LOW-TEMPERATURE THERMOCHRONOLOGY OF THE LITTLE BELT MOUNTAINS WITH IMPLICATIONS FOR MODELS OF LARAMIDE TECTONISM

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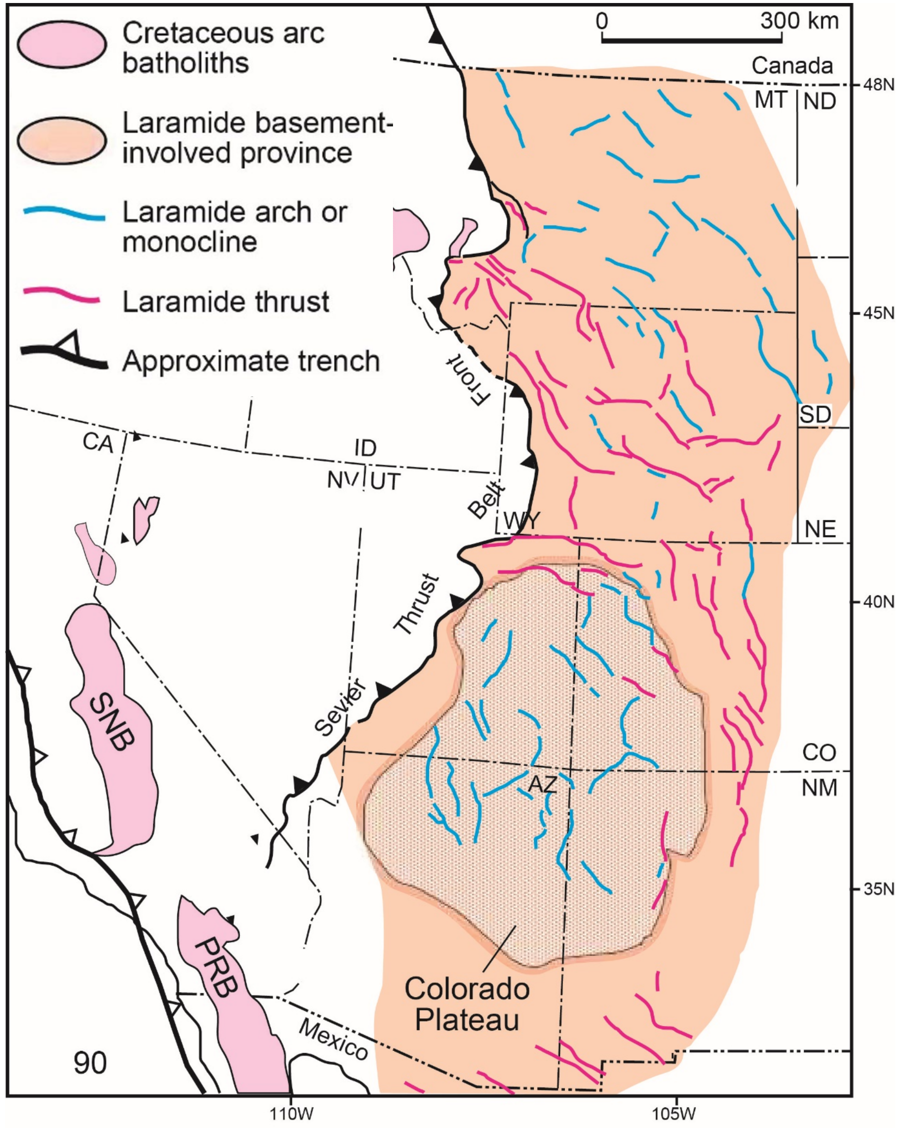
“[the Little Belt Mountains] form part of the Rocky Mountain region, being one of the eastern of the bordering or front ranges, which project from the general mountain area into the open country of the Great Plains.”
(Weed, 1900)

Background

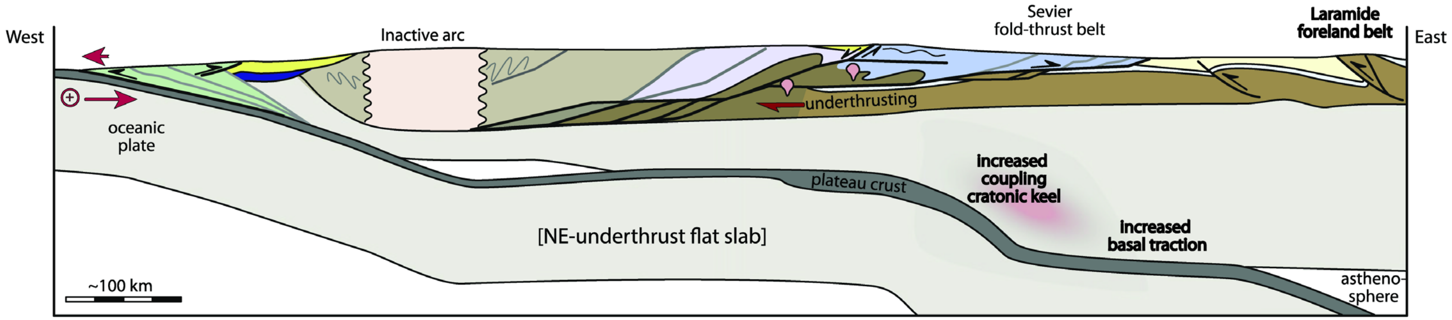
- **What are Laramide uplifts?**
  - Blocks of Proterozoic-Archean basement that were exhumed along reverse faults within the Cordilleran foreland basin



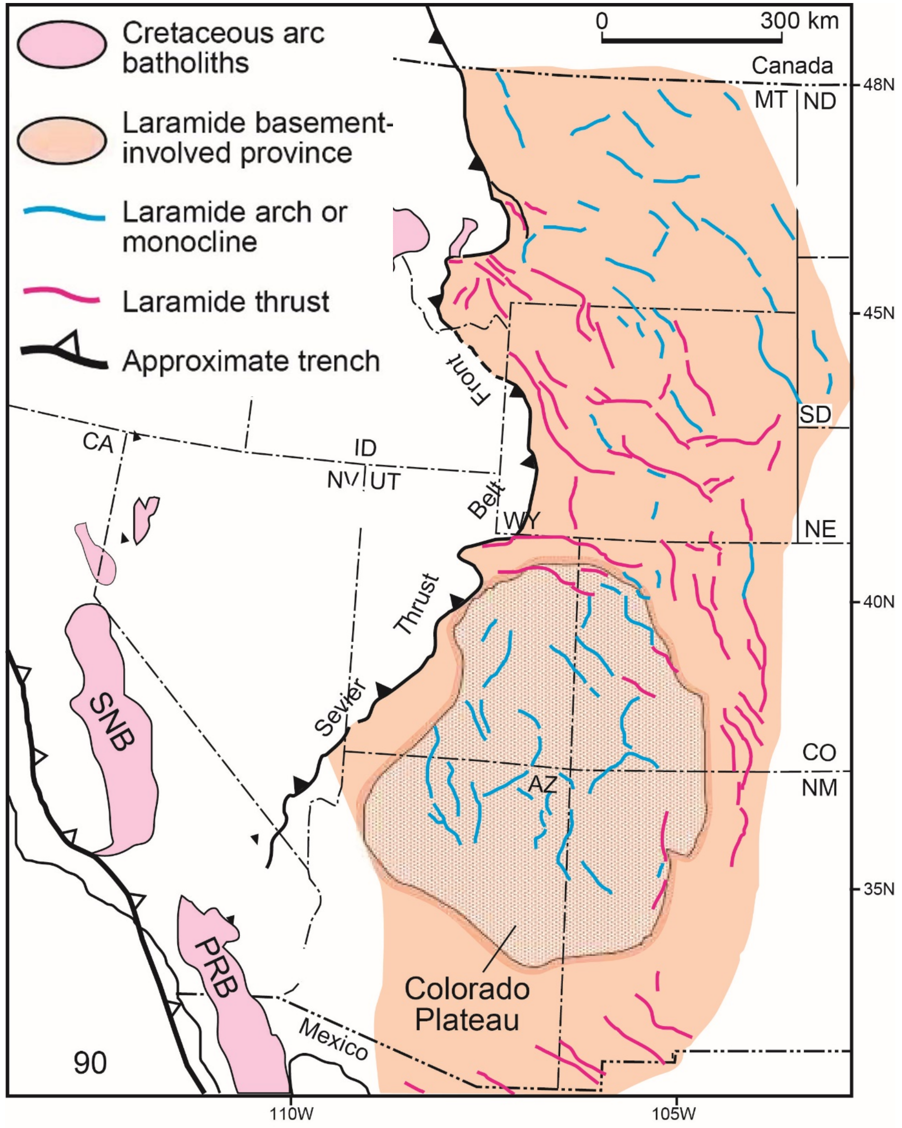
Carrapa et al. (2019)

Background

- **What are Laramide uplifts?**
  - Blocks of Proterozoic-Archean basement that were exhumed along reverse faults within the Cordilleran foreland basin
- **How do they form?**
  - Flat slab subduction
    - Subduction of buoyant ocean features?
    - Intraplate coupling + basal shear stress?



Yonkee & Weil (2015)

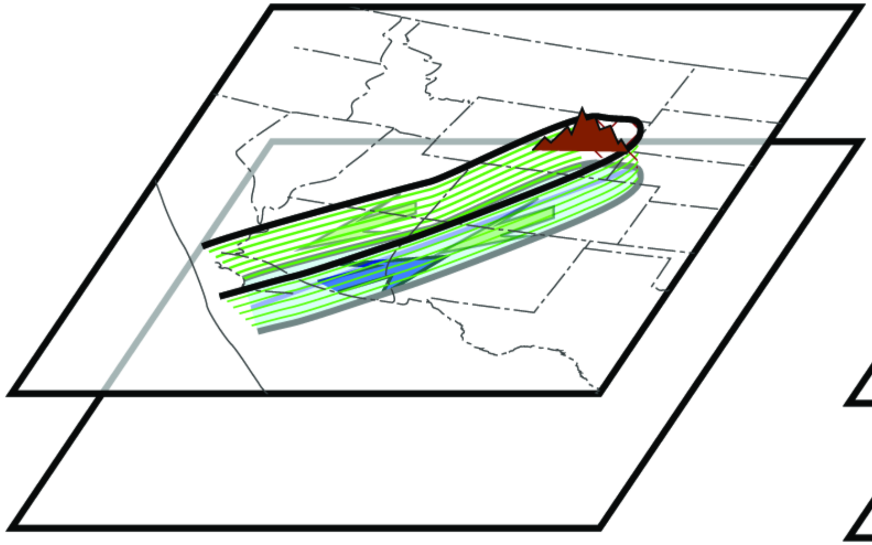


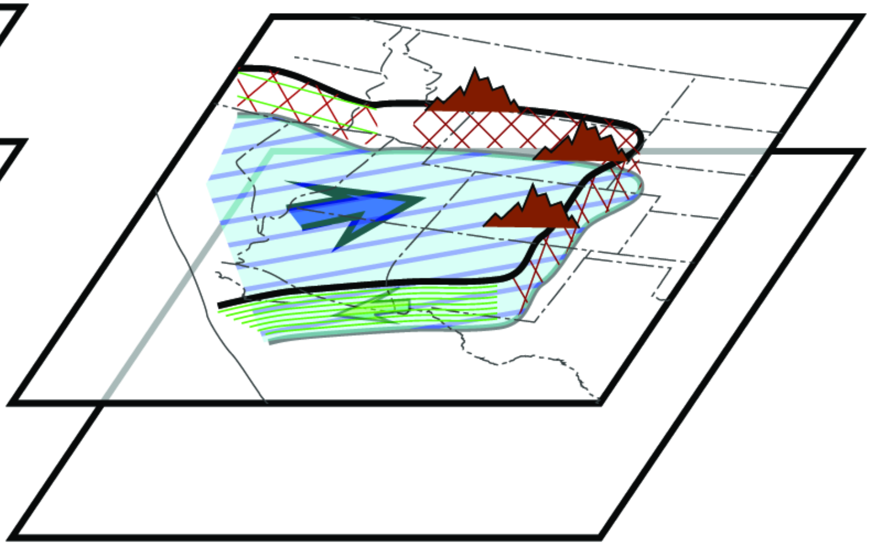
Carrapa et al. (2019)

Background

Proposed models predict different spatiotemporal migration of deformation

Modified from Jones et al. (2011)





Model 1: subduction of oceanic plateau or ridge (e.g., Liu et al., 2010)

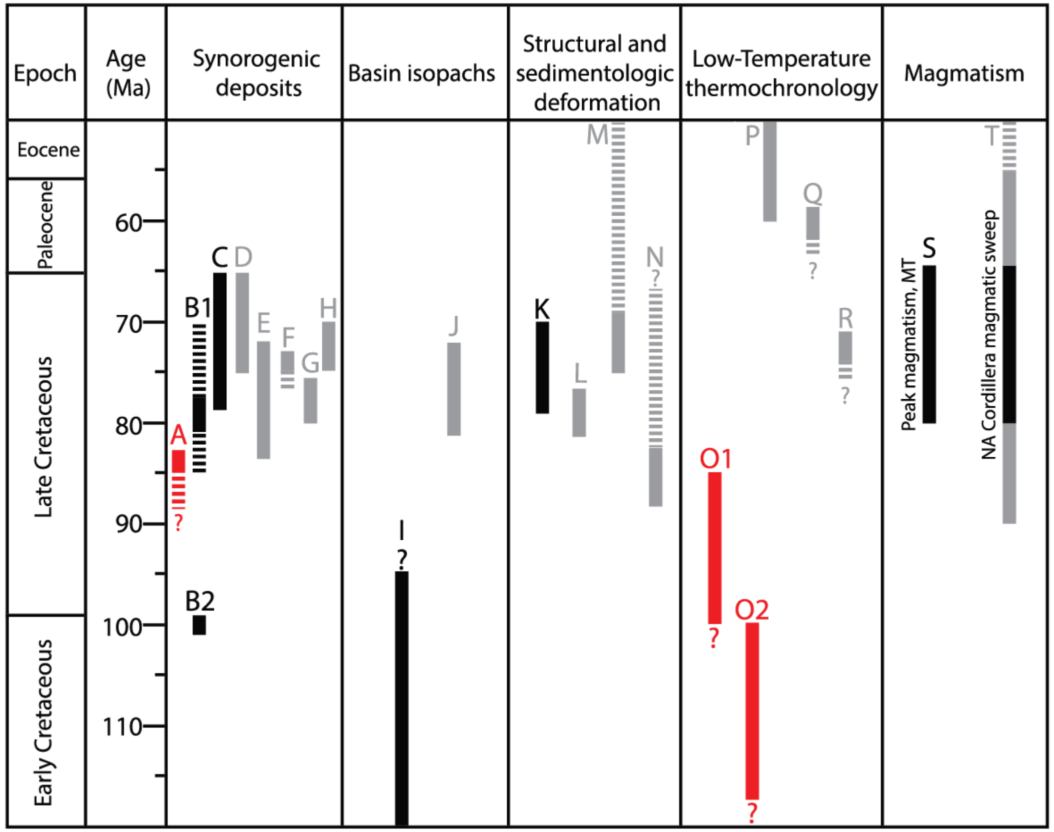
Prediction: SW-NE younging of deformation/exhumation

Model 2: basal traction by broader subducting Farallon lithosphere (e.g., Dickinson and Snyder, 1978)

Prediction: broad and temporally variable deformation

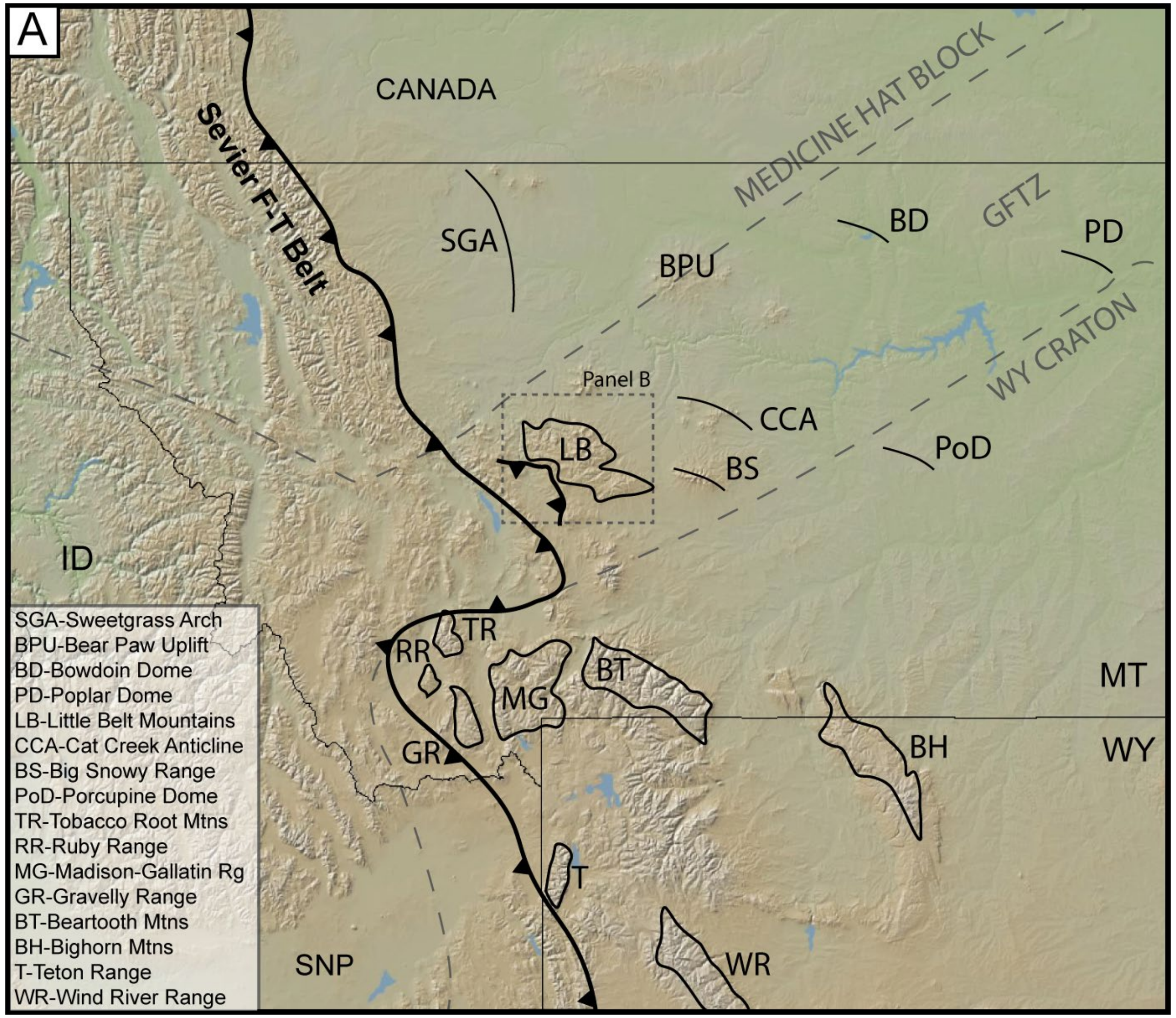
Motivation

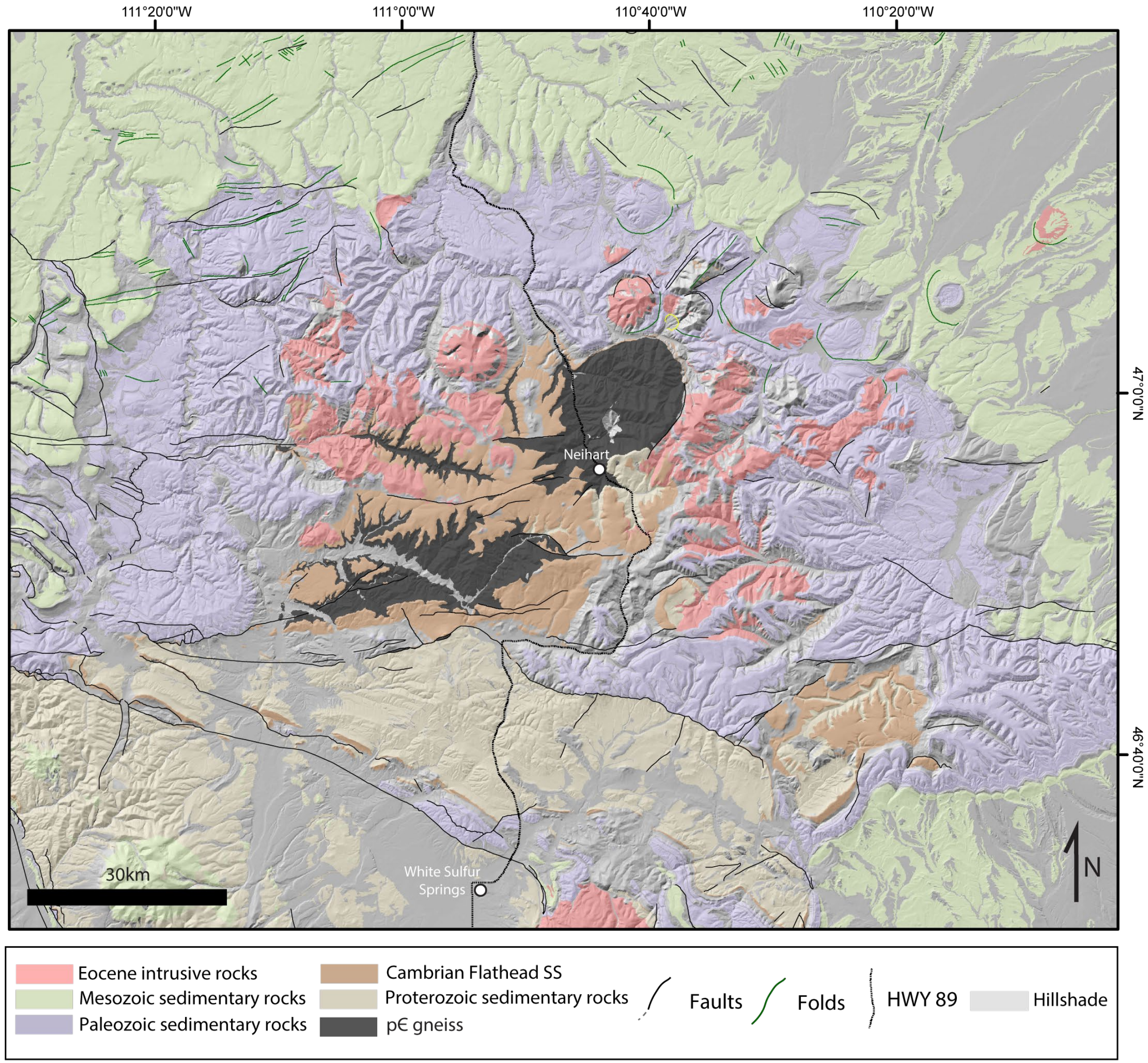
- Assessment of these models hinge on the availability of accurate estimates for the timing of exhumation of Laramide uplifts
- Recent work suggests early inception of Laramide deformation in MT and ID (Carrapa et al., 2019; Garber et al., 2020)
- **No low-temperature thermochronology cooling ages exist for the Little Belt Mountains of central MT**



Orme, 2020

The Little Belt Mountains



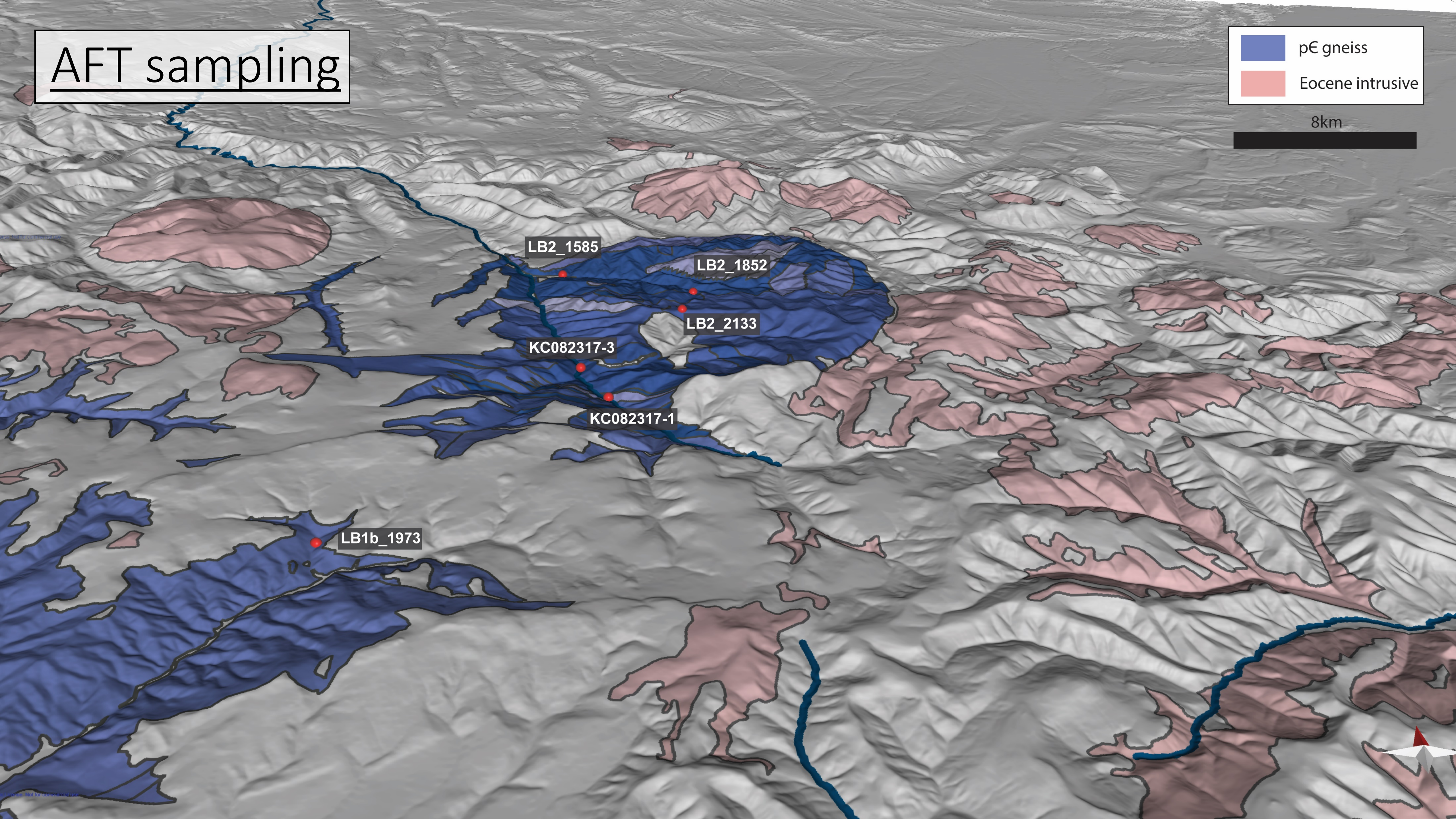


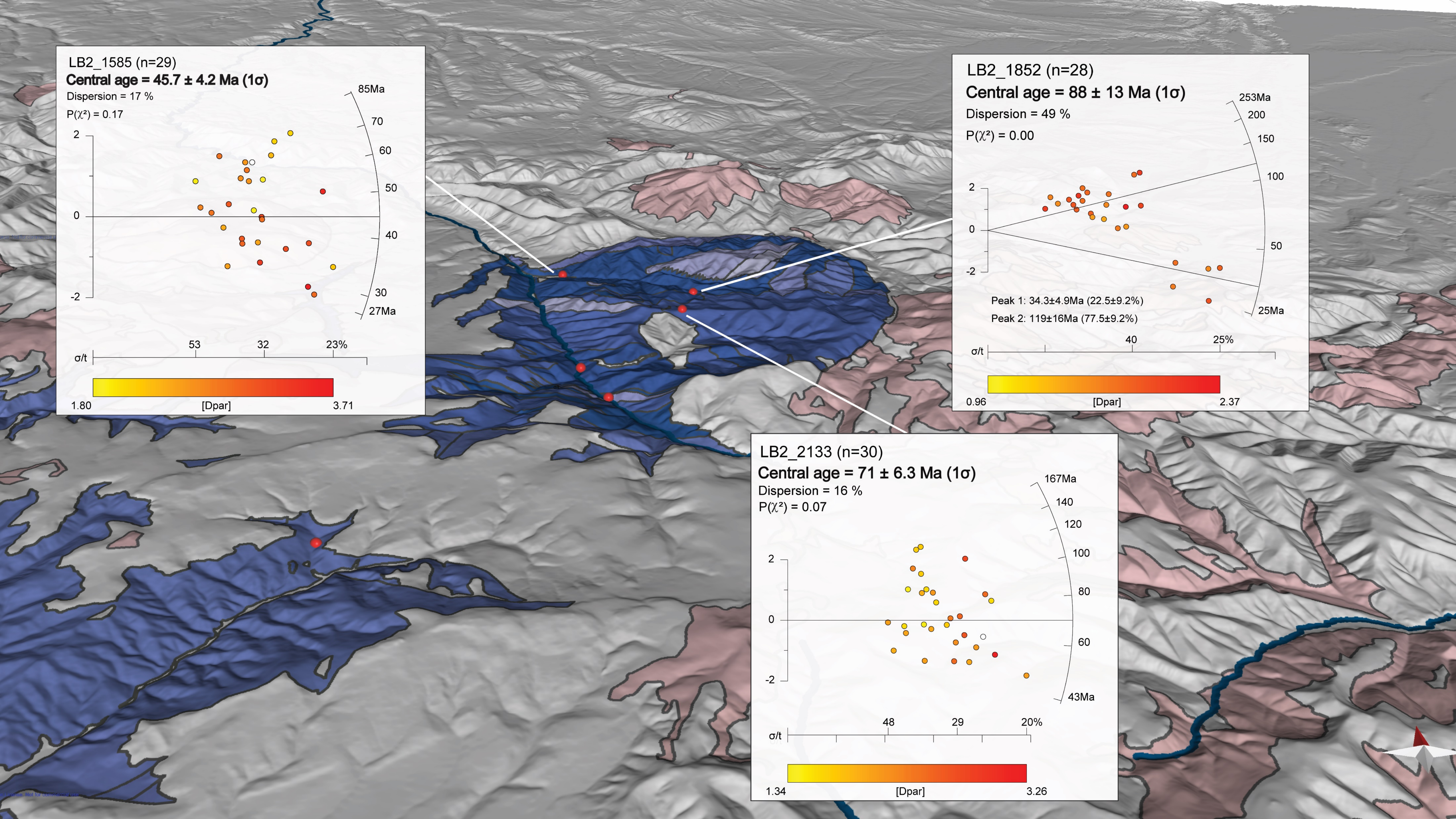
Not all Laramide uplifts are created equal…


"The mountains are very
generally forest clad, their
dark slopes being
in somber contrast to the
surrounding arid plains."
(Weed, 1900)

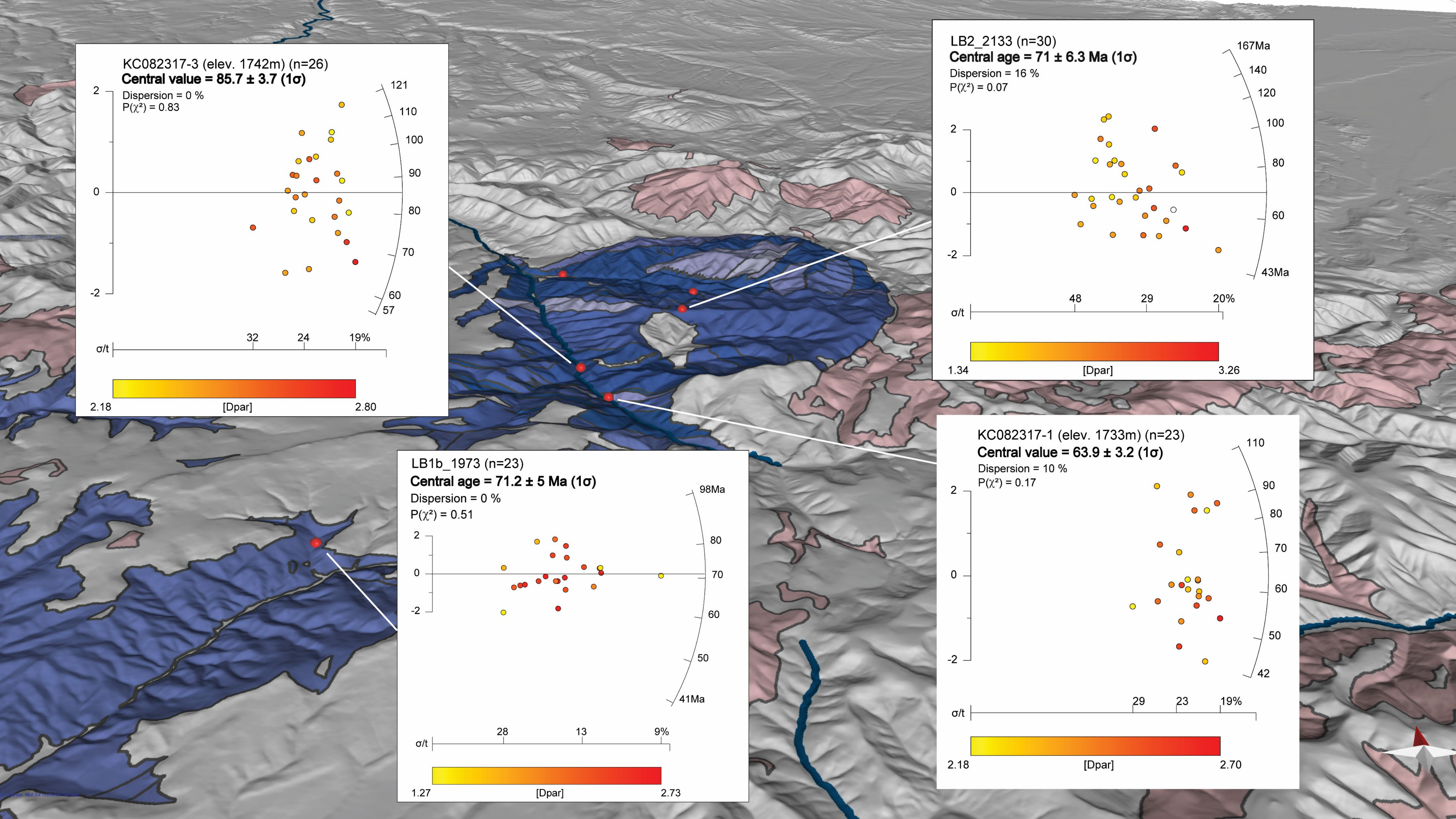

Eocene (~53 Ma) quartz monzonite
Paleoproterozoic basement ~1860 Ma (Mueller et al., 2002)

AFT sampling

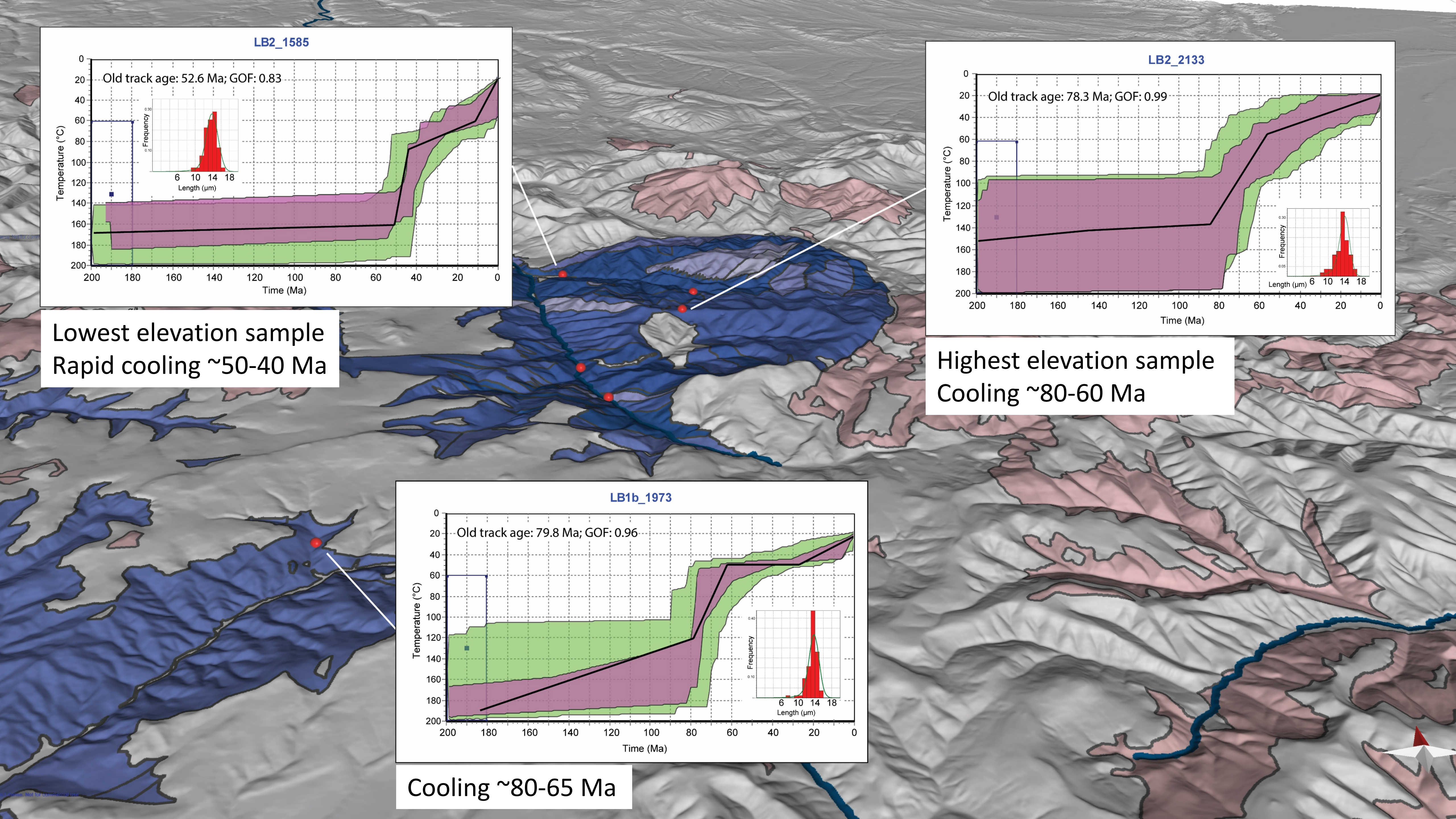


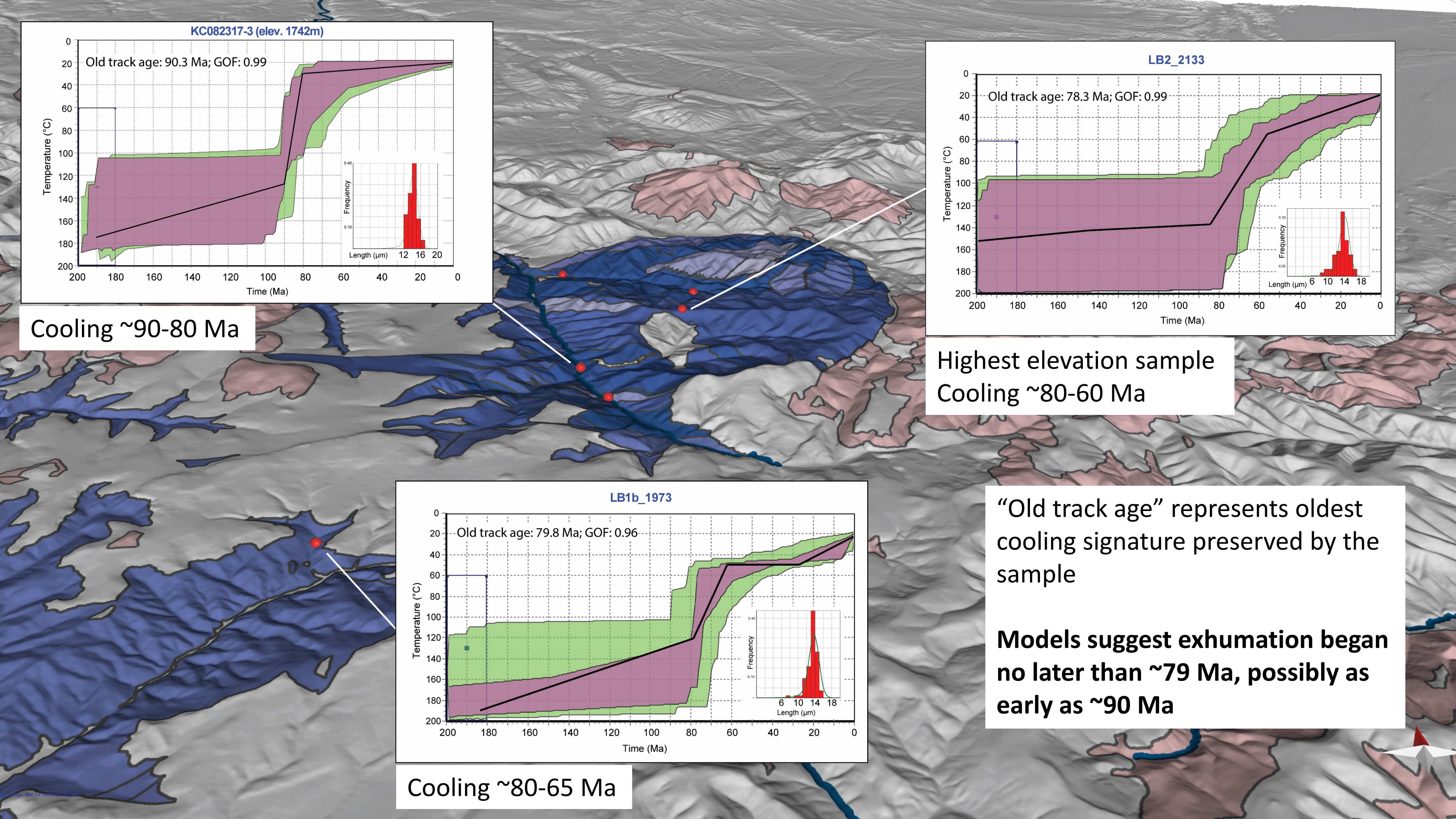


LB2_1585 (n=29)
Central age = 45.7 ± 4.2 Ma (1σ)
Dispersion = 17 %
P(χ²) = 0.17
85Ma
70
60
50
40
30
27Ma
2
0
-2
53
32
23%
σ/t
1.80
[Dpar]
3.71
LB2_1852 (n=28)
Central age = 88 ± 13 Ma (1σ)
Dispersion = 49 %
P(χ²) = 0.00
253Ma
200
150
100
50
25Ma
2
0
-2
Peak 1: 34.3±4.9Ma (22.5±9.2%)
Peak 2: 119±16Ma (77.5±9.2%)
40
25%
σ/t
0.96
[Dpar]
2.37
LB2_2133 (n=30)
Central age = 71 ± 6.3 Ma (1σ)
Dispersion = 16 %
P(χ²) = 0.07
167Ma
140
120
100
80
60
43Ma
2
0
-2
48
29
20%
σ/t
1.34
[Dpar]
3.26



KC082317-3 (elev. 1742m) (n=26)
Central value = 85.7 ± 3.7 (1σ)
Dispersion = 0 %
P(χ²) = 0.83
σ/t
[Dpar]
2.18
2.80
LB2_2133 (n=30)
Central age = 71 ± 6.3 Ma (1σ)
Dispersion = 16 %
P(χ²) = 0.07
167Ma
43Ma
σ/t
[Dpar]
1.34
3.26
LB1b_1973 (n=23)
Central age = 71.2 ± 5 Ma (1σ)
Dispersion = 0 %
P(χ²) = 0.51
98Ma
41Ma
σ/t
[Dpar]
1.27
2.73
KC082317-1 (elev. 1733m) (n=23)
Central value = 63.9 ± 3.2 (1σ)
Dispersion = 10 %
P(χ²) = 0.17
σ/t
[Dpar]
2.18
2.70

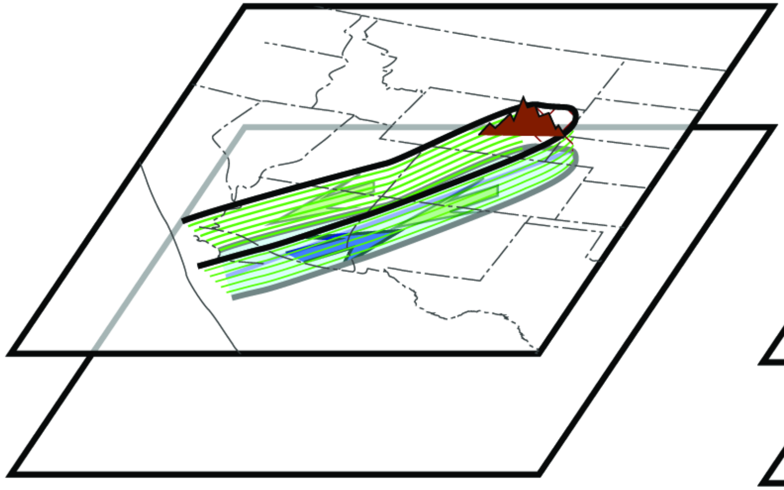

LB2_1585
Old track age: 52.6 Ma; GOF: 0.83
Temperature (°C)
Time (Ma)
Frequency
Length (µm)
Lowest elevation sample
Rapid cooling ~50-40 Ma
LB2_2133
Old track age: 78.3 Ma; GOF: 0.99
Temperature (°C)
Time (Ma)
Frequency
Length (µm)
Highest elevation sample
Cooling ~80-60 Ma
LB1b_1973
Old track age: 79.8 Ma; GOF: 0.96
Temperature (°C)
Time (Ma)
Frequency
Length (µm)
Cooling ~80-65 Ma

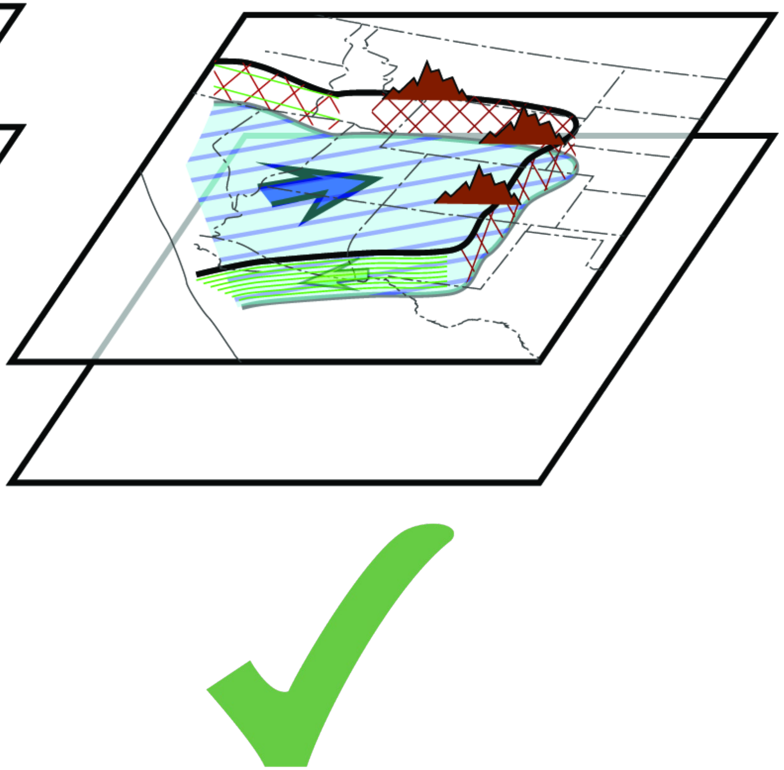

KC082317-3 (elev. 1742m)
Old track age: 90.3 Ma; GOF: 0.99
Temperature (°C)
Time (Ma)
Frequency
Length (μm)
Cooling ~90-80 Ma
LB2_2133
Old track age: 78.3 Ma; GOF: 0.99
Temperature (°C)
Time (Ma)
Frequency
Length (μm)
Highest elevation sample
Cooling ~80-60 Ma
LB1b_1973
Old track age: 79.8 Ma; GOF: 0.96
Temperature (°C)
Time (Ma)
Frequency
Length (μm)
Cooling ~80-65 Ma
"Old track age" represents oldest cooling signature preserved by the sample
Models suggest exhumation began no later than ~79 Ma, possibly as early as ~90 Ma

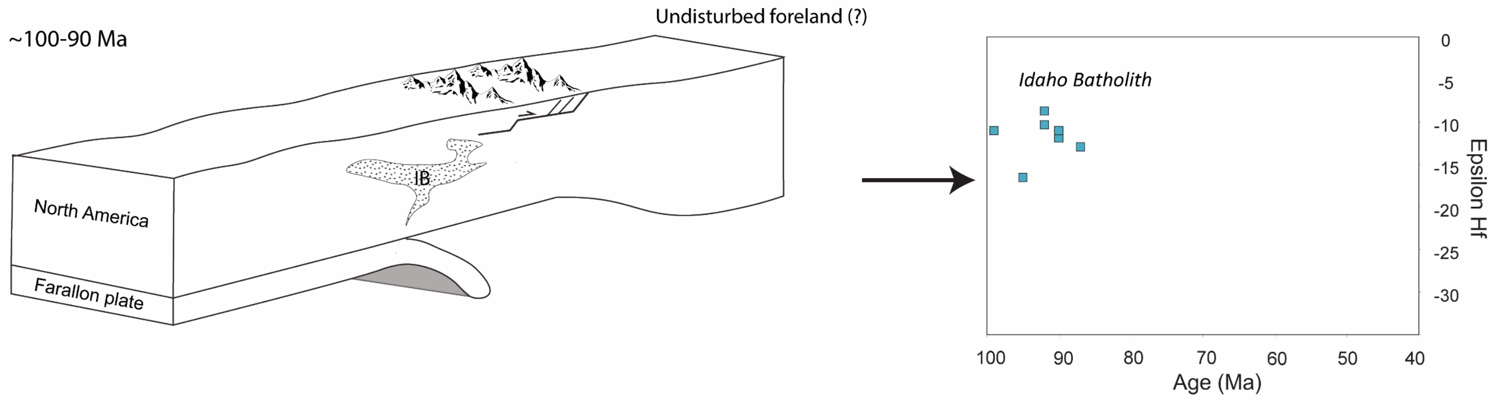
Considering the geometry of the flat slab

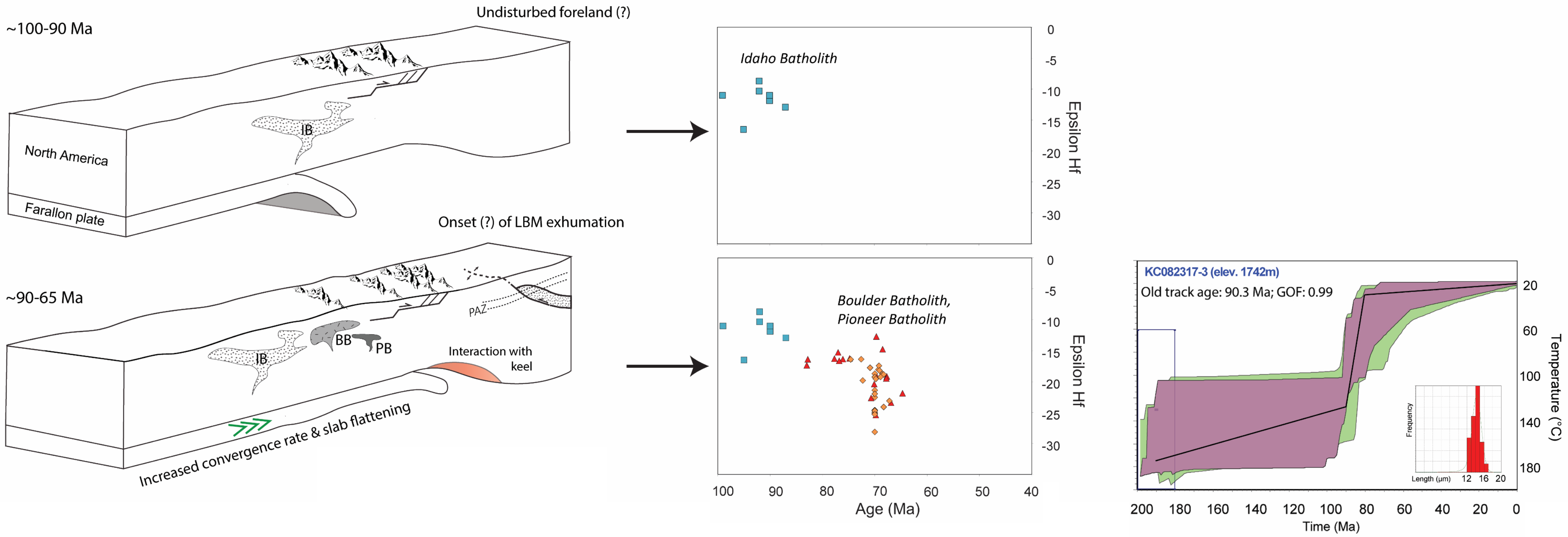
Jones et al. (2011)

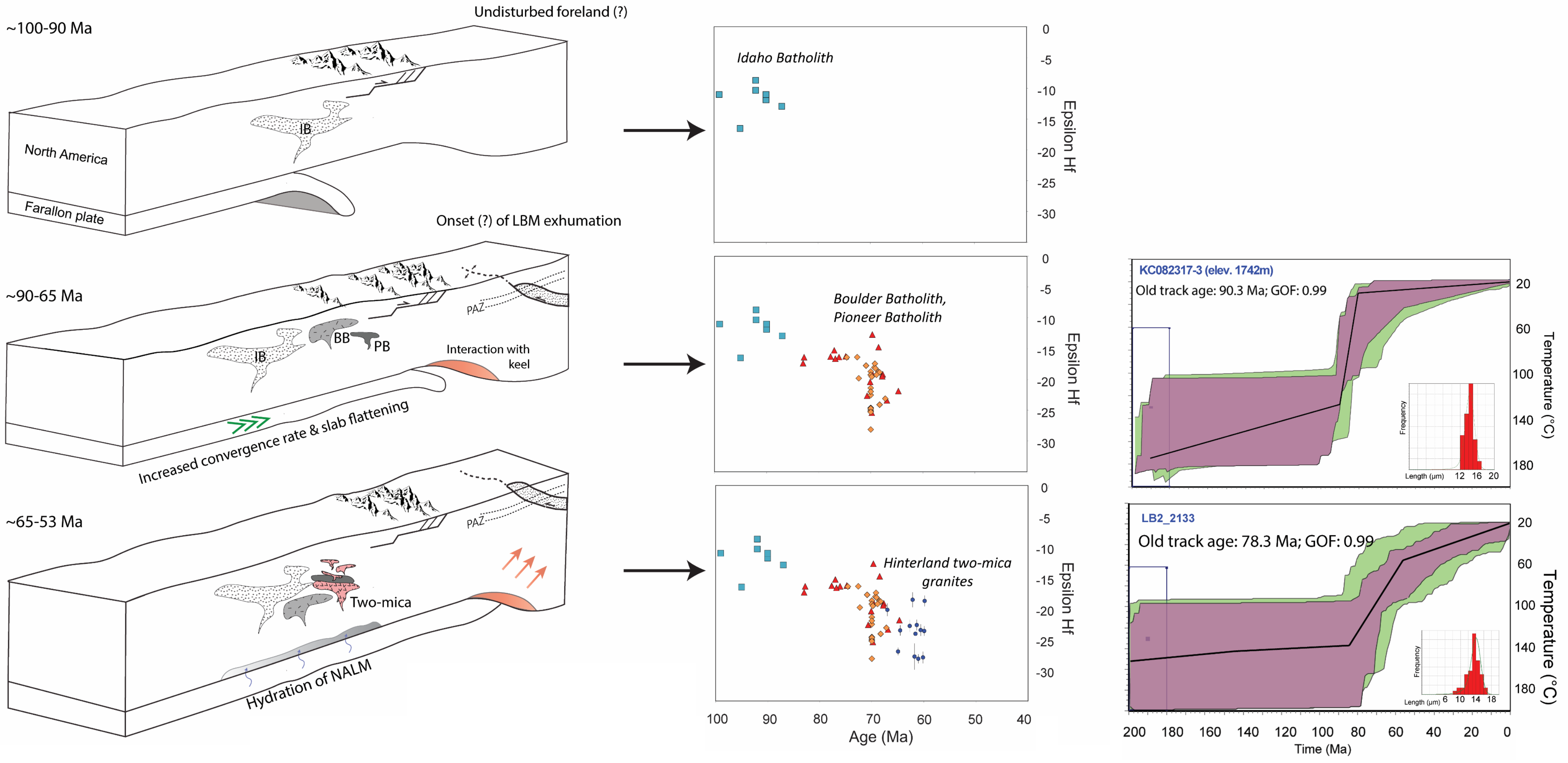
- Old cooling ages in central Montana consistent with broader flat slab region
  - Also supported by magmatic history in the Idaho-Montana segment of the arc

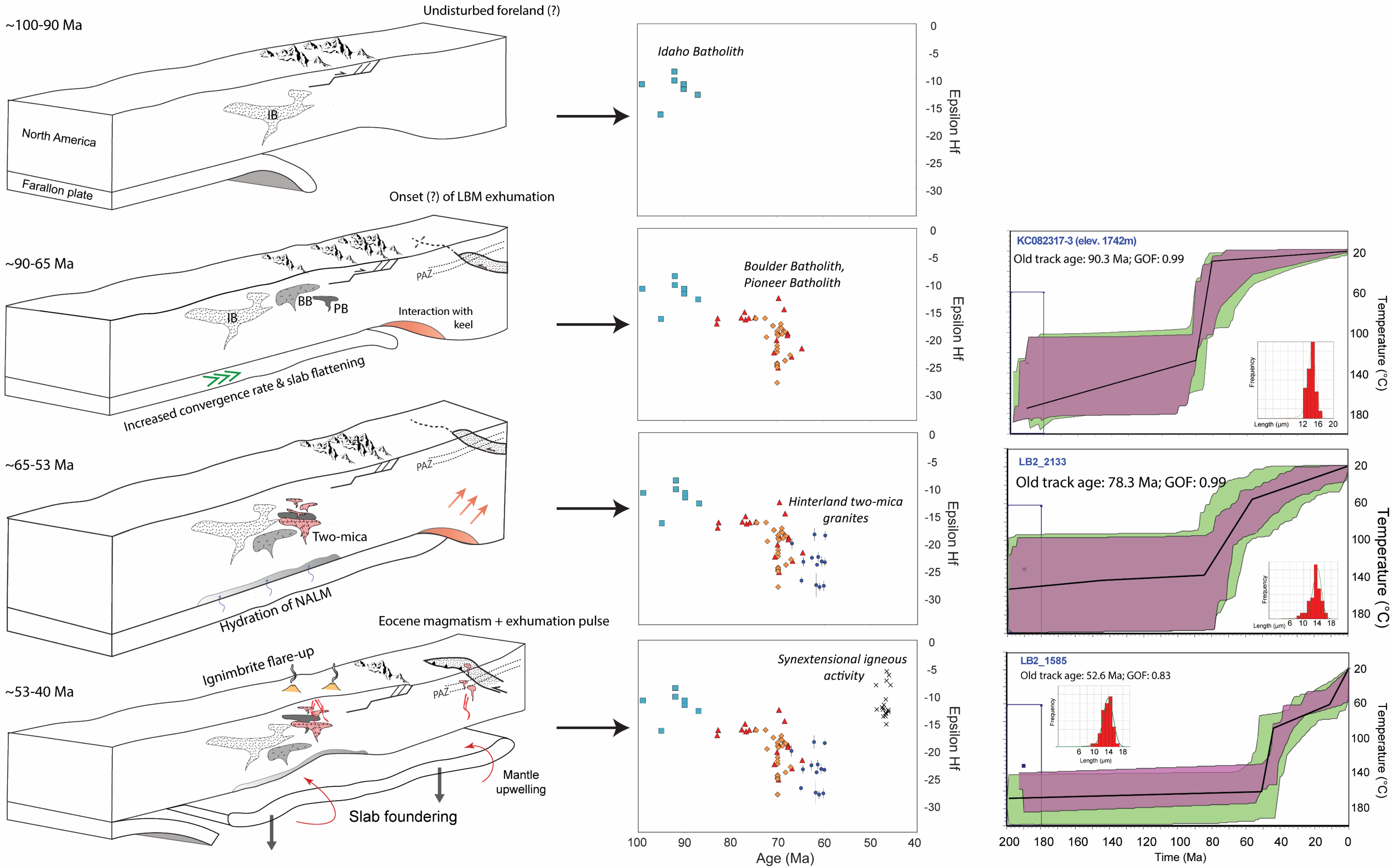





~100-90 Ma
Undisturbed foreland (?)
North America
Farallon plate
IB
Idaho Batholith
Epsilon Hf
0
-5
-10
-15
-20
-25
-30
100
90
80
70
60
50
40
Age (Ma)

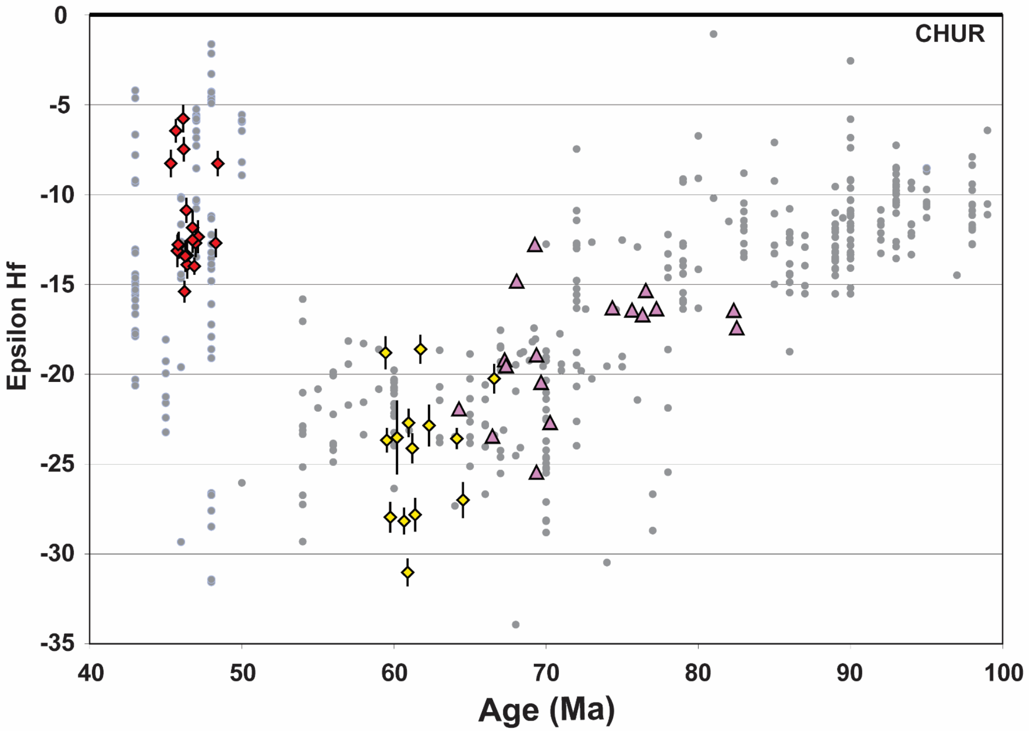

~100-90 Ma
Undisturbed foreland (?)
IB
North America
Farallon plate
~90-65 Ma
Onset (?) of LBM exhumation
PAZ
BB
PB
Interaction with keel
Increased convergence rate & slab flattening
Idaho Batholith
Boulder Batholith, Pioneer Batholith
Epsilon Hf
0
-5
-10
-15
-20
-25
-30
100
90
80
70
60
50
40
Age (Ma)
KC082317-3 (elev. 1742m)
Old track age: 90.3 Ma; GOF: 0.99
Frequency
Length (µm)
12
16
20
Temperature (°C)
20
60
100
140
180
200
180
160
140
120
100
80
60
40
20
0
Time (Ma)


~100-90 Ma
Undisturbed foreland (?)
IB
North America
Farallon plate
Onset (?) of LBM exhumation
~90-65 Ma
PAZ
BB
PB
IB
Interaction with keel
Increased convergence rate & slab flattening
~65-53 Ma
PAZ
Two-mica
Hydration of NALM
Idaho Batholith
Boulder Batholith, Pioneer Batholith
Hinterland two-mica granites
Epsilon Hf
Age (Ma)
KC082317-3 (elev. 1742m)
Old track age: 90.3 Ma; GOF: 0.99
LB2_2133
Old track age: 78.3 Ma; GOF: 0.99
Frequency
Length (µm)
Temperature (°C)
Time (Ma)

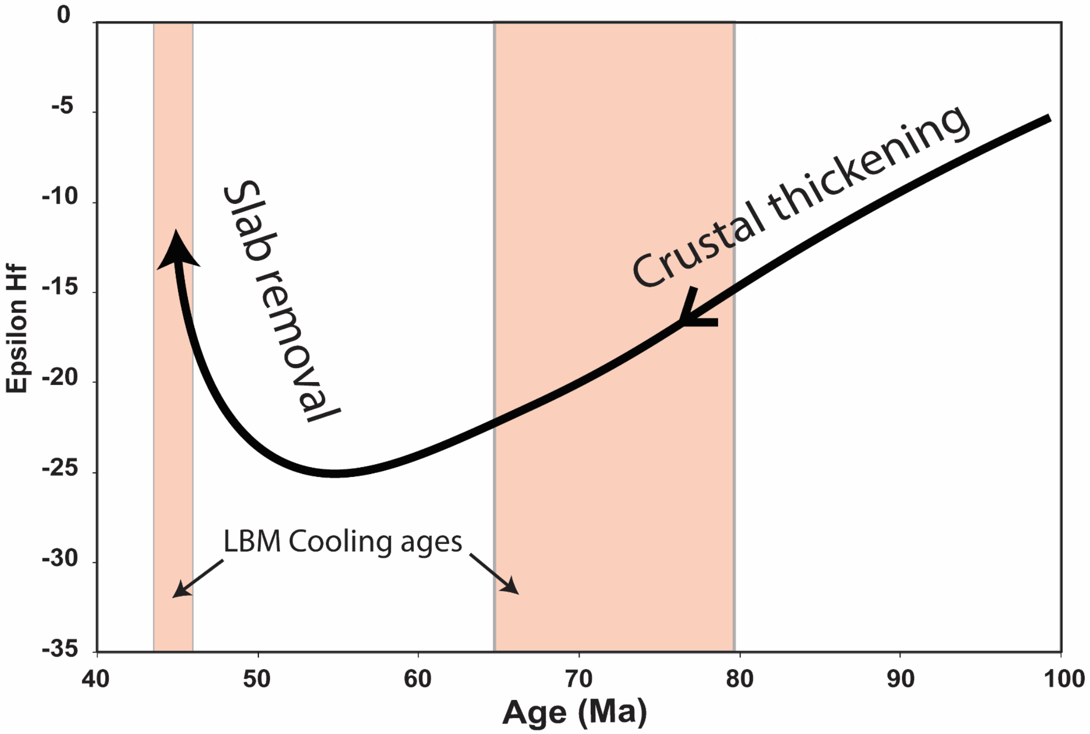


~100-90 Ma
Undisturbed foreland (?)
IB
North America
Farallon plate
Idaho Batholith
~90-65 Ma
Onset (?) of LBM exhumation
PAZ
IB
BB
PB
Interaction with keel
Increased convergence rate & slab flattening
Boulder Batholith, Pioneer Batholith
KC082317-3 (elev. 1742m)
Old track age: 90.3 Ma; GOF: 0.99
~65-53 Ma
PAZ
Two-mica
Hydration of NALM
Hinterland two-mica granites
LB2_2133
Old track age: 78.3 Ma; GOF: 0.99
~53-40 Ma
Eocene magmatism + exhumation pulse
Ignimbrite flare-up
PAZ
Mantle upwelling
Slab foundering
Synextensional igneous activity
LB2_1585
Old track age: 52.6 Ma; GOF: 0.83
Epsilon Hf
Age (Ma)
Temperature (°C)
Time (Ma)
Frequency
Length (μm)

Pairing Lu-Hf evolution with cooling ages



Modified from Howlett et al. (2021)

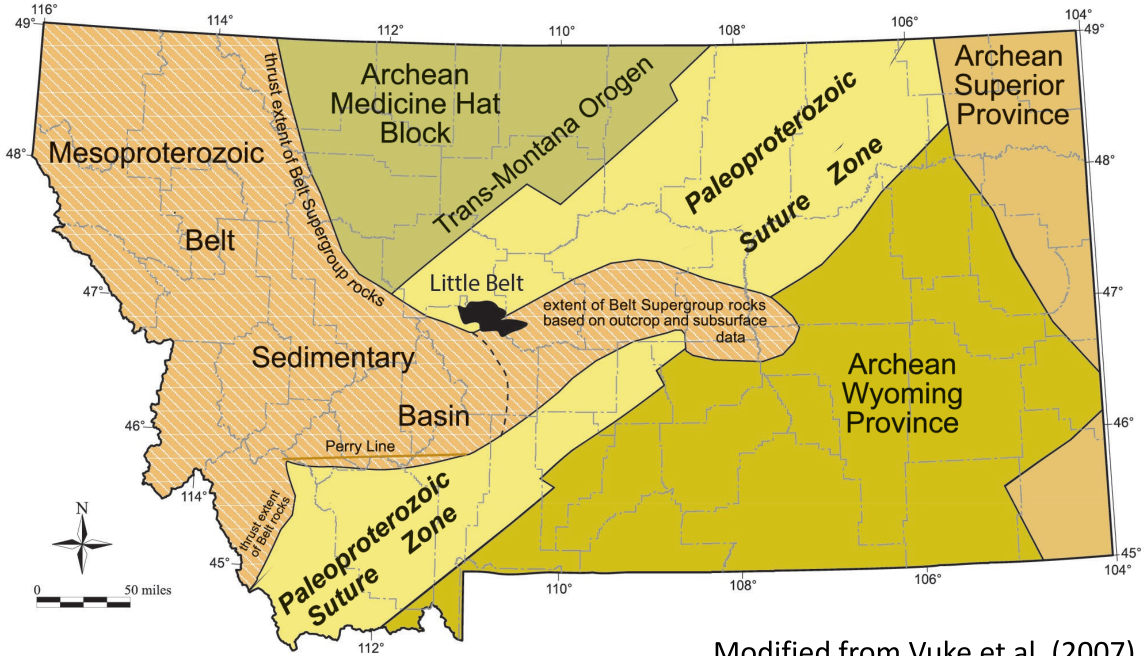


Eocene pulse due to slab removal?

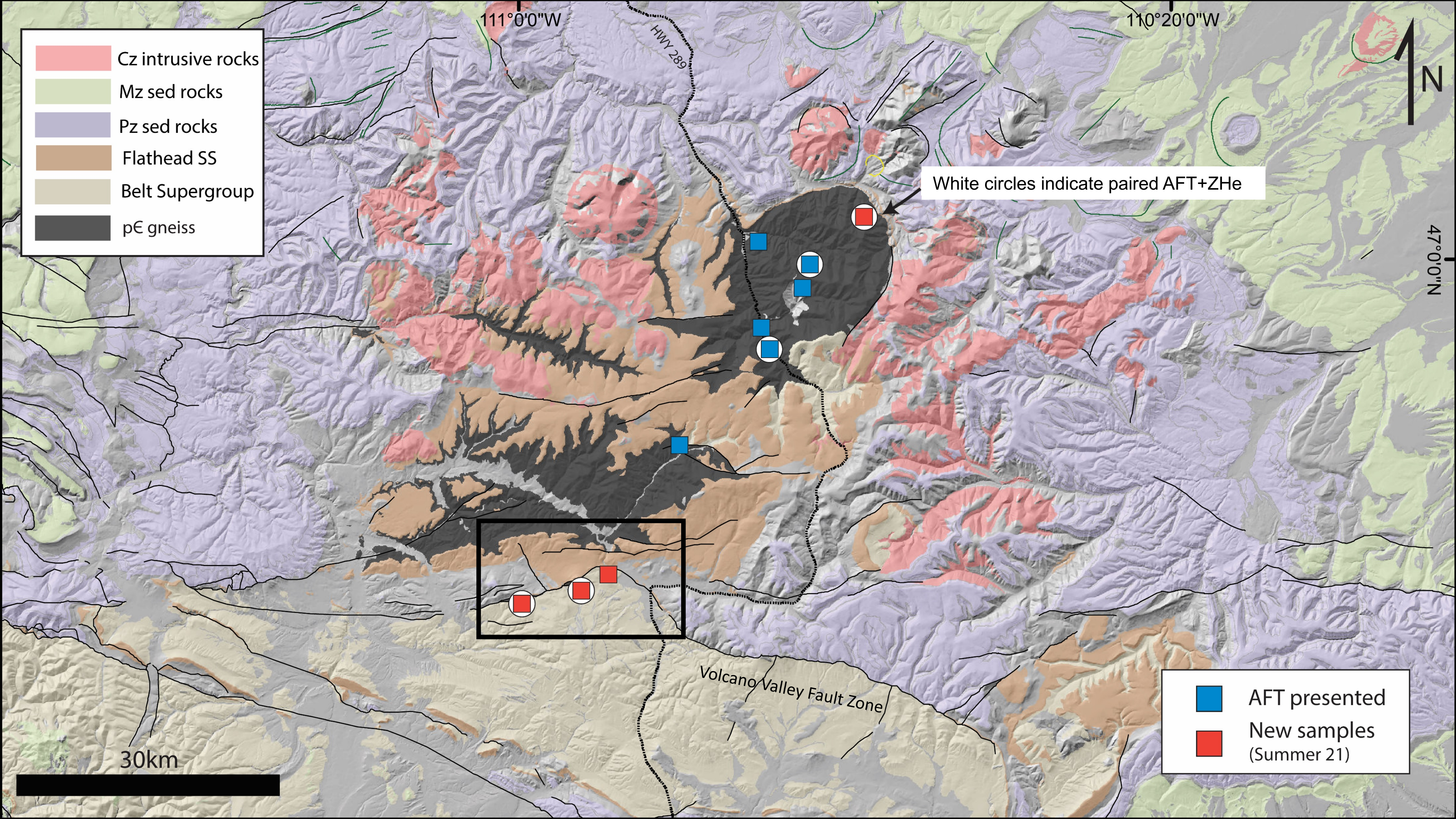
Considering basement architecture

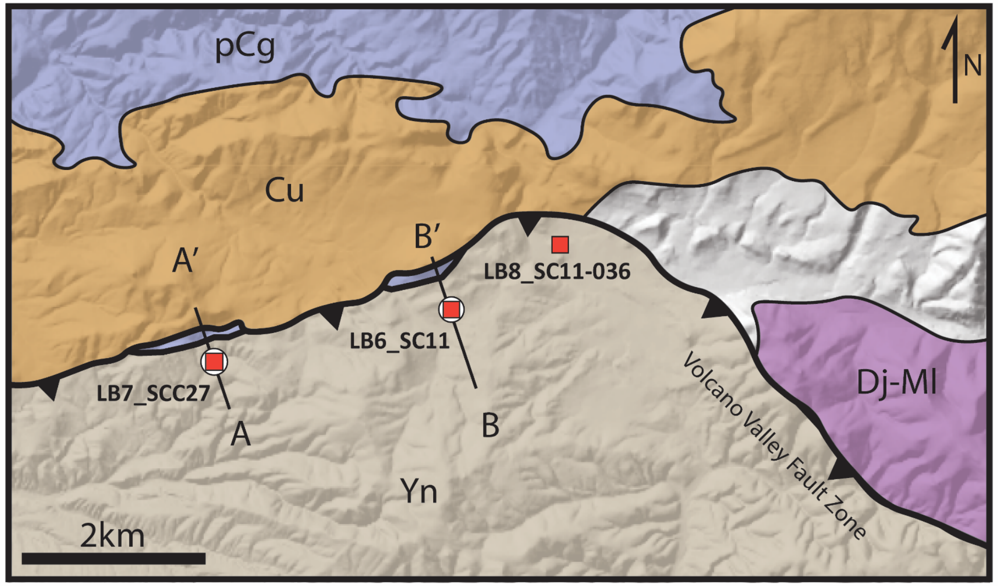
Is a flat slab necessary?

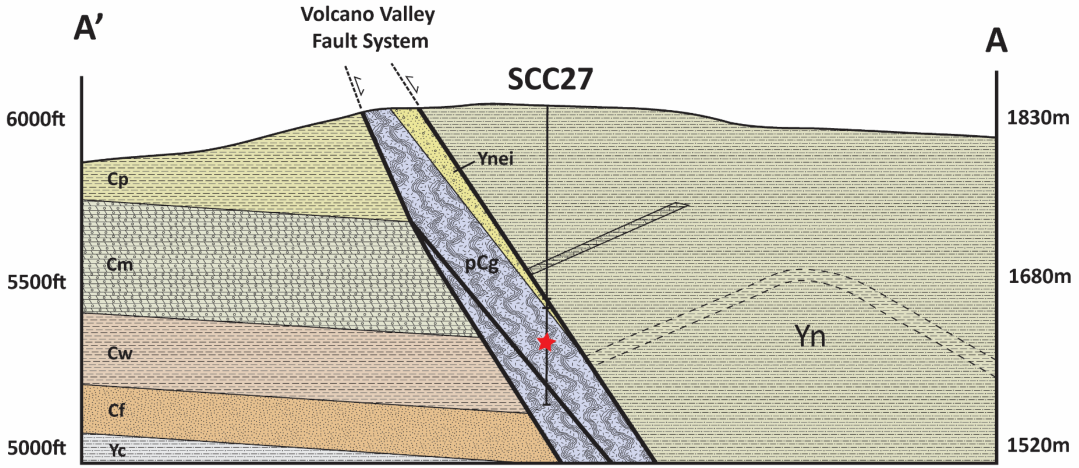
- The LBM represent the northern extent of Helena Embayment
  - **Major crustal heterogeneity**
- A Proterozoic structure reactivated during the Laramide?
- **What can additional thermochronology tell us?**

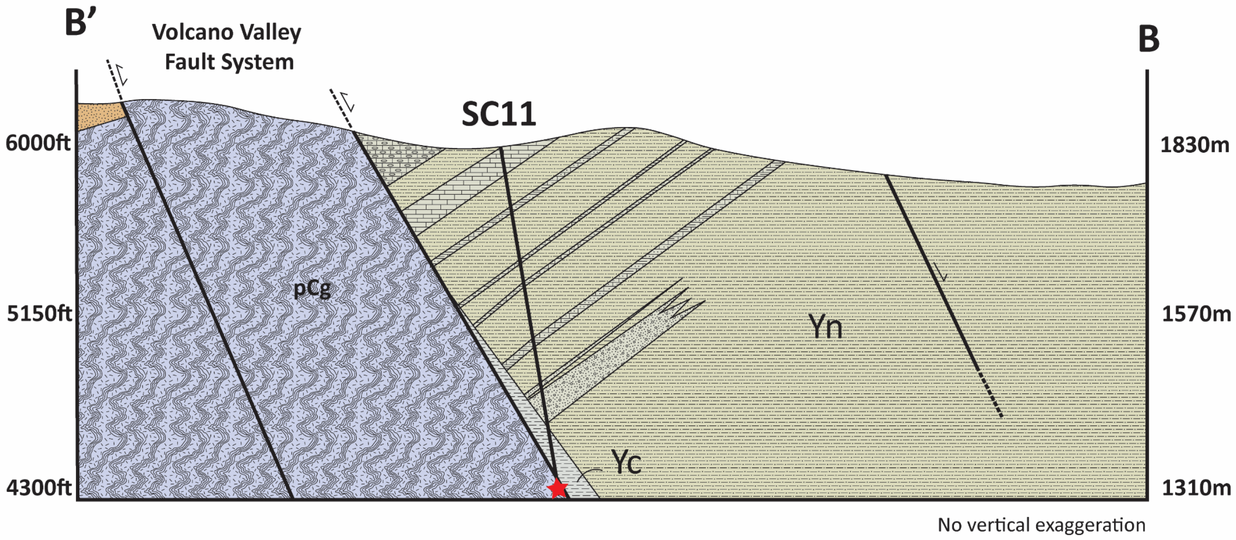


Modified from Vuke et al. (2007)


111°0'0"W
110°20'0"W
47°0'0"N
N
HWY 289
Cz intrusive rocks
Mz sed rocks
Pz sed rocks
Flathead SS
Belt Supergroup
p€ gneiss
White circles indicate paired AFT+ZHe
Volcano Valley Fault Zone
30km
AFT presented
New samples
(Summer 21)







Cross sections courtesy of Black Butte Copper Project

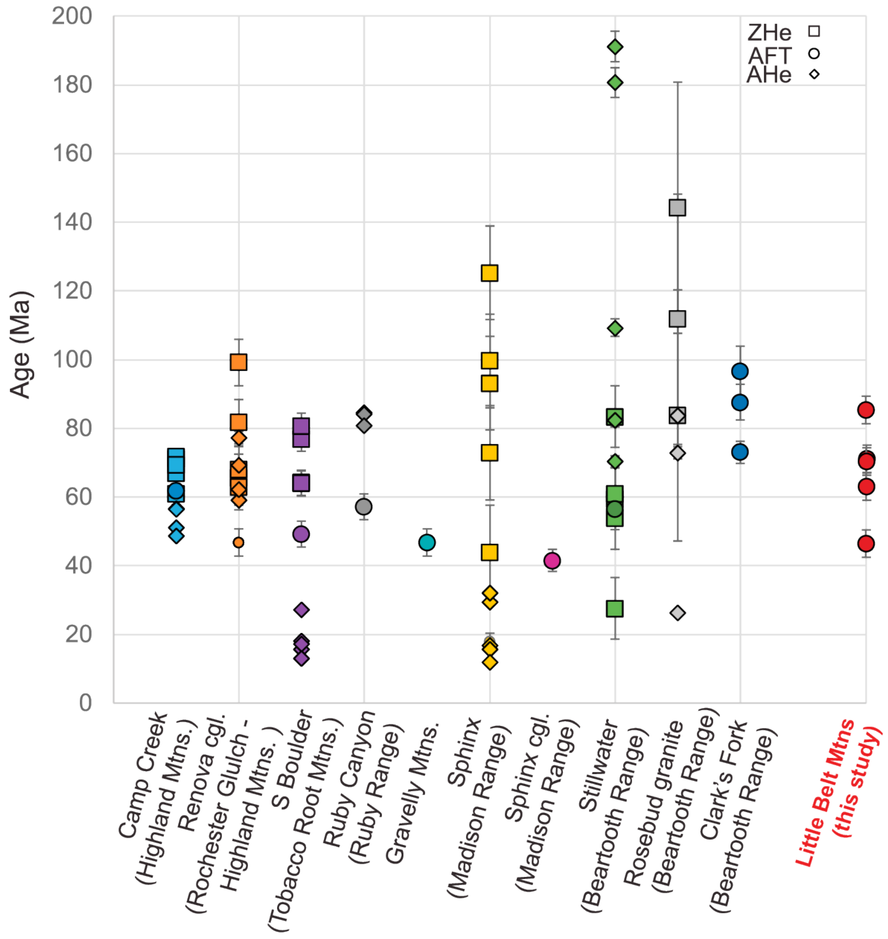
Howlett et al. (in prep)

- **Volcano Valley Fault**
  - Prominent, regionally ~E-W–trending thrust fault with a strike-slip component.
  - Likely Proterozoic normal fault reactivated during Sevier-Laramide orogenesis.

- **Basement clipped into VVF hanging wall (SCC27).** No timing constraints on most recent faulting.

Conclusions

- Exhumation of the LBM initiated as early as 85 Ma, and no later than 79 Ma
  - A later (Eocene) exhumation pulse possibly related to removal of Farallon slab
- Paired with existing data, these results are consistent with a Cretaceous onset of “Laramide deformation” in SW and central Montana
- **Stress transfer into a basement with notable pre-existing weaknesses**
- Future AFT+ZHe will provide additional constraints on LBM exhumation and timing of displacement along the Volcano Valley Fault.



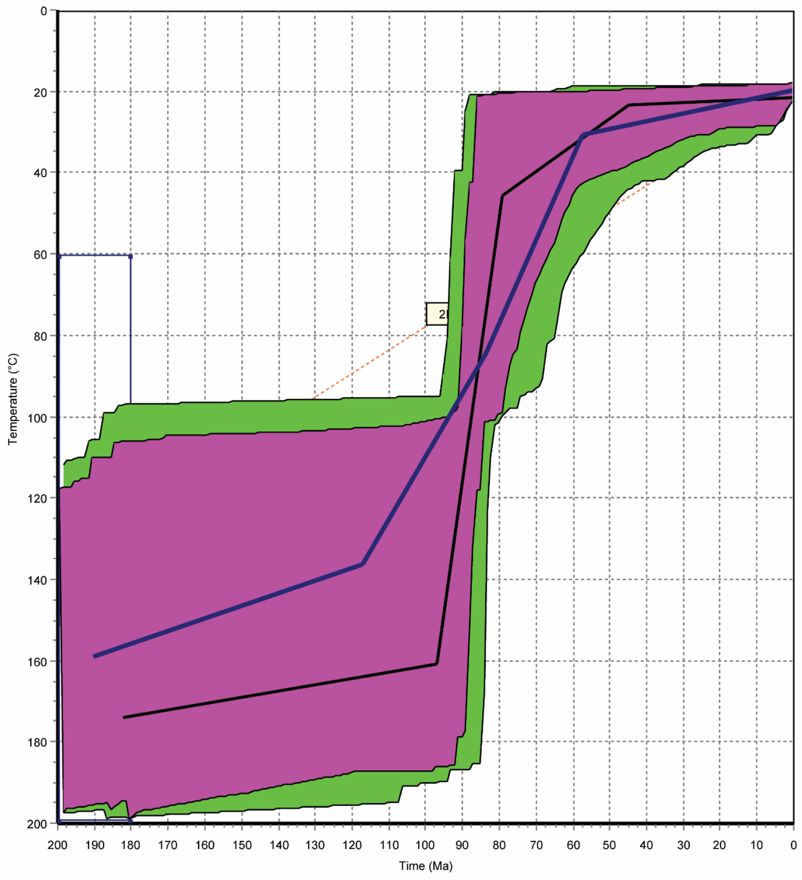
Modified from Carrapa et al. (2019)

Thank you.

Squaretop Mtn
Wind River Rg

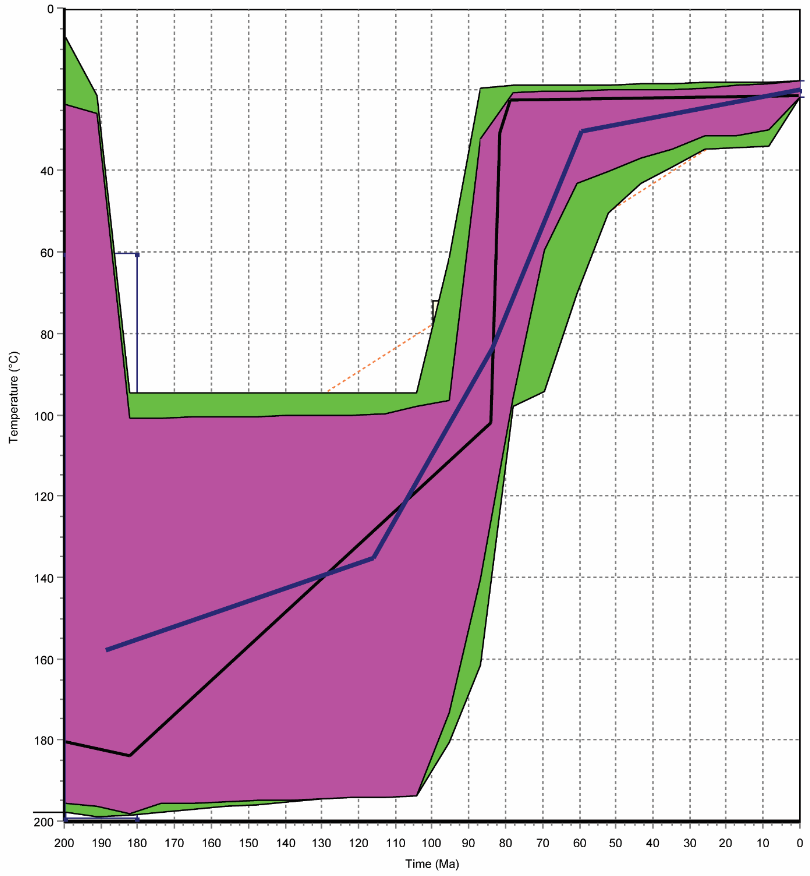
Sample KC082317-3

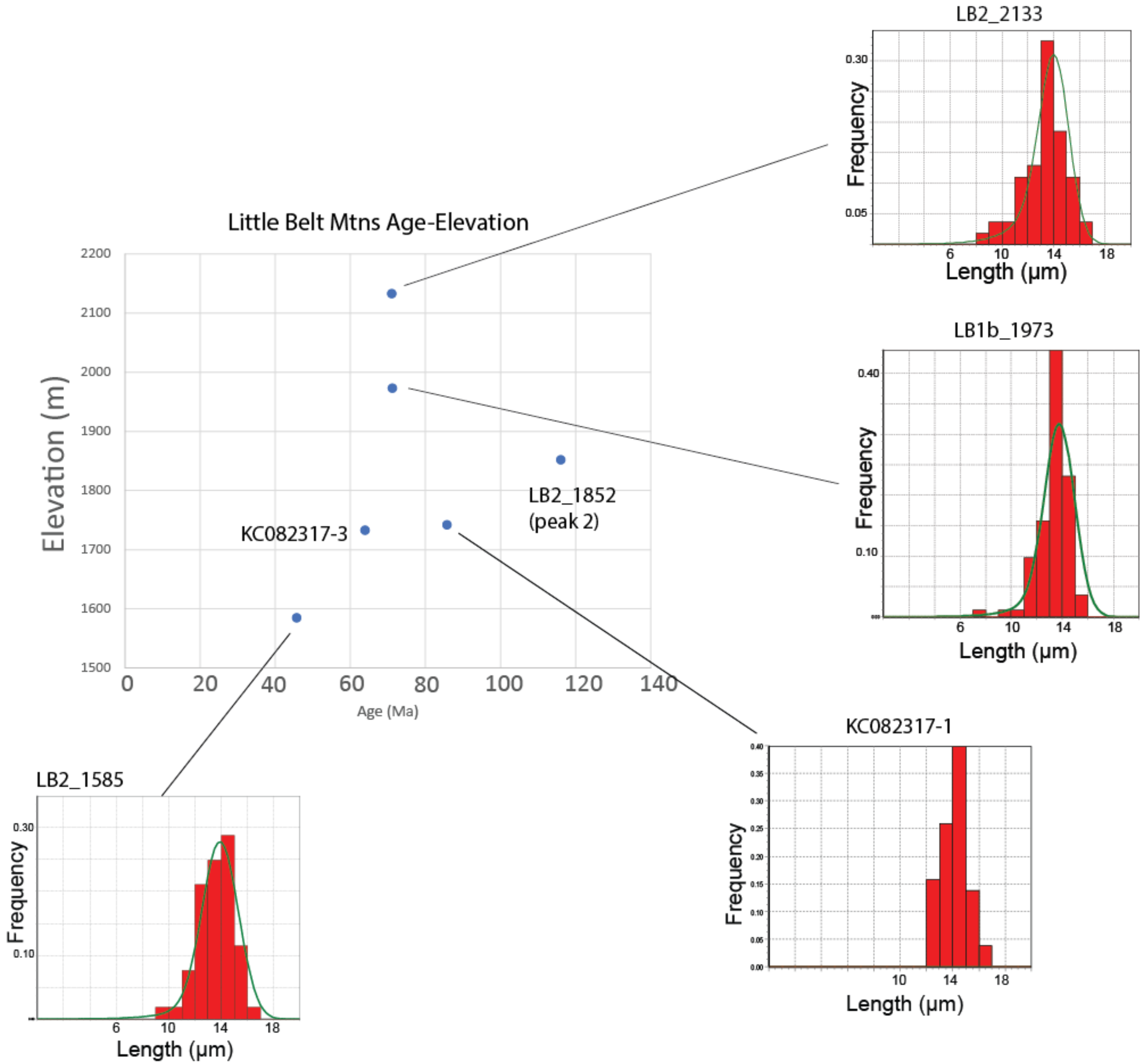
Model start @ 200 Ma



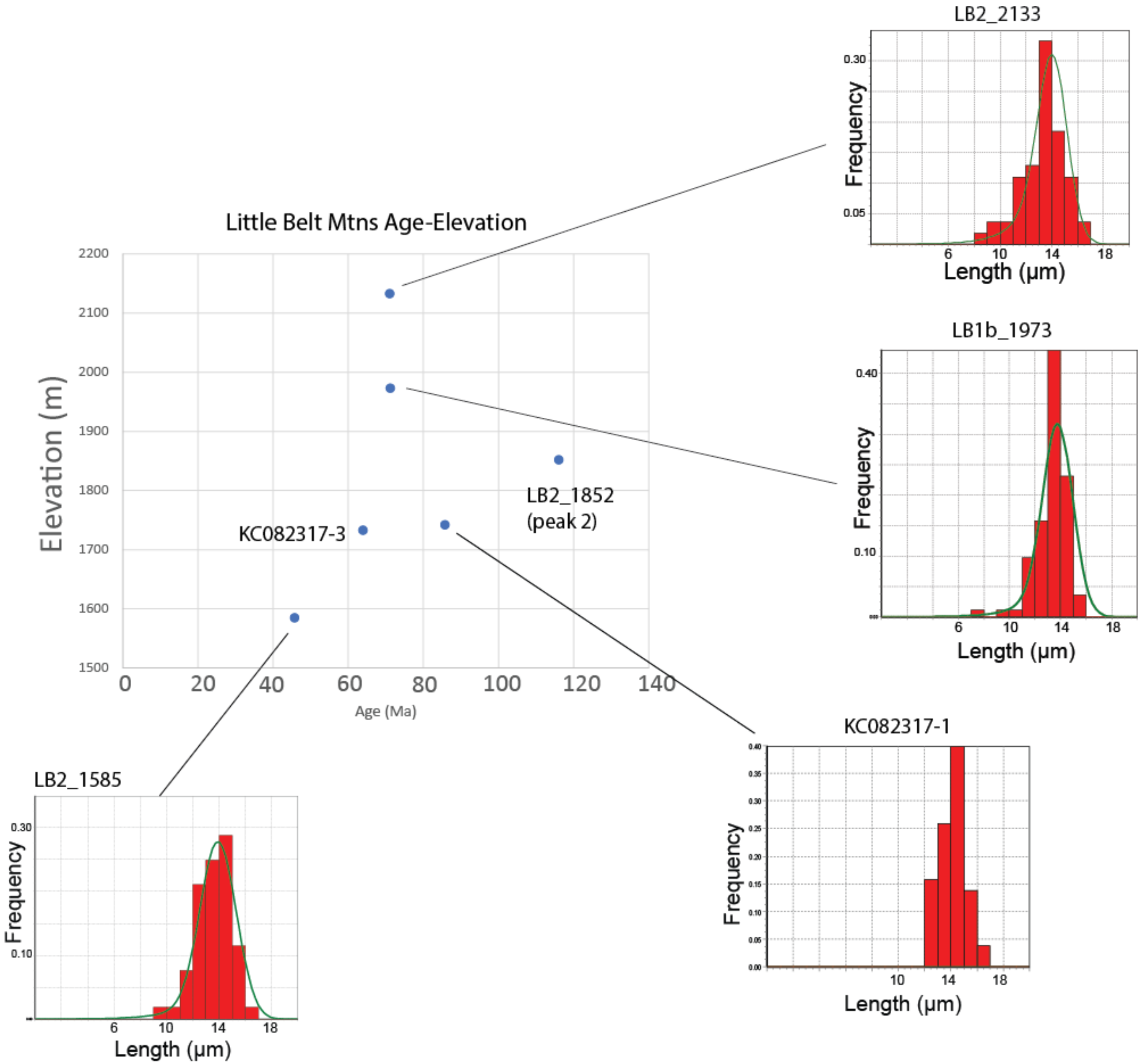
Model start @ 1800 Ma

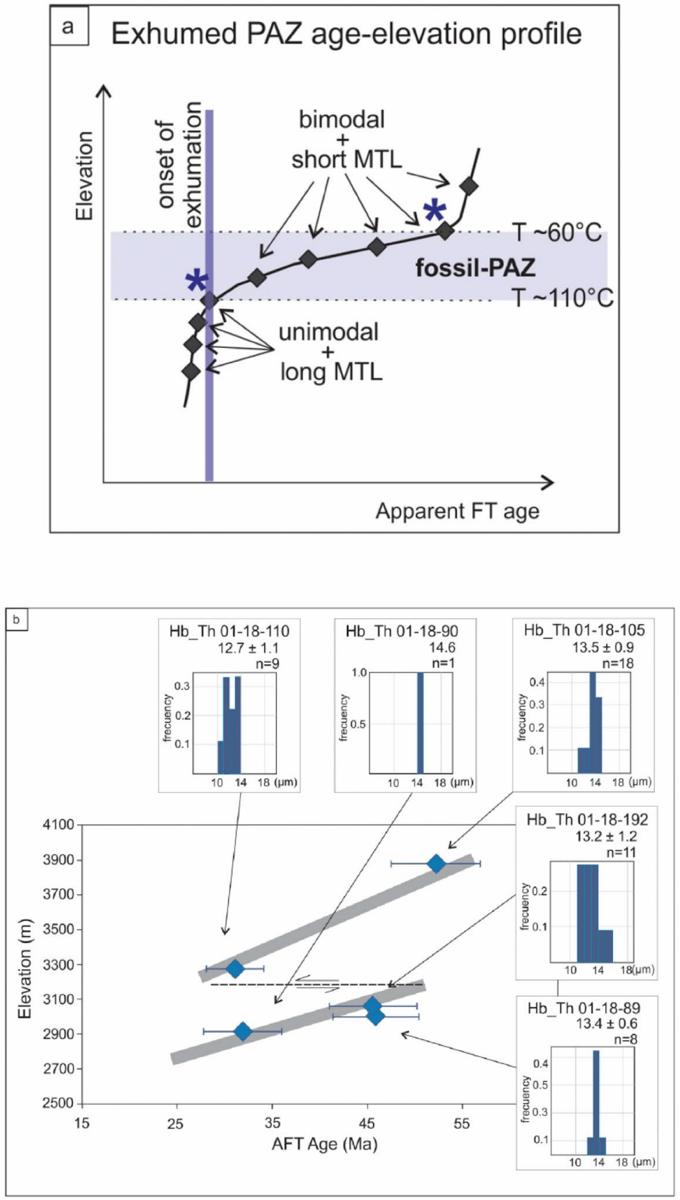
(w U-Pb, Ar/Ar, and great unconformity constraints)



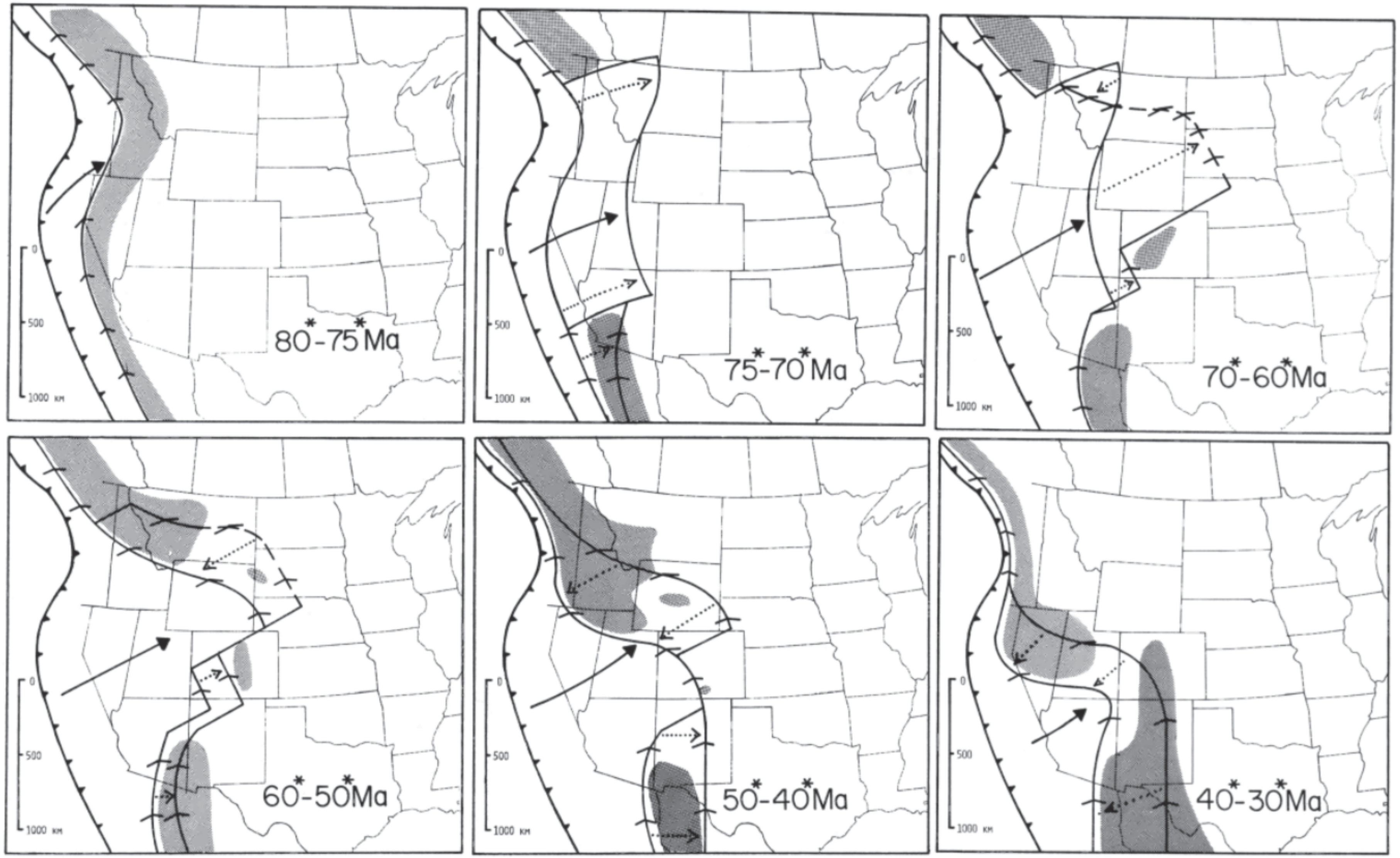


Little Belt Mtns Age-Elevation
Elevation (m)
Age (Ma)
2200
2100
2000
1900
1800
1700
1600
1500
0
20
40
60
80
100
120
140
KC082317-3
LB2_1852
(peak 2)
LB2_2133
LB1b_1973
KC082317-1
LB2_1585
Frequency
Length (μm)
0.30
0.05
0.40
0.10
6
10
14
18



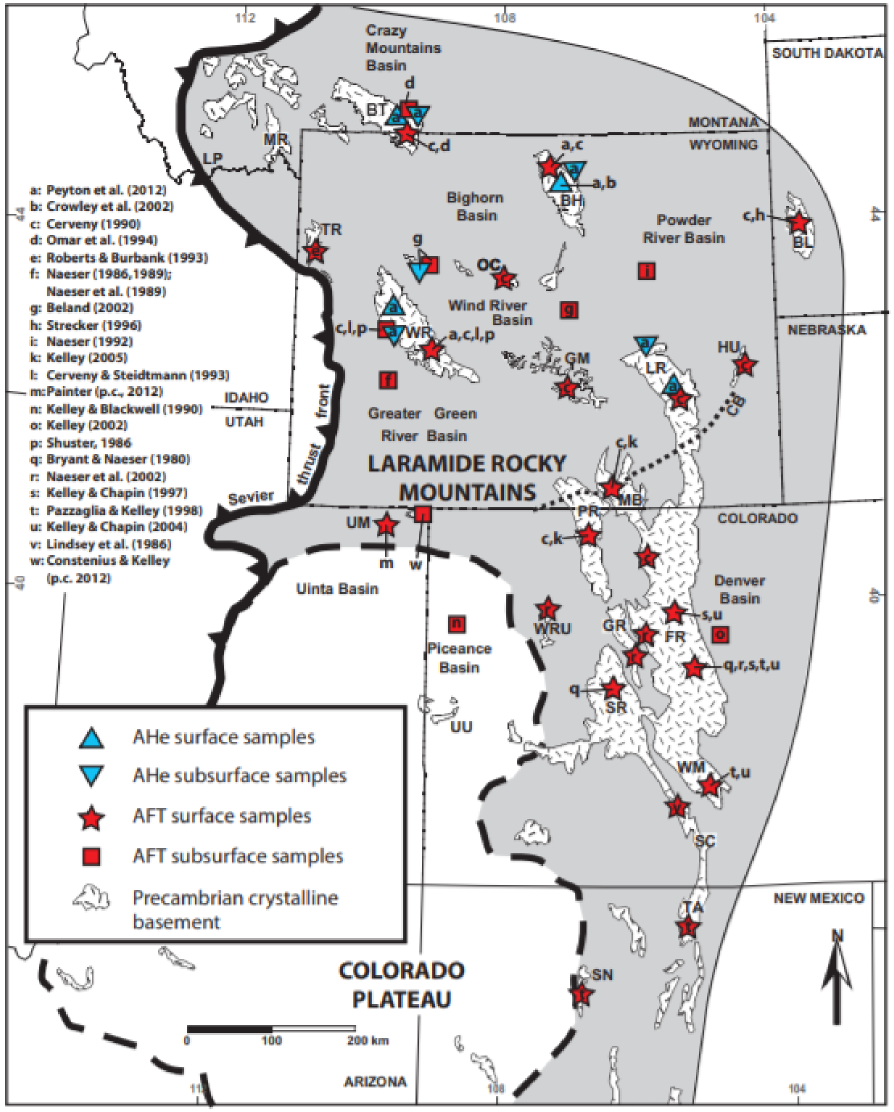


Lossada et al., 2020

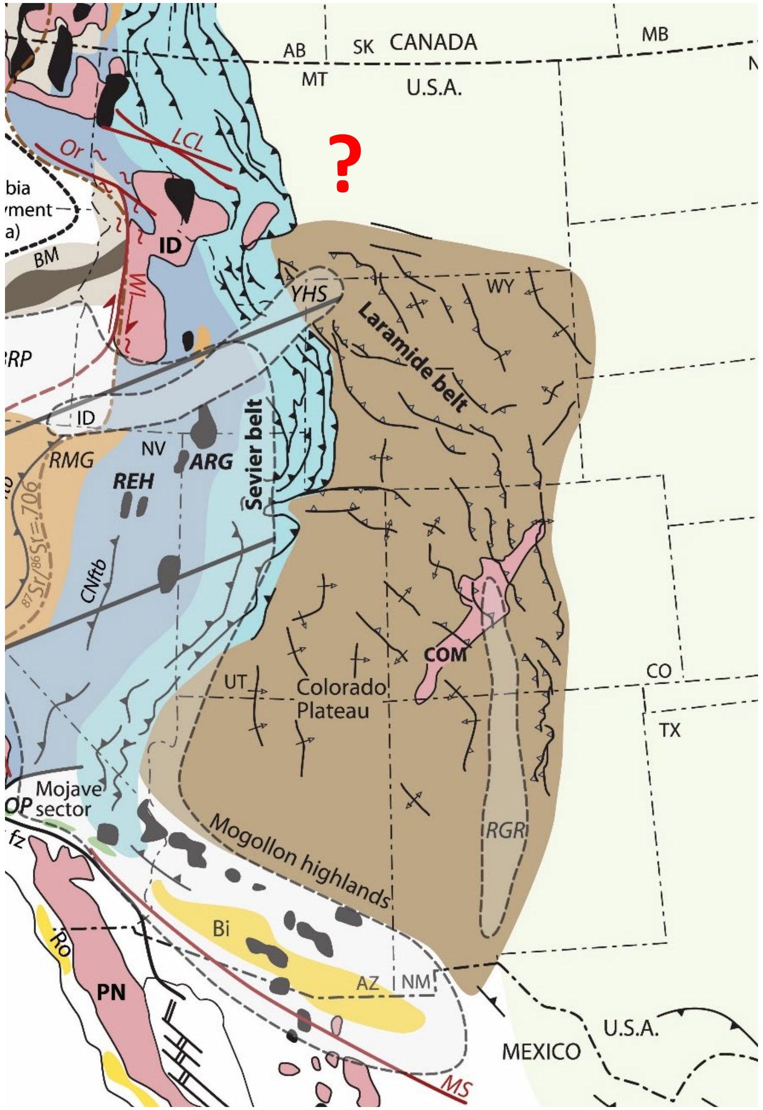


Bird (1984)

?



Peyton & Carrapa, 2013

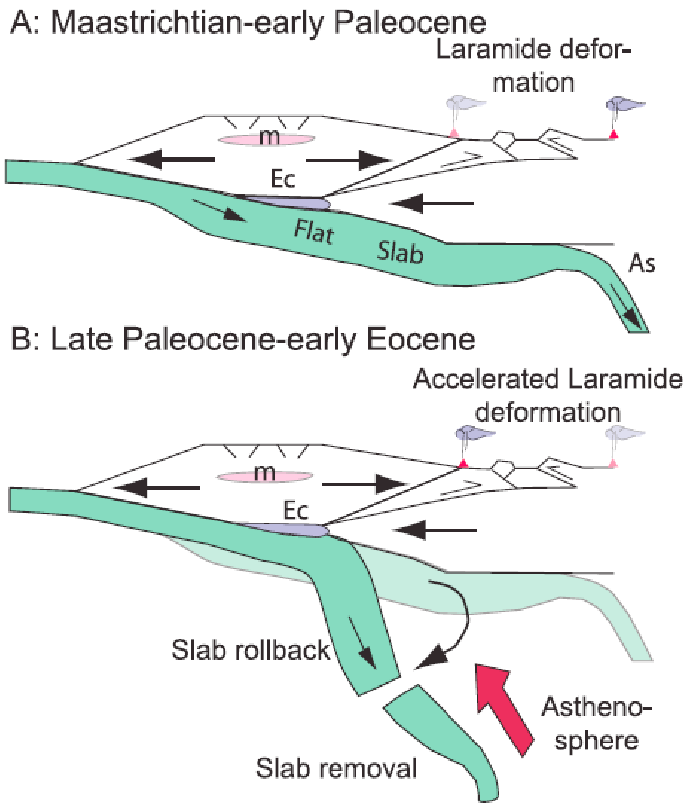


Yonkee & Weil, 2015

Slab removal and Eocene pulse

1999; *Wortel and Spakman*, 2000; *Buiter et al.*, 2002; *Ferranti and Oldow*, 2006; *Brun and Faccenna*, 2008; *Humphrey*, 2009; *Kay and Coira*, 2009; *Göğüş et al.*, 2011]. Slab rollback may have similar effects as retreating delamination of the mantle lithosphere, causing crustal deformation and magmatism on the overriding plate as a response to peeling of the mantle lithosphere away from the crust [*Krystopowicz and Currie*, 2013]. Slab rollback may be associated with lithosphere delamination of the overriding plate, causing additional surface

Asthenosphere upwelling and thermal perturbation [e.g., *Moucha et al.*, 2008; *Humphreys*, 2009] as well as the isostatic adjustment [e.g., *Gvirtzman and Amos*, 1999] associated with the westward peeling of the flat slab away from the overriding plate may explain the westward sweep of magmatism, extension in the Sevier hinterland, and our observed accelerated uplift and uplift/exhumation patterns during stage 2. Additional



Fan & Carrapa, 2014