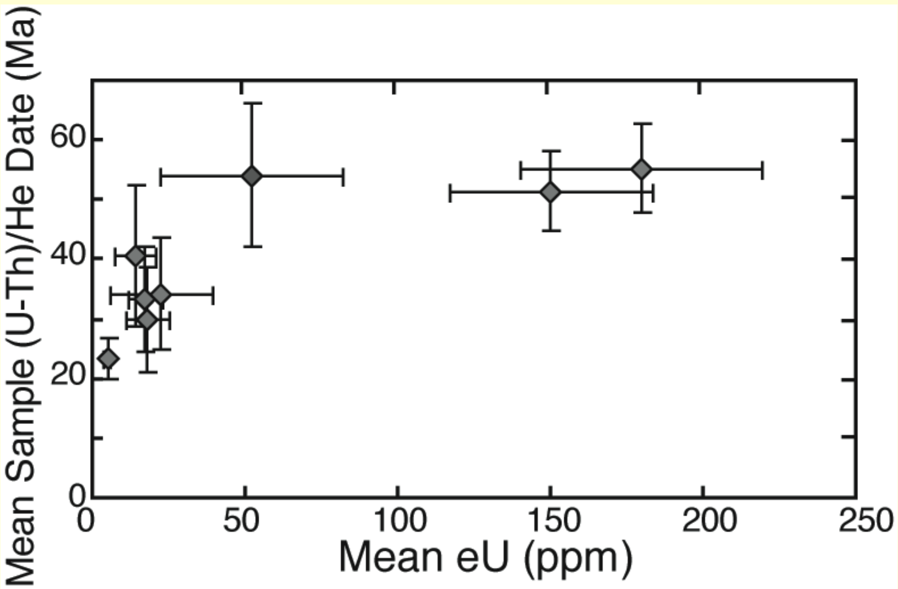
•Dispersion in some (U-Th)/He datasets is geologically meaningful

• Possible to extract additional information about details of tT path because of this effect





Thermal history simulations of apatite (U-Th)/He data



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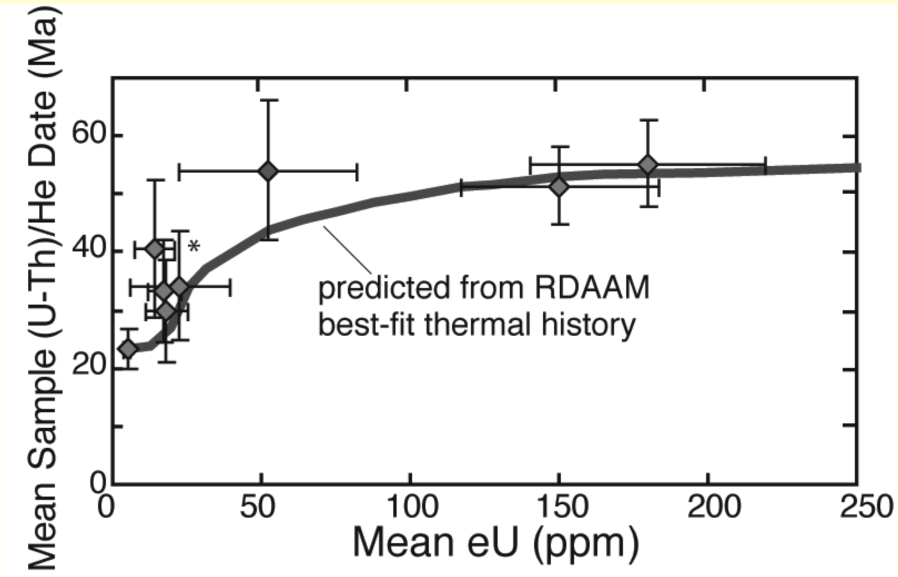
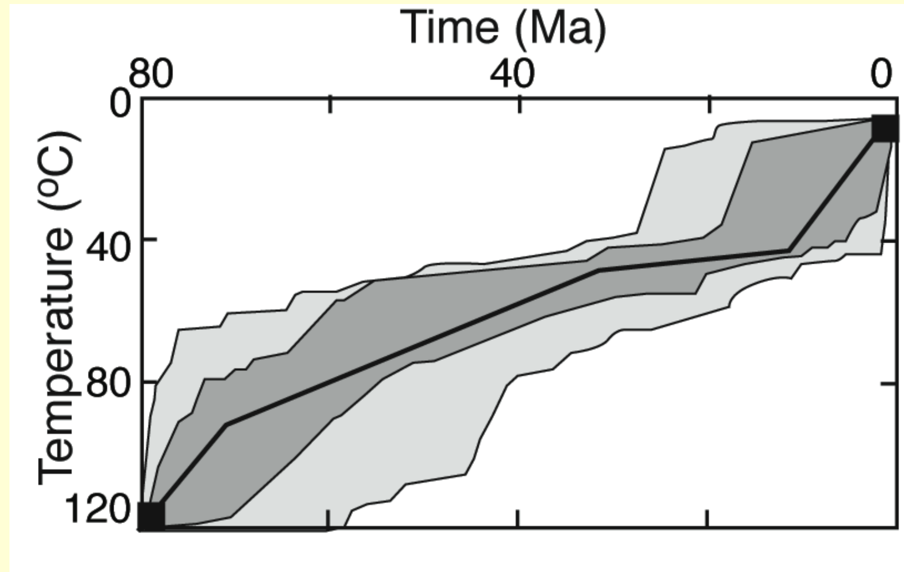
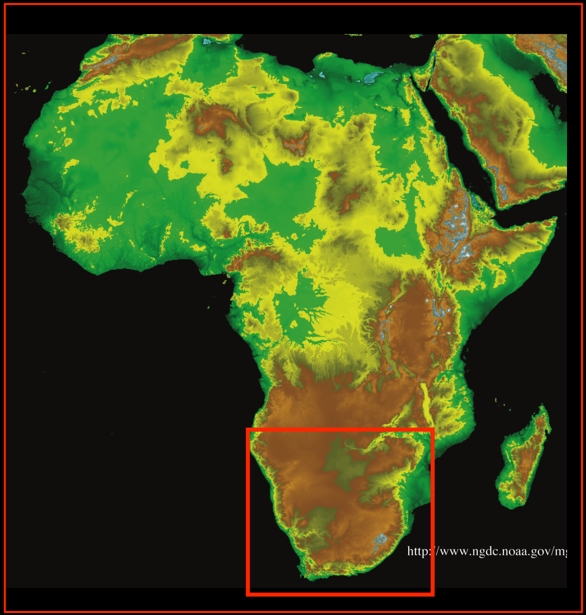




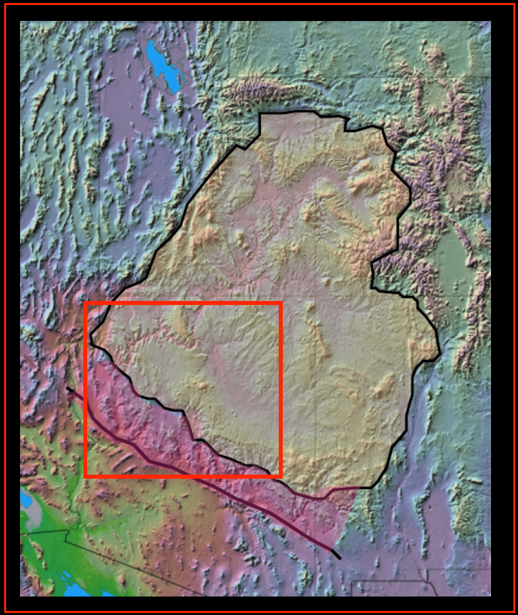
How stable are continents?

North American cratonic interior

Southern African Plateau

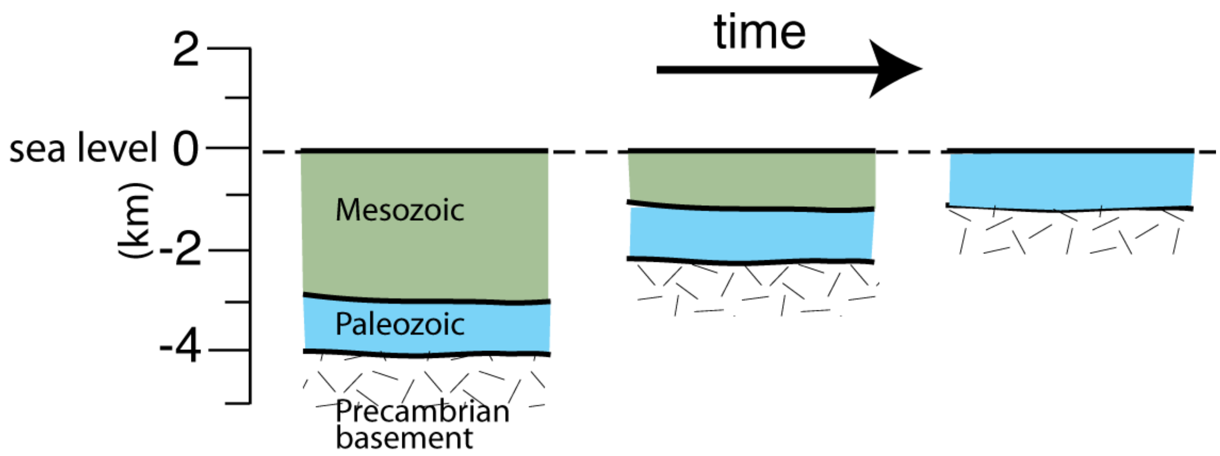


Colorado Plateau



- Rocks are Proterozoic or Archean in age
- Settings located far from plate margins
- Significant controversy over the timing and causes of elevation change

Unroofing vs. Uplift



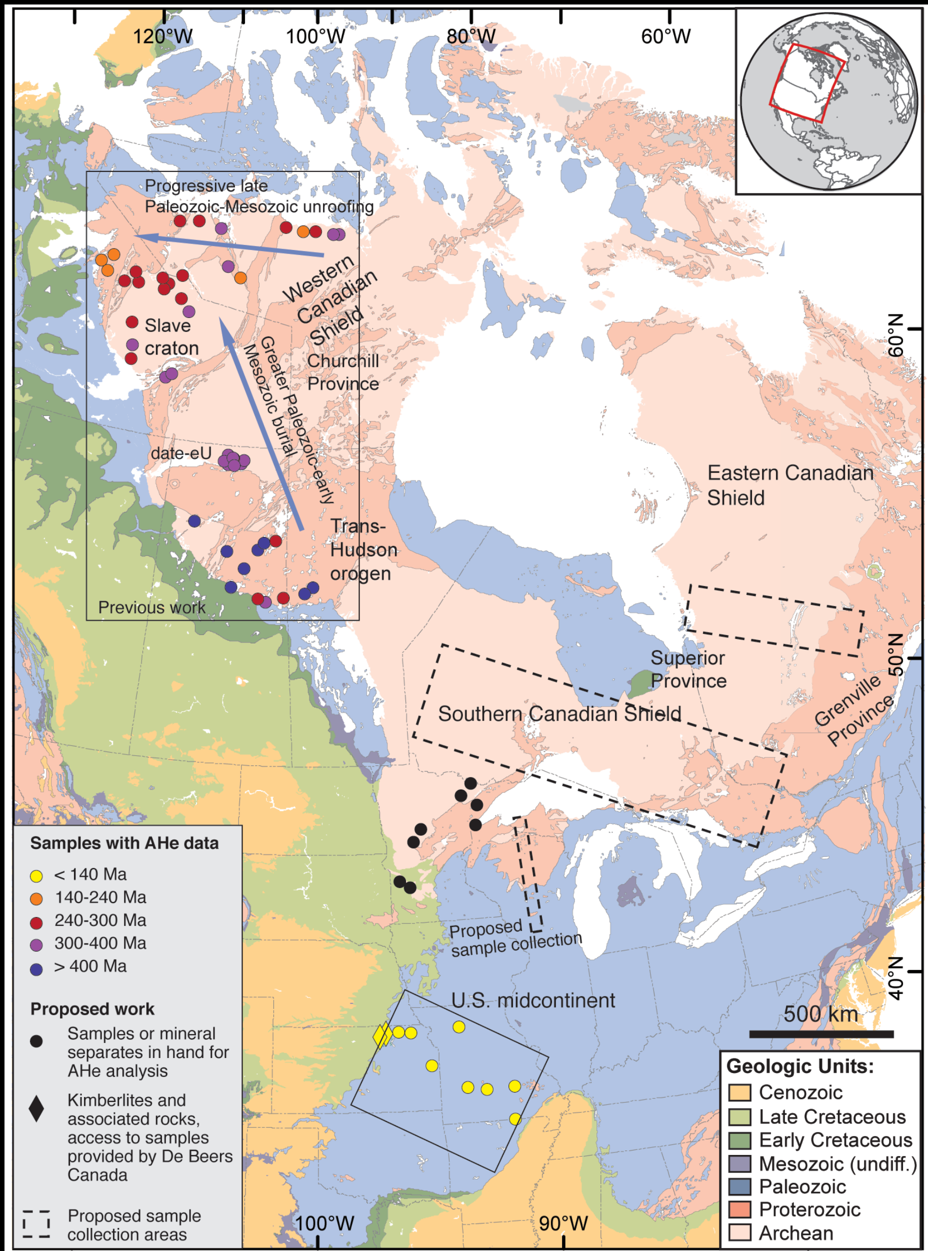
Unroofing

Thickness of rock removed through erosion or tectonism (can occur at sea level)

Thermochronology can provide excellent resolution of **unroofing** histories

How stable are cratons?

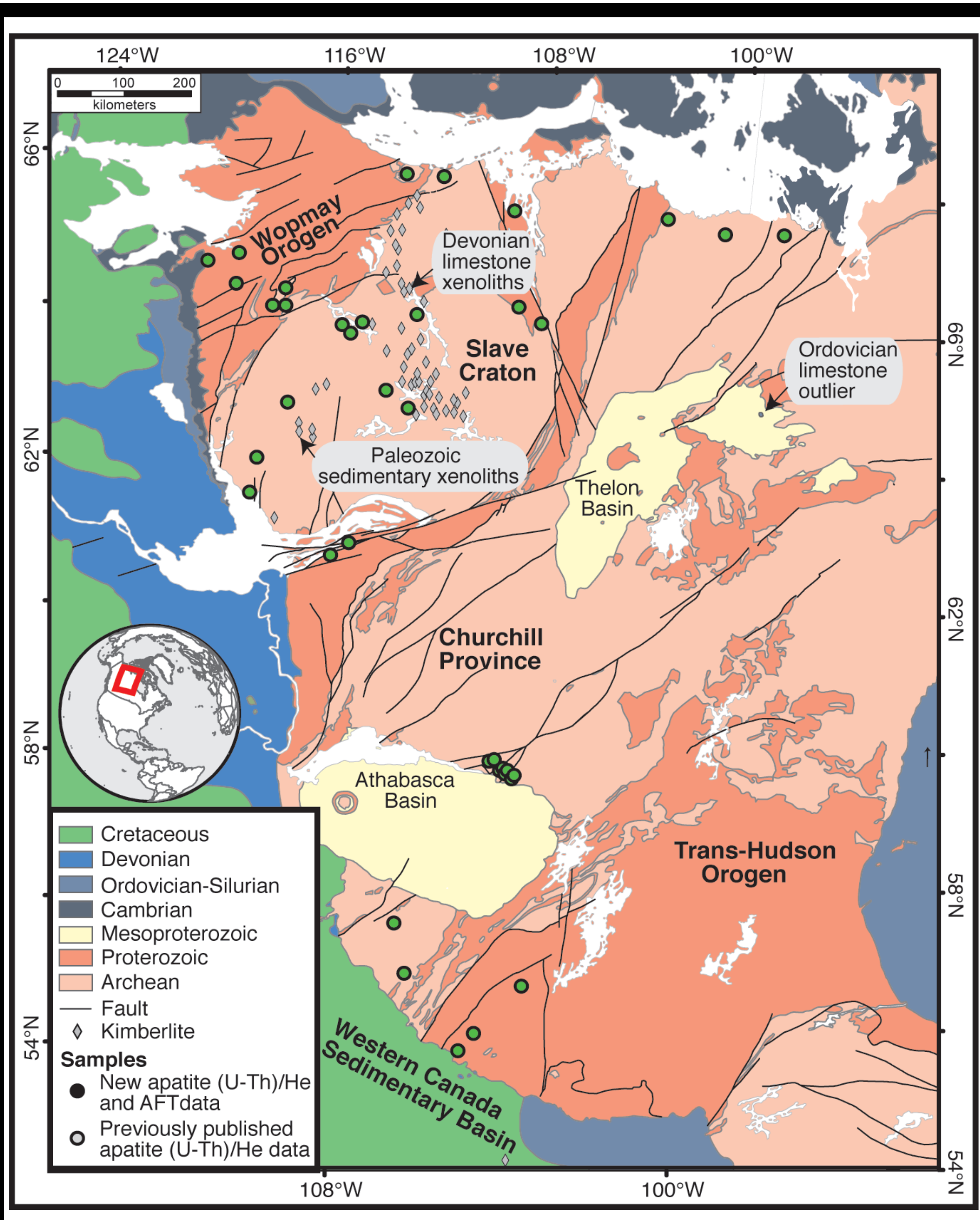
How stable are cratons?



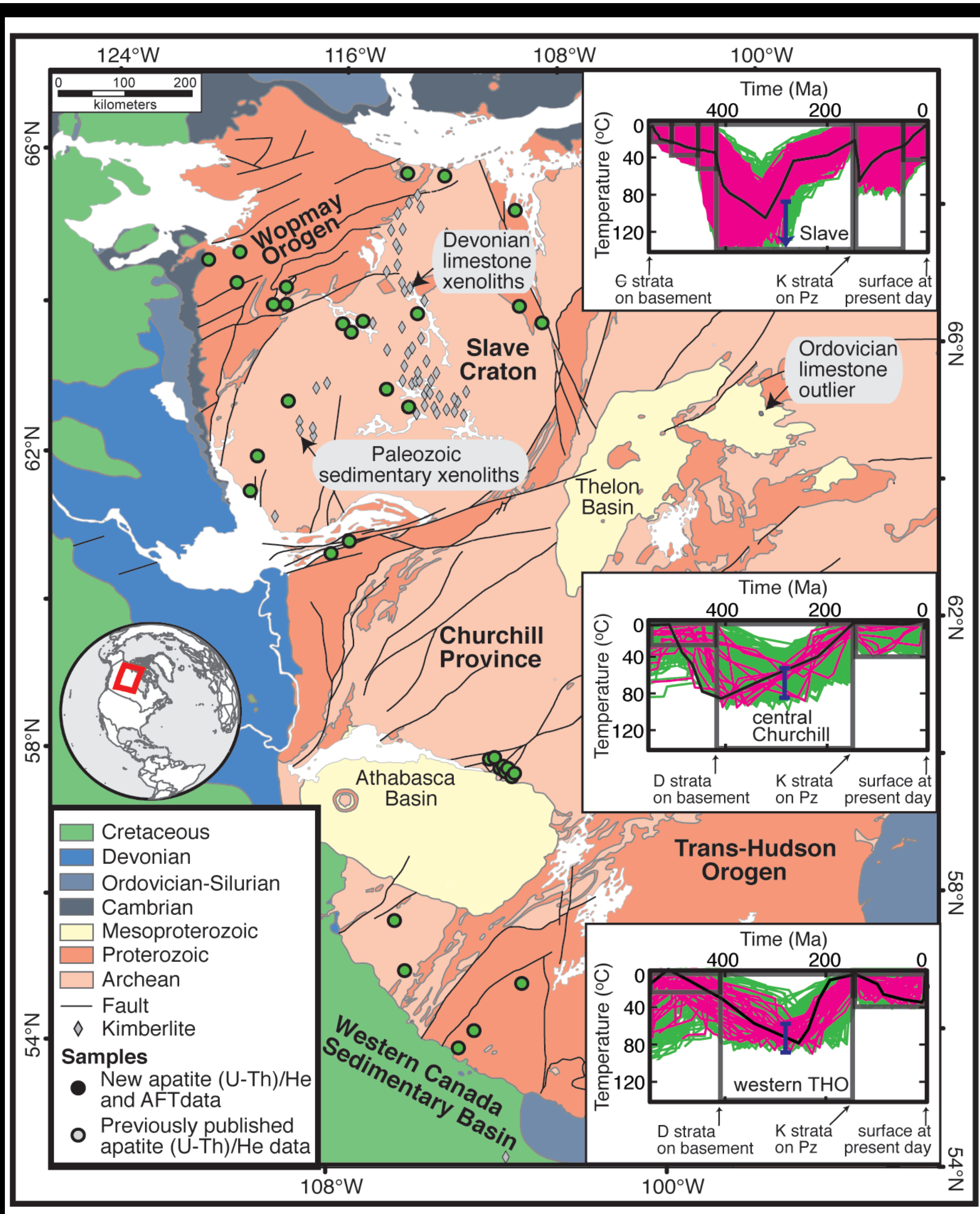
Deposition of Paleozoic sequences: Epeirogeny or eustasy?

Mantle dynamic studies use the preserved sedimentary record to calibrate their models, but an intrinsic limitation is that this record is incomplete.

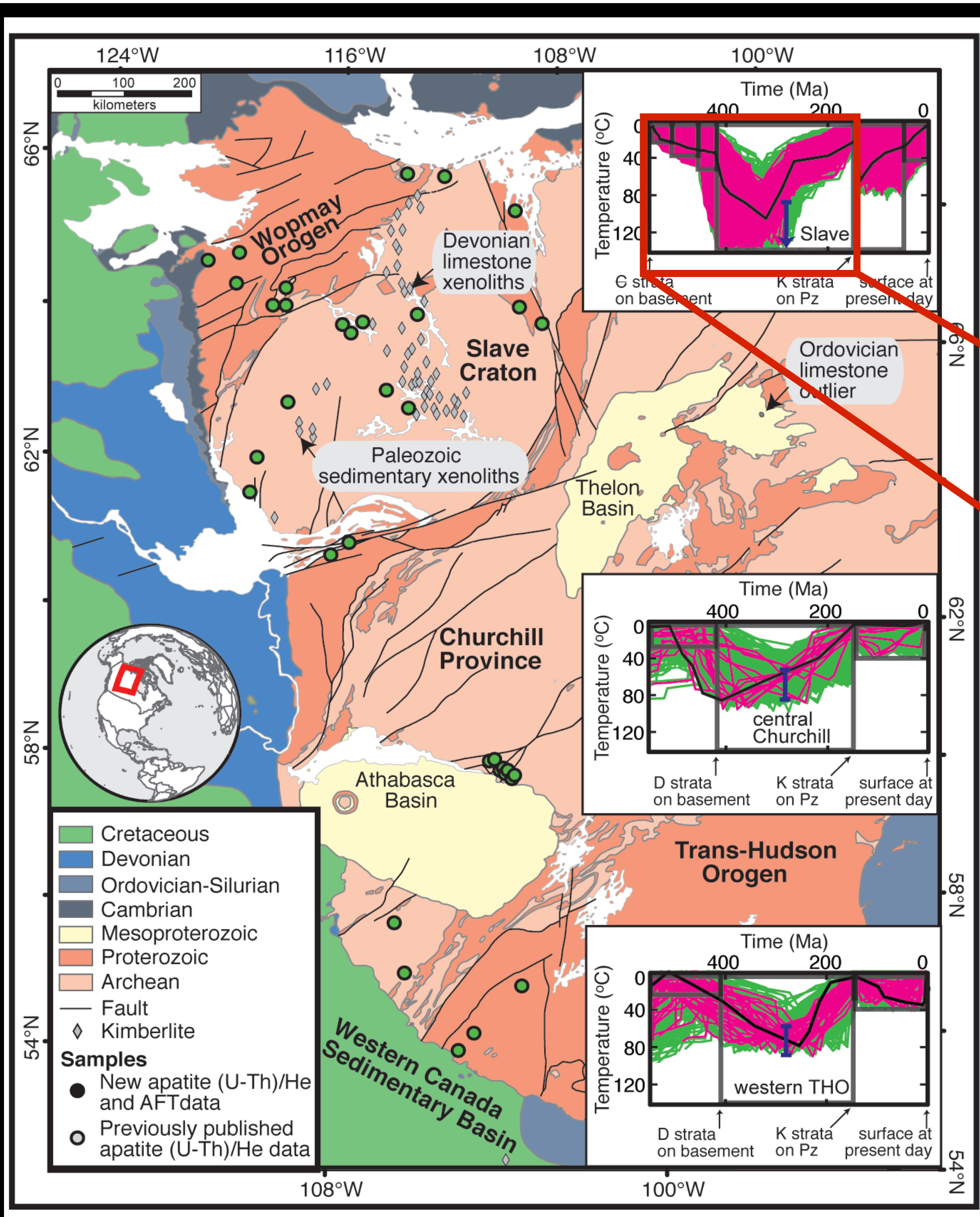
AHe enables resolution of shallow (1-6 km) depositional and erosional episodes, even if the rocks associated with those events are no longer preserved.


124°W
116°W
108°W
100°W
0 100 200
kilometers
66°N
62°N
58°N
54°N
Wopmay Orogen
Devonian limestone xenoliths
Slave Craton
Ordovician limestone outlier
Paleozoic sedimentary xenoliths
Thelon Basin
Churchill Province
Athabasca Basin
Trans-Hudson Orogen
Western Canada Sedimentary Basin
Cretaceous
Devonian
Ordovician-Silurian
Cambrian
Mesoproterozoic
Proterozoic
Archean
Fault
Kimberlite
Samples
New apatite (U-Th)/He and AFTdata
Previously published apatite (U-Th)/He data

Objectives

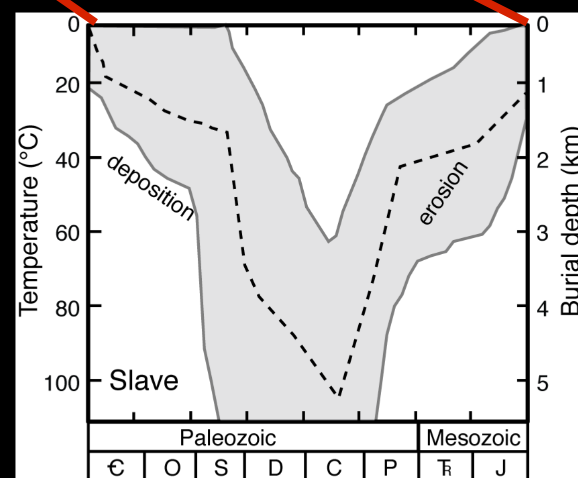


Flowers, 2009; Ault et al., 2009, in review; Flowers et al., 2012



Key Result

Overall pattern of substantial heating and cooling in Paleozoic-early Mesozoic time



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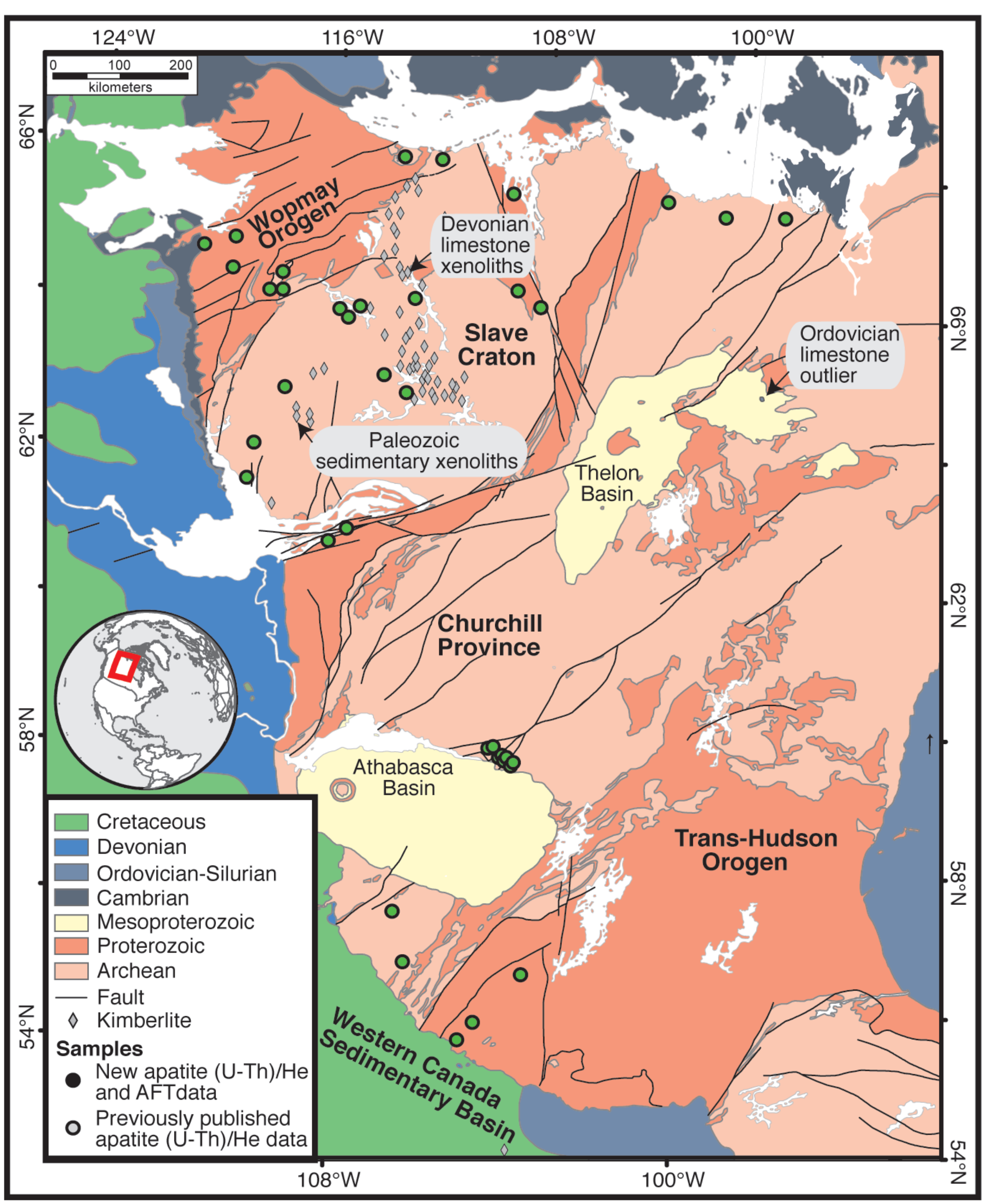
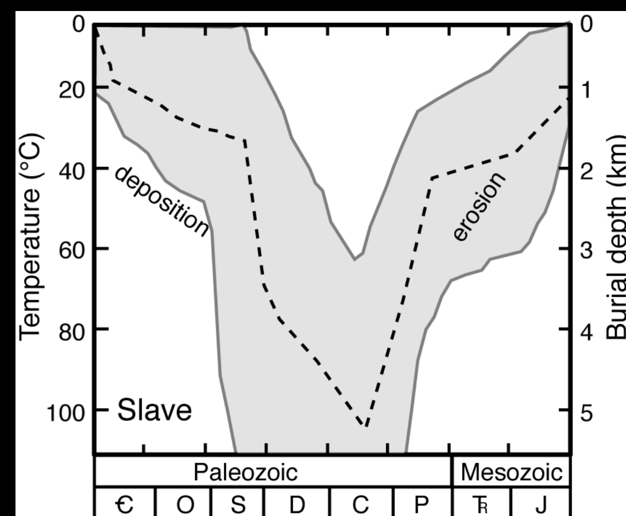
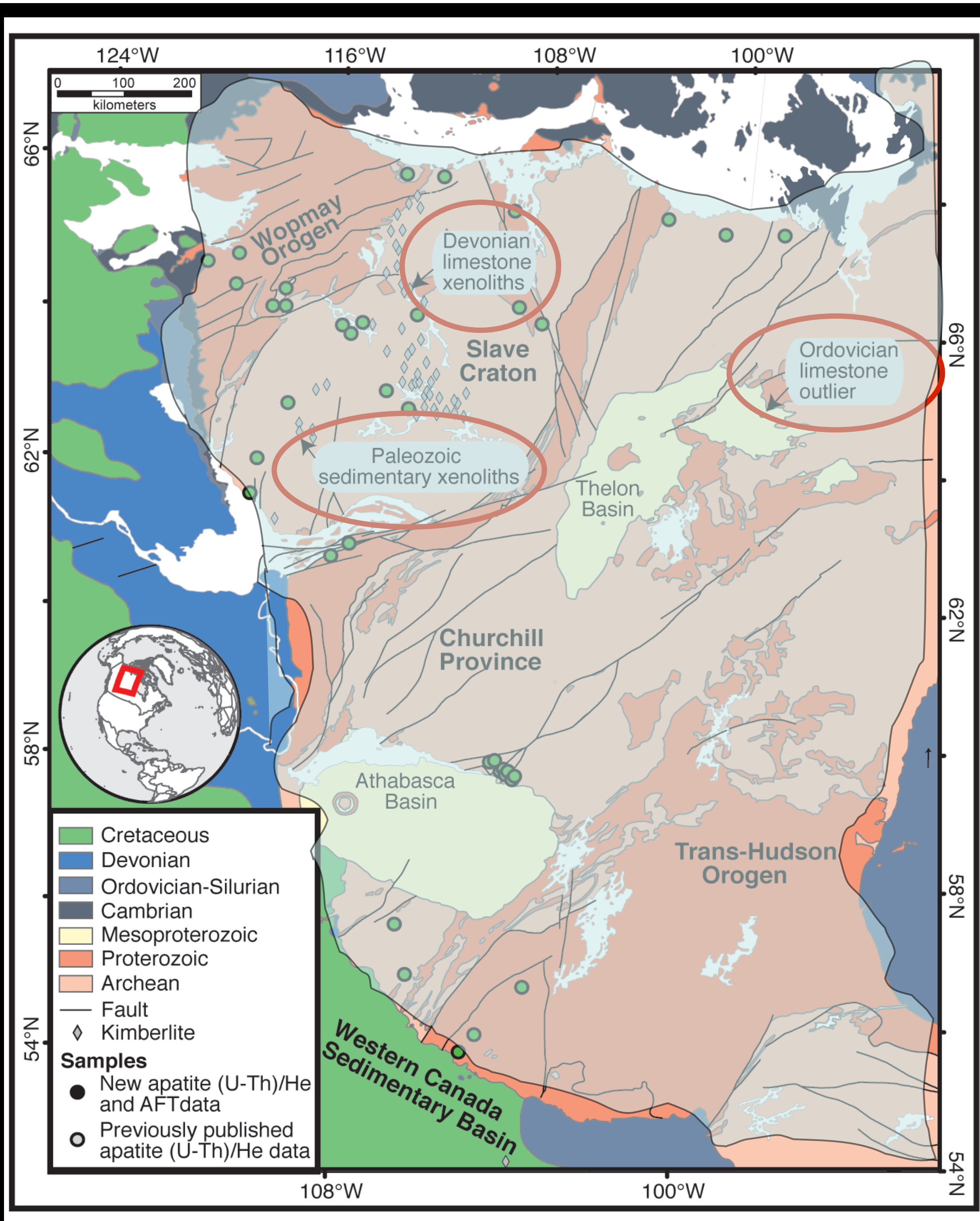


What does this mean?

1) Craton substantially buried and unroofed in the Paleozoic-Mesozoic

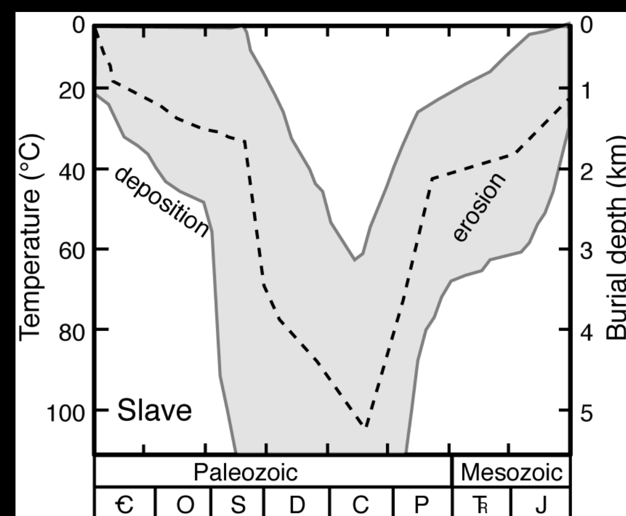




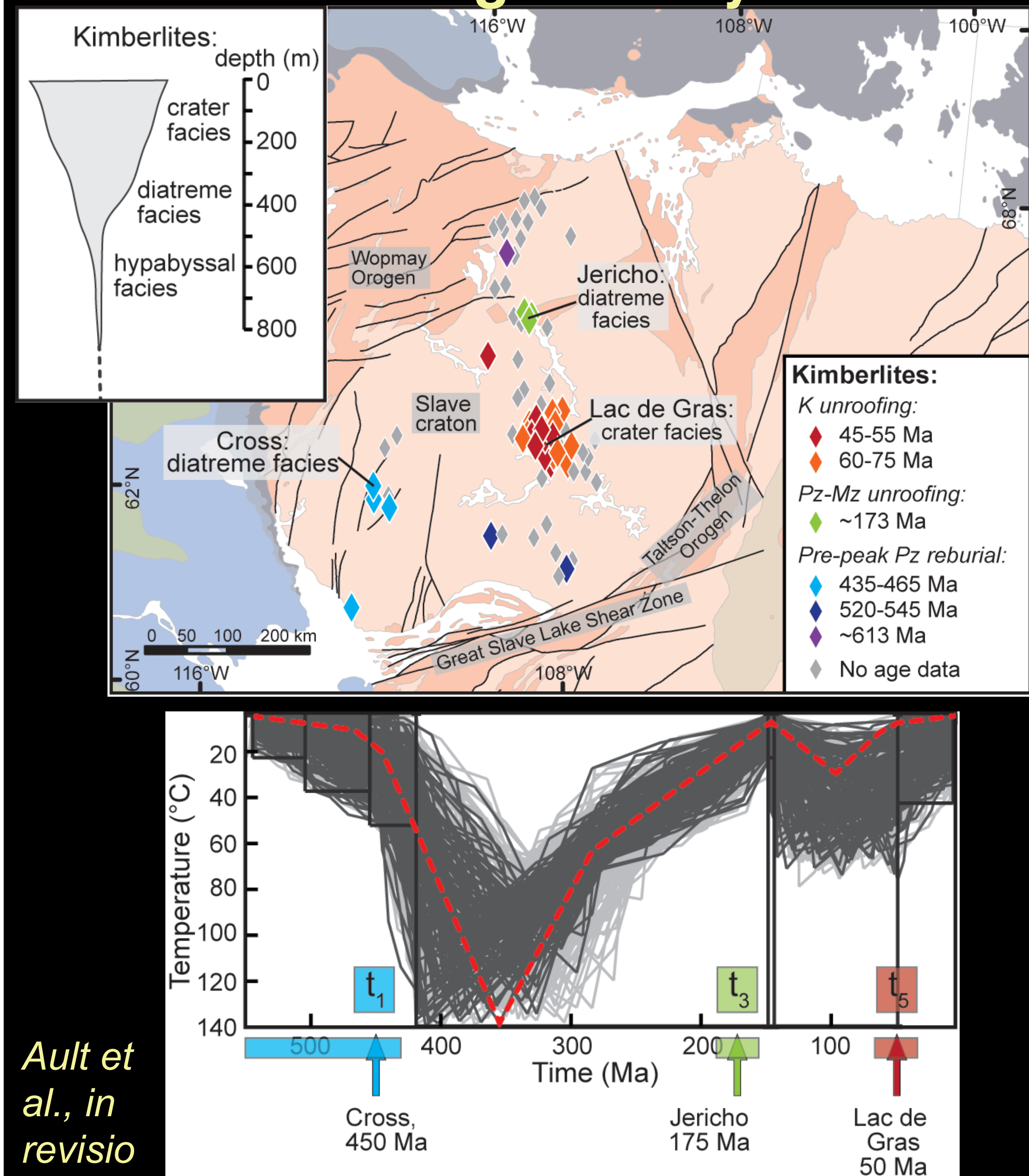
What does this mean?

1) Craton substantially buried and unroofed in the Paleozoic-Mesozoic

2) Marine environment and inundation of entire continental interior

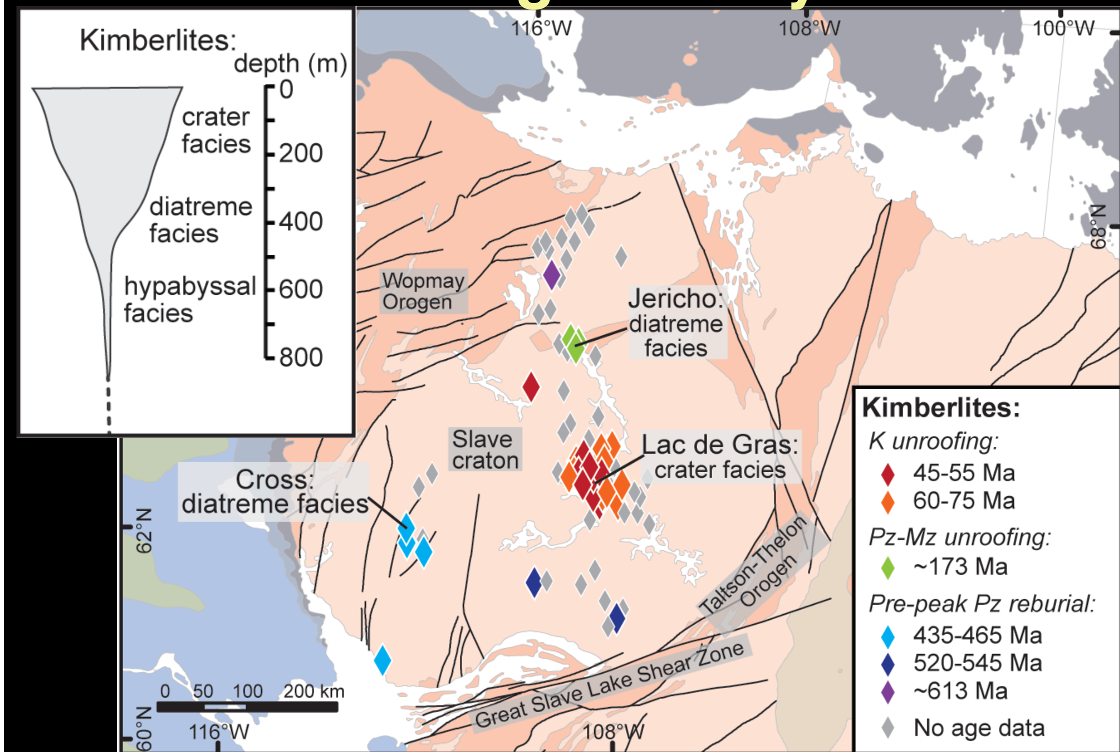


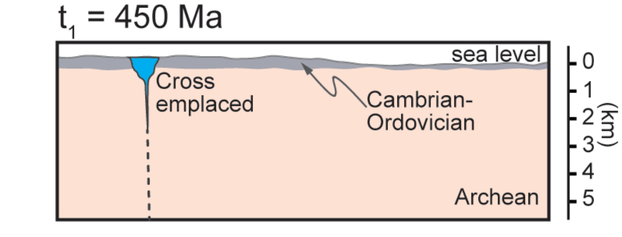
Burial, unroofing, and elevation change history

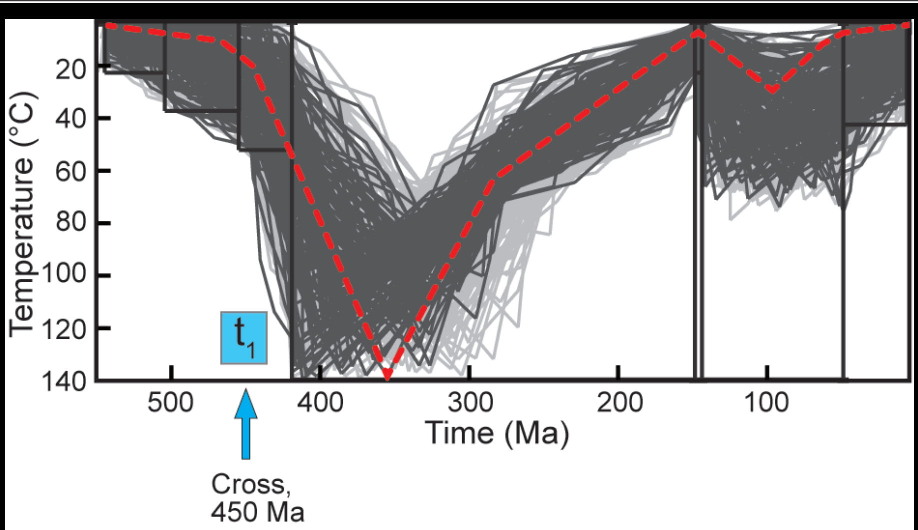


Ault et al., in revision

Burial, unroofing, and elevation change history

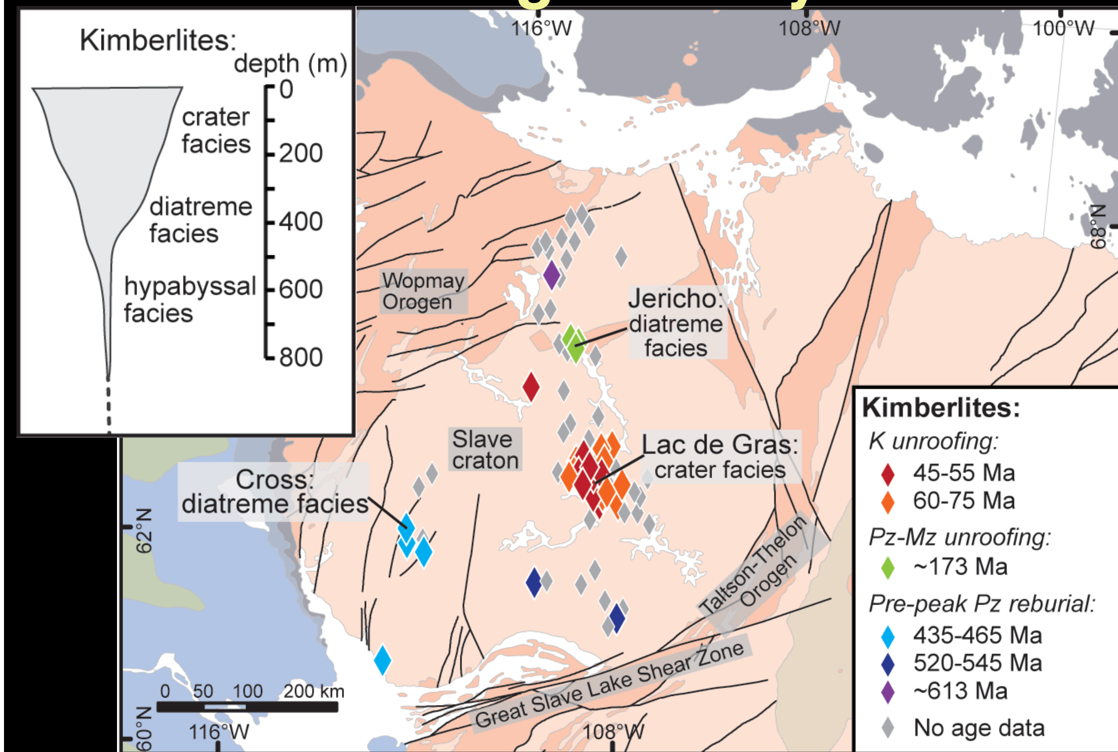


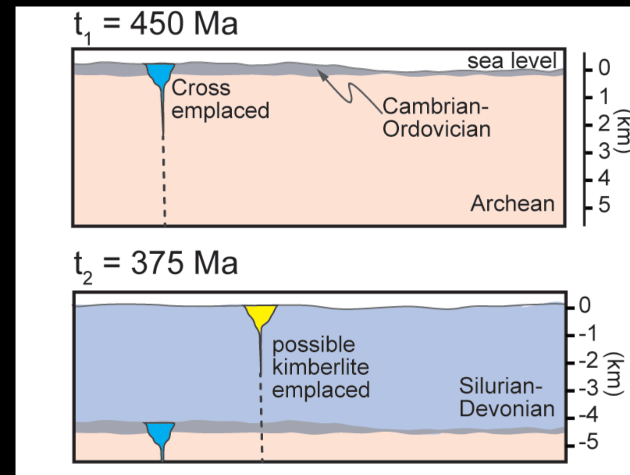


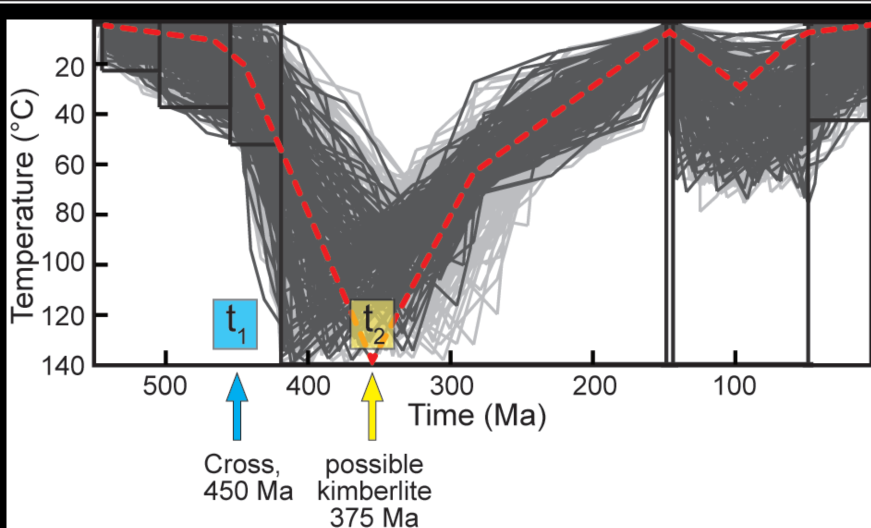


Ault et al., in revision

Burial, unroofing, and elevation change history







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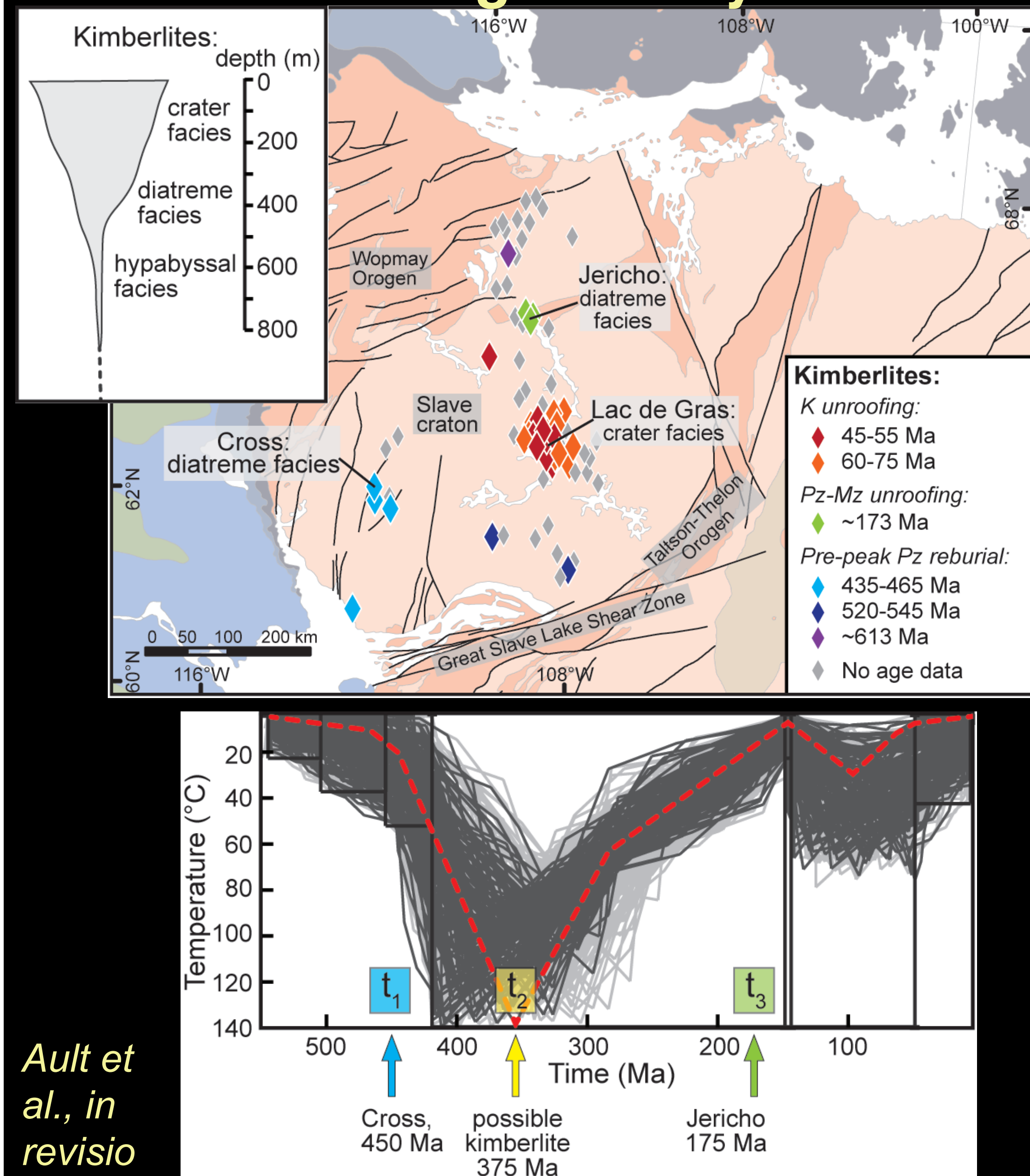

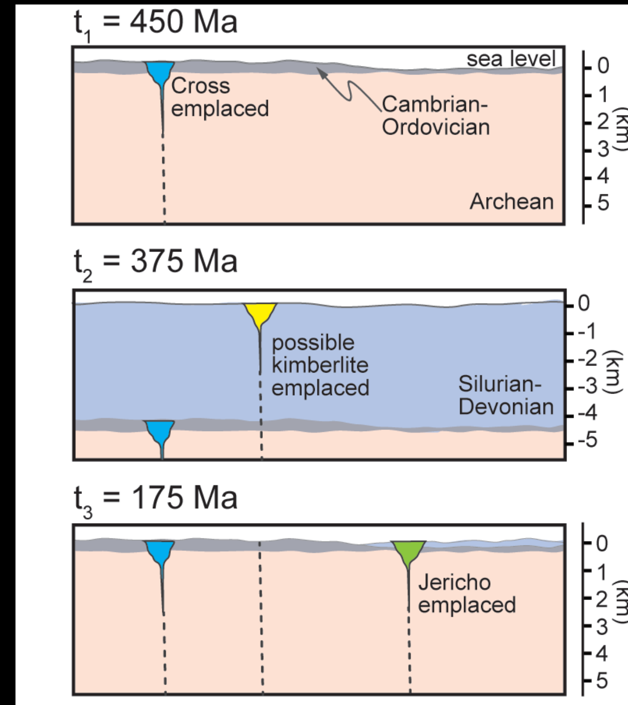

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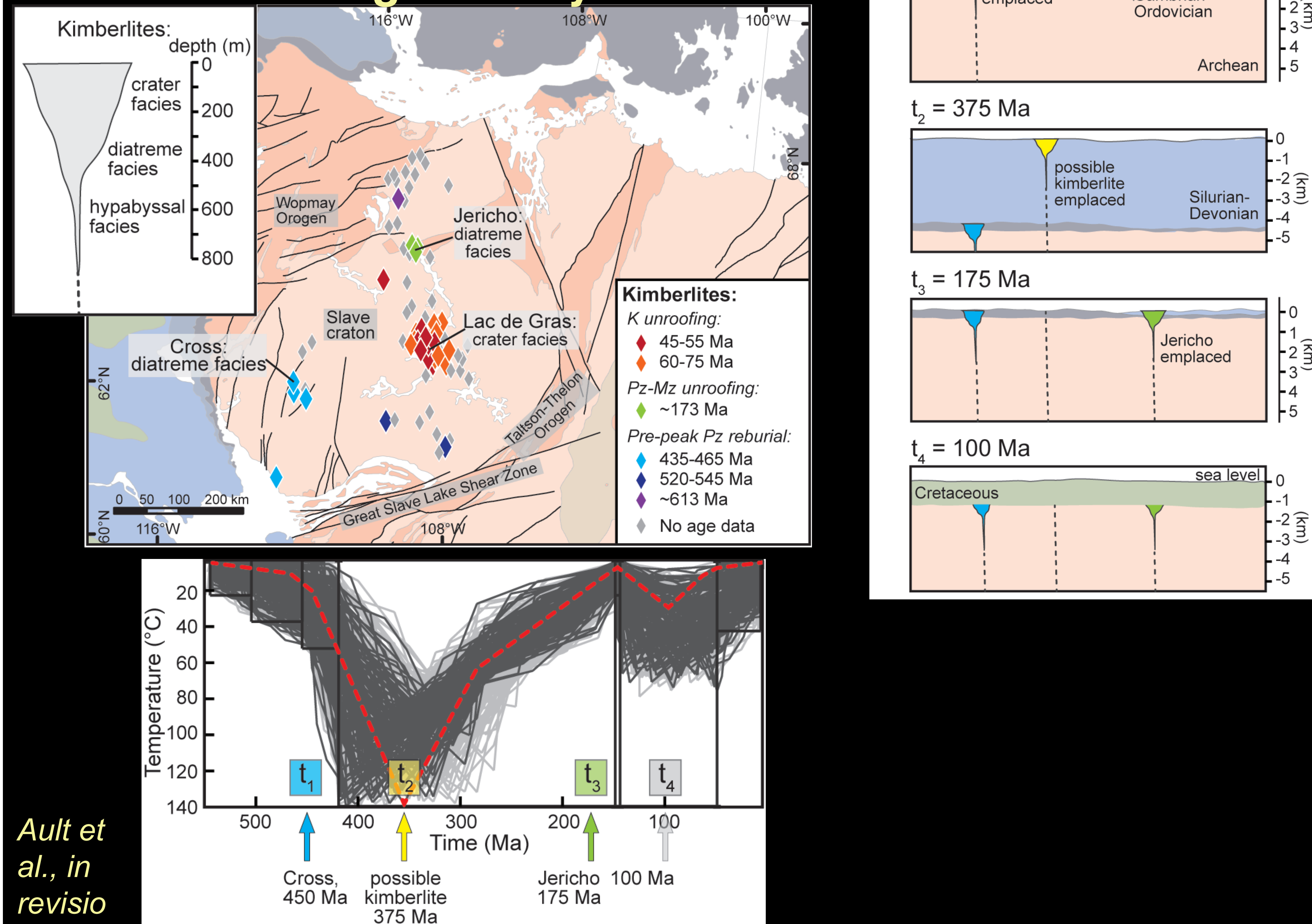

Ault et al., in revisio n

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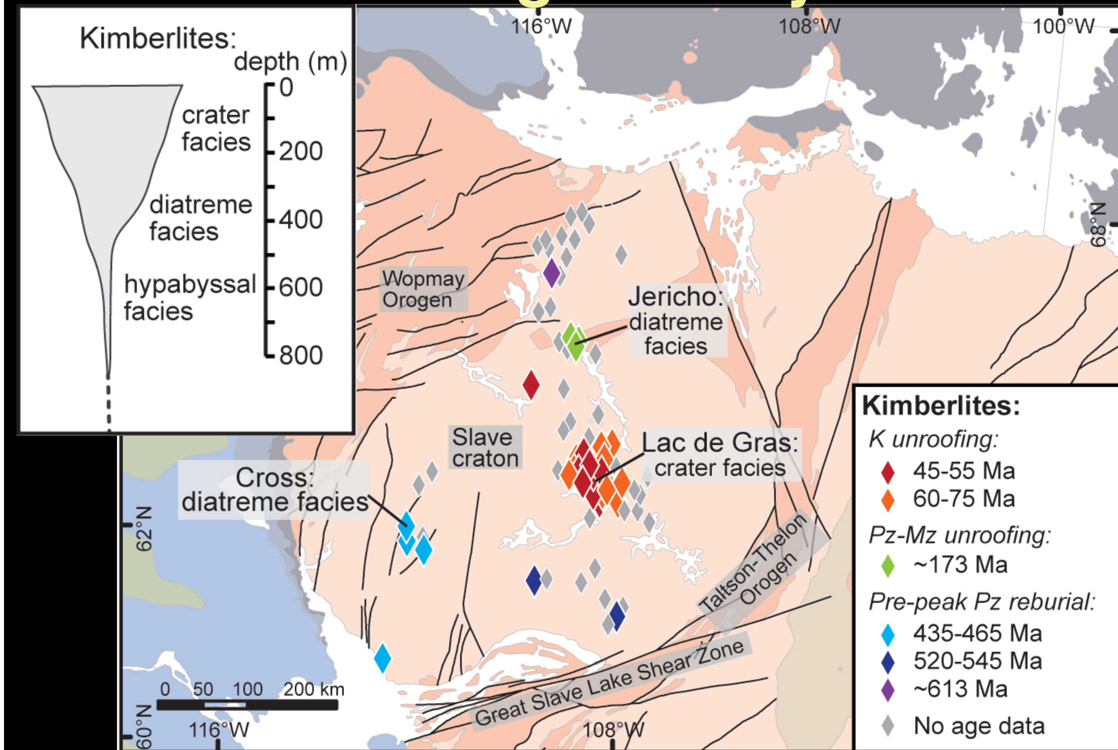

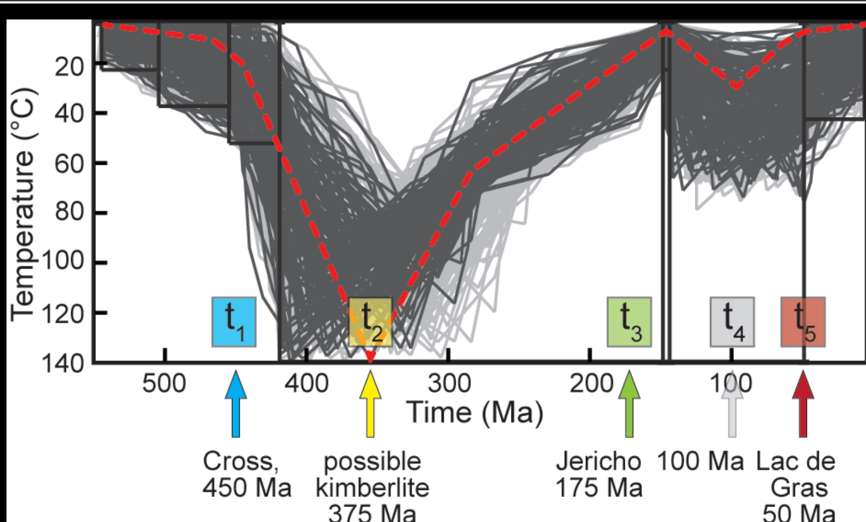

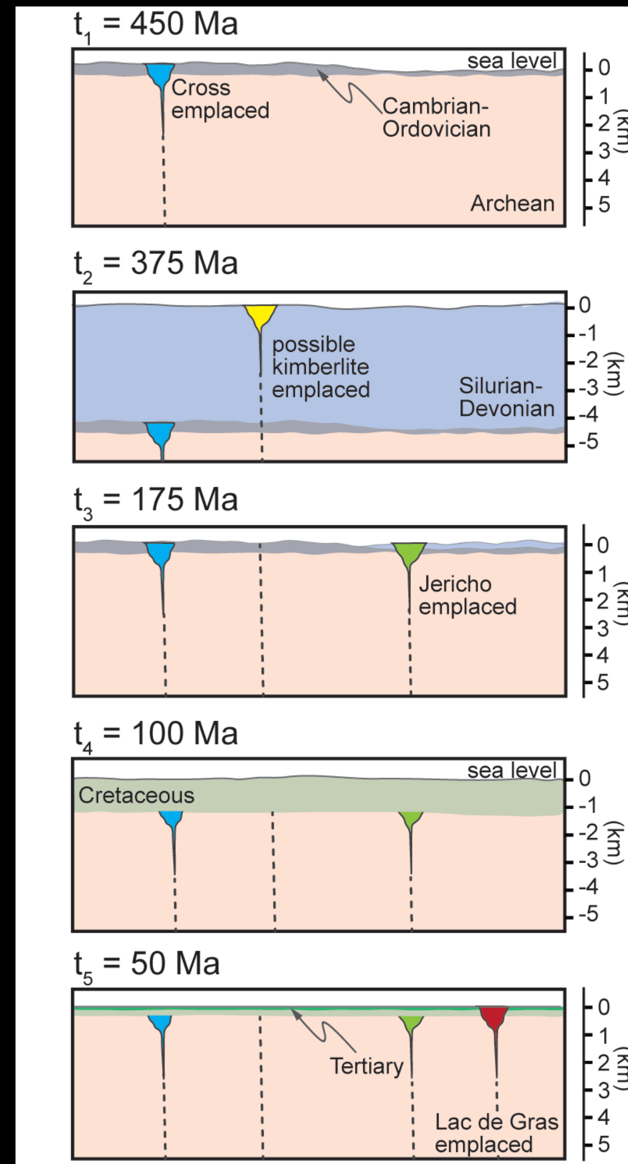

Ault et al., in revision

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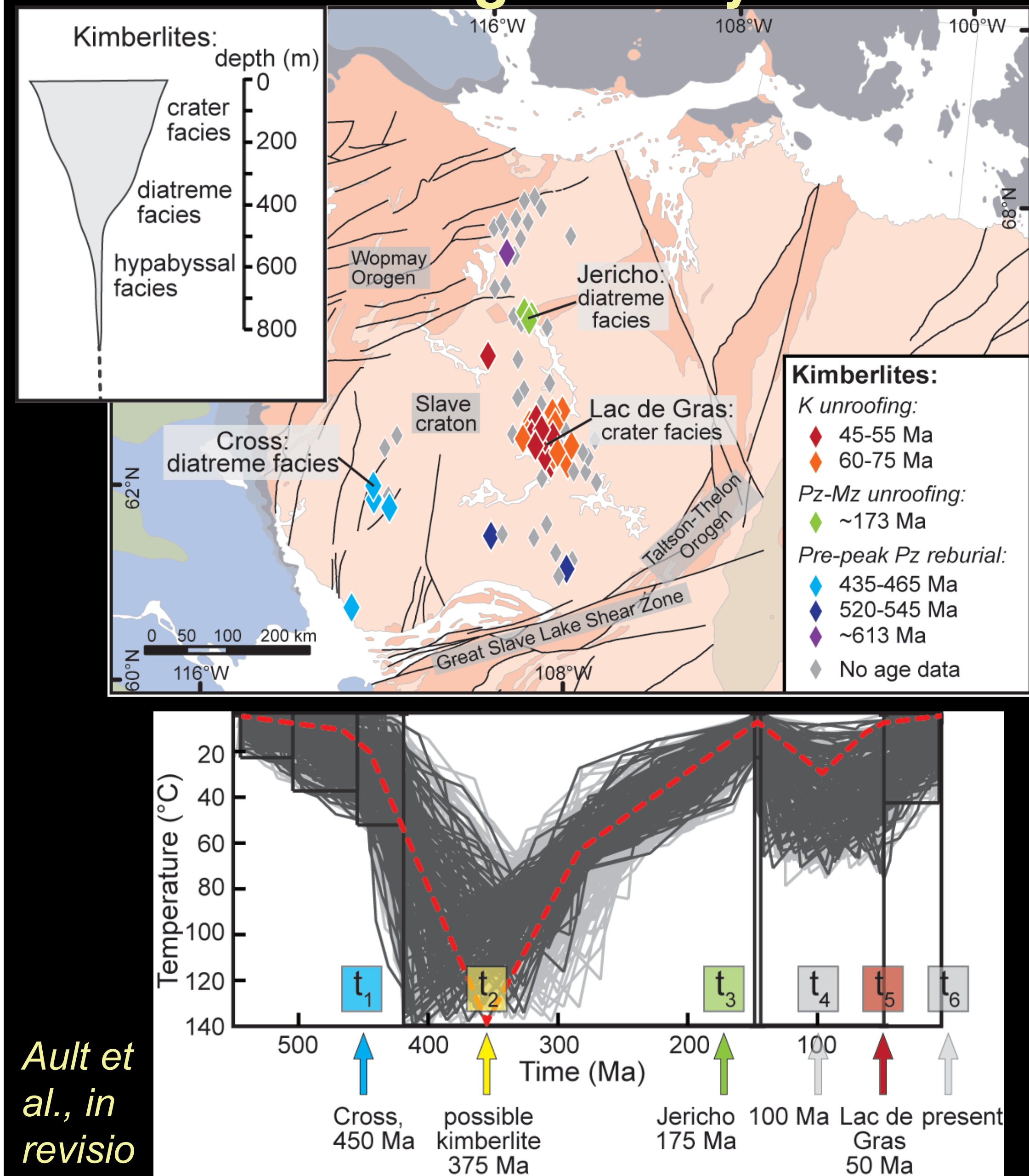
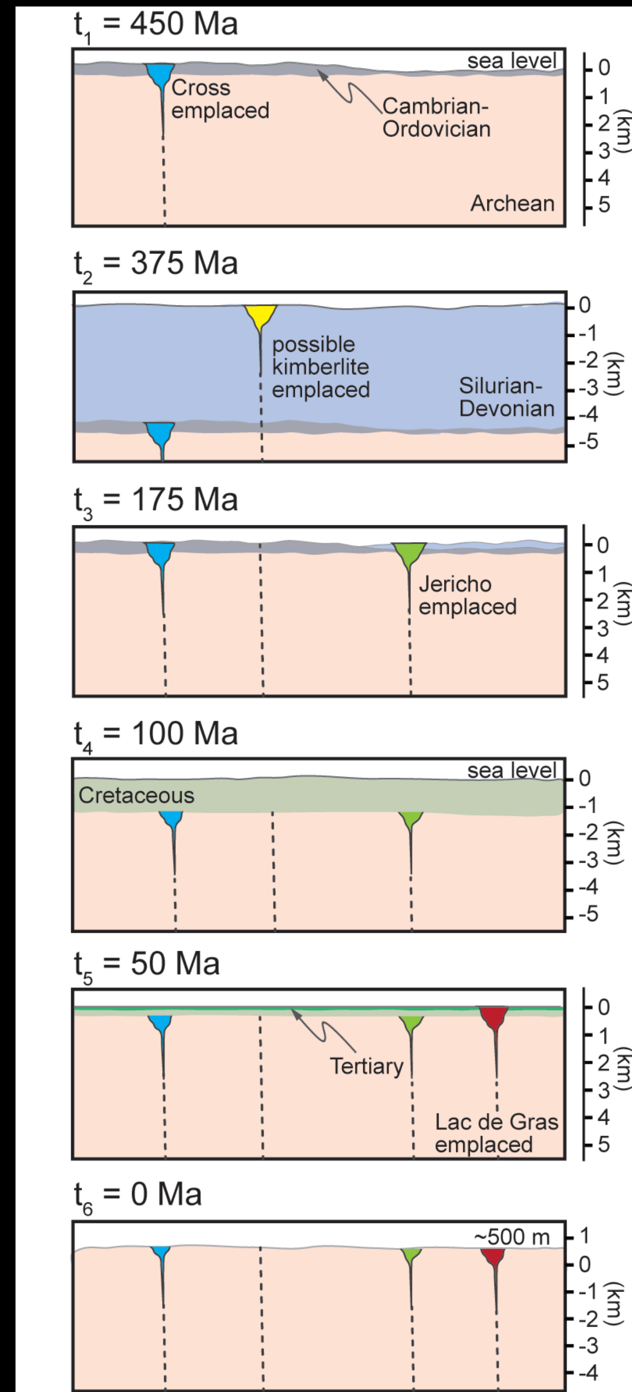
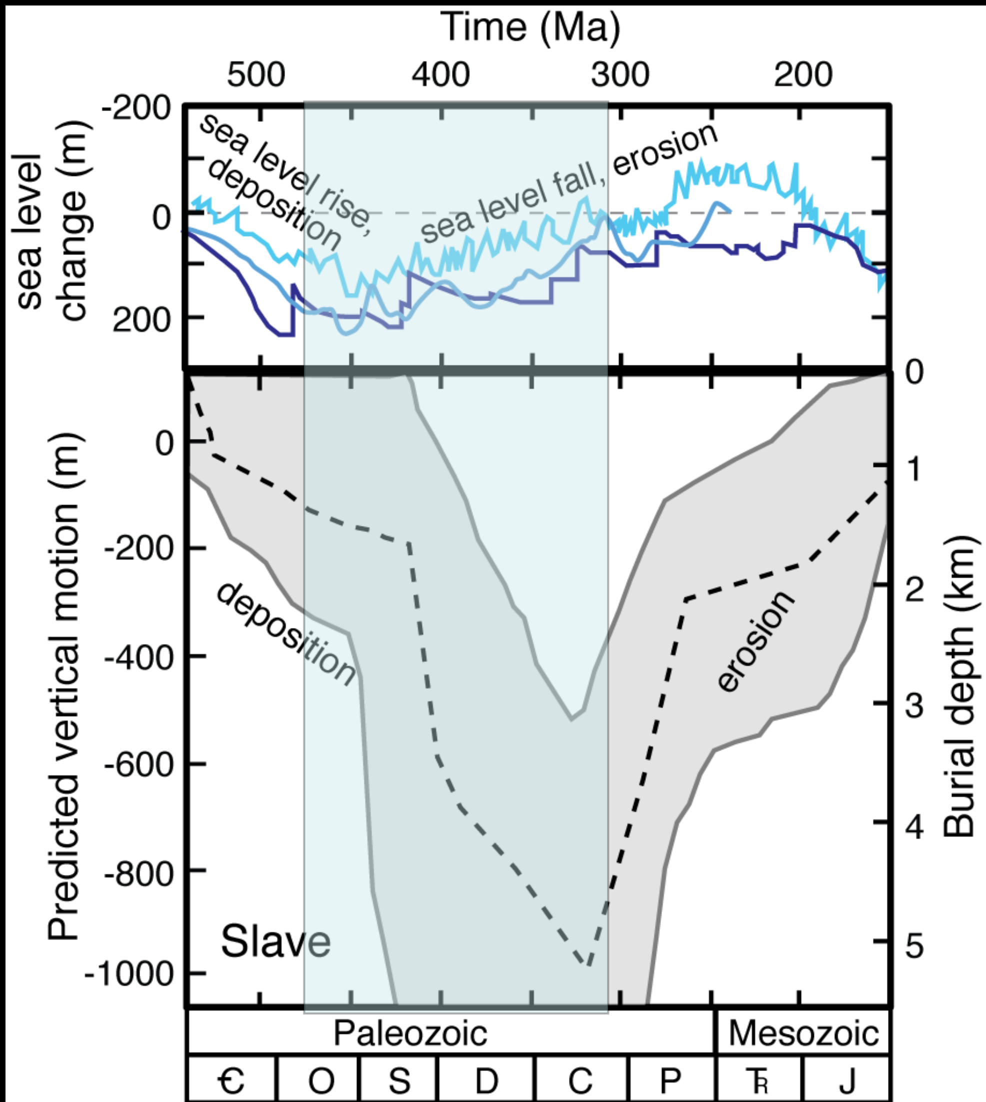




Ault et al., in revision

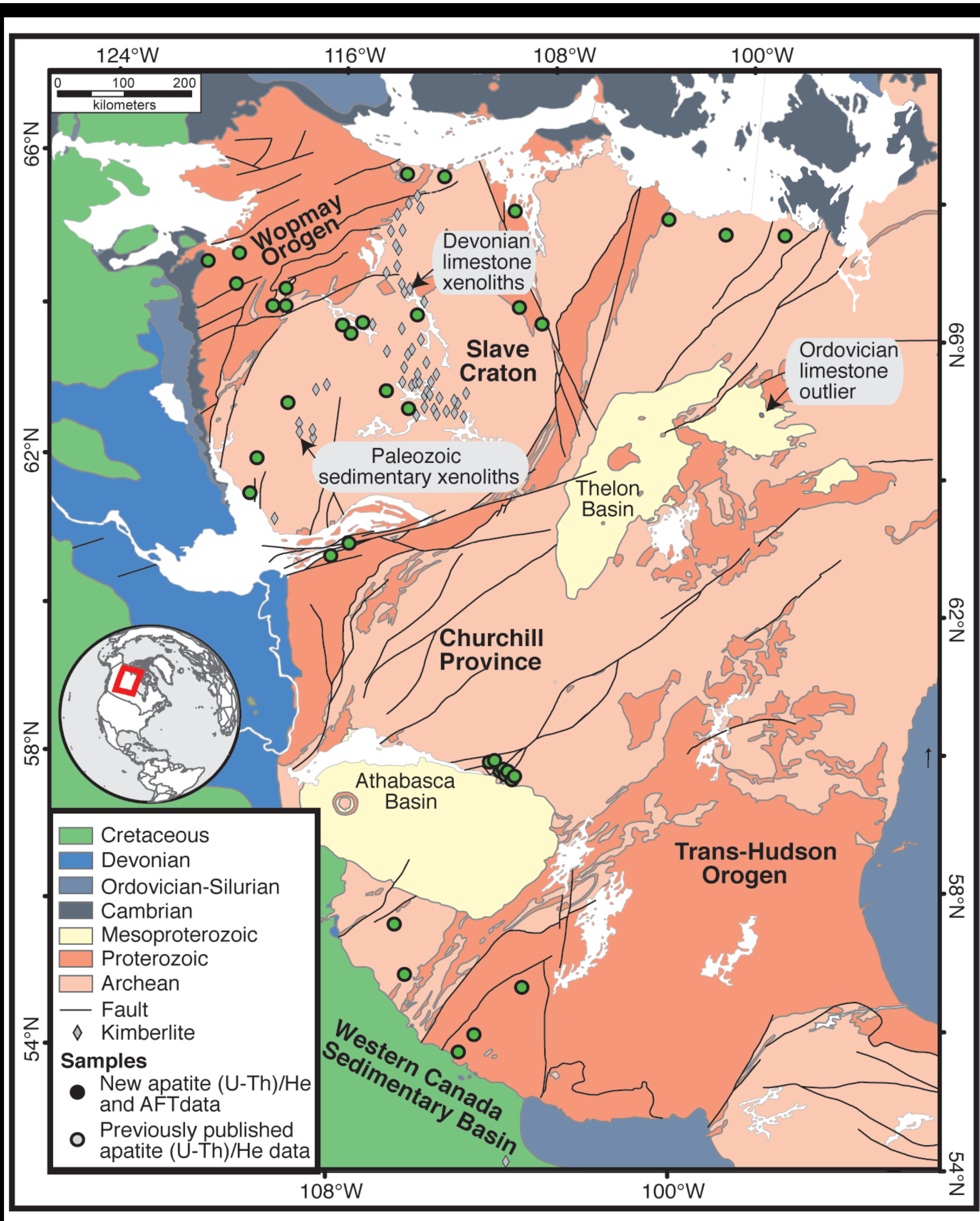


Flowers et al., 2012, EPSL

Epeirogeny or Eustasy?

1) ~~Long-term sea level rise and fall~~

2) Subsidence followed by uplift of the craton



Epeirogeny or Eustasy?

~~1) Long-term sea level rise and fall~~

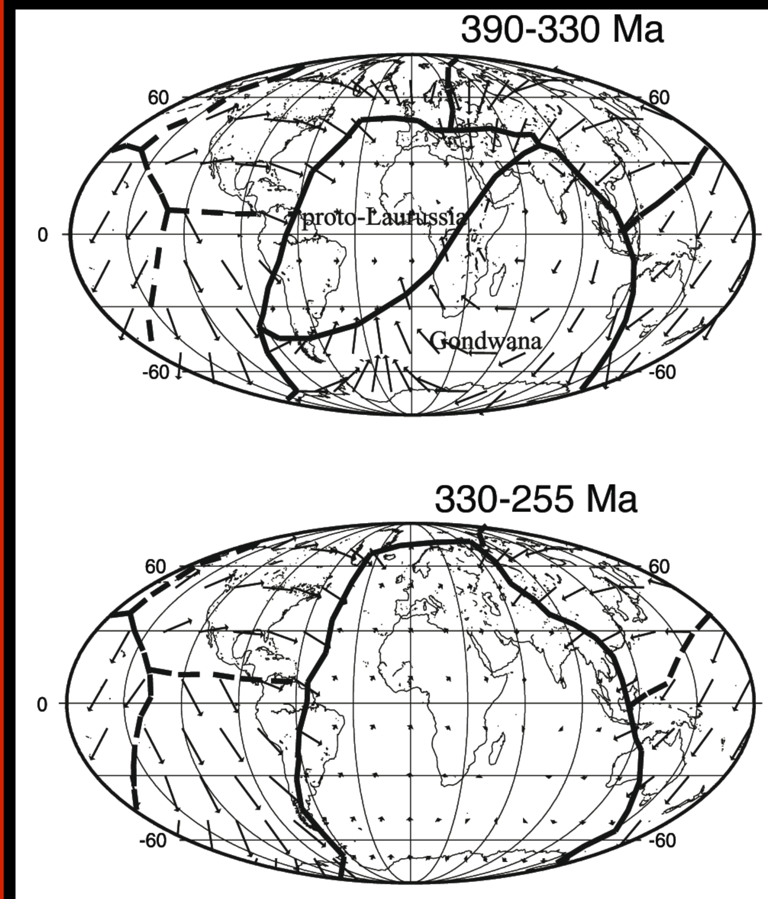
2) Subsidence followed by uplift of the craton

- Tectonics? Probably not…

Predicting time-dependent dynamic topography from 3-D spherical mantle convection model

First model to explore evolution of Earth's mantle structure during supercontinent assembly and breakup

- Global mantle convection models with imposed plate motion history for the last 450 Ma.
- Time-dependent thermo-chemical mantle structures are used to predict dynamic topography at different times.

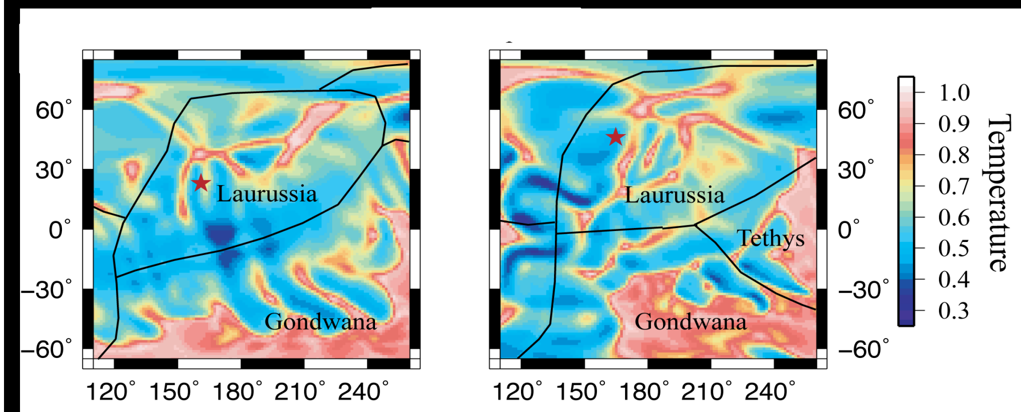


(Zhang et al., 2010; Zhang et al., 2012)

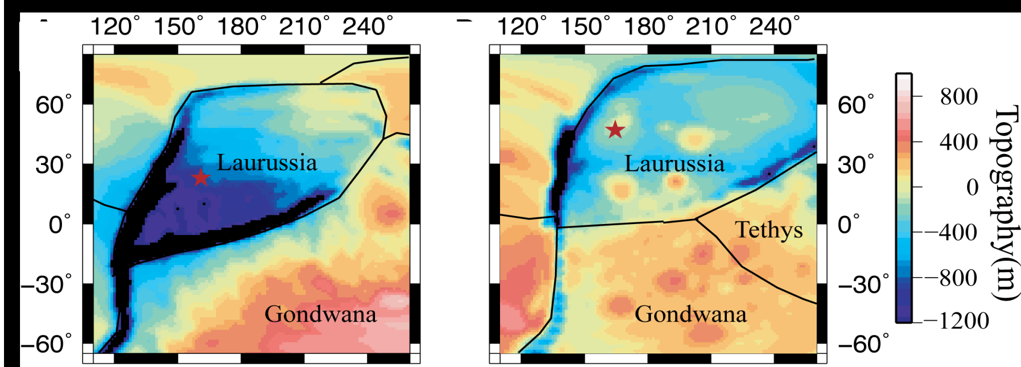
Slave Craton Predicted Vertical Motion

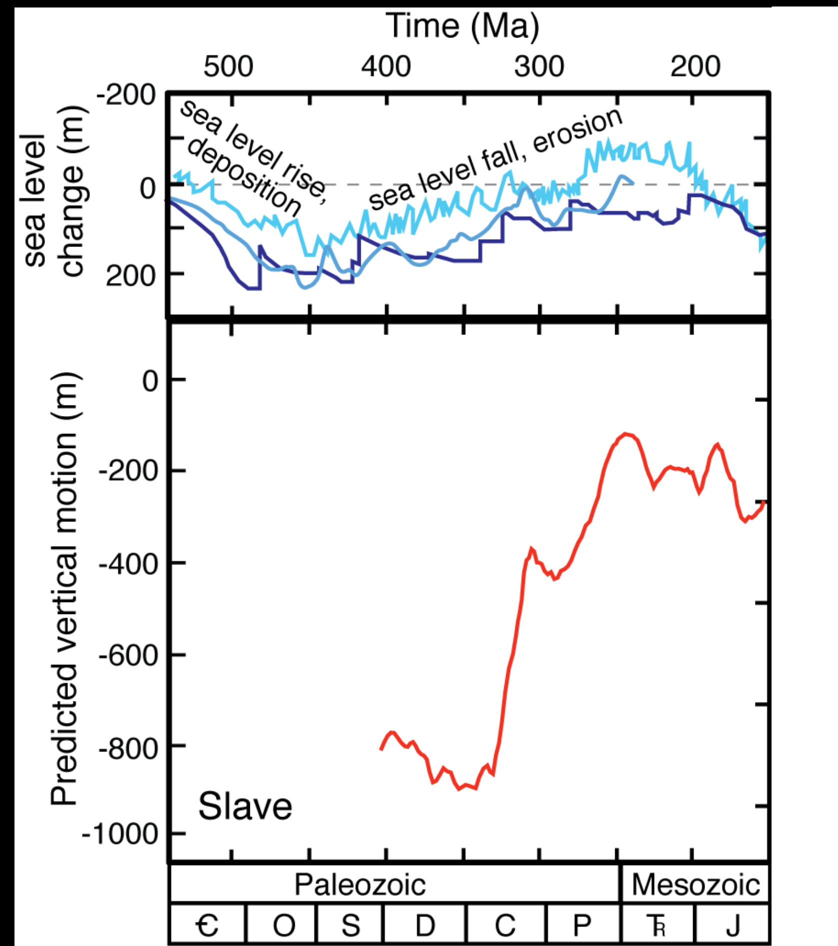
330 Ma 220 Ma

Temperature 2830 km depth



Predicted dynamic topography





Flowers et al., 2012, EPSL; Zhang et al., 2012, EPSL

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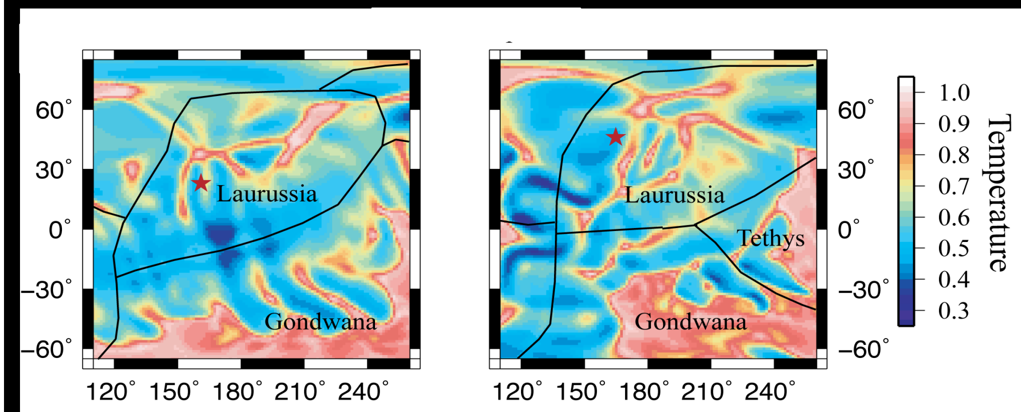
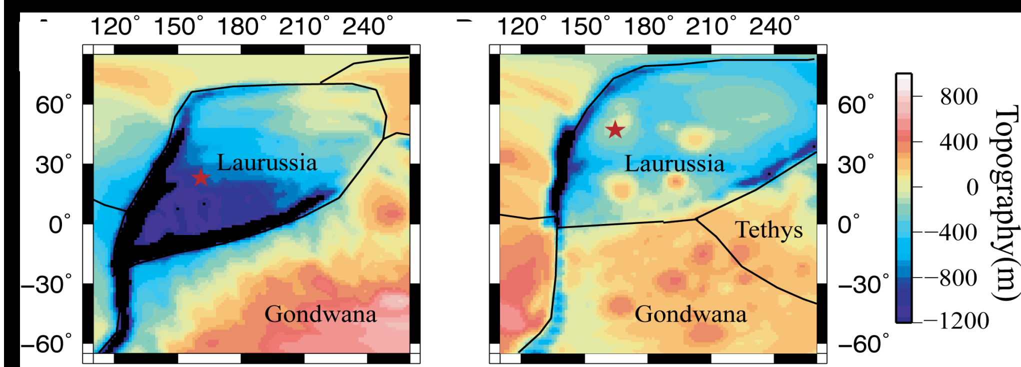
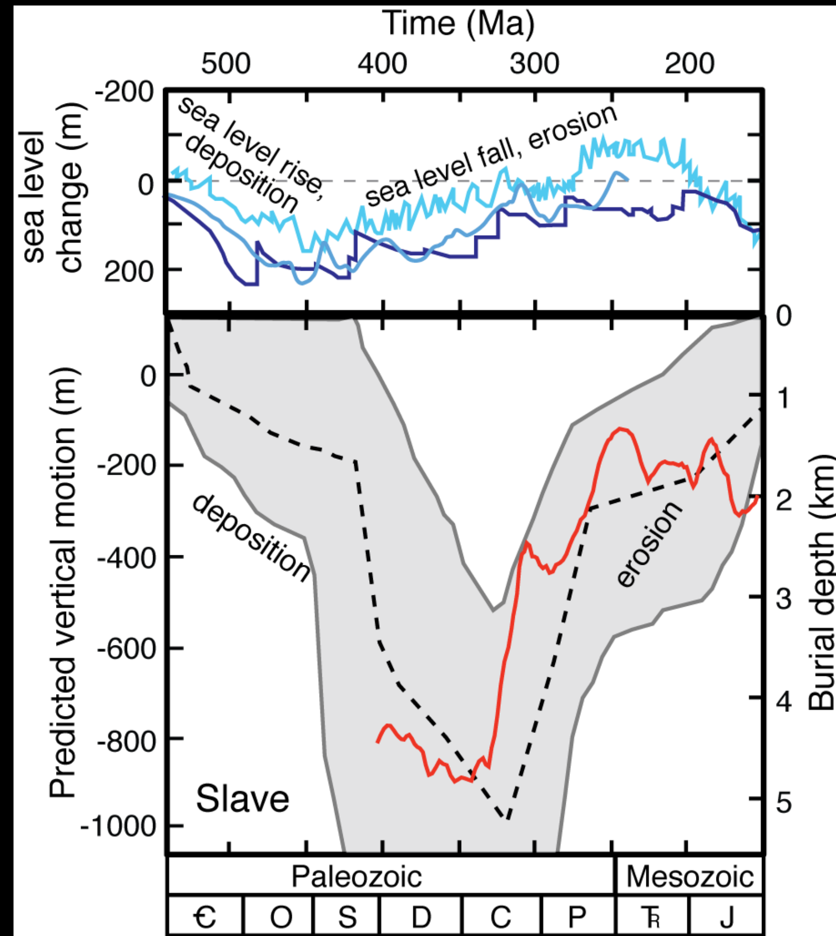


Predicted dynamic topography

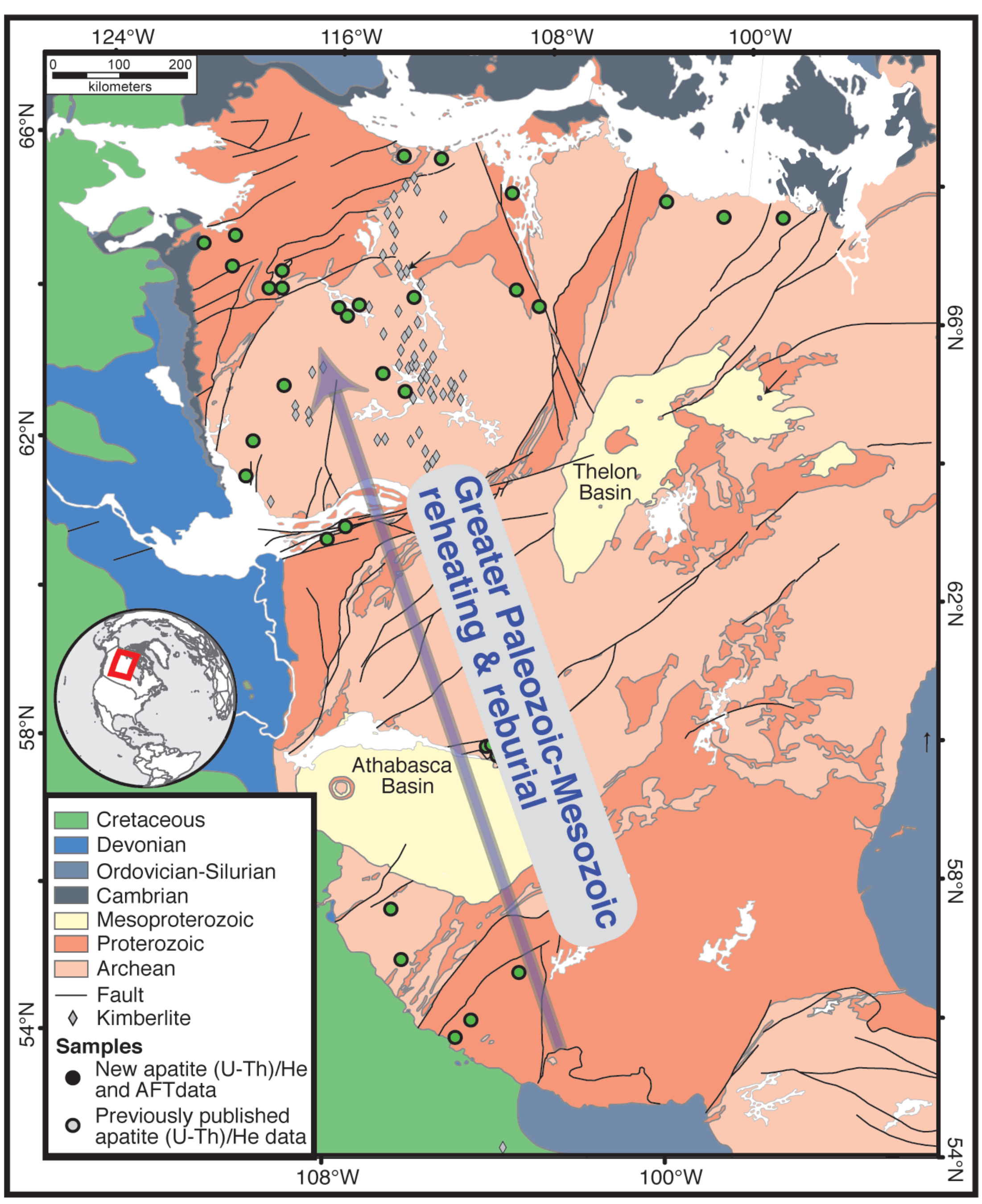


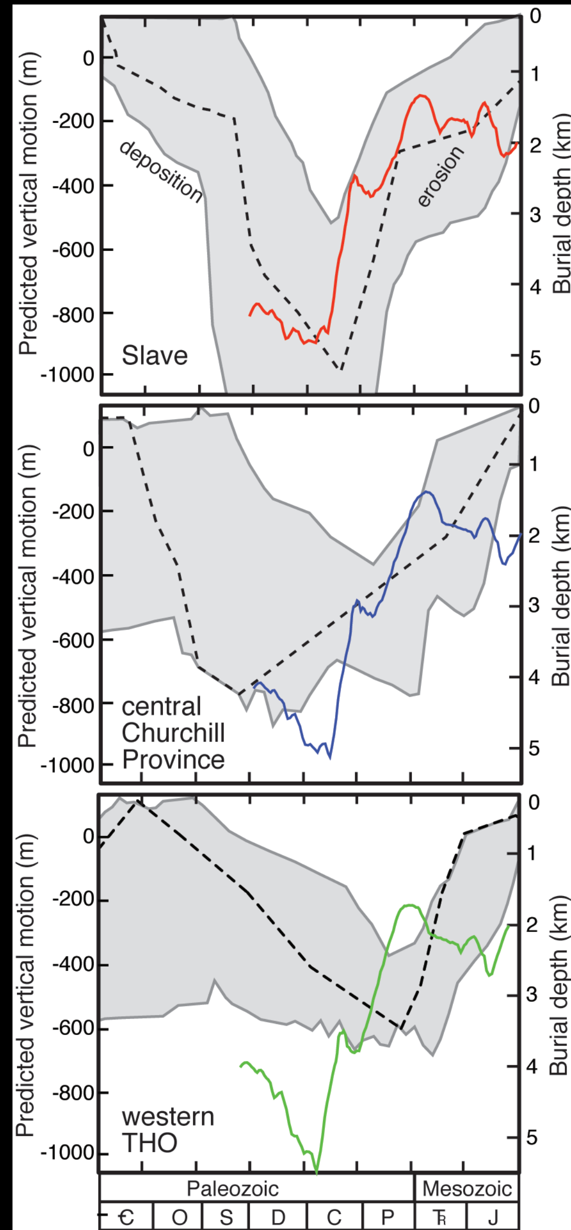


Dynamic topography is a plausible first order cause of long-wavelength elevation change in this region

Flowers et al., 2012, EPSL; Zhang et al., 2012, EPSL

New Constraints for Mantle Dynamic Models





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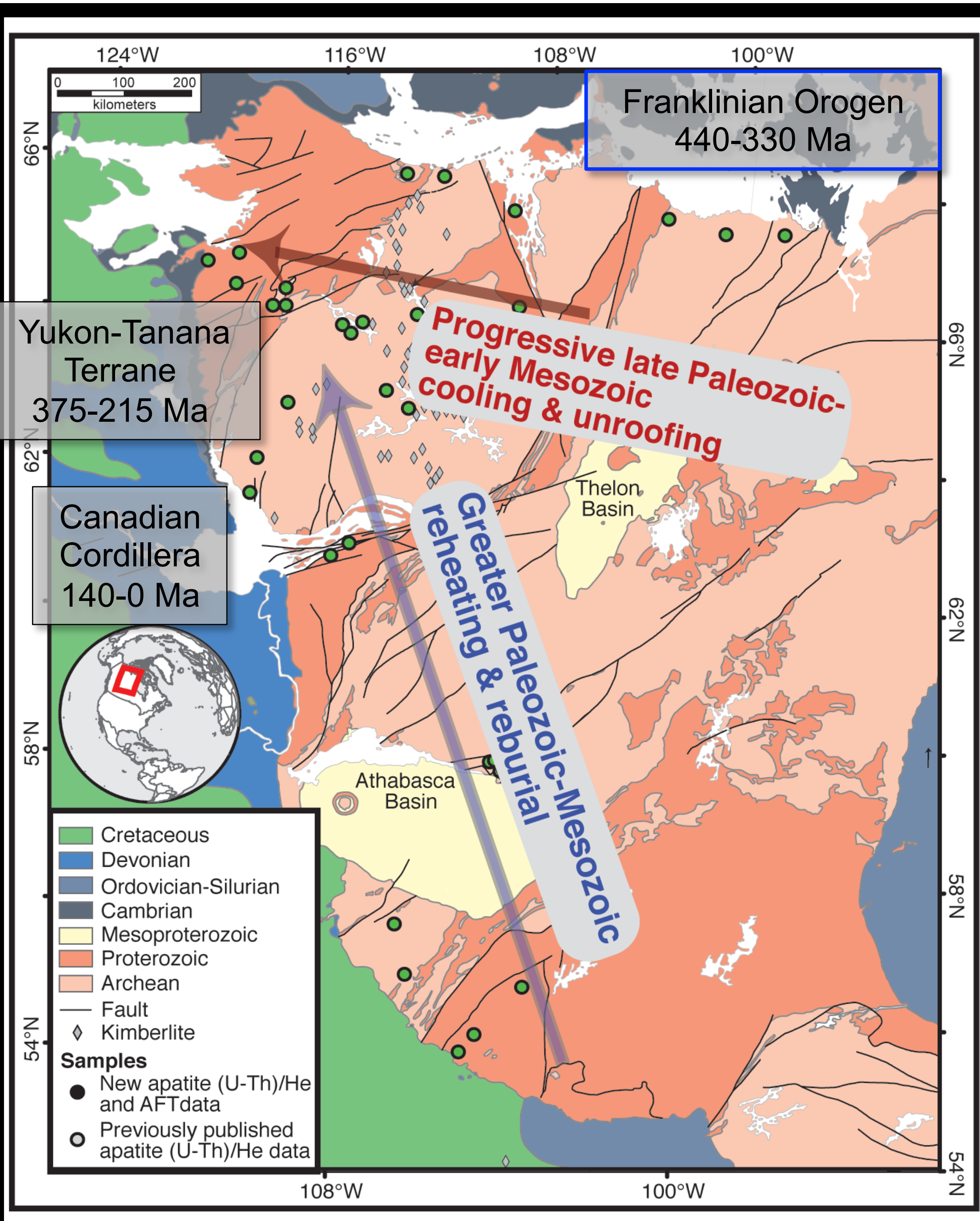

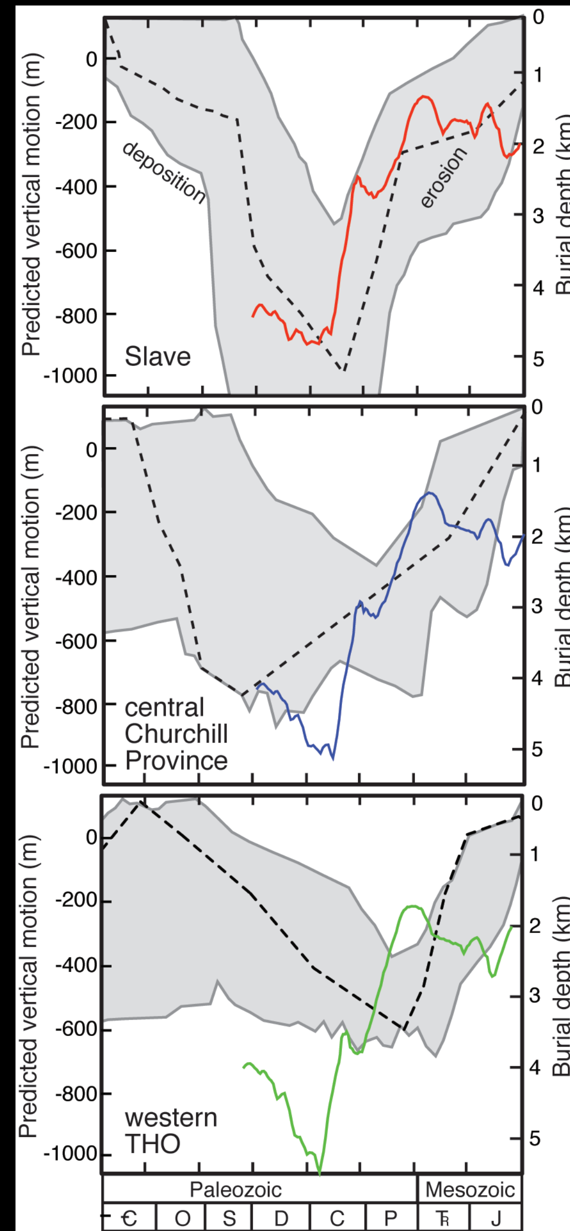

Flowers et al., 2012, EPSL; Ault et al., in review

How stable are cratons?