The Growth of the Tibetan Plateau and its Possible Effects on Evolving Asian Climate over the past 15 Million years

“Monsoons - Past, Present and Future:” Workshop
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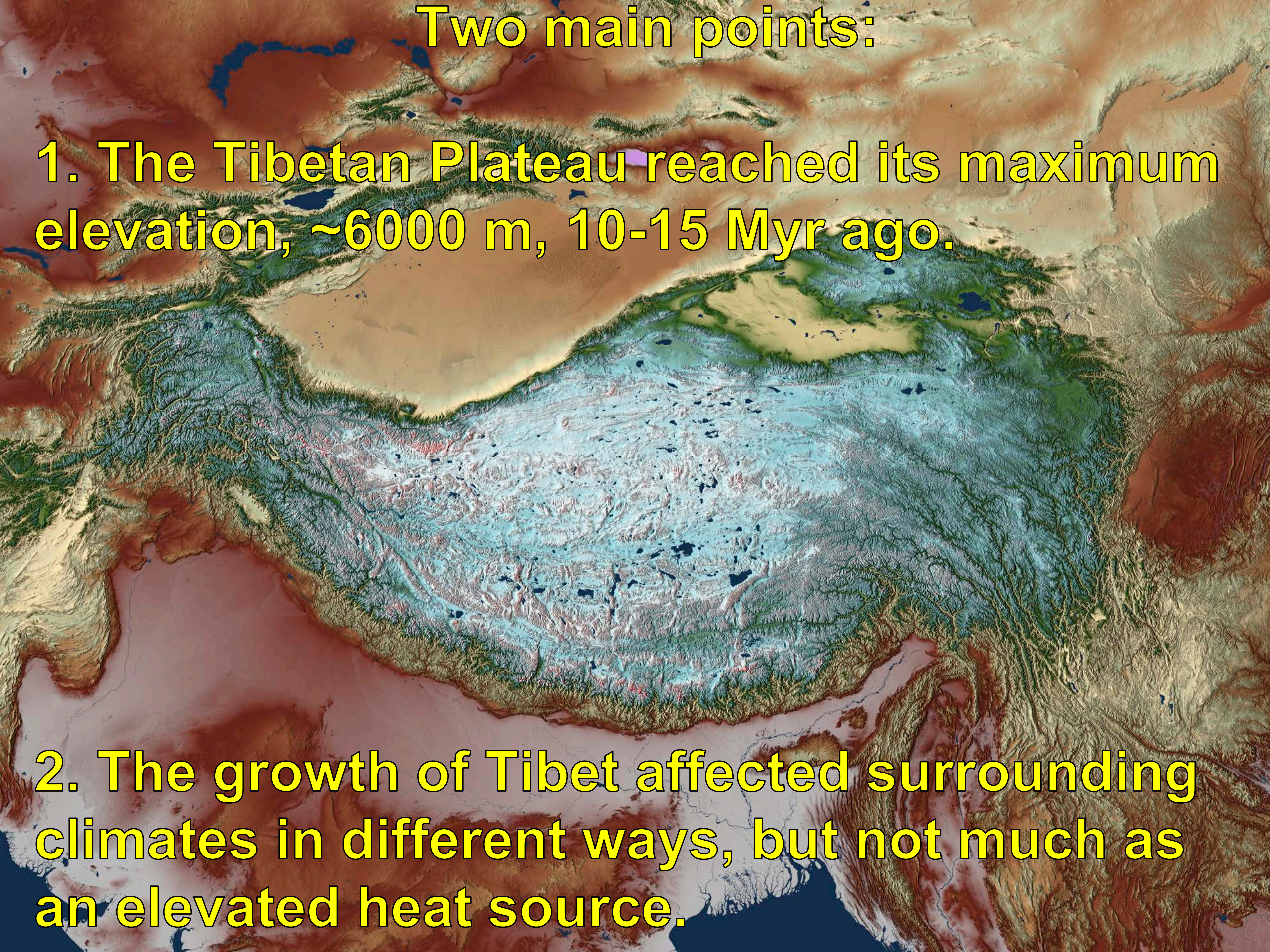


Two main points:

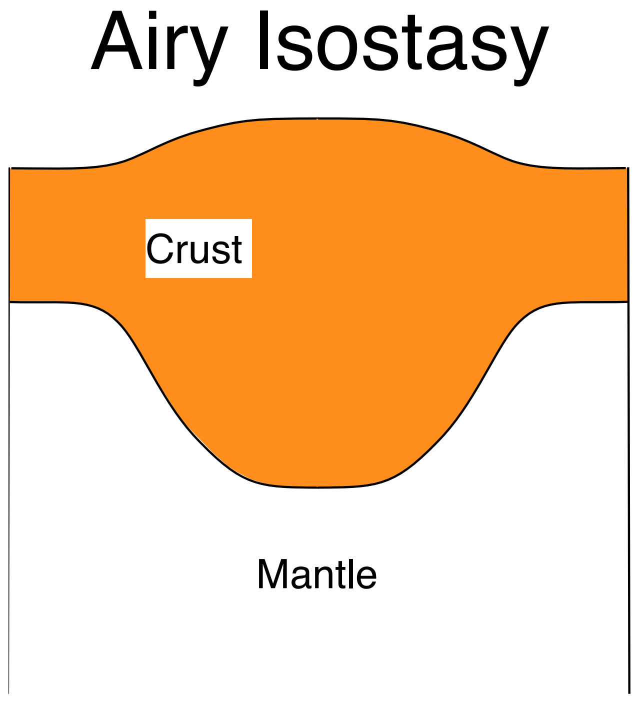
1. The Tibetan Plateau reached its maximum elevation, ~6000 m, 10-15 Myr ago.

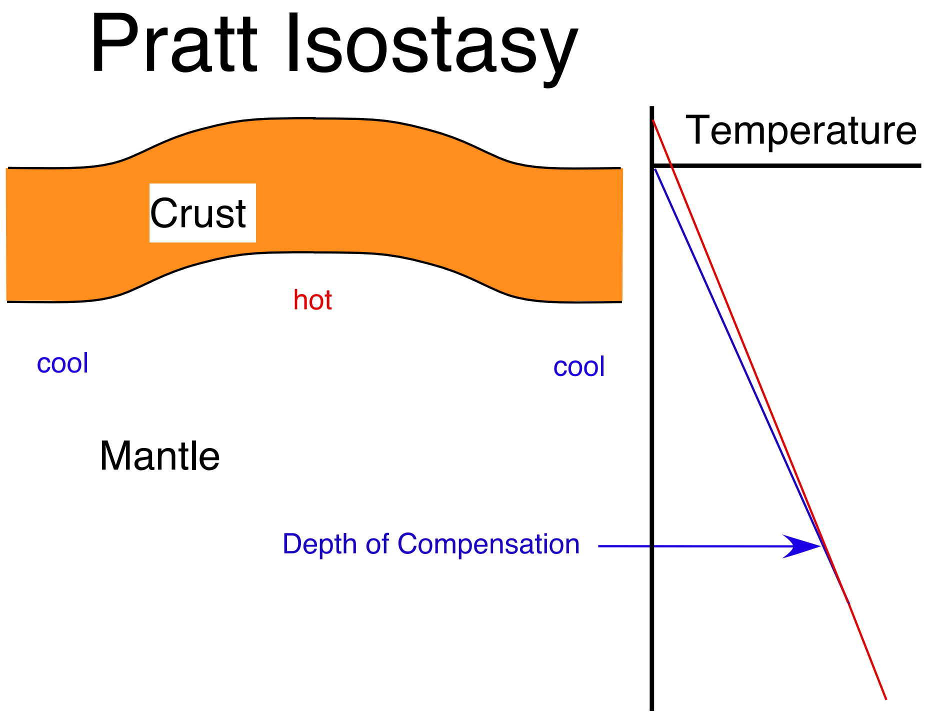
2. The growth of Tibet affected surrounding climates in different ways, but not much as an elevated heat source.

Archimedes' Principle: applied to icebergs

http://www.accuweather.com/en/weather-news/icebergs-still-a-threat-100-ye/63626

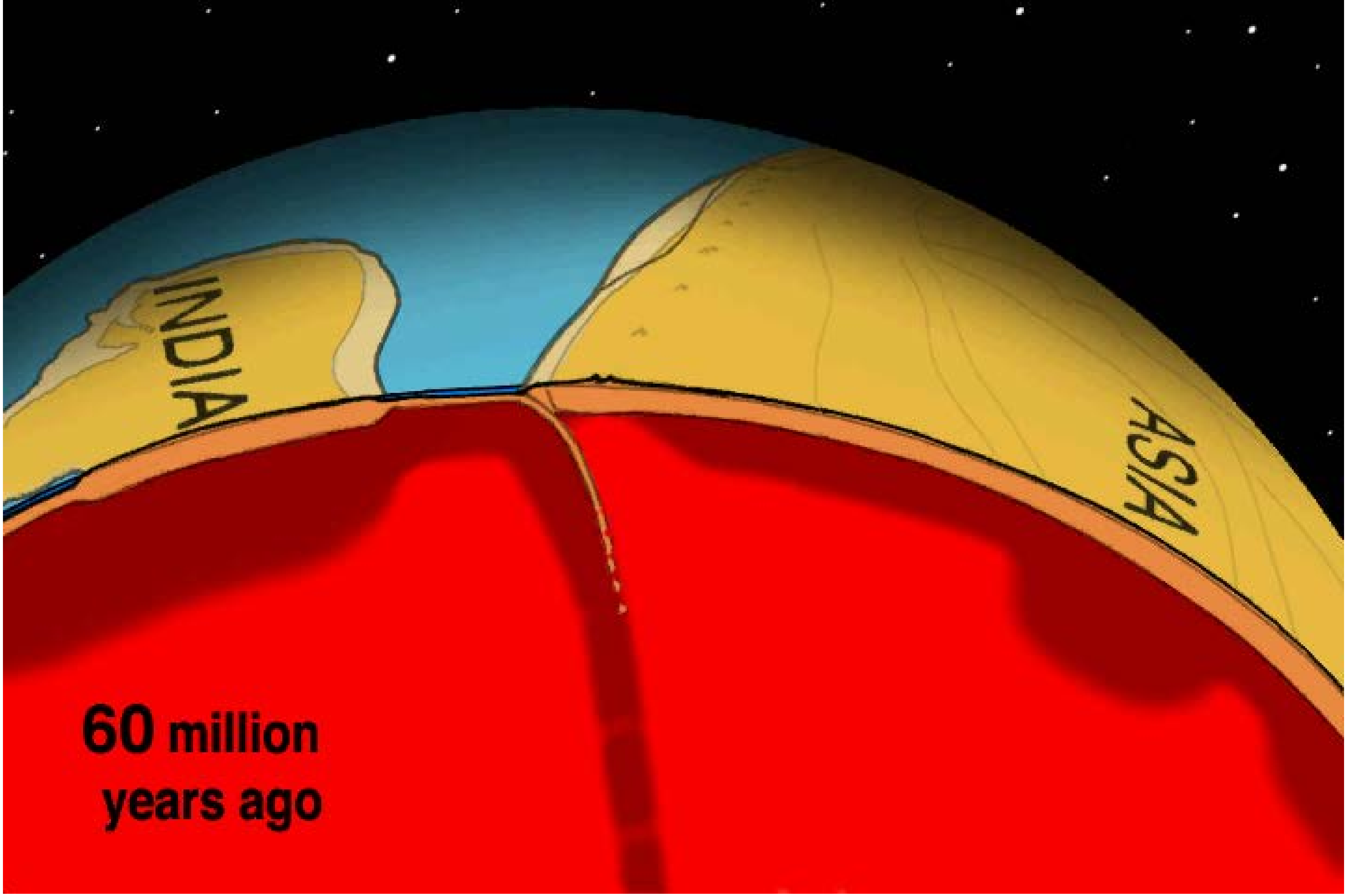
Isostasy (Archimedes Principle)





At the **Depth of Compensation**, the vertical normal stress, or "lithostatic pressure," is equal everywhere.

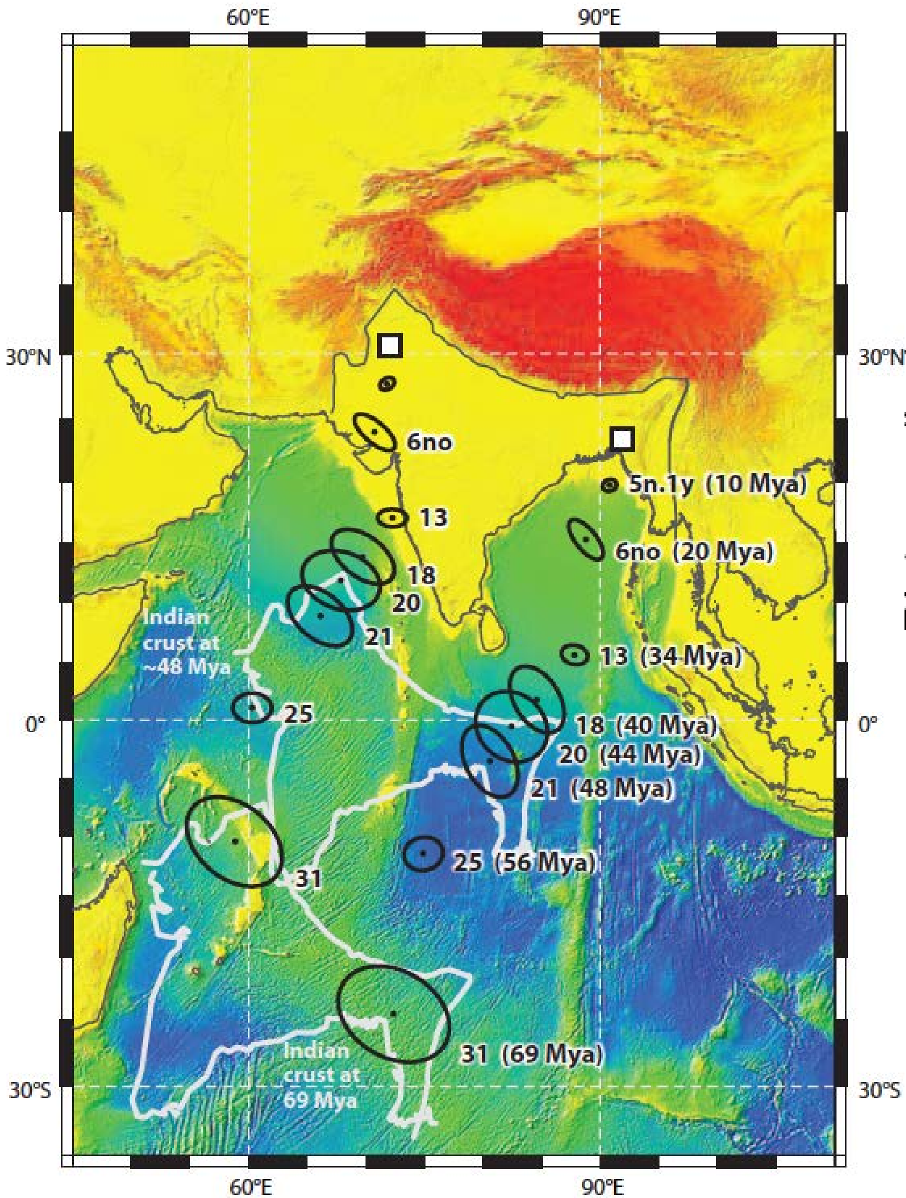
Therefore, the weight of a column (per unit area) above the **Depth of Compensation** is the same everywhere, *assuming that vertical shear stresses are negligible*.

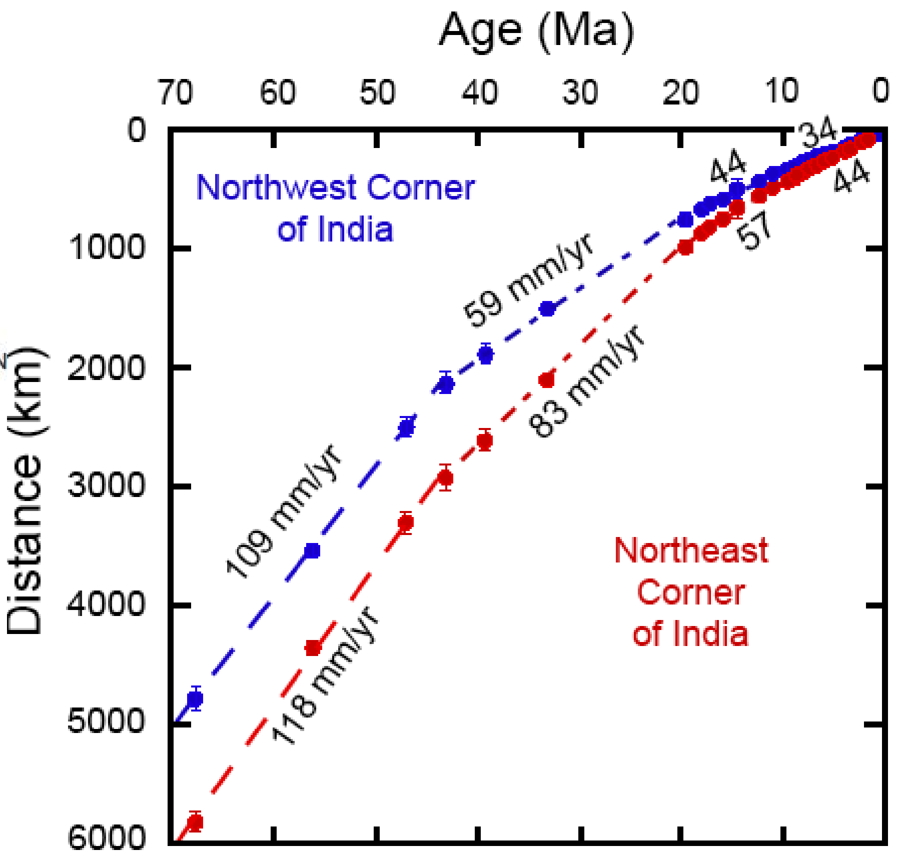


Animation by Tanya Atwater

(given to me for my 60th birthday, and hence honoring all of my prejudices, but not necessarily all of the facts)

Reconstructed positions of India with respect to Eurasia: the history of their convergence



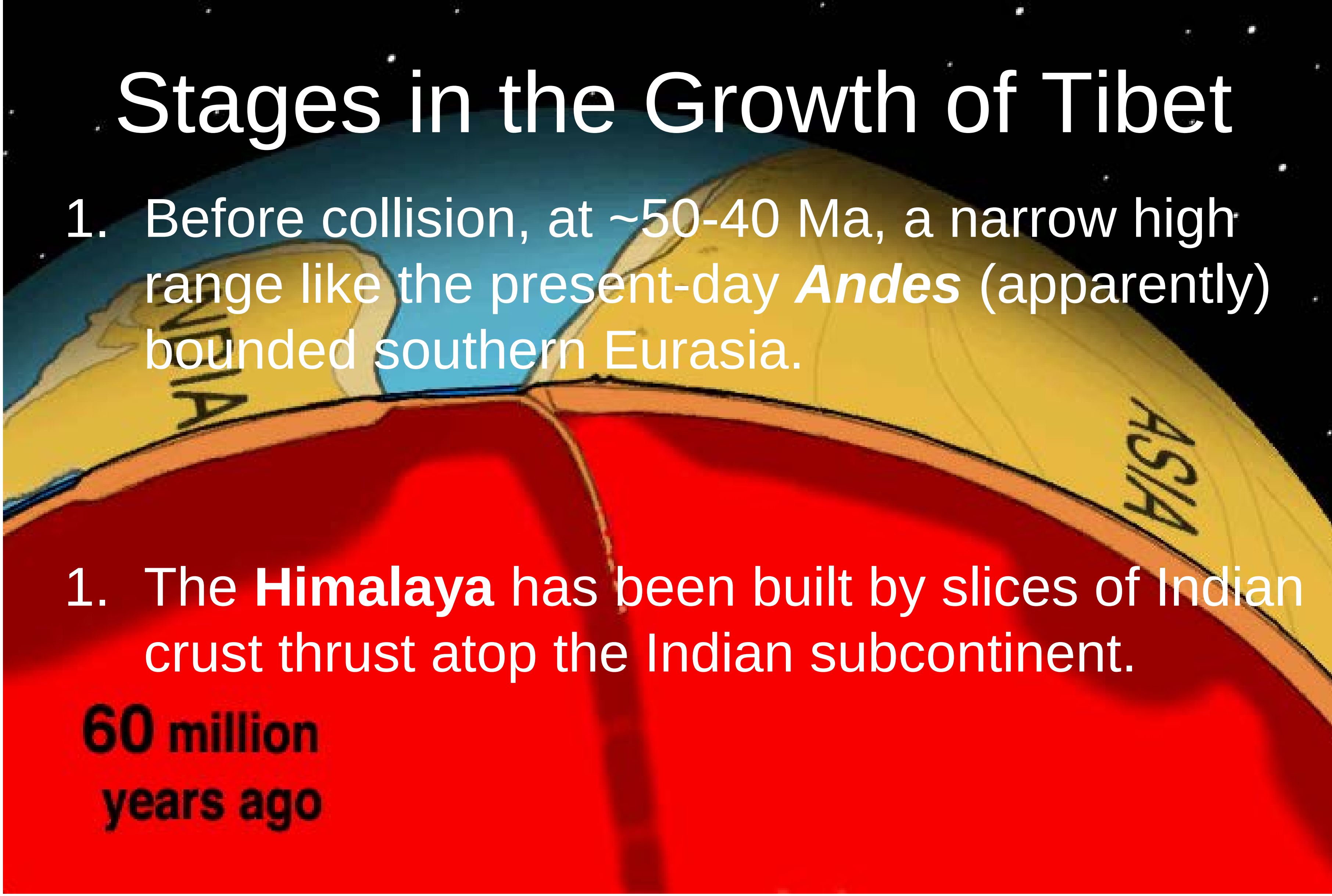


Molnar and Stock [2009], based on work of *Horner-Johnson et al*. [2005, 2007], *Lemaux et al.* [2002], *McQuarrie et al*. [2003], *Merkouriev & DeMets* [2006], and *Molnar et al*. [1988].

Stages in the Growth of Tibet

1. Before collision, at ~50-40 Ma, a narrow high range like the present-day ***Andes*** (apparently) bounded southern Eurasia.

1. The **Himalaya** has been built by slices of Indian crust thrust atop the Indian subcontinent.



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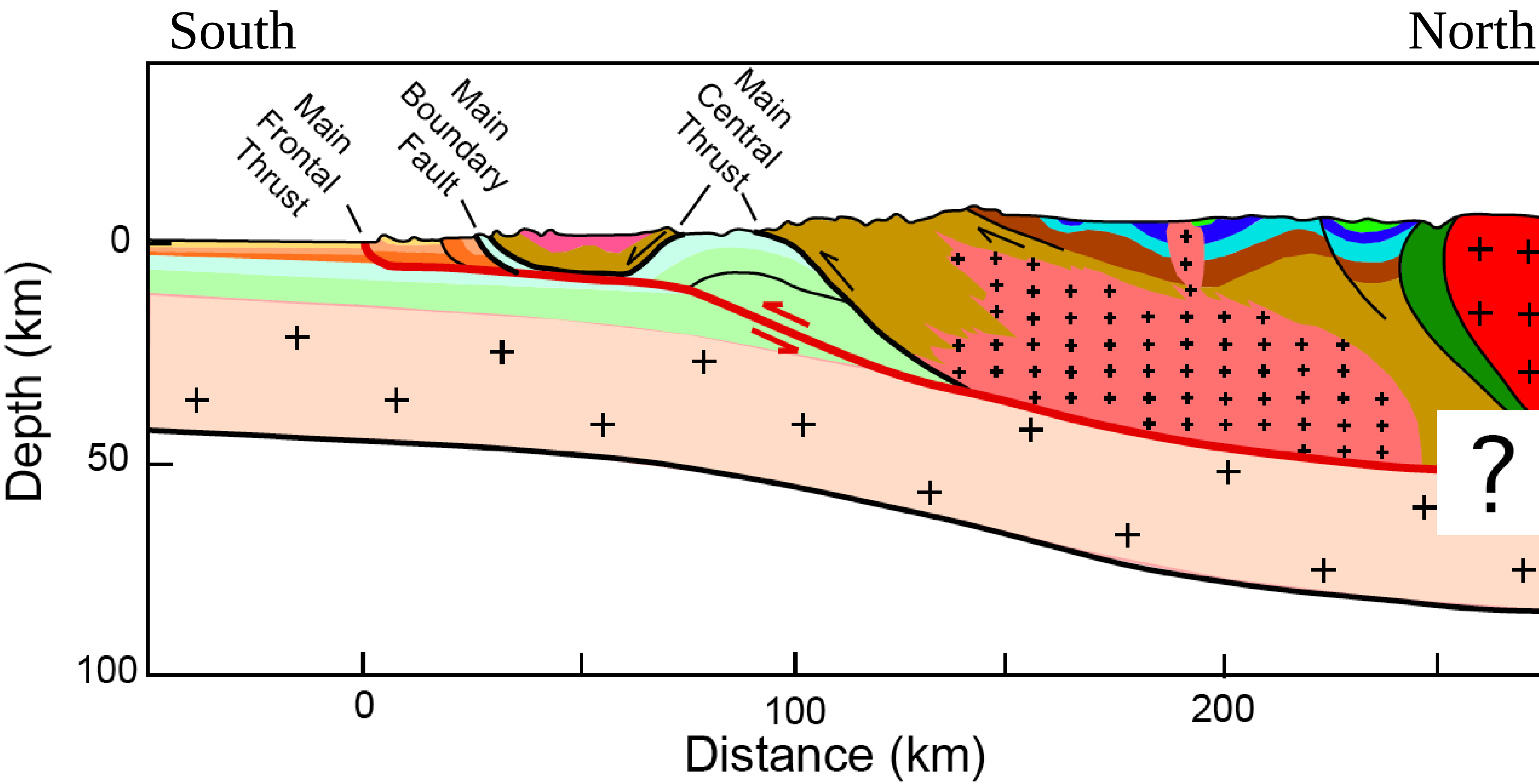
Adapted from *Avouac* [2003]



The Himalaya has been built by the stacking of slices of India's crust.

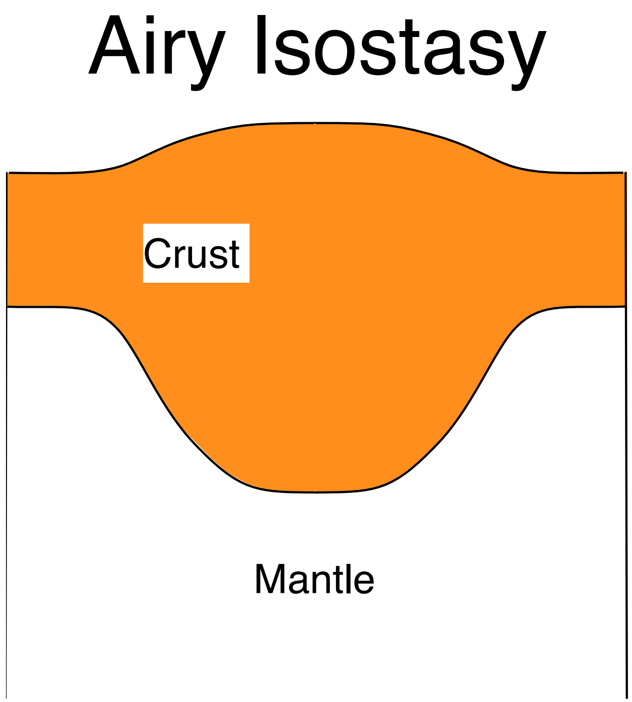
Stages in the Growth of Tibet

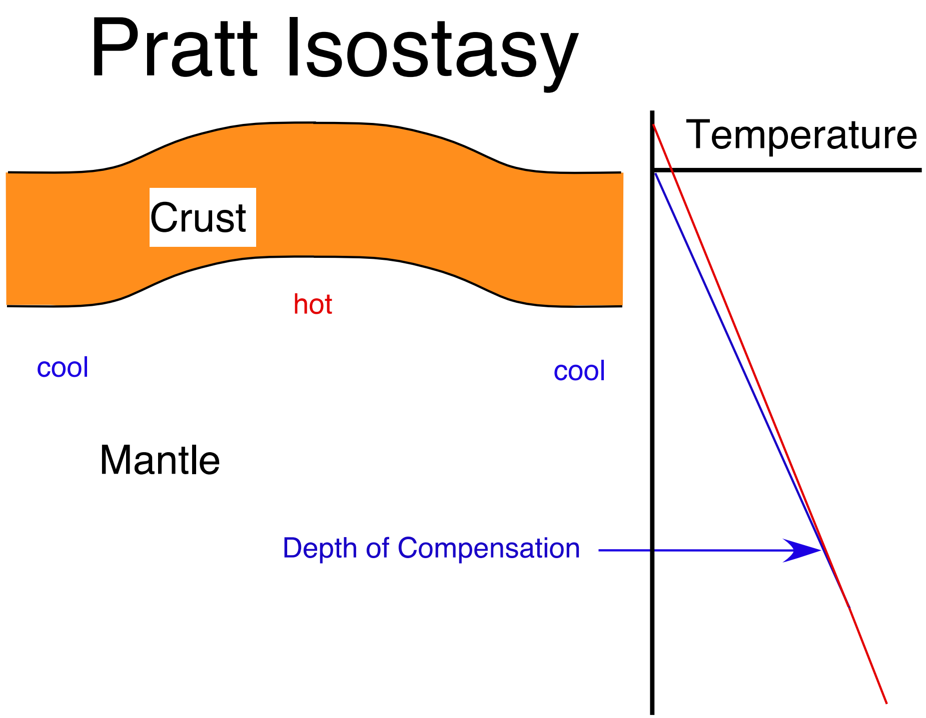
3. Since Collision, India has penetrated steadily into Eurasia, **shortening and thickening Asian crust** to build the wide **high Tibetan Plateau**.

Animation by Tanya Atwater

(given to me for my 60th birthday, and hence honoring all of my prejudices, but not necessarily all of the facts)

Isostasy (Archimedes Principle)

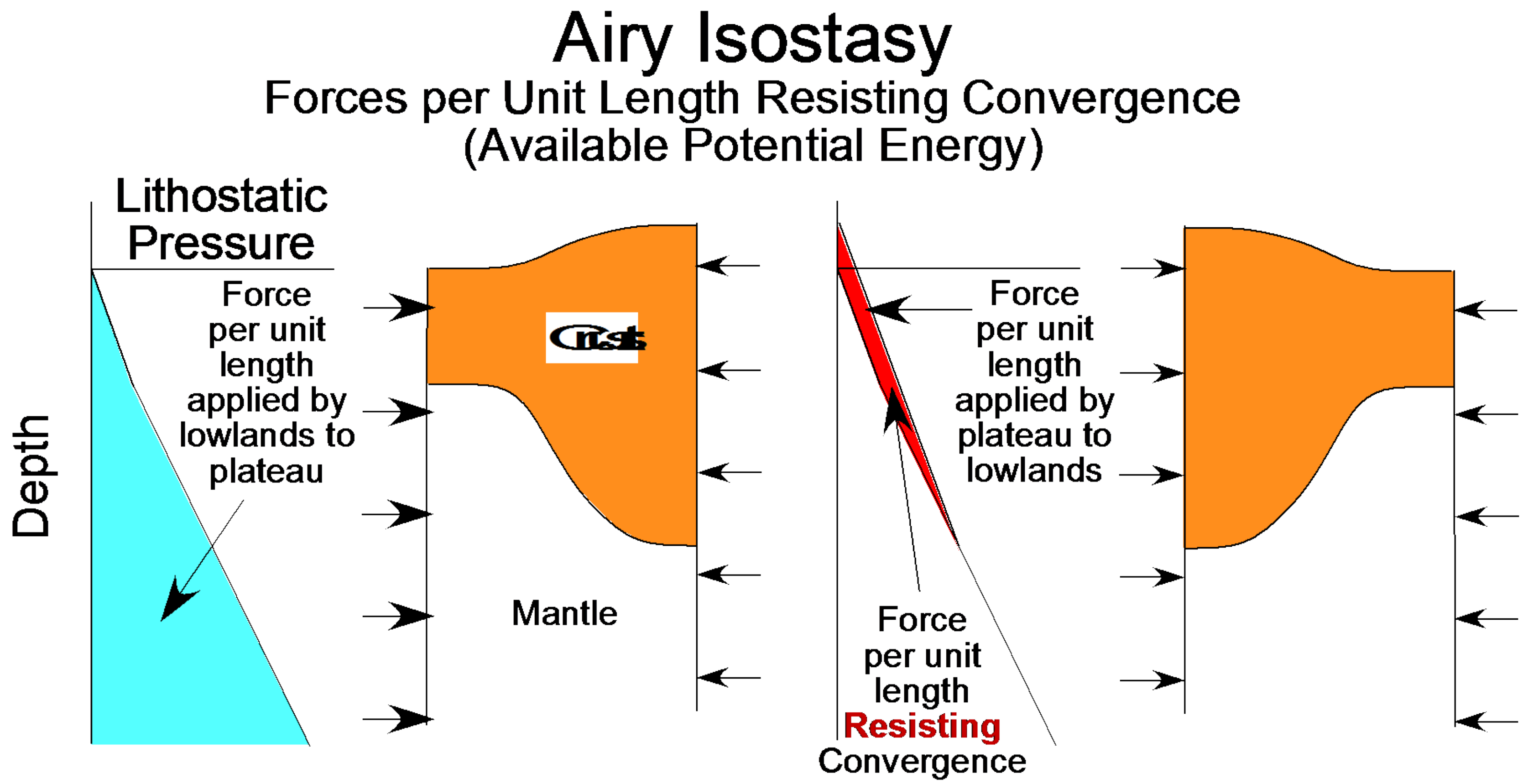




Airy isostasy accounts for high terrain of most mountain belts and high plateaus like Tibet and the Altiplano.

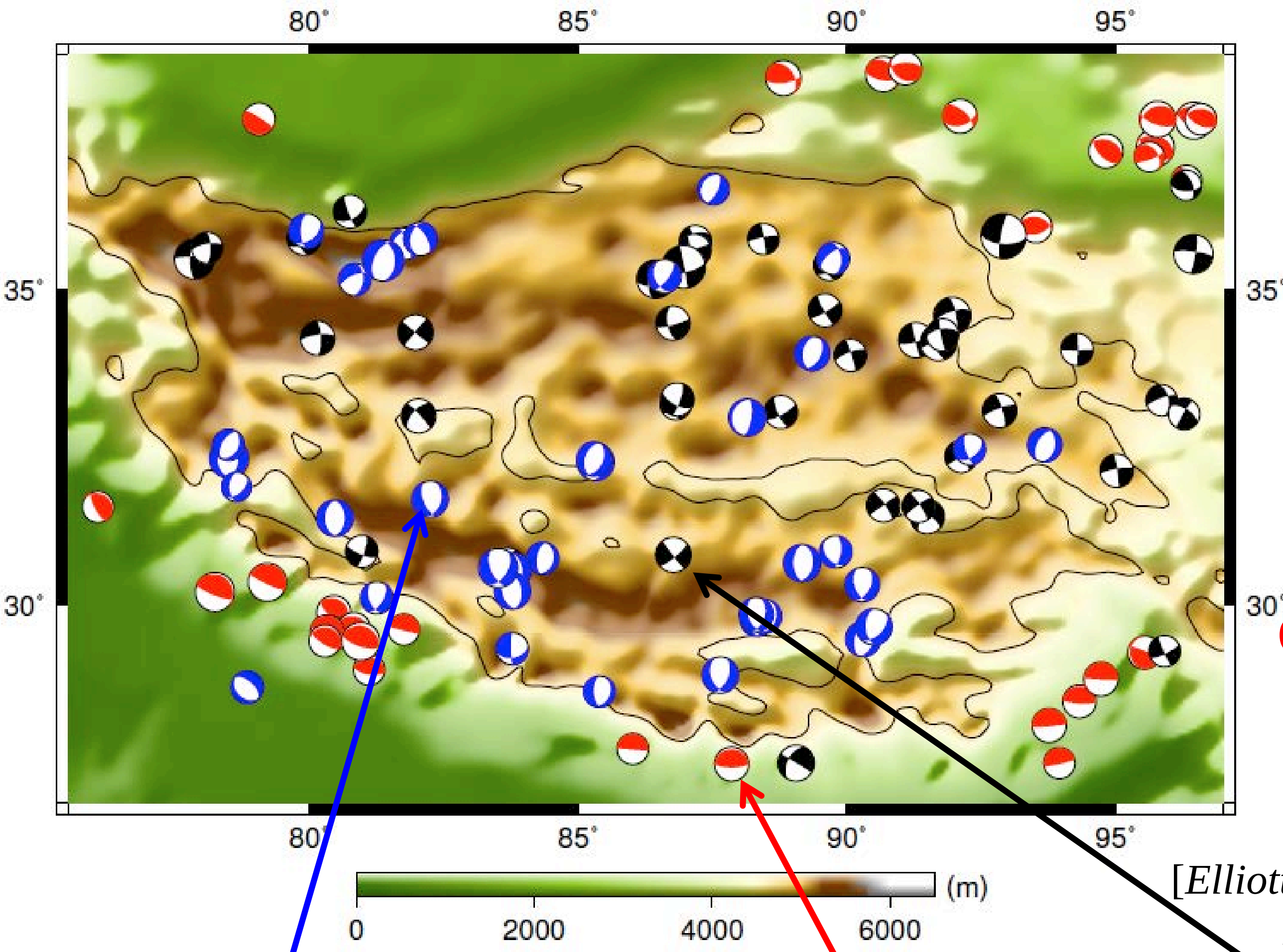
Pratt isostasy accounts for the depth of the sea floor and high regions like East Africa, the Basin-and-Range province, and maybe the Southern Rocky Mountains.

Lithostatic Pressure, Available Potential Energy, and Force per unit length



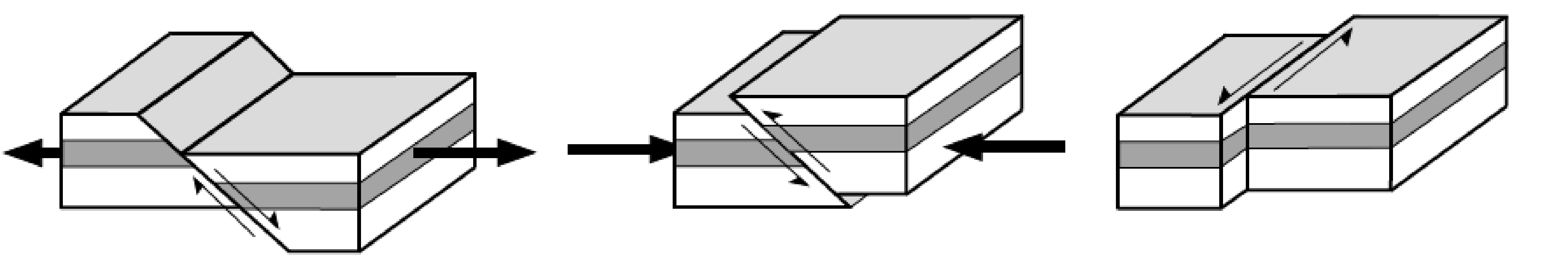
Throughout Tibet: normal faulting, E-W crustal extension, and crustal thinning.

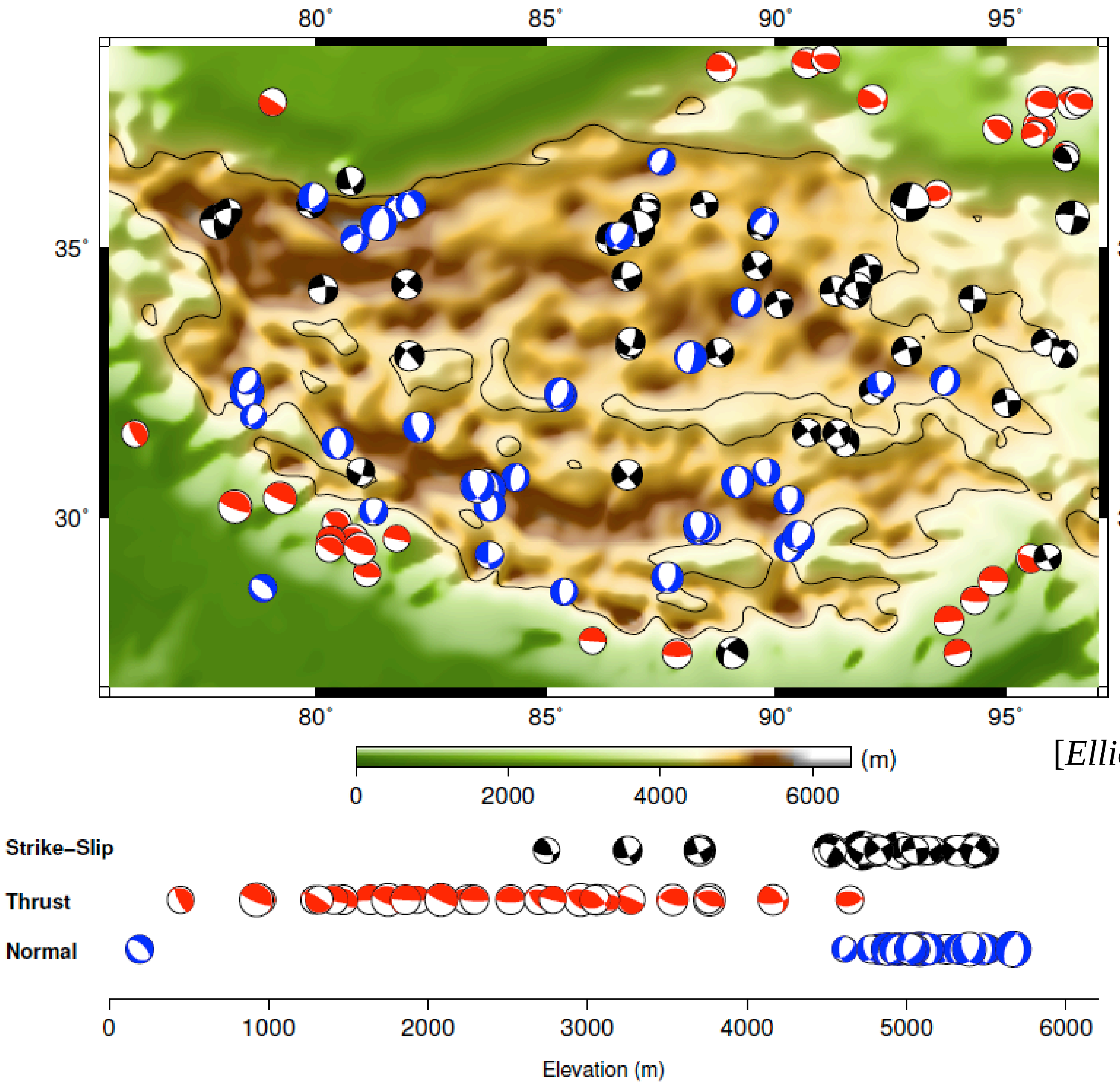
Surroundings : thrust faulting, crustal shortening, and crustal thickening.



[*Elliott, Walters, England, Jackson, Li, and Parsons* 2010]

Normal fault | Thrust fault | Strike-slip fault

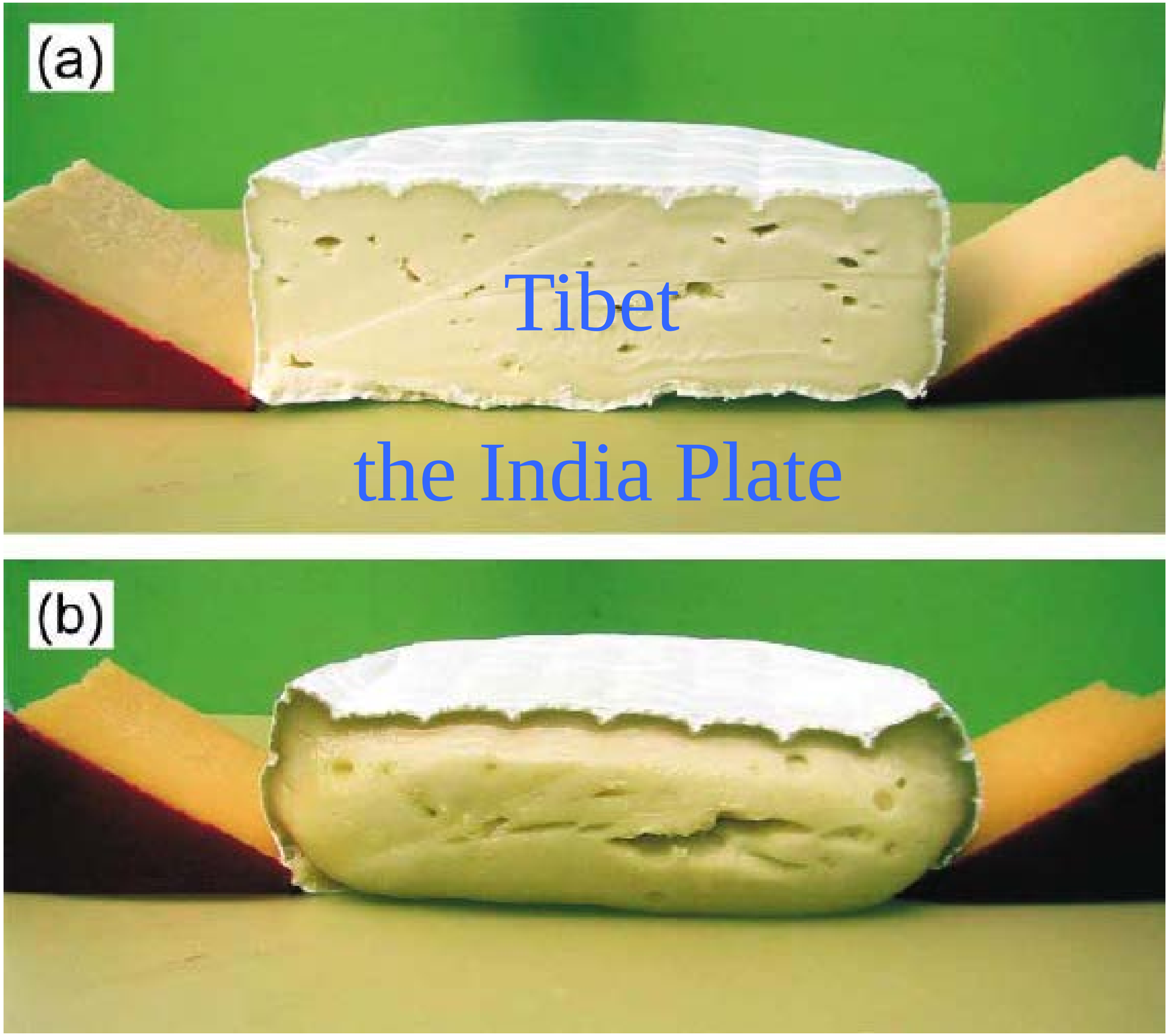




Throughout Tibet: normal faulting, E-W crustal extension, and crustal thinning. Surroundings : thrust faulting, crustal shortening, and crustal thickening.

[*Elliott, Walters, England, Jackson, Li, and Parsons* 2010]

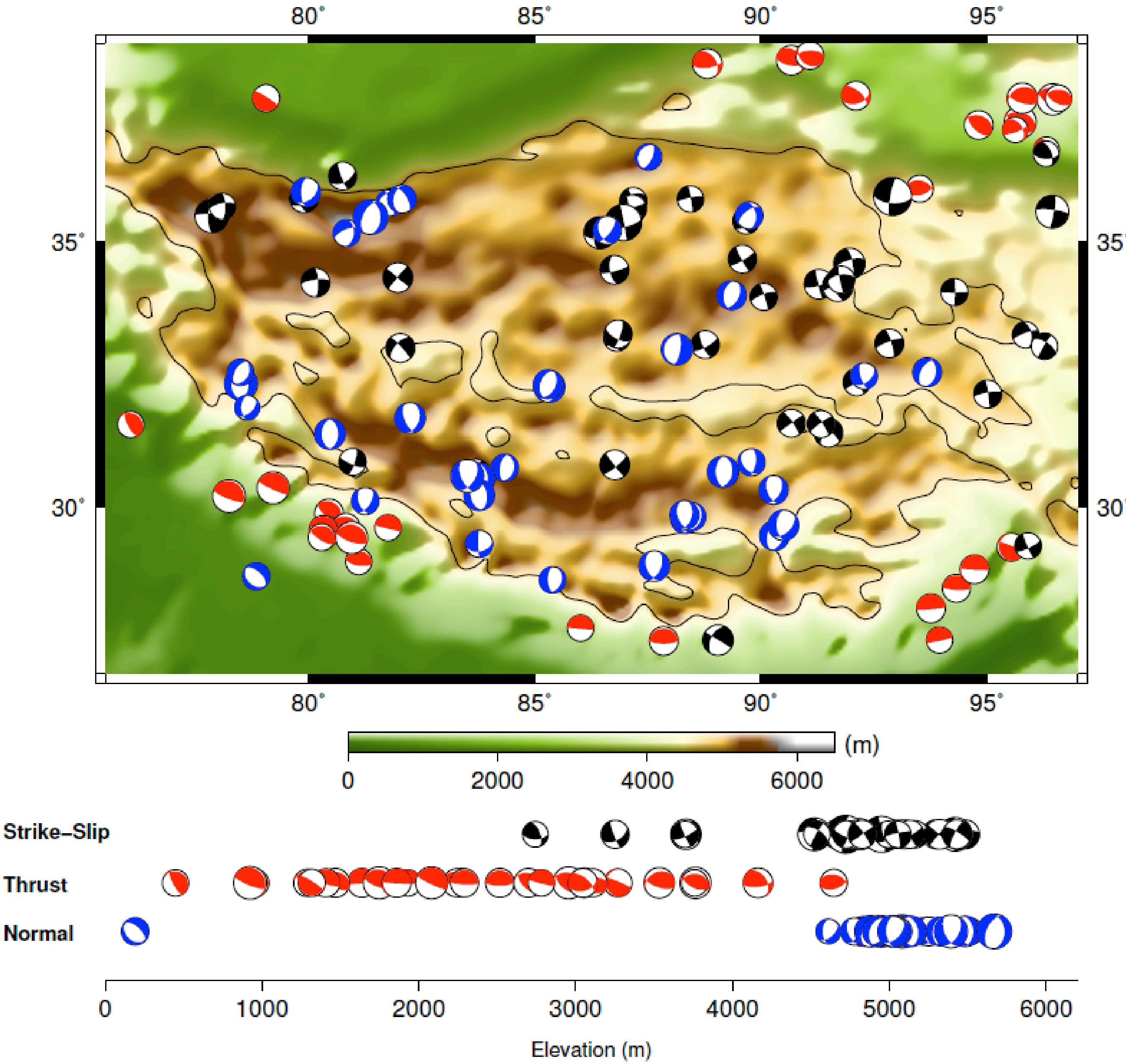
The high region spreads apart, and onto the lower, surrounding regions.



From *Selverstone* [2005]

Tibet:

a humongous piece of ripe Camembert (or Brie) cheese spreading out, onto SE China and the India Plate.

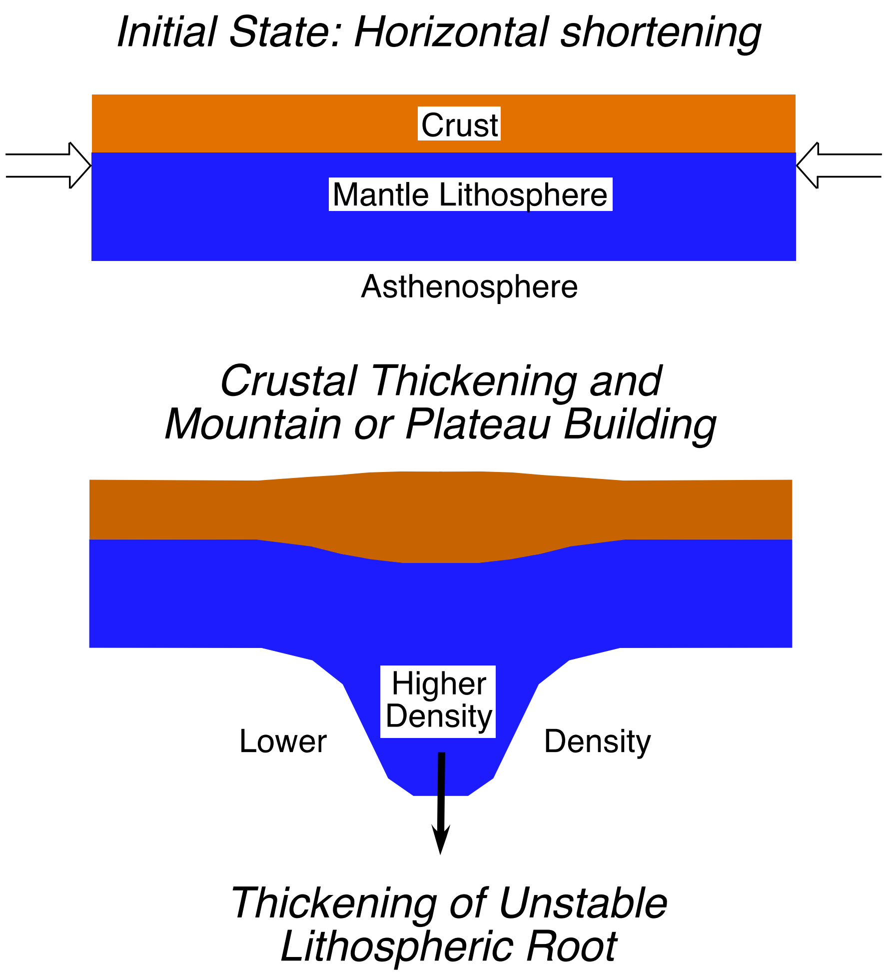


[*Elliott, Walters, England, Jackson, Li, and Parsons* 2010]

*A high plateau **cannot** be built by normal faulting.*

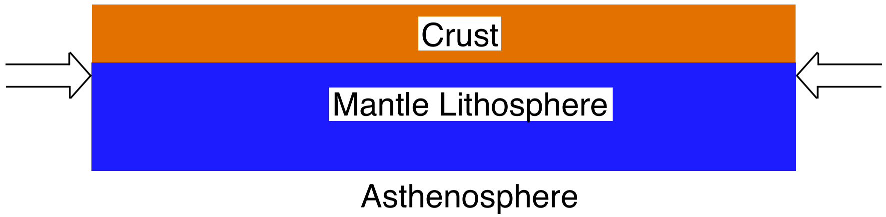
*Some **change** must have occurred.*

Shortening and Thickening of lithosphere (crust and mantle)

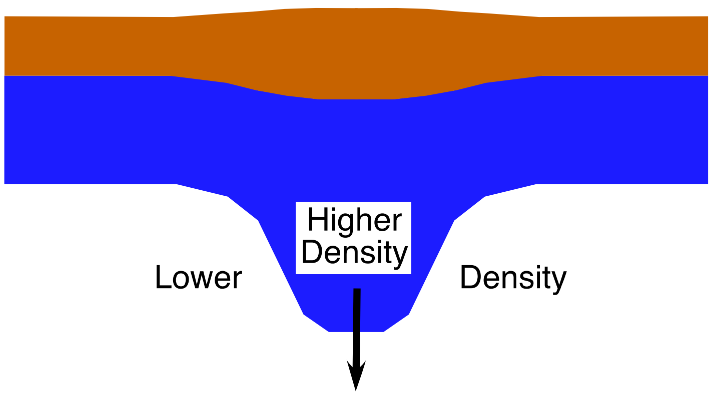


Shortening and Thickening of lithosphere (crust and mantle)

Initial State: Horizontal shortening

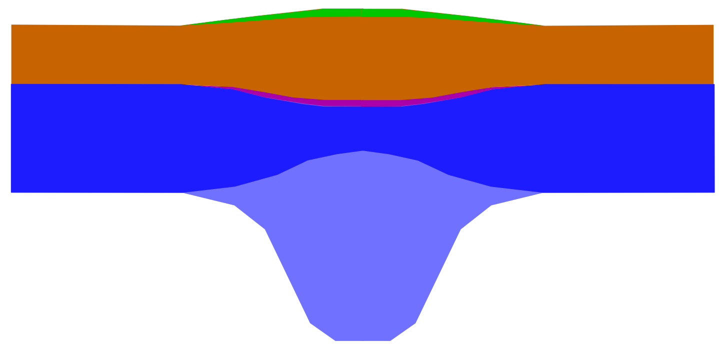


Crustal Thickening and Mountain or Plateau Building



Thickening of Unstable Lithospheric Root

Surface Uplift, due to removal of Lithospheric Load

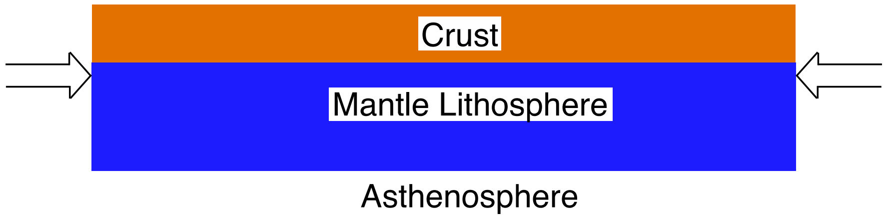


Removal of Lithospheric Root

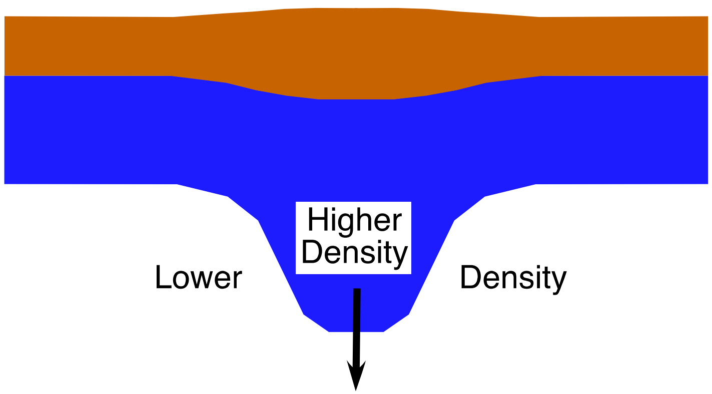
Removal of blobs of dense mantle lithosphere (“deblobbing”) reduces load to base of lithosphere: and available potential energy within the lithosphere, à la *Lorenz* [1955], increases.

Shortening and Thickening of lithosphere (crust and mantle)

Initial State: Horizontal shortening



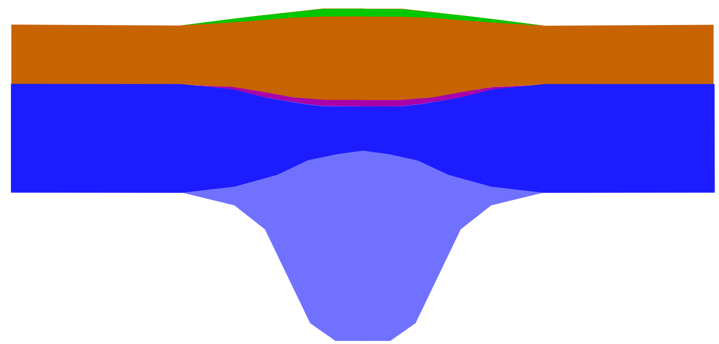
Crustal Thickening and Mountain or Plateau Building



Thickening of Unstable Lithospheric Root

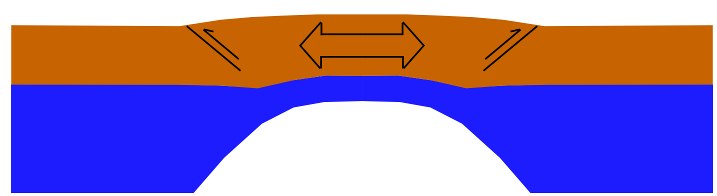
Surface rises, and available potential energy powers outward growth of the plateau and crustal extension within it

Surface Uplift, due to removal of Lithospheric Load



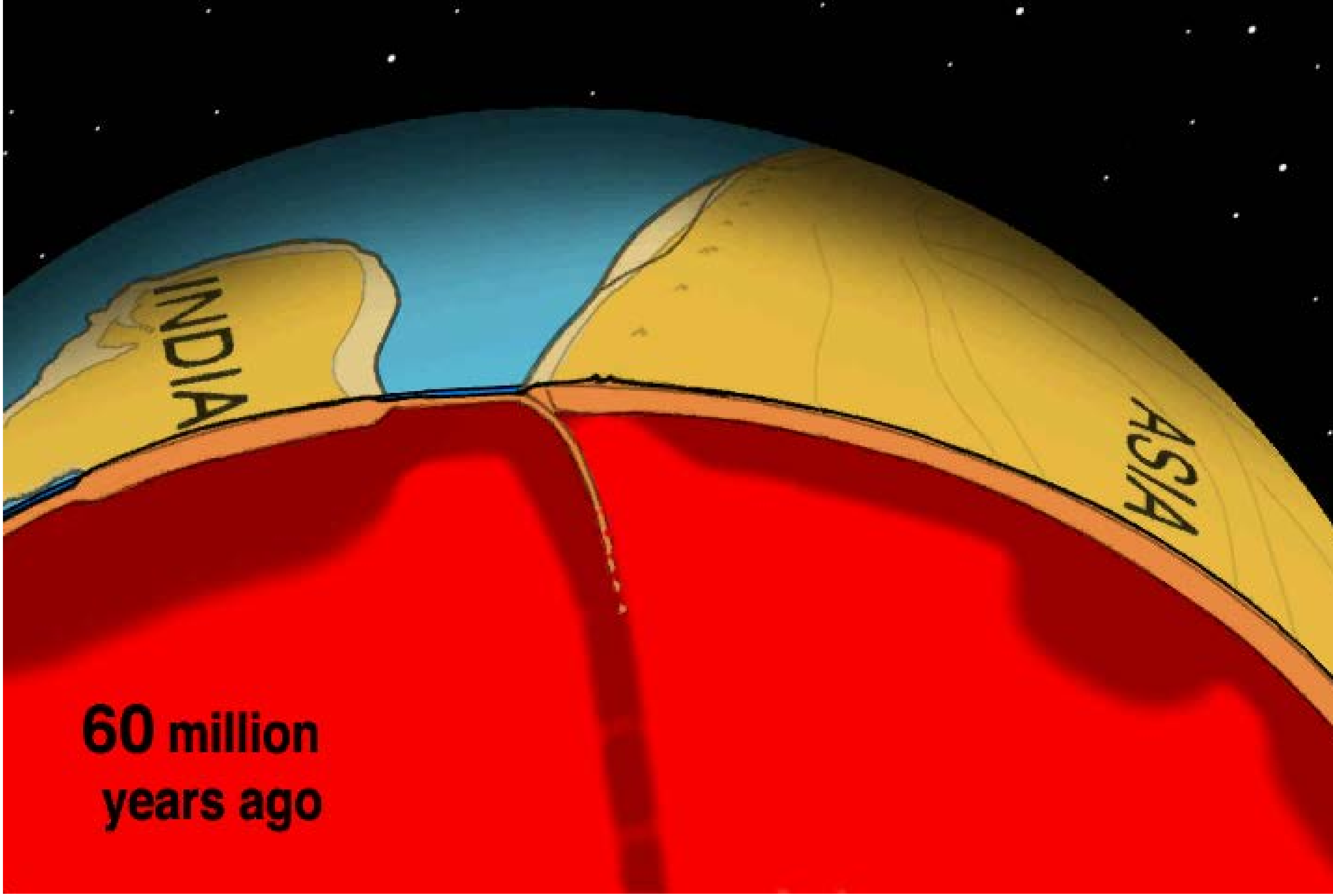
Removal of Lithospheric Root

Horizontal Extension and Subsidence



Further Lithospheric Thinning, and Possibly Volcanism

Removal of blobs of dense mantle lithosphere ("deblobbing") reduces load to base of lithosphere: and available potential energy within the lithosphere, à la *Lorenz* [1955], increases.

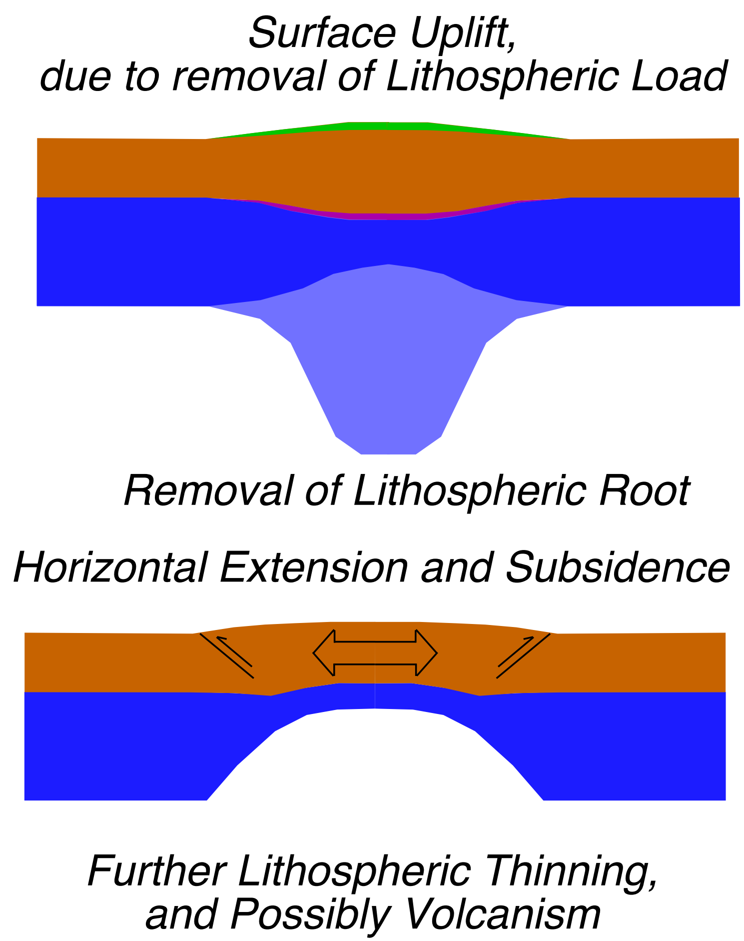


Animation by Tanya Atwater

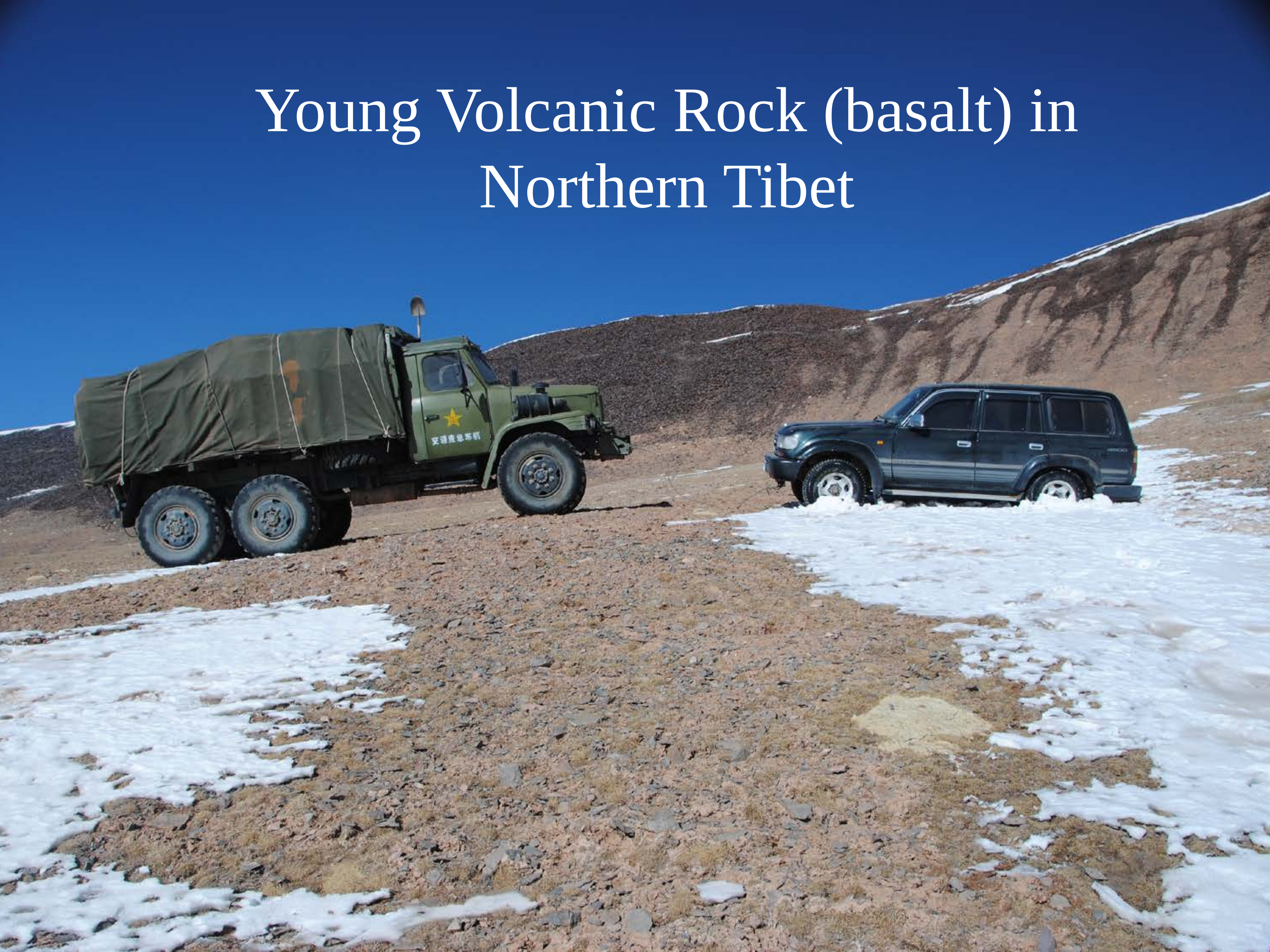
(given to me for my 60th birthday, and hence honoring all of my prejudices, but not necessarily all of the facts)

Removal of mantle lithosphere from beneath mountain belts and plateaus: What does this predict?

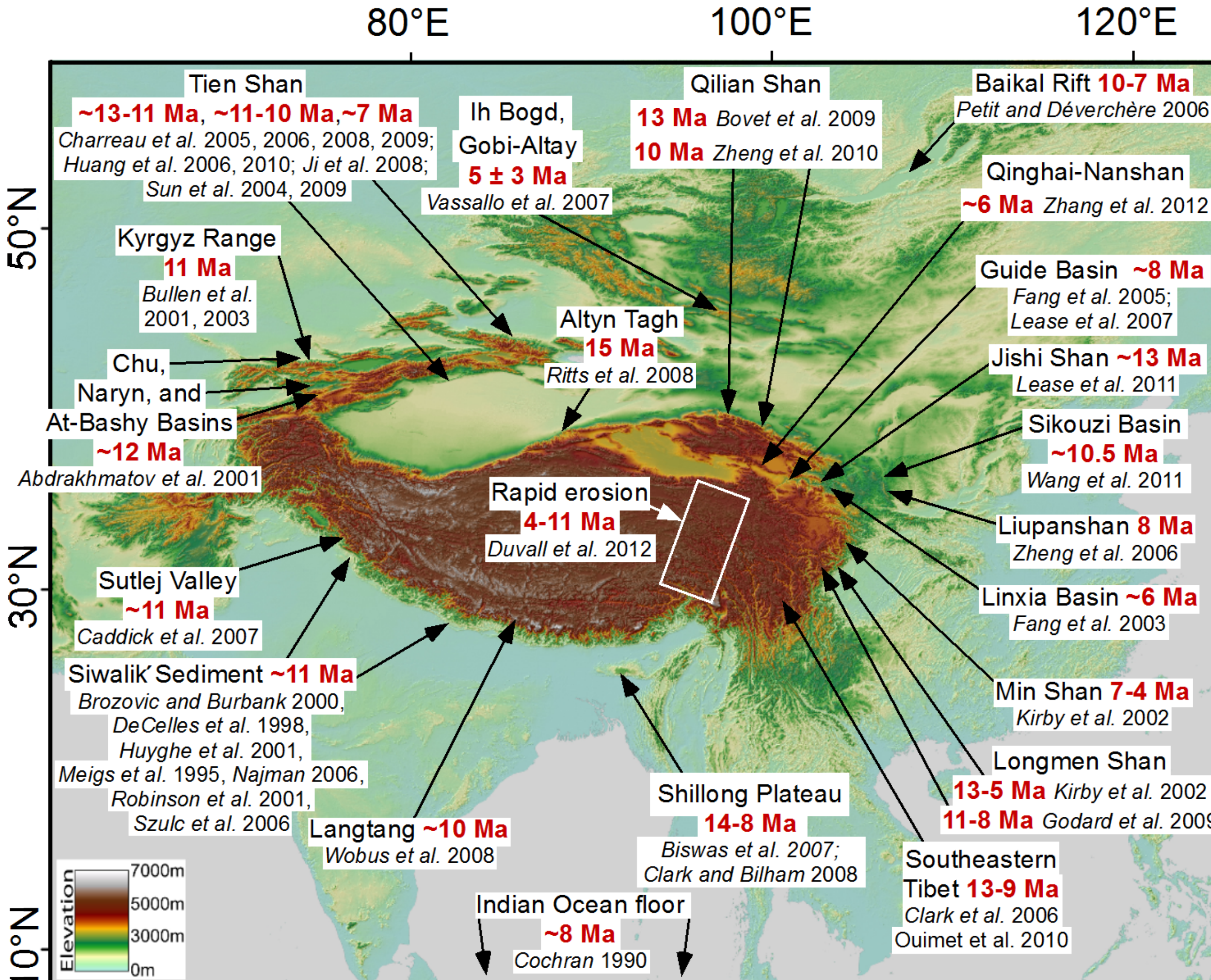
1. Geophysical evidence for a hot uppermost mantle.
2. Enhanced volcanism.
3. Outward growth of the range or plateau.
4. Crustal thinning beneath the high plateau.
5. Increase in surface elevation.

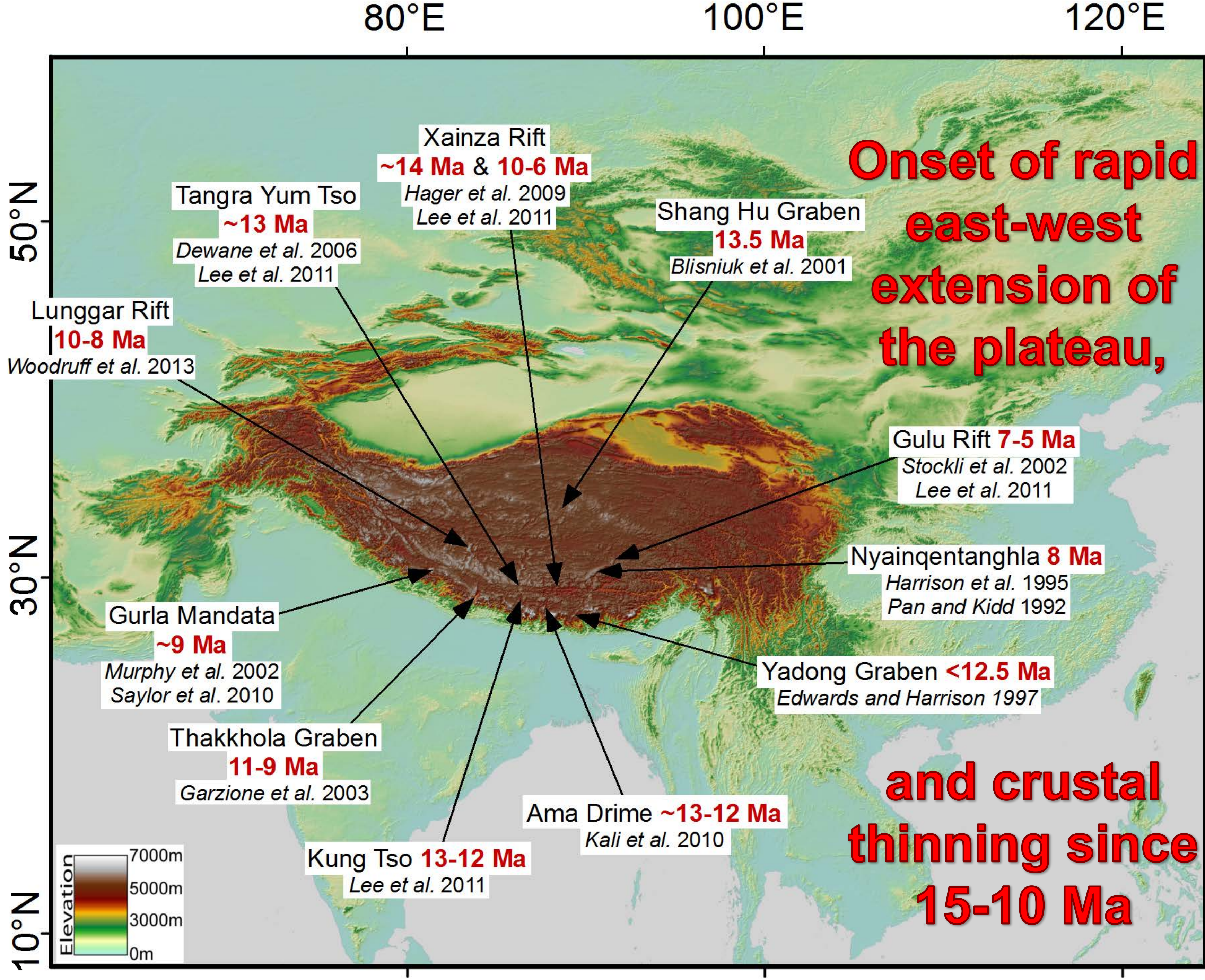


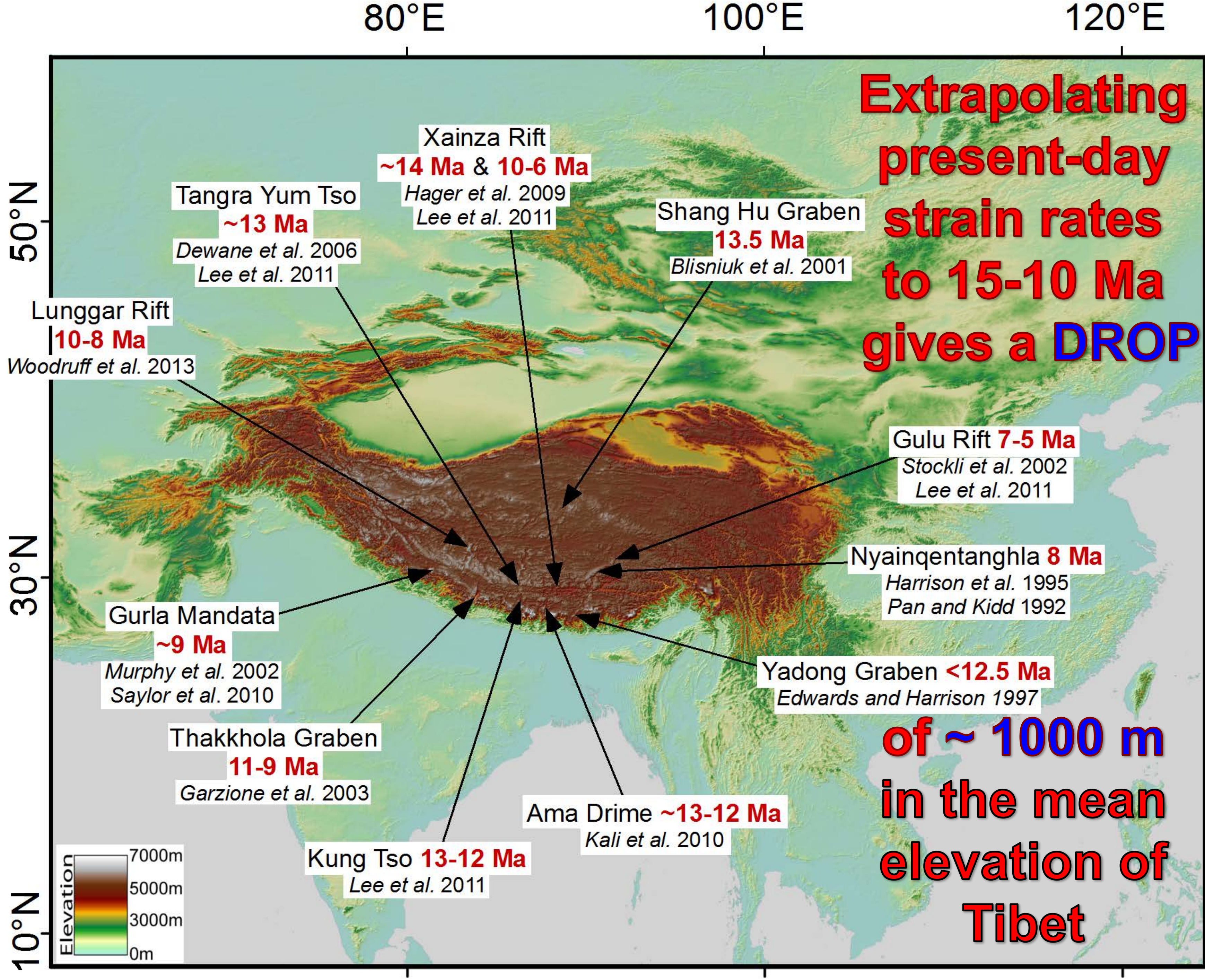
Young Volcanic Rock (basalt) in Northern Tibet



Deformation surrounding Tibet beginning at, or since, ~15 Ma; but collision occurred at ~50-40 Ma




80°E
100°E
120°E
50°N
30°N
10°N
Xainza Rift
~14 Ma & 10-6 Ma
Hager et al. 2009
Lee et al. 2011
Tangra Yum Tso
~13 Ma
Dewane et al. 2006
Lee et al. 2011
Shang Hu Graben
13.5 Ma
Blisniuk et al. 2001
Lunggar Rift
10-8 Ma
Woodruff et al. 2013
Onset of rapid east-west extension of the plateau,
Gulu Rift 7-5 Ma
Stockli et al. 2002
Lee et al. 2011
Nyainqentanghla 8 Ma
Harrison et al. 1995
Pan and Kidd 1992
Gurla Mandata
~9 Ma
Murphy et al. 2002
Saylor et al. 2010
Yadong Graben <12.5 Ma
Edwards and Harrison 1997
Thakkhola Graben
11-9 Ma
Garzione et al. 2003
Ama Drime ~13-12 Ma
Kali et al. 2010
Kung Tso 13-12 Ma
Lee et al. 2011
and crustal thinning since 15-10 Ma
Elevation
7000m
5000m
3000m
0m



80°E
100°E
120°E
50°N
30°N
10°N
Extrapolating present-day strain rates to 15-10 Ma gives a DROP
of ~ 1000 m in the mean elevation of Tibet
Xainza Rift
~14 Ma & 10-6 Ma
Hager et al. 2009
Lee et al. 2011
Tangra Yum Tso
~13 Ma
Dewane et al. 2006
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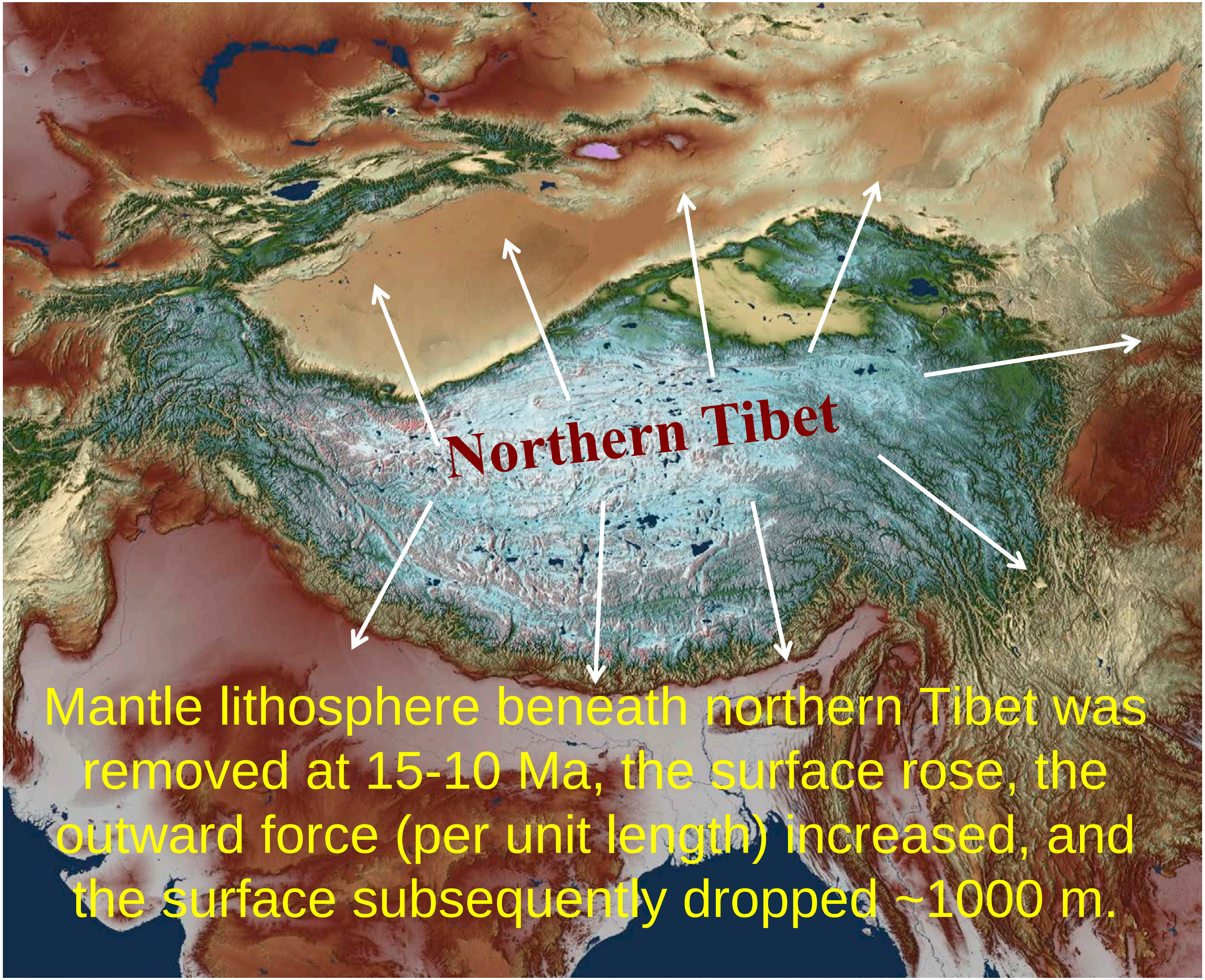
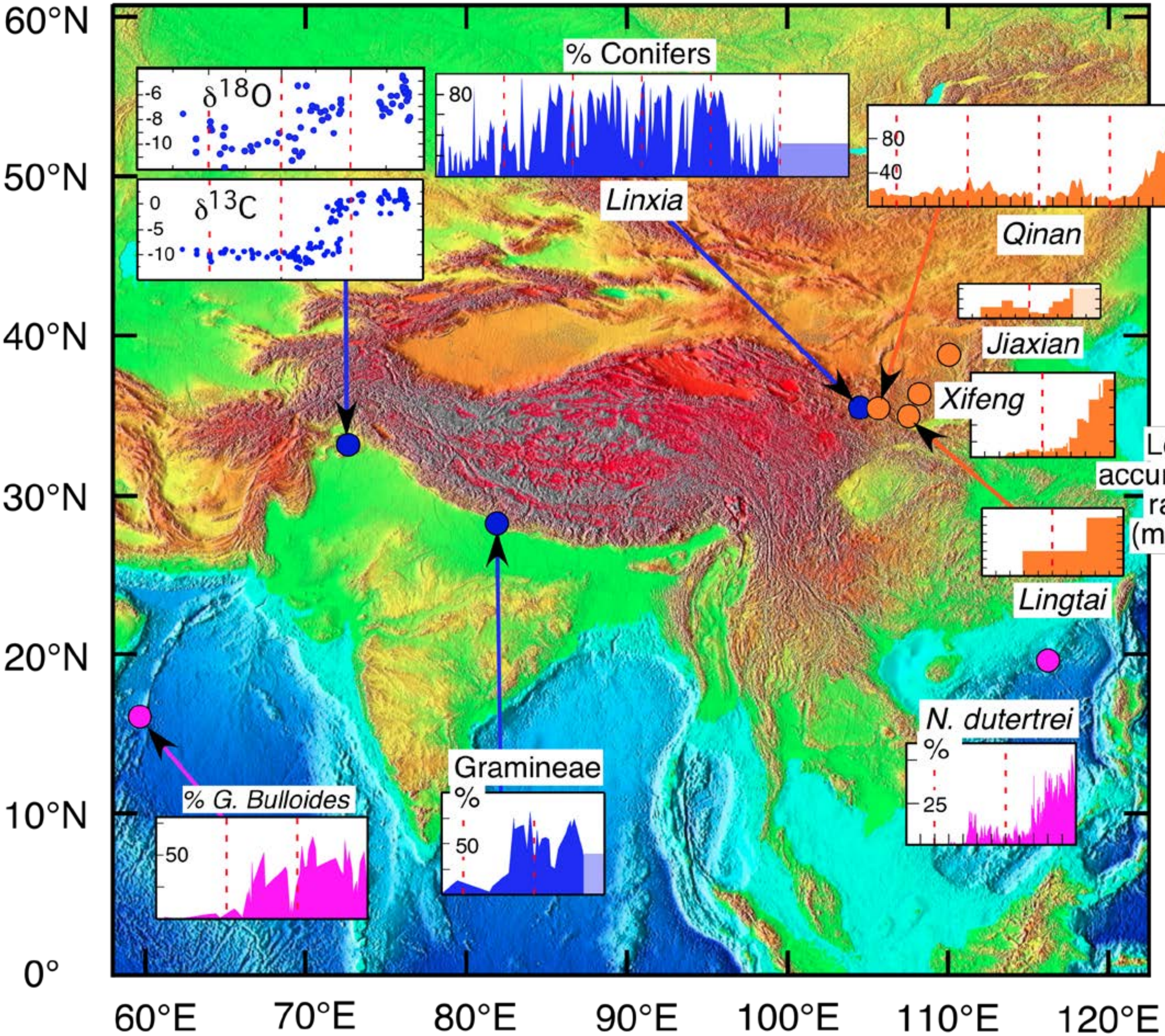
Lee et al. 2011
Elevation
7000m
5000m
3000m
0m

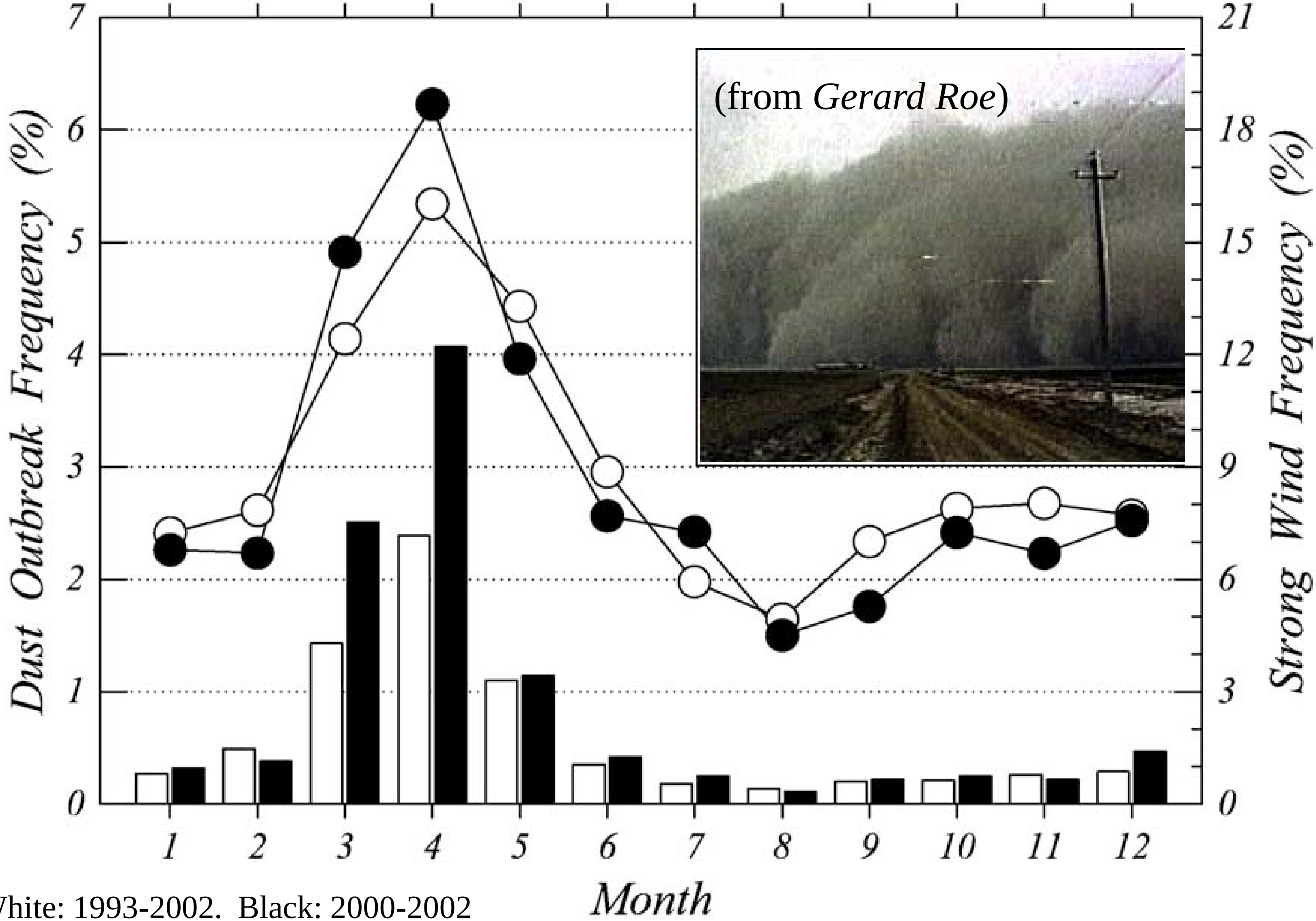

Northern Tibet
Mantle lithosphere beneath northern Tibet was removed at 15-10 Ma, the surface rose, the outward force (per unit length) increased, and the surface subsequently dropped ~1000 m.



Million-year time series of paleoclimate *suggest some climate change(s) since ~10 Ma surrounding Tibet.*

Compiled by *Molnar, Boos, and Battisti* [2010]

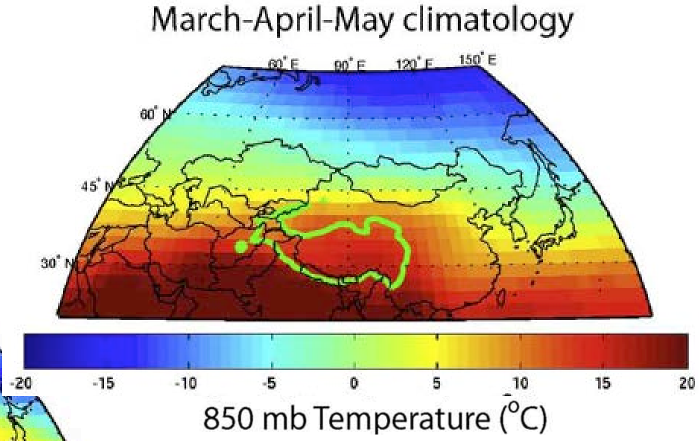
Dust-storm and strong wind frequency in northern China: Spring is the season (not winter or summer)

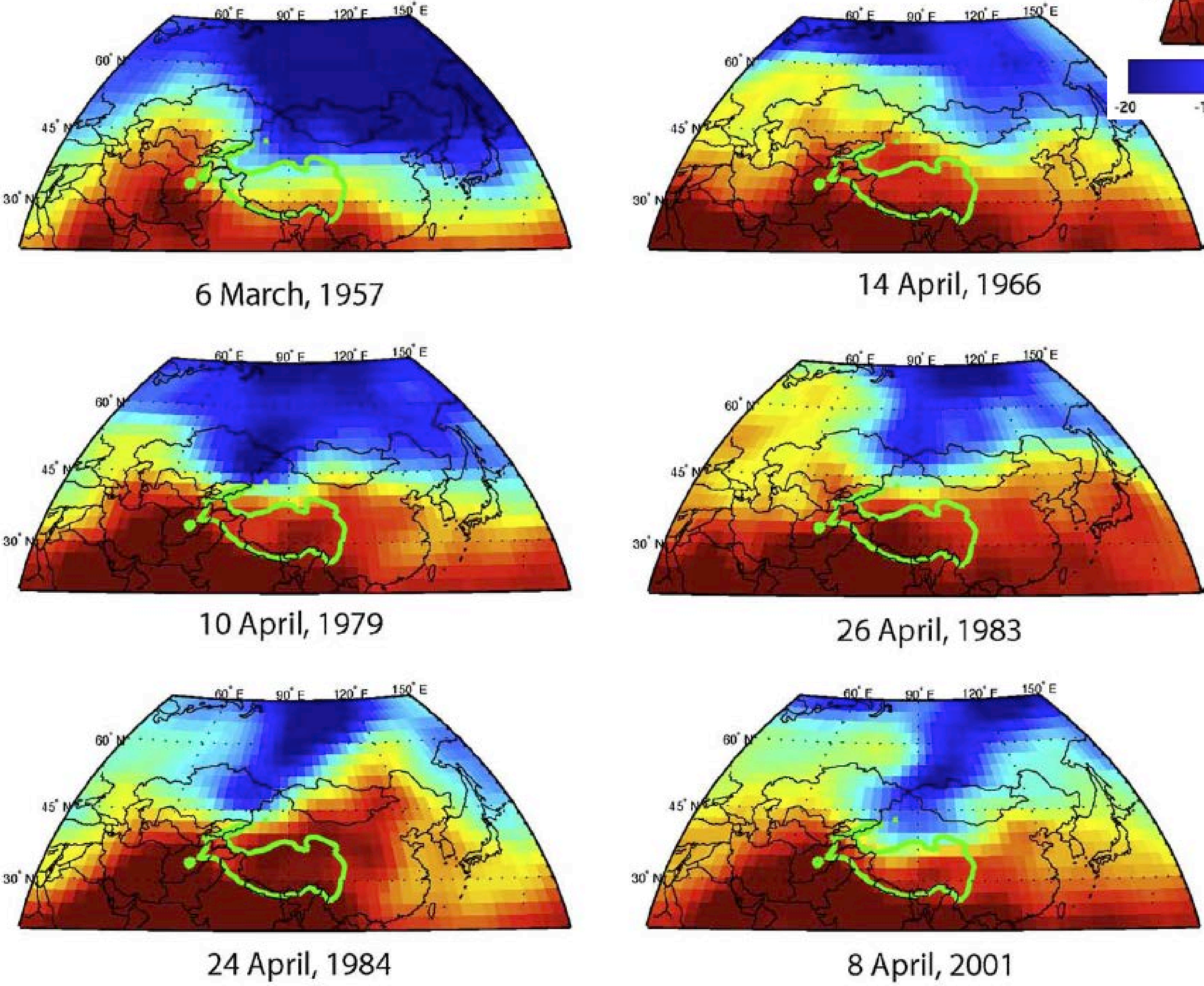


White: 1993-2002. Black: 2000-2002
Dust outbreak: bars. Strong winds: circles.

[*Kurosaki and Mikami* 2003; *Roe* 2009]

850-millibar temperature during major dust storms:

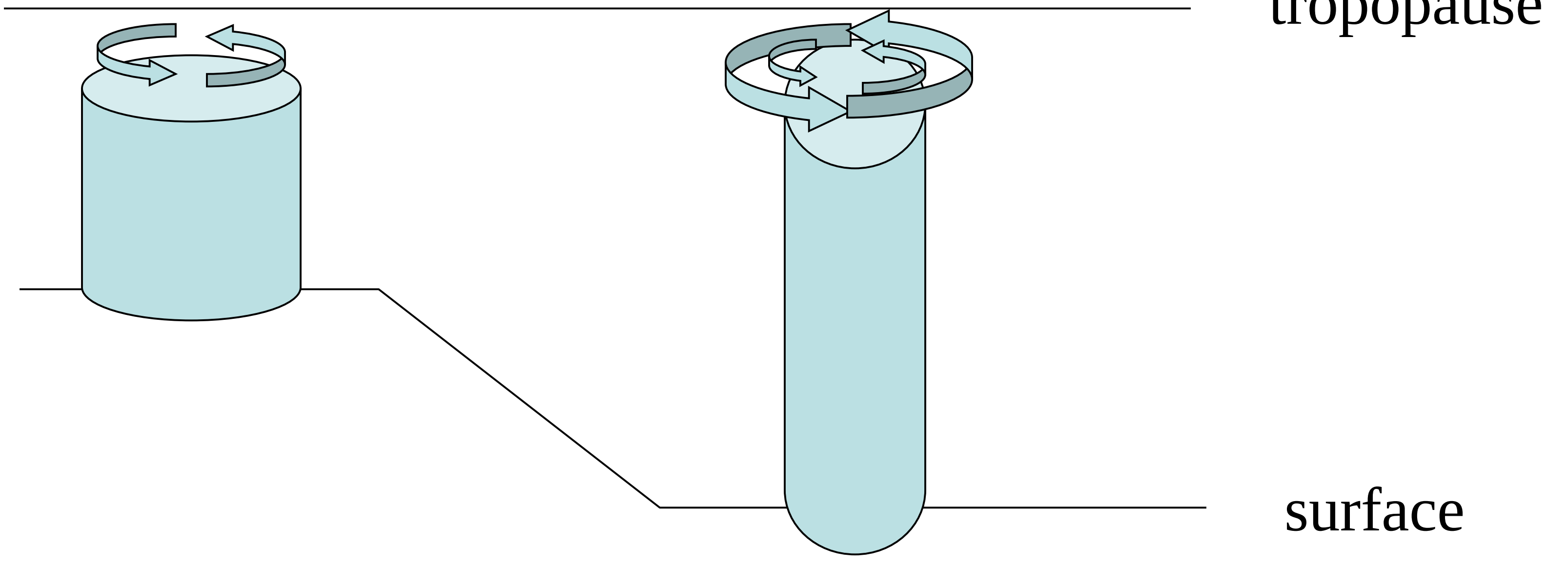




Dust storms occur when outbreaks of cold air from the Arctic pass over high terrain in and near Mongolia (*not Tibet*), and storms grow by lee cyclogenesis in the lee of this high terrain.

[Roe, *Quaternary Research*, 2009]

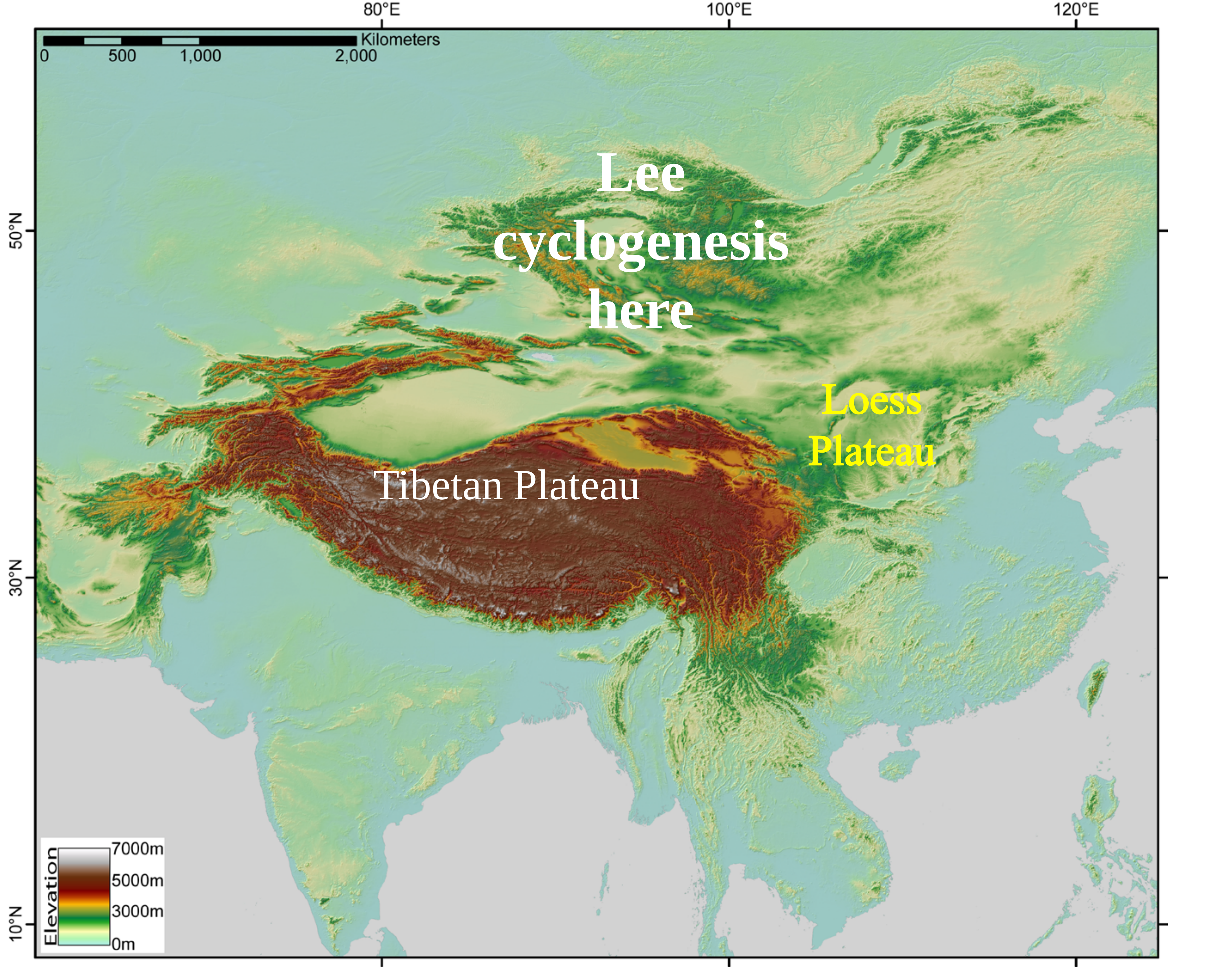
Lee cyclogenesis

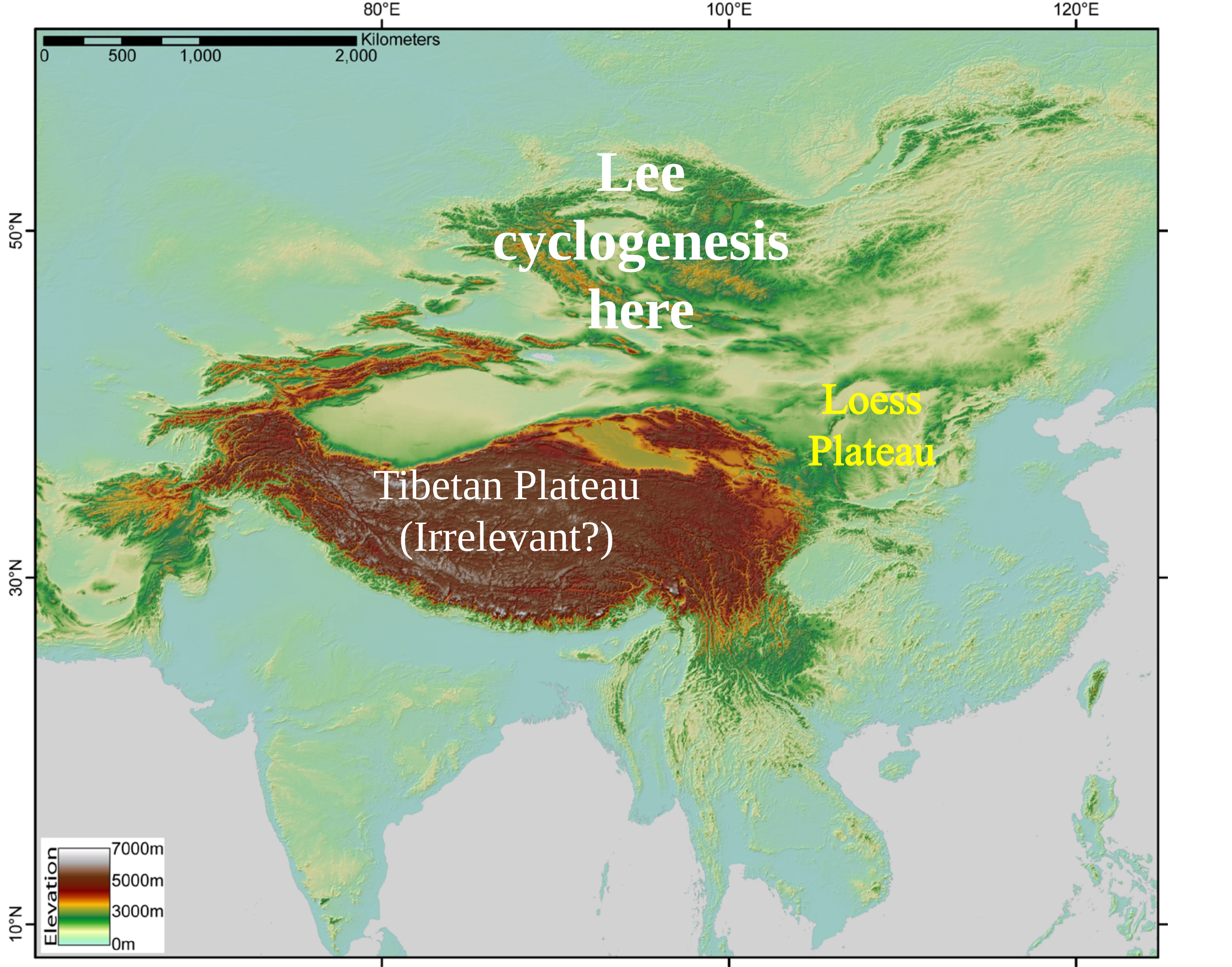


Stretching of atmospheric columns causes spin-up (cyclonic rotation) and promotes development of storms east of the Mongolian Altay.

Does Tibet have anything to do with loess accumulation?

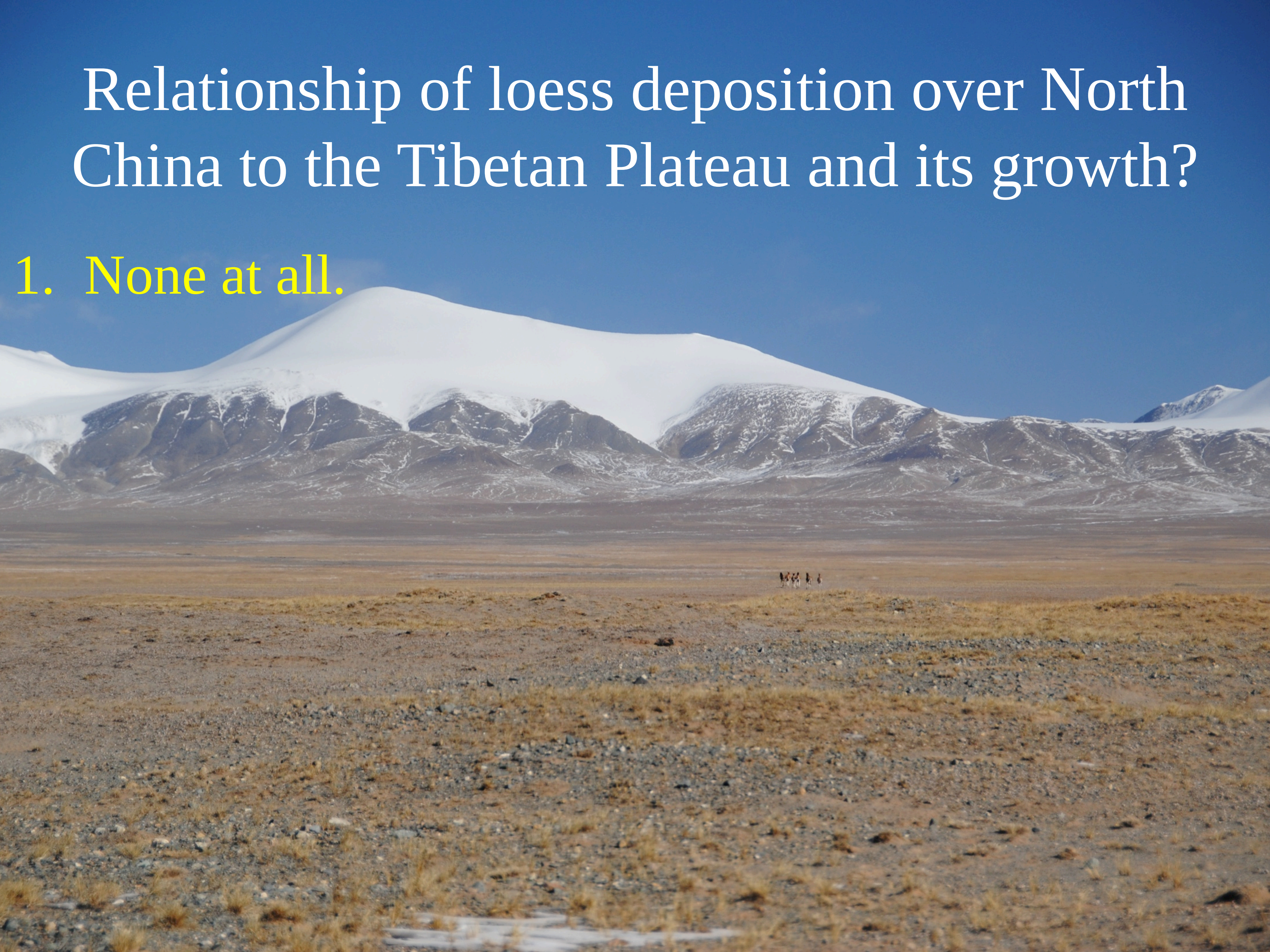
(from *Gerard Roe*)


80°E
100°E
120°E
Kilometers
0
500
1,000
2,000
50°N
30°N
10°N
Lee cyclogenesis here
Loess Plateau
Tibetan Plateau
Elevation
7000m
5000m
3000m
0m

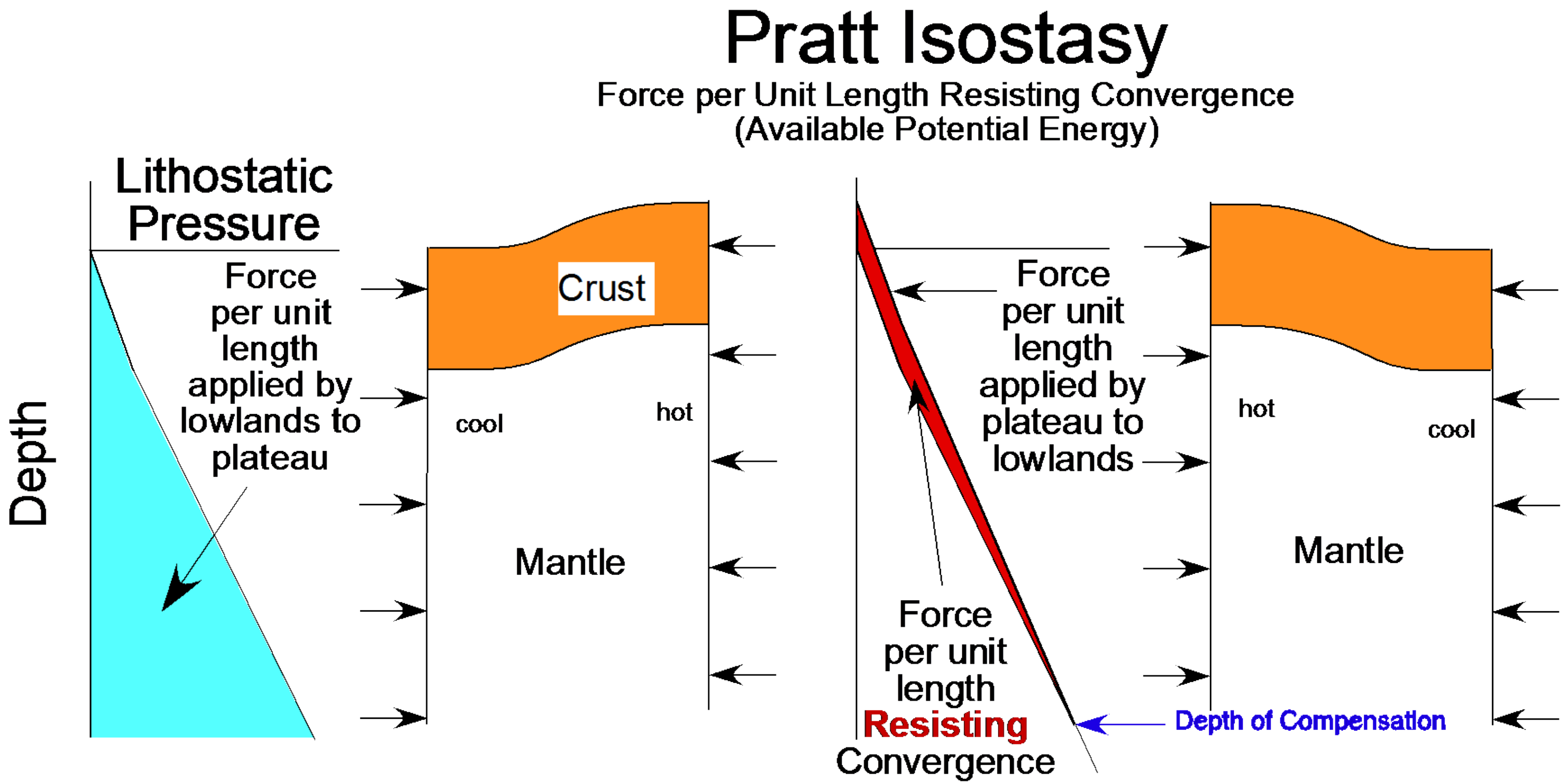

80°E
100°E
120°E
Kilometers
0
500
1,000
2,000
50°N
30°N
10°N
Lee cyclogenesis here
Loess Plateau
Tibetan Plateau (Irrelevant?)
Elevation
7000m
5000m
3000m
0m

Relationship of loess deposition over North China to the Tibetan Plateau and its growth?

1. None at all.



Lithostatic Pressure, Available Potential Energy, and Force per unit length

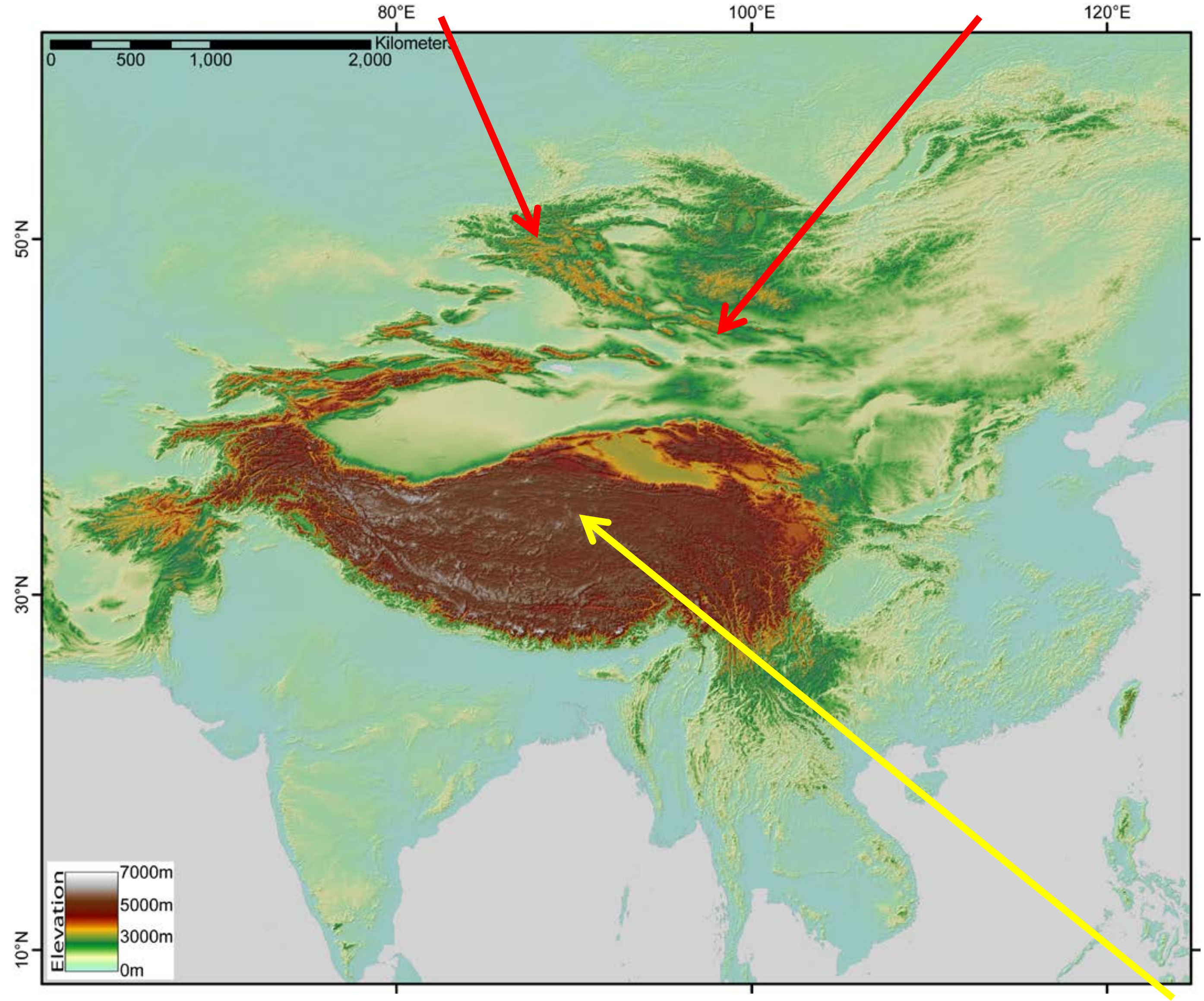


Relationship of loess deposition over North China to the Tibetan Plateau and its growth?

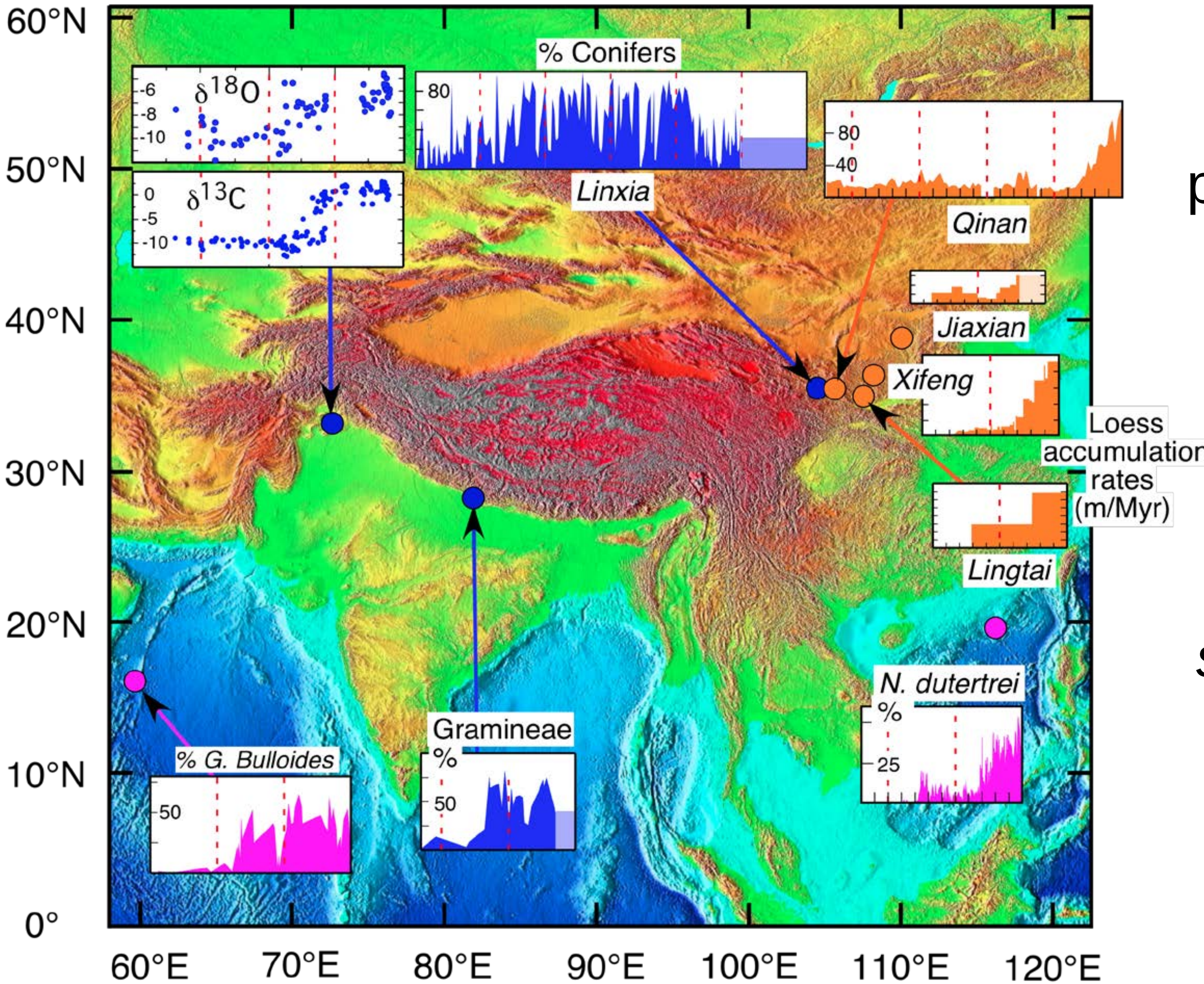
1. None at all.

1. Maybe geodynamically. A rise of Tibet increased the lithostatic pressure (strictly, the force per unit length) that its lithosphere applies to Asian lithosphere farther north, which caused the Mongolia Altay and Gobi Altay to rise, and made lee cyclogenesis possible.

Rise of the Mongolian Altay and Gobi Altay



as “geodynamic teleconnections” from Tibet



Million-year time series of paleoclimate

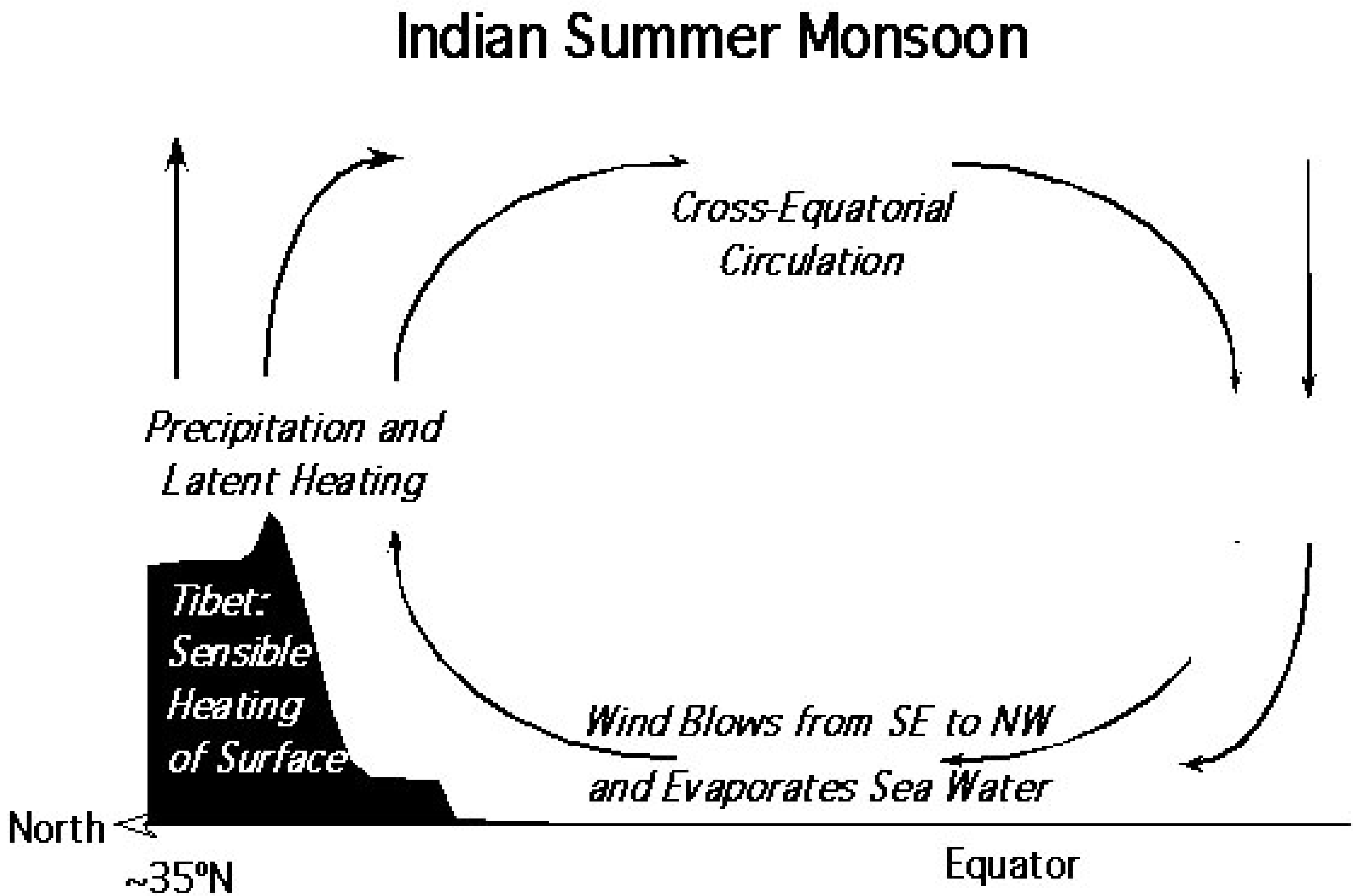
a suggestion of climate change since ~10 Ma surrounding Tibet.

Compiled by *Molnar, Boos, and Battisti* [2010]

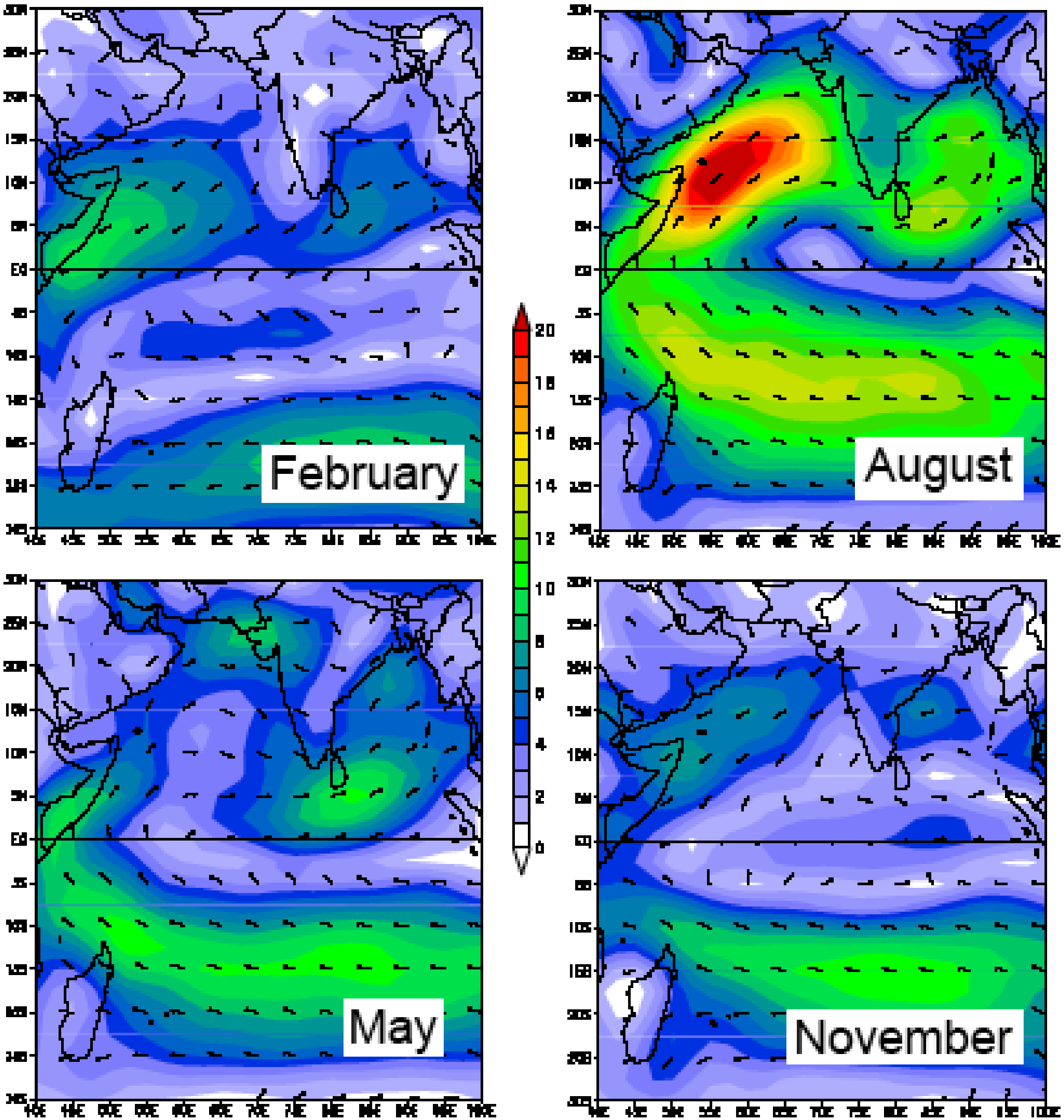
Sensible heating over India & Tibet and latent heating aloft lead to monsoonal circulation

Hot upper troposphere

Cooler (but not cold) upper troposphere



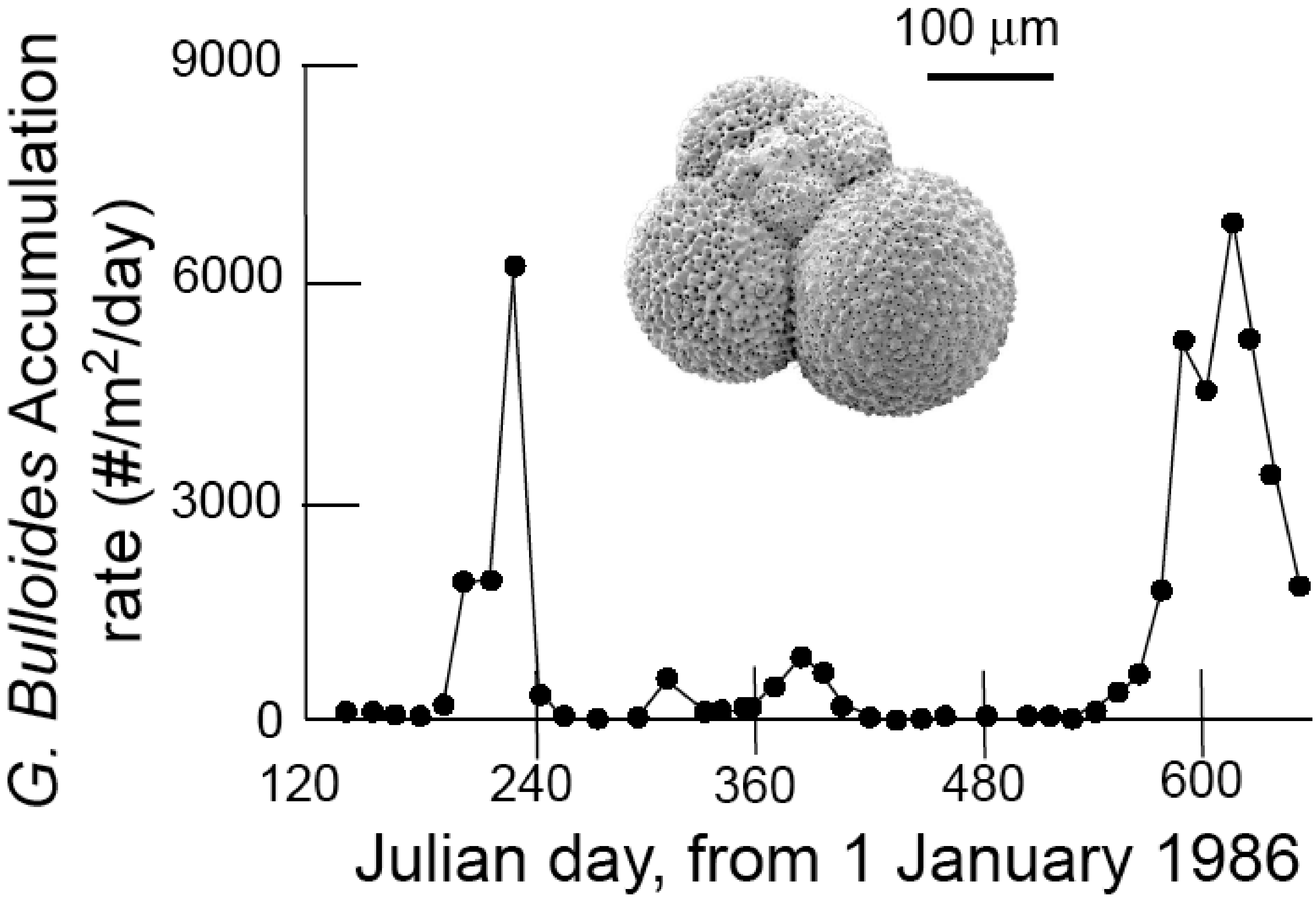
From *Molnar et al.* [1993]



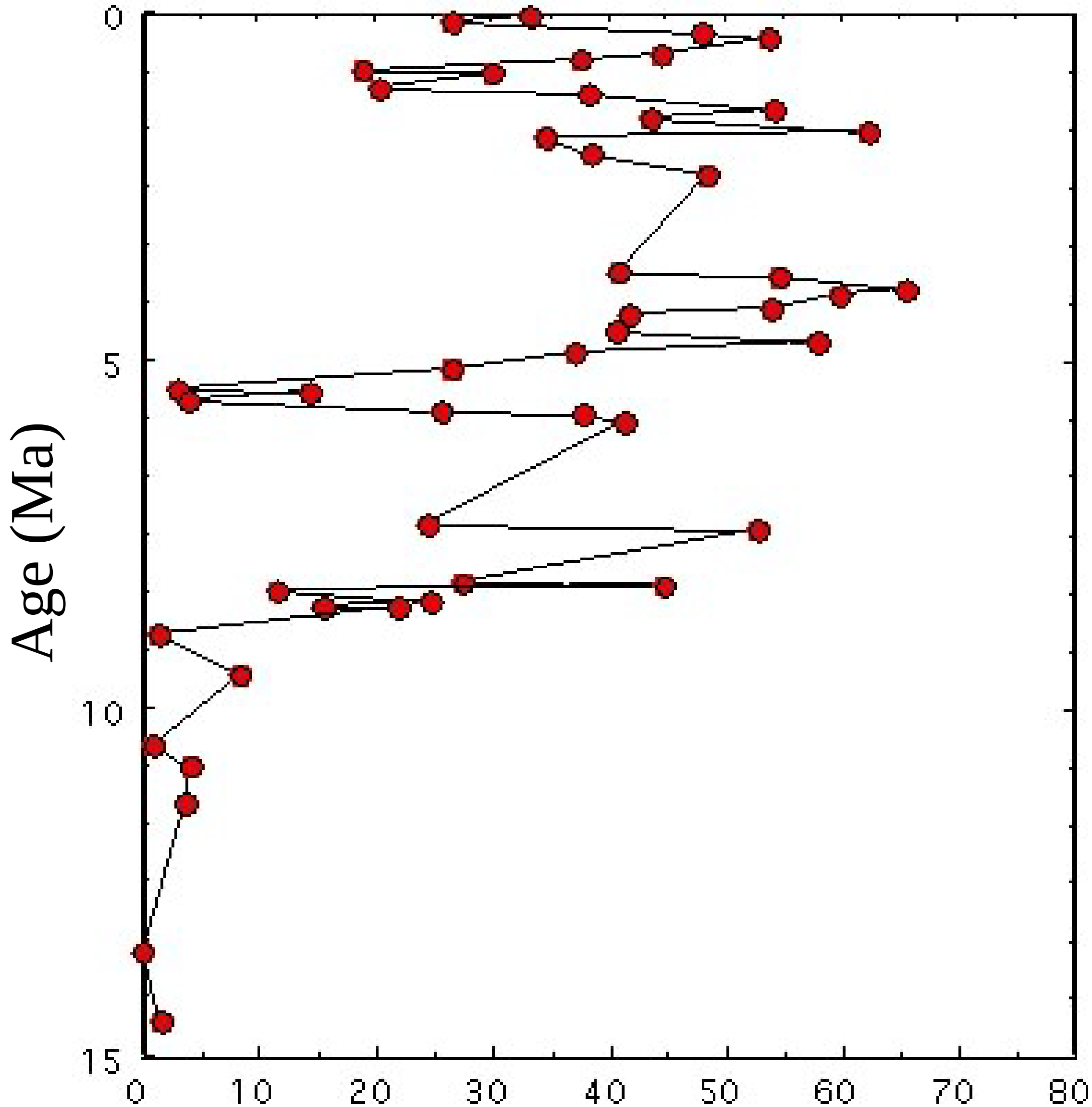
Seasonal Differences in Winds over the Indian Ocean:

in summer (winter) monsoons, winds blow toward the NE (SW)

Data: *Curry, Ostermann, Guptha, and Ittekkot* [1992]; Photo: L. Northcote



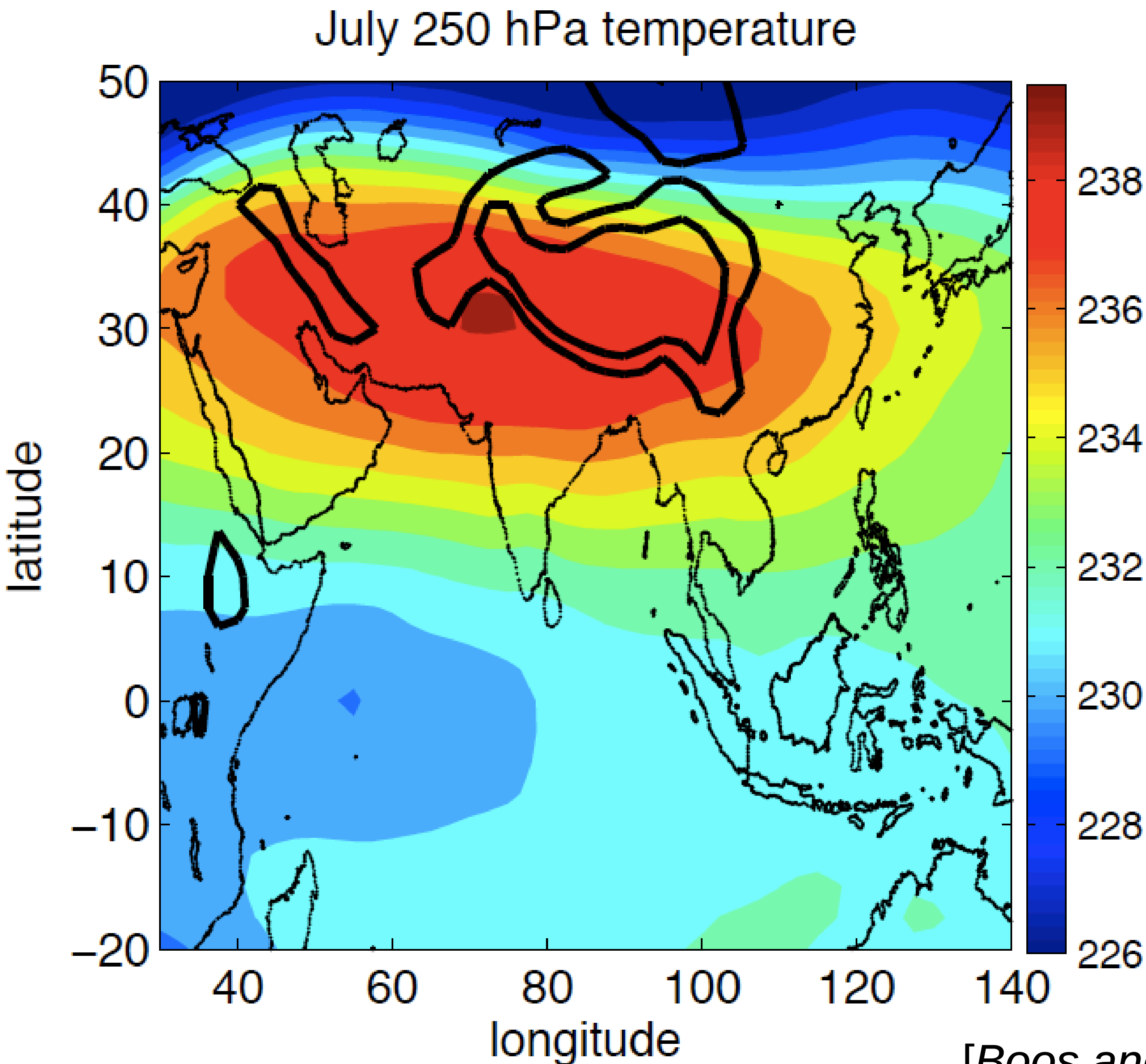
Globigerina bulloides **flourishes** during the monsoon, and **disappears** during the rest of the year.



Percentage of *Globigerina Bulloides* at ODP Site 722 (Arabian Sea)

Increase in the fraction of *Globigerina Bulloides* in the Arabian Sea at ~8-9 Ma: Strengthening of the Indian monsoon?

From *Kroon, Steens, and Troelstra* [1991]; *Prell, Murray, Clemens, and Anderson* [1992] show the same.

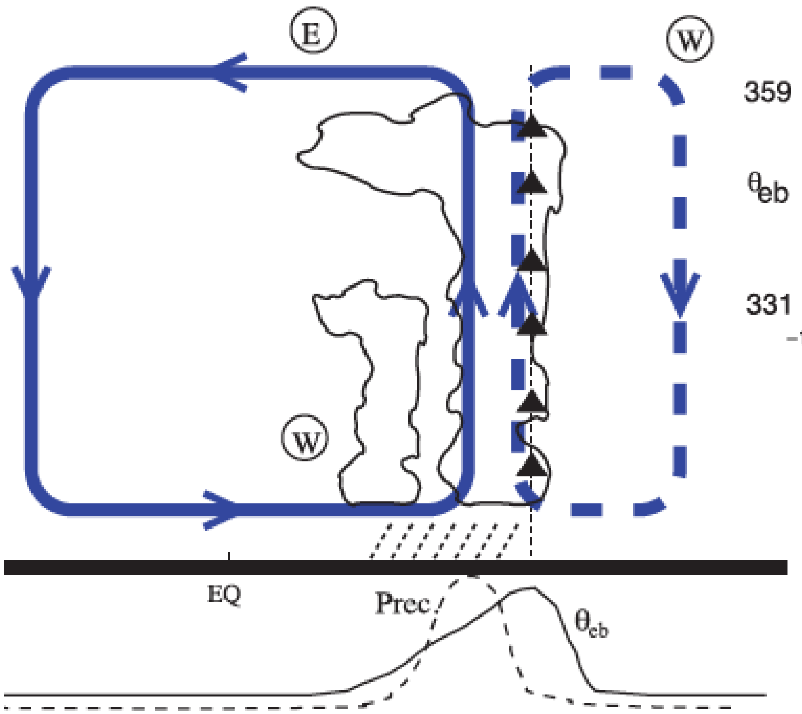


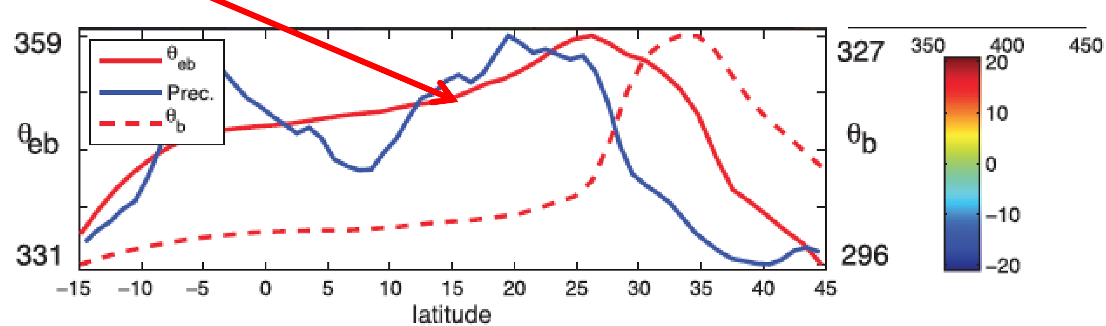
High upper atmospheric temperature: **not** centered over Tibet.

[*Boos and Emanuel* 2009]

Elementary monsoon theory: quasi-equilibrium

Maximum ascent rate lies slightly equatorward of **maximum** subcloud specific entropy, s_b, or moist static energy, h.





$$h = C_p T + L_v q + gz$$

$$\approx s_b / T_b$$

$$s_b = C_p \ln \vartheta_{eb} \qquad \vartheta_{eb} \approx T_b \left(\frac{p_b}{p}\right)^{\frac{R}{c_p}} exp\left(\frac{L_v q}{c_p T_b}\right)$$

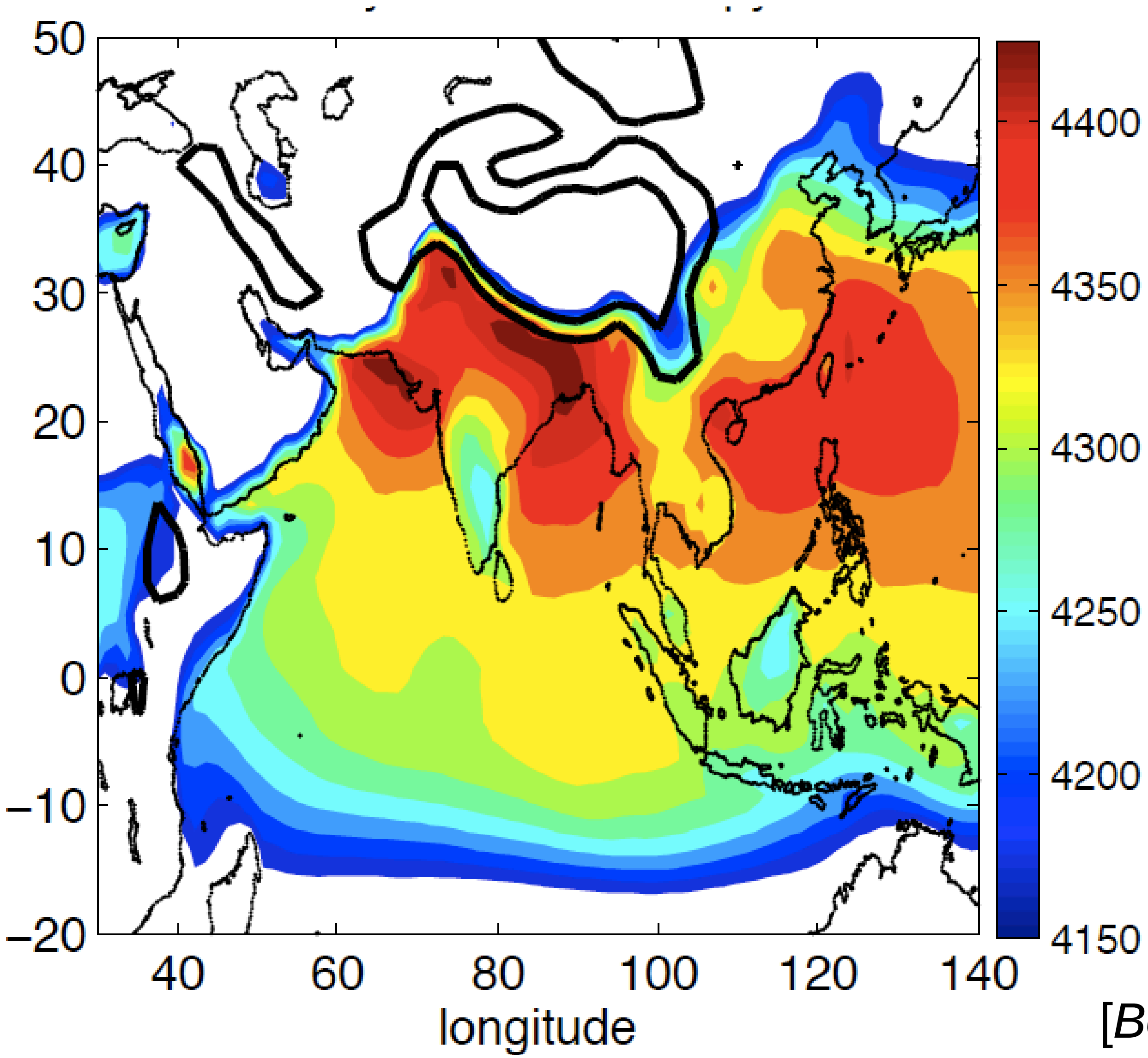
[*Emanuel*, 1995, 2007;
Emanuel et al., 1994;
Lindzen and Hou, 1988;
Neelin, 2007; *Plumb*, 2007;
Privé and Plumb, 2007].

Figures from *Nie, Boos, and Kuang* [*Journal of Climate*, 2010]

Subcloud moist entropy (like moist static energy) (in July):

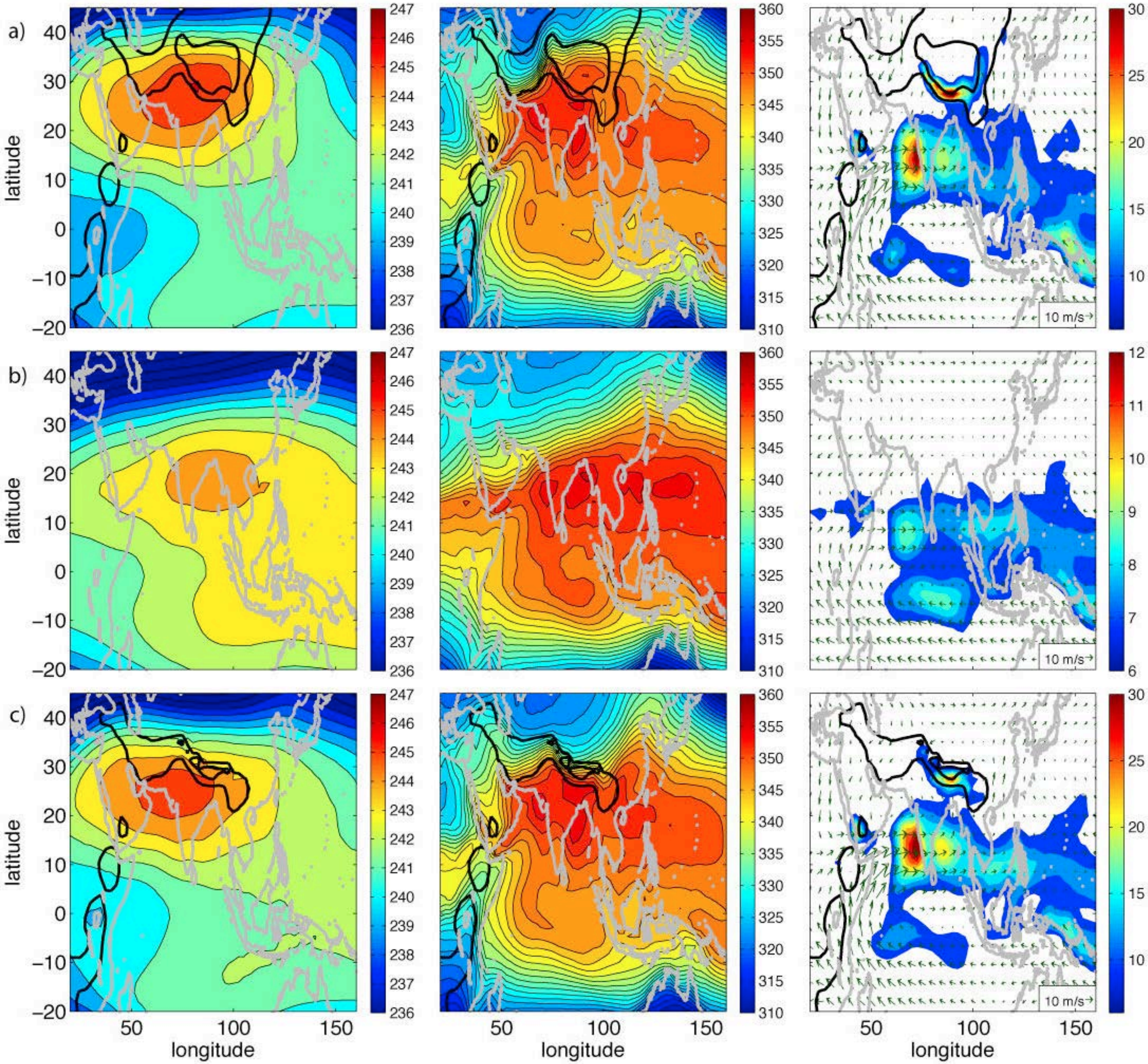
$s_b = (C_{pd} + qC_{pl}) \ln \theta_{eb}$, θ_{eb} = equivalent potential temperature

$$h = C_P T + L_v q + gz$$



The potentially **most unstable** surface air lies **NOT** over Tibet, but over northern India.

[*Boos and Emanuel* 2009]



175-450 mb Temperature   subcloud θ_{eb} Precipitation and winds: **all for summer**

$$h = C_p T + L_v q + gz$$

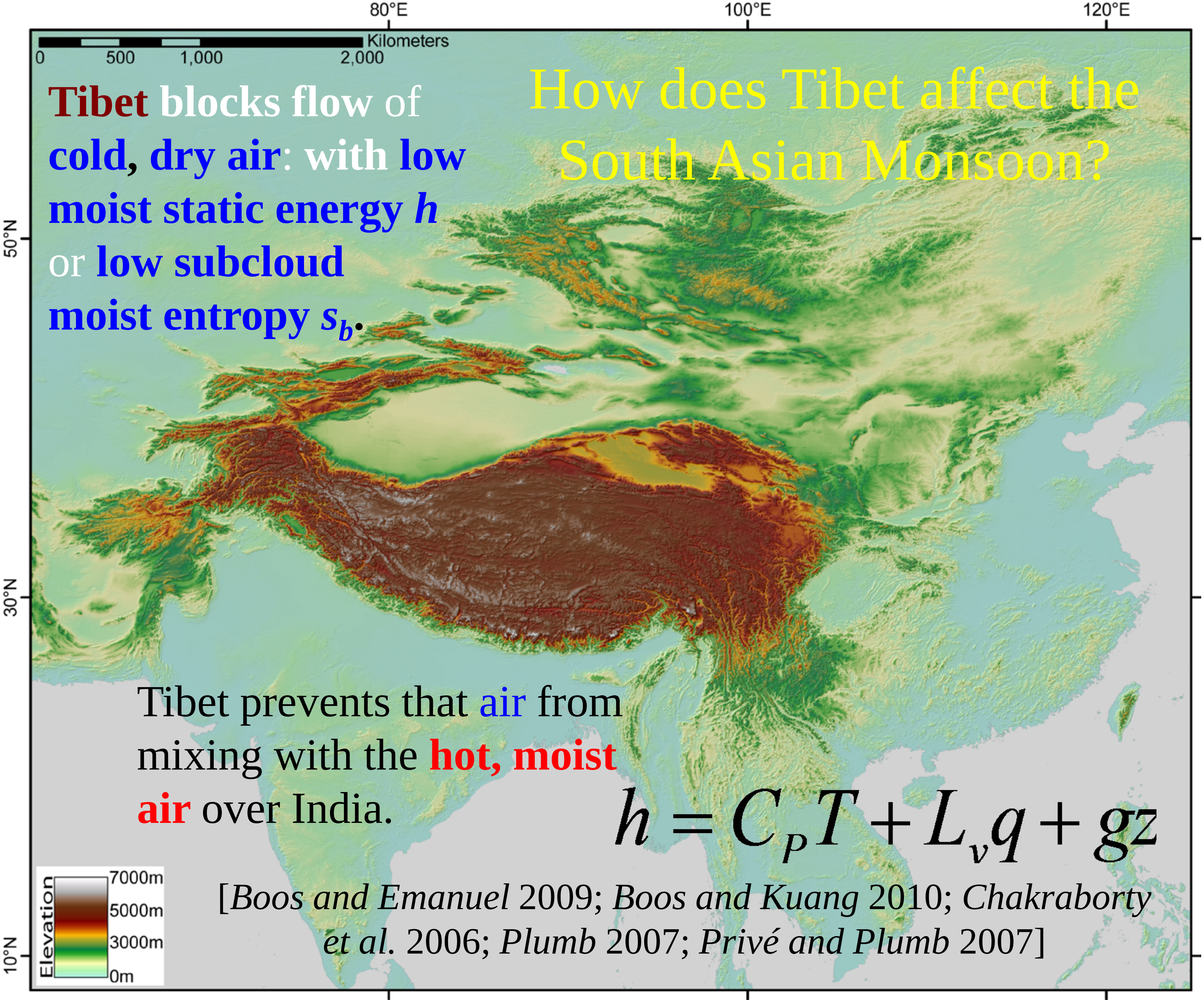
Present-day topography

Importance of the Himalaya, but not Tibet.

No topography

No Tibet, but with the Himalaya (and east Africa)

[*Boos and Kuang* 2010]



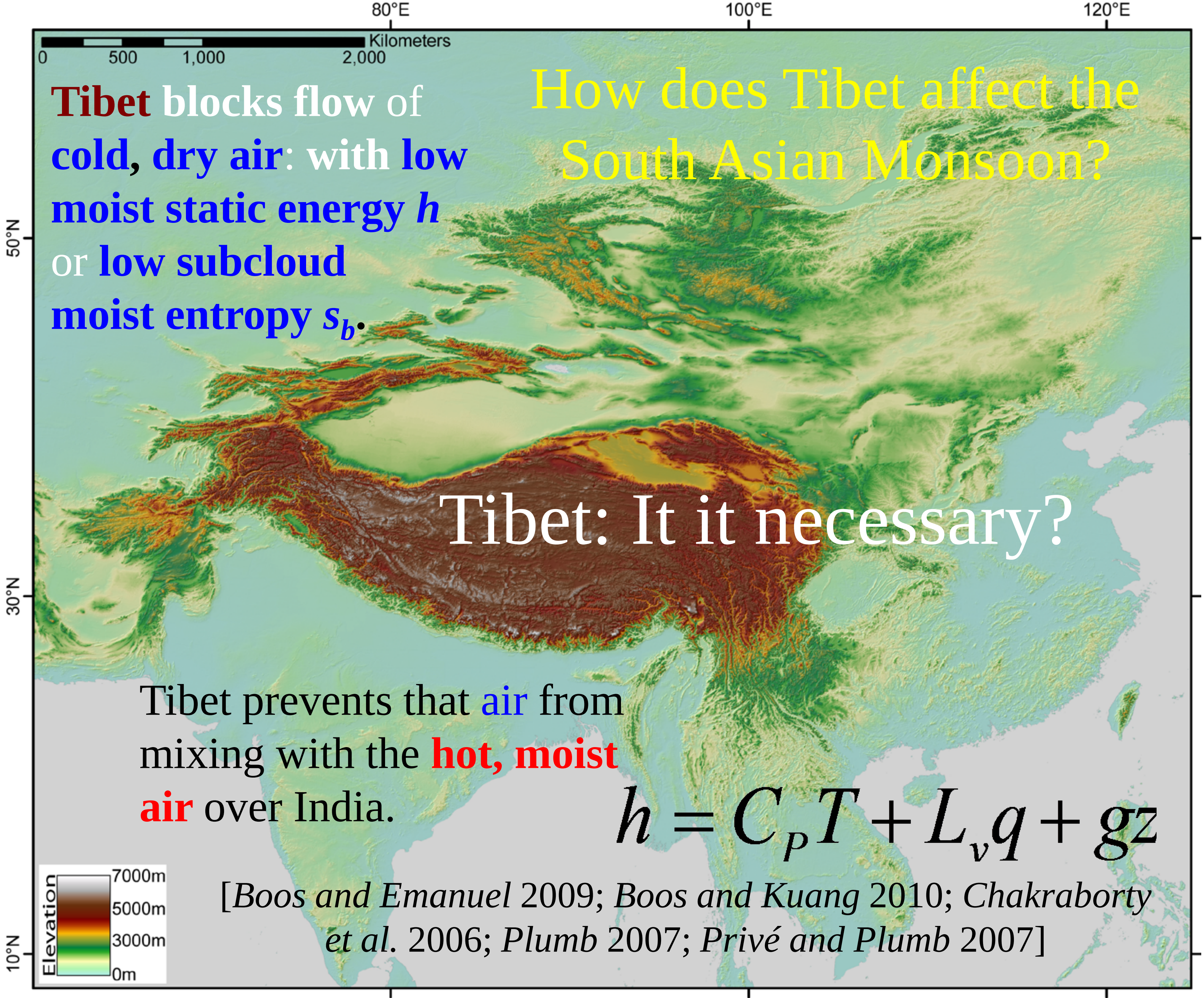
How does Tibet affect the South Asian Monsoon?

Tibet blocks flow of **cold**, **dry air**: **with low moist static energy *h*** or **low subcloud moist entropy s_b**.

Tibet prevents that air from mixing with the **hot, moist air** over India.

$$h = C_p T + L_v q + gz$$

[*Boos and Emanuel* 2009; *Boos and Kuang* 2010; *Chakraborty et al.* 2006; *Plumb* 2007; *Privé and Plumb* 2007]


How does Tibet affect the South Asian Monsoon?
Tibet blocks flow of cold, dry air: with low moist static energy h or low subcloud moist entropy s_b.
Tibet: It it necessary?
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$h = C_p T + L_v q + gz$
[*Boos and Emanuel* 2009; *Boos and Kuang* 2010; *Chakraborty et al.* 2006; *Plumb* 2007; *Privé and Plumb* 2007]
80°E
100°E
120°E
50°N
30°N
10°N
Kilometers
0
500
1,000
2,000
Elevation
7000m
5000m
3000m
0m

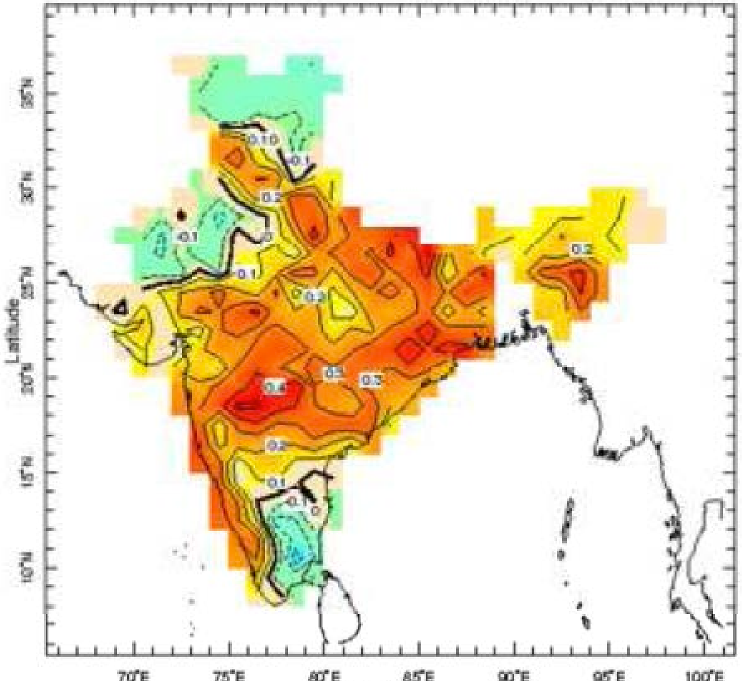
Does heating over Tibet matter for the monsoon?

A test:

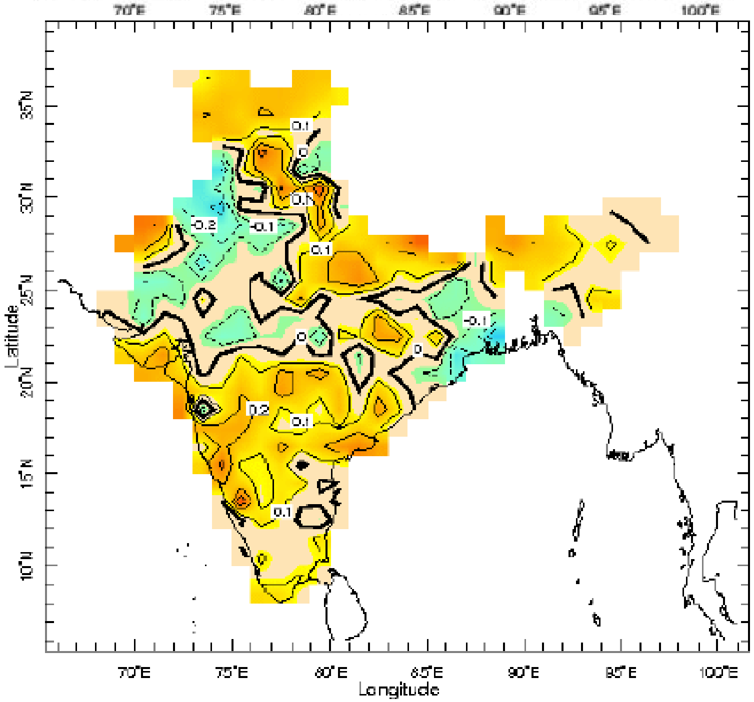
correlate most static energy over Tibet with monsoon rainfall over India

$$h = C_p T + L_v q + gz$$

Rainfall correlated with moist static energy over Tibet

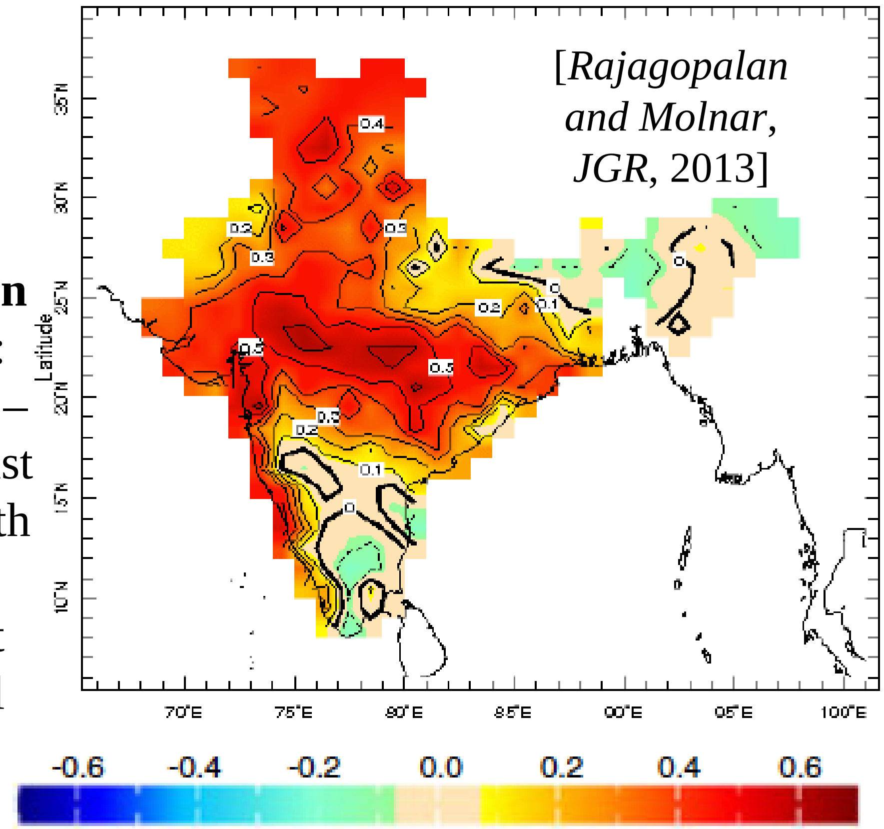


Early monsoon season: May *MSE* with 20 May - 15 June rainfall



Main monsoon season: 15 June – 31 August *MSE* with July – August rainfall

Late monsoon season: September *MSE* with 20 September – 15 October rainfall



[*Rajagopalan and Molnar*, *JGR*, 2013]

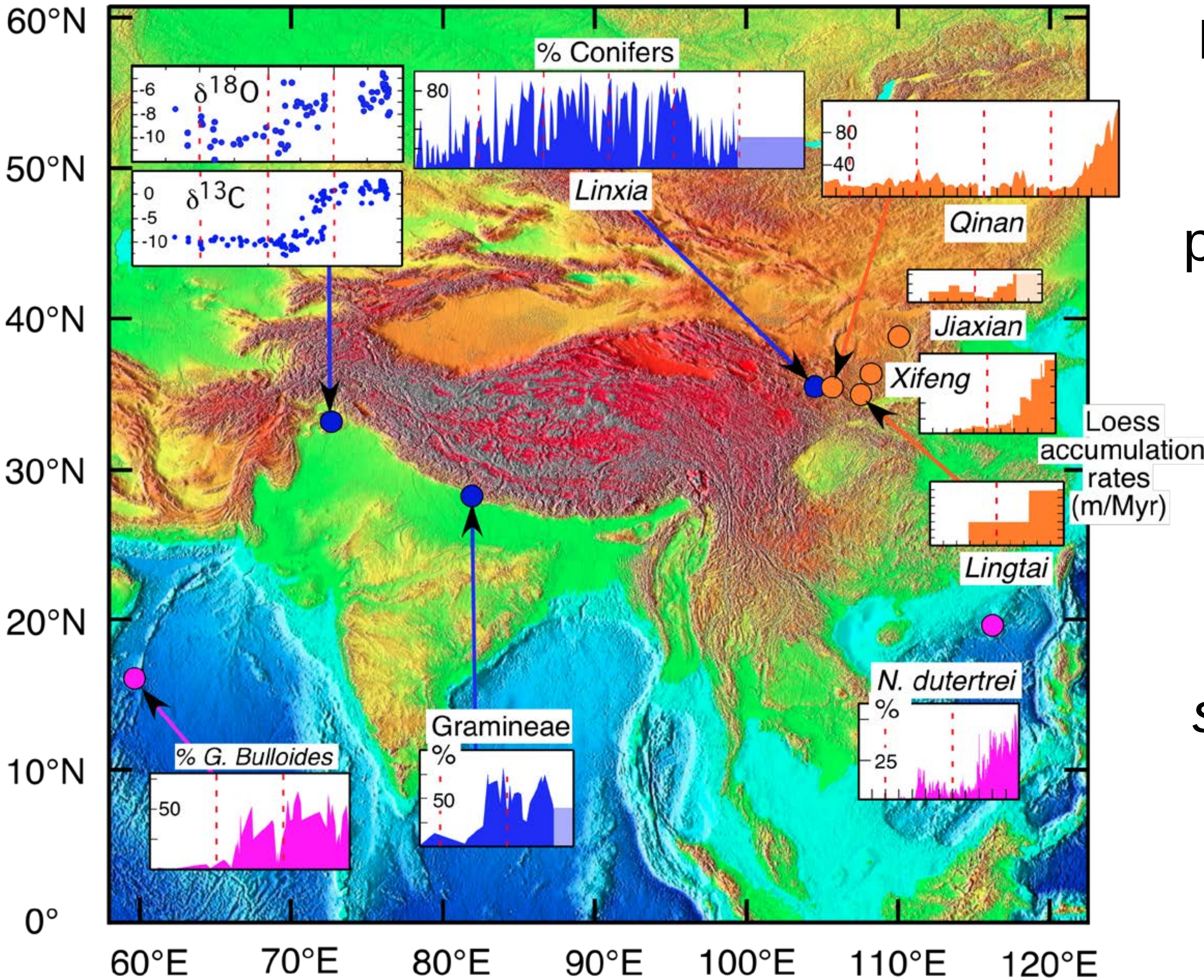
Does heating over Tibet matter for the monsoon?

$$h = C_p T + L_v q + gz$$

A test:

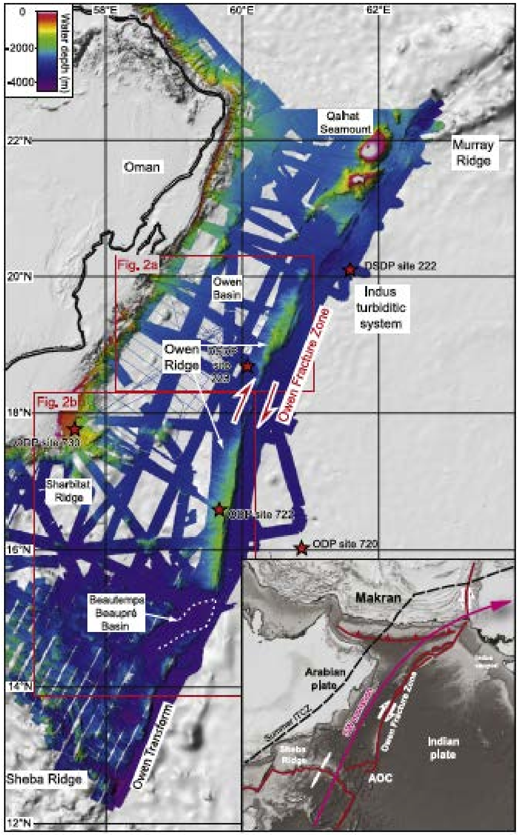
correlate most static energy over Tibet
with monsoon rainfall over India:

Mild success, only in early and late seasons.
Maybe Tibet ought not be ignored,
but it does not seem to be very important.



Million-year time series of paleoclimate *suggest some climate change(s) since ~10 Ma surrounding Tibet.*

Compiled by *Molnar, Boos, and Battisti* [2010]



Earth and Planetary Science Letters 394 (2014) 1–12

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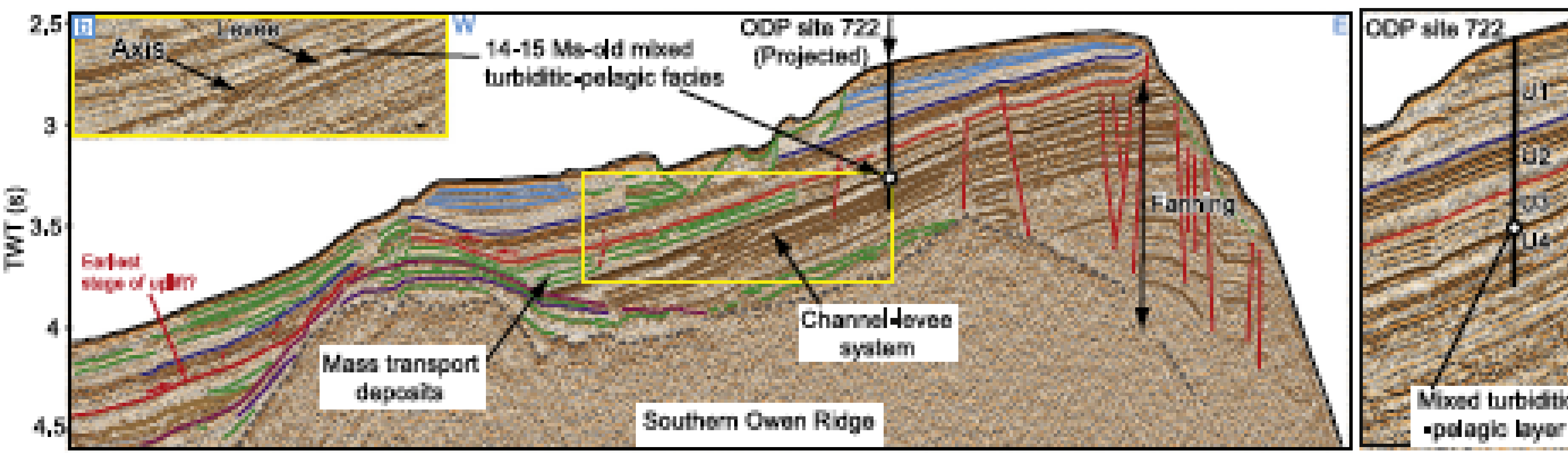
www.elsevier.com/locate/epsl

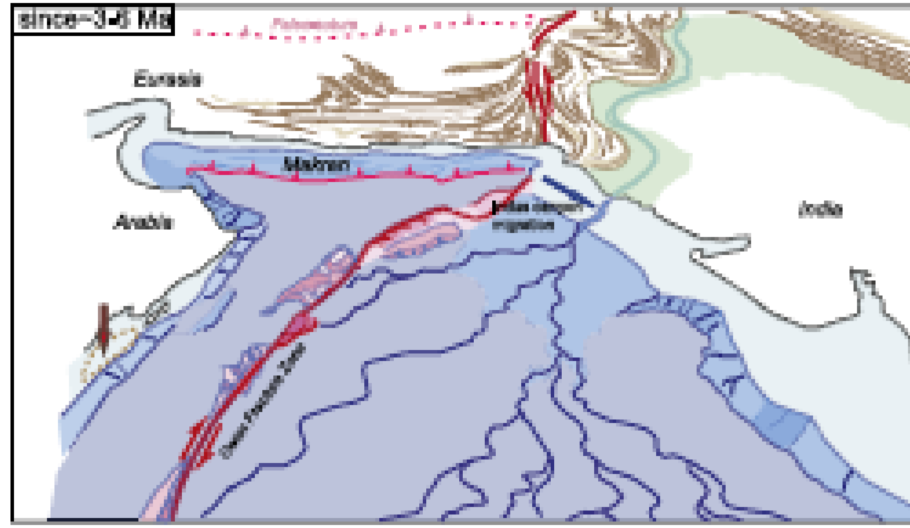
The Owen Ridge uplift in the Arabian Sea: Implications for the sedimentary record of Indian monsoon in Late Miocene

Mathieu Rodriguez [a,*], Nicolas Chamot-Rooke [a], Philippe Huchon [b,c], Marc Fournier [b,c], Matthias Delescluse [a]

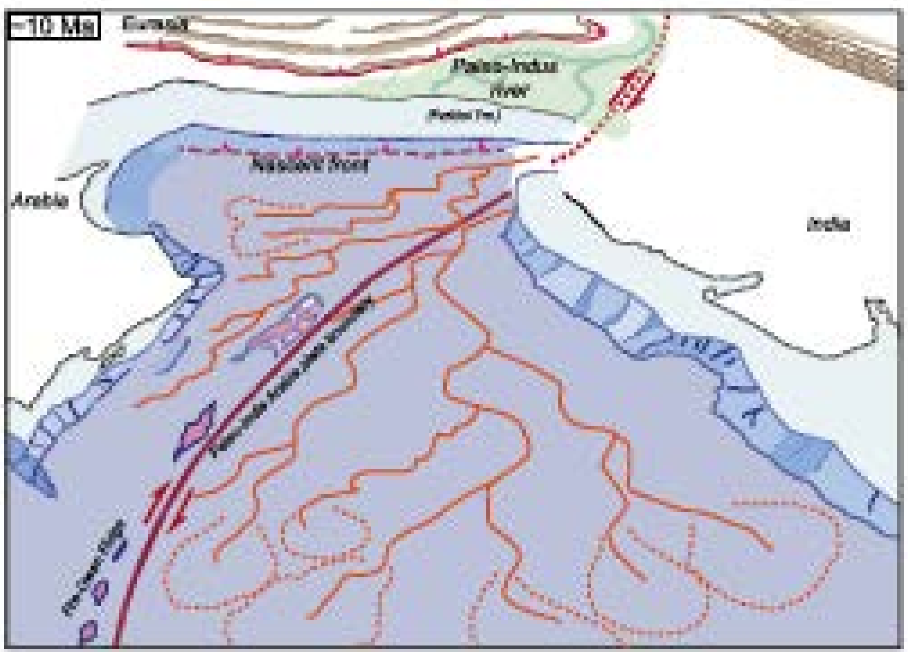


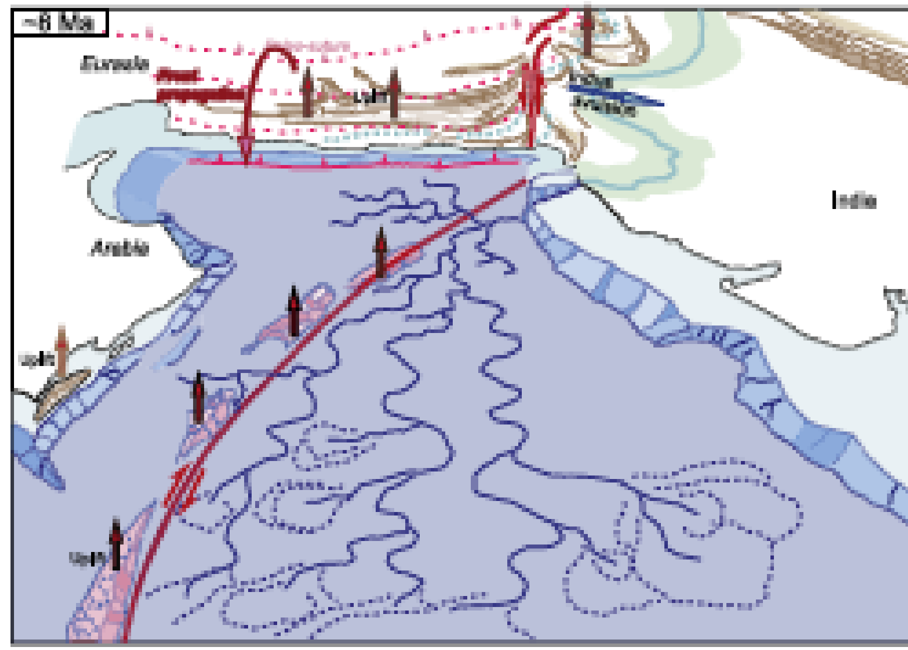
Owen Ridge formed as a topographic high at ~ 8-9 Ma

6-3 Ma: Owen Ridge is fully formed



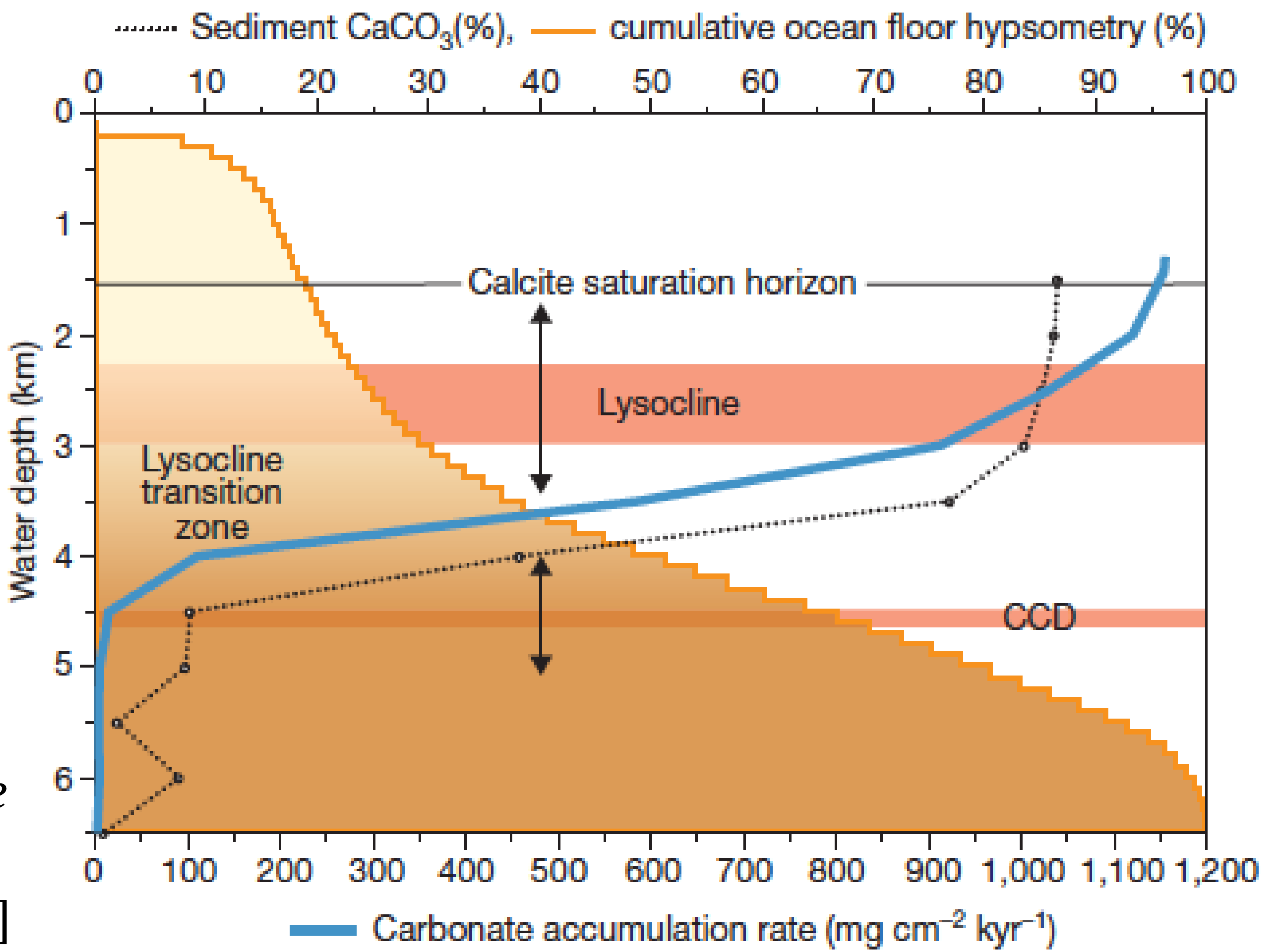
10 Ma: zilch





8 Ma: Owen Ridge emerges

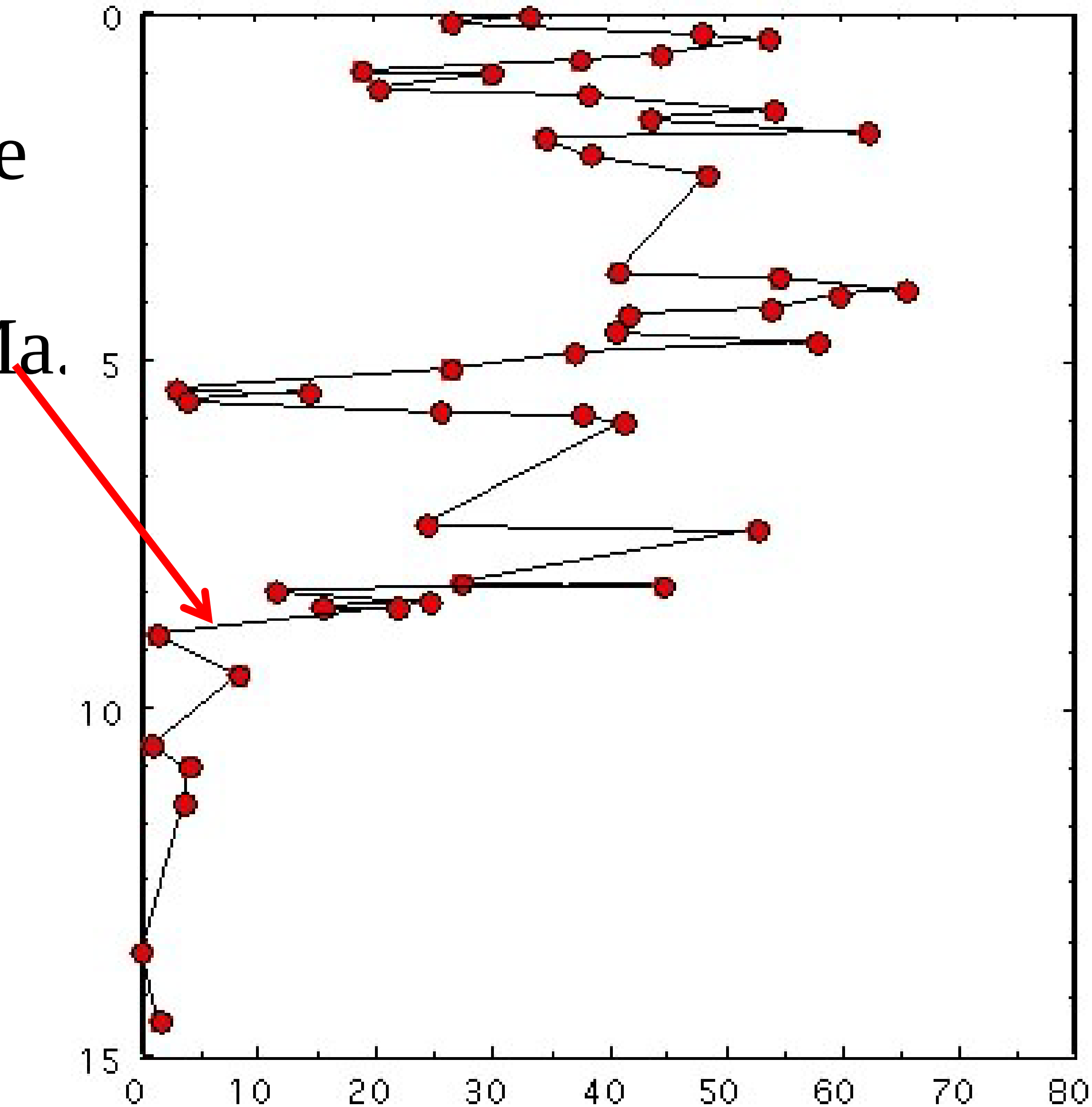
Carbonate Compensation Depth (CCD)



Pälike et al. [2012]

G. bulloides at 9 Ma and the Indian monsoon?

1. Big increase in the percentage of *G. bulloides* at 8-9 Ma.



G. bulloides at 9 Ma and the Indian monsoon?

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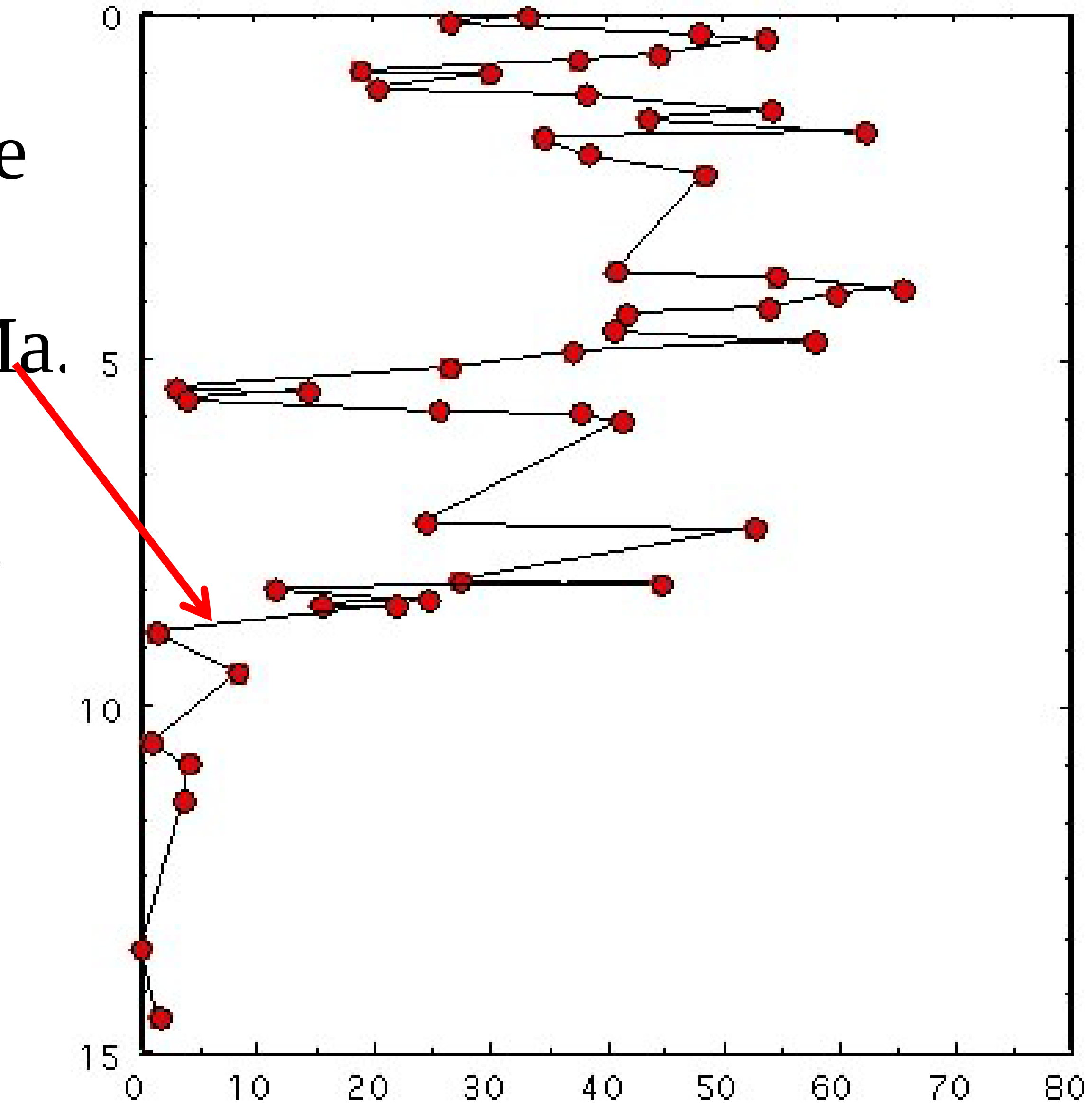
2. Owen Ridge rose above the CCD at 8-9 Ma.



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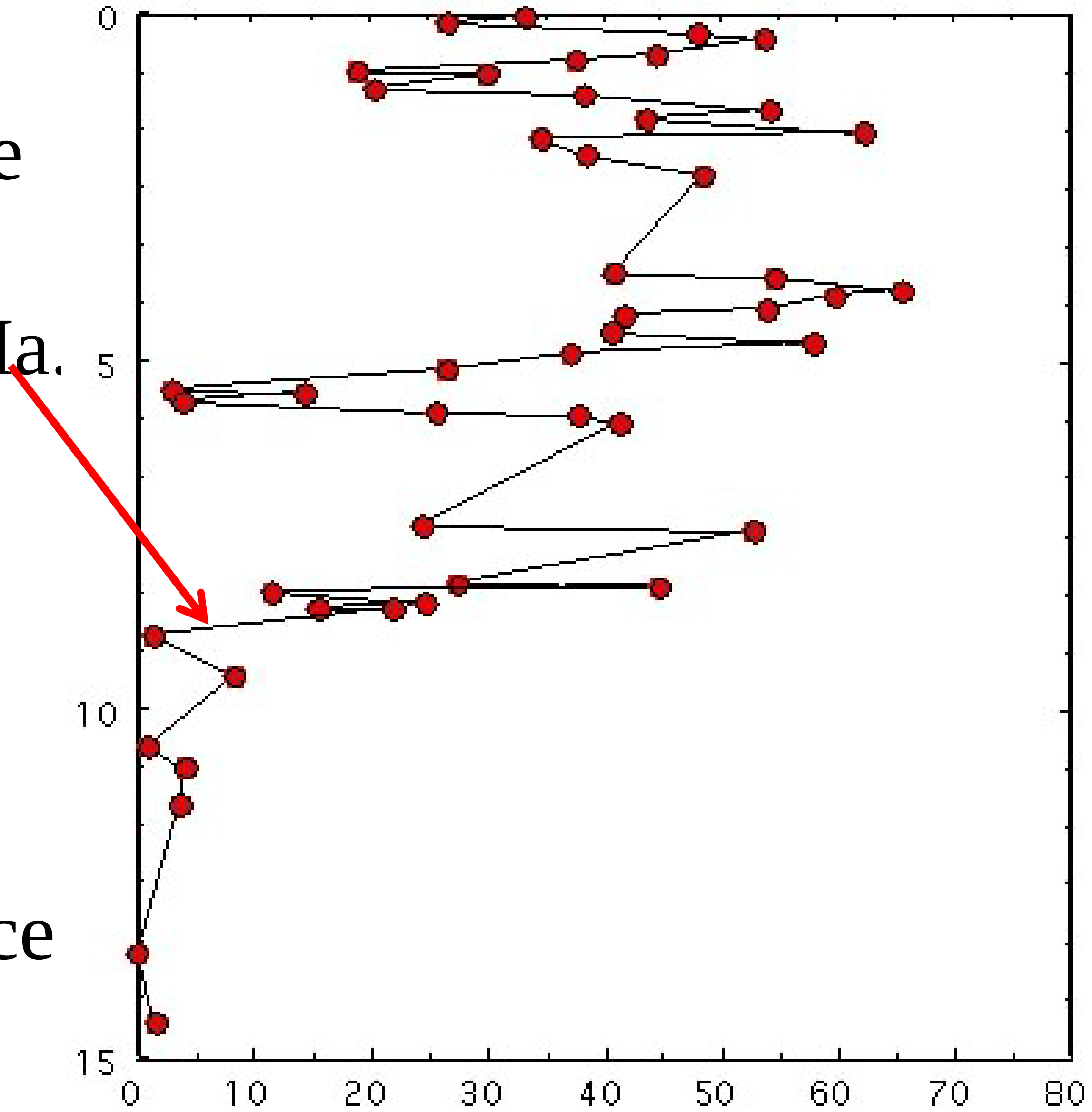

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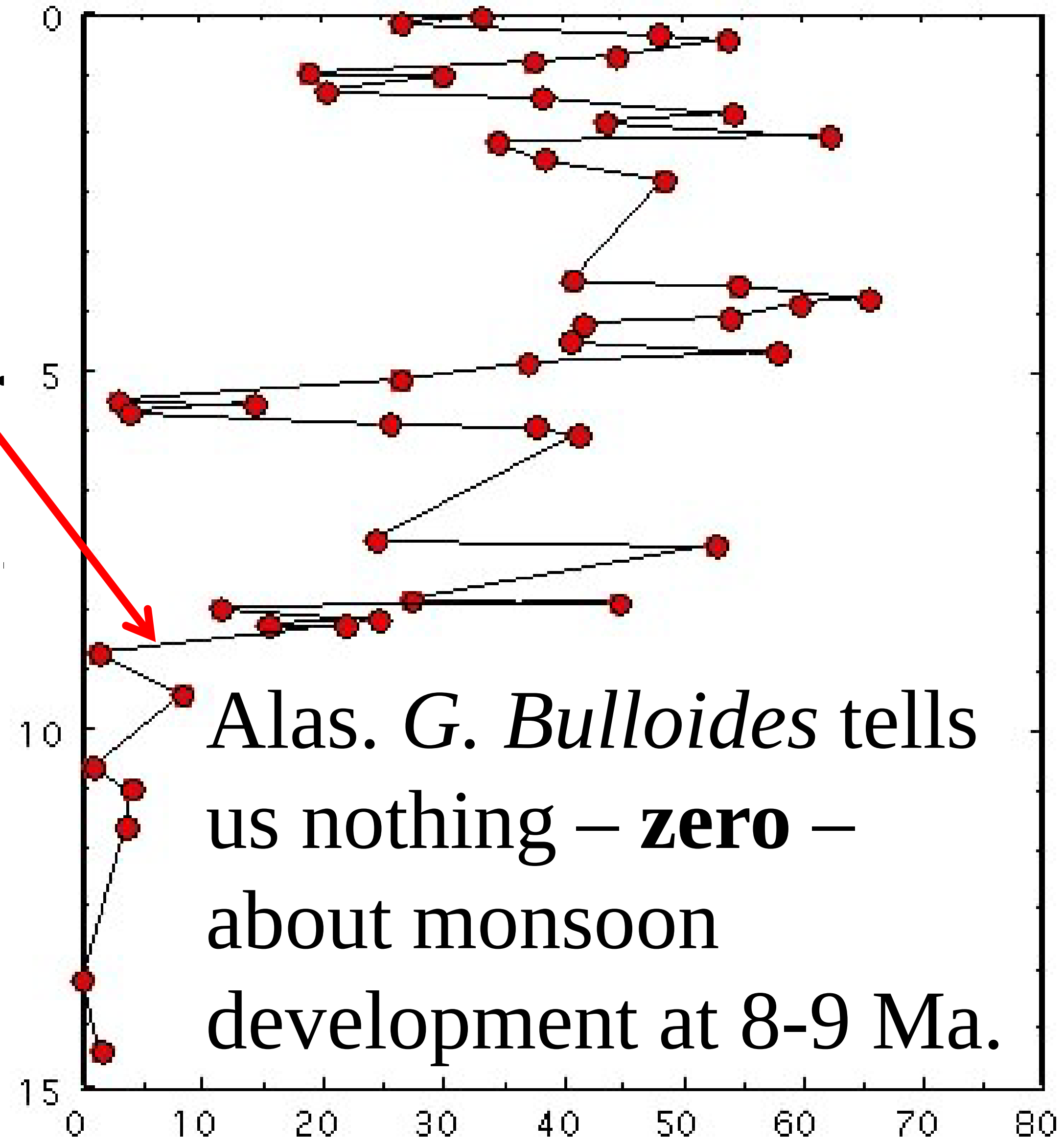
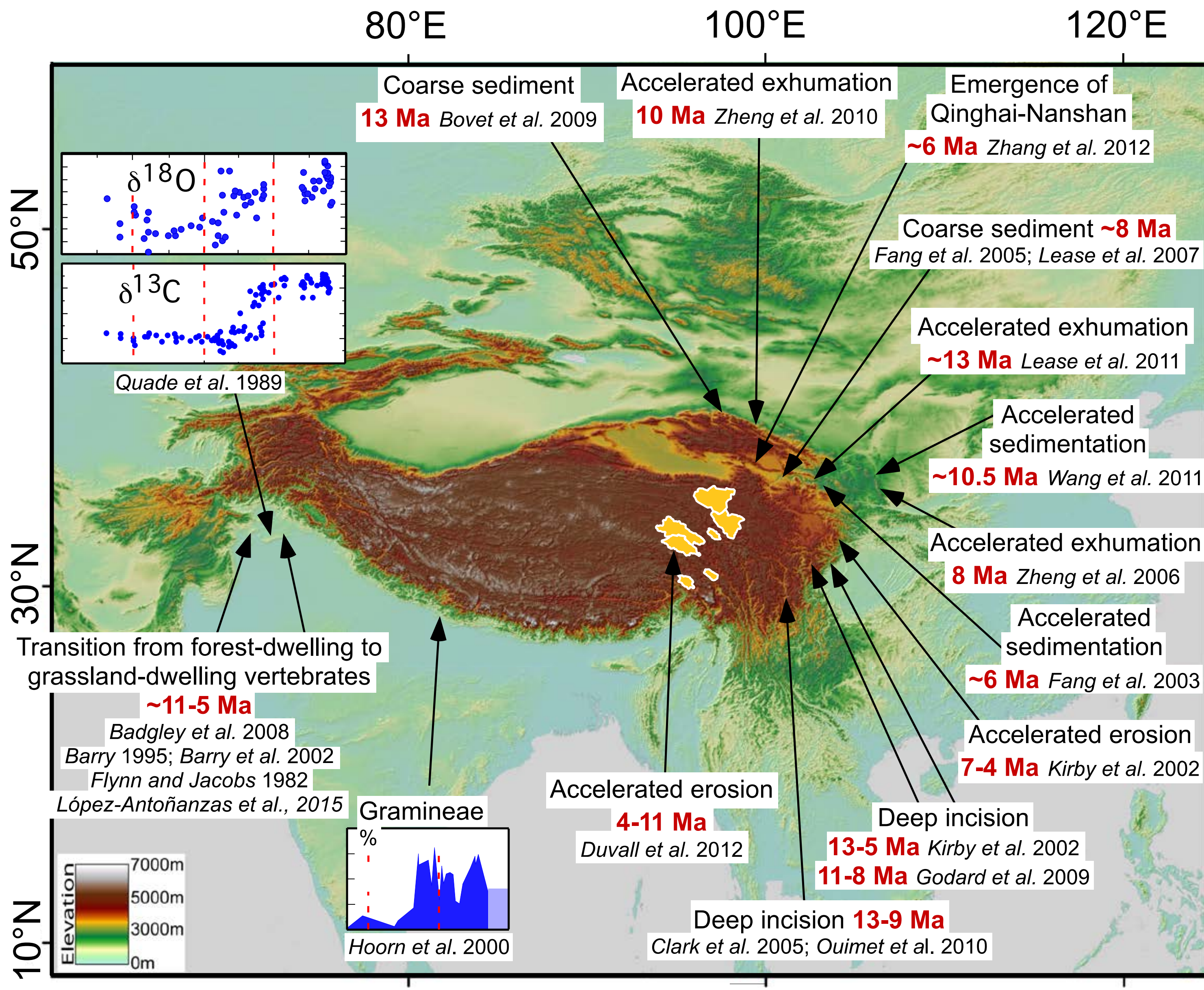
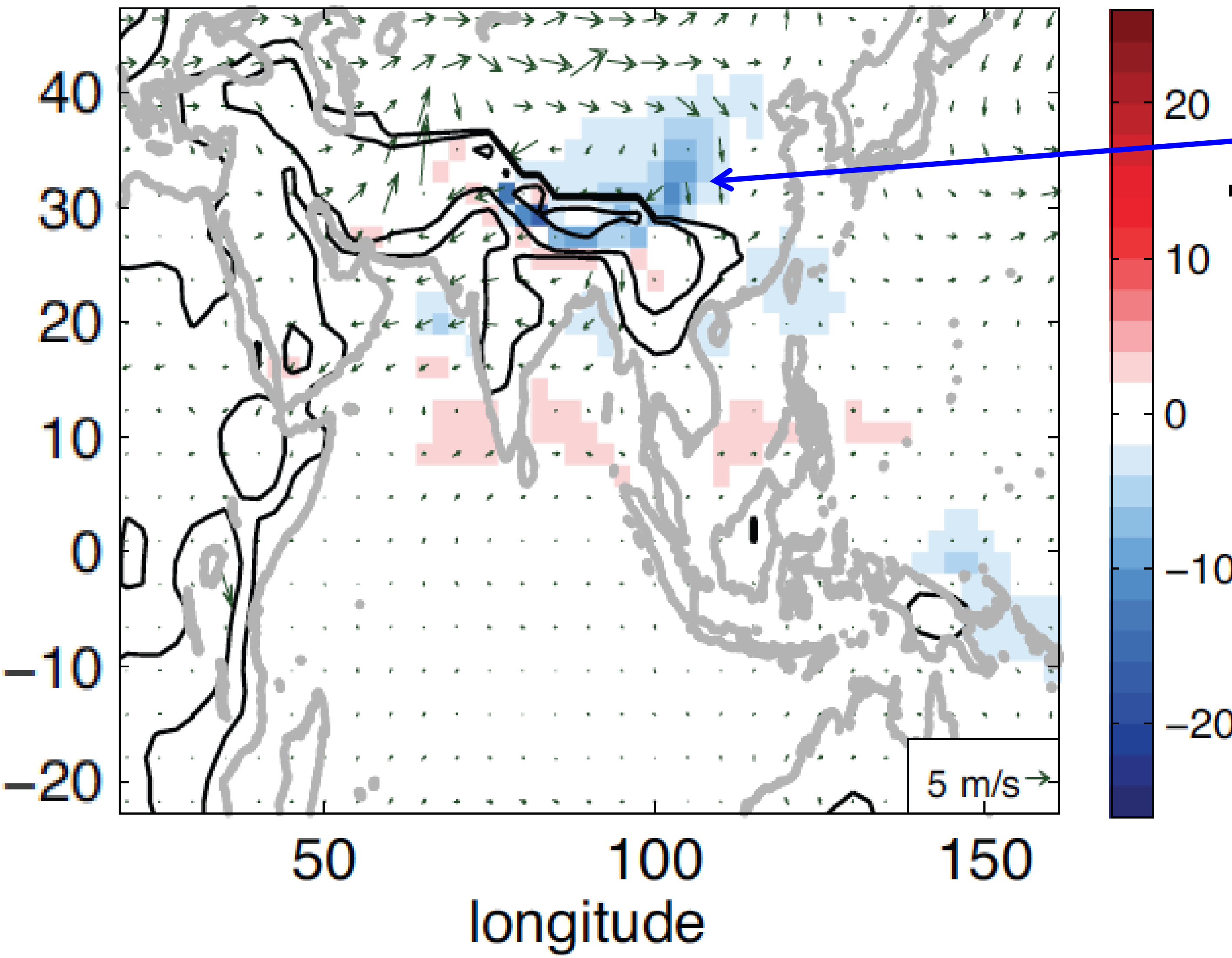


Alas. *G. Bulloides* tells us nothing – **zero** – about monsoon development at 8-9 Ma.

Upward and outward growth of Tibet since 15-10 Ma and aridification of NW India since ~10 Ma



Simulated rainfall difference (mm/day)
Himalaya minus Himalaya + Tibet



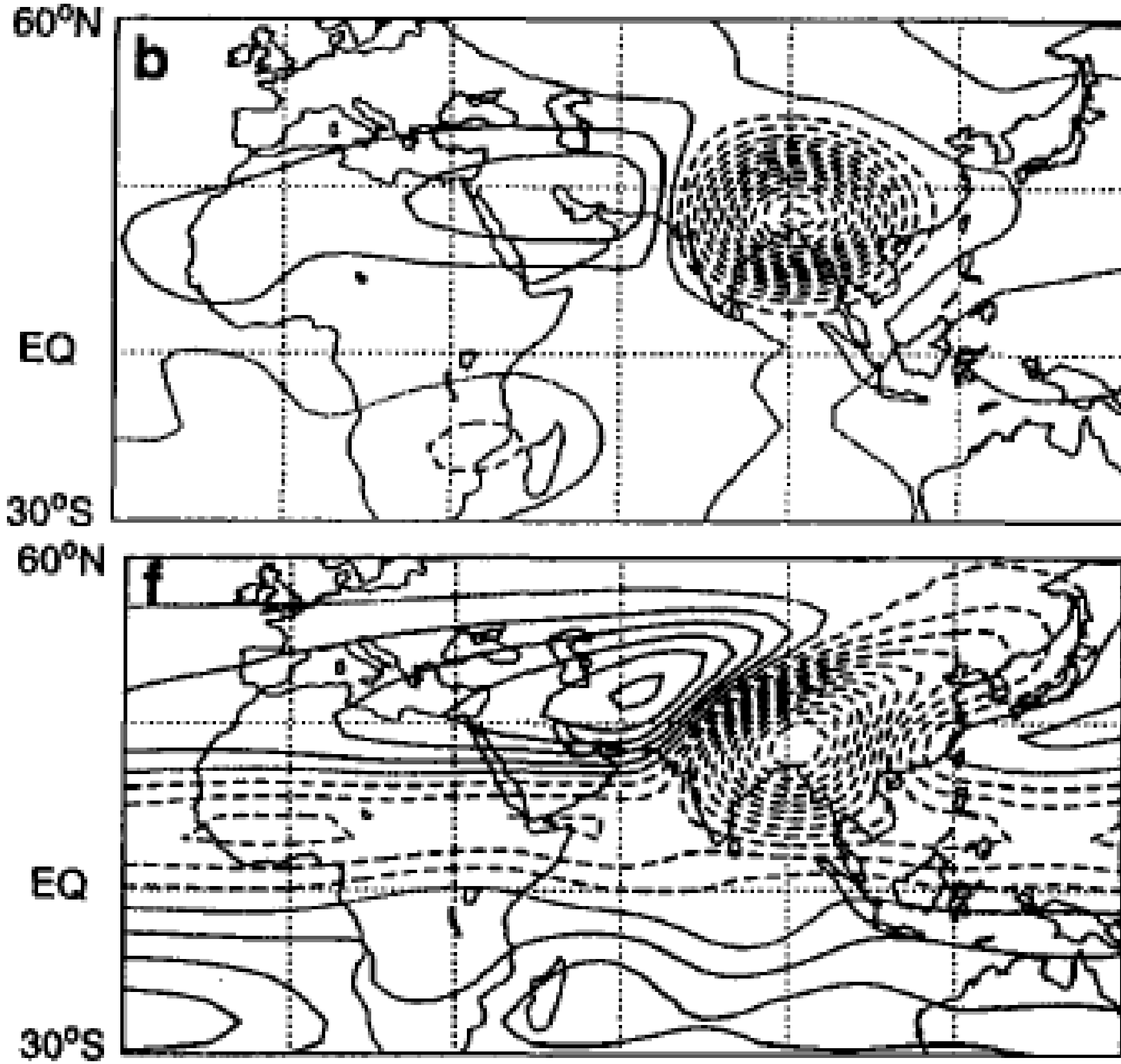
It rains in eastern Tibet, when eastern Tibet is high.

[*Boos and Kuang*, 2010, Online Supplementary Material]

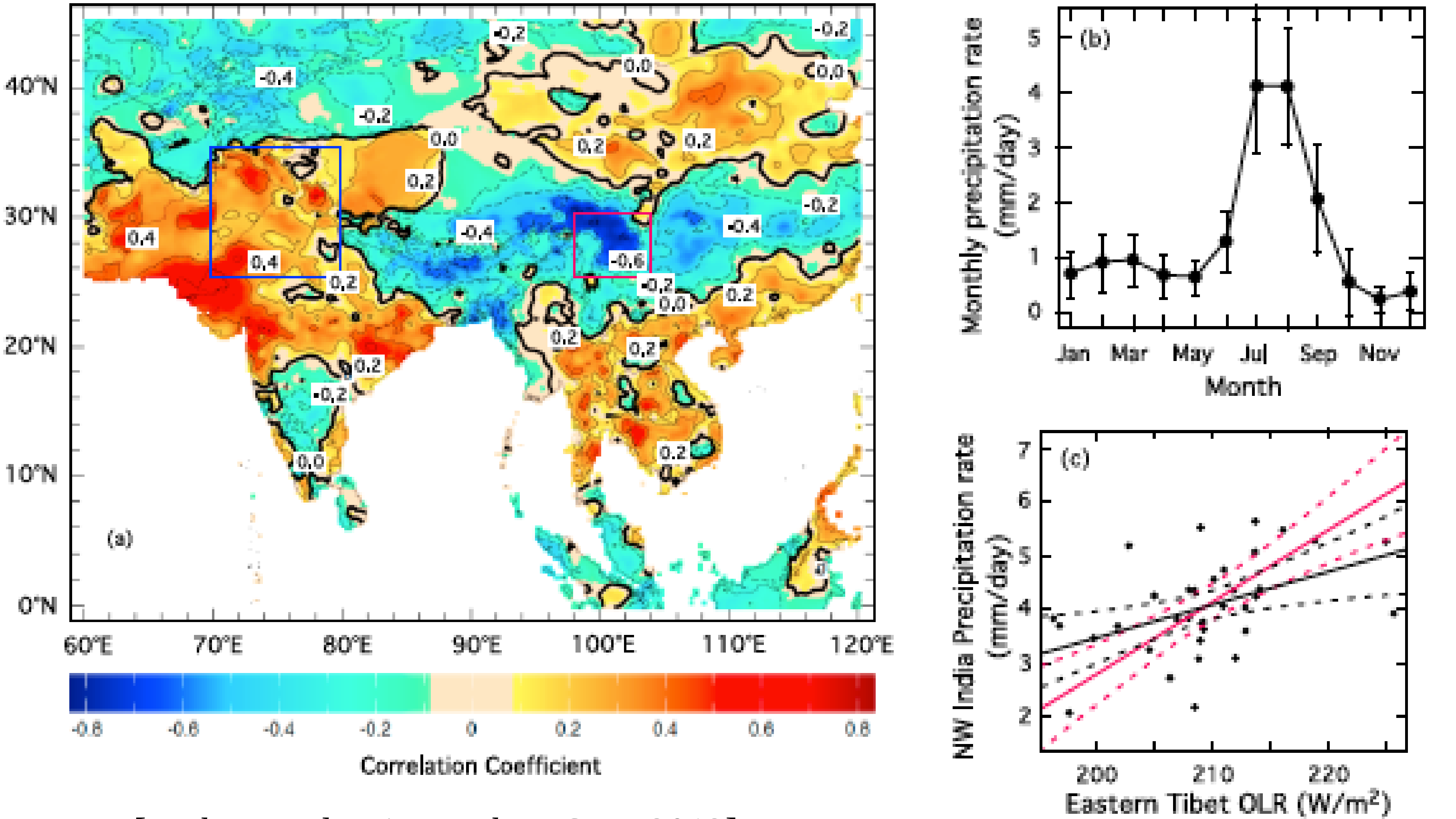
Effect of a heat source over the Bay of Bengal

Contours of vertical component of velocity on 477 mbar surface (mid-troposphere)

[*Rodwell and Hoskins*, 1996]



Correlation of July-August rainfall [*Xie et al*. 2007] over eastern Asia with July-August Outgoing Longwave Radiation (OLR) over Eastern Tibet (red box)



[*Molnar and Rajagopalan, GRL*, 2012]

Connection between eastern Tibet and NW India (and Pakistan)

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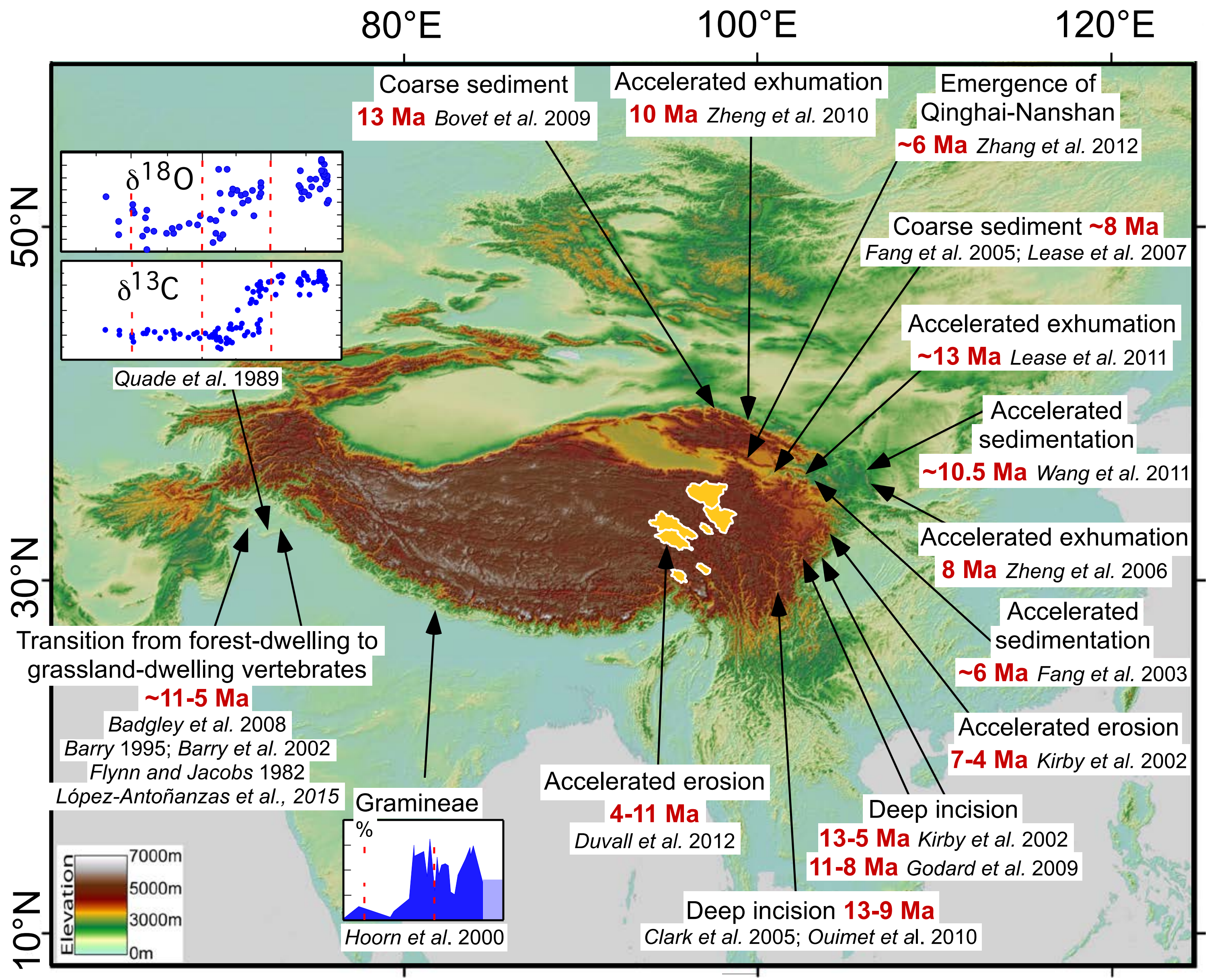
Connection between eastern Tibet and NW India (and Pakistan)

1. Eastern Tibet grew upward and outward since ~10 Ma.
2. Increased elevations enhanced condensation and orographic precipitation.
3. Latent heating over eastern Tibet sent Rossby waves westward and induced descent over NW India.
4. Descent of dry air suppressed precipitation, and led to aridification of NW India.

Upward and outward growth of Tibet since 15-10 Ma and aridification of NW India since ~10 Ma

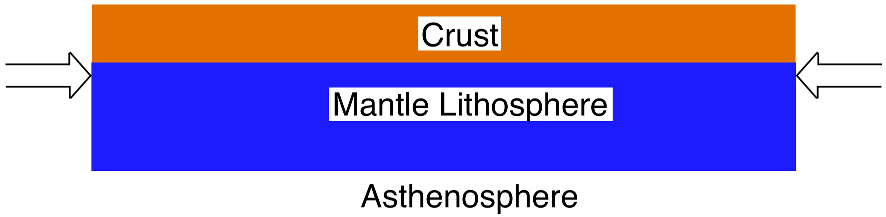


How might the growth of Tibet affect Asian paleoclimate?

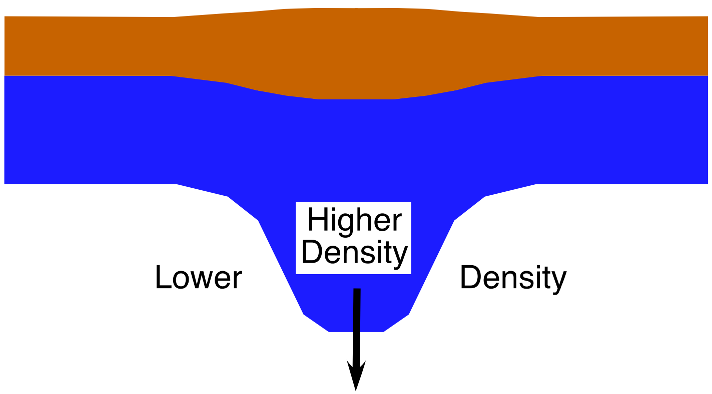
1. **Monsoon rainfall, in general, over India?** ***Weakly*, only in early and late seasons.**
2. **Loess plateau – dust?** ***Maybe, but only via a geodynamic teleconnection.***
3. **Rainfall (aridification) over NW India? Maybe, and if so, *via a Rodwell-Hoskins (Gill-Model) teleconnection*. But, this means the monsoon (*sensu lato*) became WEAKER, not stronger, at ~10 Ma.**

Shortening and Thickening of lithosphere (crust and mantle)

Initial State: Horizontal shortening



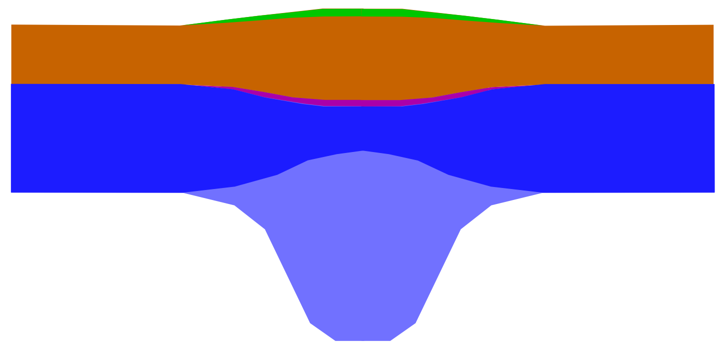
Crustal Thickening and Mountain or Plateau Building



Thickening of Unstable Lithospheric Root

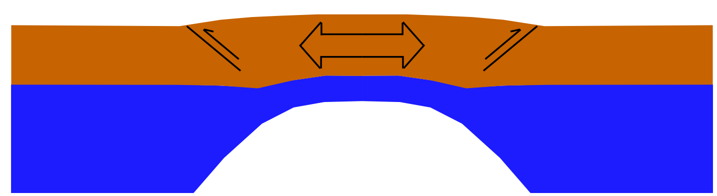
Surface rises, and available potential energy powers outward growth of the plateau and crustal extension within it

Surface Uplift, due to removal of Lithospheric Load



Removal of Lithospheric Root

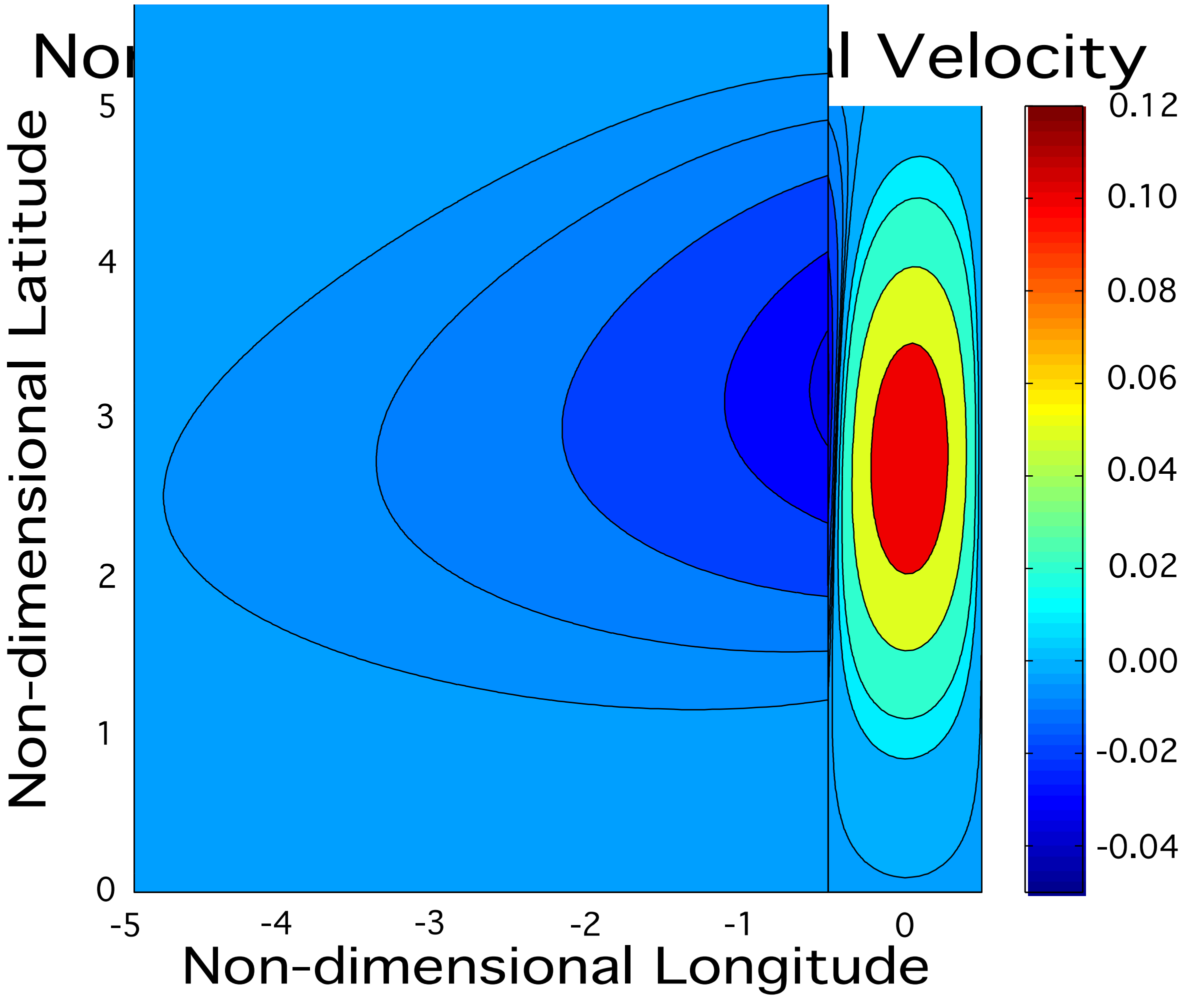
Horizontal Extension and Subsidence



Further Lithospheric Thinning, and Possibly Volcanism

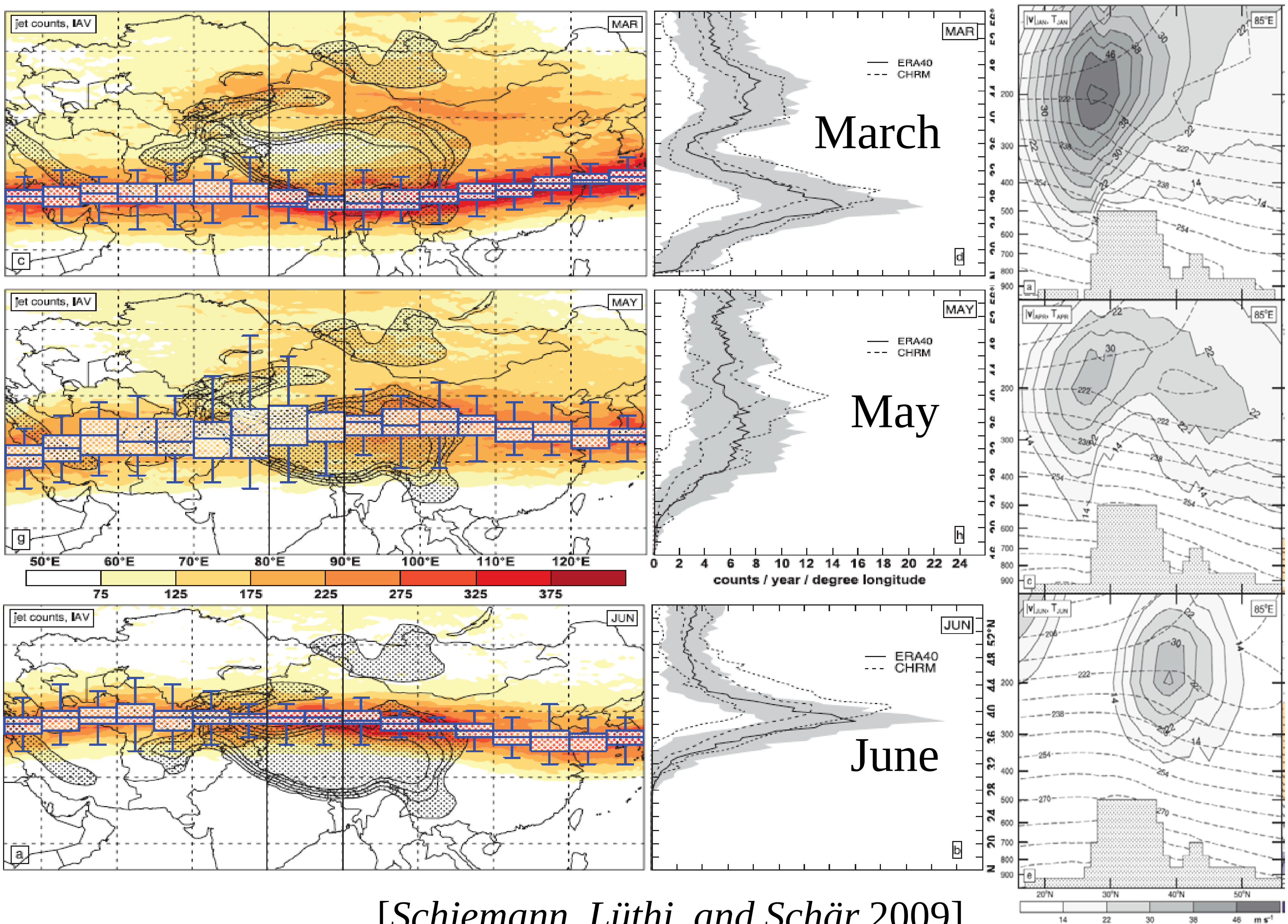
Removal of blobs of dense mantle lithosphere ("deblobbing") reduces load to base of lithosphere: available potential energy, à la *Lorenz* [1955], increases.

Gill-model calculations of the vertical component of velocity in the mid-tropospere, forced by a heat source displaced (by ~30°) from the equator [*Gill*, 1980]



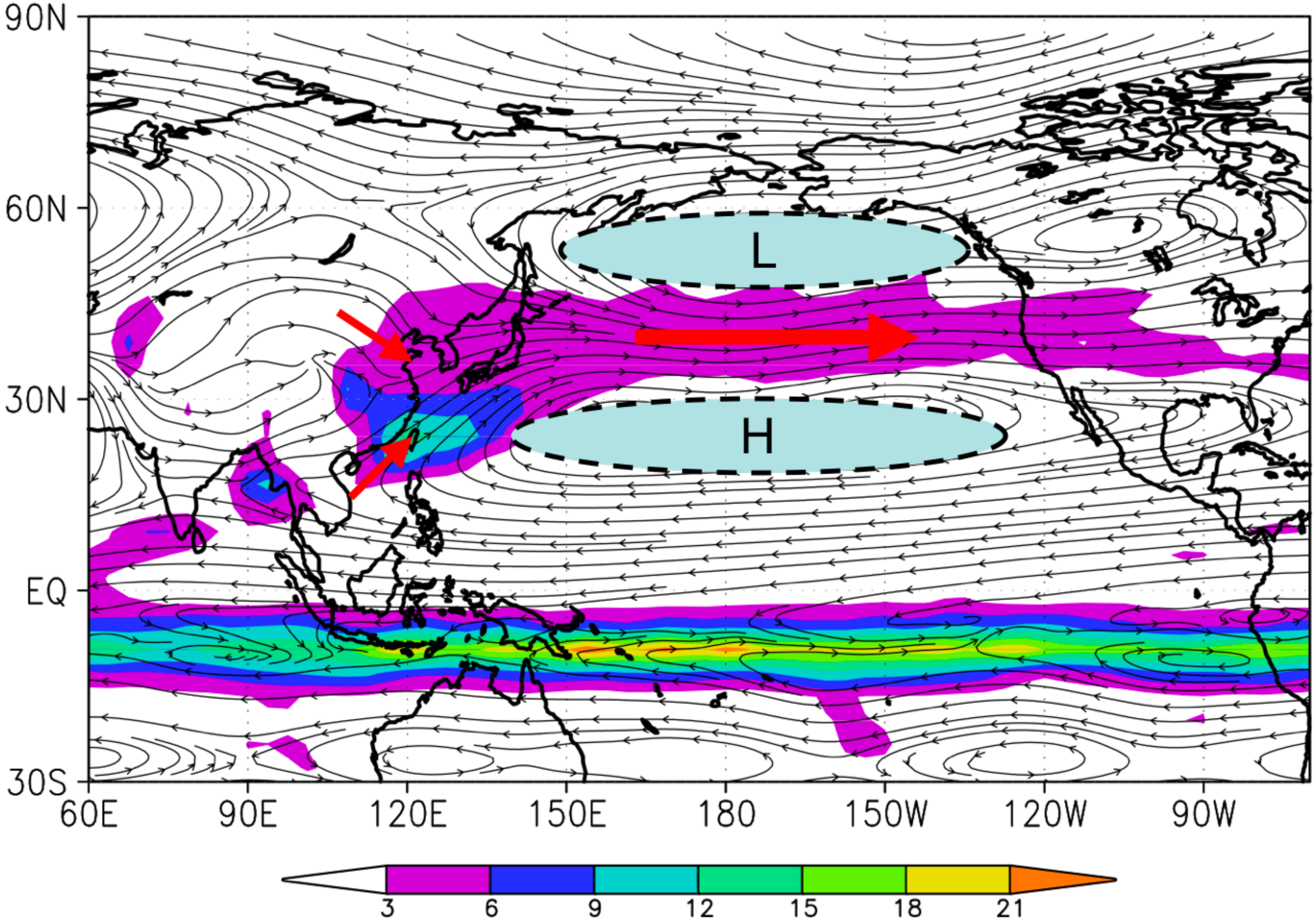
[*Molnar and Rajagopalan, GRL*, 2012]

Jet speed and position



[*Schiemann, Lüthi, and Schär* 2009]

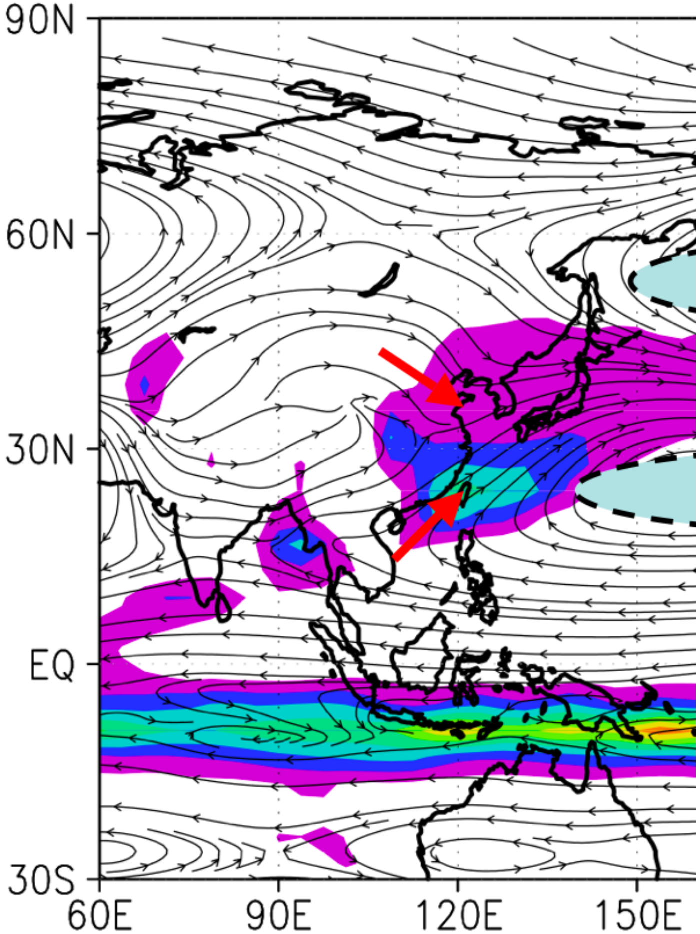
Winds and Precipitation (mm/day) and streamlines at 850 mb in an Aquaplanet GCM (with an ocean surface at ~5000 m over Tibet)

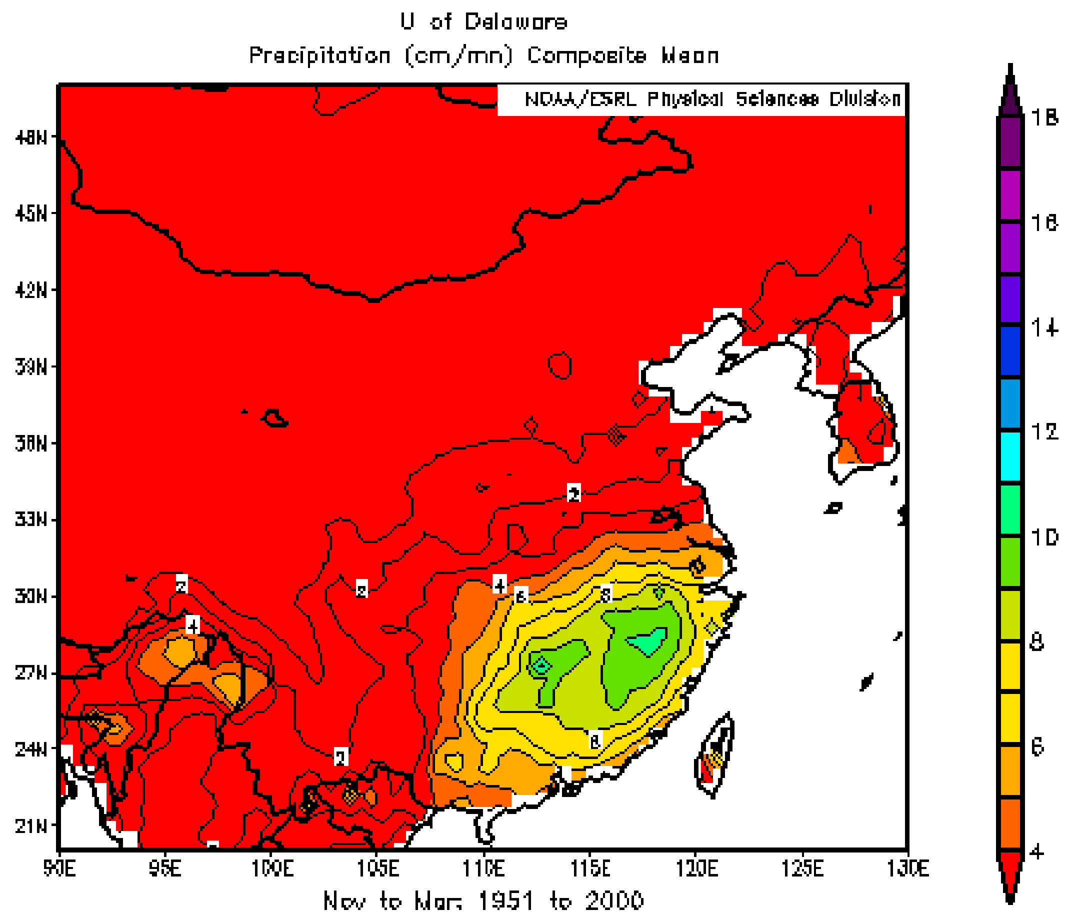


[*Takahashi and Battisti* 2007] (but still in preparation)

Reproduced by *Molnar, Boos, and Battisti* [2010]

Aquaplanet GCM and observed Precipitation (mm/day) over China

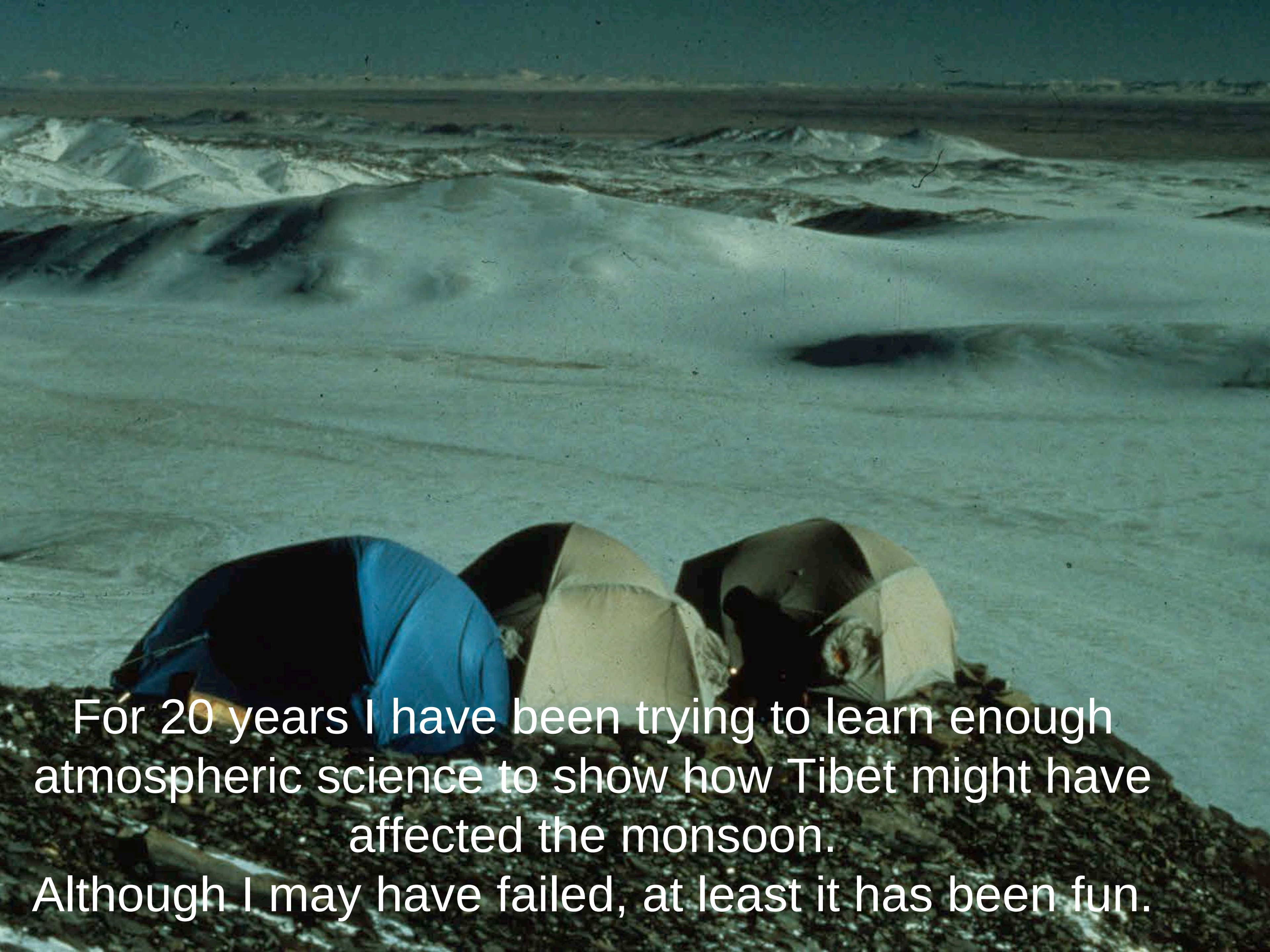


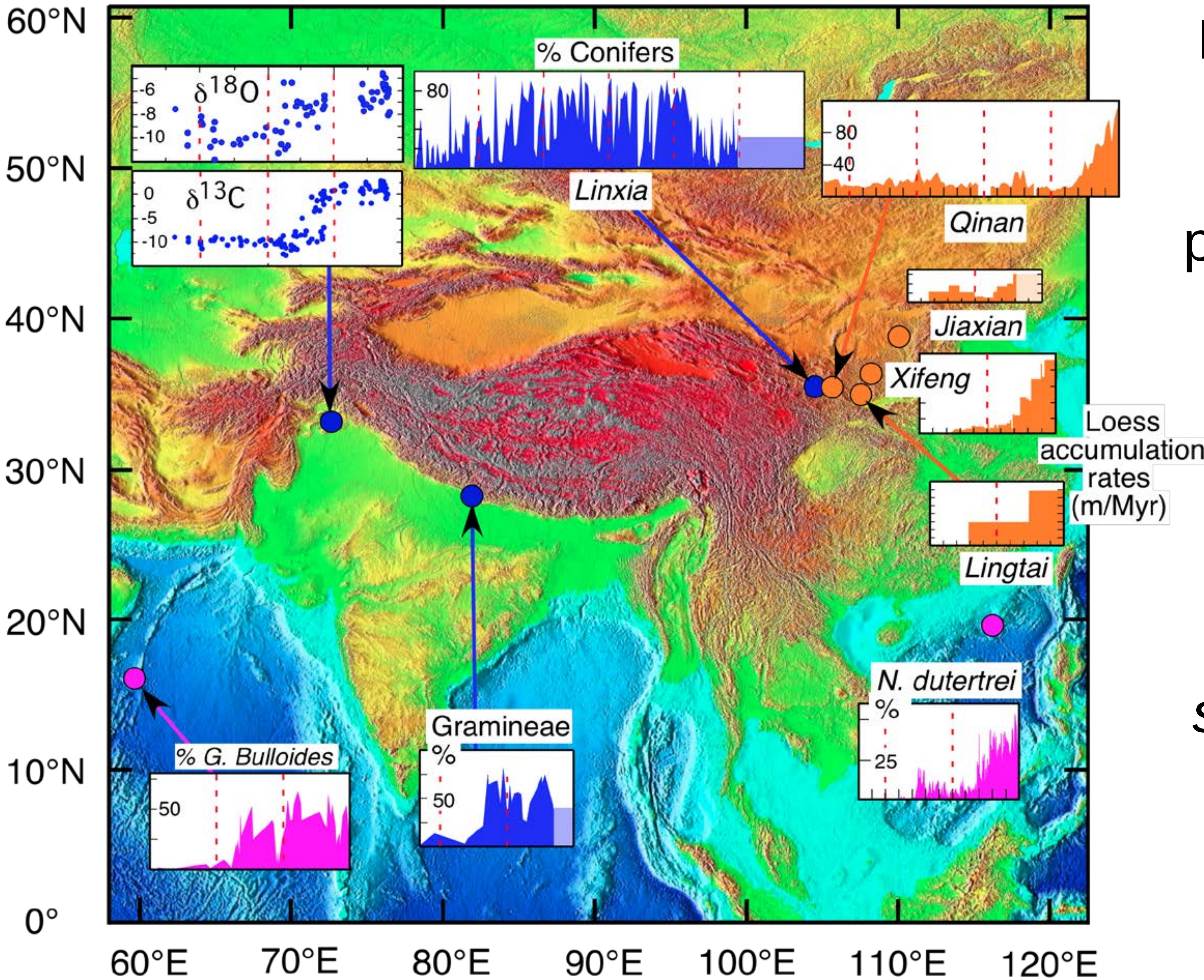


[*Takahashi and Battisti* 2007] (but still in preparation)

How might Tibet, and its growth, affect climate and paleoclimate?

1. Loess plateau – dust? *Maybe, but* ***only*** *via a* ***geodynamic teleconnection****.*
2. Rainfall over South China and winds over the South China Sea? ***Mechanically, by deflecting the jet.***
3. Monsoon rainfall over India and winds over the Arabian Sea? **Weakly, only in early and late seasons.**
4. Aridification over NW India? ***Maybe, via a Gill-model teleconnection***, but this means the monsoon (*sensu lato*) became weaker, not stronger, at ~10 Ma.

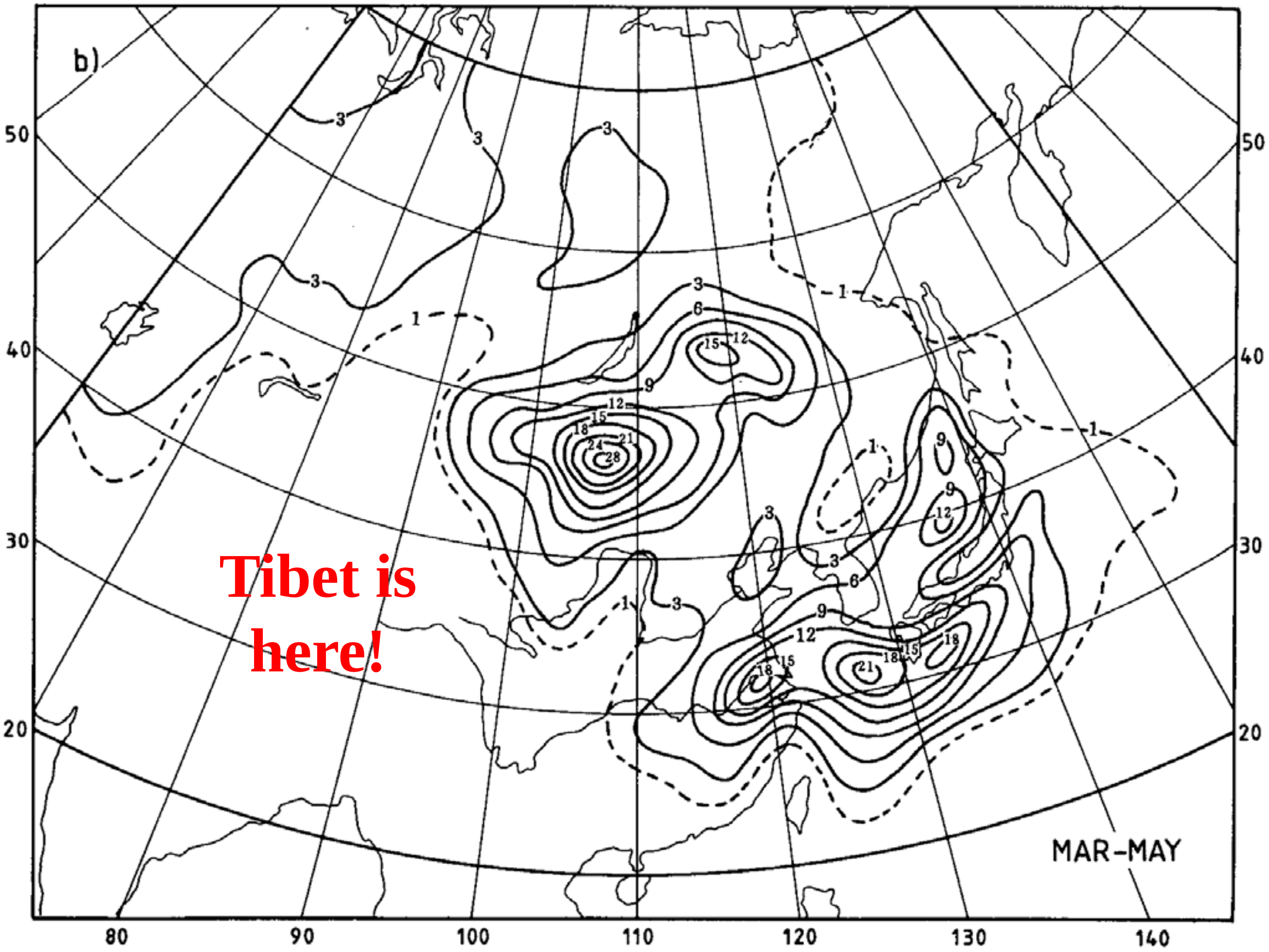

For 20 years I have been trying to learn enough atmospheric science to show how Tibet might have affected the monsoon.
Although I may have failed, at least it has been fun.



Million-year time series of paleoclimate *suggest some climate change(s) since ~10 Ma surrounding Tibet.*

Compiled by *Molnar, Boos, and Battisti* [2010]

Sources of springtime (March-May) storms:
Note concentration over Mongolia (not Tibet)



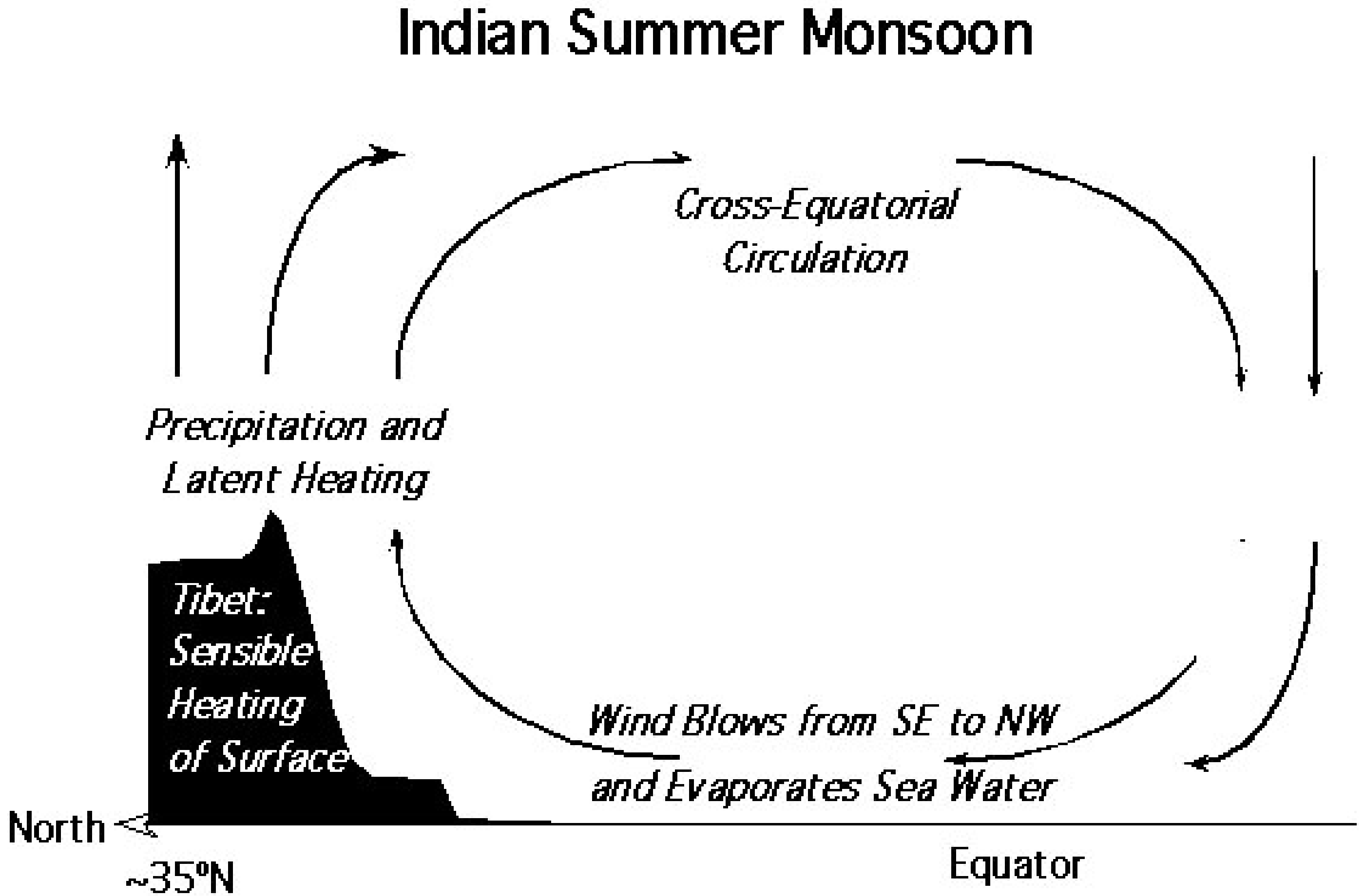
Number (÷ 100) of cyclogenic events, per 2.5° box, for 1958-1987

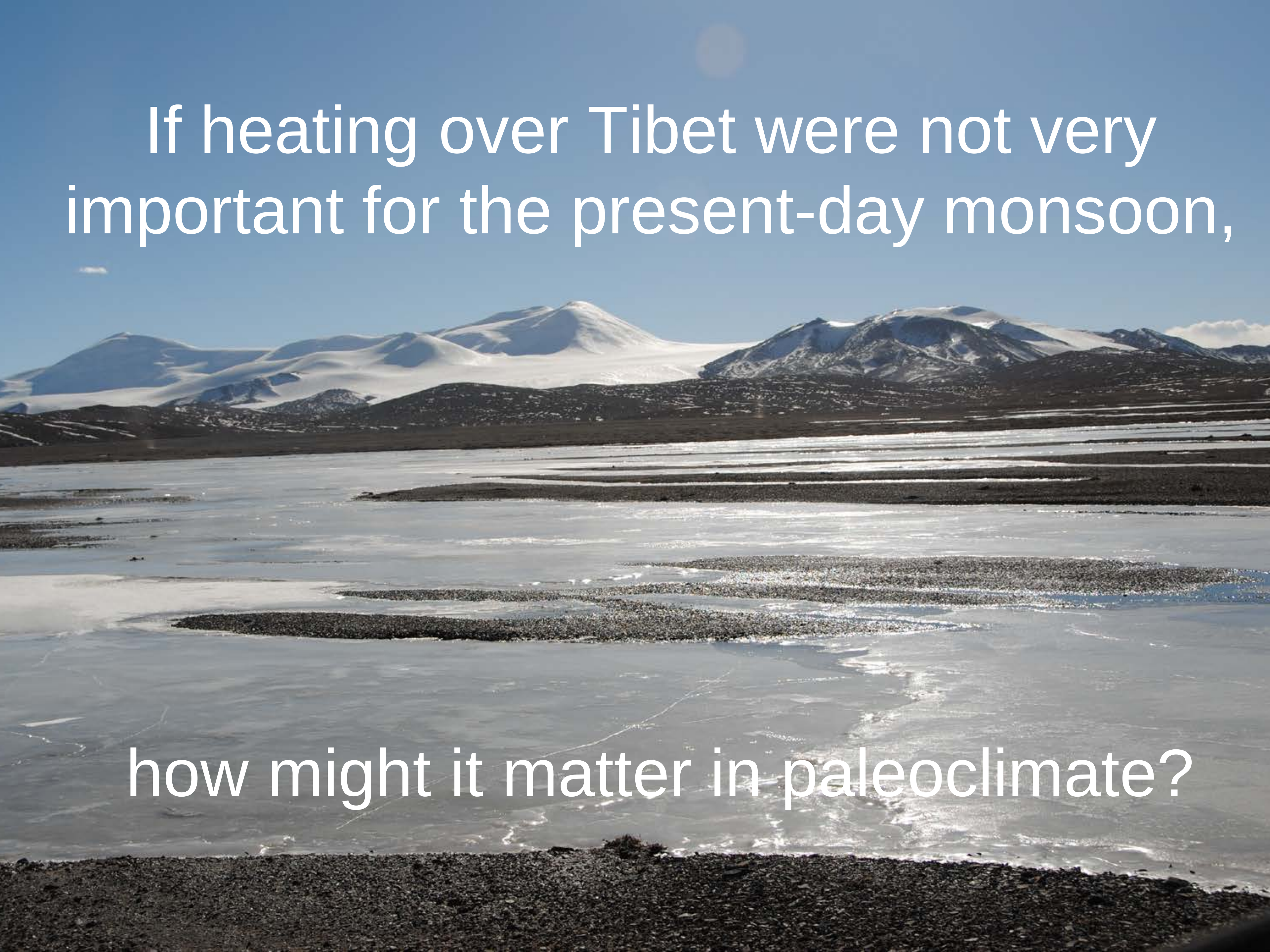
[*Chen*, *Kuo*, *Zhang*, *and Bai* 1991]

Sensible heating over India & Tibet and latent heating aloft lead to monsoonal circulation

Hot upper troposphere

Cooler (but not cold) upper troposphere




If heating over Tibet were not very important for the present-day monsoon,
how might it matter in paleoclimate?

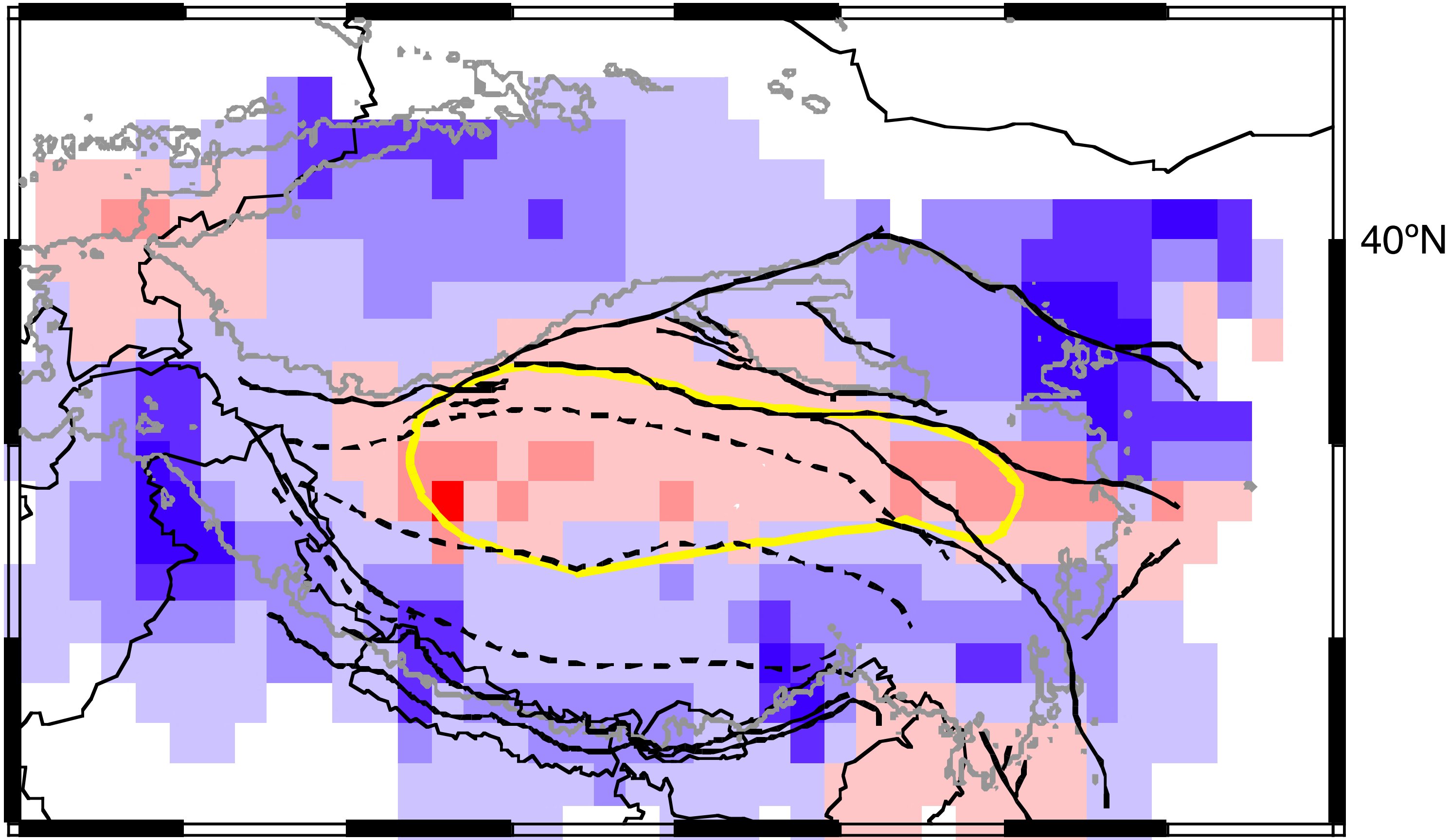
Two hypotheses

1. Removal of mantle lithosphere beneath northern Tibet, tens of millions of years after India collided with Eurasia, led to additional surface uplift and a major change in the distribution of Asian surface topography.

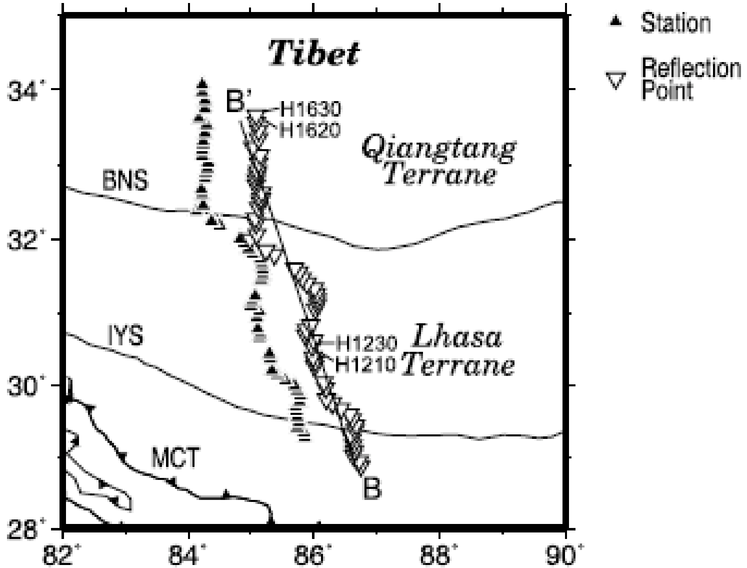
2. The growth of the Tibetan Plateau has, in particular near 10 Ma, altered East Asian climate (to some measureable extent).

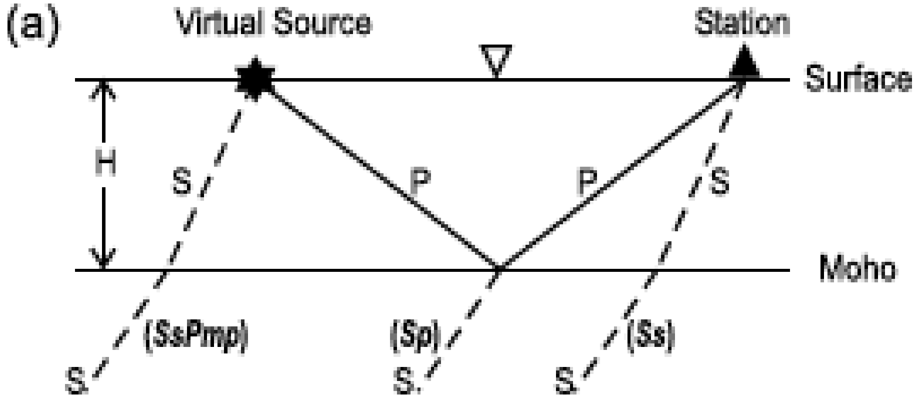
Pn speeds across Tibet and surroundings

[McNamara, Walter, Owens, and Ammon, *Journal of Geophysical Research*,1996]



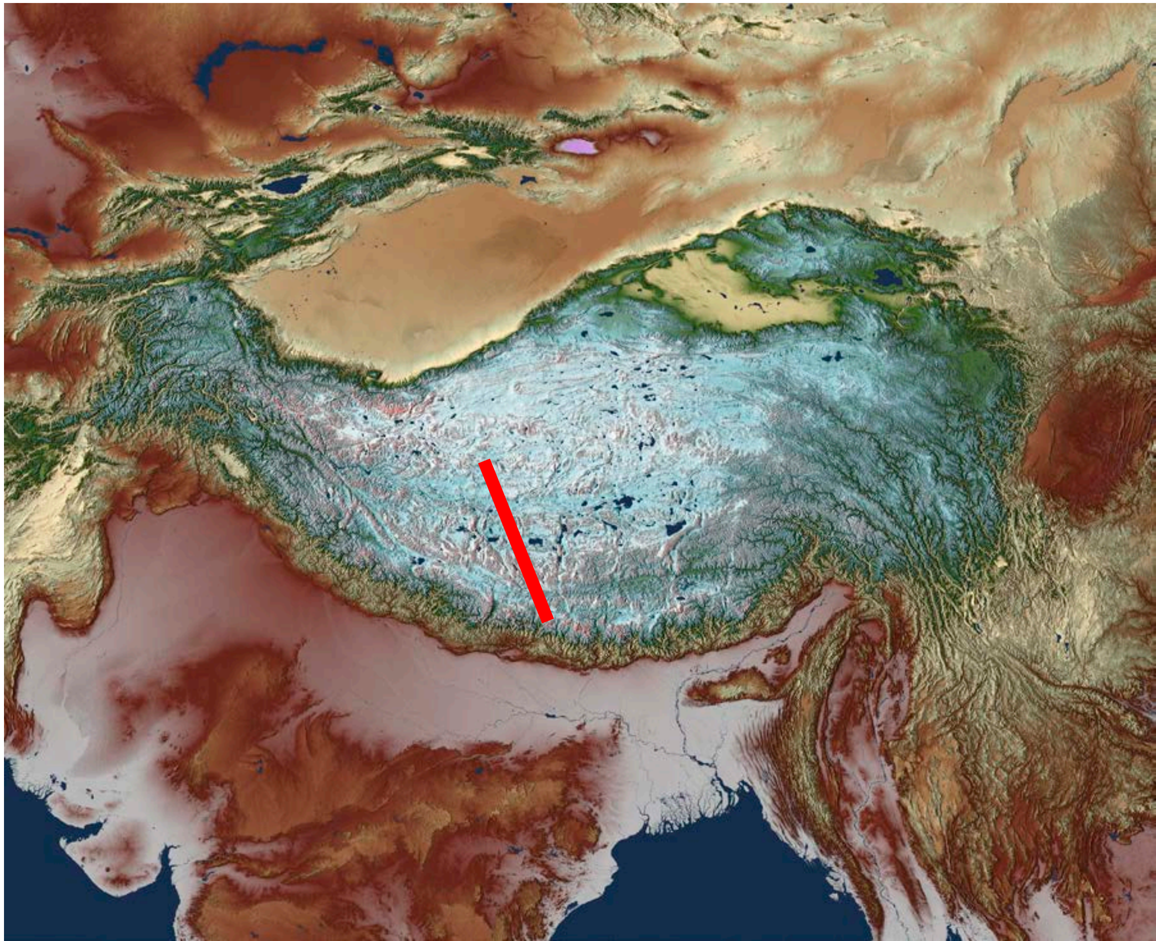
Vp > 8.1 km/s –> **Cold** *Vp* < 8.1 km/s –> **Warm**

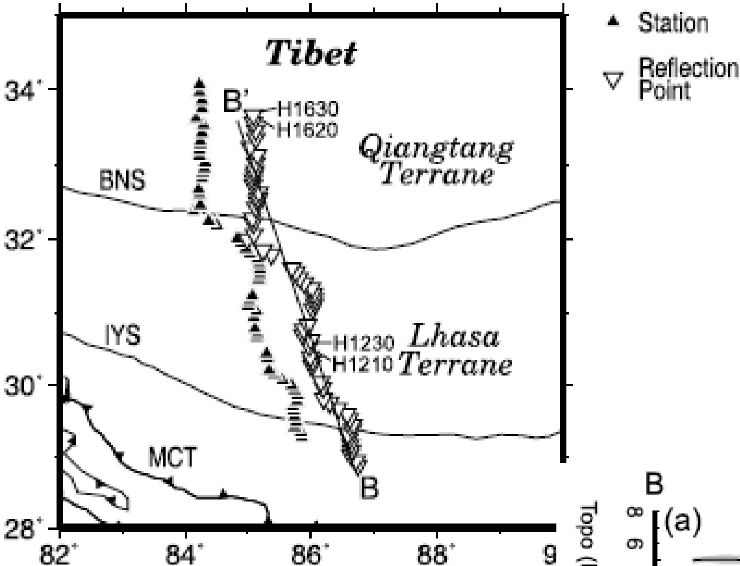


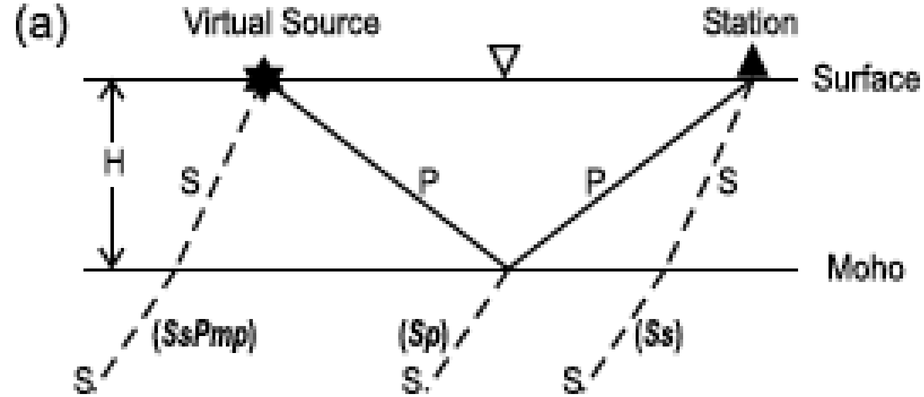


Crustal thickness across Tibet on a north-south profile

[Tseng, Chen, and Nowack, *Geophysical Research Letters*, 2009]







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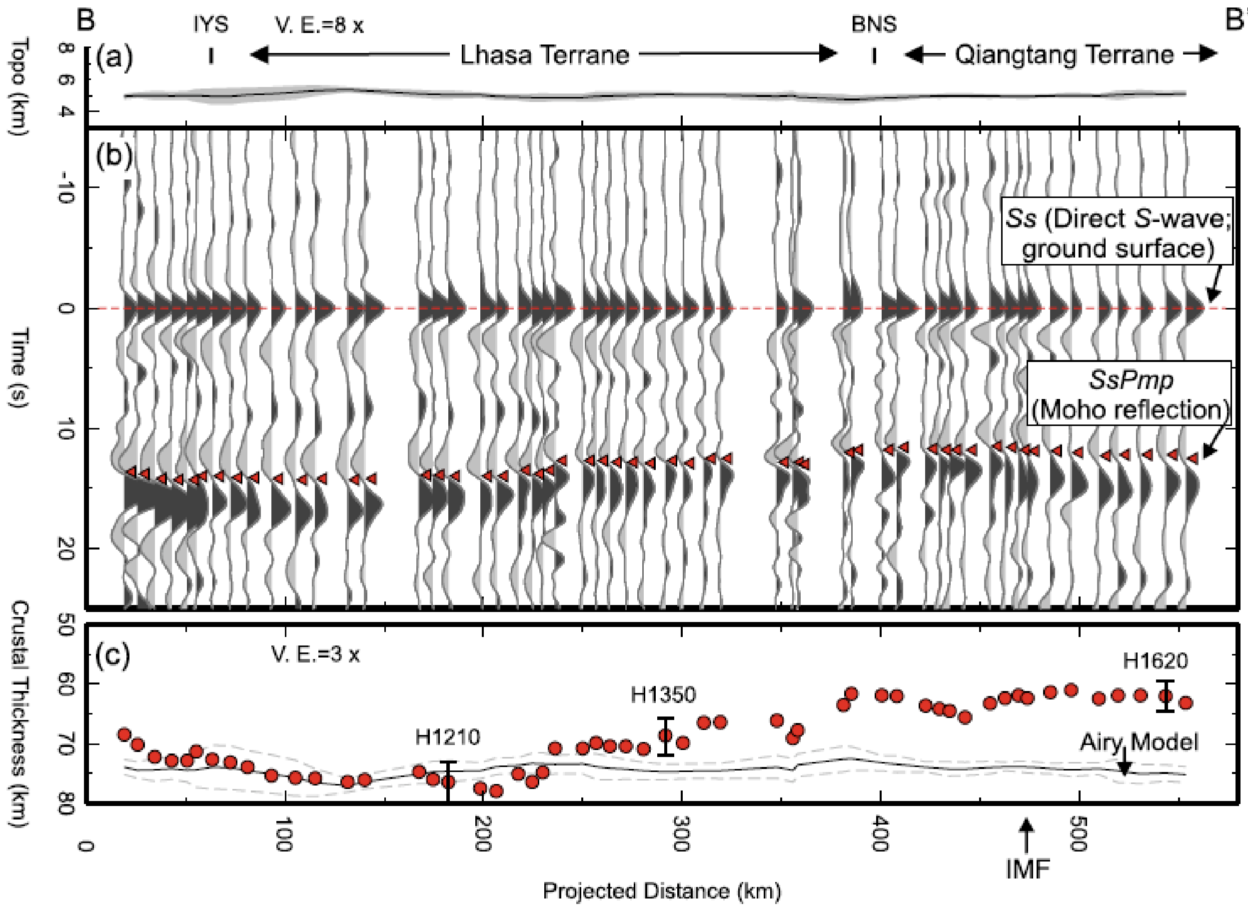
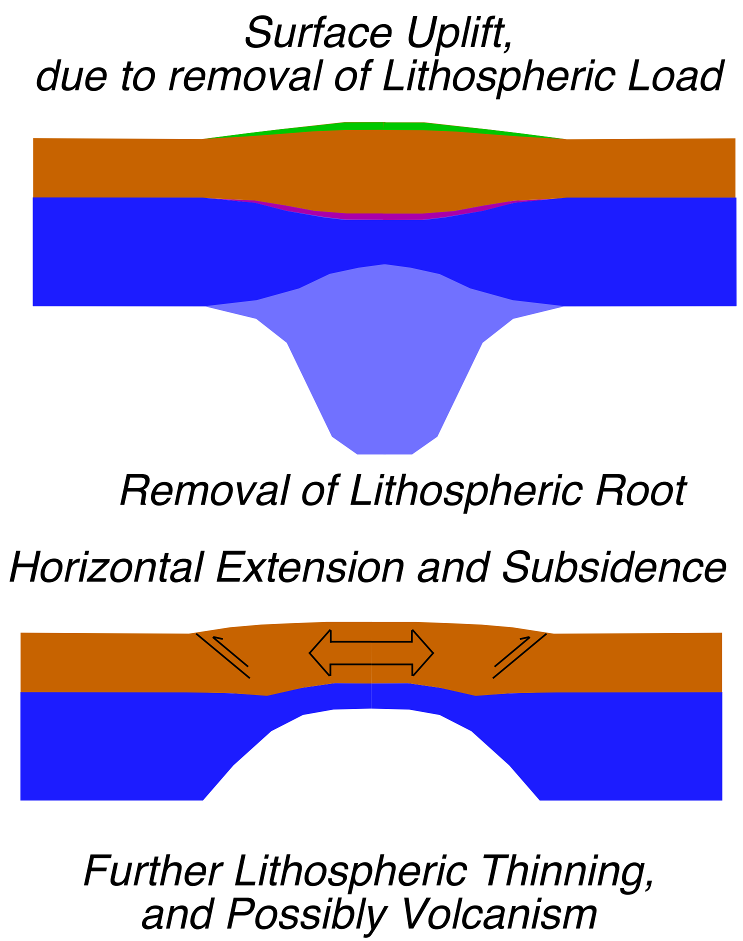


[Tseng, Chen, and Nowack, *Geophysical Research Letters*, 2009]

Removal of mantle lithosphere from beneath mountain belts and plateaus: What does this predict?

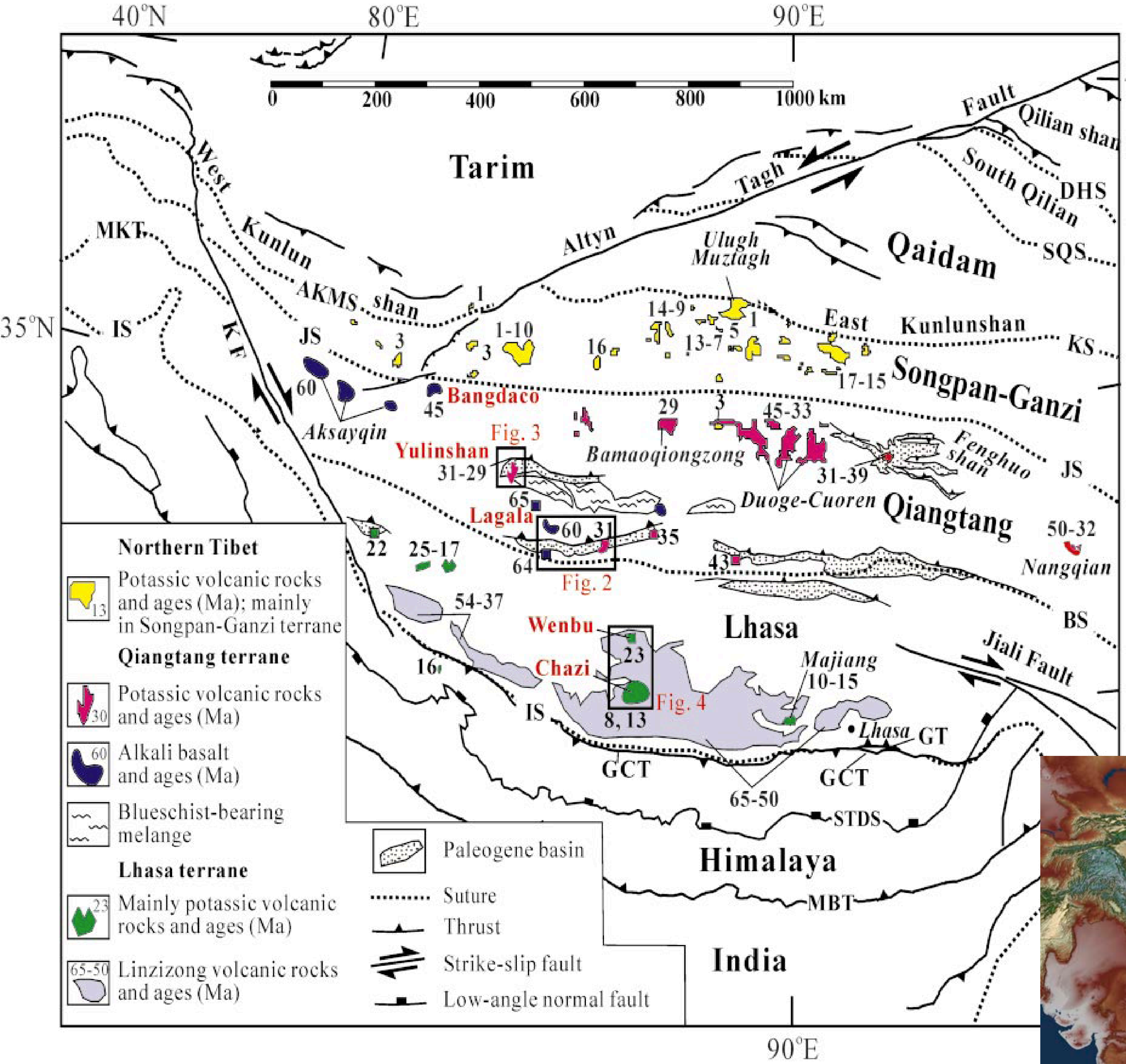
1. Lateral variations in density and in seismic wave-speeds.
2. Enhanced volcanism.
3. Outward growth of the range or plateau.
4. Crustal thinning beneath the high plateau.
5. Increase in surface elevation.

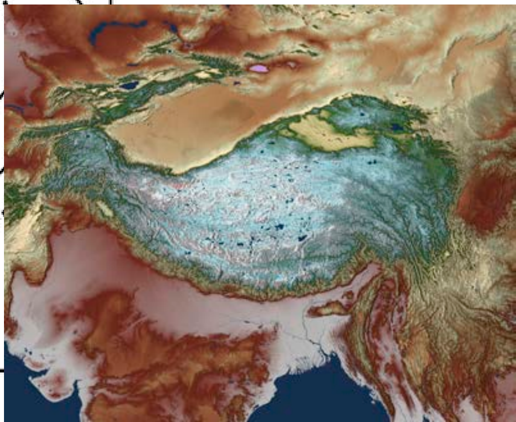


Normal faulting in northern Tibet

Volcanism in northern Tibet

[*Ding et al.*, 2003]





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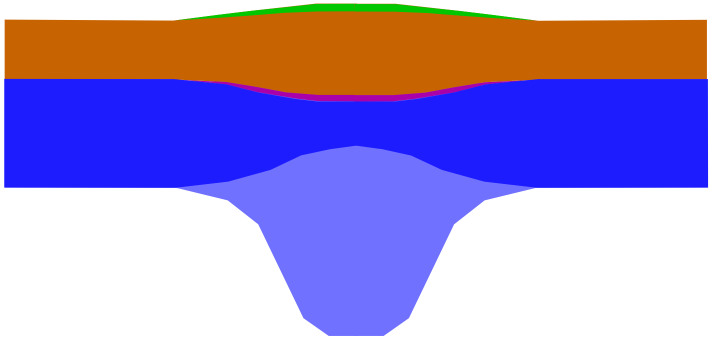
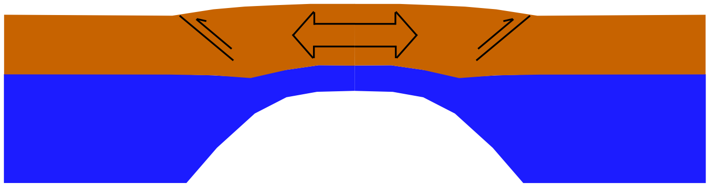
Surface Uplift,
due to removal of Lithospheric Load



Removal of Lithospheric Root

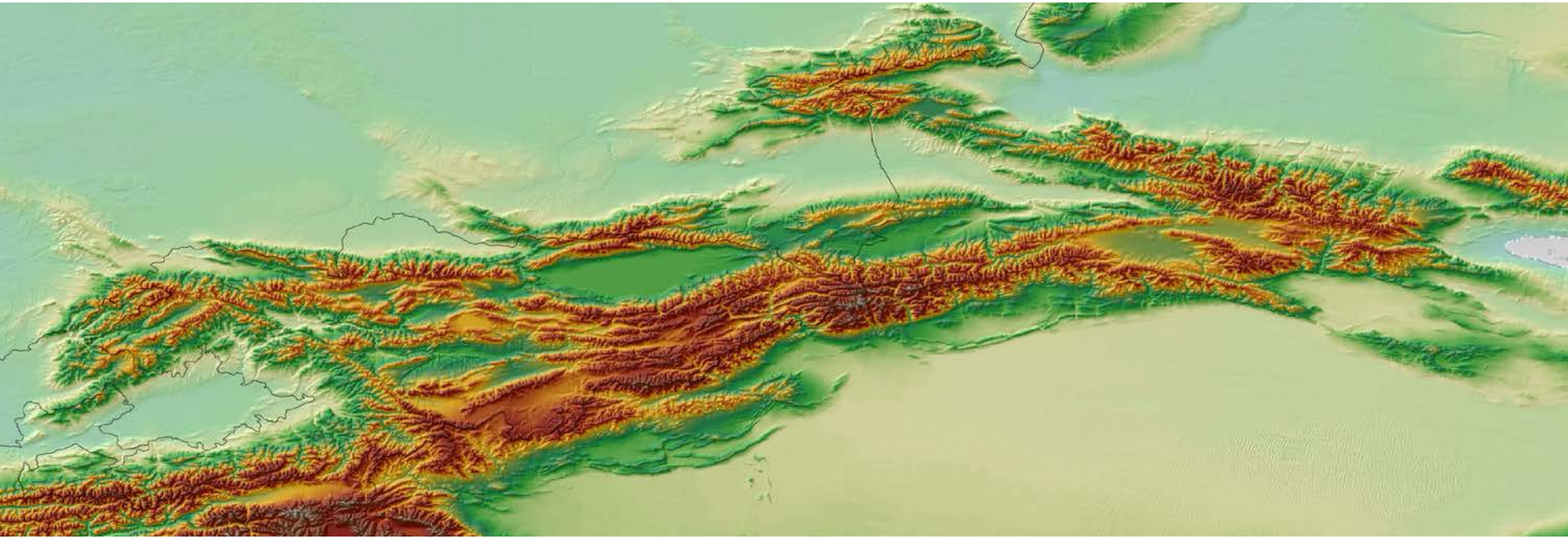
Horizontal Extension and Subsidence



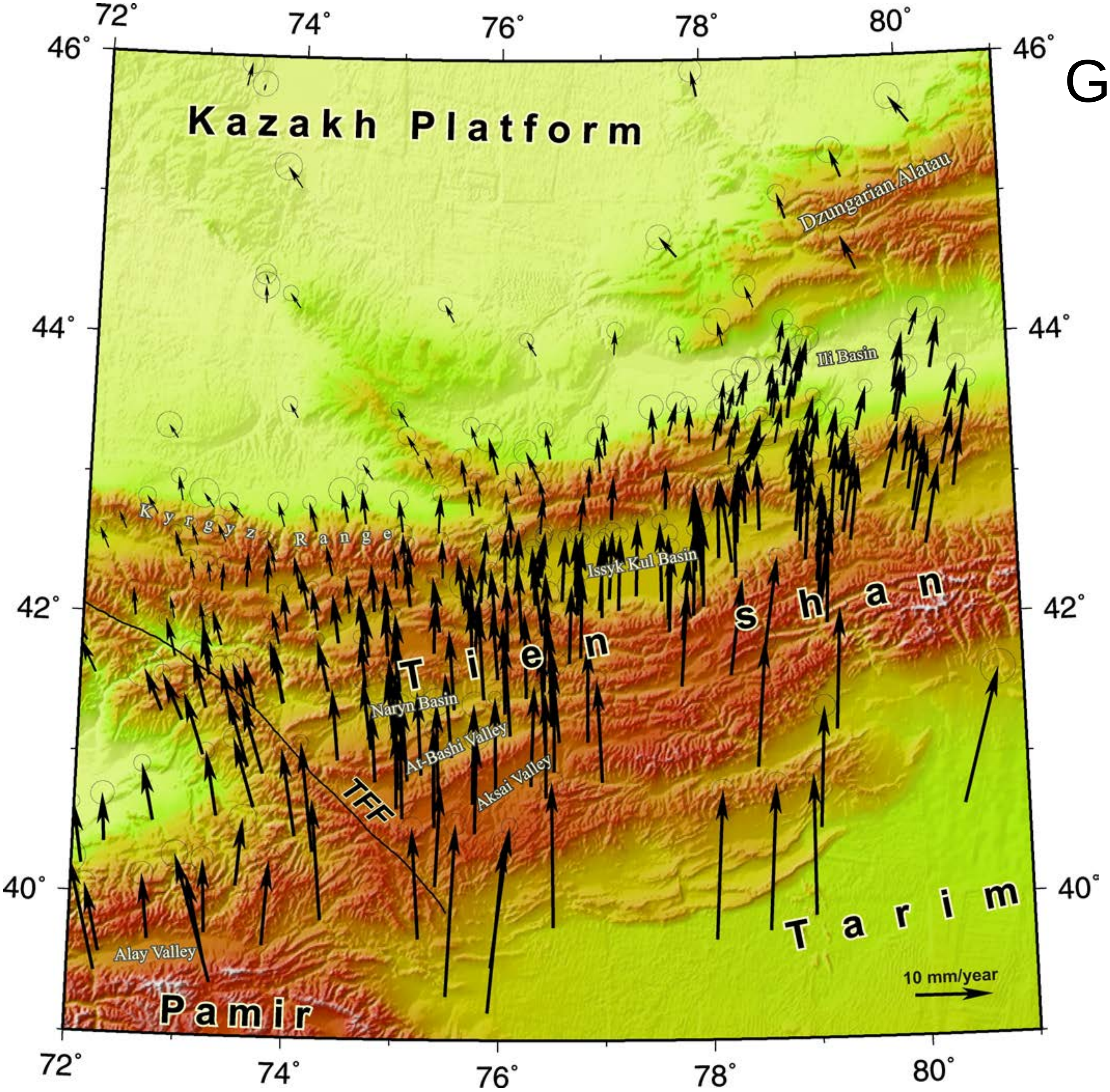
Further Lithospheric Thinning,
and Possibly Volcanism

Tibetan Plateau, the Himalaya, and the **Tien Shan**

Total crustal Shortening is at least 50 km, but no more than ~200 km

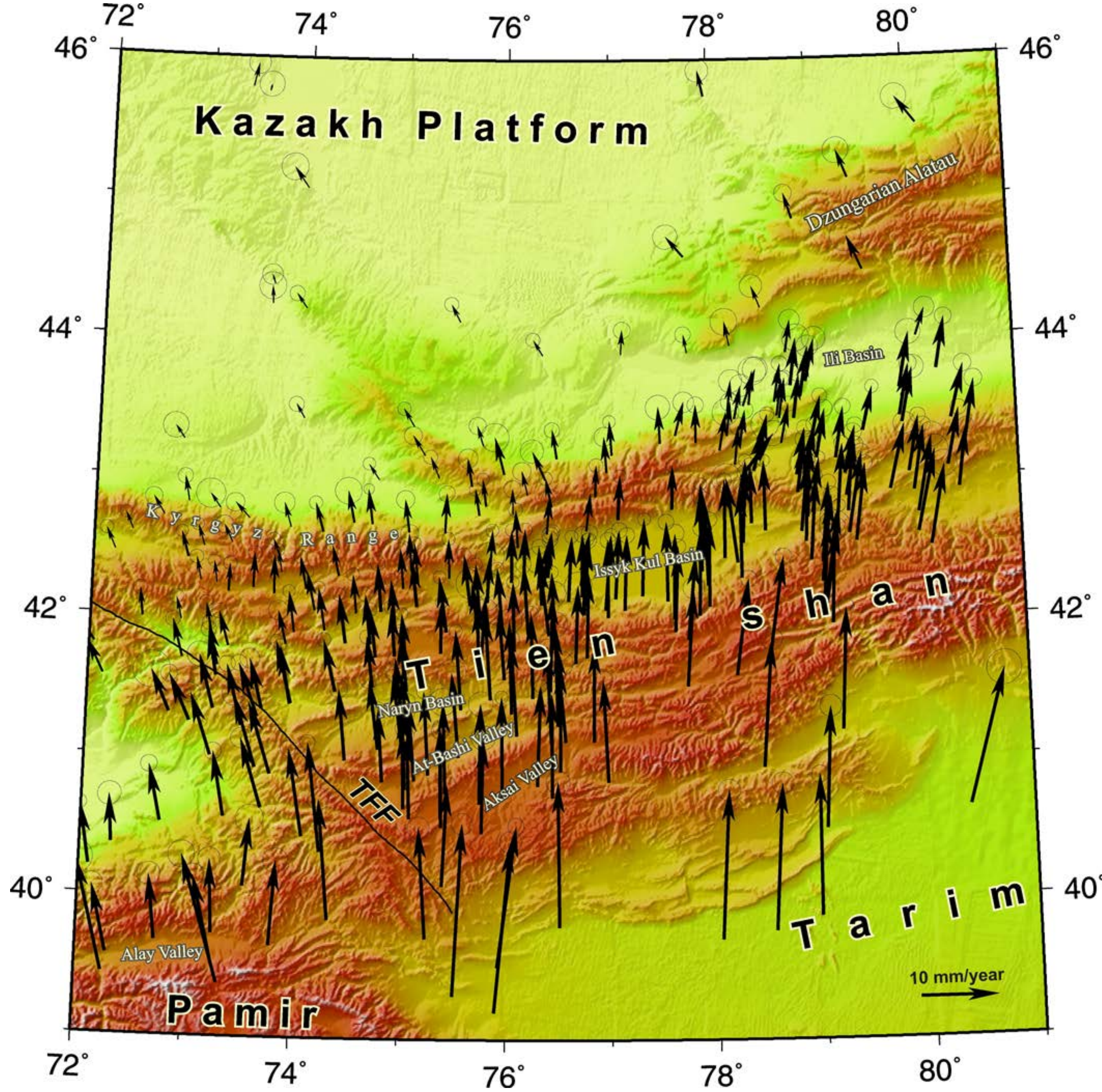


(SRTM data, plotted by Jean-Daniel Champagnac)



GPS velocities across the Tien Shan: **fast**, ~20 mm/yr.

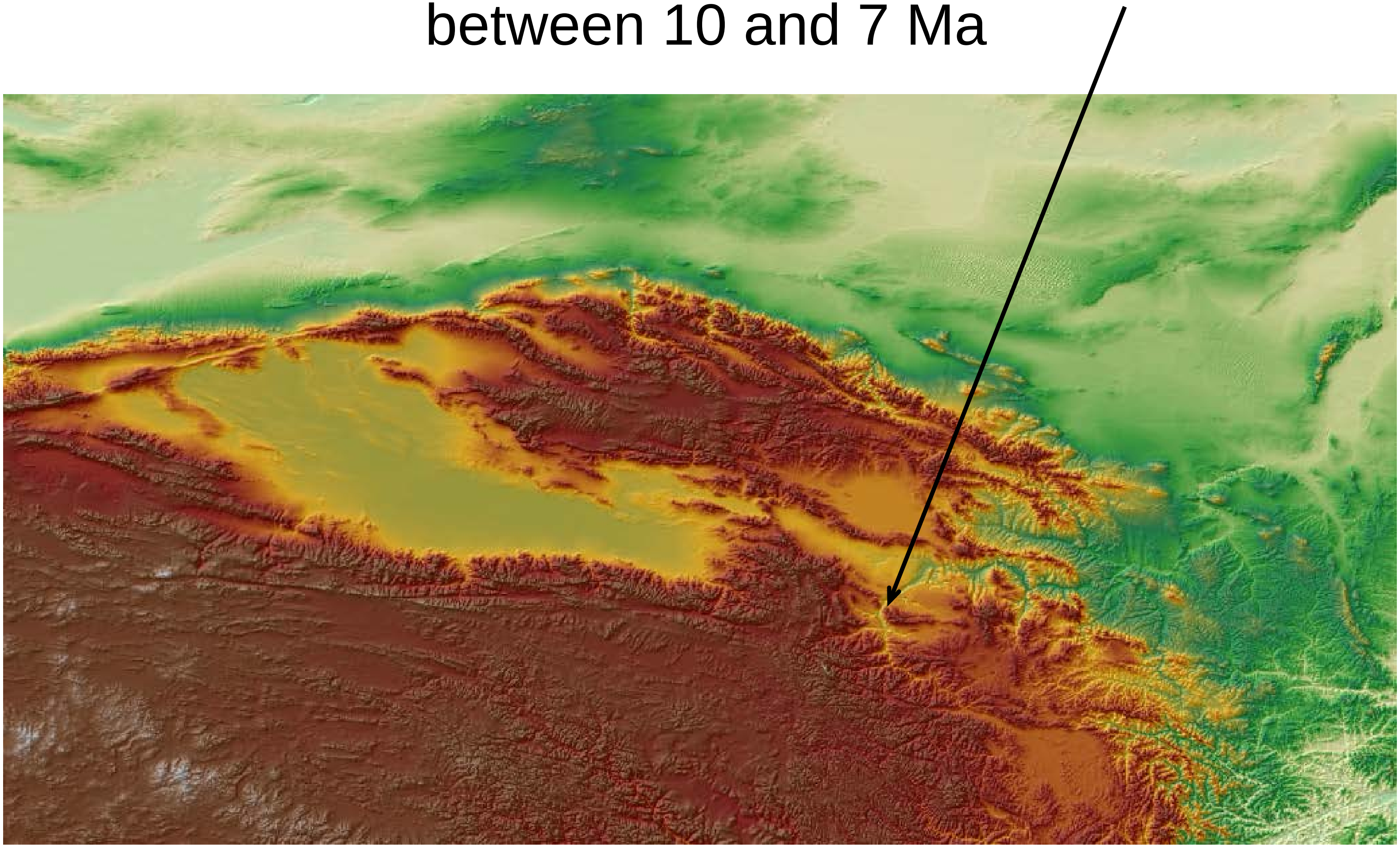
[*Zubovich et al. Tectonics*, 2010]



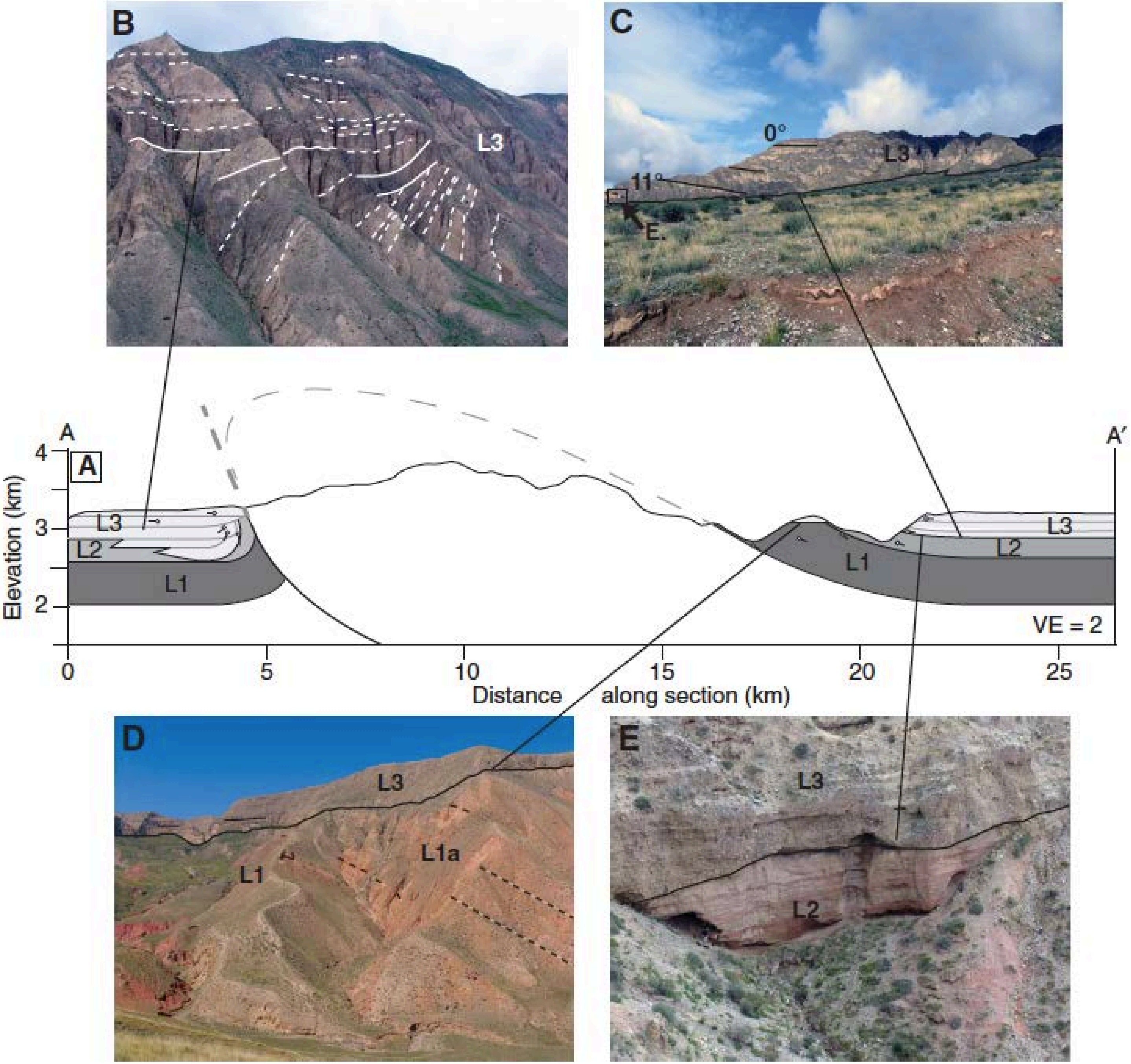
<200 km divided by 20 mm/yr or by 20 km/Myr suggests ***≤10 Myr*** to make the belt.

[*Zubovich et al. Tectonics*, 2010]

Emergence of the Southern Gonghe Nanshan between 10 and 7 Ma



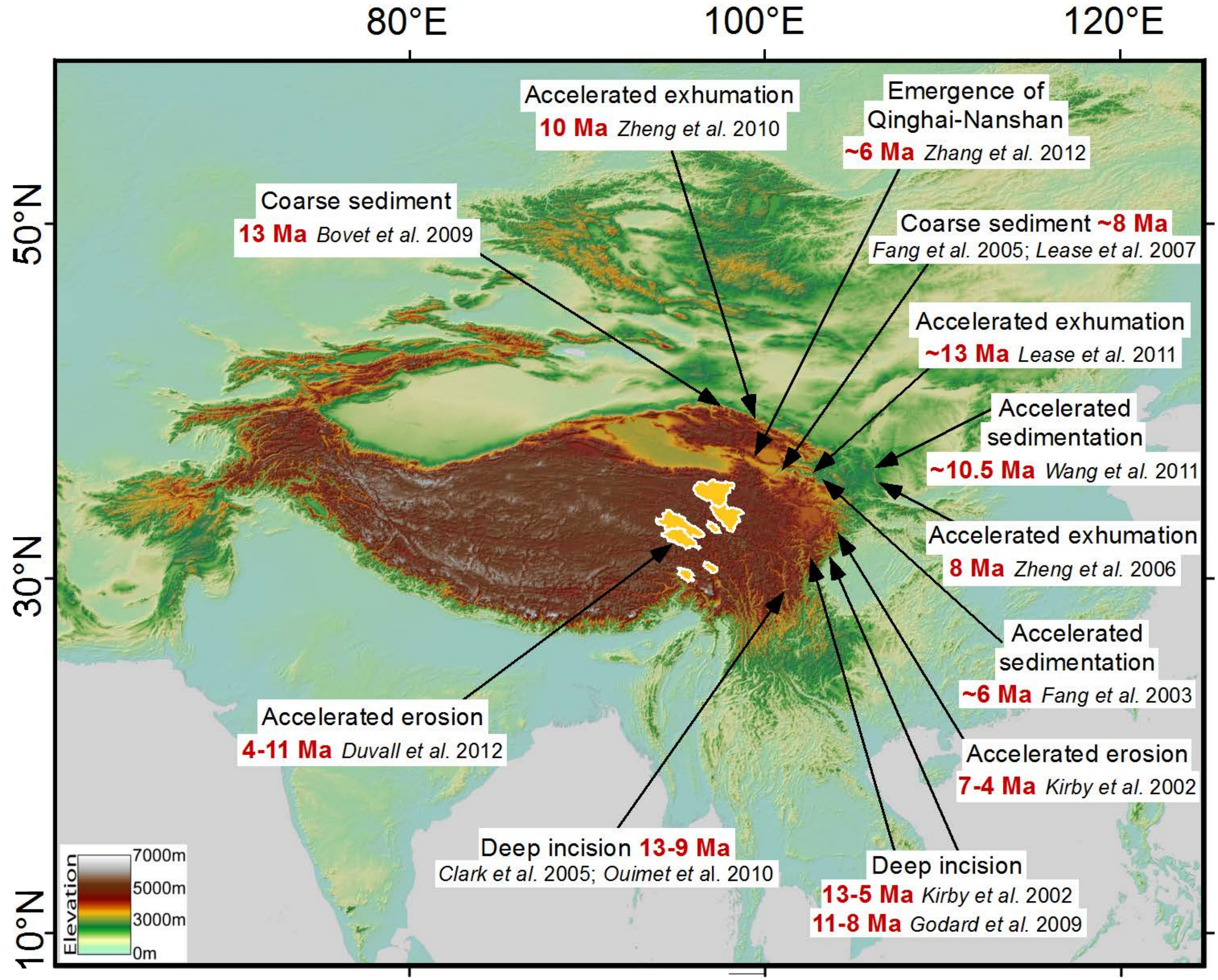
[*W. H. Craddock, E. Kirby, and Zhang Hui-Ping, Lithosphere,* 2011]



Emergence of the Southern Gonghe Nanshan between 10 and 7 Ma

W. H. Craddock, E. Kirby, and Zhang Hui-Ping, Lithosphere, 2011]

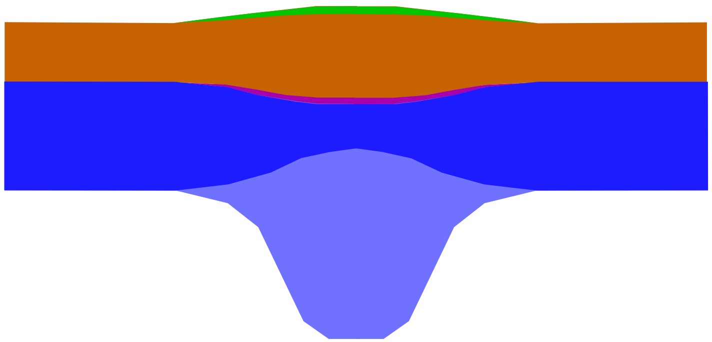
Upward and outward growth of high Tibetan terrain since 15-10 Ma



Removal of mantle lithosphere from beneath mountain belts and plateaus: What does this predict?

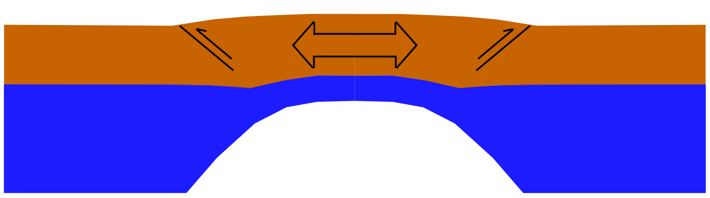
1. Lateral variations in density and in seismic wave-speeds.
2. Enhanced volcanism.
3. Outward growth of the range or plateau.
4. Crustal thinning beneath the high plateau.
5. Increase in surface elevation.

Surface Uplift,
due to removal of Lithospheric Load



Removal of Lithospheric Root

Horizontal Extension and Subsidence



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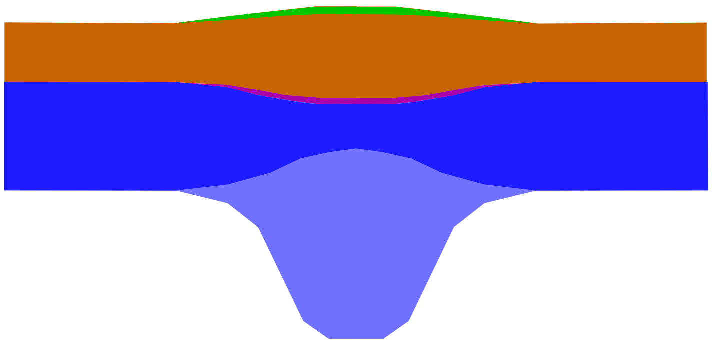

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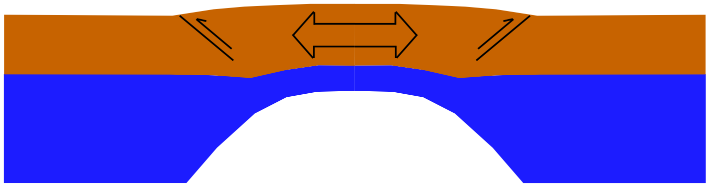
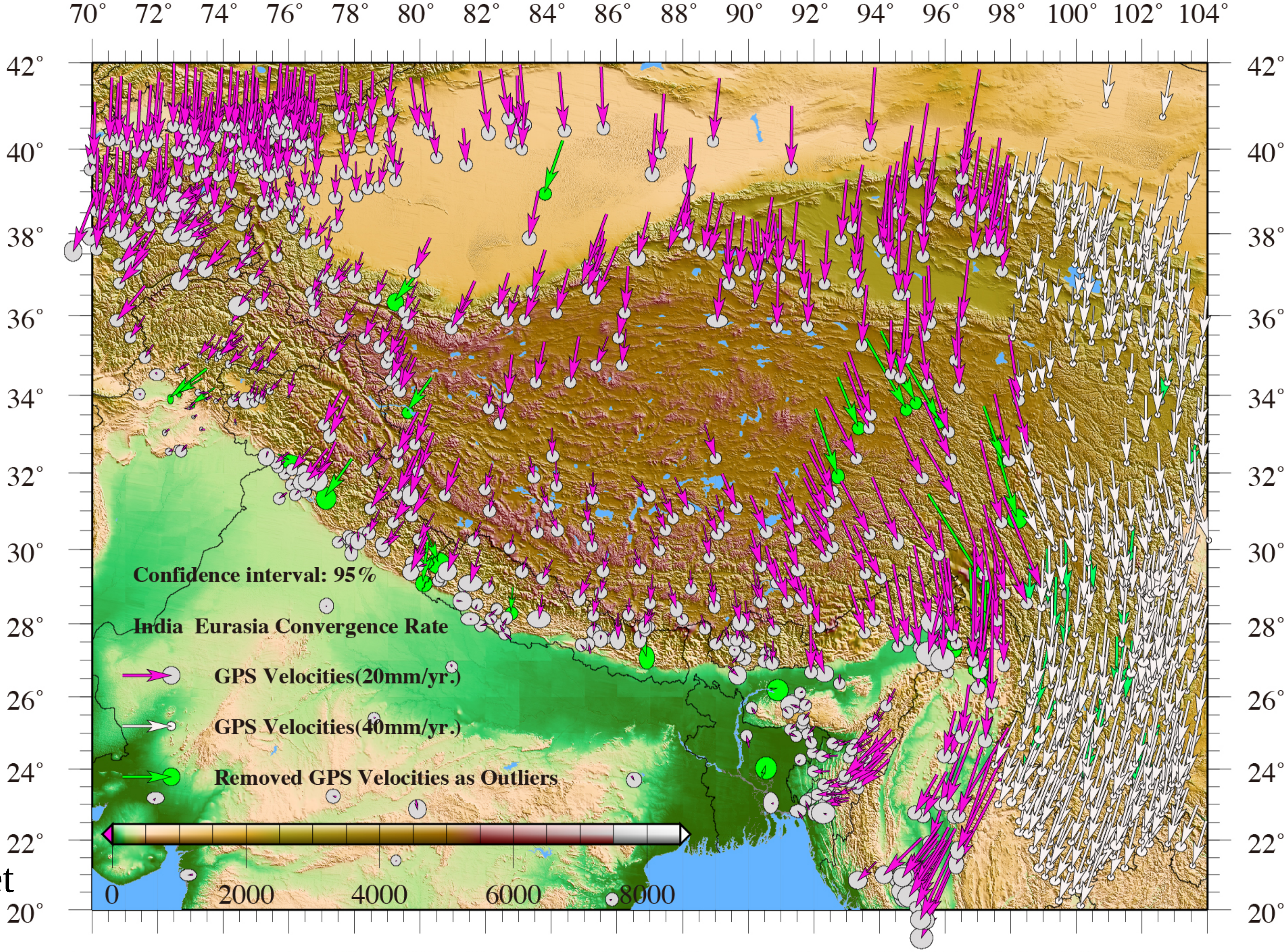


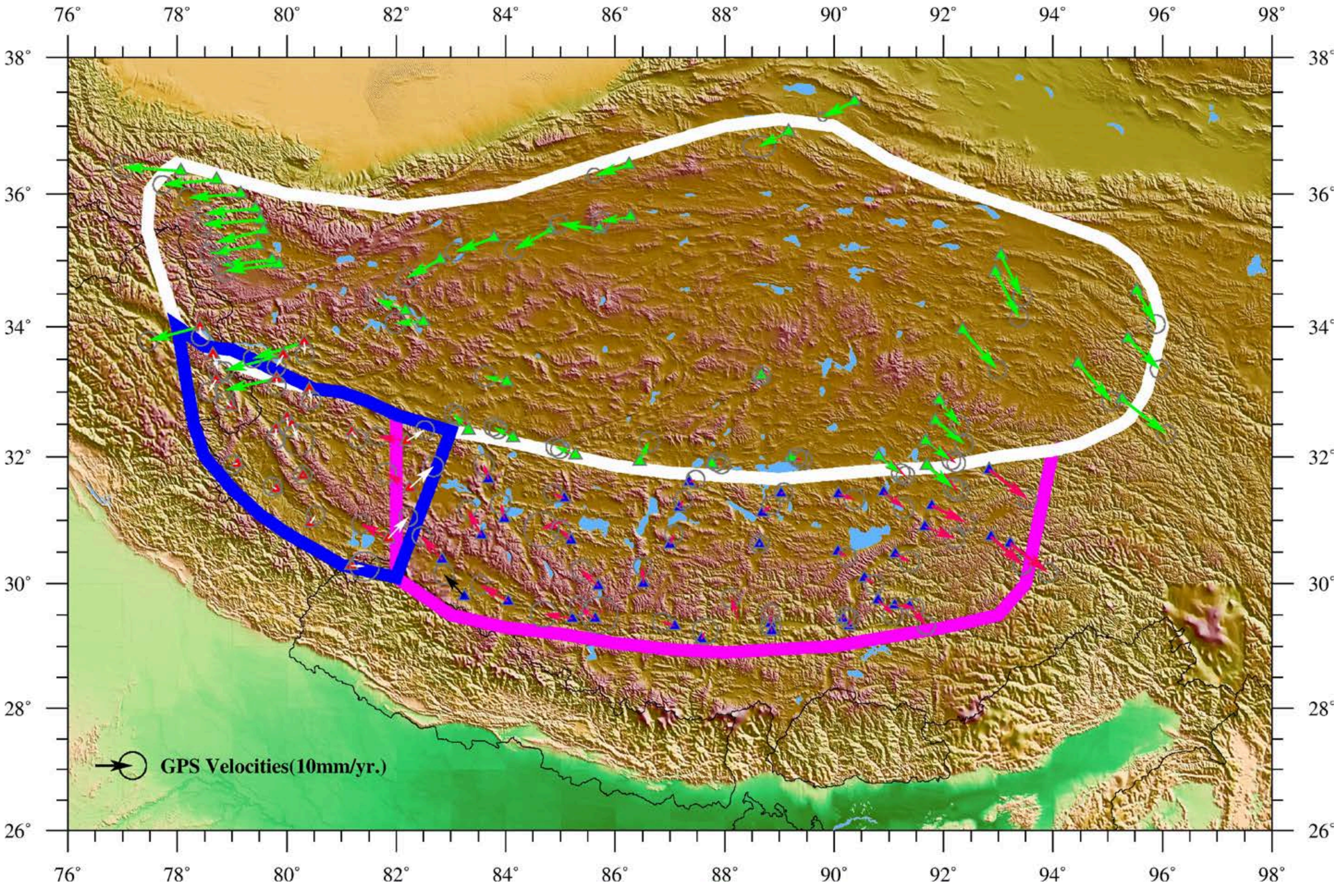
Further Lithospheric Thinning,
and Possibly Volcanism

GPS velocities relative to India

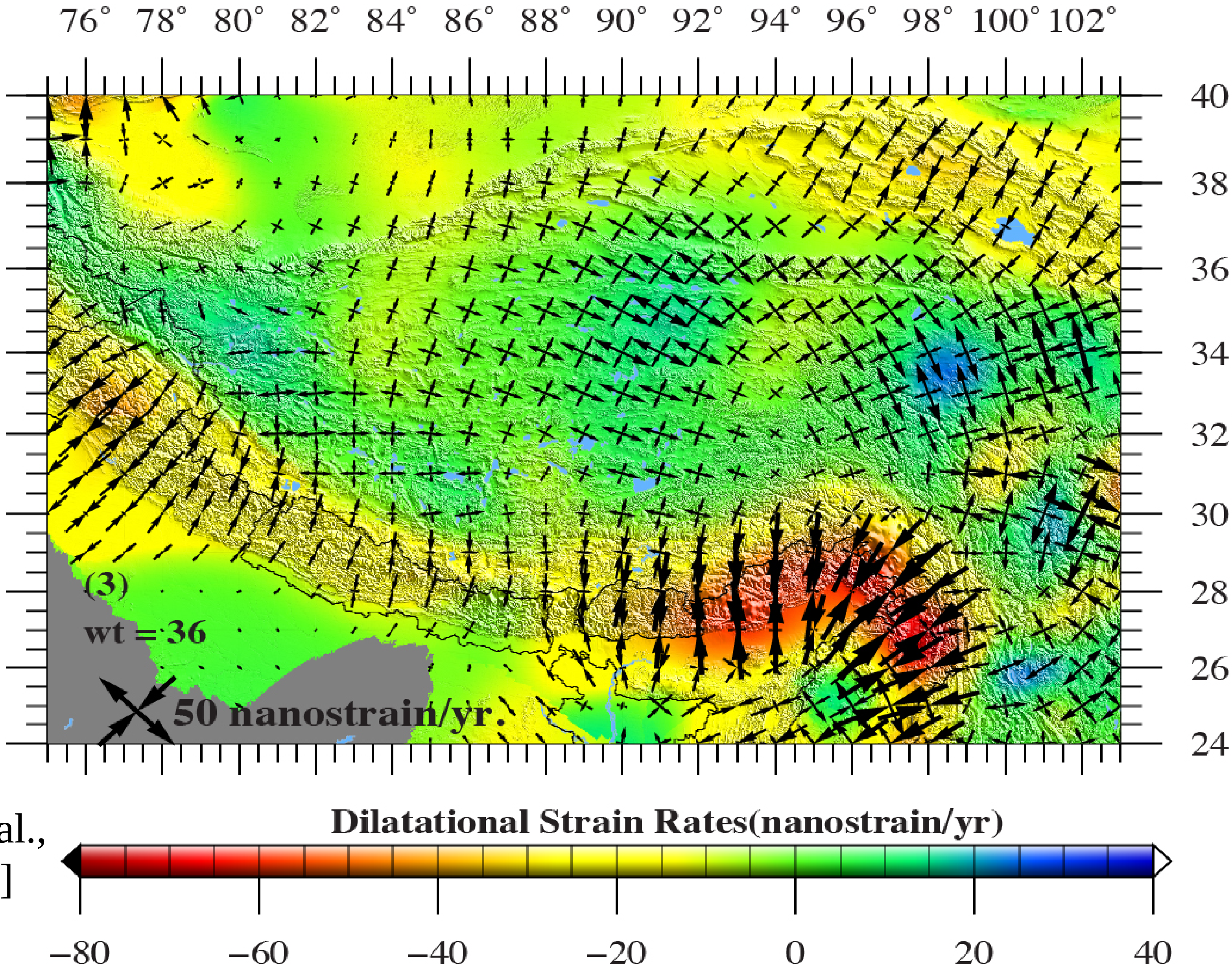


[Ge et al., 2015]

GPS velocities relative to Shuang Hu in the middle of Tibet



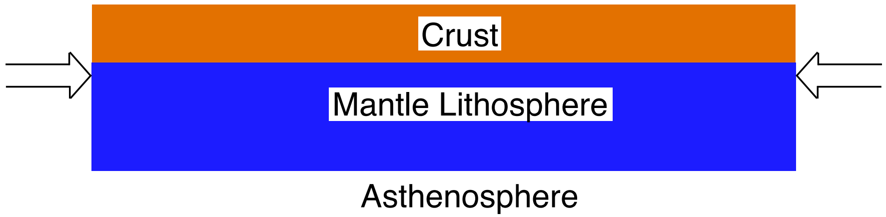
Ongoing strain in Tibet, from GPS



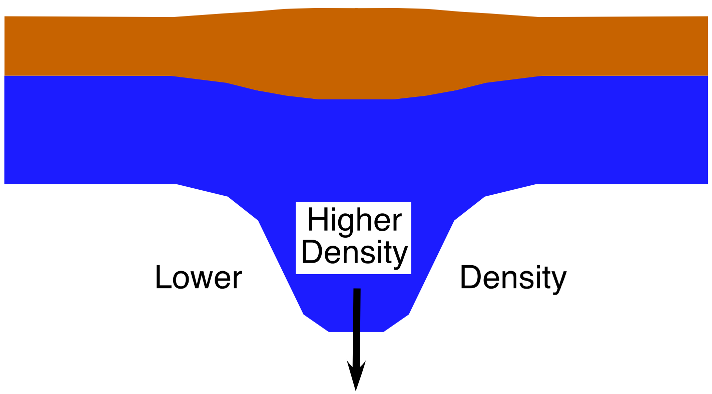
[Ge et al., 2015]

Shortening and Thickening of lithosphere (crust and mantle)

Initial State: Horizontal shortening



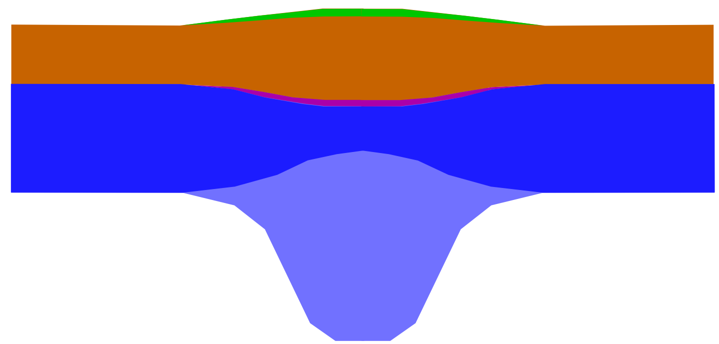
Crustal Thickening and Mountain or Plateau Building



Thickening of Unstable Lithospheric Root

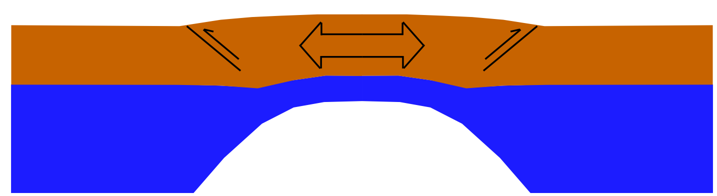
Surface rises, and available potential energy powers outward growth of the plateau and crustal extension within it

Surface Uplift, due to removal of Lithospheric Load



Removal of Lithospheric Root

Horizontal Extension and Subsidence



Further Lithospheric Thinning, and Possibly Volcanism

Removal of blobs of dense mantle lithosphere (“deblobbing”) reduces load to base of lithosphere: available potential energy, à la *Lorenz* [1955], increases.

Removal of mantle lithosphere from beneath mountain belts and plateaus: What does this predict?

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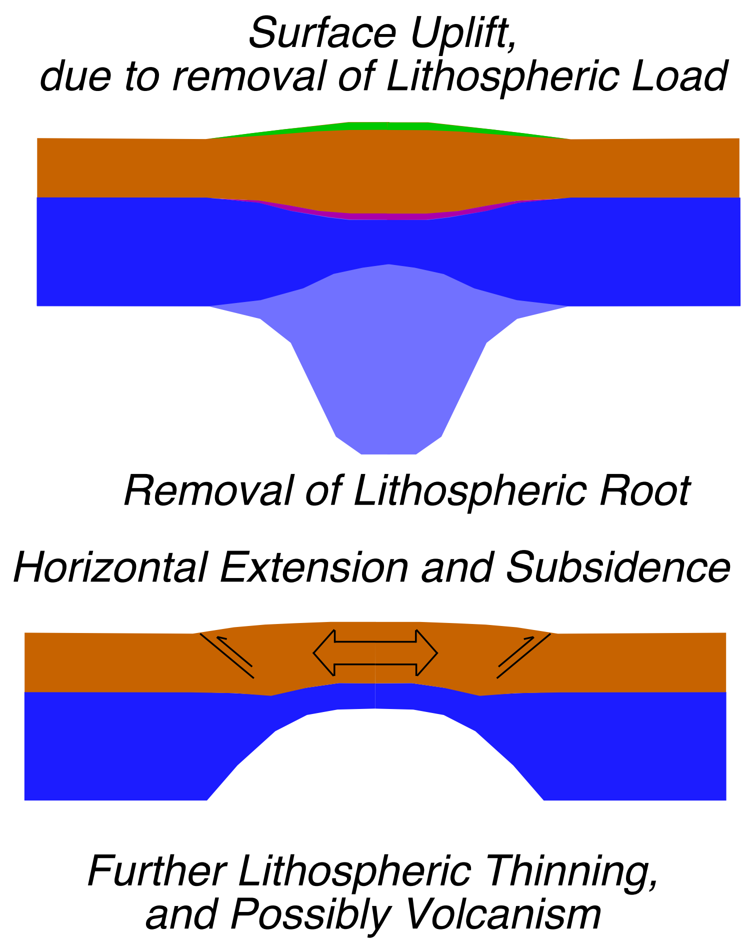
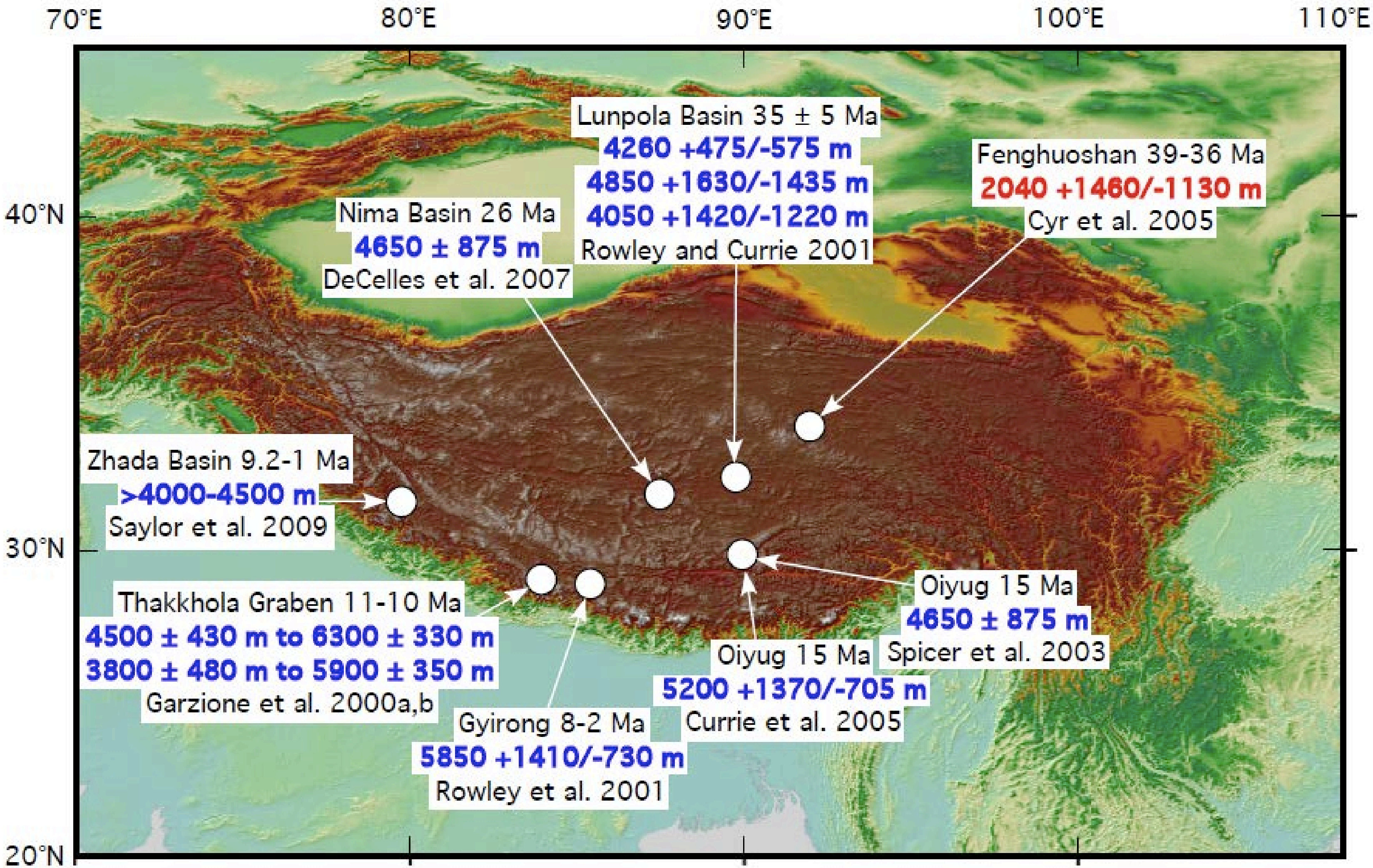
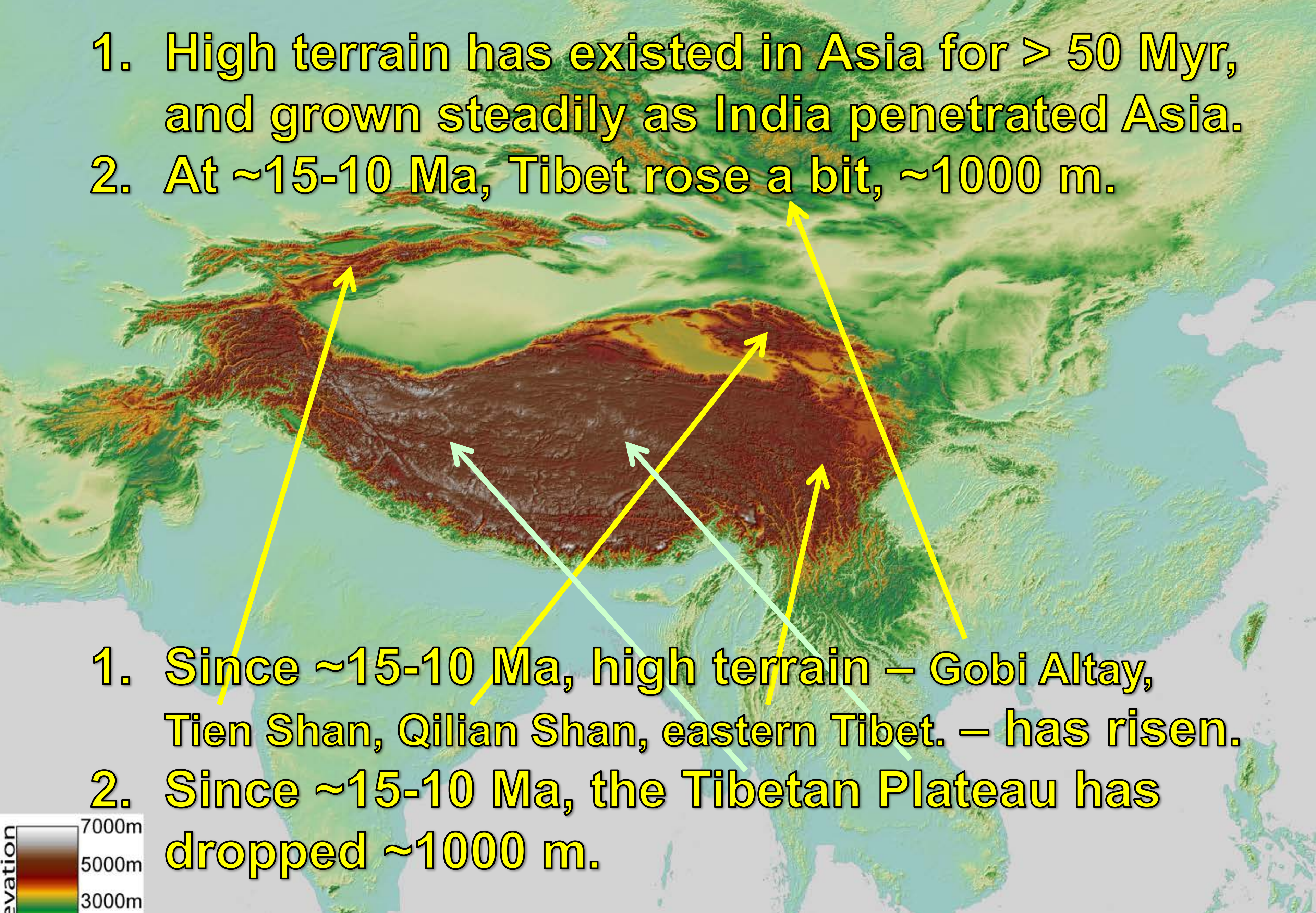


Tibet Paleo-elevations



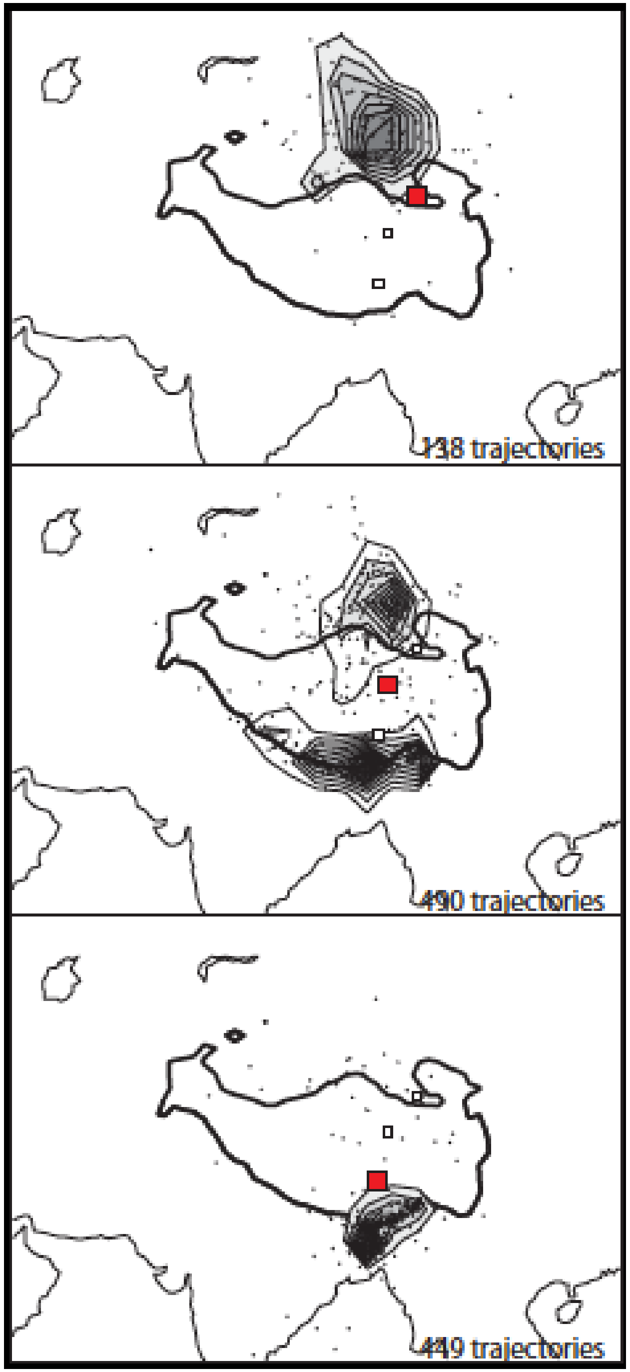
Little change (± 1000 m) in southern Tibet; (but no constraint on the elevation of northern Tibet).

Interim Summary



1. High terrain has existed in Asia for > 50 Myr, and grown steadily as India penetrated Asia.
2. At ~15-10 Ma, Tibet rose a bit, ~1000 m.

1. Since ~15-10 Ma, high terrain – Gobi Altay, Tien Shan, Qilian Shan, eastern Tibet. – has risen.
2. Since ~15-10 Ma, the Tibetan Plateau has dropped ~1000 m.



Sources of water:

Today, half of $\delta^{18}O$ in northern Tibet comes from the north!

What was its source at 40-30 Ma?

[Bershaw, Penny, and Garzione, *Journal of Geophysical Research*, 2012]

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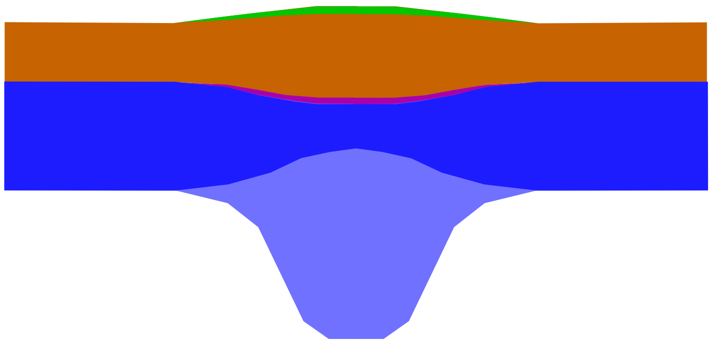

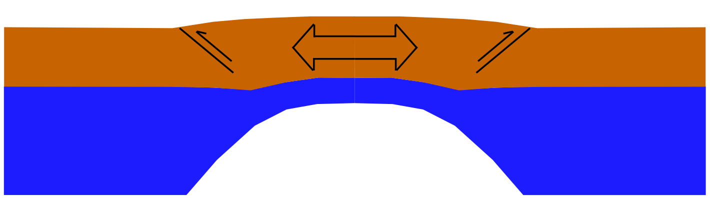

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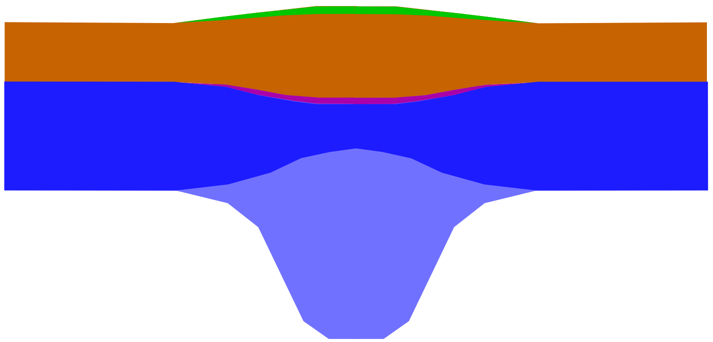
5. Increase in surface elevation? Maybe not, but tests are not yet convincing.

Surface Uplift,
due to removal of Lithospheric Load



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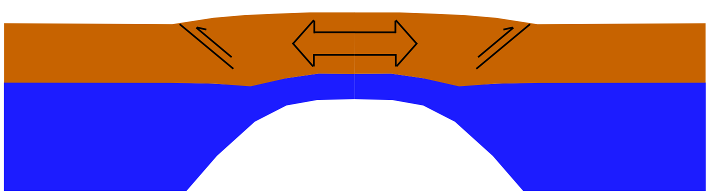


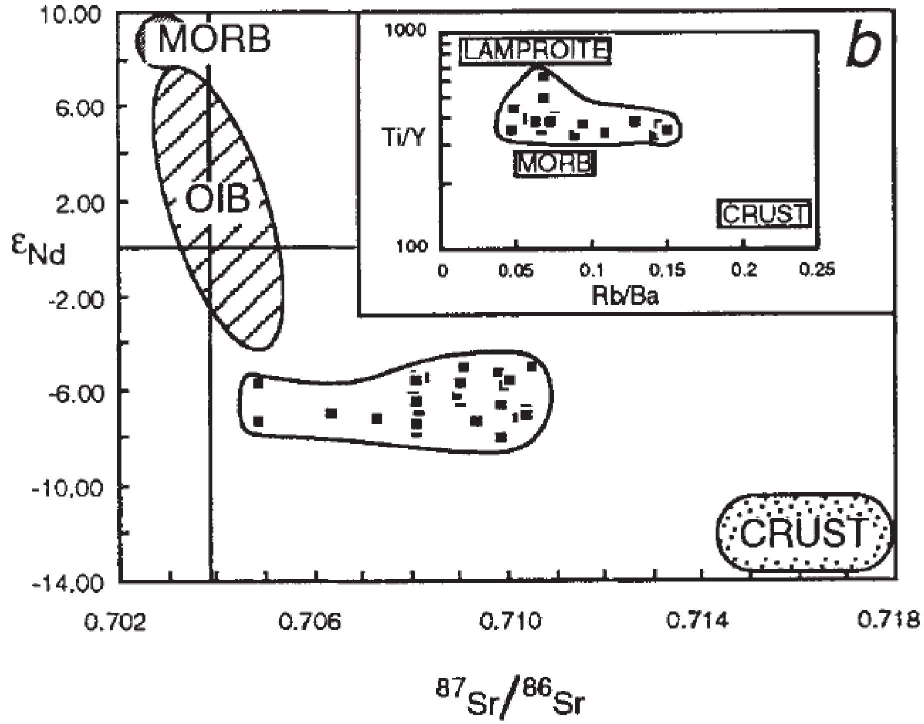
Further Lithospheric Thinning,
and Possibly Volcanism

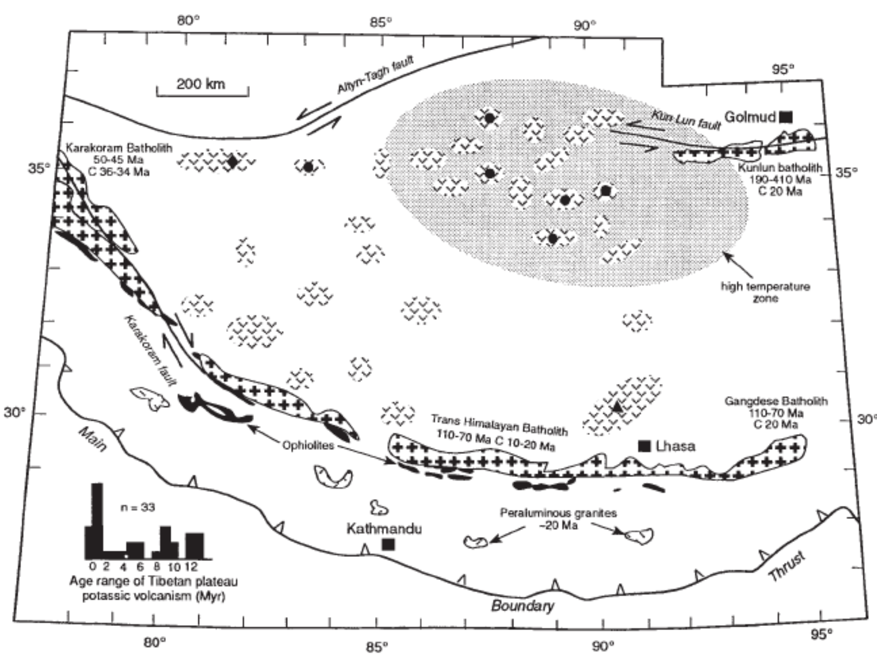
Regardless of what processes (crustal thickening and/or removal of mantle lithosphere), did and, if so, how did the growth of high topography affect climate in Asia, and in particular the Indian Monsoon?

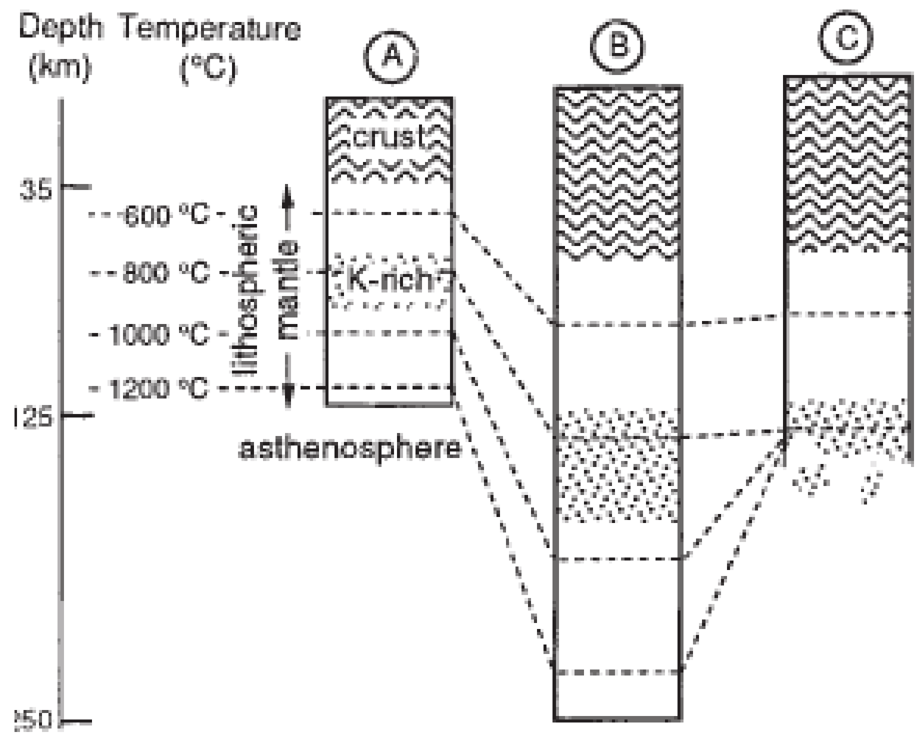
Volcanism in northern Tibet

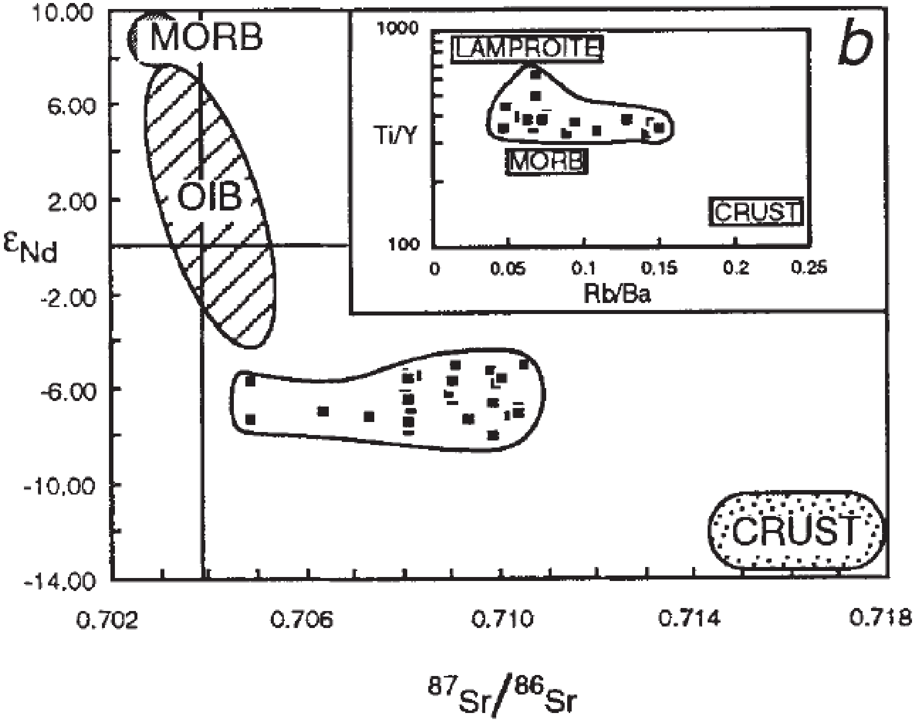
[*Turner et al.*, 1993]

Potassium rich, rich in other incompatible elements, and with high $^{87}Sr/^{86}Sr$ (for mantle rock).









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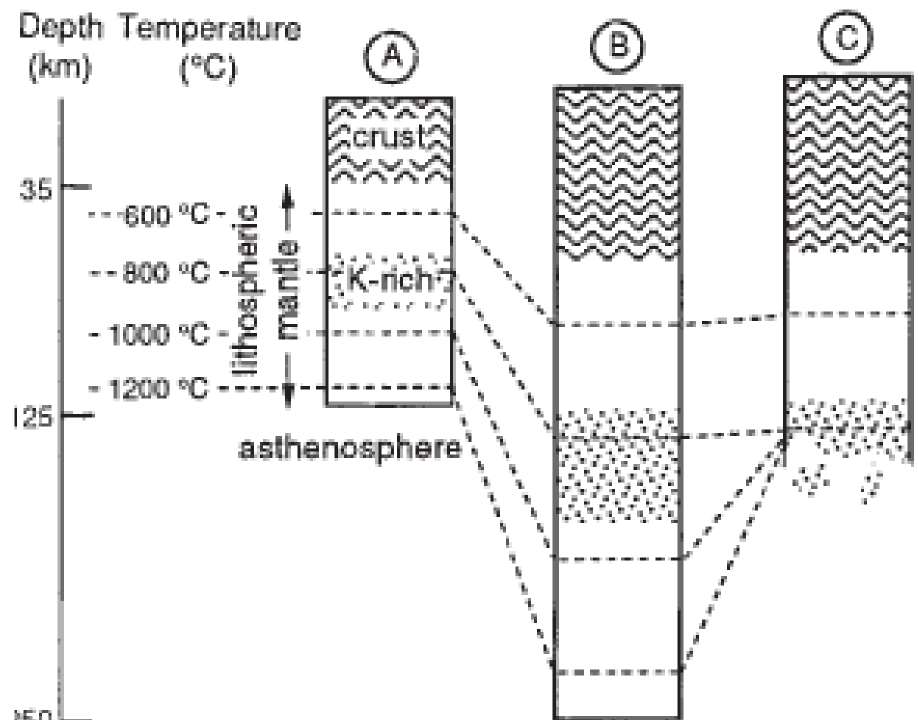
A. Potassium-rich melt seeps into mantle lithosphere.



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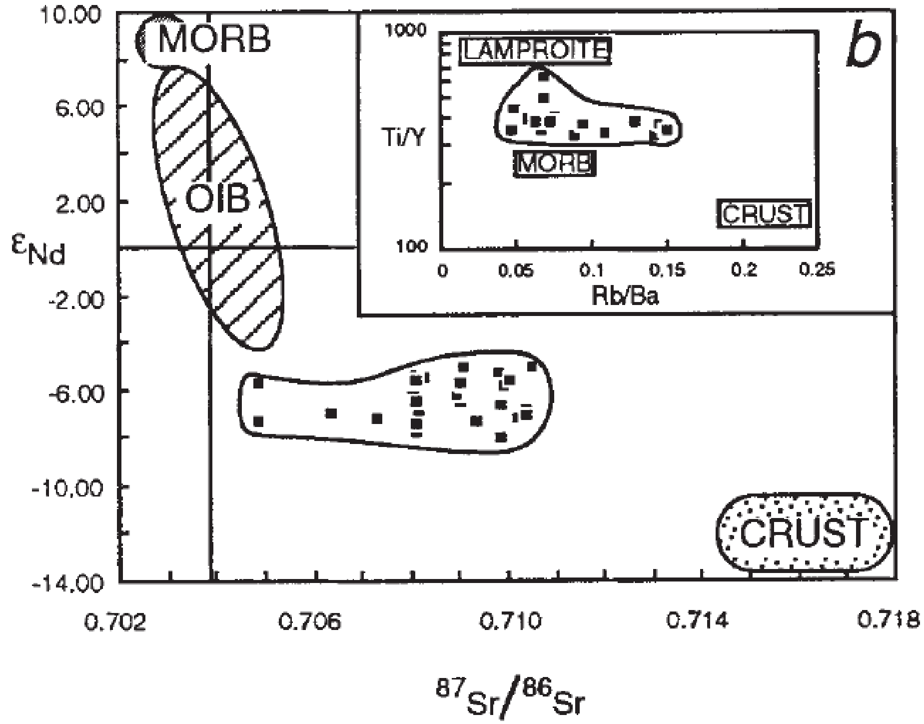
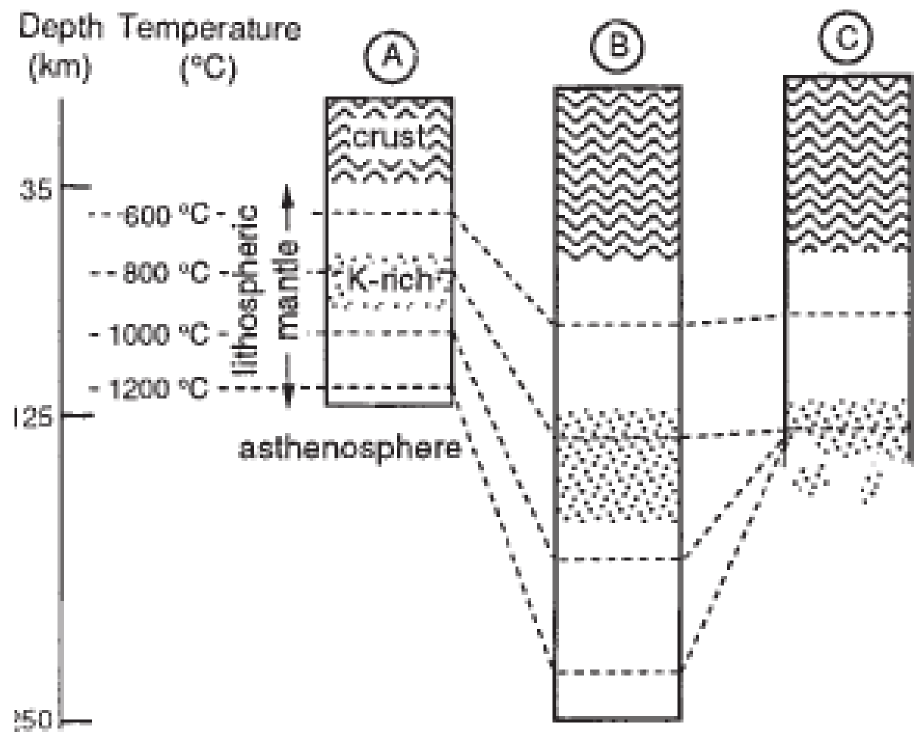


A. Potassium-rich melt seeps into mantle lithosphere.
B. Lithosphere is thickened.



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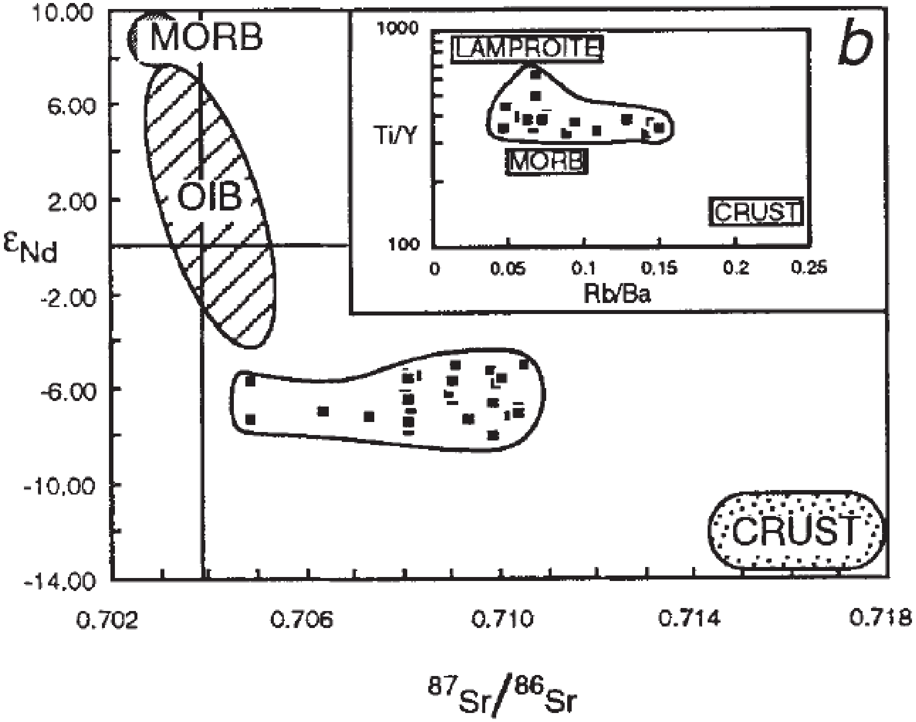
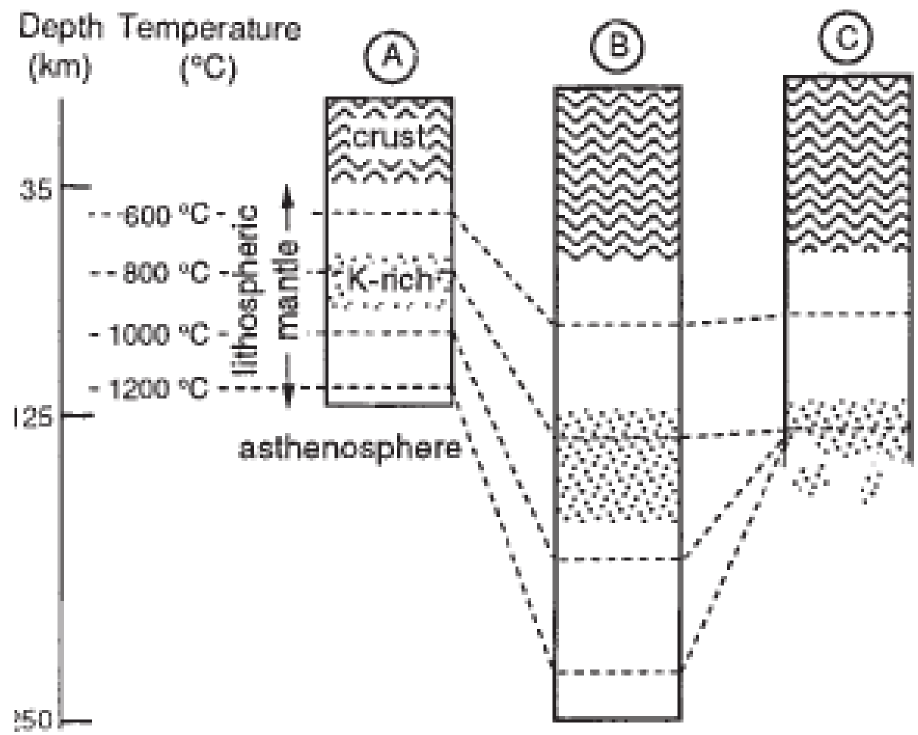


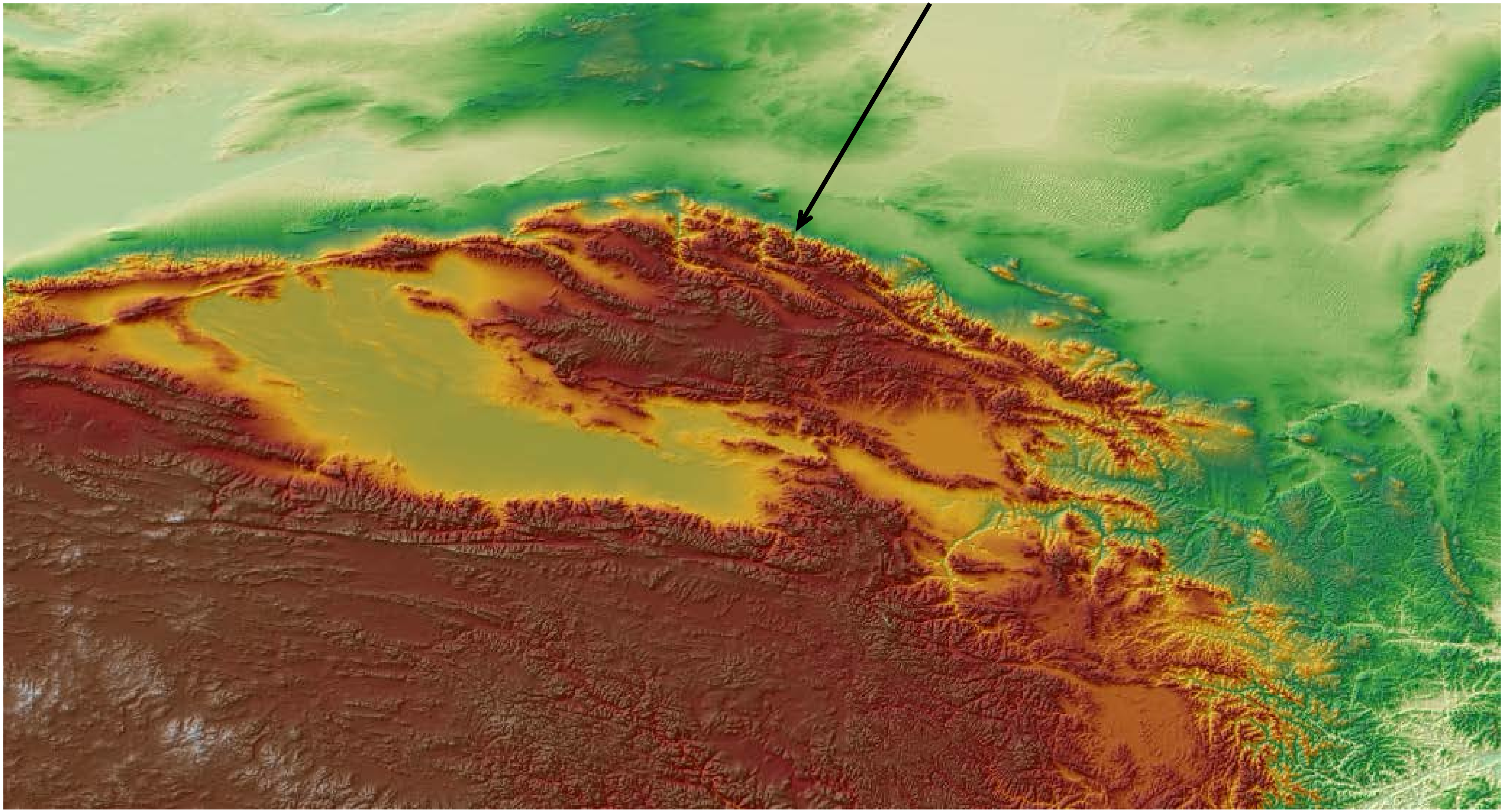


A. Potassium-rich melt seeps into mantle lithosphere.
B. Lithosphere is thickened.
C. Lower lithosphere is removed, which heats the overlying potassium rich material, and it erupts as volcanic rock.

How might Tibet, and its growth, affect climate, and paleoclimate?

1. Loess plateau – dust? *Maybe, but **only** via a **geodynamic teleconnection**.*
2. Rainfall over South China? ***Mechanically!***
3. Rainfall (aridification) over NW India? Maybe, and if so, ***thermally**, via a **Gill-Model teleconnection***.
4. Monsoon rainfall, in general, over India? ***Thermally***, only in early and late seasons.

Emergence of the northern Qilian Shan at ~ 9 Ma



[*Zheng Dewen*, *Marin Clark*, *Zhang Peizhen*, *Zheng Wenjun*, *and Ken Farley*, *Geosphere*, 2010]

North Qilian Shan:

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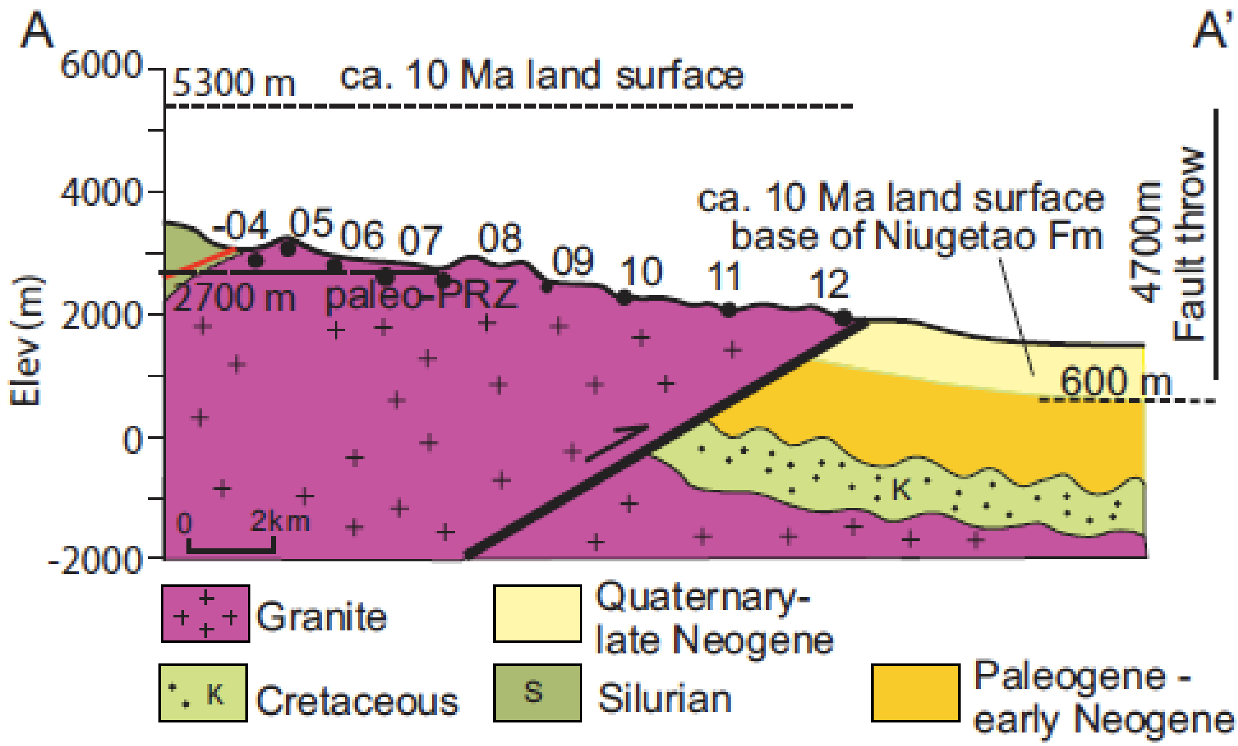

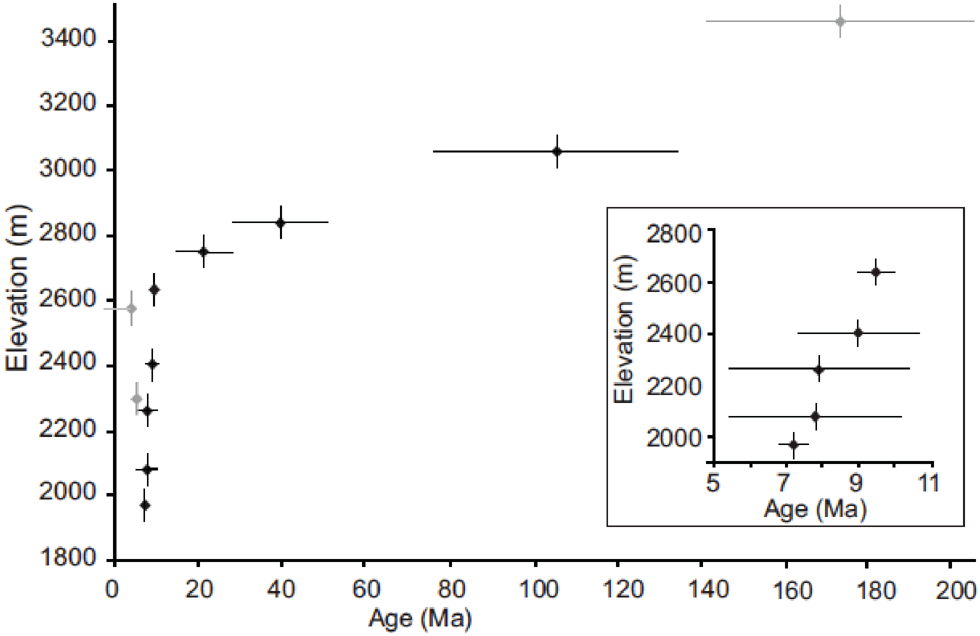

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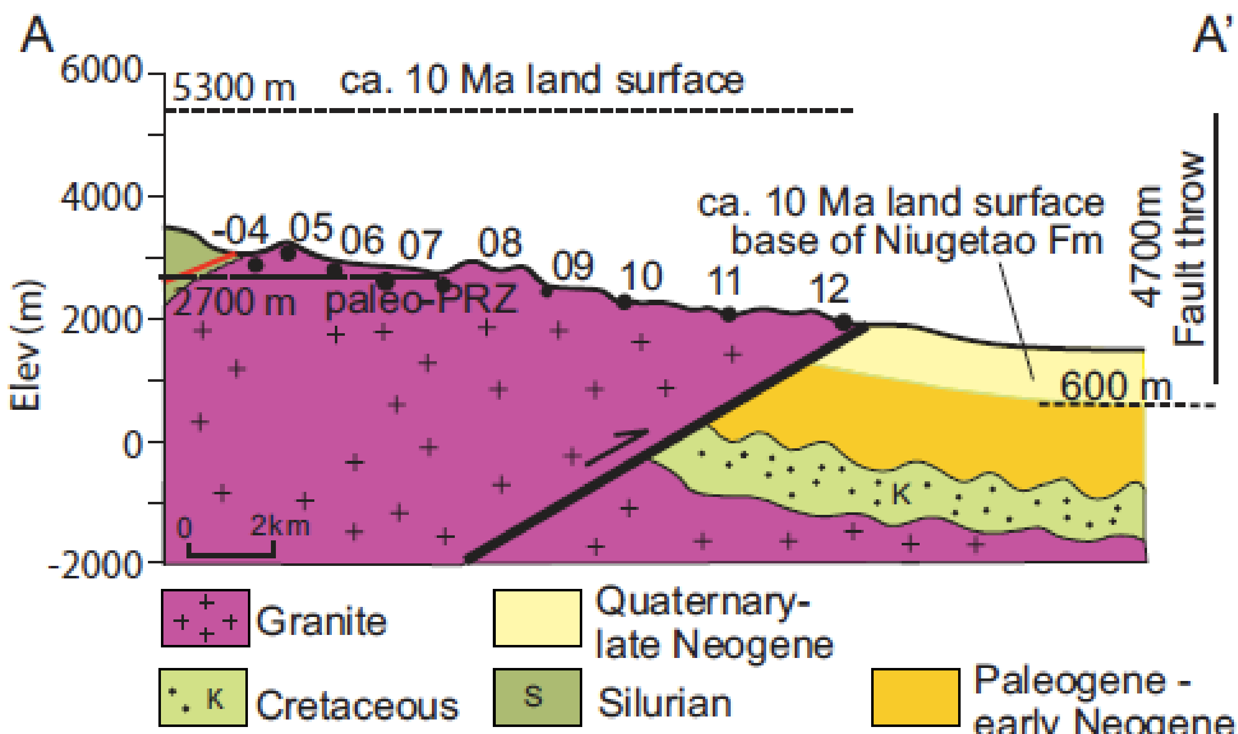
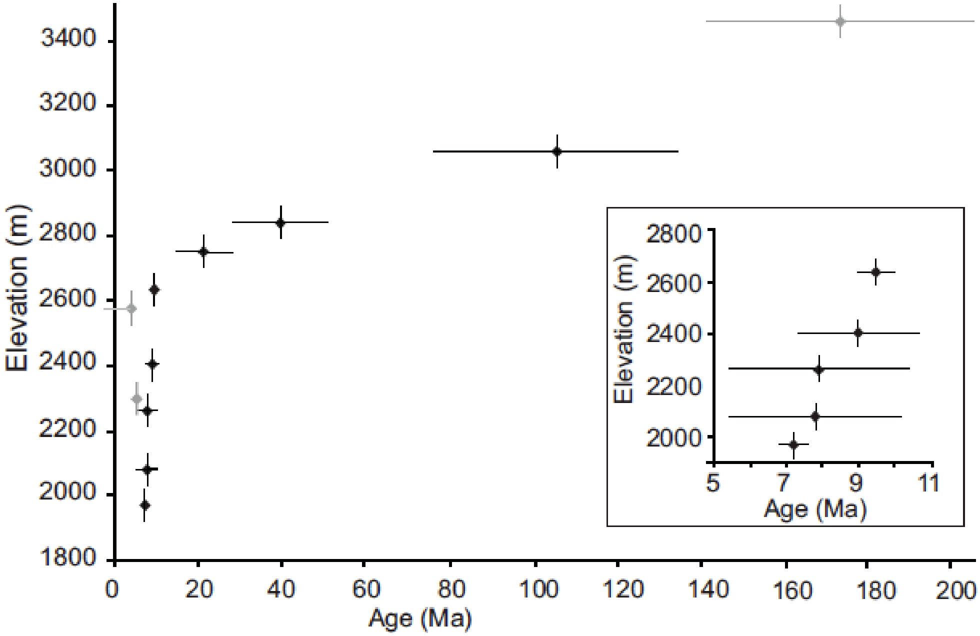
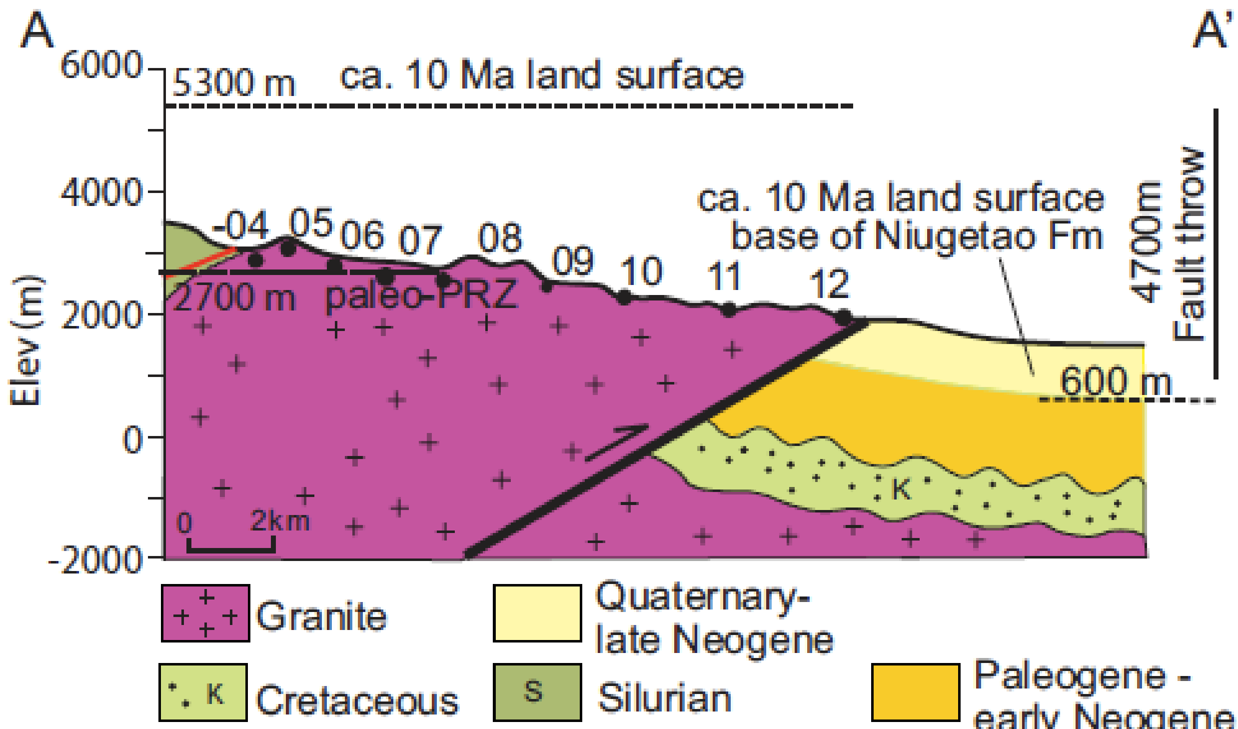




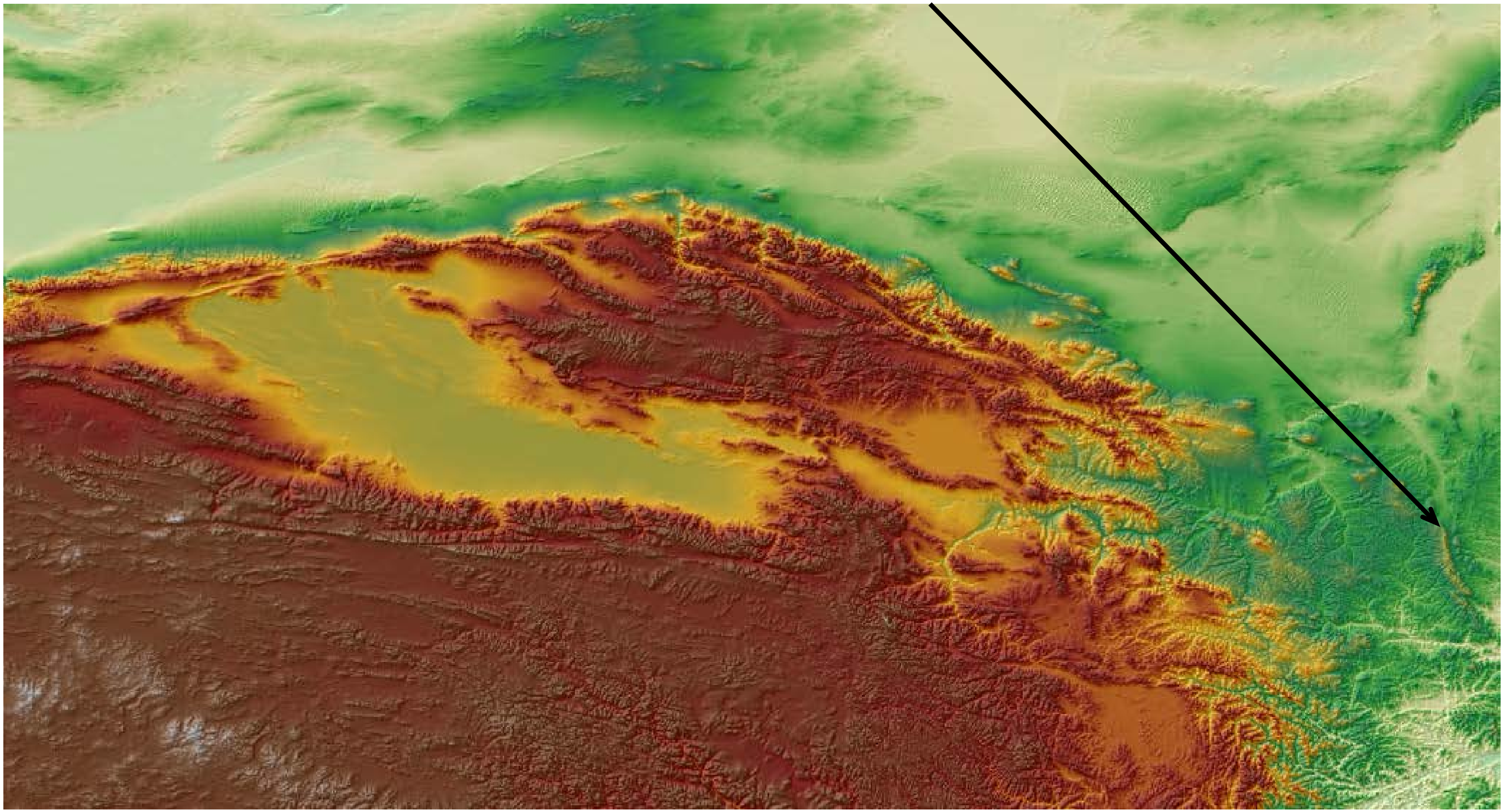
North Qilian Shan:

Rapid cooling near 9 Ma



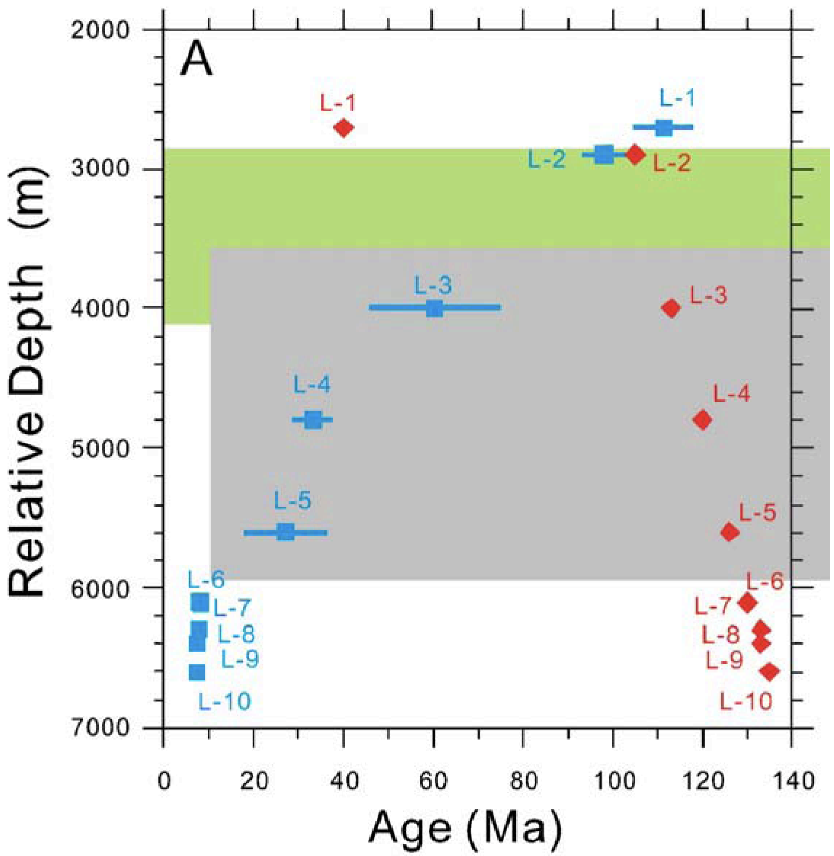
[*Zheng Dewen, Marin Clark, Zhang Peizhen, Zheng Wenjun, and Ken Farley, Geosphere*, 2010]

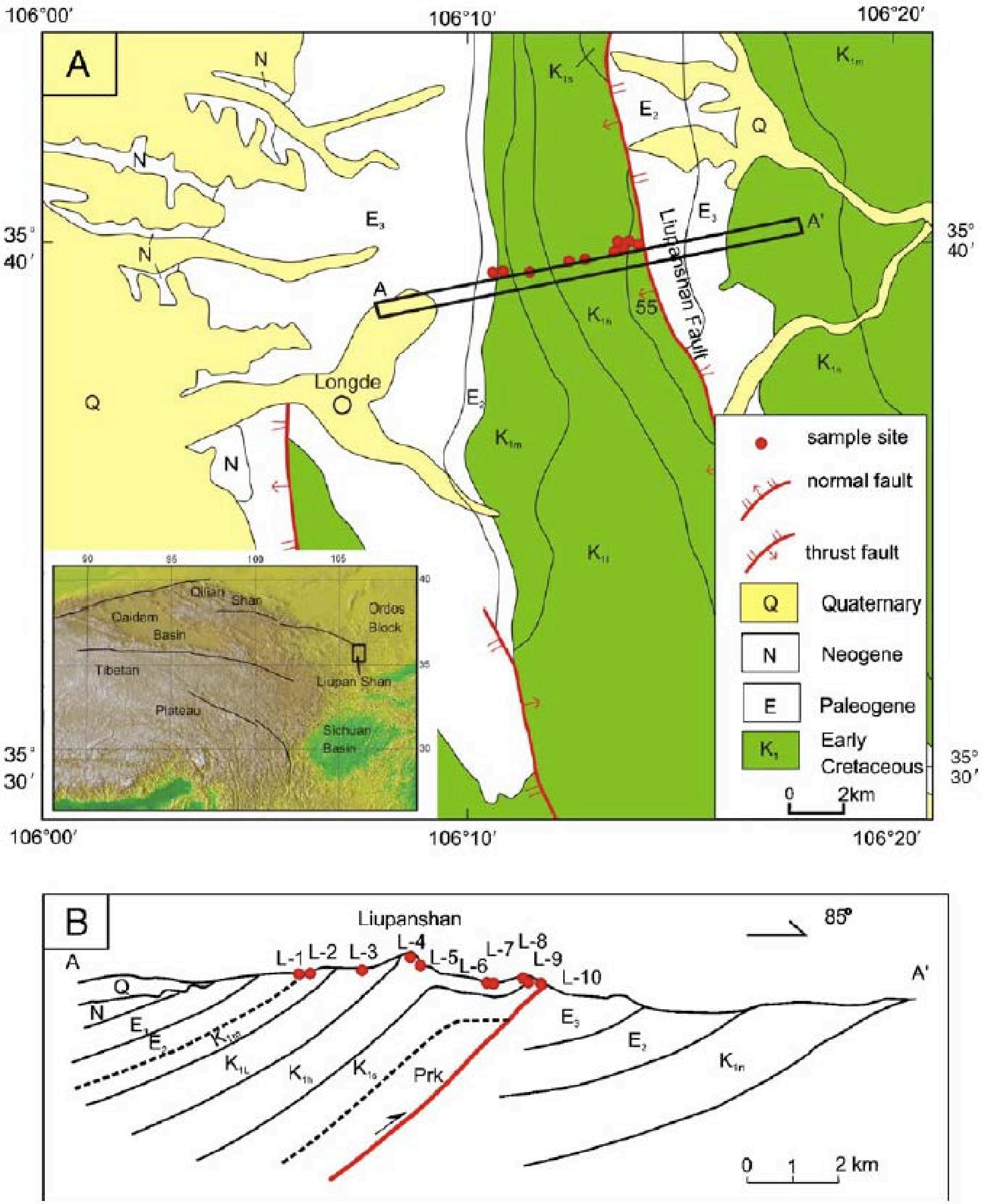
Emergence of the Liupanshan at ~ 8 Ma



[*Zheng Dewen et al.*, *EPSL*, 2007]

Fission Track ages: Liupanshan

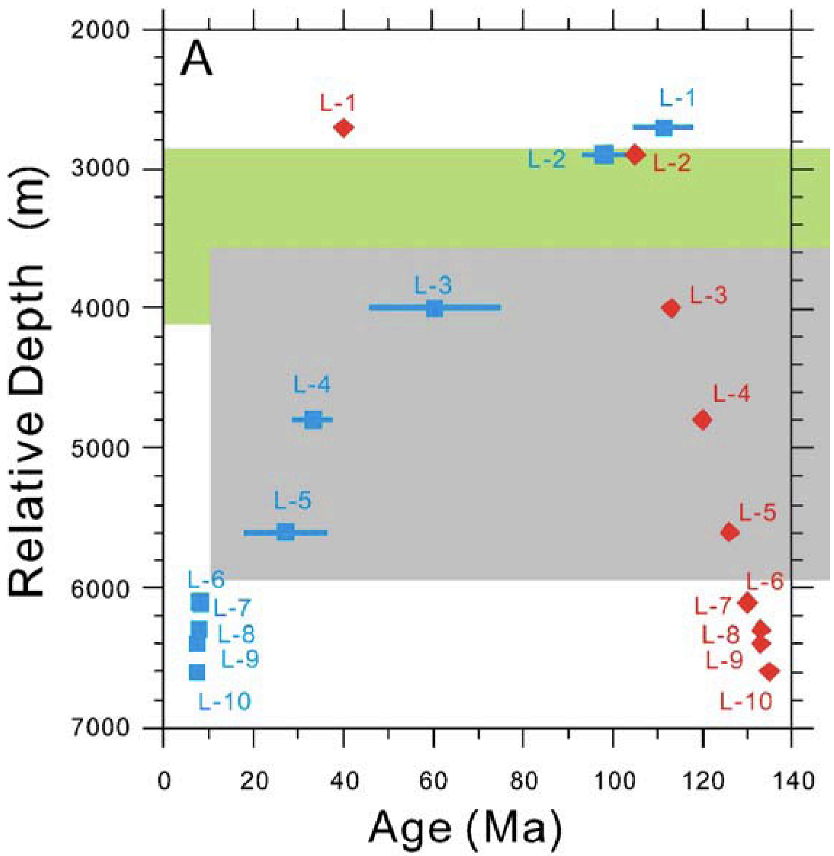


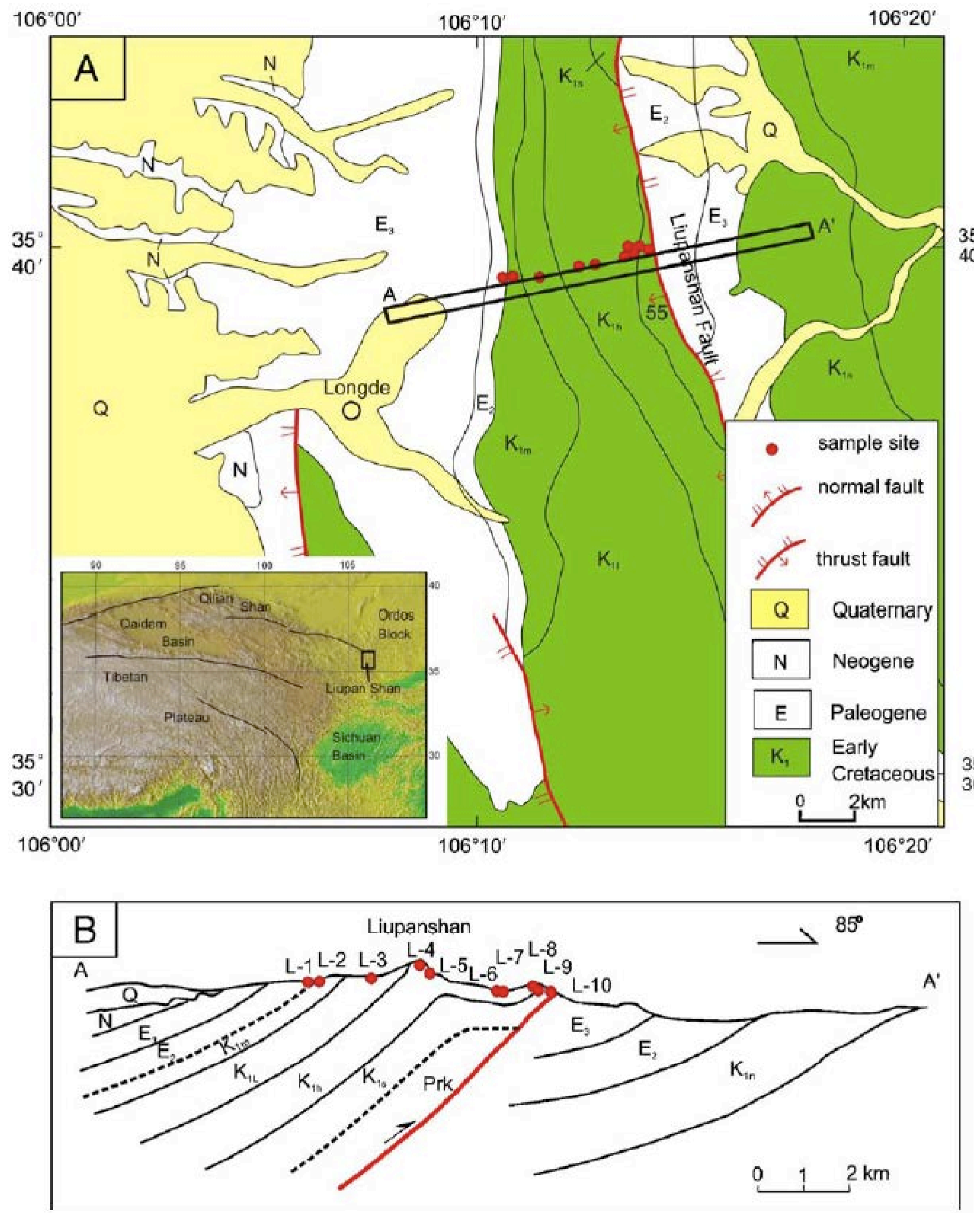


[*Zheng, Zhang, Wan, Yuan, Li, Yin, Zhang, Wang, Min, and Chen* 2007]

Fission Track ages: Liupanshan

Rapid exhumation at ~8 Ma





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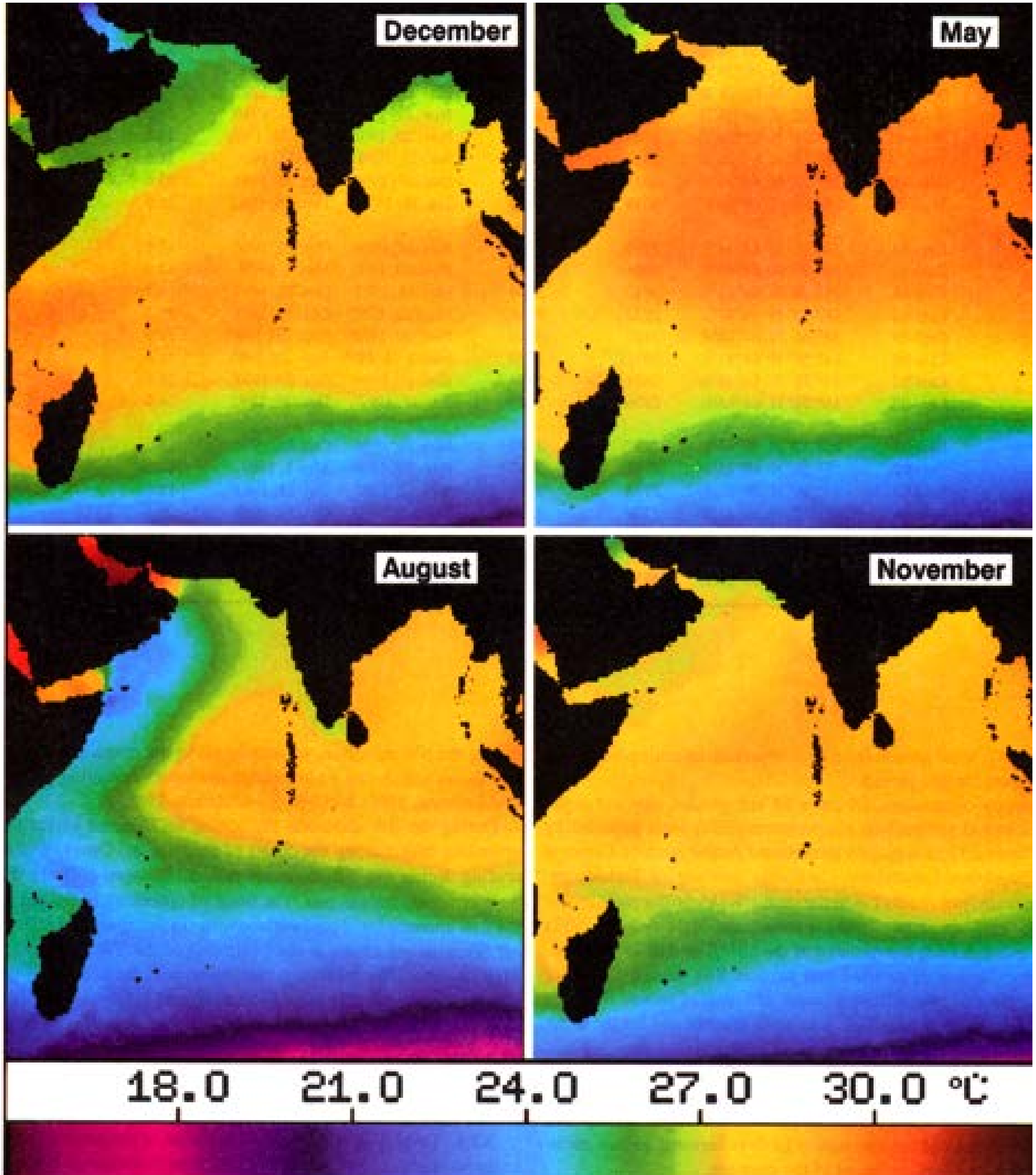
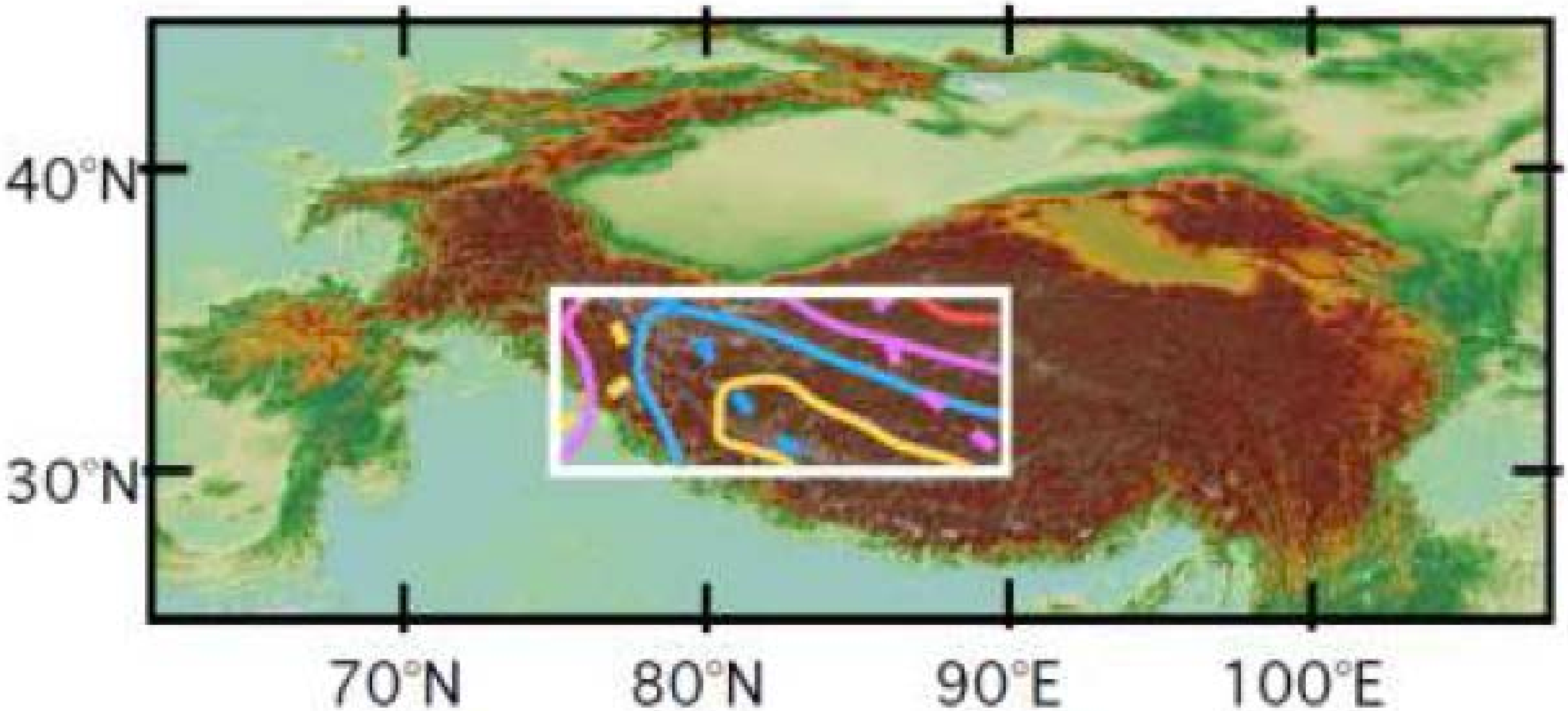


Indian Ocean Sea-Surface Temperature

During summer monsoons (June-August), northeastward (southeasterly) winds blow the surface water away from the coast and draw deep, cold, nutrient-rich water to the surface

[*Rixen, Haake, & Ittekot* 2000]

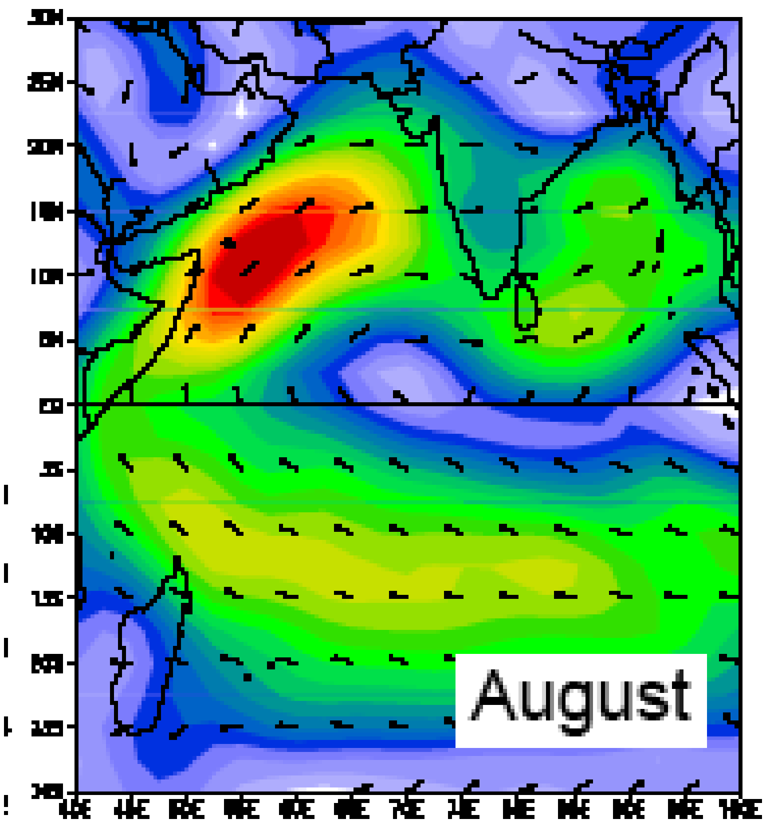
Heating over Tibet and the South Asian Monsoon: are they related at all?



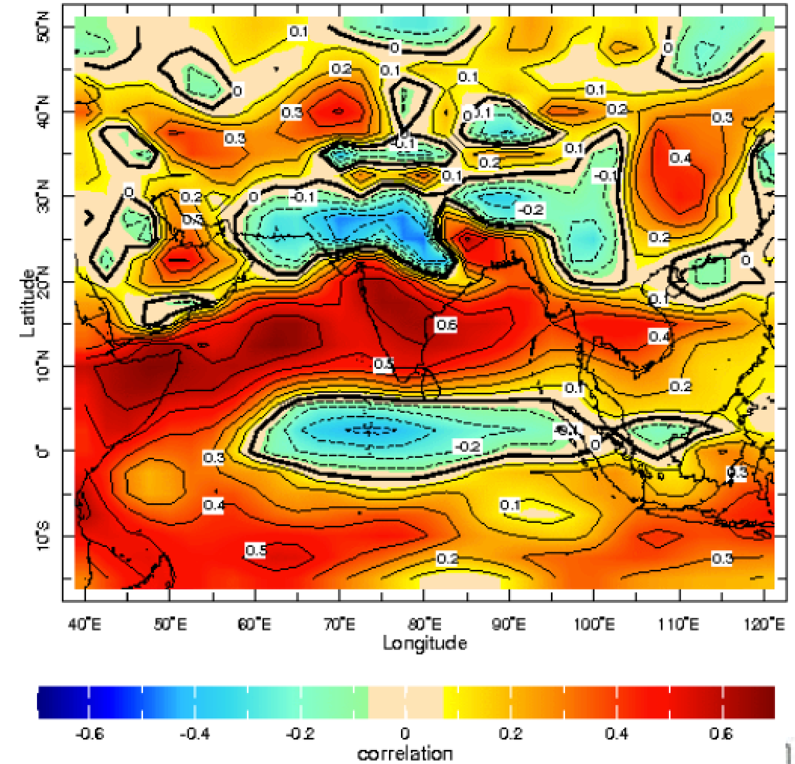
Moist static energy over Tibet

$$h = C_p T + L_v q + gz$$

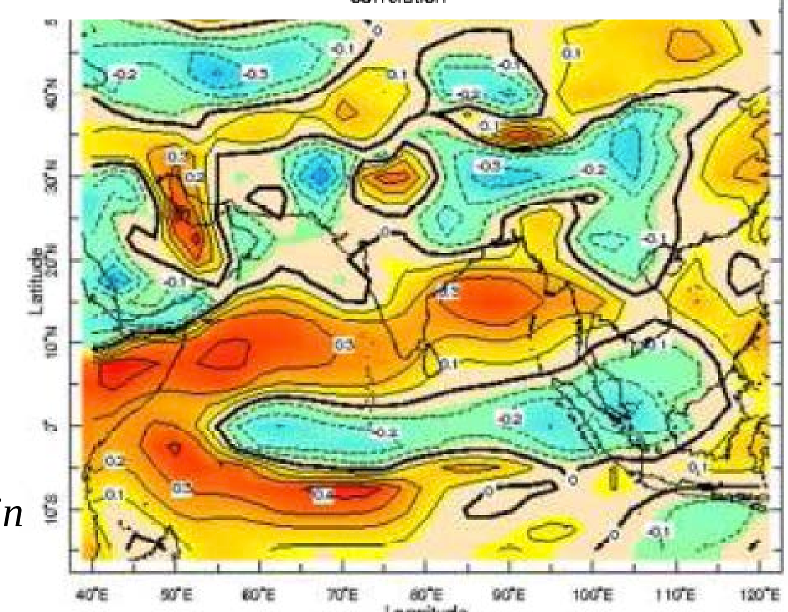
Correlation of moist static energy over Tibet with wind speeds



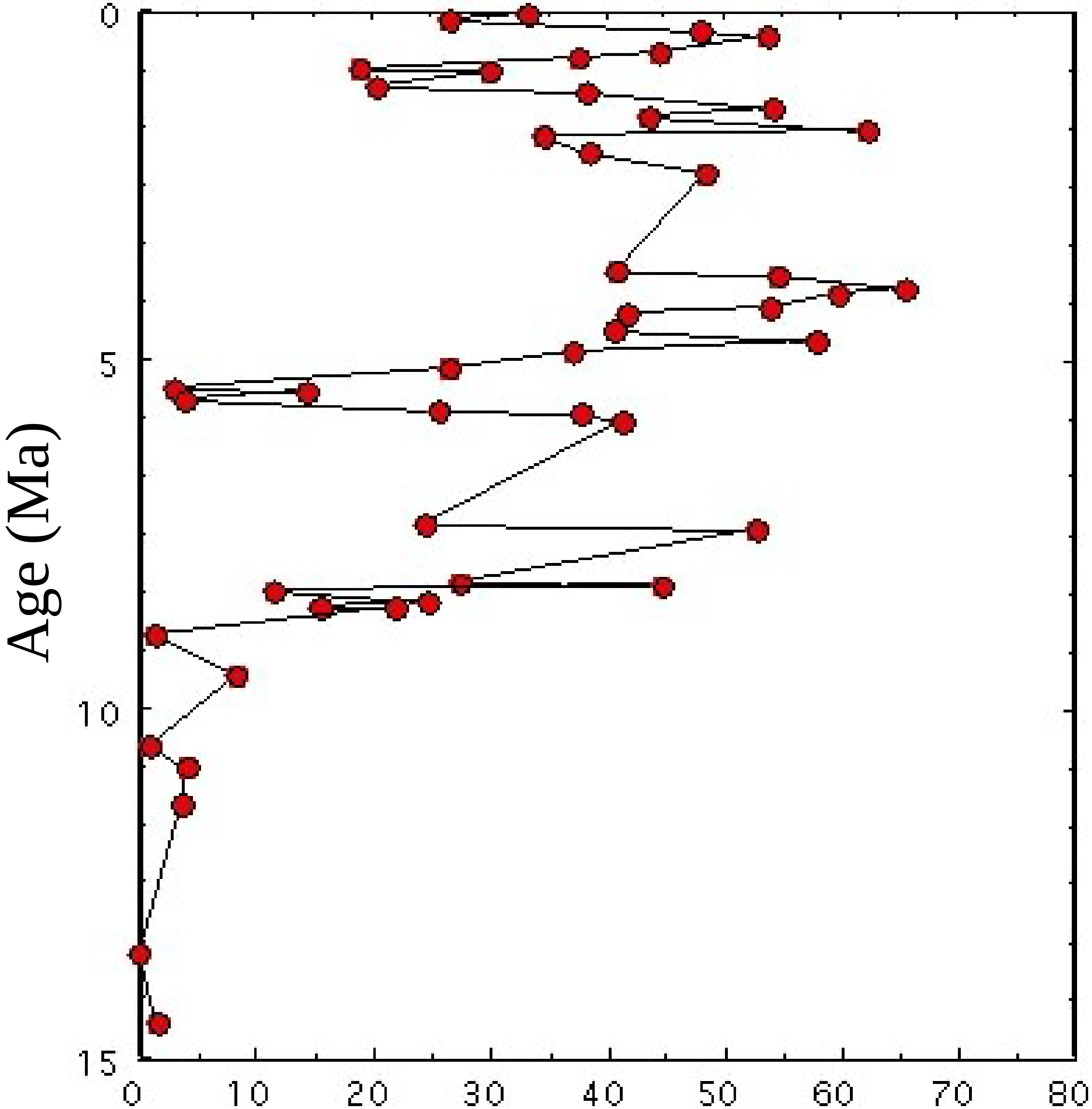
Late season



Early season



[*Rajagopalan and Molnar, in review*, 2013]



Percentage of *Globigirina Bulloides* at ODP Site 722 (Arabian Sea)

Increase in the fraction of *Globigirina Bulloides* in the Arabian Sea at ~8-9 Ma: Strengthening of the Indian monsoon?

From *Kroon, Steens, and Troelstra* [1991]; *Prell, Murray, Clemens, and Anderson* [1992] show the same.

Summary

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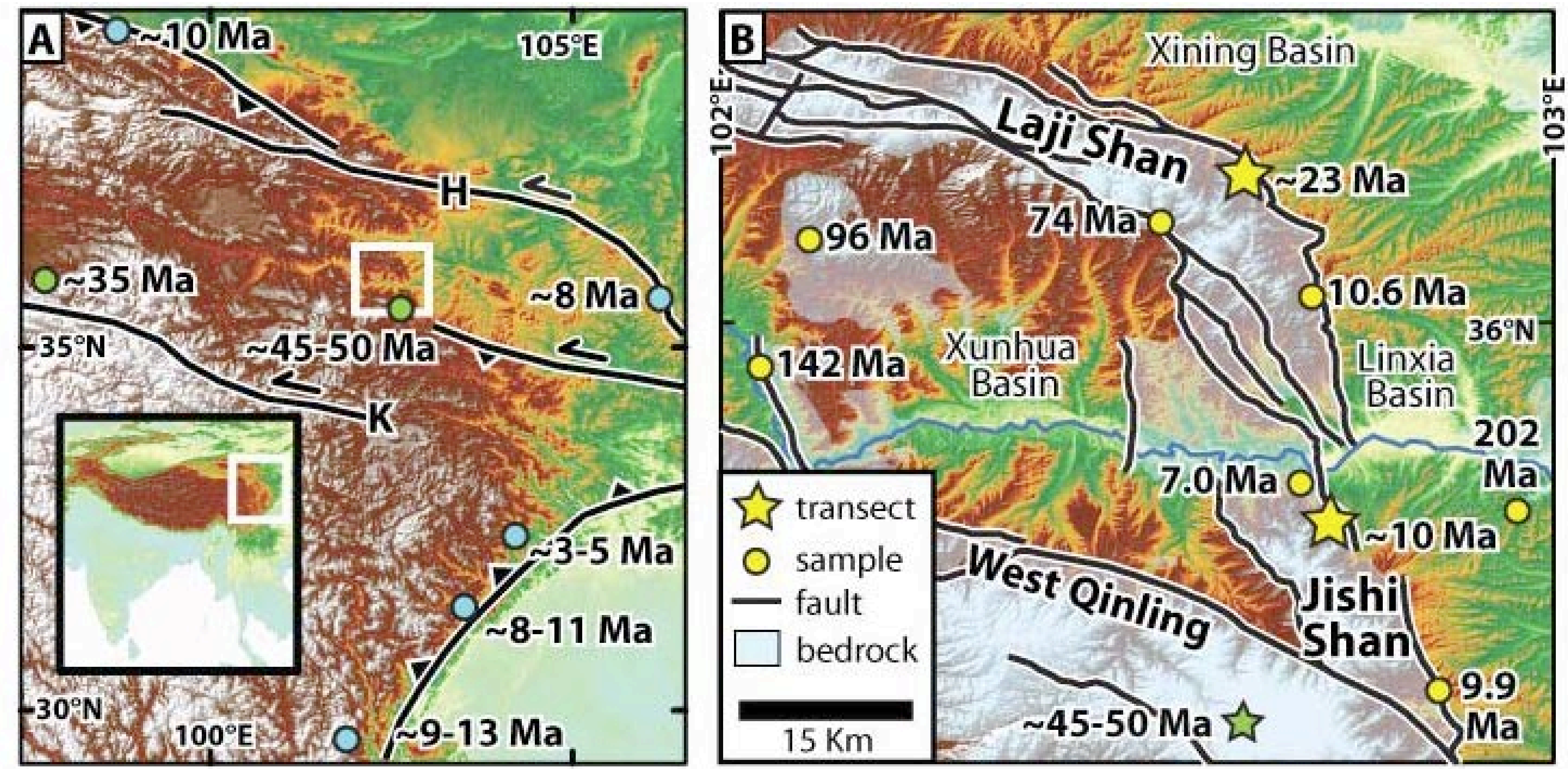
Summary

1. Tibet's rock started to deform at collision.
2. A big change occurred near 10-15 Ma (outward expansion of the plateau, normal faulting, and tilting of its eastern flank.)
3. Removal of mantle lithosphere beneath northern Tibet can account for these changes. It passes tests (so far).
4. A rise of Tibet may have affected regional climate, but that effect is more subtle than many, certainly I, have thought.

Growth of the Laji and Jishi Shan

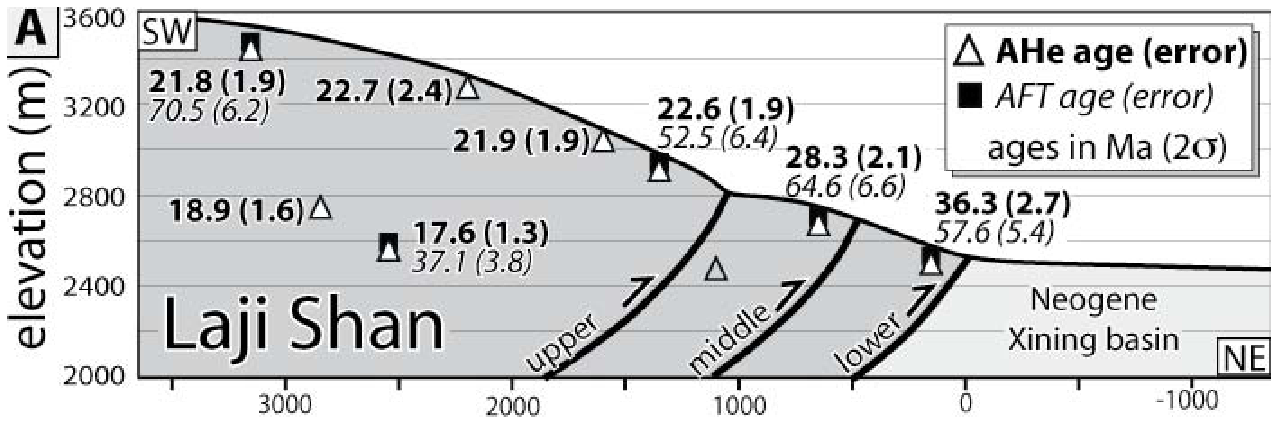


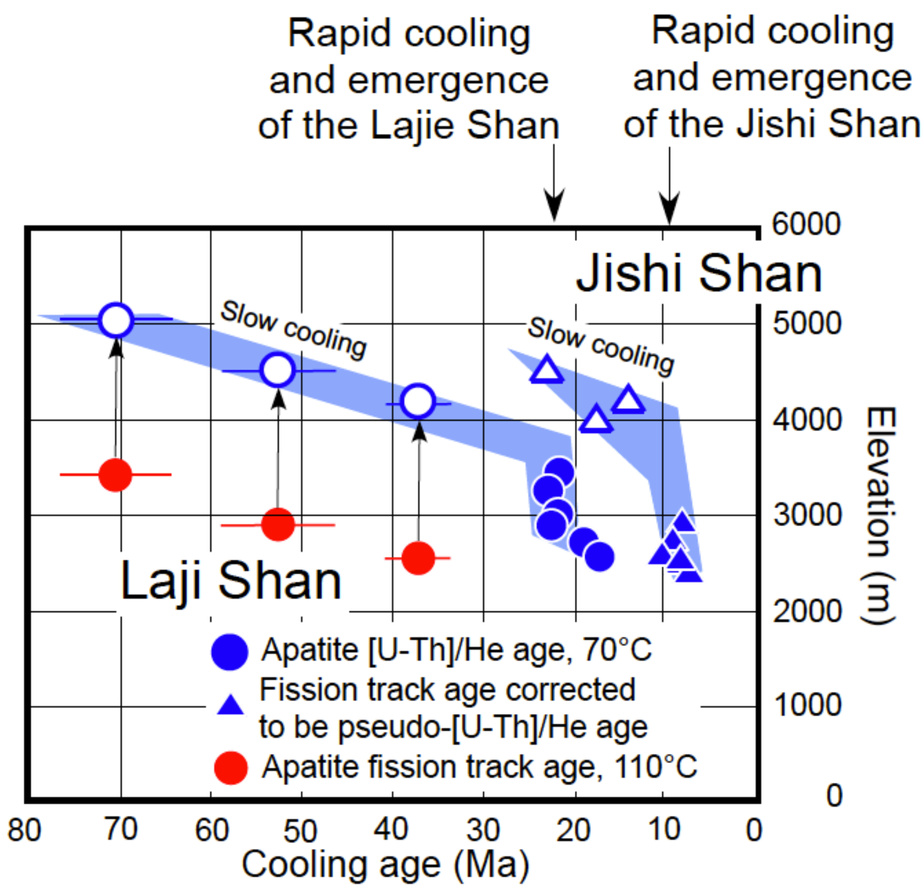
[*Richard Lease, Doug Burbank, Ken Farley, Marin Clark, & Zhang Huiping, Geology,* 2011]

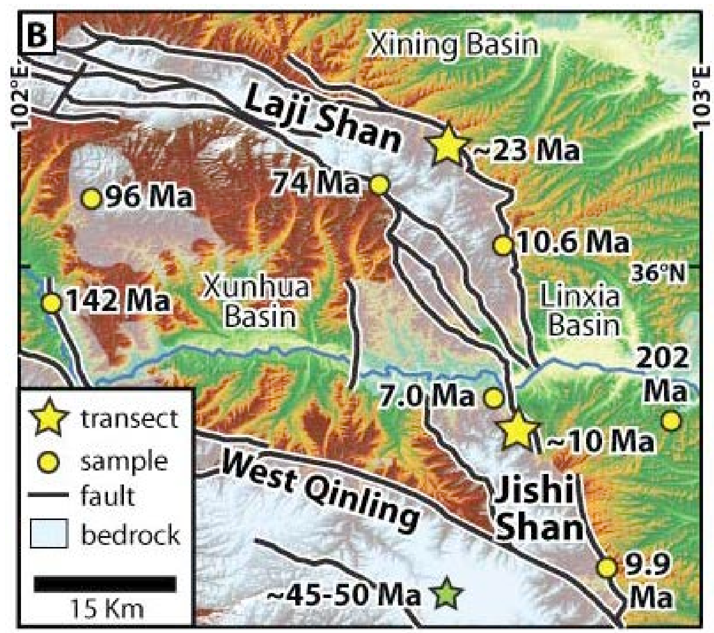
[*Brian Hough, Carmie Garzione, Wang Zhicai, Richard Lease, Doug Burbank, & Yuan Daoyang GSA Bulletin, 2011]*

Growth of the Laji Shan

N-S shortening beginning near 23 Ma



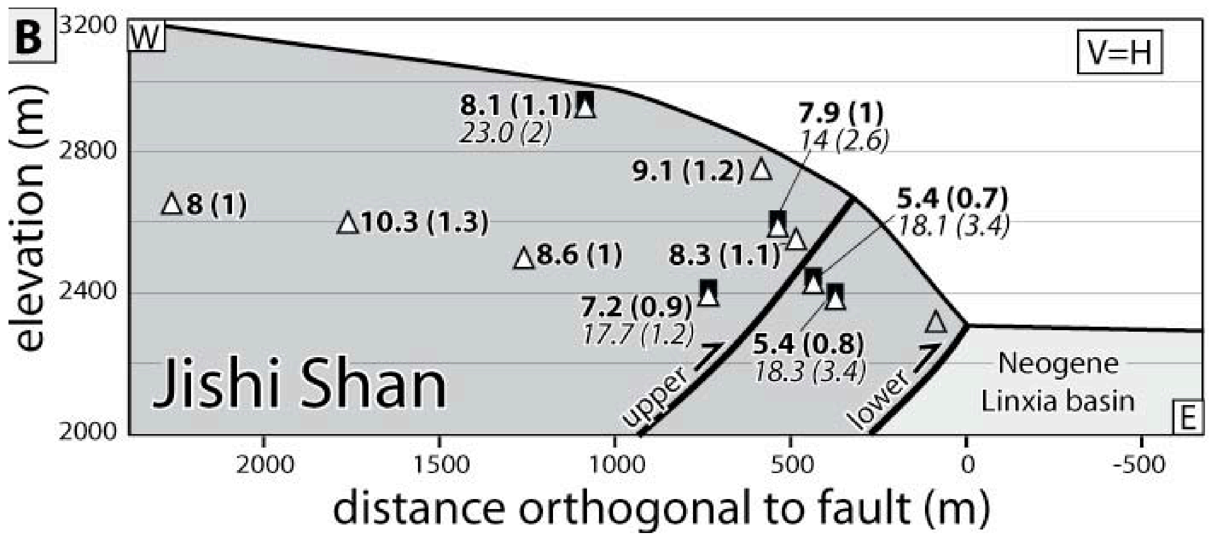


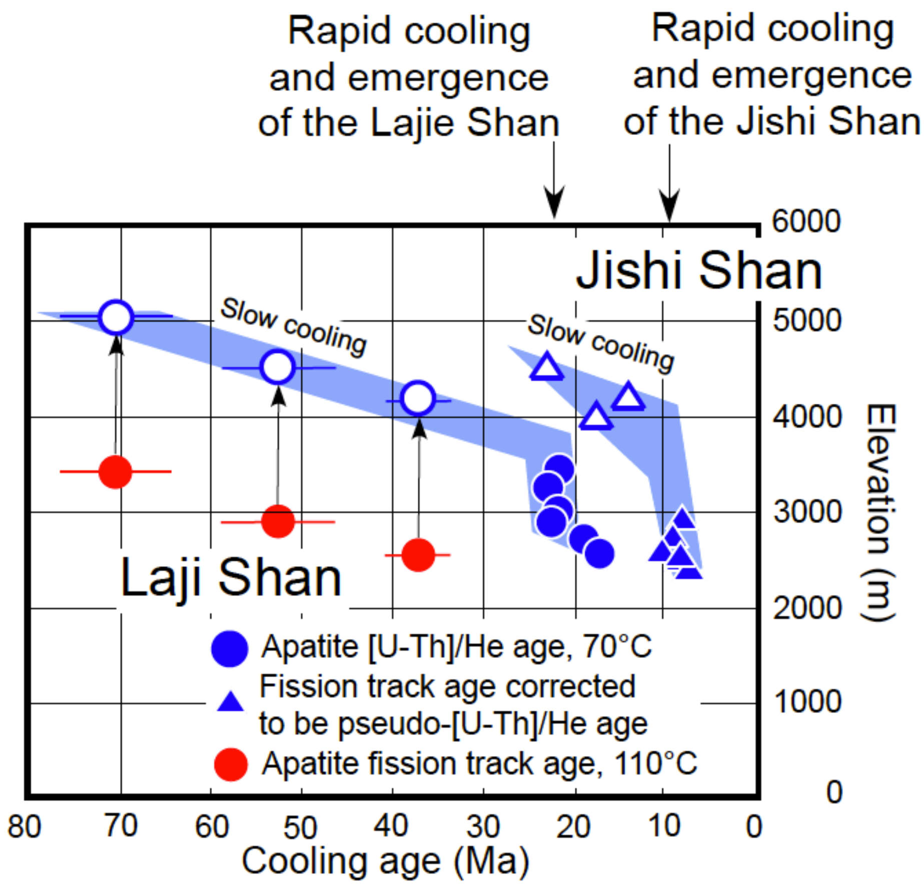


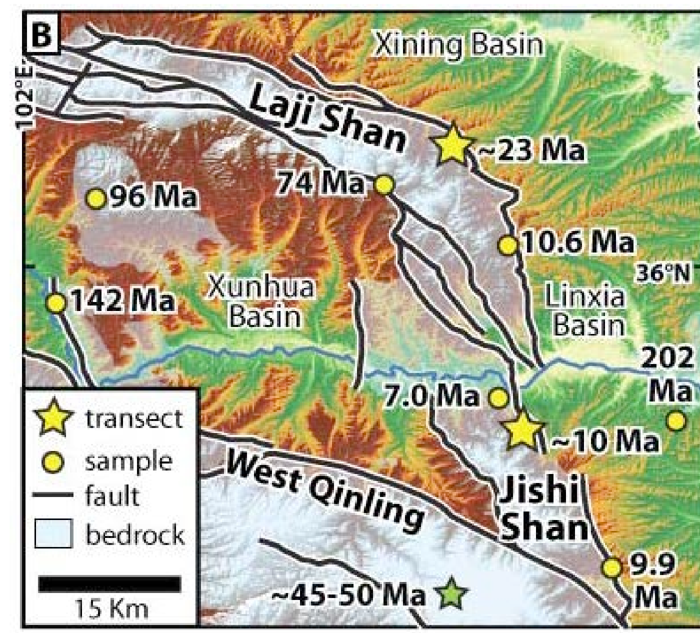
[*Lease, Burbank, Farley, Clark, and Zhang Huiping*, 2011]

Growth of the Jishi Shan

E-W shortening beginning near 10 Ma







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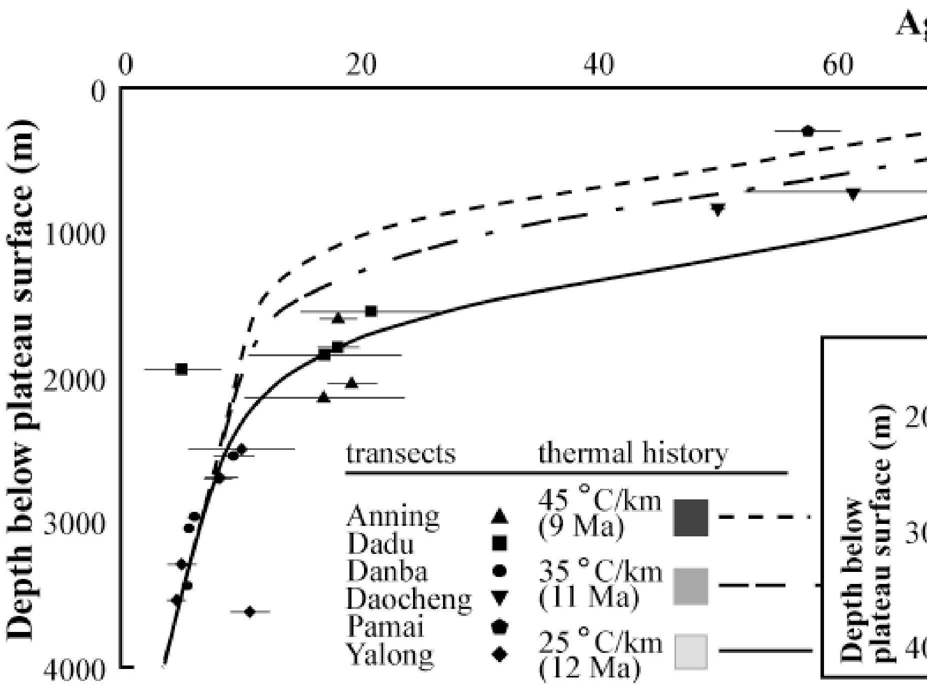
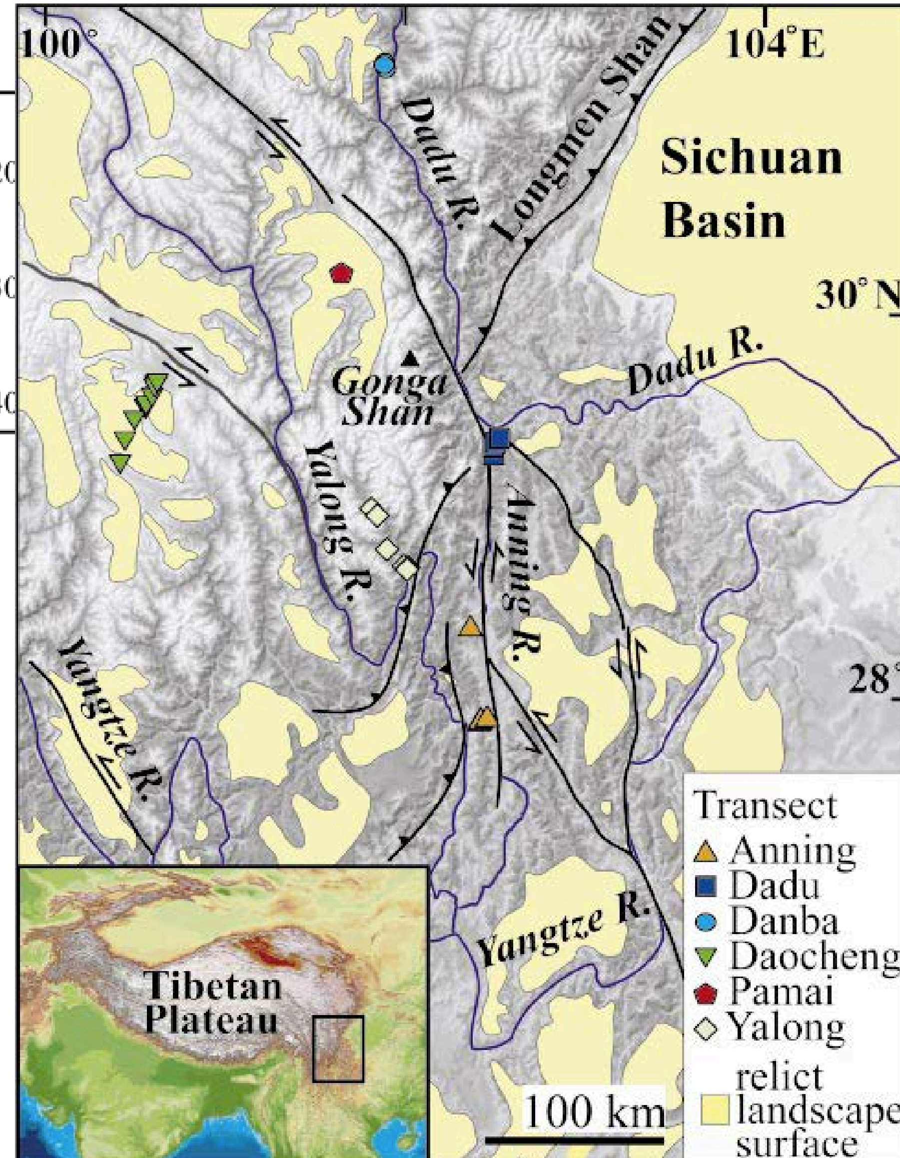
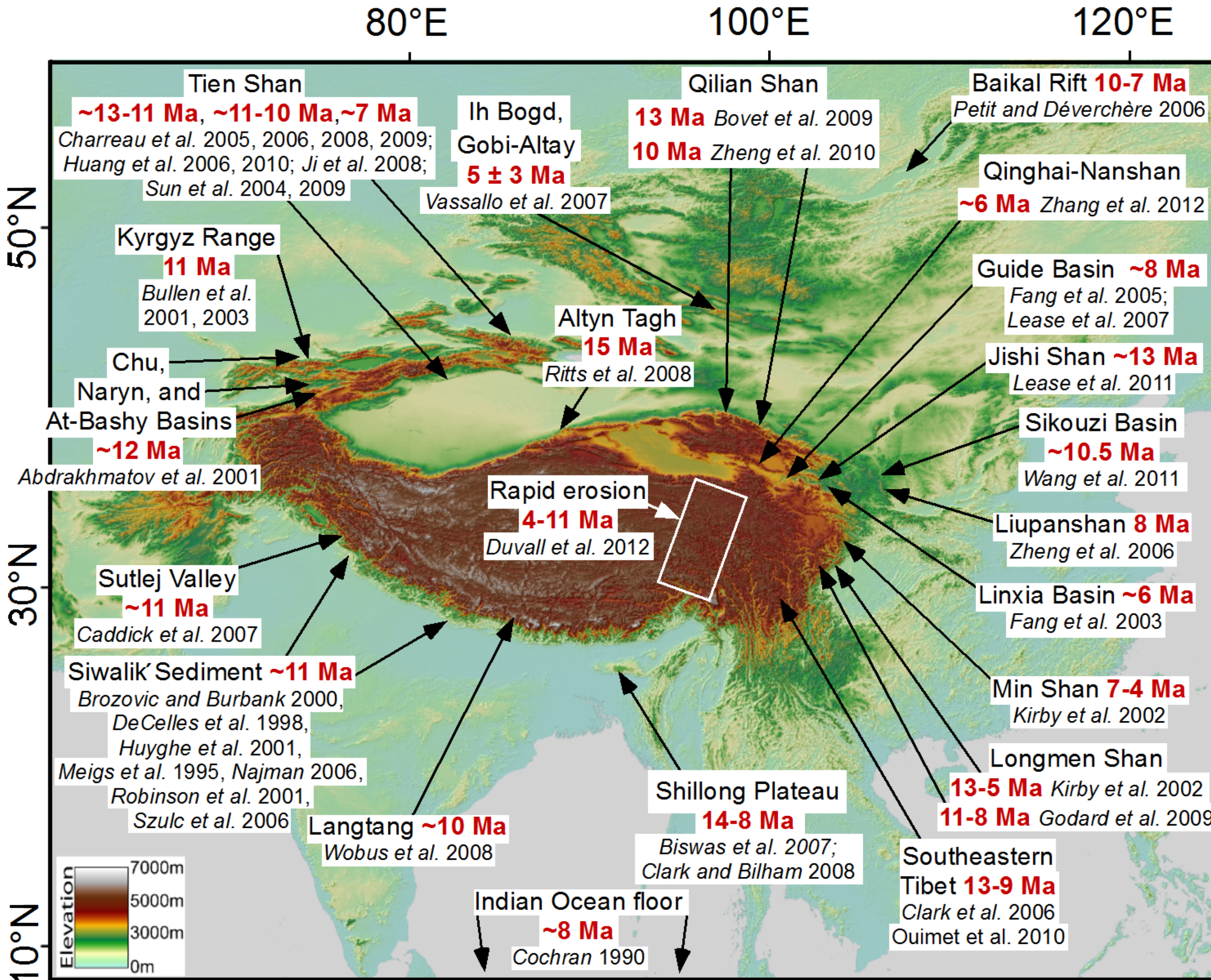




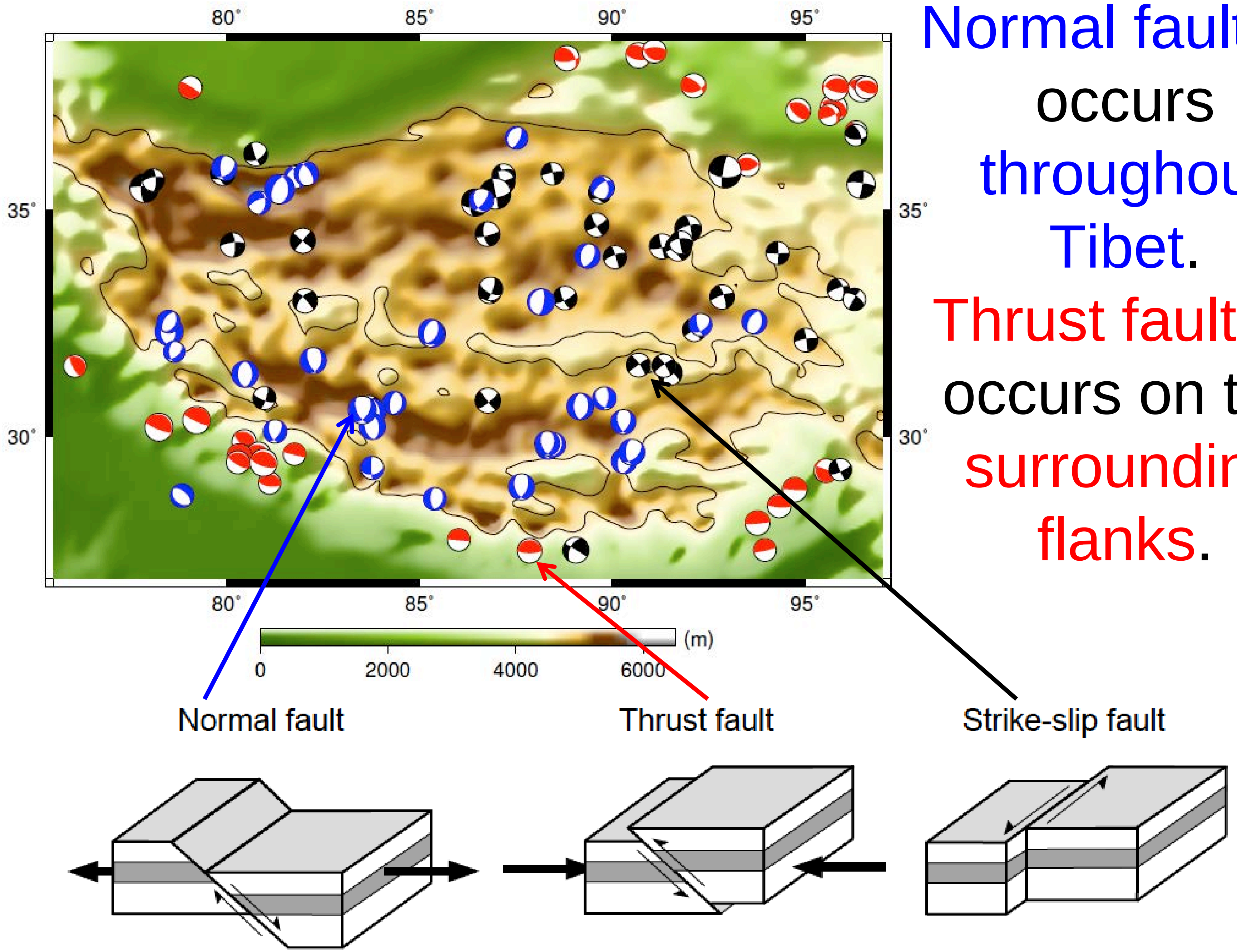
Abrupt incision of eastern Tibet at ~10 Ma

[*Clark, House, Royden, Whipple, Burchfiel, Zhang and Tang*, 2005]

Deformation surrounding Tibet beginning at, or since, ~15 Ma; but collision occurred at ~45 Ma

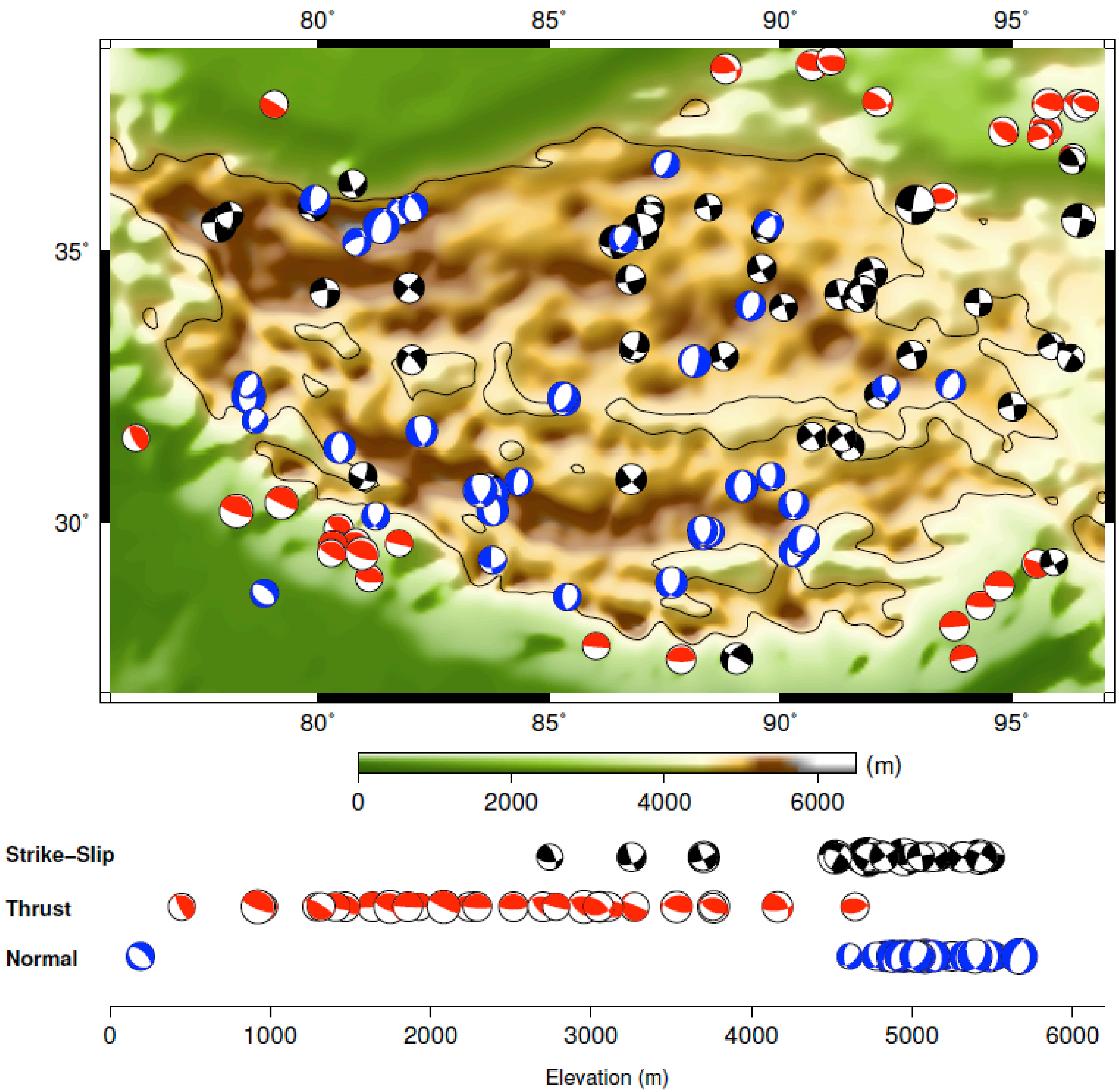


[*Elliott, Walters, England, Jackson, Li, and Parsons* 2010]



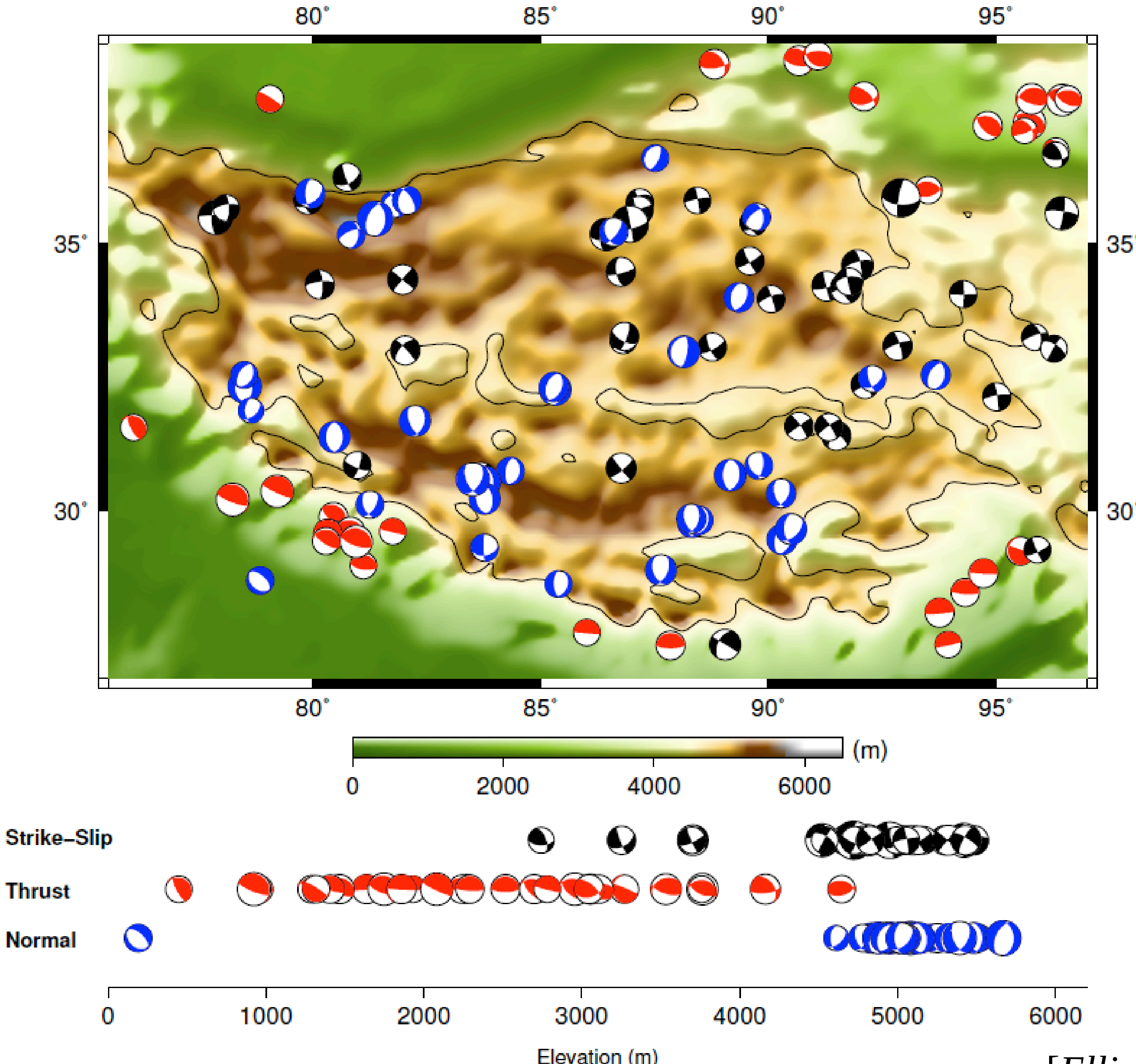
Normal faulting occurs throughout Tibet.

Thrust faulting occurs on the surrounding flanks.



[*Elliott, Walters, England, Jackson, Li, and Parsons* 2010]

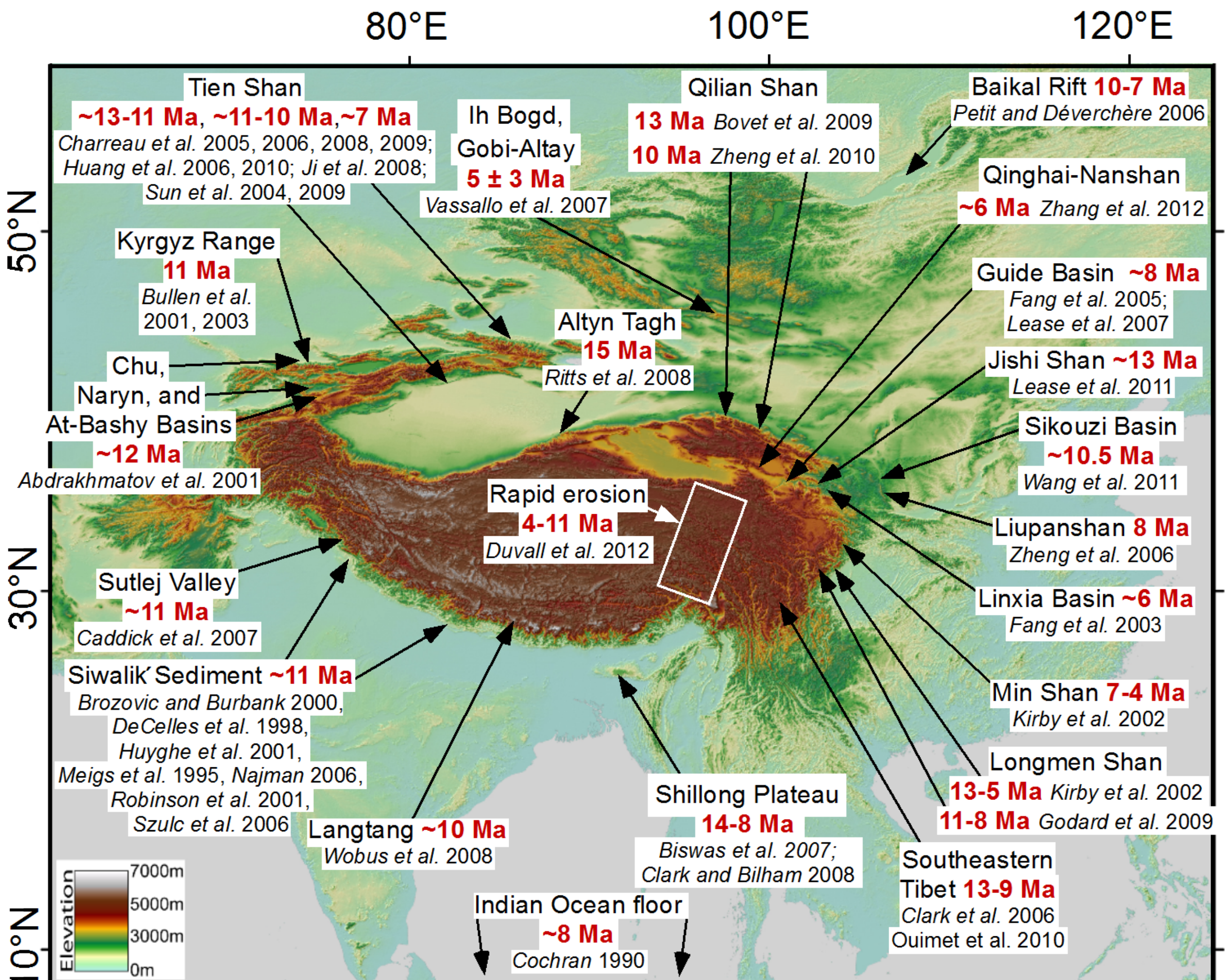
Normal faulting and E-W crustal extension occur throughout Tibet; thrust faulting and crustal shortening occur on the surrounding flanks.

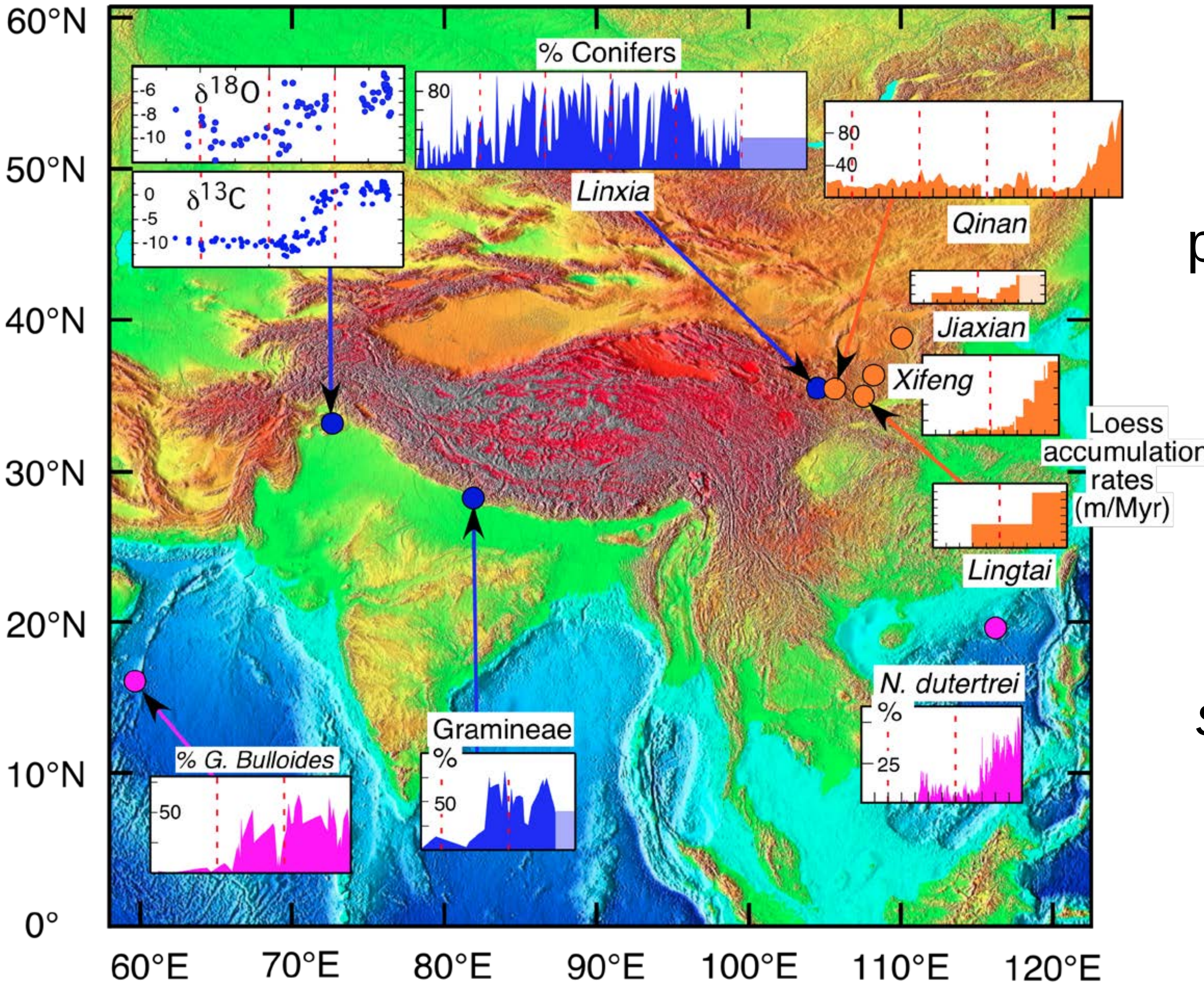


Present-day normal faulting requires a **change** in the balance of forces (*per unit length on the margins*)

[*Elliott, Walters, England, Jackson, Li, and Parsons* 2010]

Deformation surrounding Tibet beginning at, or since, ~15 Ma; but collision occurred at ~45 Ma





Million-year time series of paleoclimate *suggest some climate change(s) since ~10 Ma surrounding Tibet.*

Compiled by *Molnar, Boos, and Battisti* [2010]

Francis Birch

Elasticity and constitution of the Earth's interior,
Journal of Geophysical Research, 57, 227-286, 1952.

"Unwary readers should take warning **that ordinary language** undergoes **modification** to a **high-pressure form** when applied to the interior of the earth; a few equivalents follow:

High-pressure form:	**Ordinary meaning:**
Certain	**Dubious**
Undoubtedly	**Perhaps**
Positive Proof	**Vague Suggestion**
Unanswerable Argument	**Trivial Objection**
Pure Iron	**Uncertain Mixture of all of the Elements**

An earthquake seismologist's view of time in Pre-Pliocene paleoclimate

10 Ma = 5 Ma

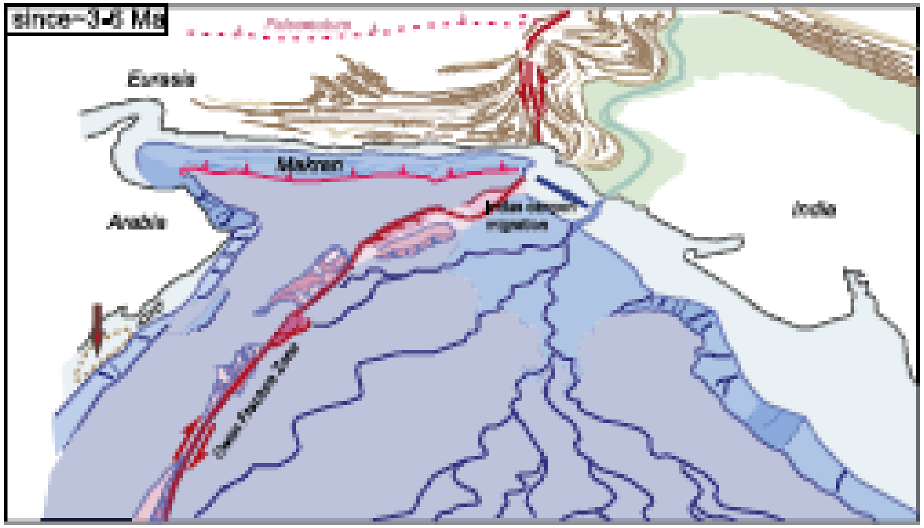
and

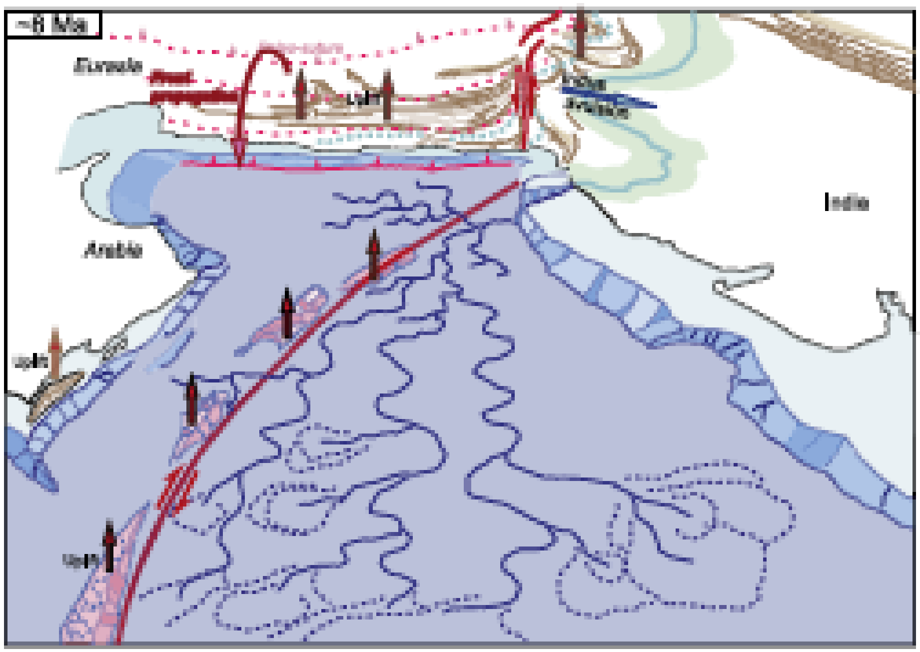
10 Ma = 15 Ma

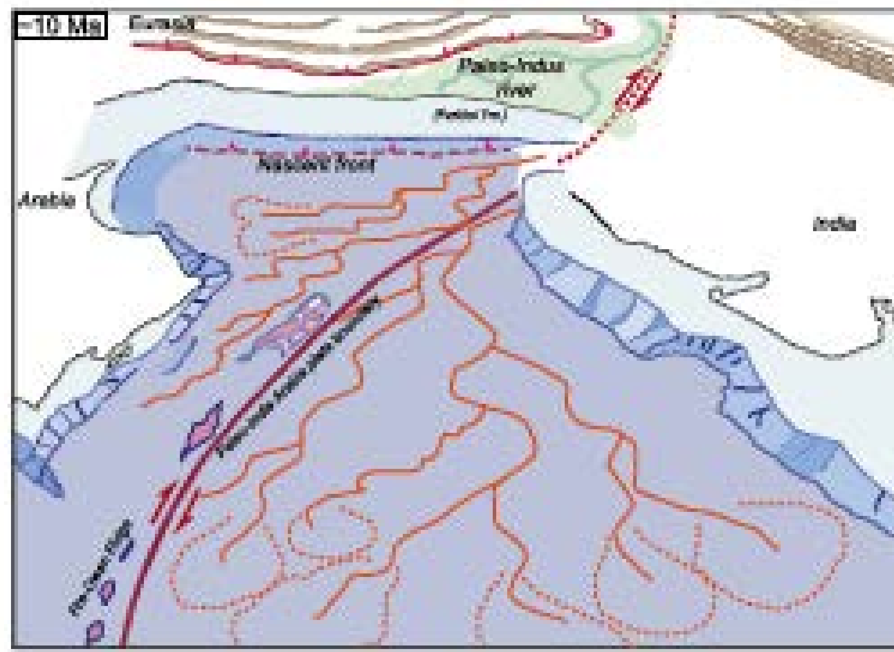
in addition to

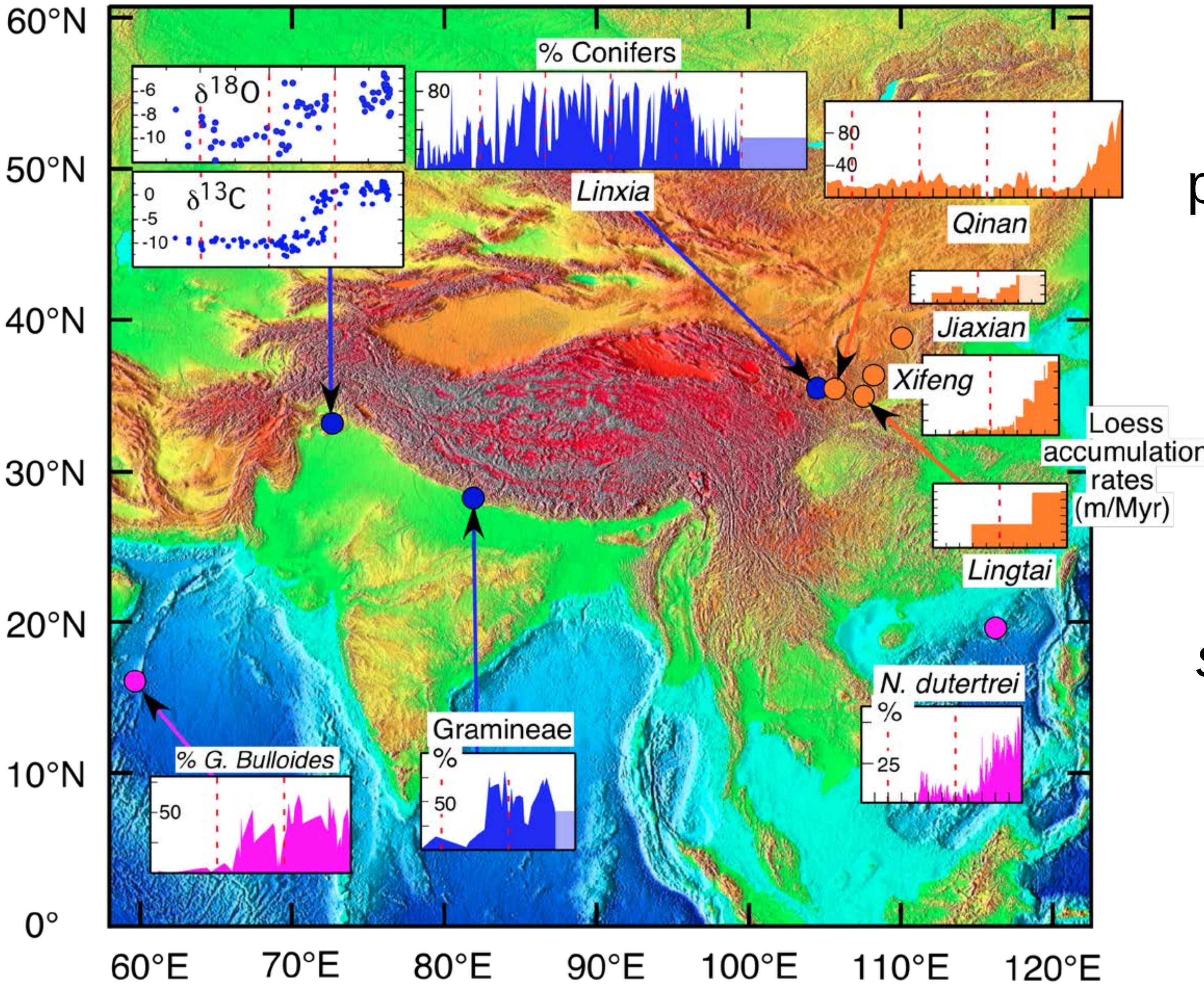
10 Ma = 10 ± 1 Ma

Owen Ridge rose above the Calcite Compensation Depth (CCD) at ~ 8-9 Ma







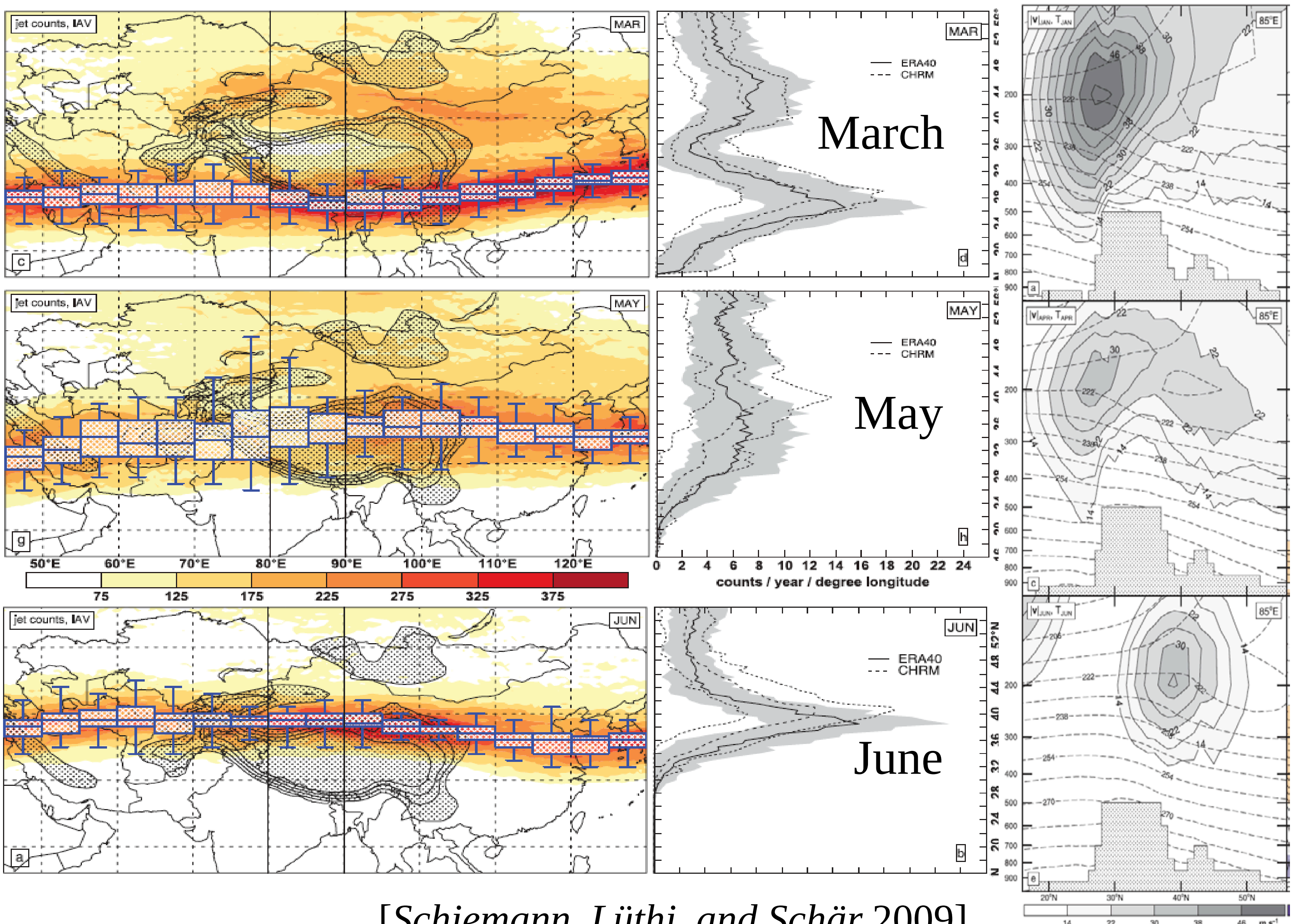


Million-year time series of paleoclimate

a suggestion of climate change since ~10 Ma surrounding Tibet.

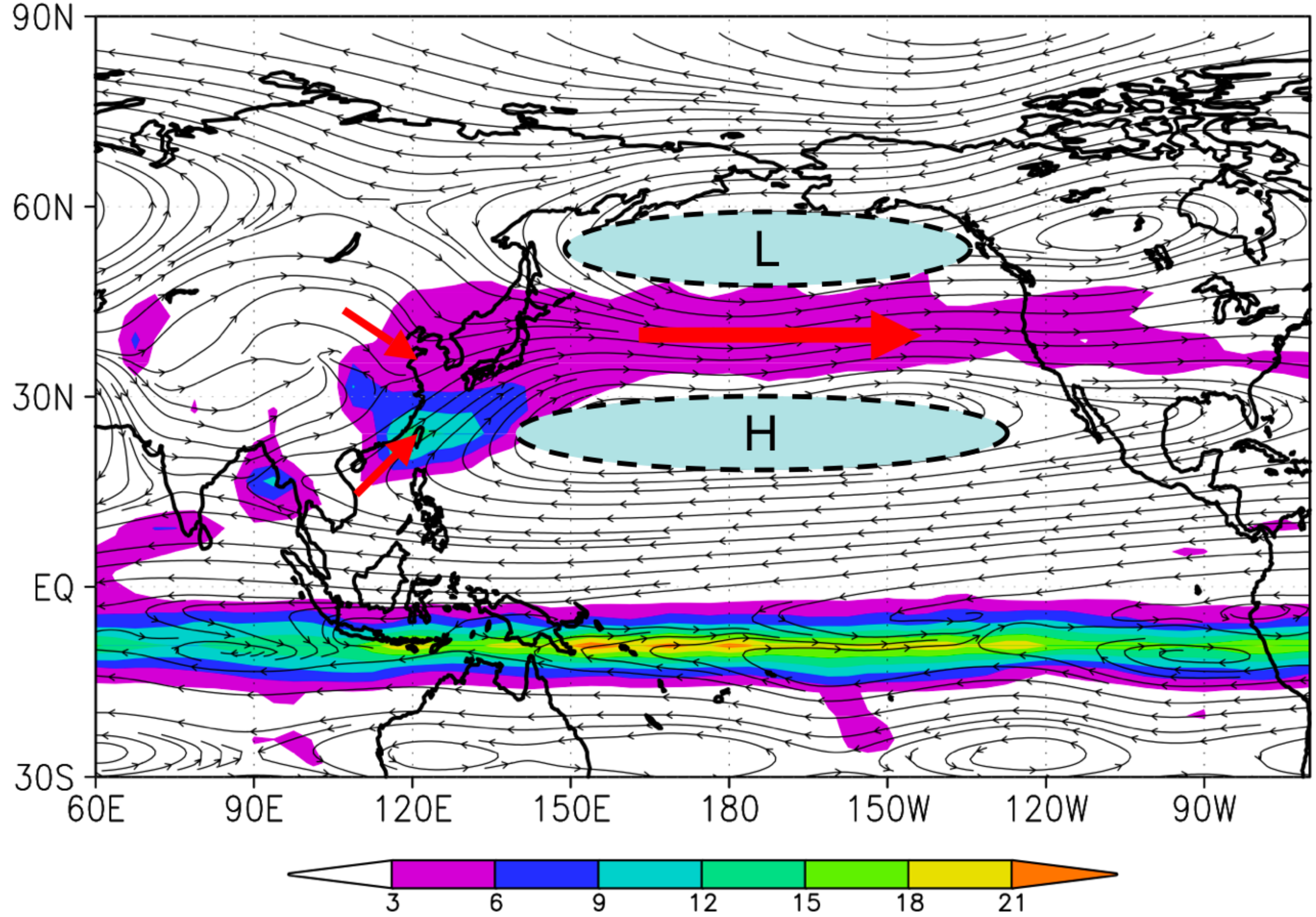
Compiled by *Molnar, Boos, and Battisti* [2010]

Jet speed and position



[*Schiemann, Lüthi, and Schär* 2009]

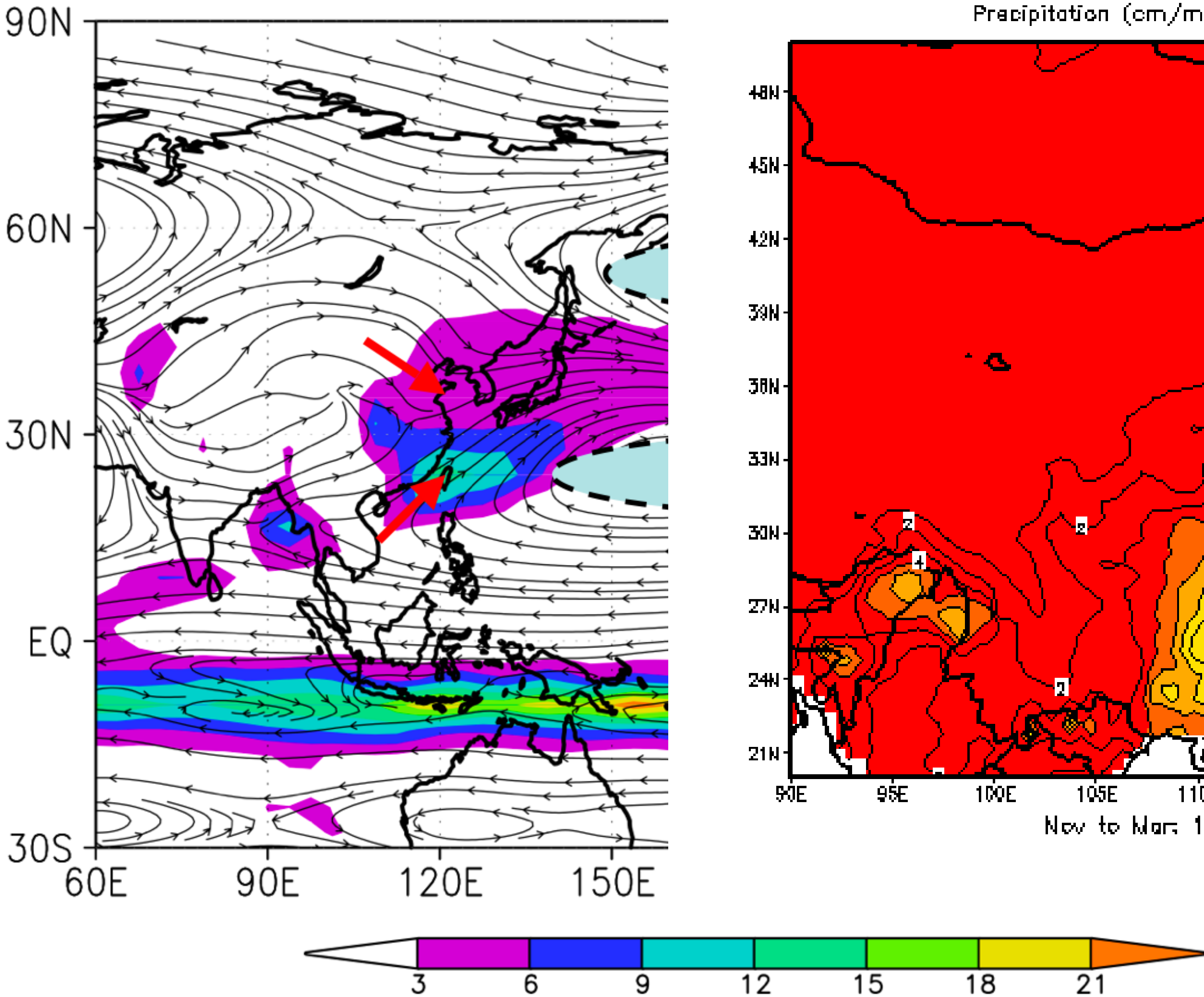
Winds and Precipitation (mm/day) and streamlines at 850 mb in an Aquaplanet GCM (with an ocean surface at ~5000 m over Tibet)

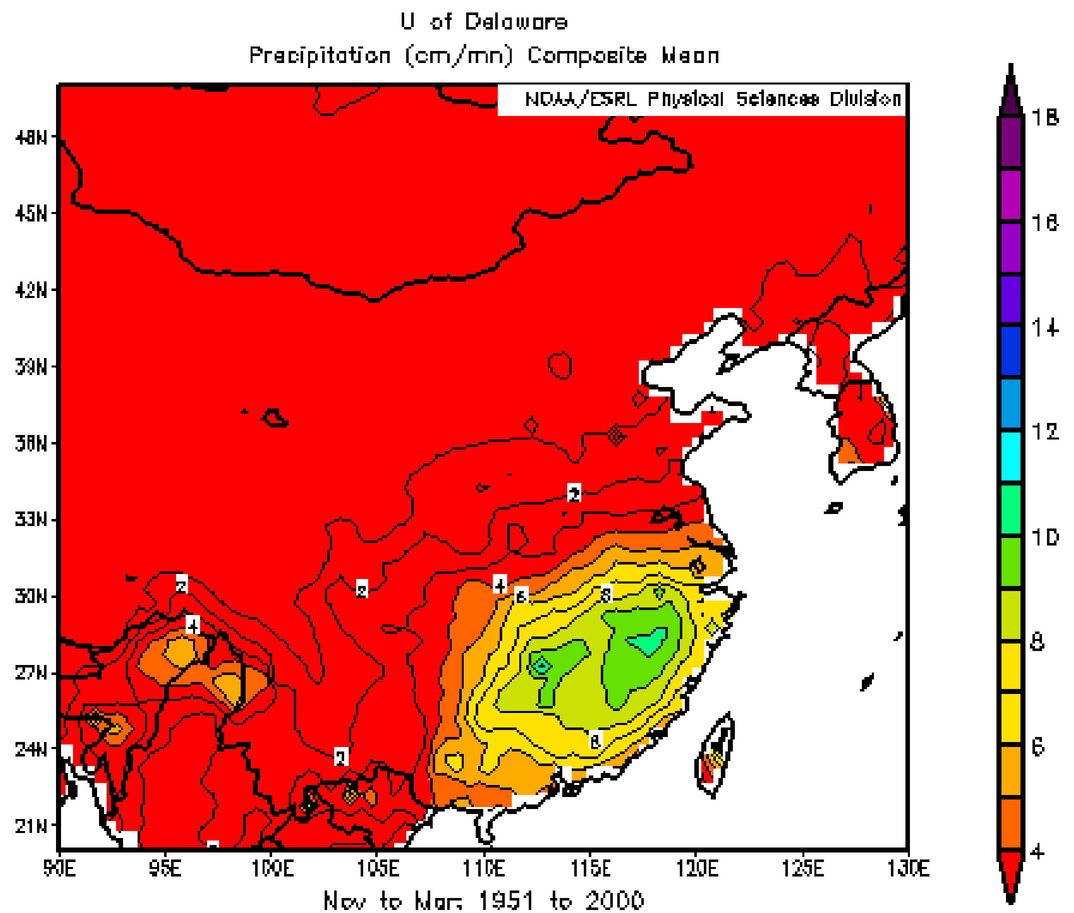


[*Takahashi and Battisti* 2007] (but still in preparation)

Reproduced by *Molnar, Boos, and Battisti* [2010]

Aquaplanet GCM and observed Precipitation (mm/day) over China





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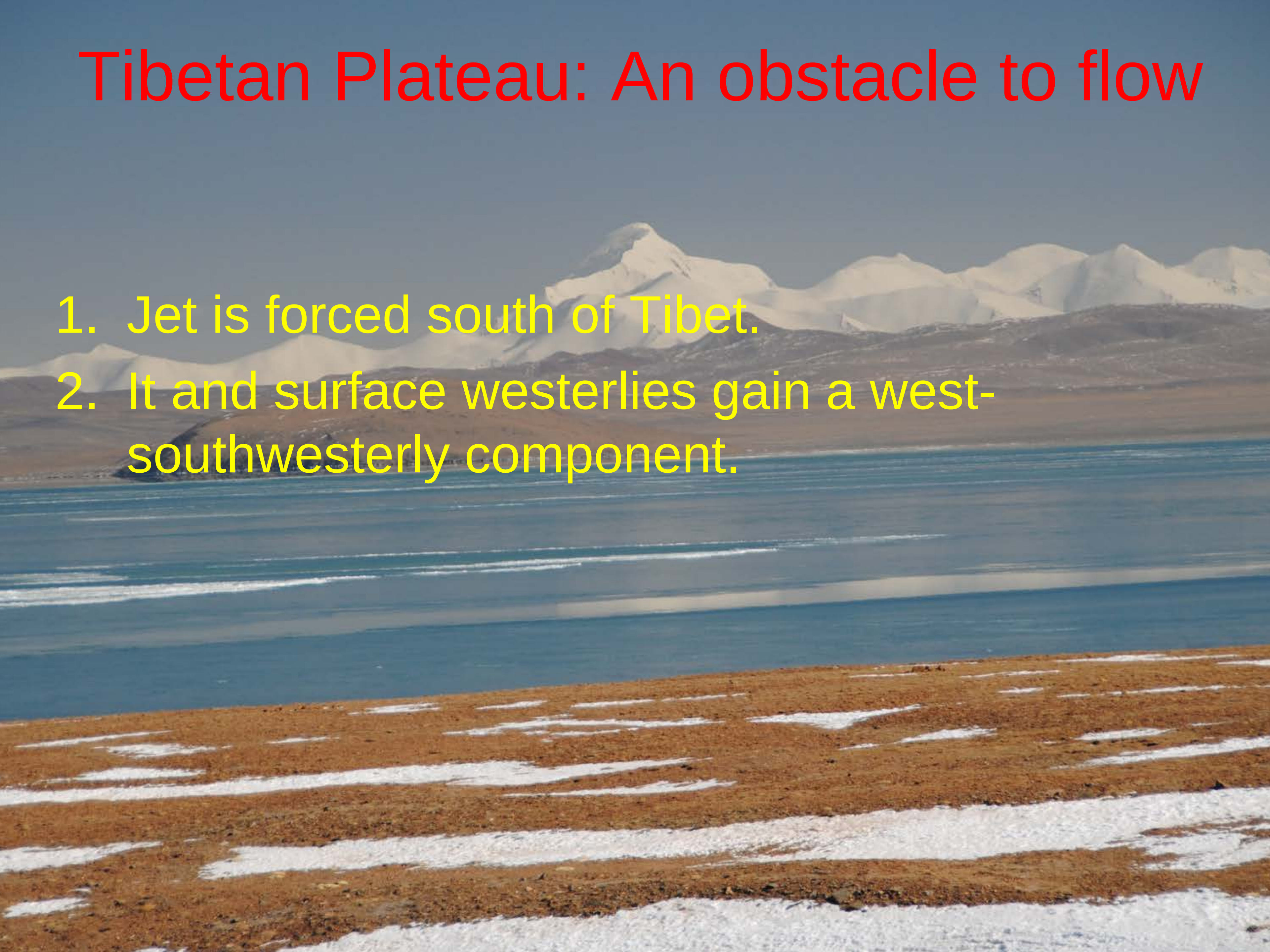
Tibetan Plateau: An obstacle to flow

1. Jet is forced south of Tibet.

Tibetan Plateau: An obstacle to flow



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2. It and surface westerlies gain a west-southwesterly component.

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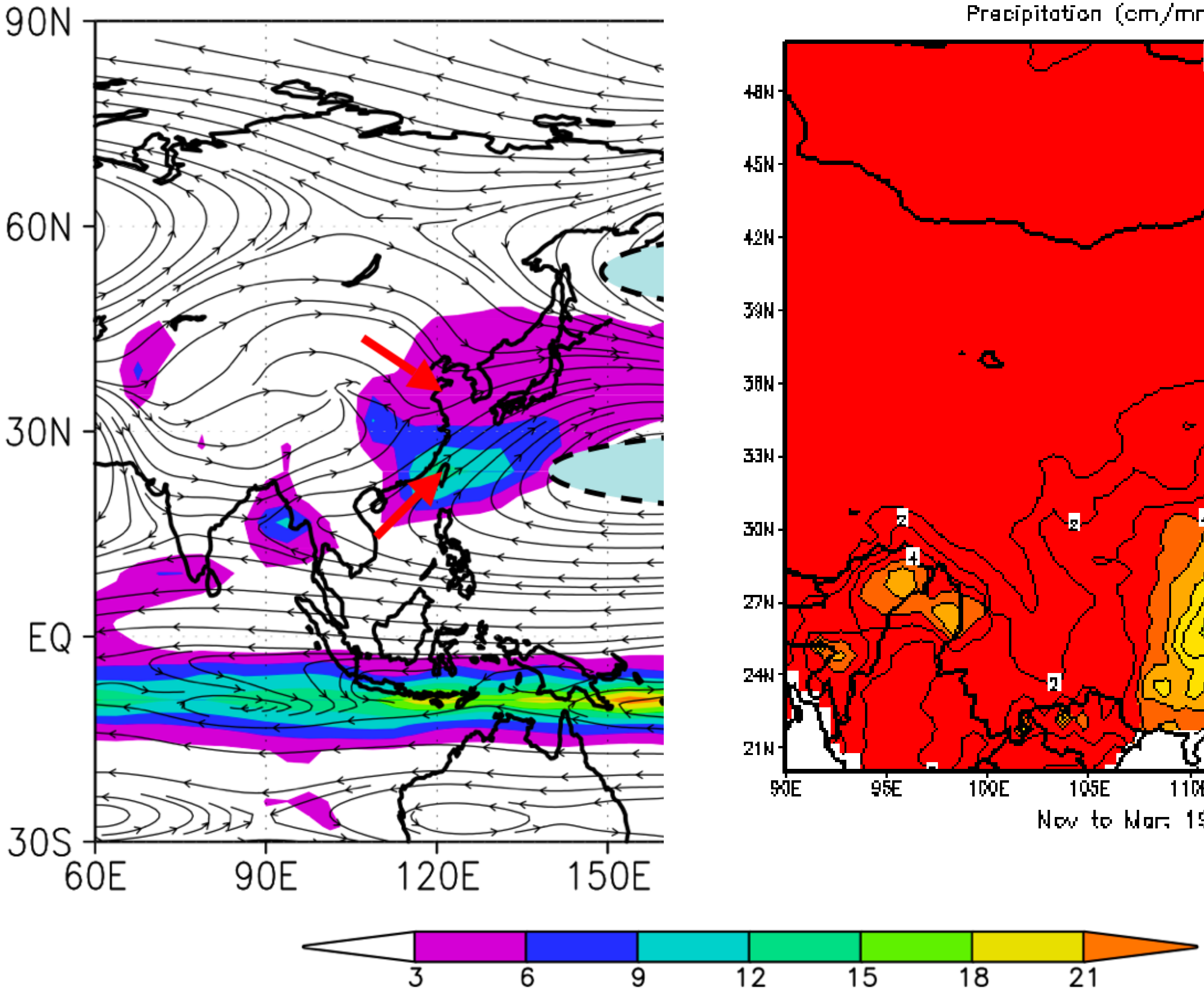

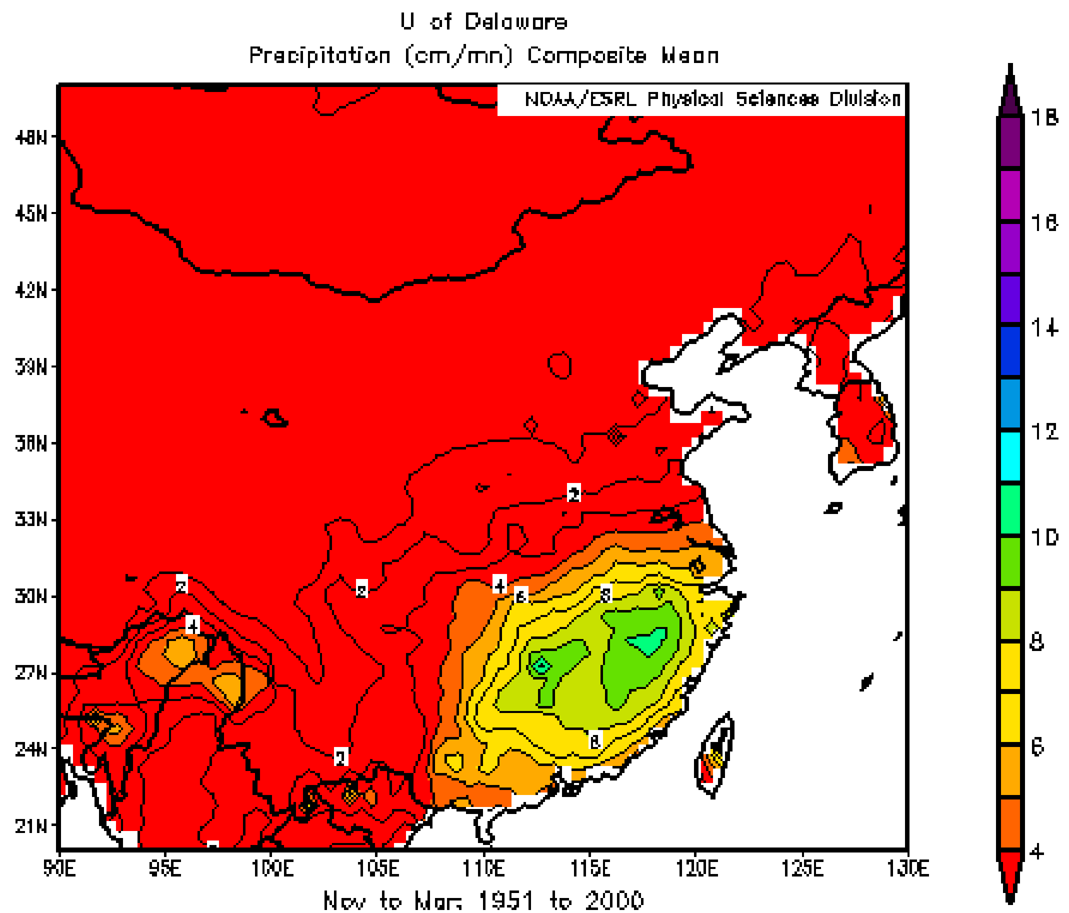

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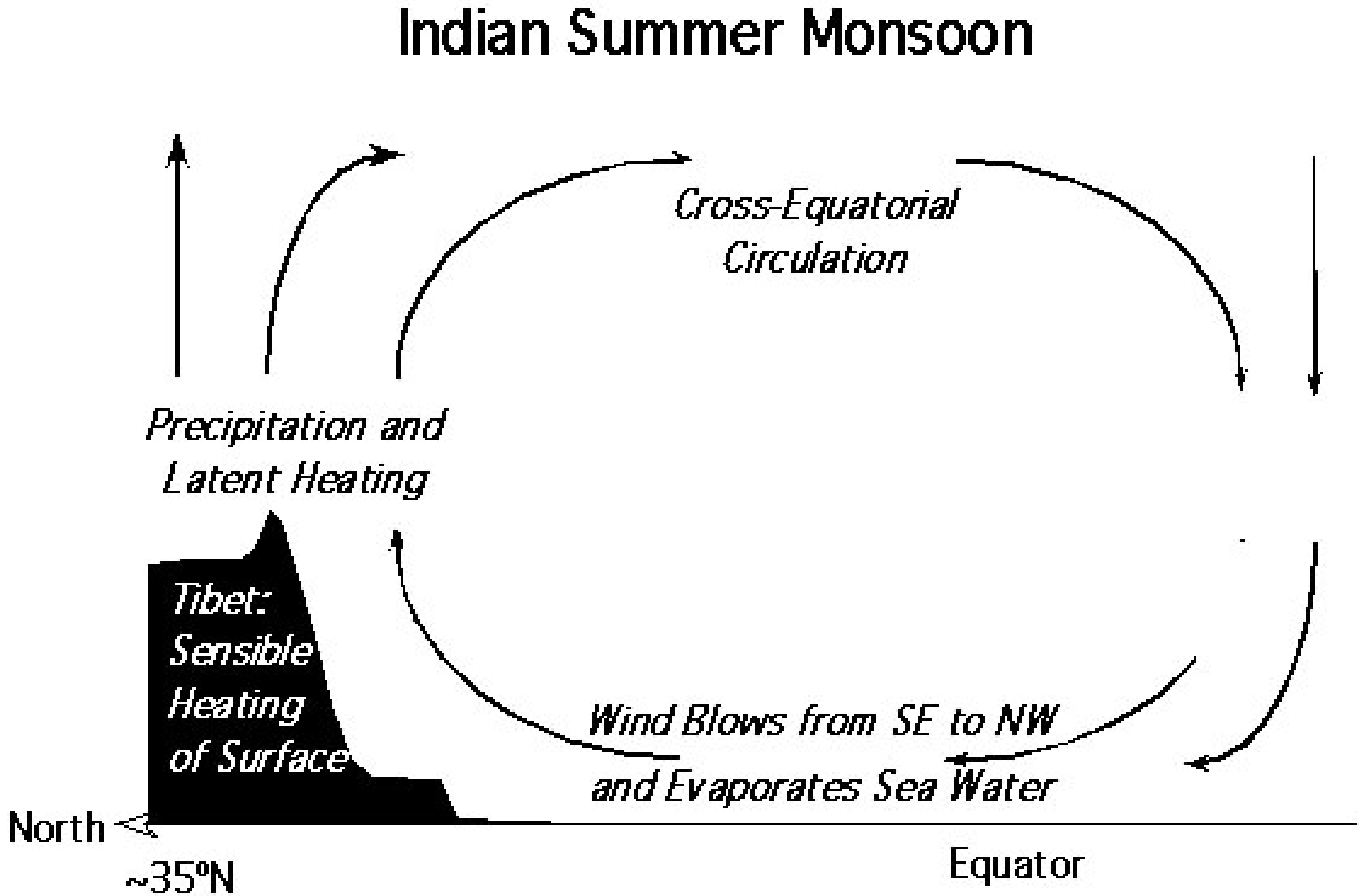
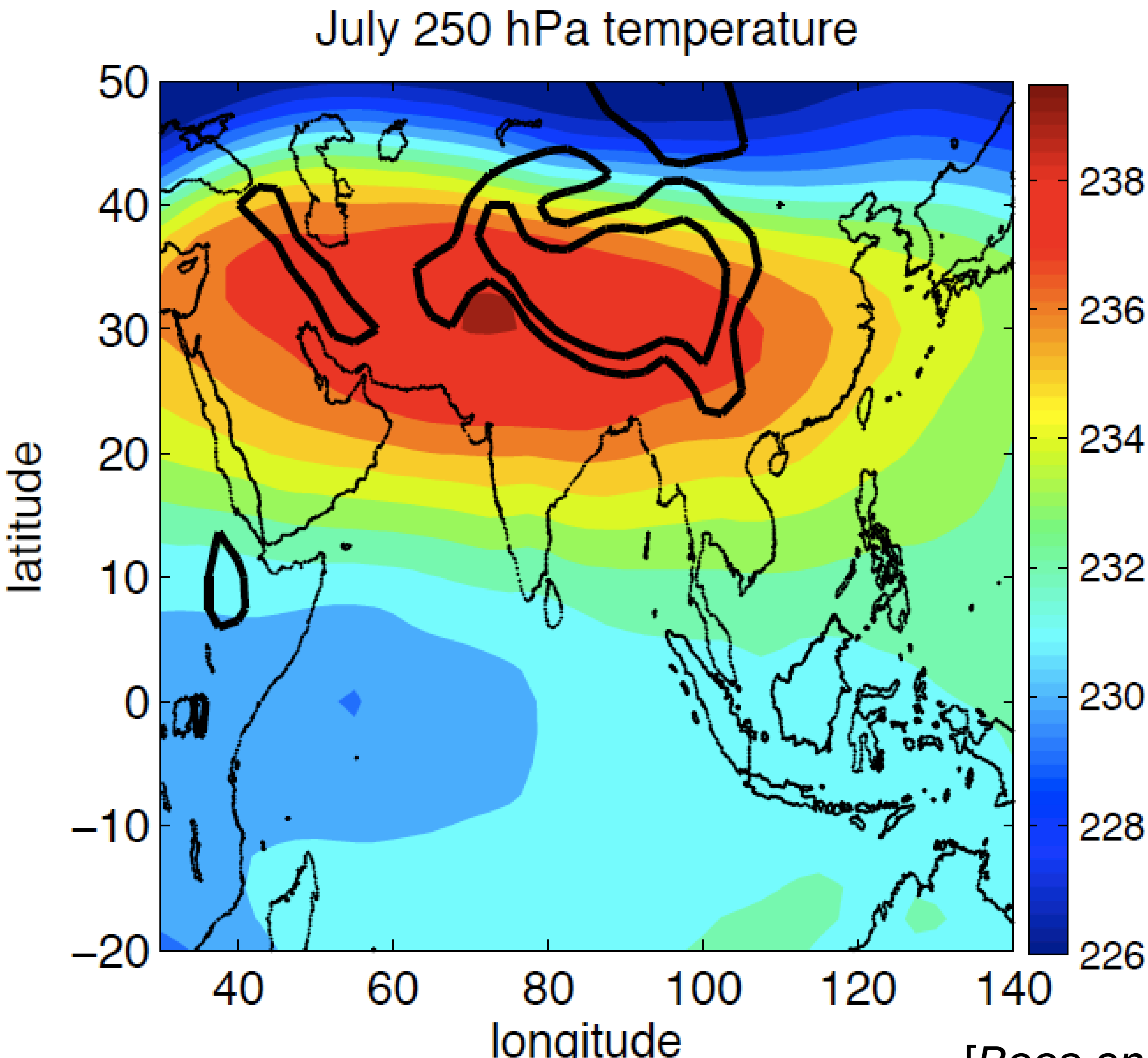
6. Latent heat adds a zonal pressure gradient.
7. The jet accelerates east of the plateau.

Sensible heating over India & Tibet and latent heating aloft lead to monsoonal circulation

Hot upper troposphere

Cooler (but not cold) upper troposphere



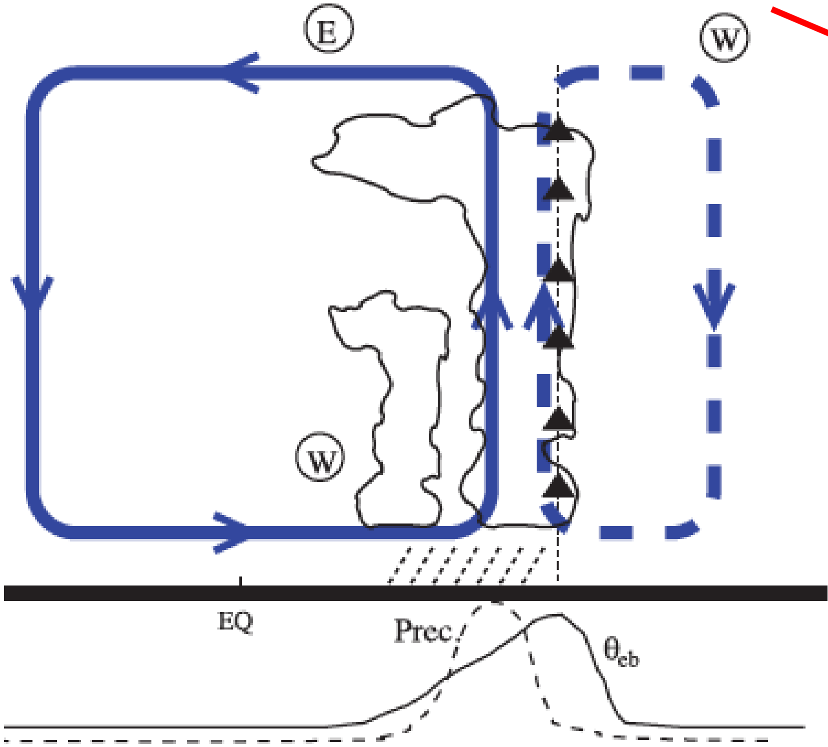


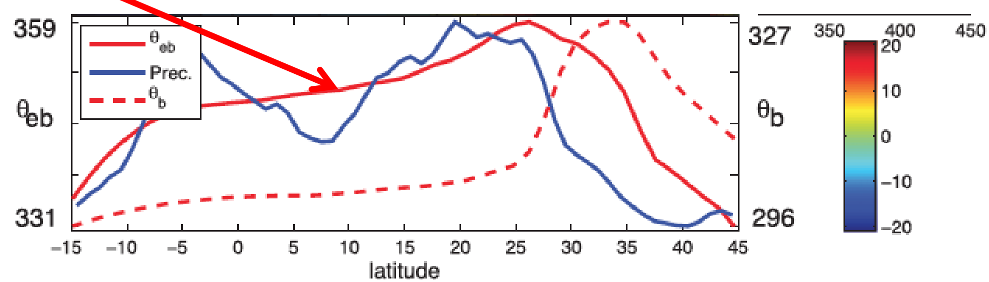
High upper atmospheric temperature: **not** centered over Tibet.

[*Boos and Emanuel* 2009]

Elementary monsoon theory: quasi-equilibrium

Maximum ascent rate lies slightly equatorward of **maximum** subcloud specific entropy, s_b, or moist static energy, h.





$$s_b = C_p \ln \vartheta_{eb}$$

$$\vartheta_{eb} \approx T_b \left(\frac{p_b}{p}\right)^{\frac{R}{c_p}} exp\left(\frac{L_v q}{c_p T_b}\right)$$

$$h = C_p T + L_v q + gz \approx s_b / T_b$$

[*Emanuel*, 1995, 2007; *Emanuel et al.*, 1994; Lindzen and Hou, 1988; *Neelin*, 2007; *Plumb*, 2007; *Privé and Plumb*, 2007].

Figures from *Nie, Boos, and Kuang* [*Journal of Climate*. 2010]

Elementary monsoon theory: quasi-equilibrium

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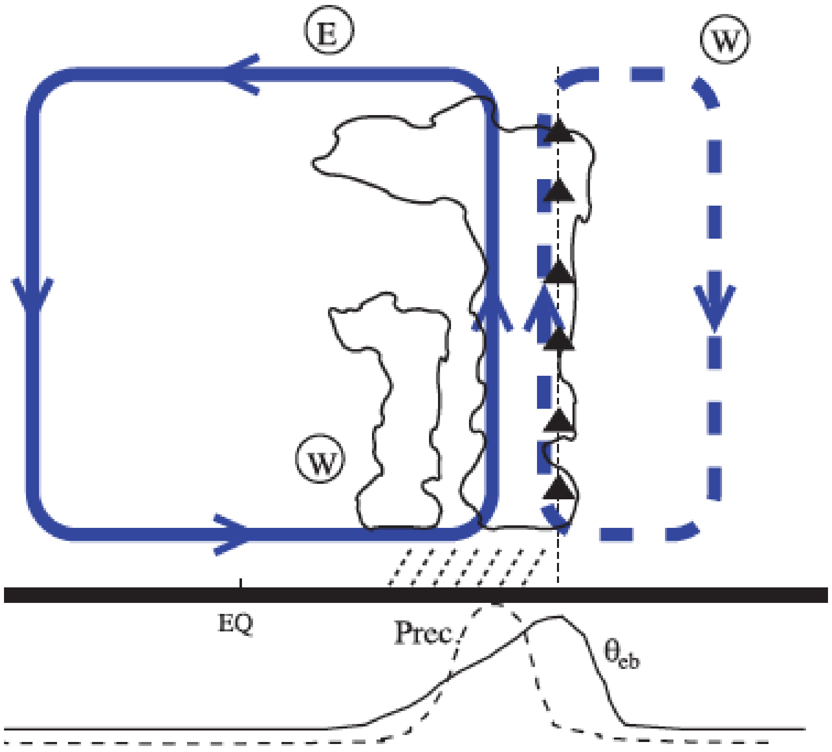

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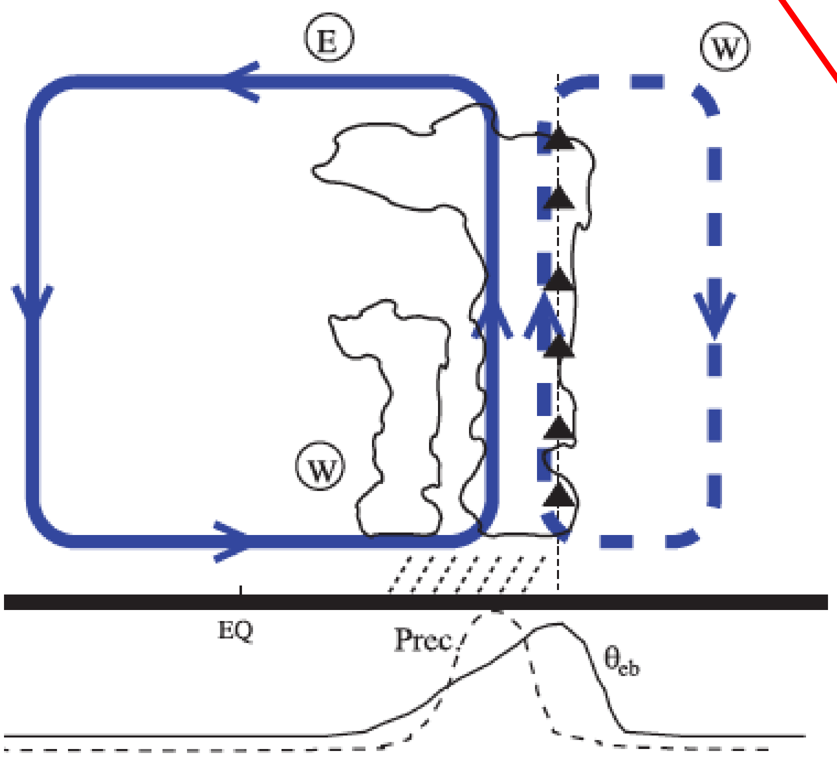

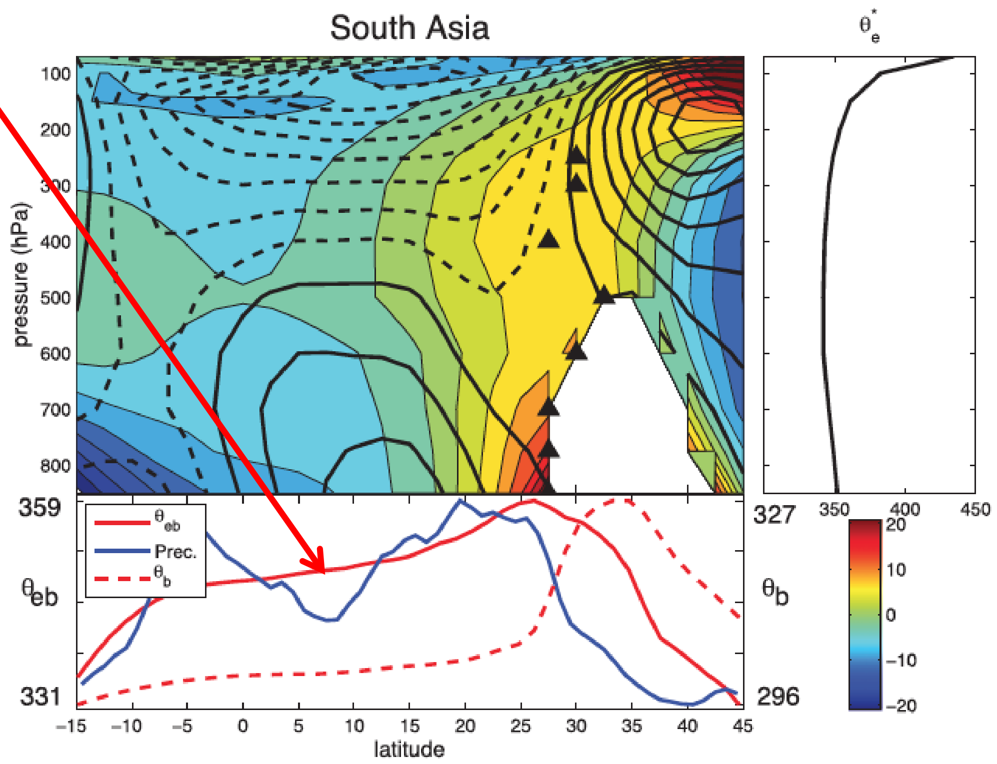

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Privé and Plumb, 2007].

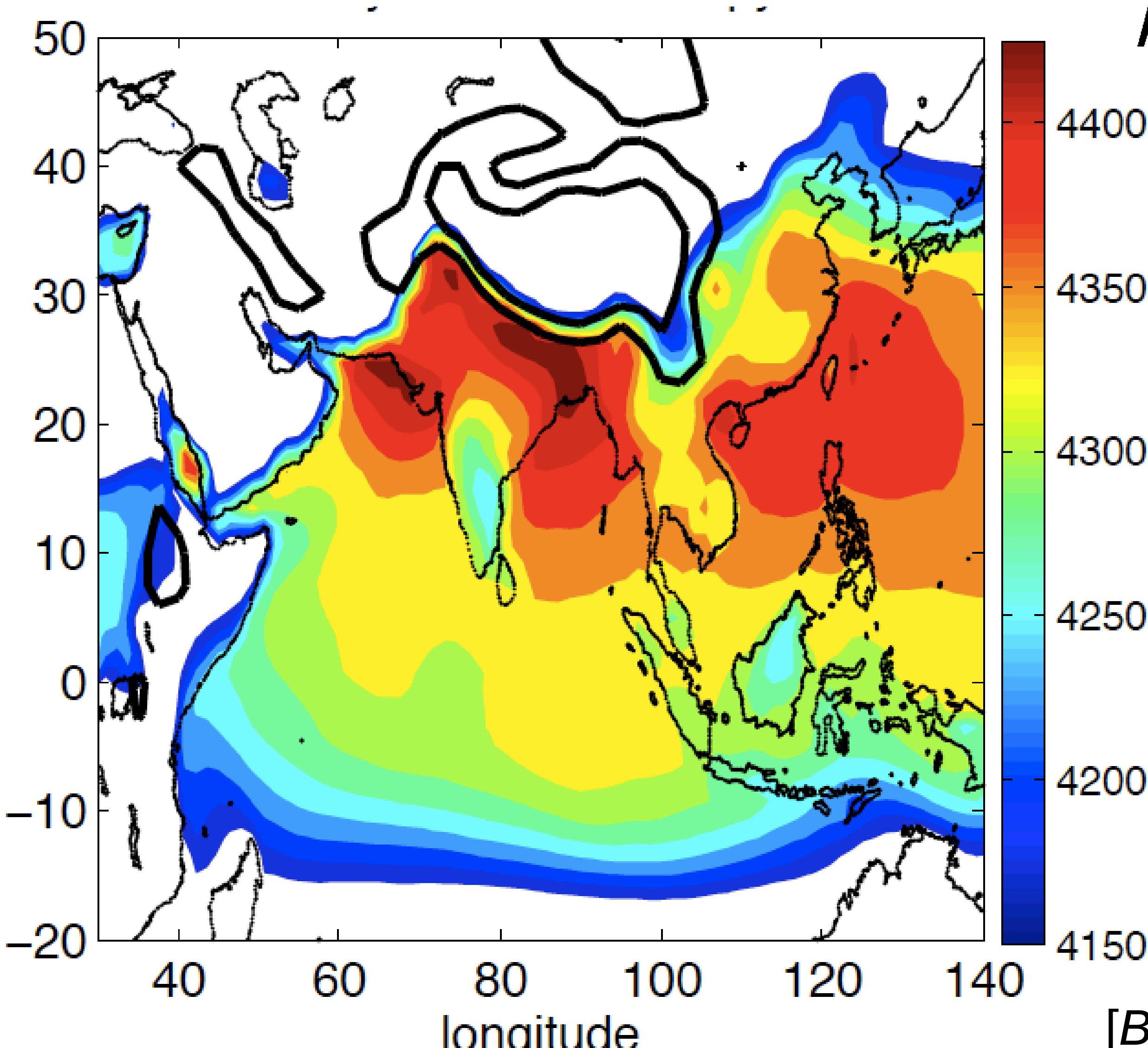
$$s_b = C_p \ln \vartheta_{eb}$$

(from *Nie, Boos, and Kuang* [*Journal of Climate*. 2010])

Subcloud moist entropy (like moist static energy) (in July):

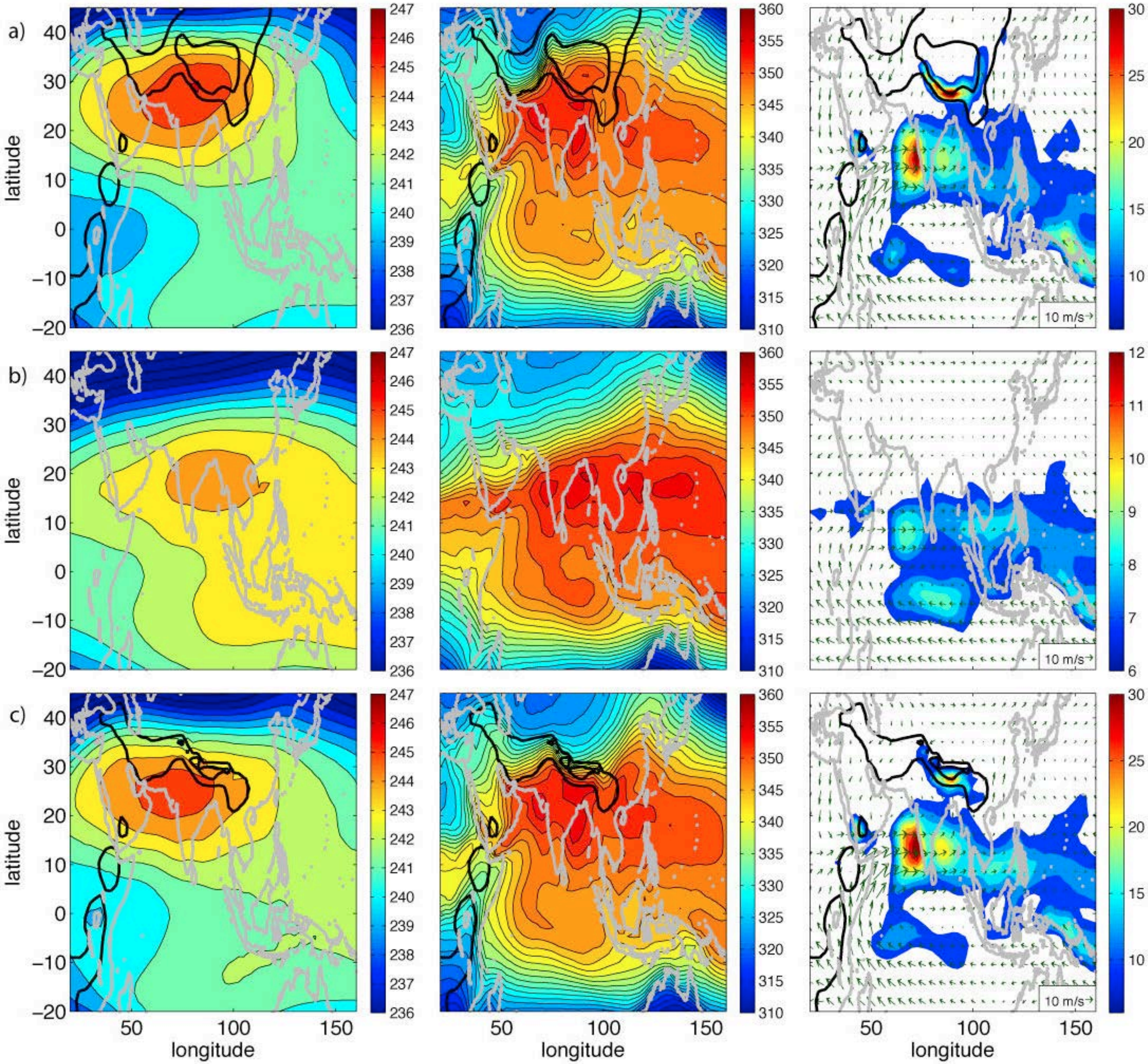
$s_b = (C_{pd} + qC_{pl}) \ln \theta_{eb}$, θ_{eb} = equivalent potential temperature

$$h = C_p T + L_v q + gz$$



The potentially **most unstable** surface air lies **NOT** over Tibet, but over northern India.

[*Boos and Emanuel* 2009]



175-450 mb Temperature subcloud θ_{eb} Precipitation and winds: **all for summer**

Present-day topography

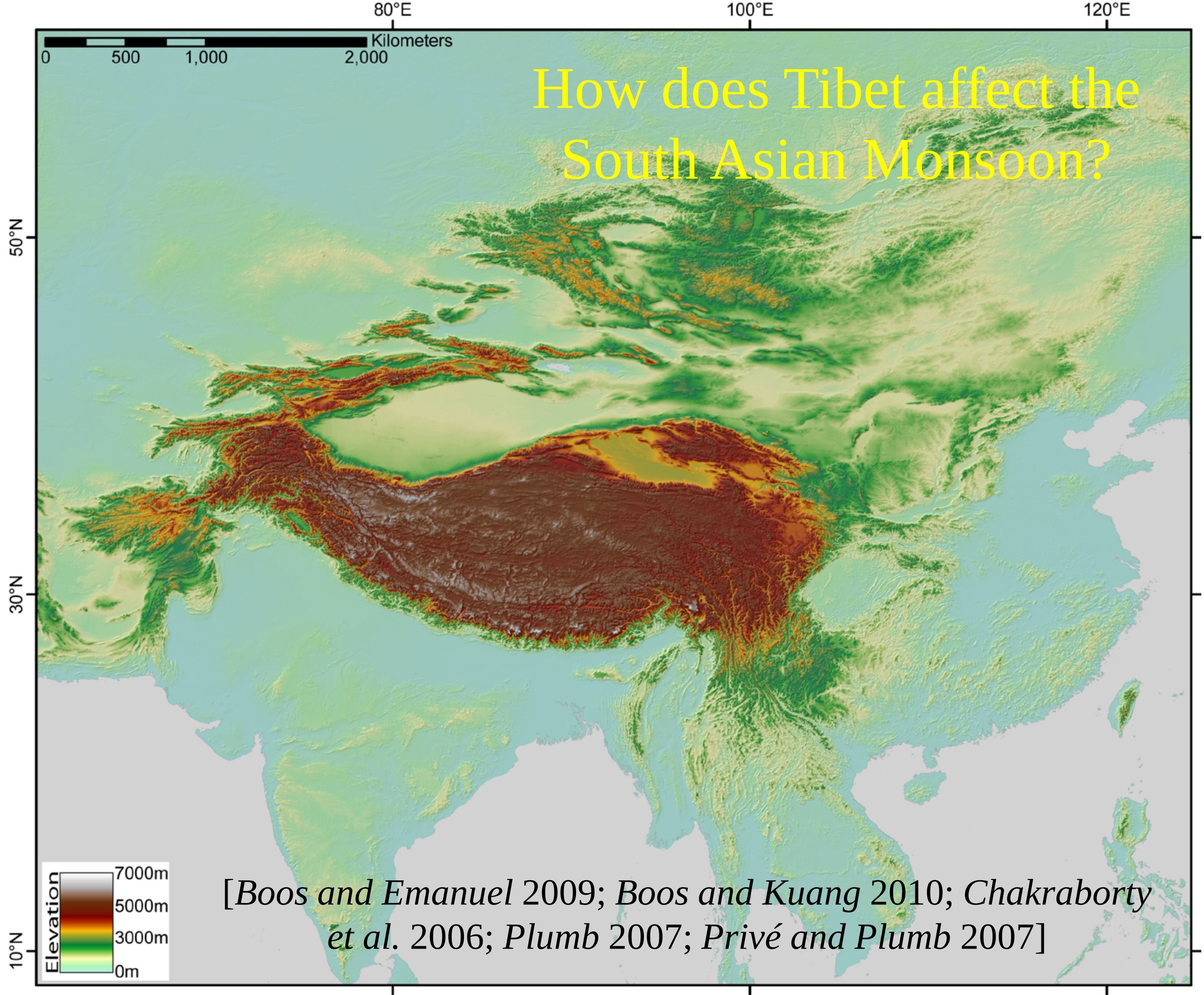
Importance of the Himalaya, but not Tibet.

No topography

No Tibet, but with the Himalaya (and east Africa)

[*Boos and Kuang* 2009]

How does Tibet affect the South Asian Monsoon?



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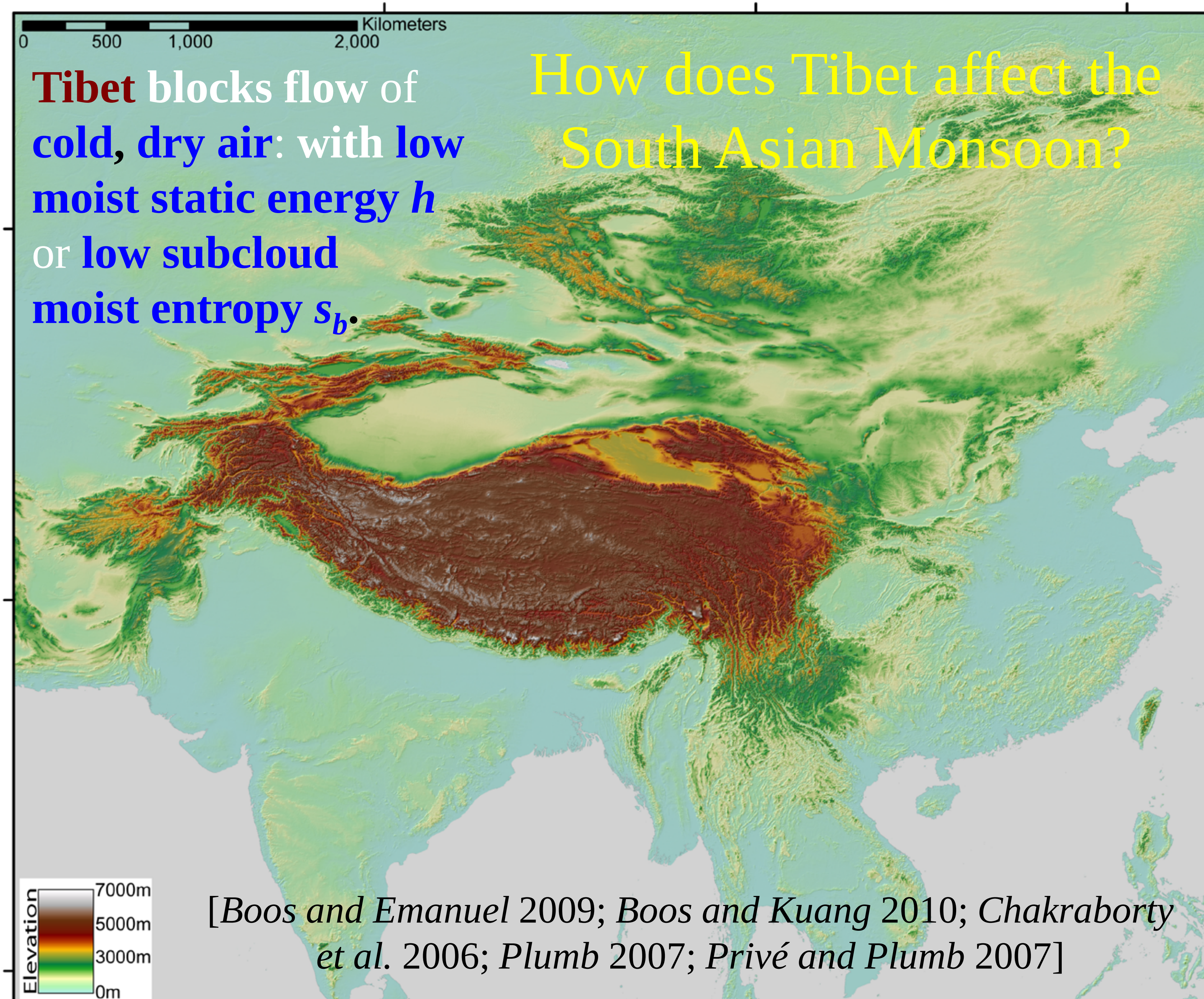
Tibet blocks flow of **cold, dry air**: **with low moist static energy h** or **low subcloud moist entropy s_b.**



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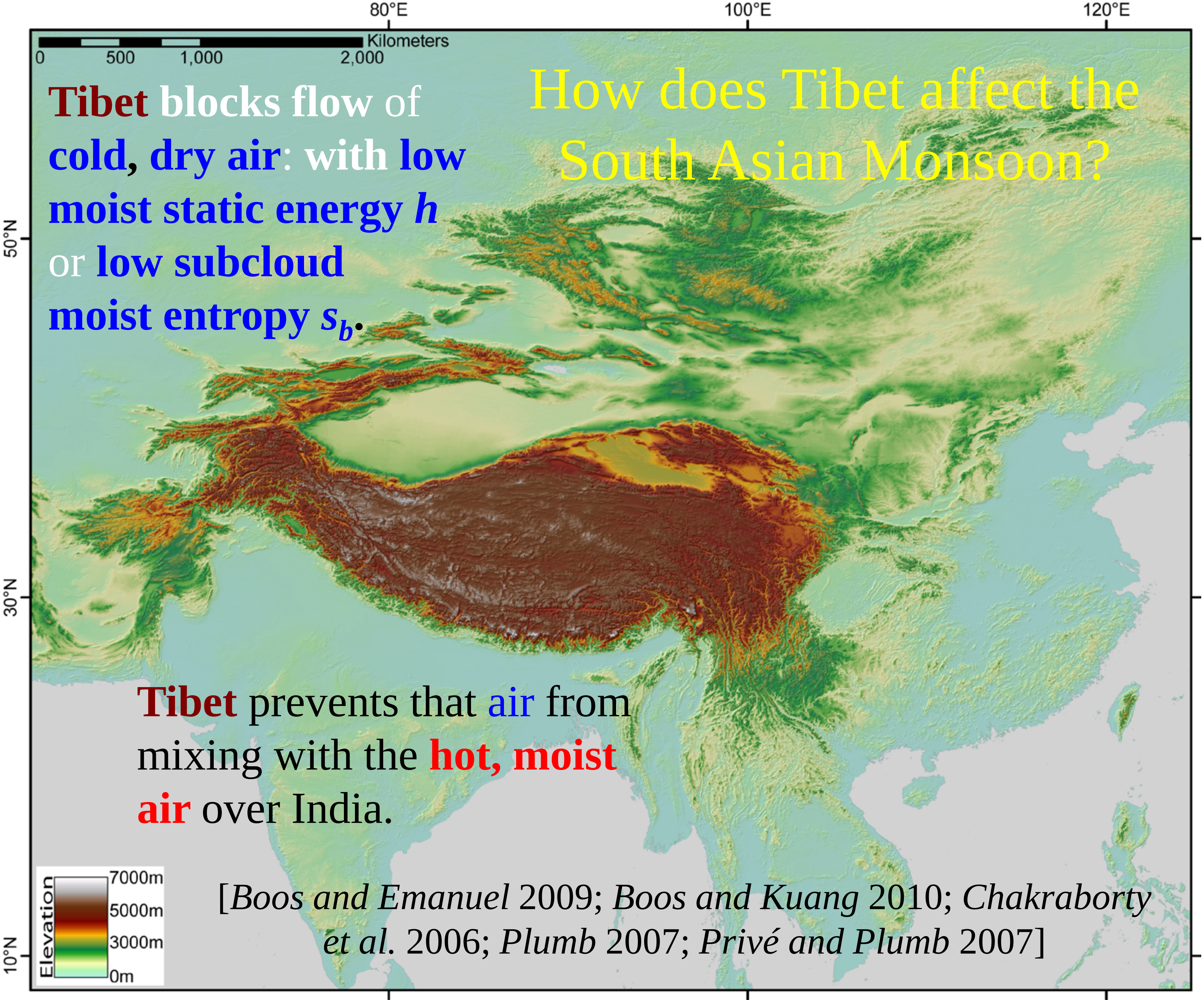

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Tibet prevents that air from mixing with the **hot, moist air** over India.

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Tibet: It it necessary?

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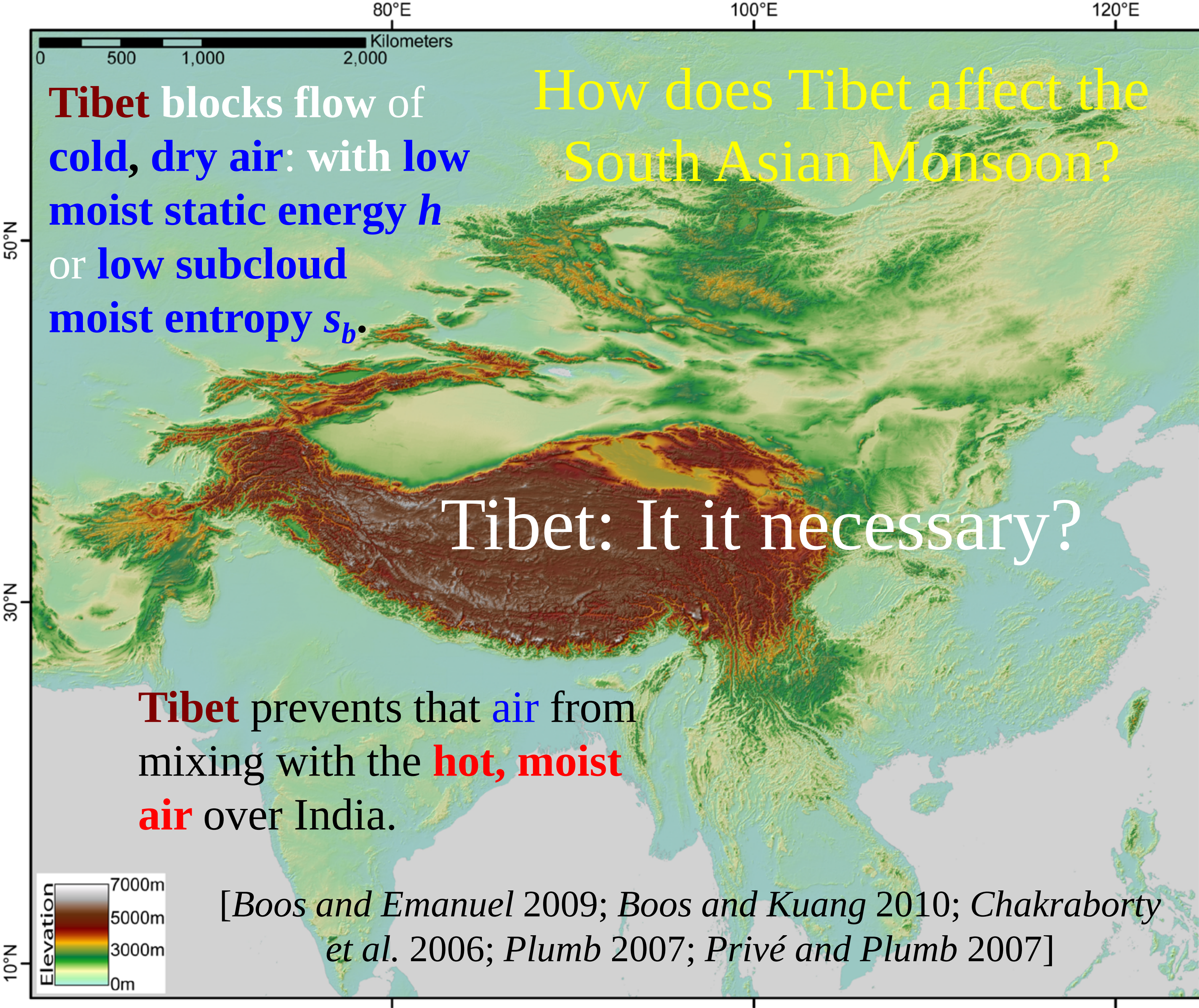

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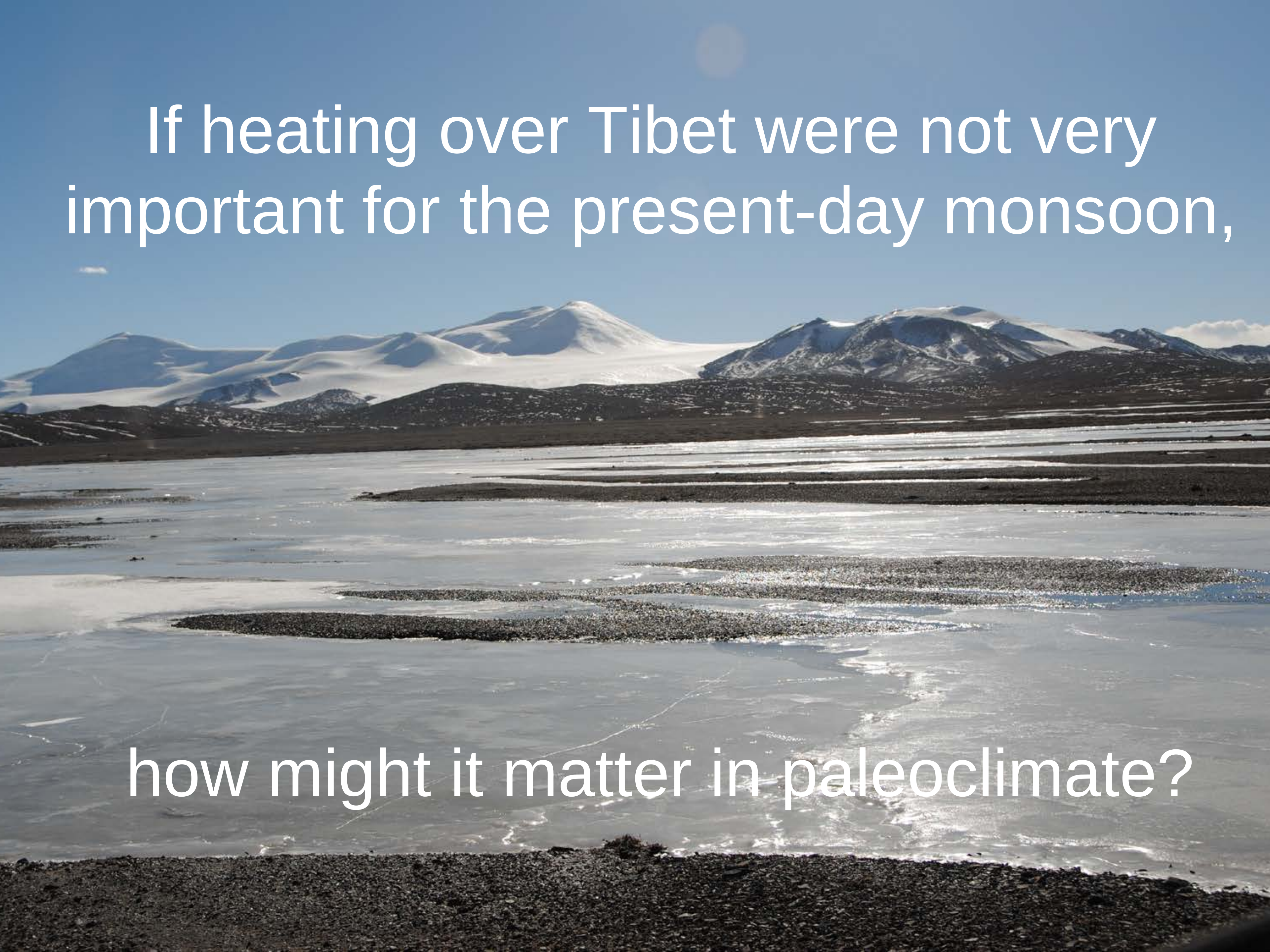

If heating over Tibet were not very important for the present-day monsoon,
how might it matter in paleoclimate?

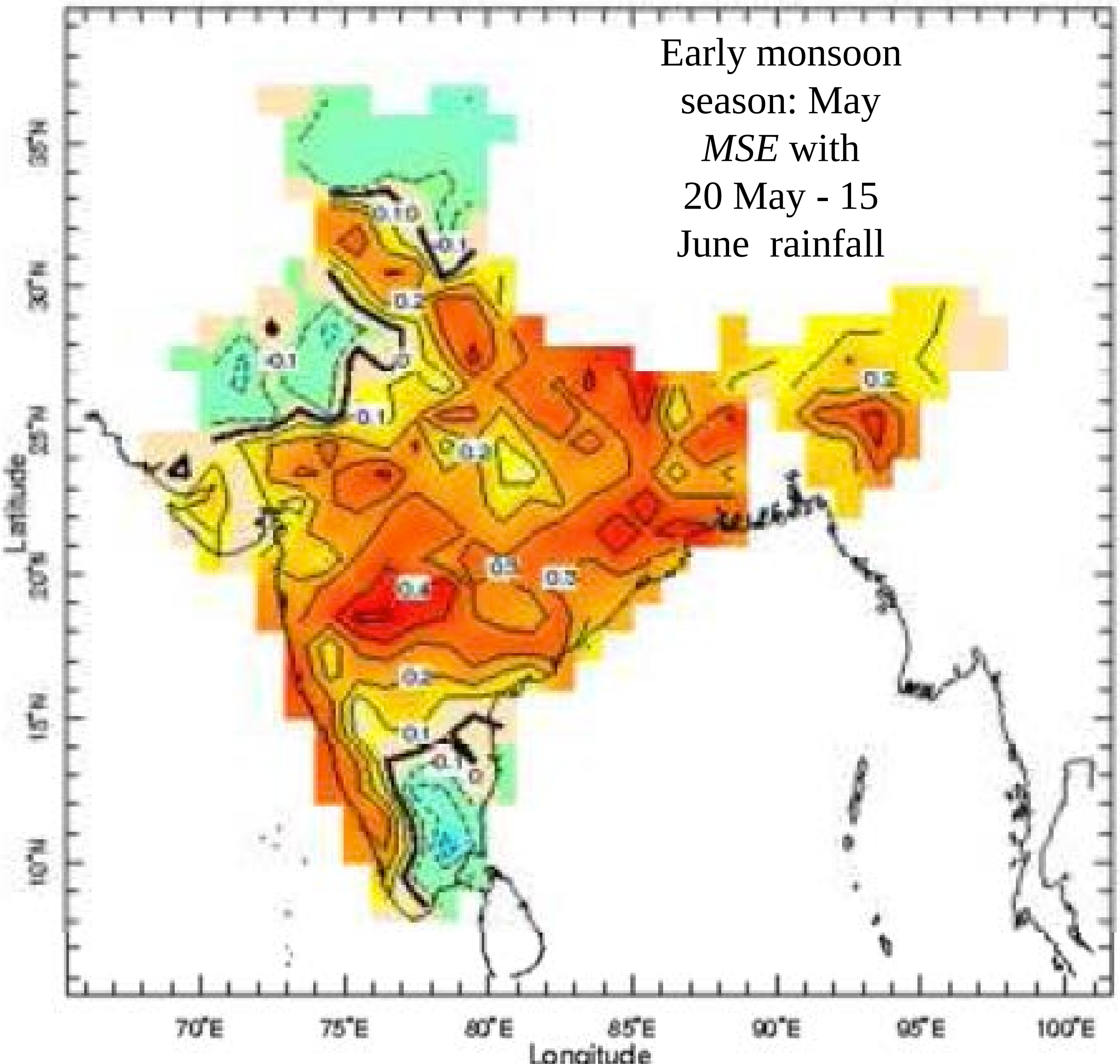
Does heating over Tibet matter for the Indian monsoon?

A test:

correlate most static energy over Tibet with monsoon rainfall over India

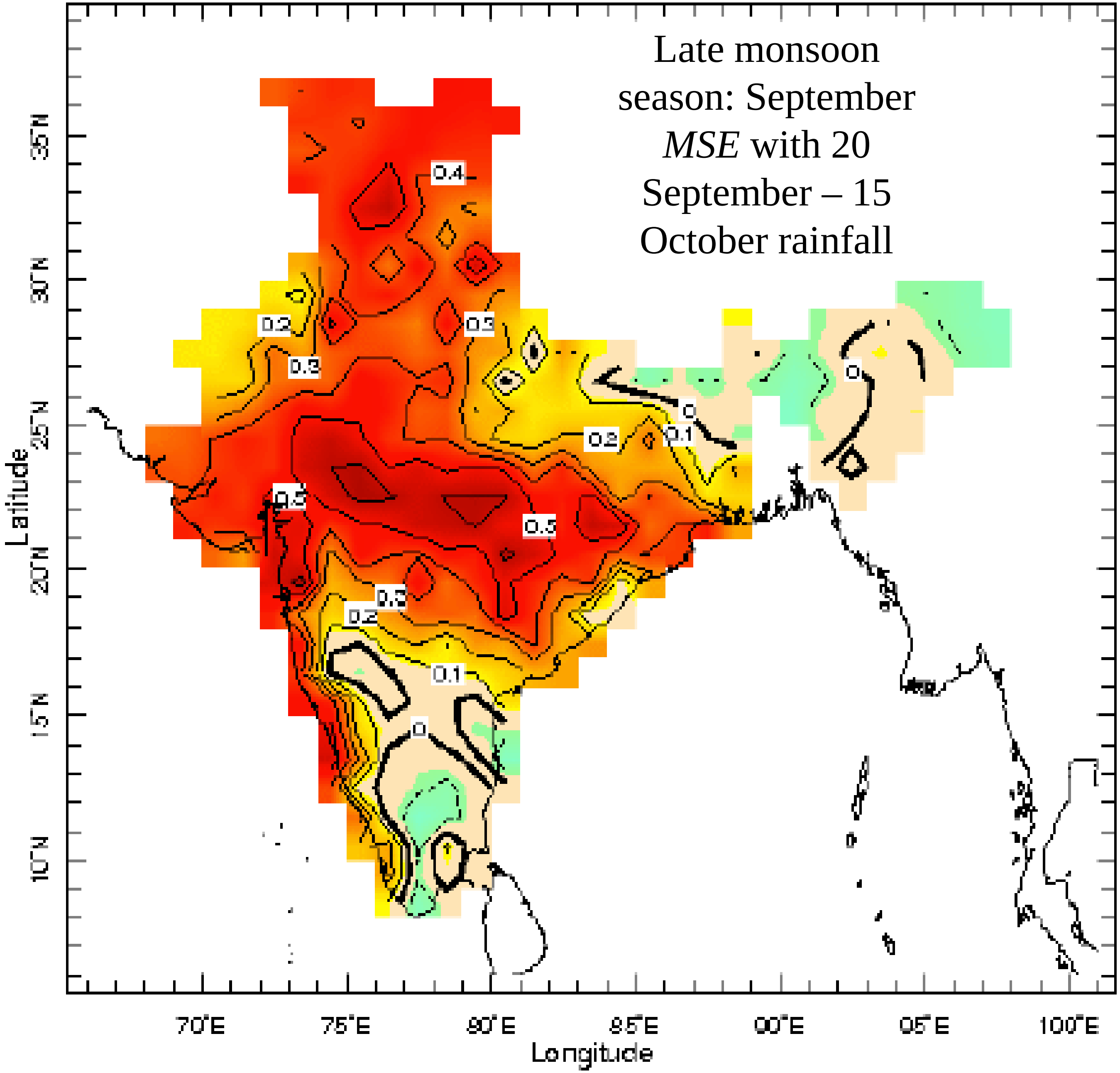
$$h = C_p T + L_v q + gz$$

Rainfall correlated with moist static energy over Tibet: Early season



[*Rajagopalan and Molnar, JGR*, 2013]

Rainfall correlated with moist static energy over Tibet: Late season



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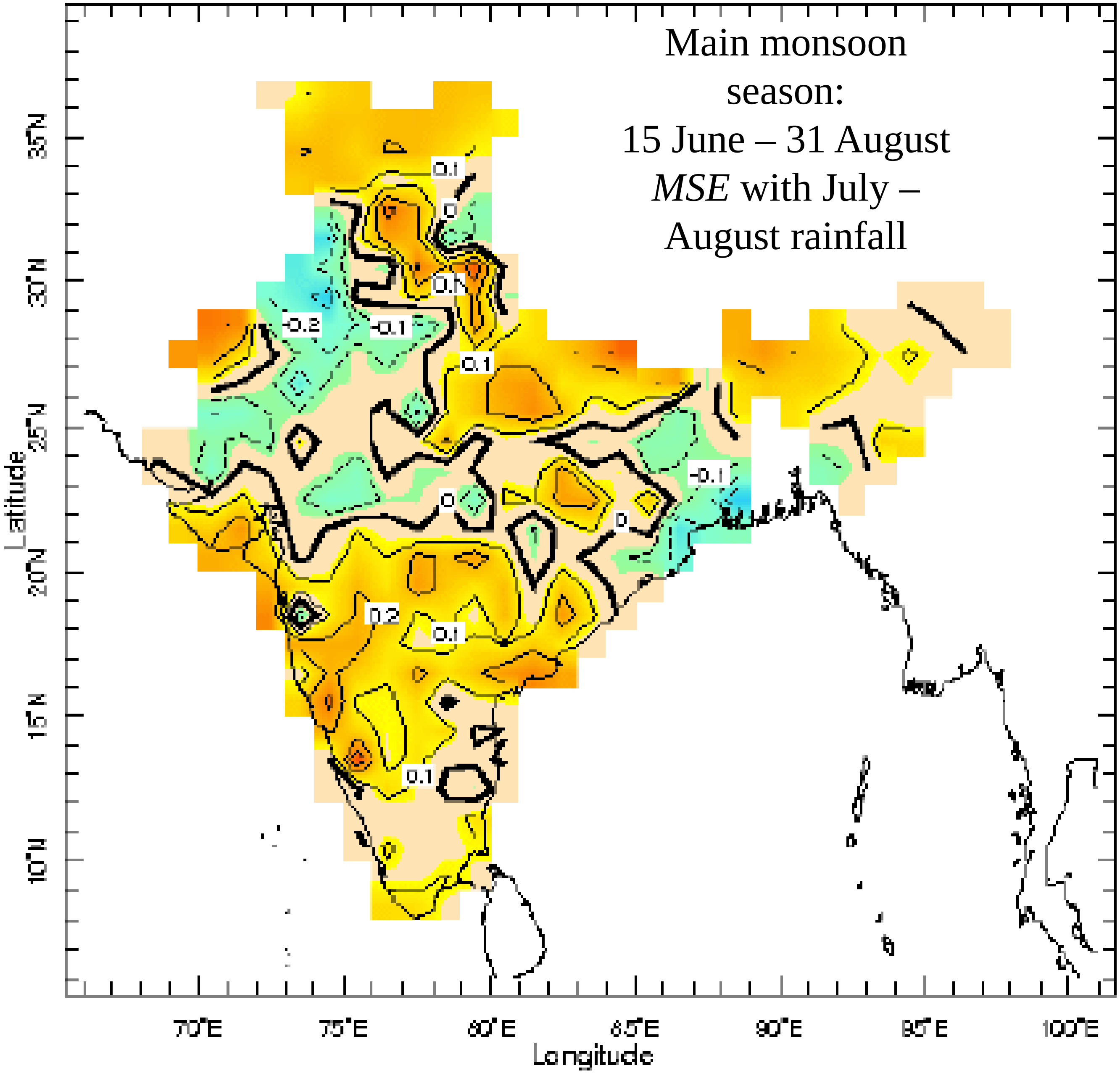
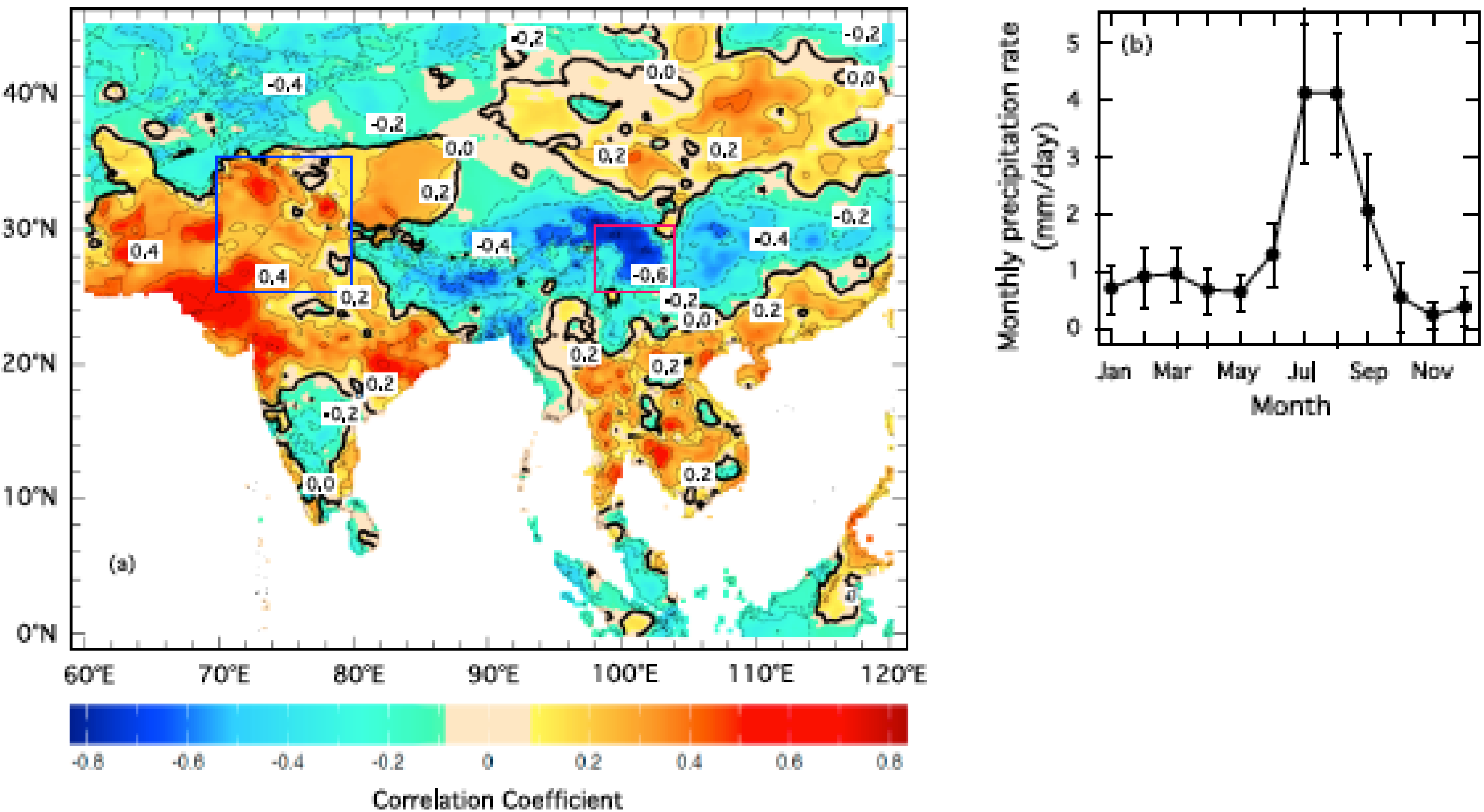


Rainfall correlated with moist static energy over Tibet: Main season

[*Rajagopalan and Molnar*, *JGR*, 2013]

Correlation of July-August rainfall [*Xie et al*. 2007] over eastern Asia with July-August Outgoing Longwave Radiation (OLR) over Eastern Tibet (red box)



[*Molnar and Rajagopalan*, *GRL*, 2012]

Does heating over Tibet matter for the Indian monsoon?

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Mild success: only in early and late seasons.

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Tibet does not seem to be very important.

How might Tibet, and its growth, affect climate, and paleoclimate?

1. Loess plateau – dust?

   *Maybe, but only **geodynamically**.*

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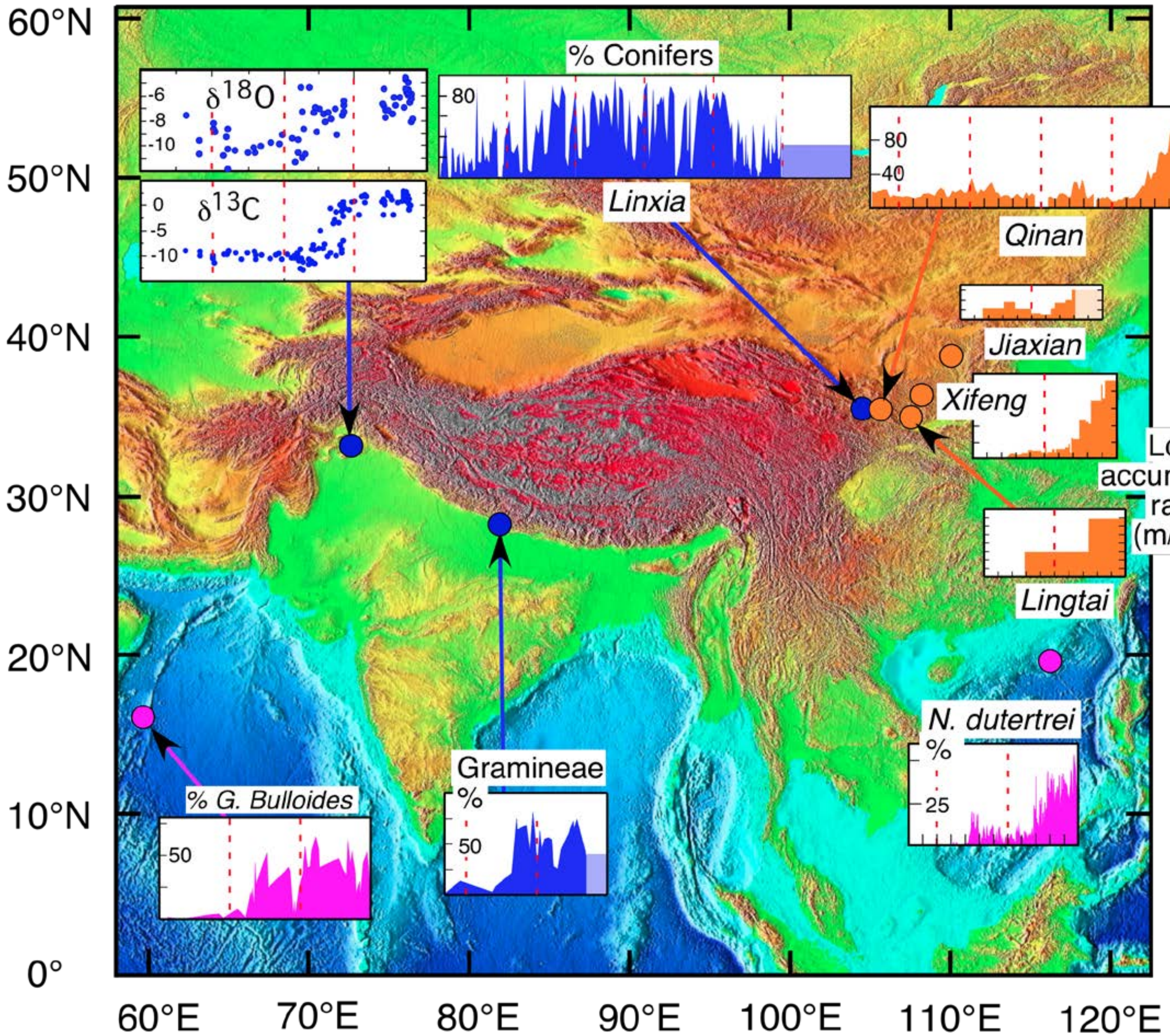
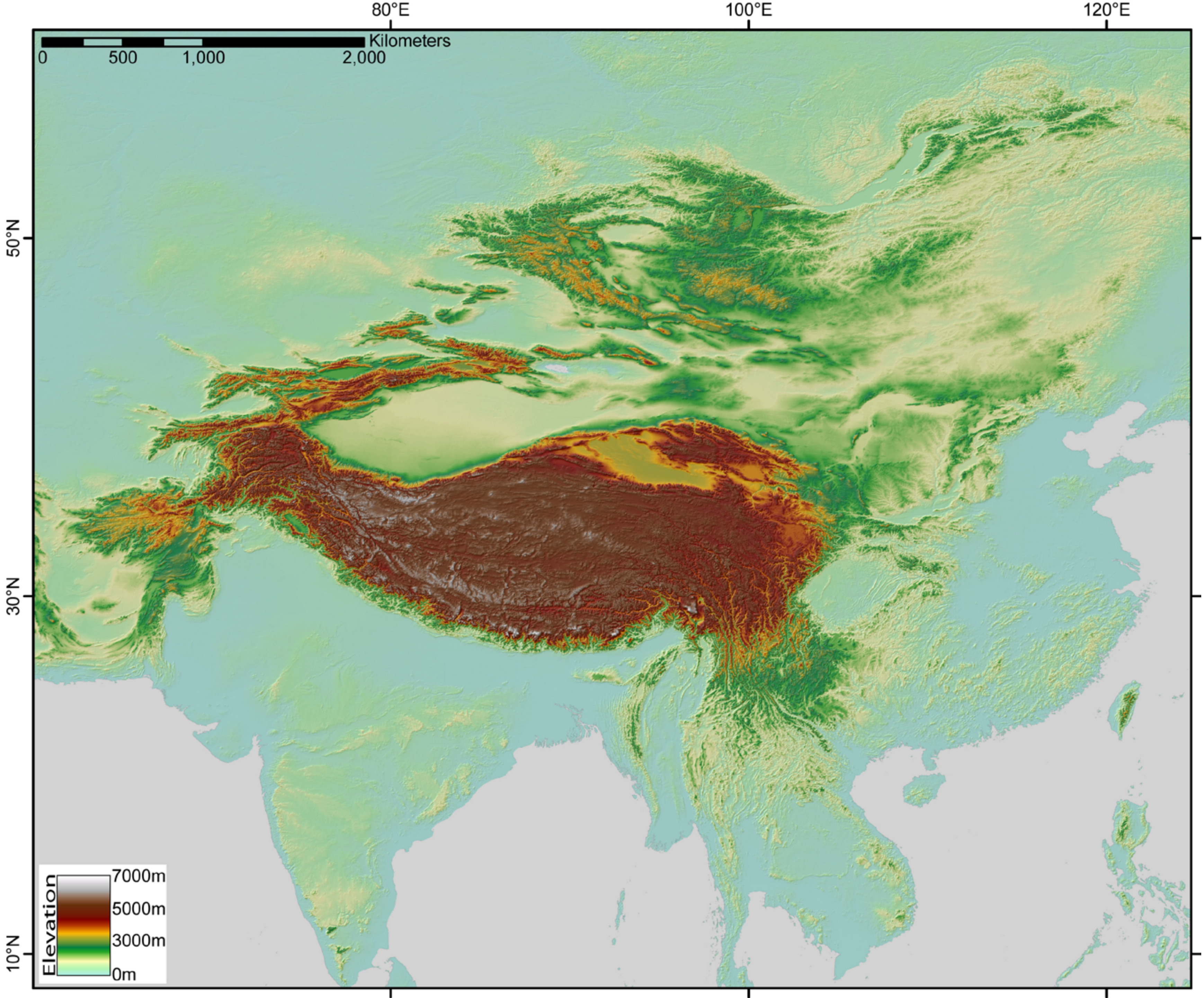
   Maybe, and if so, ***thermally***.
4. Monsoon rainfall, in general, over India?
   Thermally, only in early and late seasons.



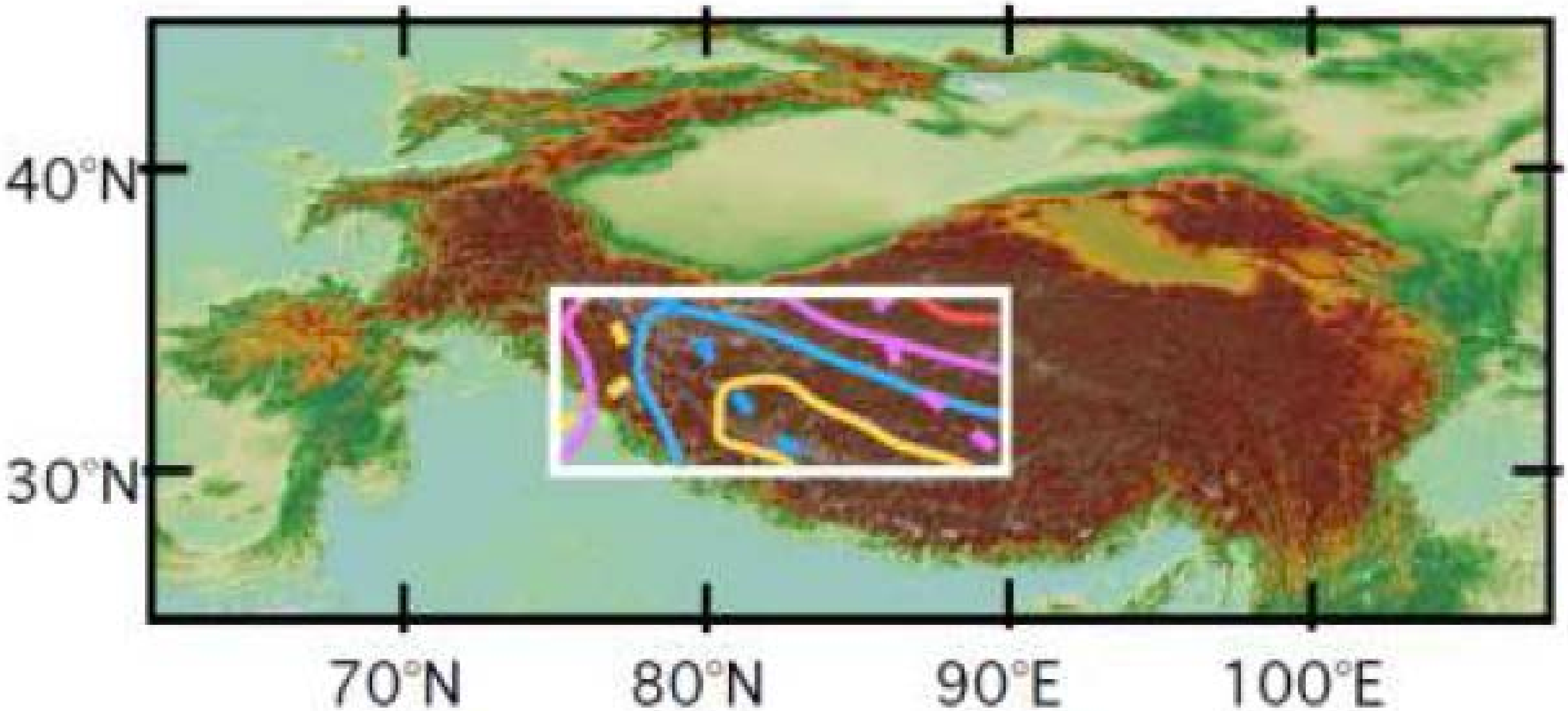
Million-year time series of paleoclimate

Compiled by *Molnar, Boos, and Battisti* [2010]



80°E
100°E
120°E
Kilometers
0
500
1,000
2,000
50°N
30°N
10°N
Elevation
7000m
5000m
3000m
0m

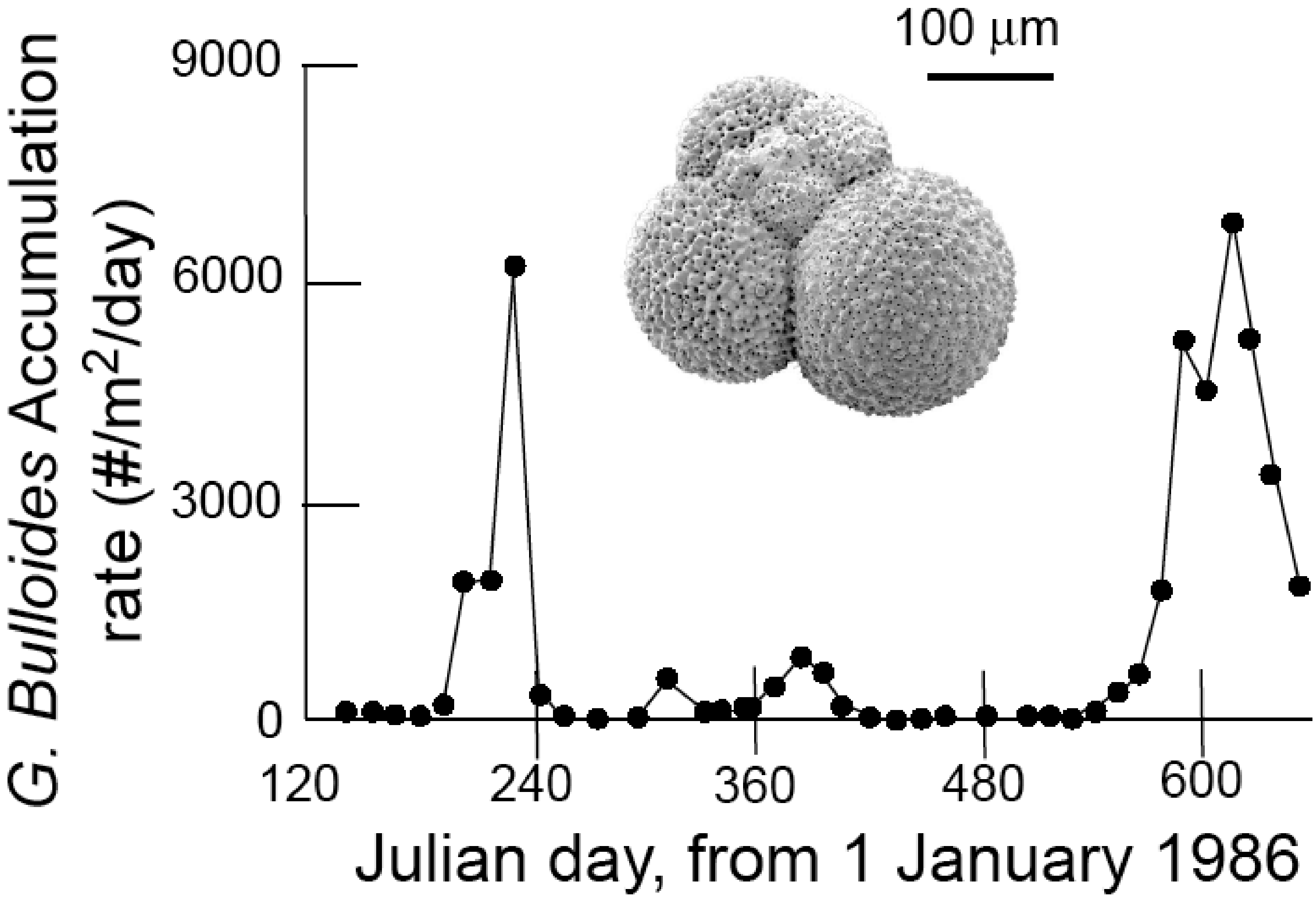
Heating over Tibet and the South Asian Monsoon: are they related at all?



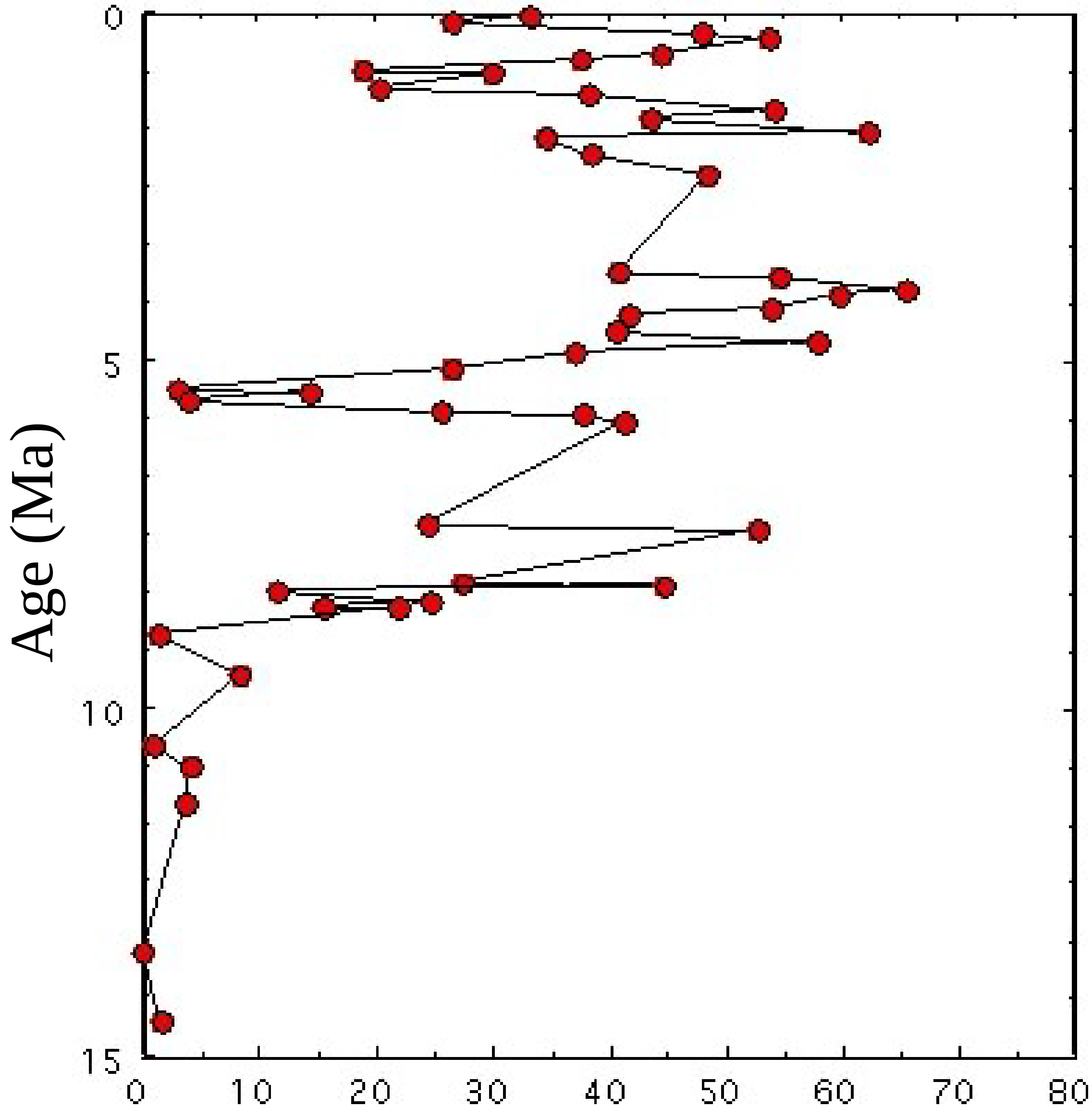
Moist static energy over Tibet

$$h = C_p T + L_v q + gz$$

Data: *Curry, Ostermann, Guptha, and Ittekkot* [1992]; Photo: L. Northcote



Globigerina bulloides **flourishes** during the monsoon, and **disappears** during the rest of the year.

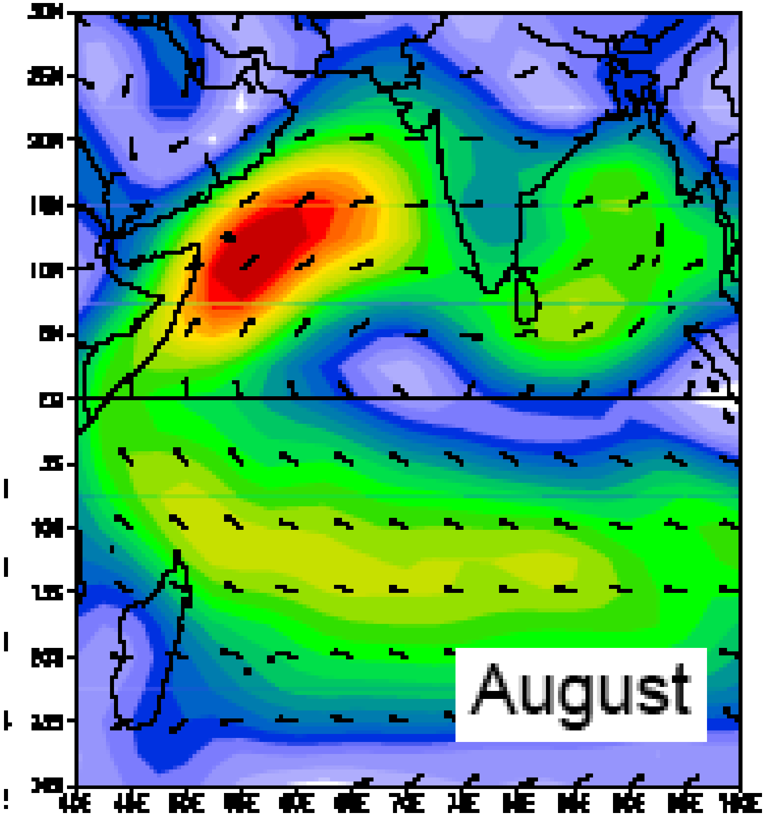


Percentage of *Globigirina Bulloides* at ODP Site 722 (Arabian Sea)

Increase in the fraction of *Globigirina Bulloides* in the Arabian Sea at ~8-9 Ma: Strengthening of the Indian monsoon?

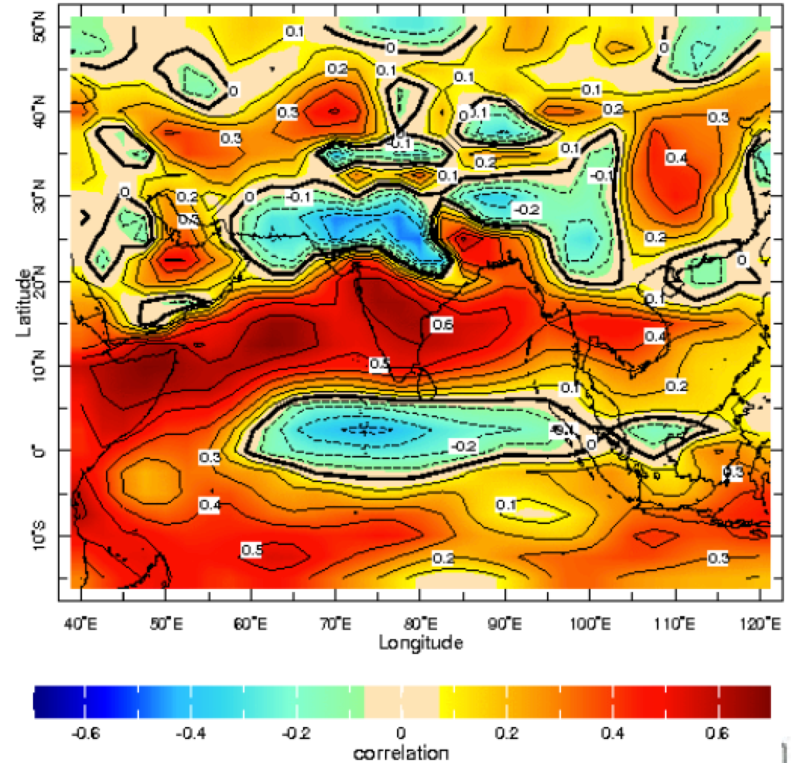
From *Kroon, Steens, and Troelstra* [1991]; *Prell, Murray, Clemens, and Anderson* [1992] show the same.

Correlation of moist static energy over Tibet with wind speeds

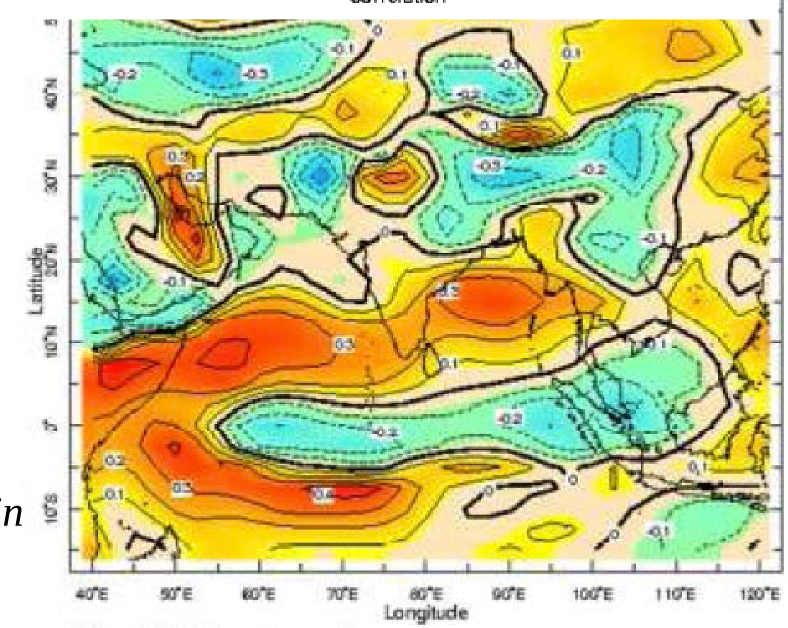


[*Rajagopalan and Molnar, in review*, 2013]

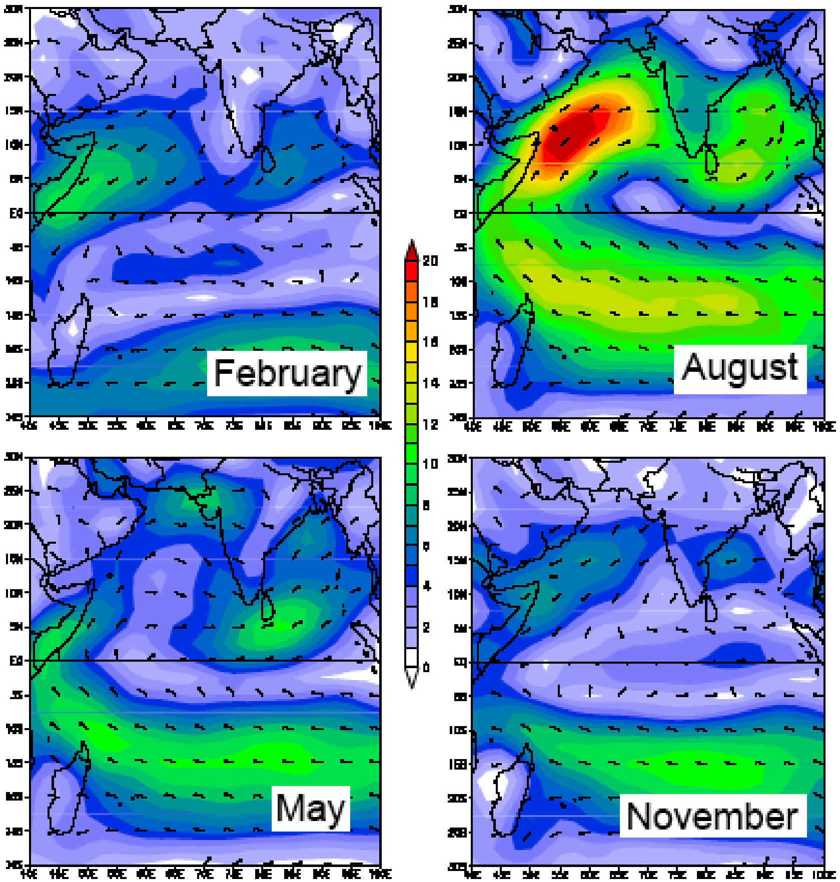
Late season



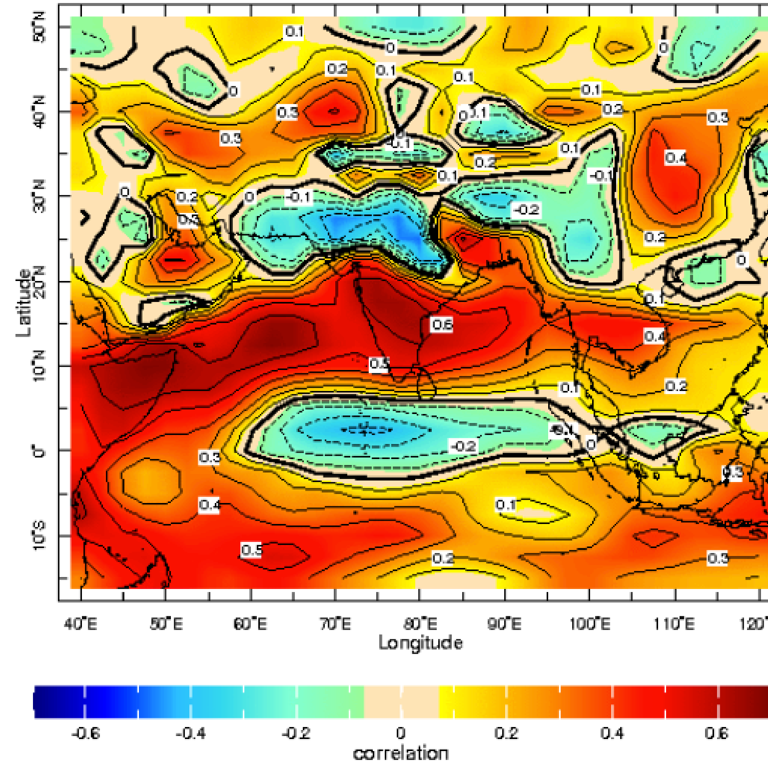
Early season



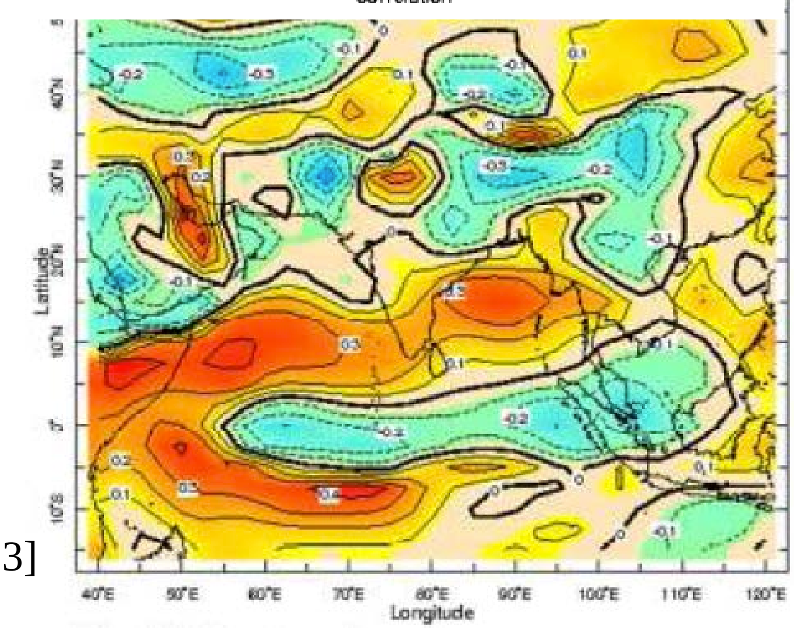
Correlation of moist static energy over Tibet with wind speeds



Late season

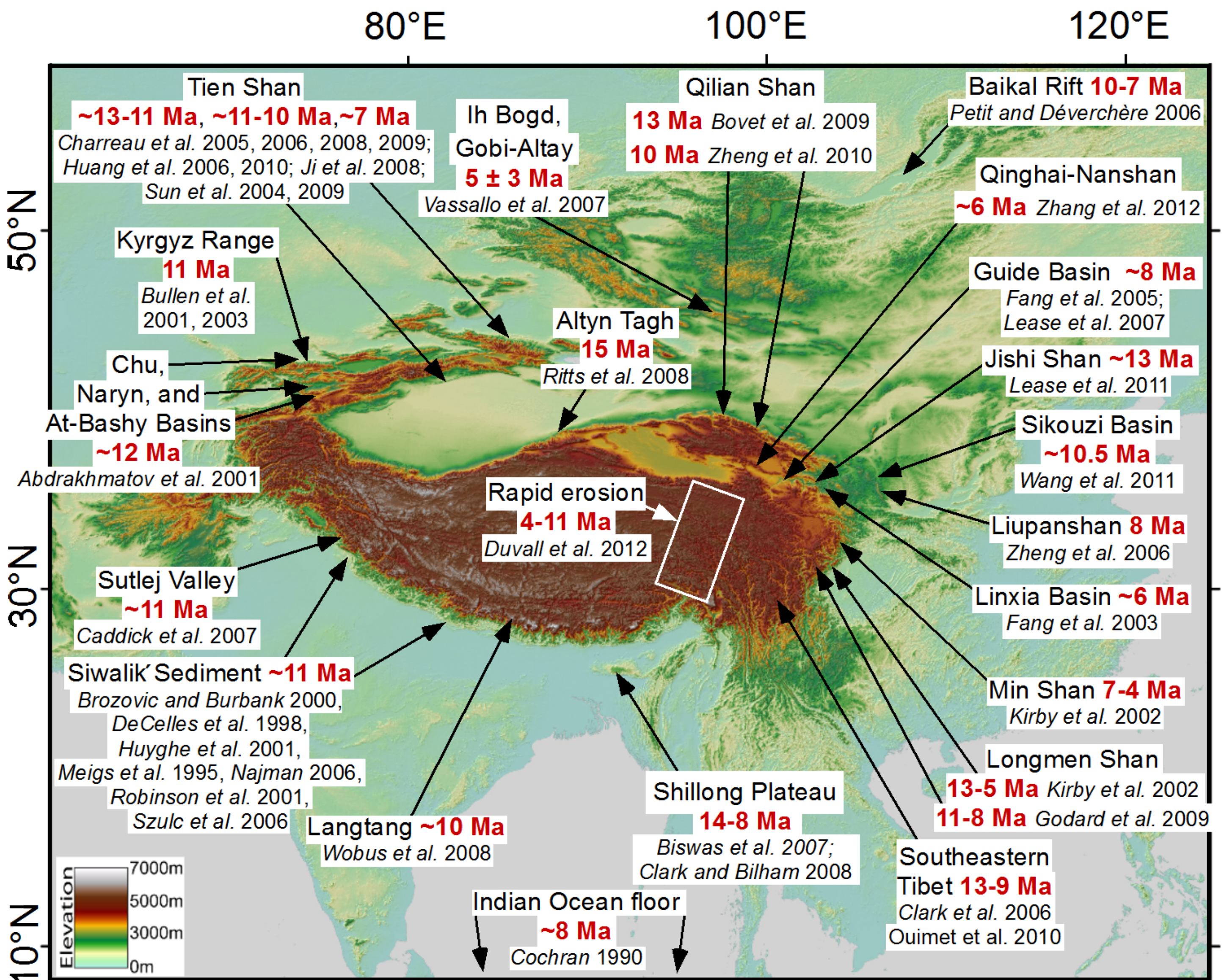


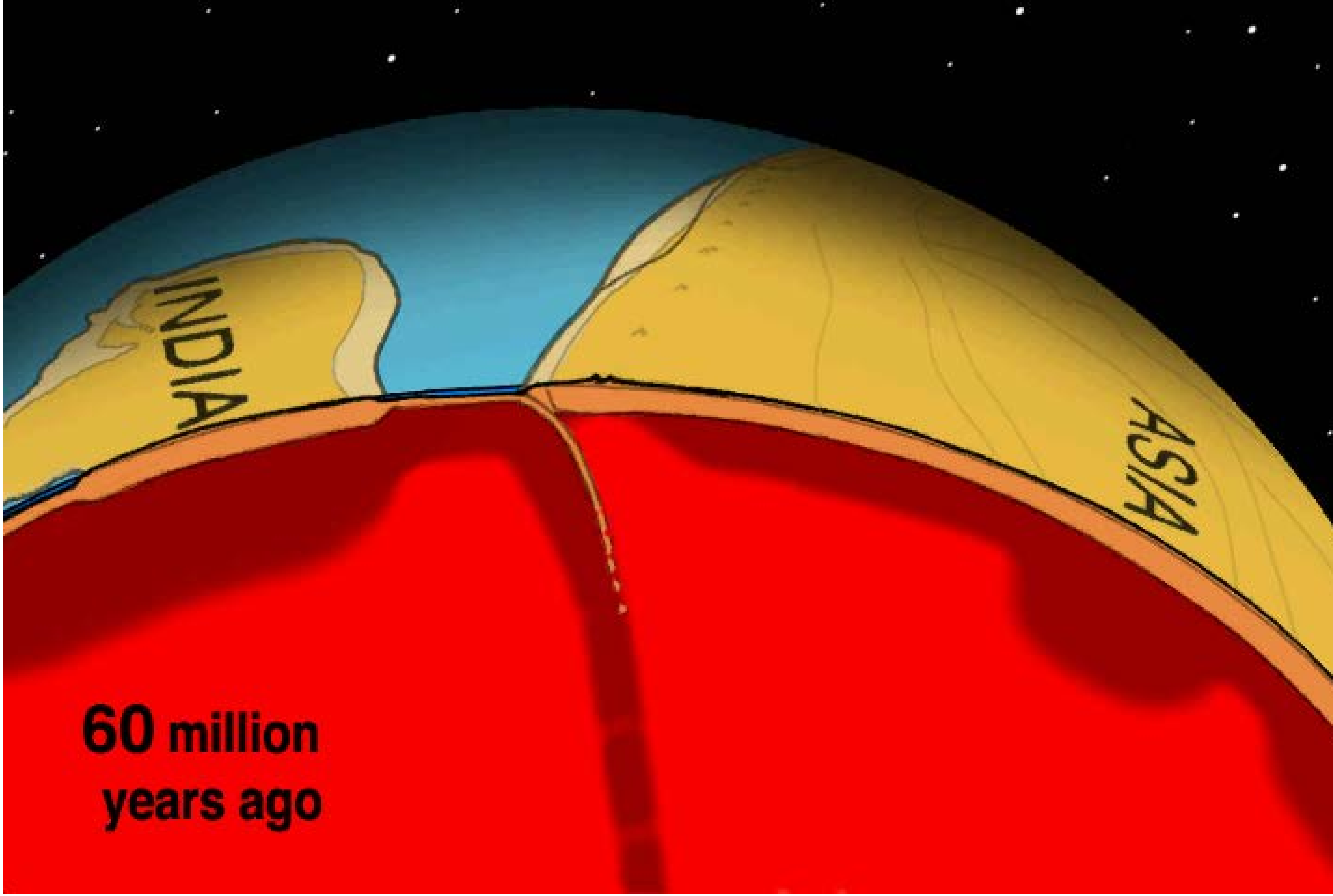
Early season



[*Rajagopalan and Molnar, JGR,* 2013]

Deformation surrounding Tibet beginning at, or since, ~15 Ma; but collision occurred at ~45 Ma

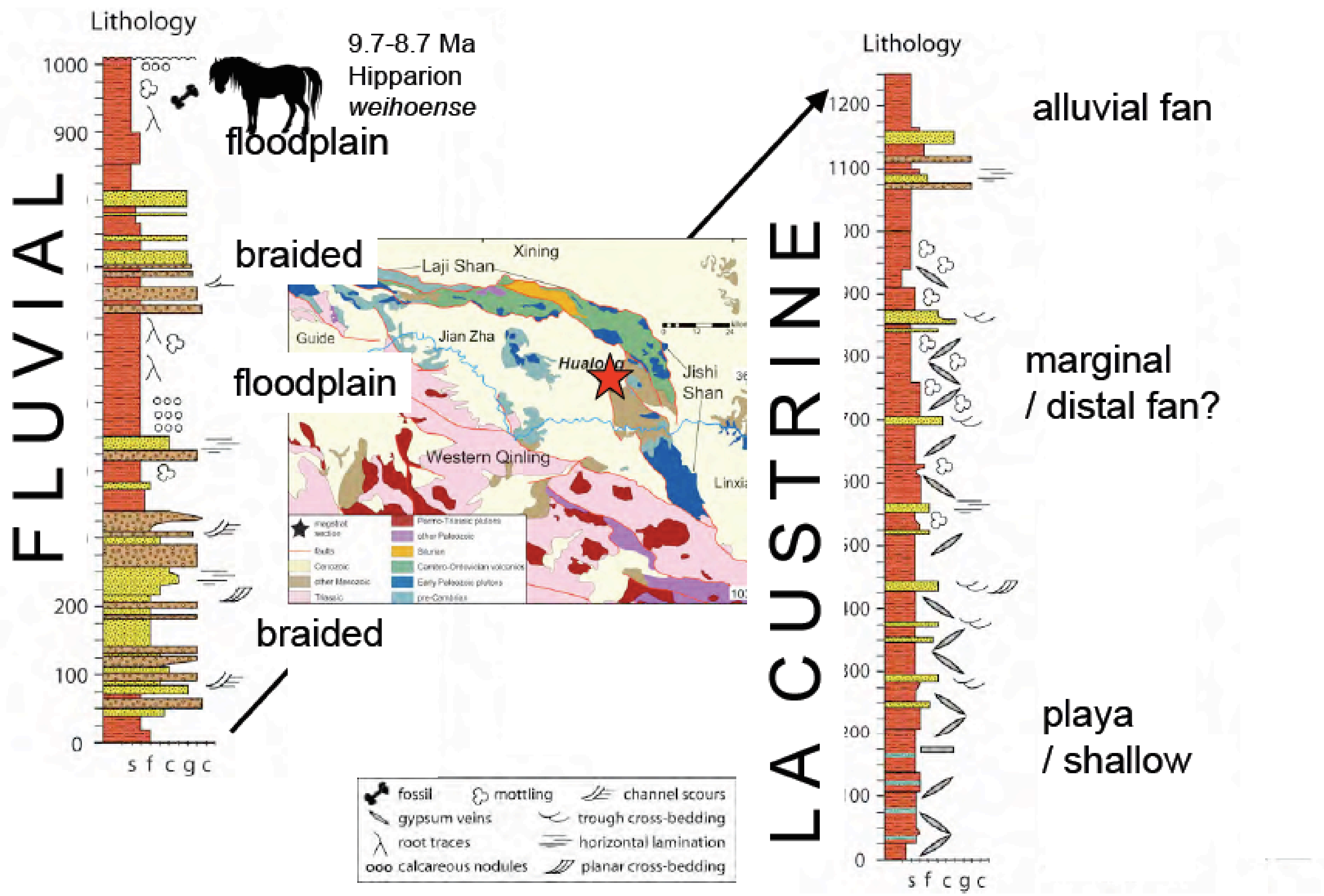




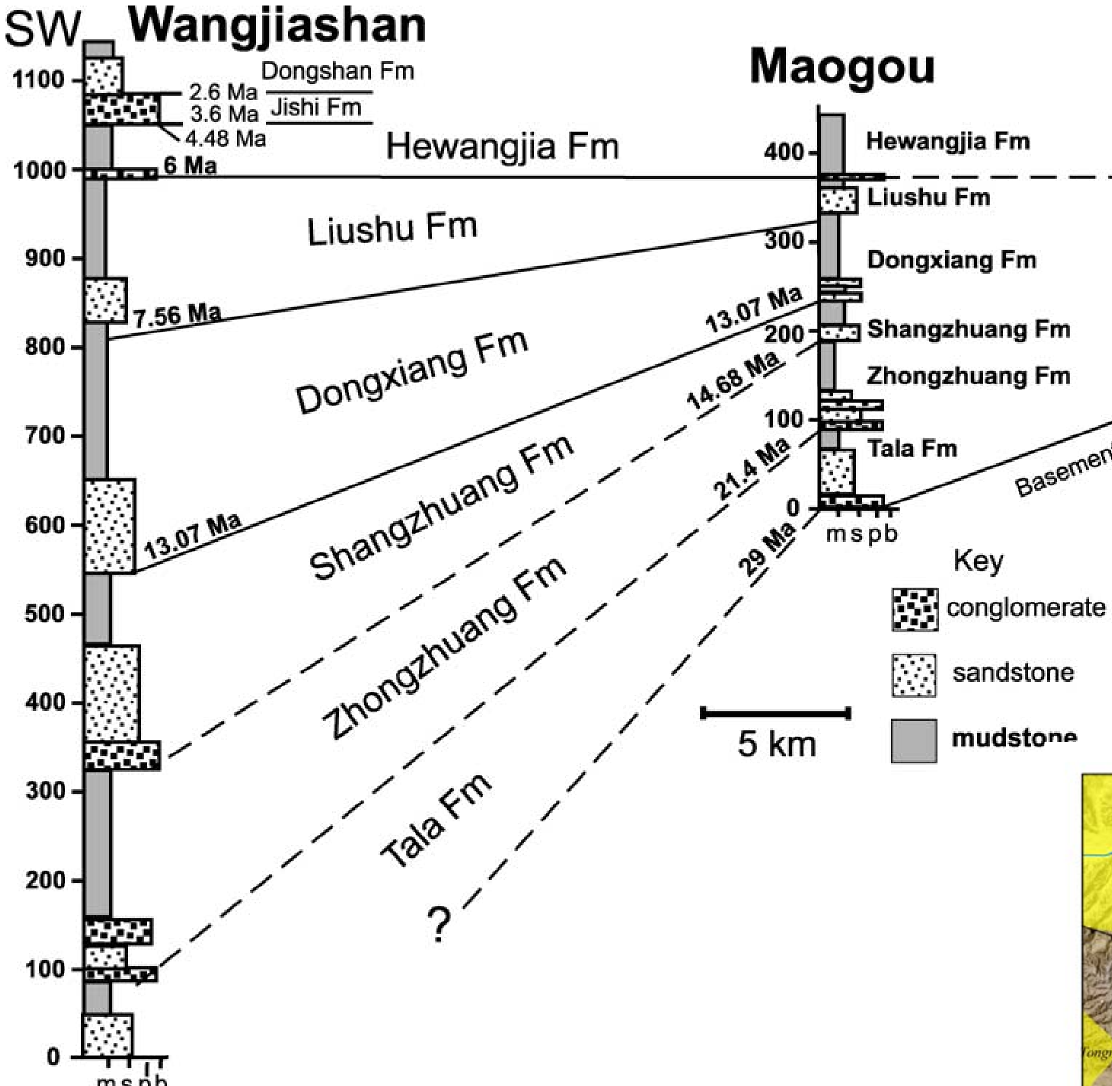
Animation by Tanya Atwater

(given to me for my 60th birthday, and hence honoring all of my prejudices, but not necessarily all of the facts)

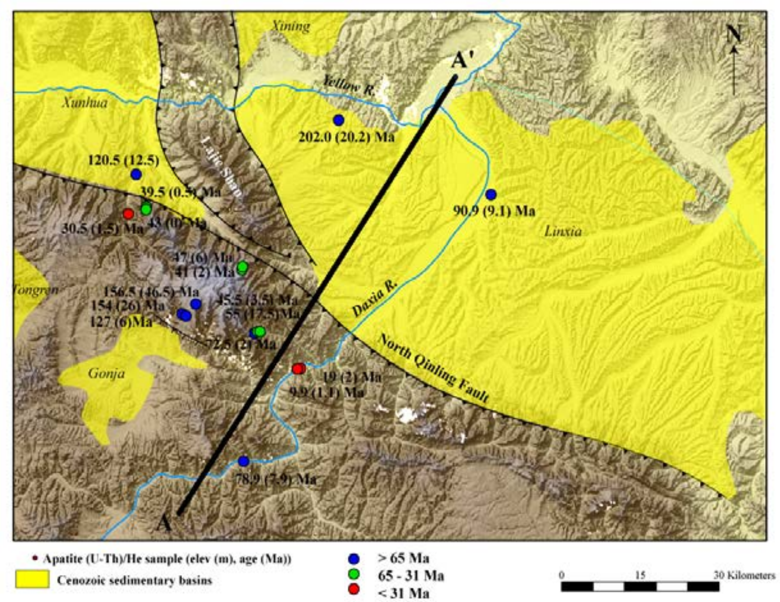
Xunhua Basin Sedimentology



Work of *Lease, Hough, Wang Zhi-Cai, Yuan Dao-Yang, and Burbank* [2010]

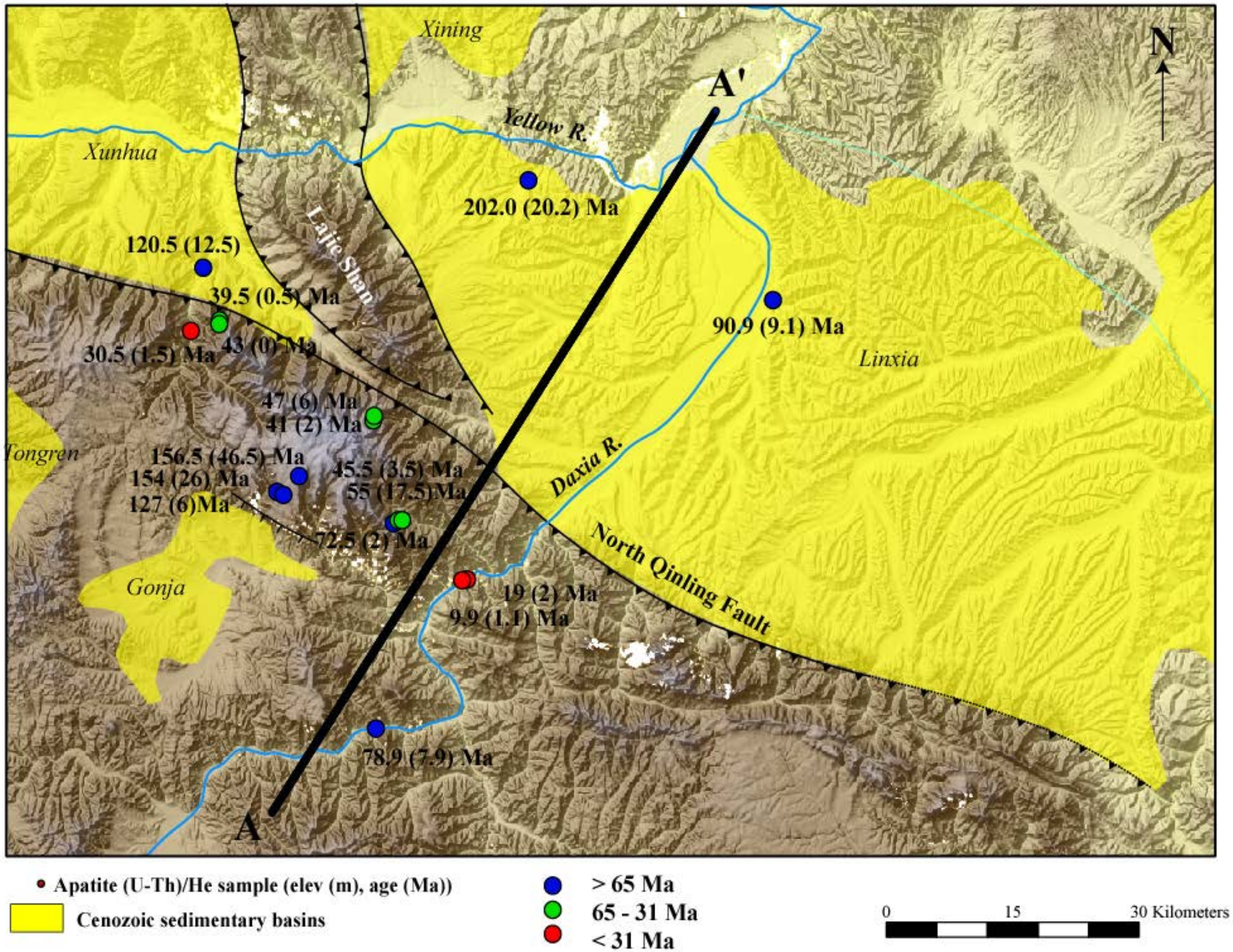


[*Fang et al.*, *EPSL*, 2003]



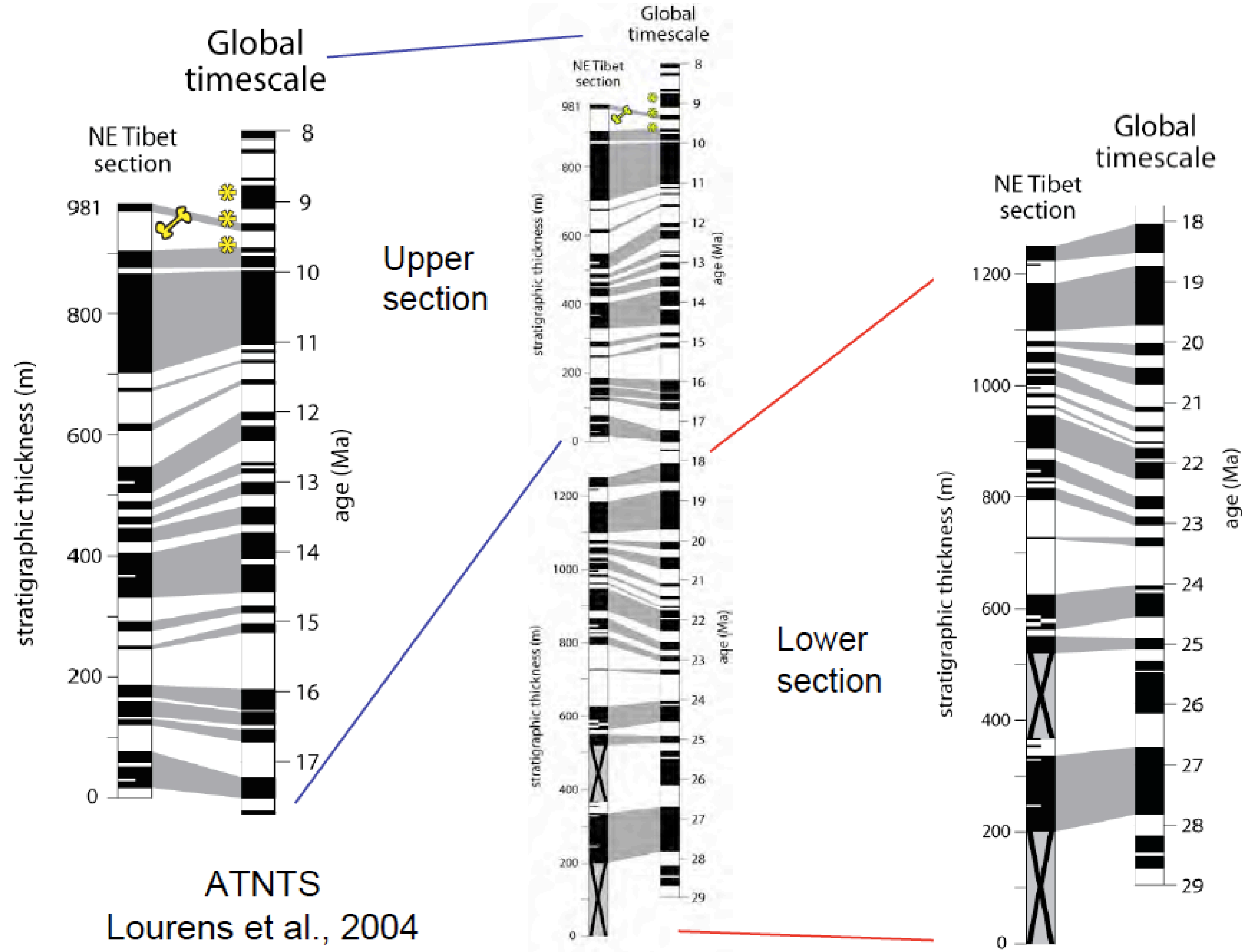
Linxia Basin:
Dates from before 29 Ma
Due to Flexure

Xiqinling (West Qinling) Fault



[*Marin Clark, Ken Farley, Zheng Dewen, Wang Zhicai, and Alison Duvall, EPSL*, 2010]

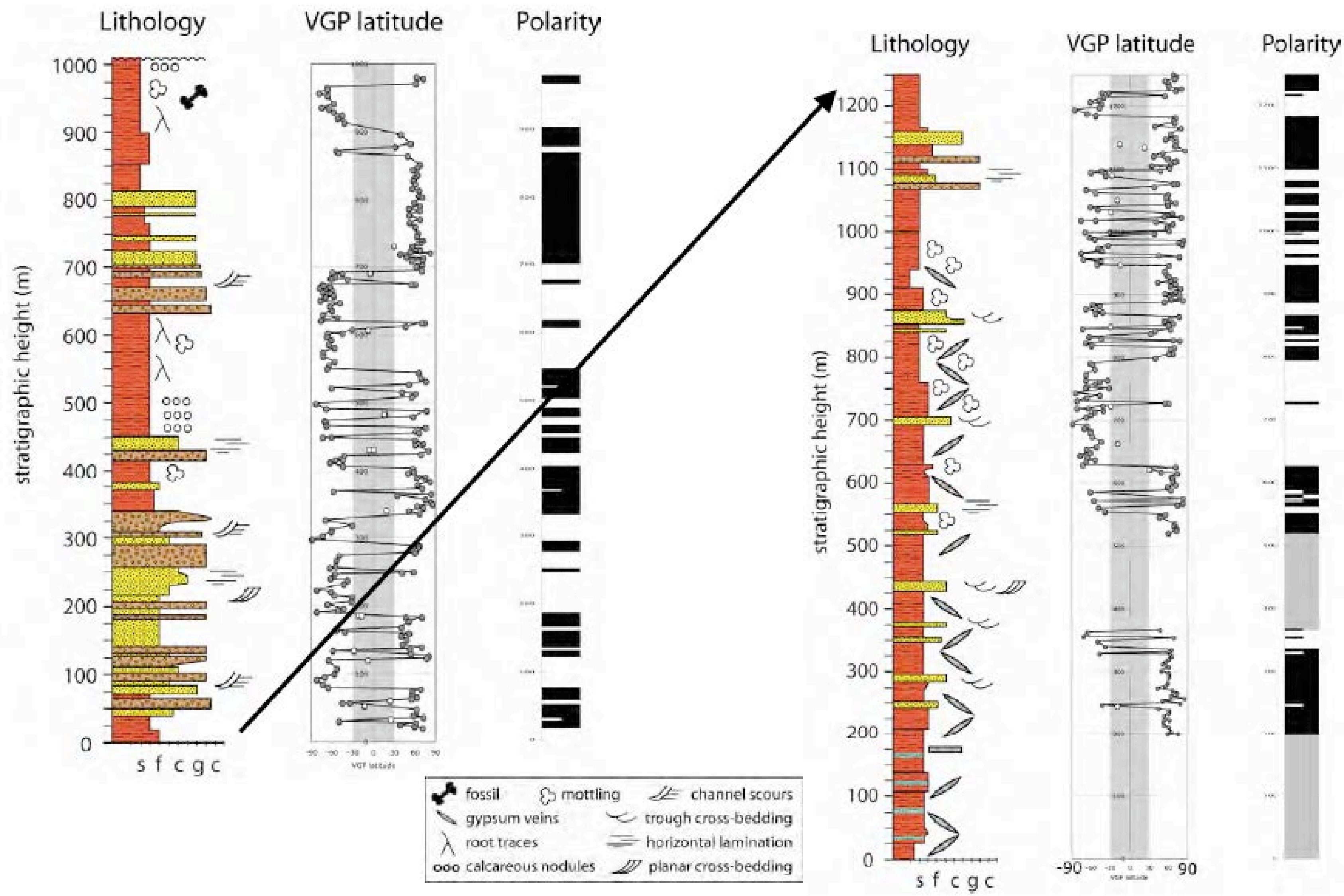
Xunhua Basin Magnetostratigraphy



As in the Linxia Basin, deposition since before 28 Ma

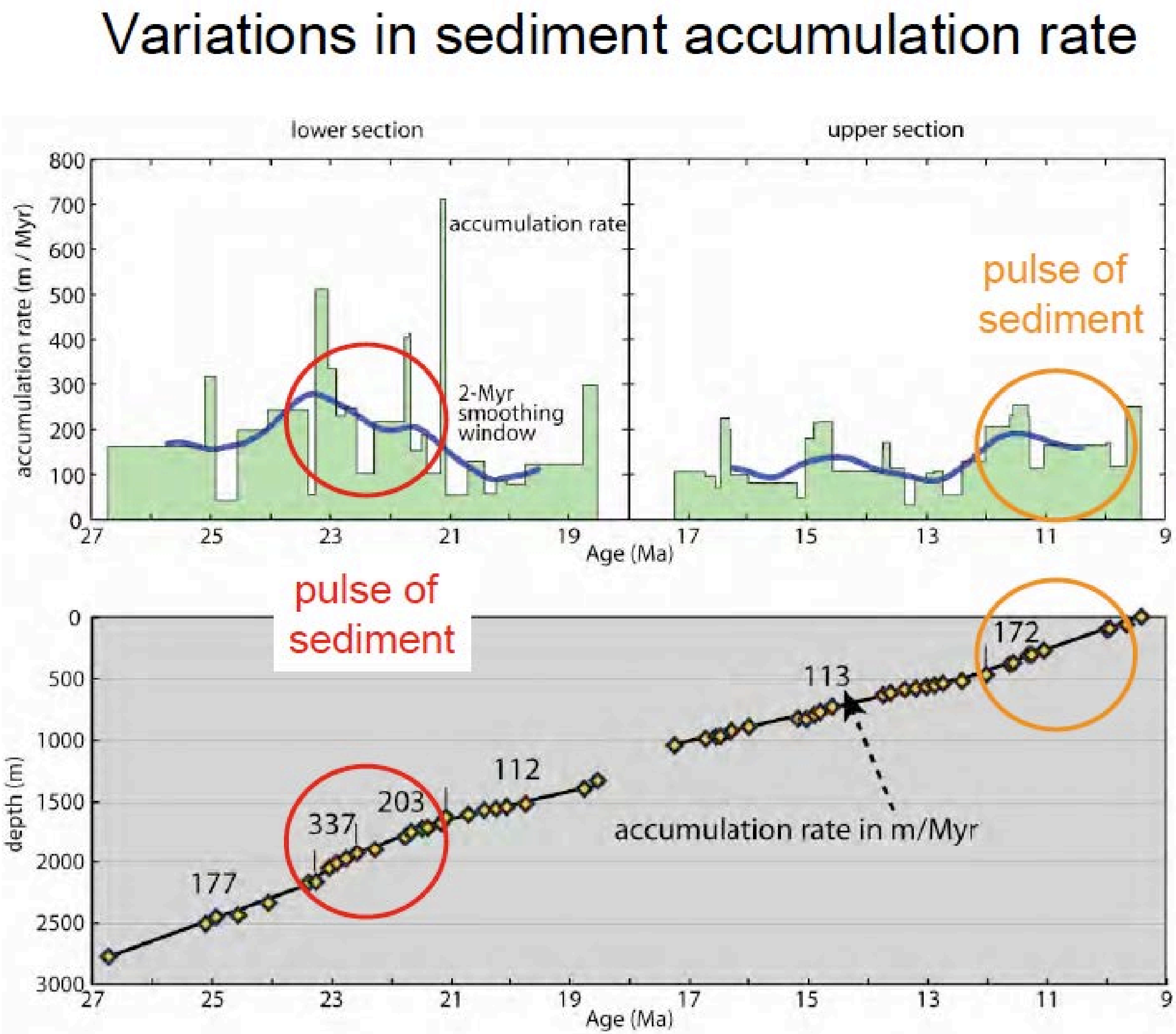
Work of *Lease, Hough, Wang Zhi-Cai, Yuan Dao-Yang, and Burbank* [2011]

Xunhua Basin Magnetostratigraphy



Work of *Lease*, *Hough*, *Wang Zhi-Cai*, *Yuan Dao-Yang*, *and Burbank* [2011]

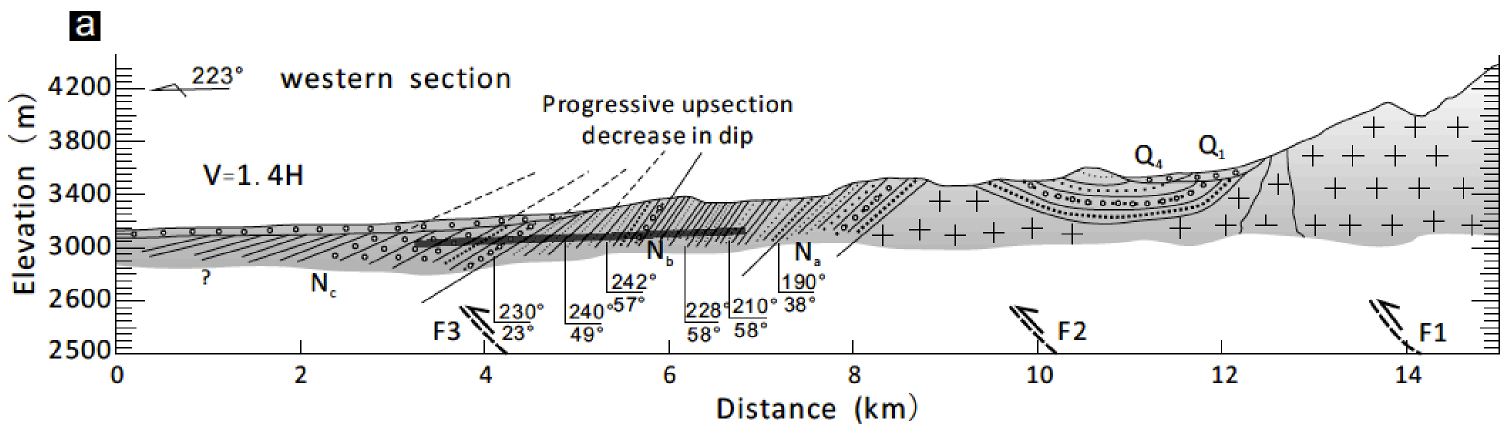
Xunhua Basin Sedimentation Rates

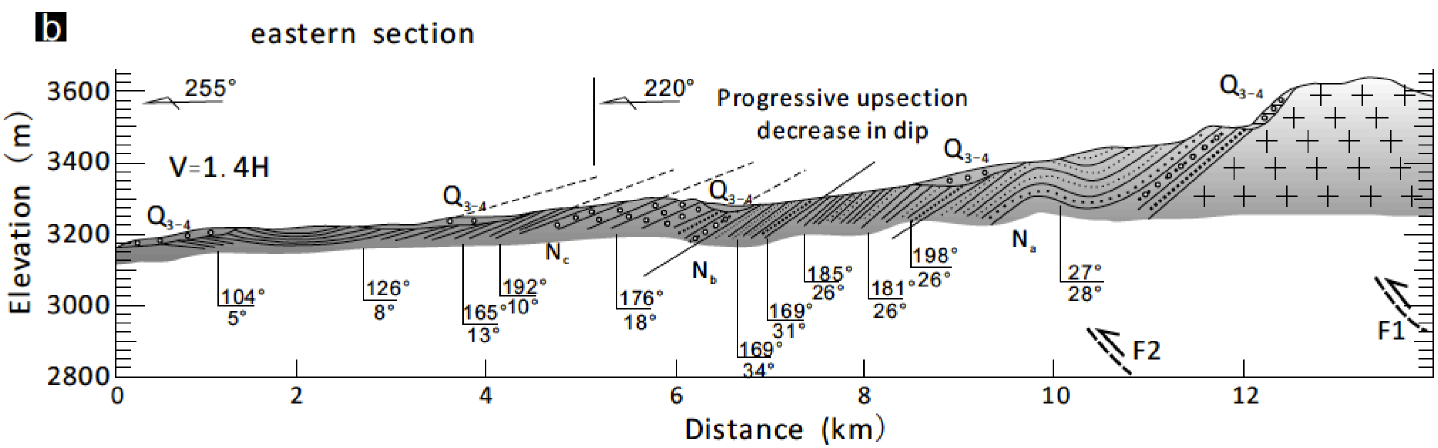


Note two periods of rapid deposition: near 23 Ma and near 11 Ma

Work of *Lease, Hough, Wang Zhi-Cai, Yuan Dao-Yang, and Burbank* [2011]

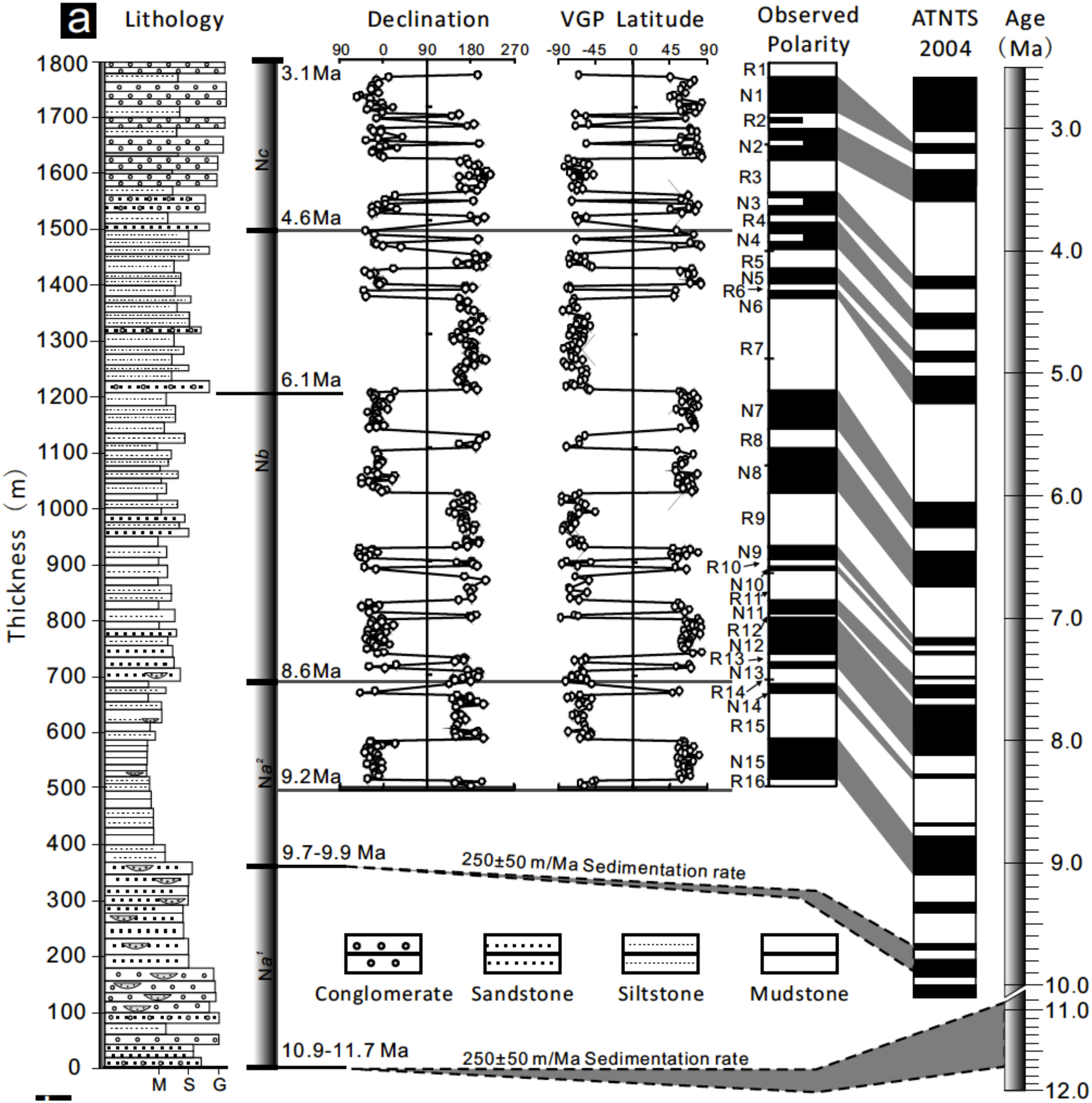
Tilted and folded late Miocene-early Pliocene sedimentary rock, including growth strata, in the Chaka basin





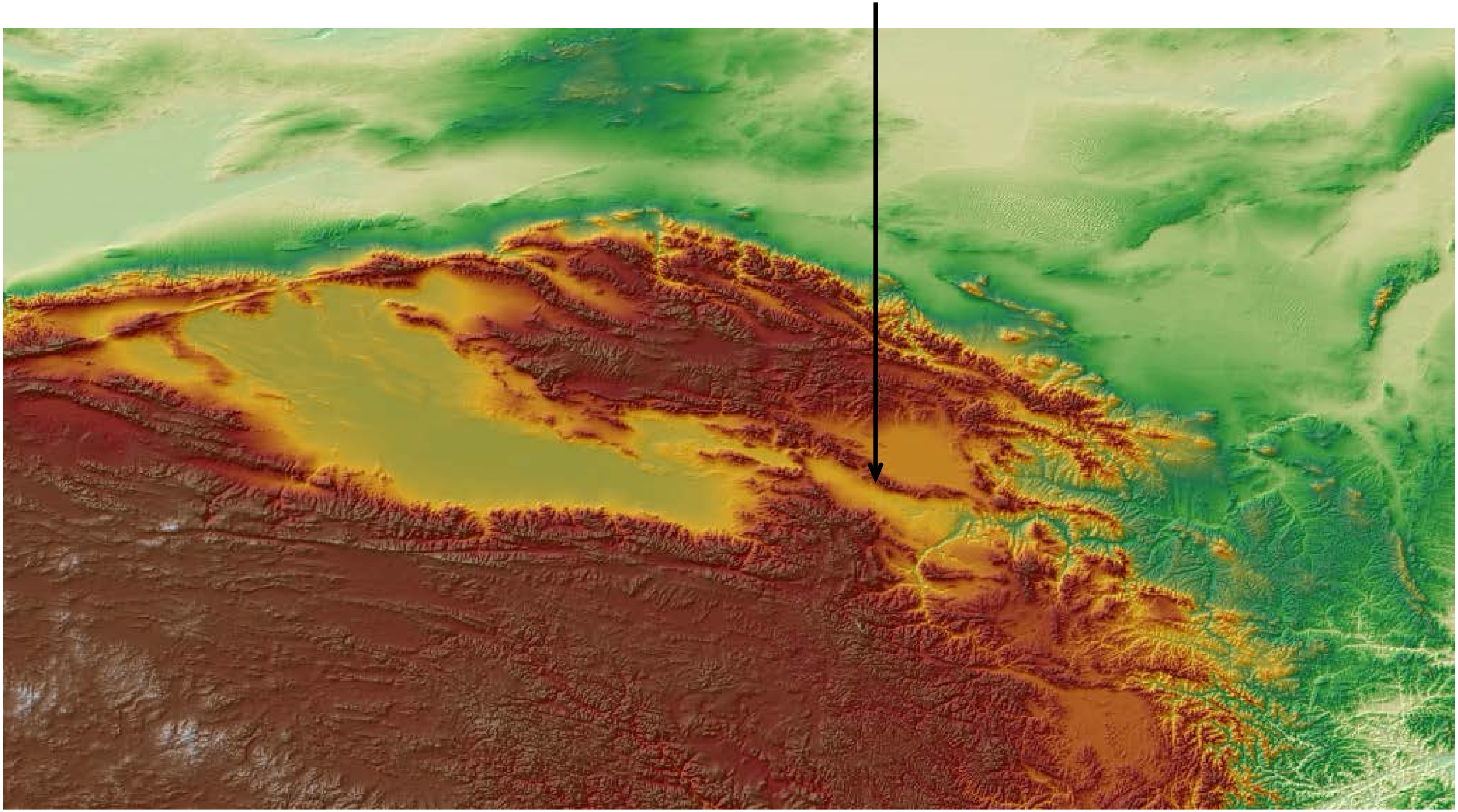
[*Zhang Hui-Ping, William H. Craddock, Richard O. Lease, Wang Wei-tao, Yuan Dao-Yang, Zhang Pei-Zhen, Peter Molnar, Zheng De-Wen, and Zheng Wen-Jun, Basin Research,* 2012]

Chaka Basin Magnetostratigraphy



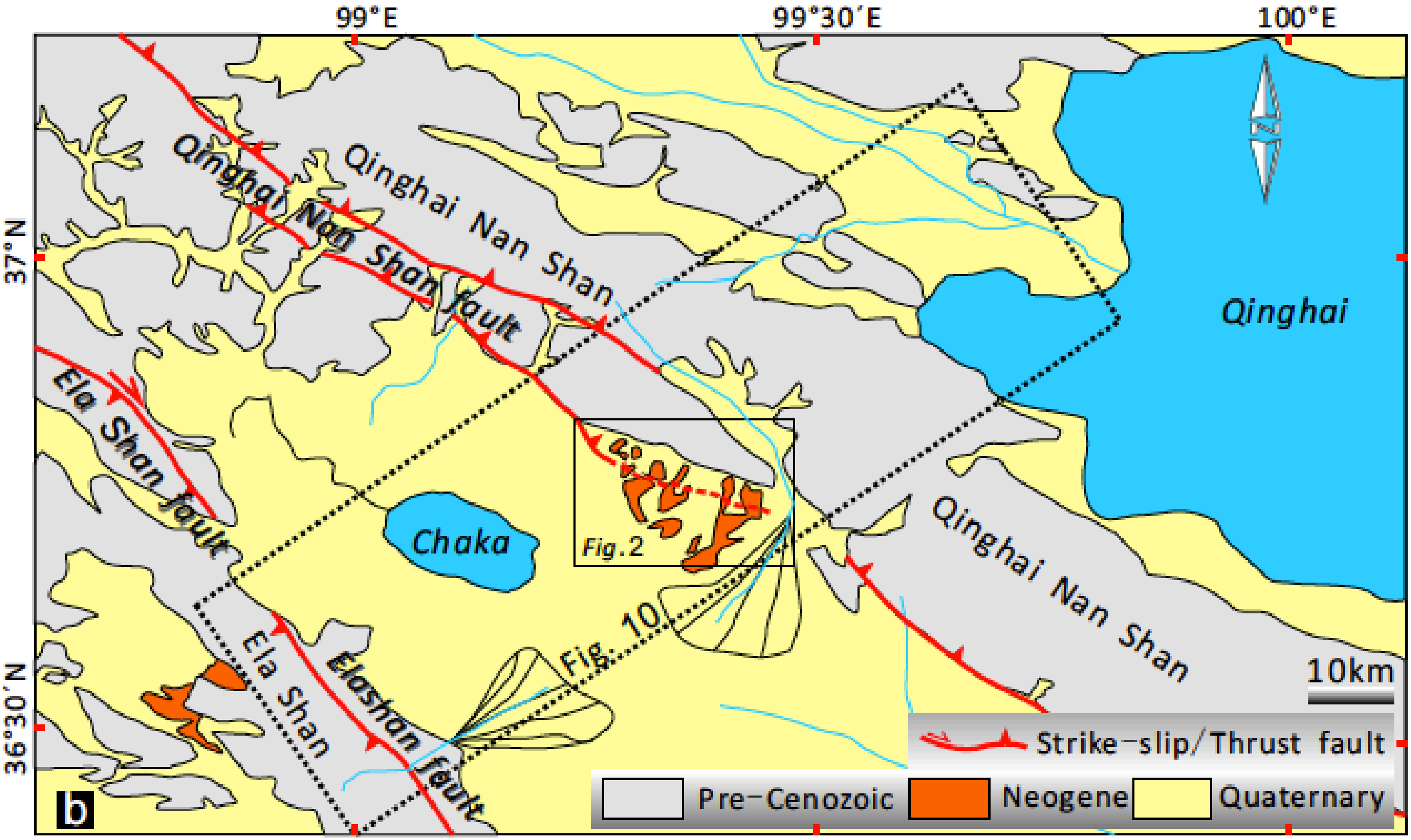
[*Zhang Hui-ping et al.*, *Basin Research* 2012]

Emergence of the Qinghai Nanshan at ~ 6 Ma



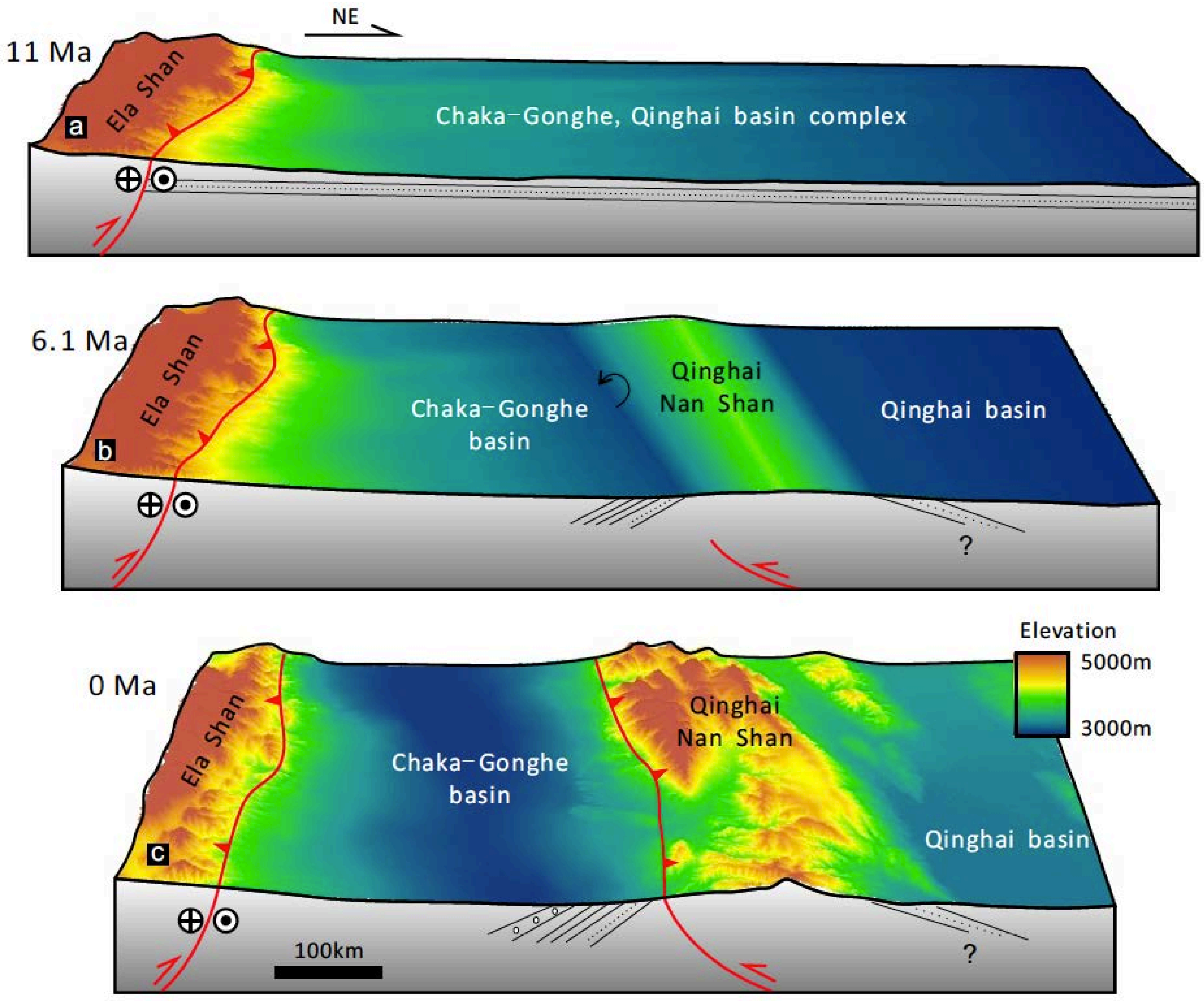
[*Zhang Hui-Ping, W. H. Craddock, R. O. Lease, Wang Wei-tao, Yuan Dao-Yang, Zhang Pei-Zhen, P. Molnar, Zheng De-Wen, and Zheng Wen-Jun, Basin Research*, 2011]

Chaka Basin



[*Zhang Hui-Ping, W. H. Craddock, R. O. Lease, Wang Wei-tao, Yuan Dao-Yang, Zhang Pei-Zhen, P. Molnar, Zheng De-Wen, and Zheng Wen-Jun, Basin Research*, 2012]

Simple history of the Chaka Basin and Qinghai Nanshan



[*Zhang Hui-ping et al.*, *Basin Research*, 2012]

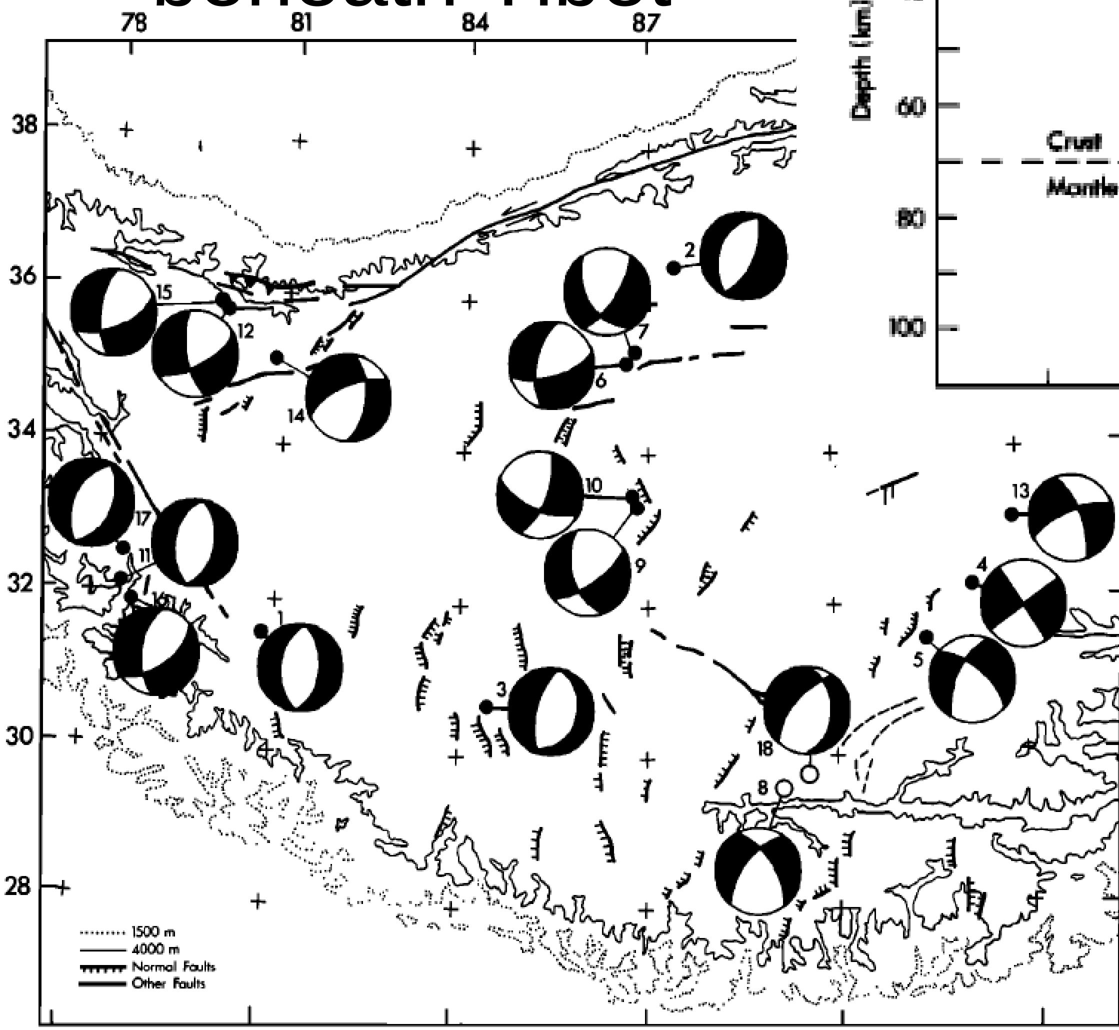
Interim Summary

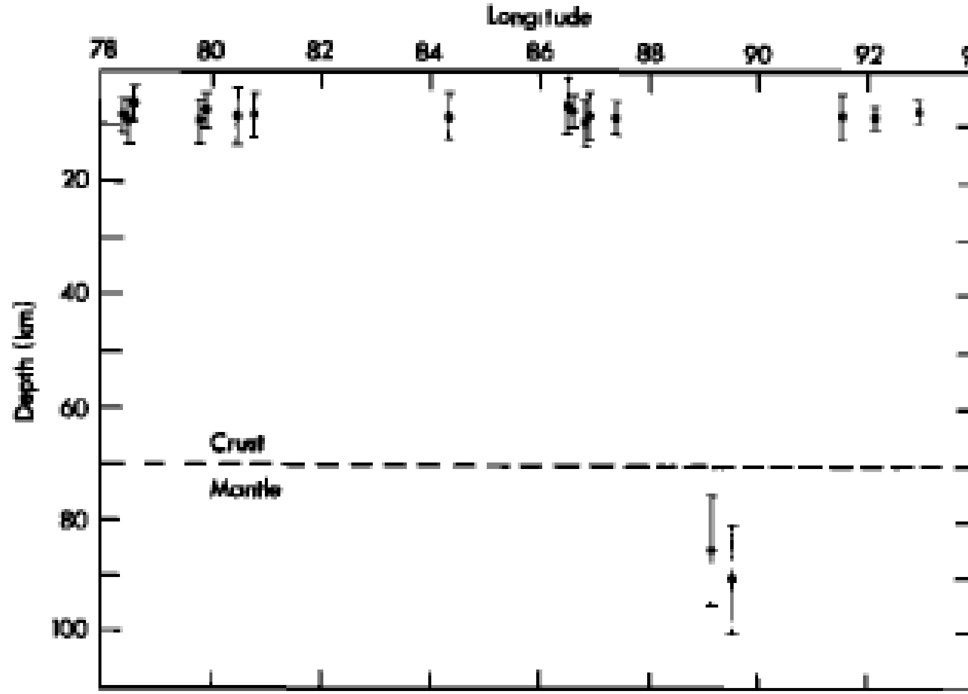
1. Active faulting, associated with north-south shortening in northern Tibet, began shortly after collision [*Clark et al.*, 2010; *Dupont-Nivet et al*., 2004; *Duvall et al*., 2011; *Ritts et al*., 2004; *Yin et al*., 2007, 2008].
2. Such shortening continued until ~22 Ma, if not somewhat more recently [*Clark et al*., 2010; *Lease et al*., 2011, 2012].
3. Such shortening, at low rates of a few mm/yr, ought not be a surprise given the width of the indentor [*Dayem et al*., 2009].

Stages in the Growth of Tibet

1. Before collision, at ~45 Ma, a narrow high range like the present-day ***Andes*** (apparently) bounded southern Eurasia.
2. The **Himalaya** has been built by slices of Indian crust thrust atop the Indian subcontinent.
3. Since Collision, India has penetrated steadily into Eurasia, **shortening and thickening Asian crust** to build the wide **high Tibetan Plateau**.
4. Near **~15-10 Ma**, a change took place; the plateau started to **collapse**, **spread apart**, and (presumably) **subside** slowly (perhaps because of removal of mantle lithosphere that took a load off the bottom)**.**

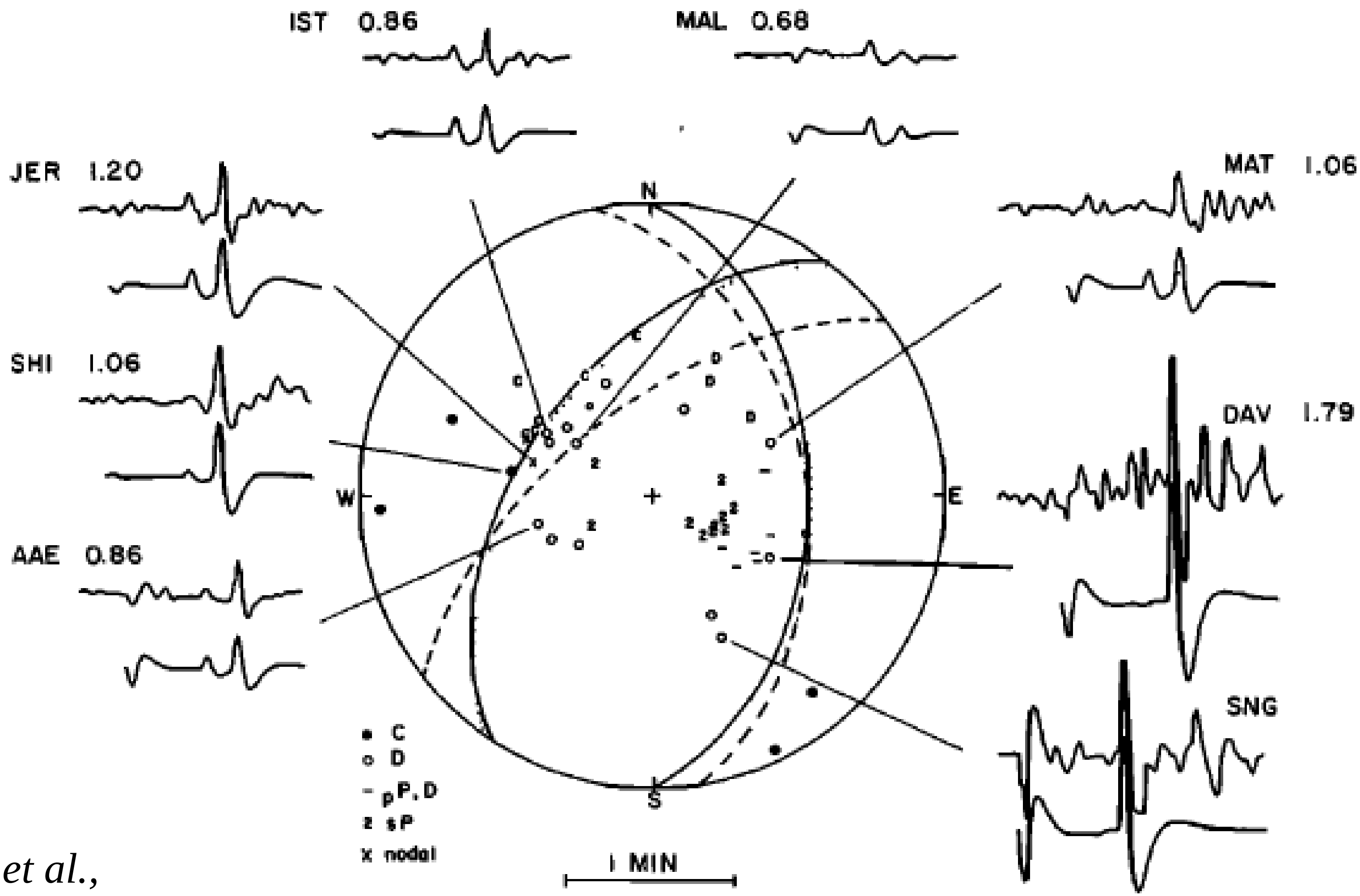
Depths of earthquakes beneath Tibet





Molnar and Chen, *JGR*, 1983]

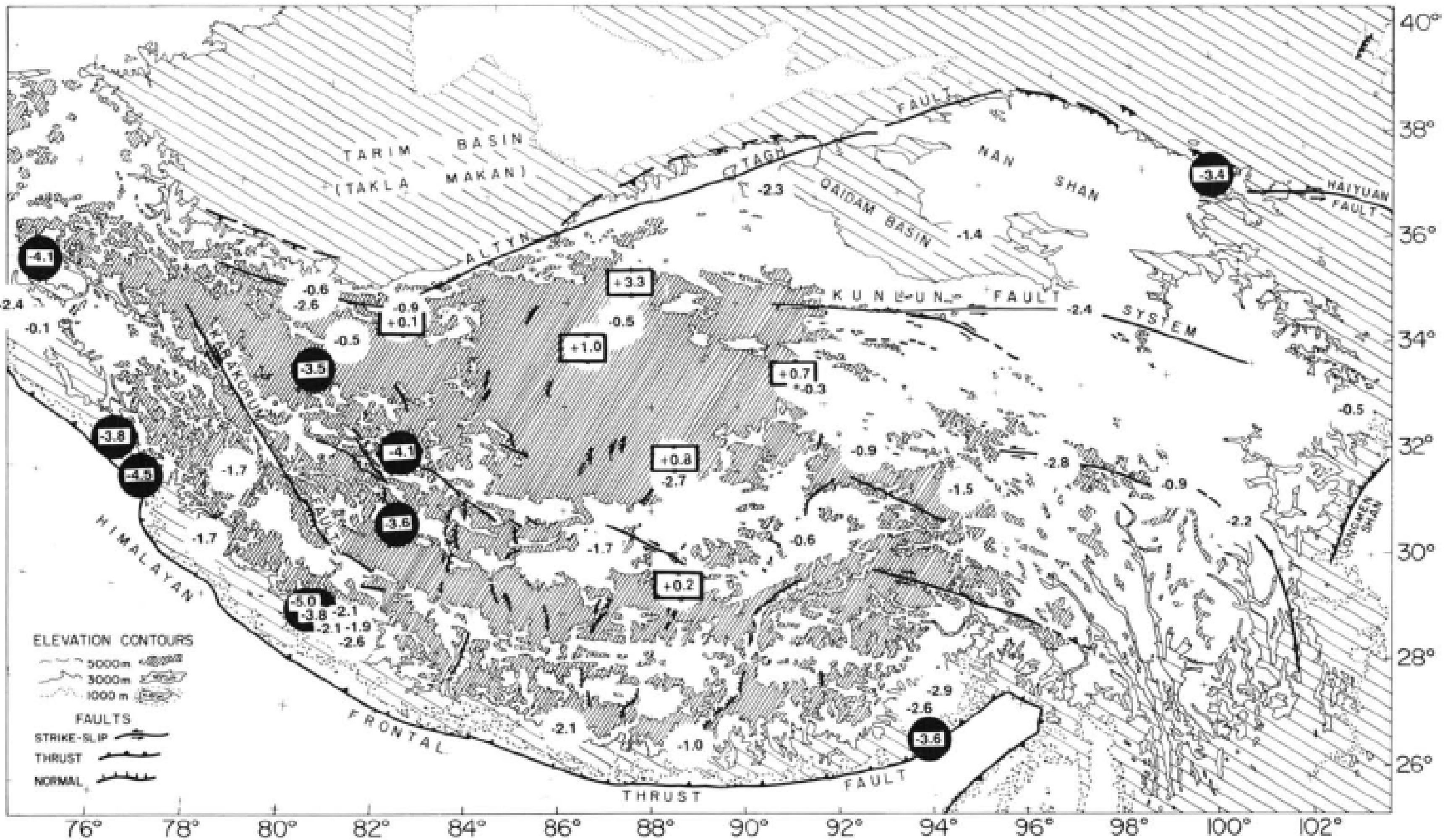
Intermediate-depth earthquakes



September 14, 1976 Tibet 29.81° N, 89.57°E 90 km

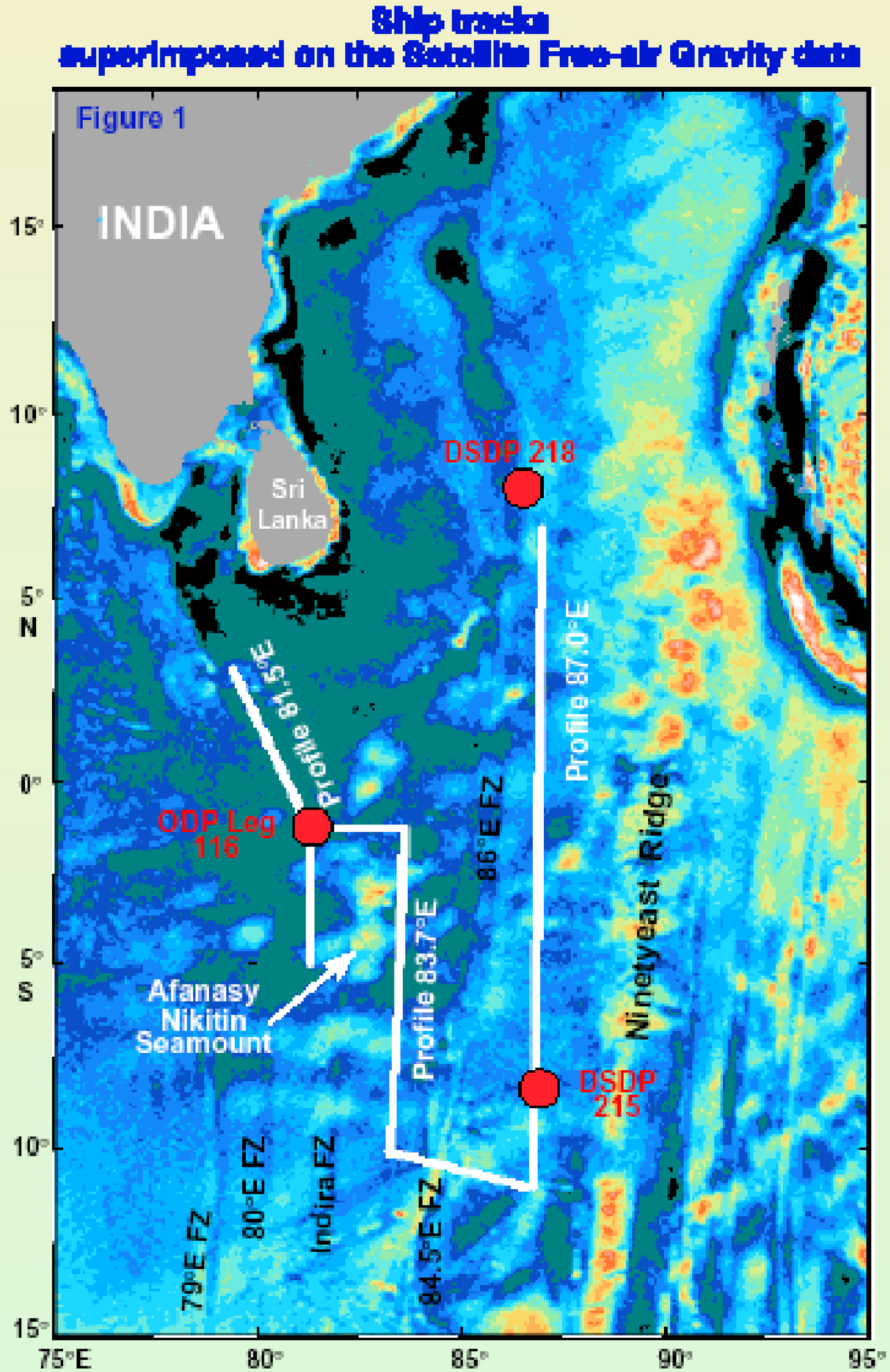
[*Chen et al.*, *JGR*, 1981]

S-wave residuals from Tibetan earthquakes



Negative: early arrivals, high speeds
Positive, late arrivals, low speeds

[*Molnar, EPSL*, 1990]



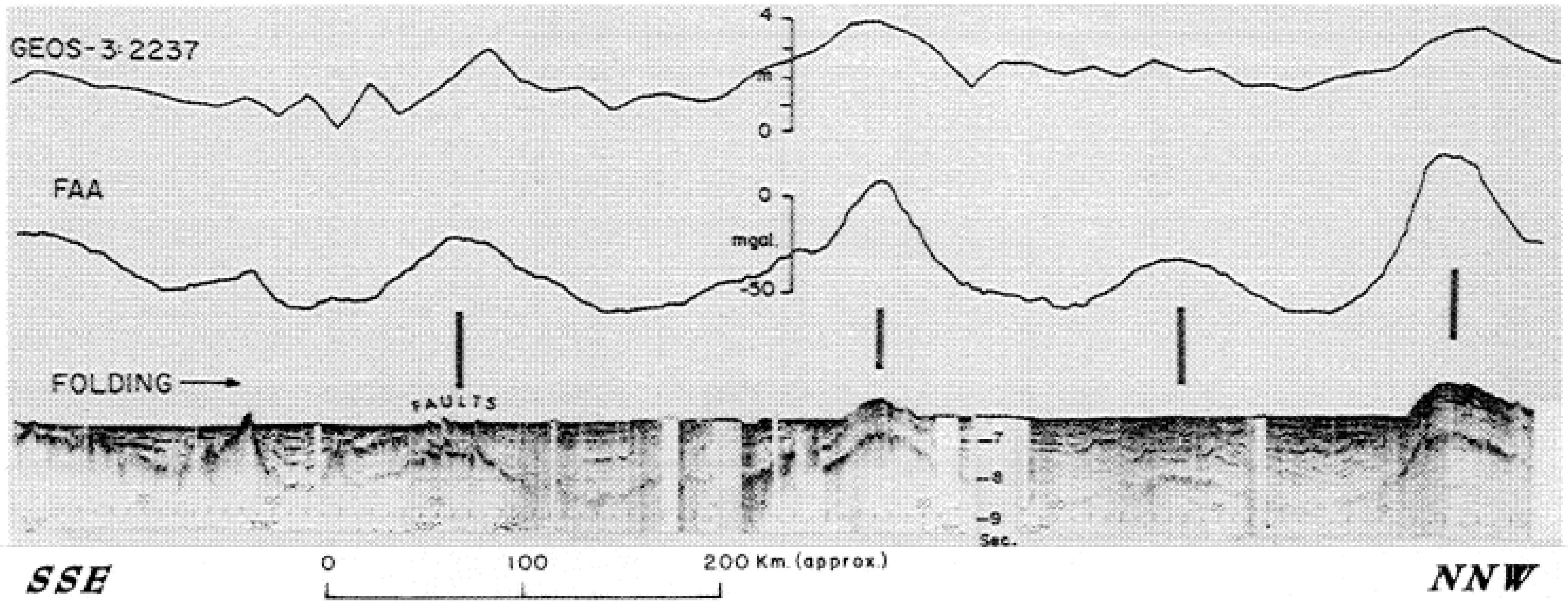
Folding South of India, on free-air gravity map

Work of Bull, Krisha, and Scrutton

(from Bull's webpage)

Geoid & Gravity Anomalies over Folds in the Indian Ocean Lithosphere

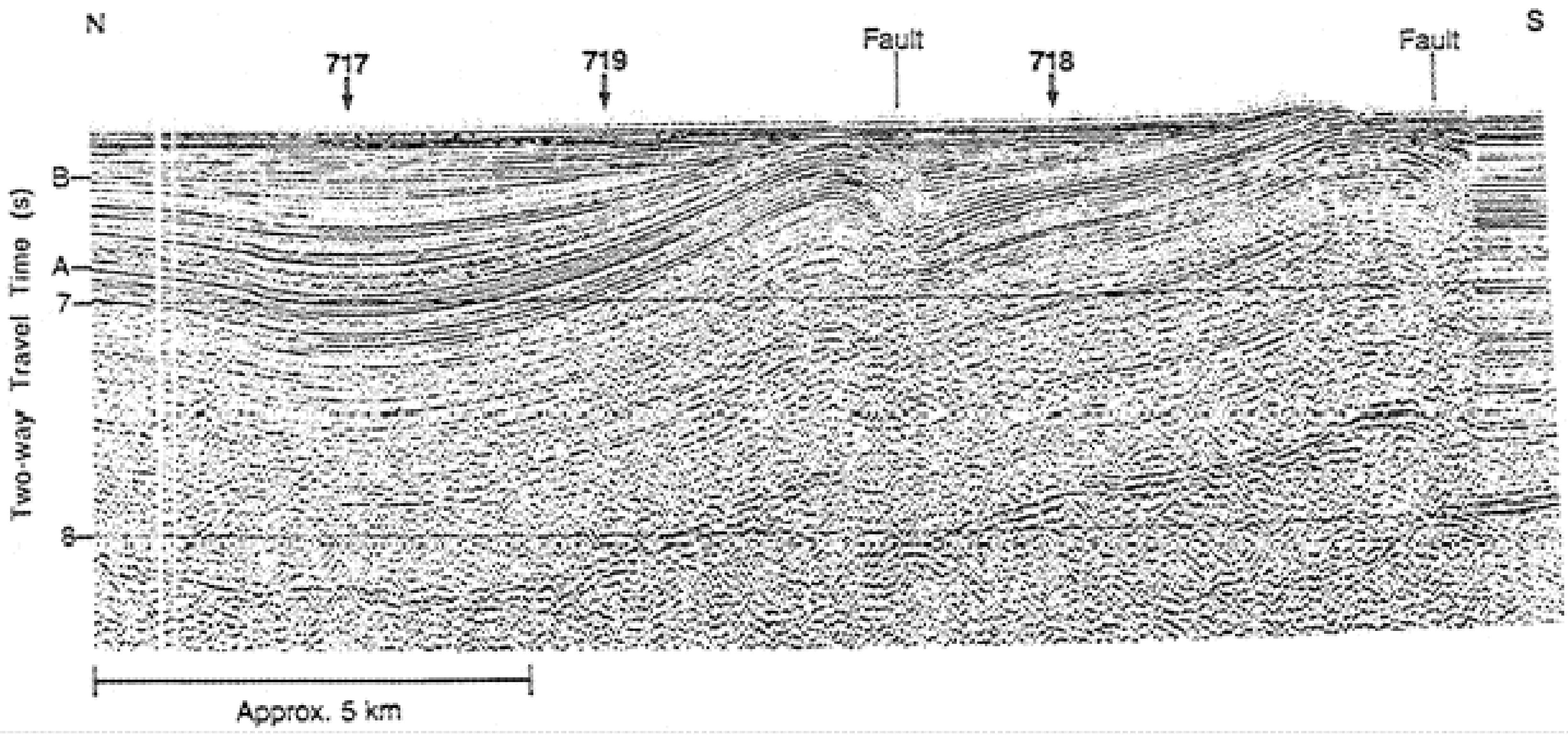
[Weissel, Anderson, & Geller, 1980]



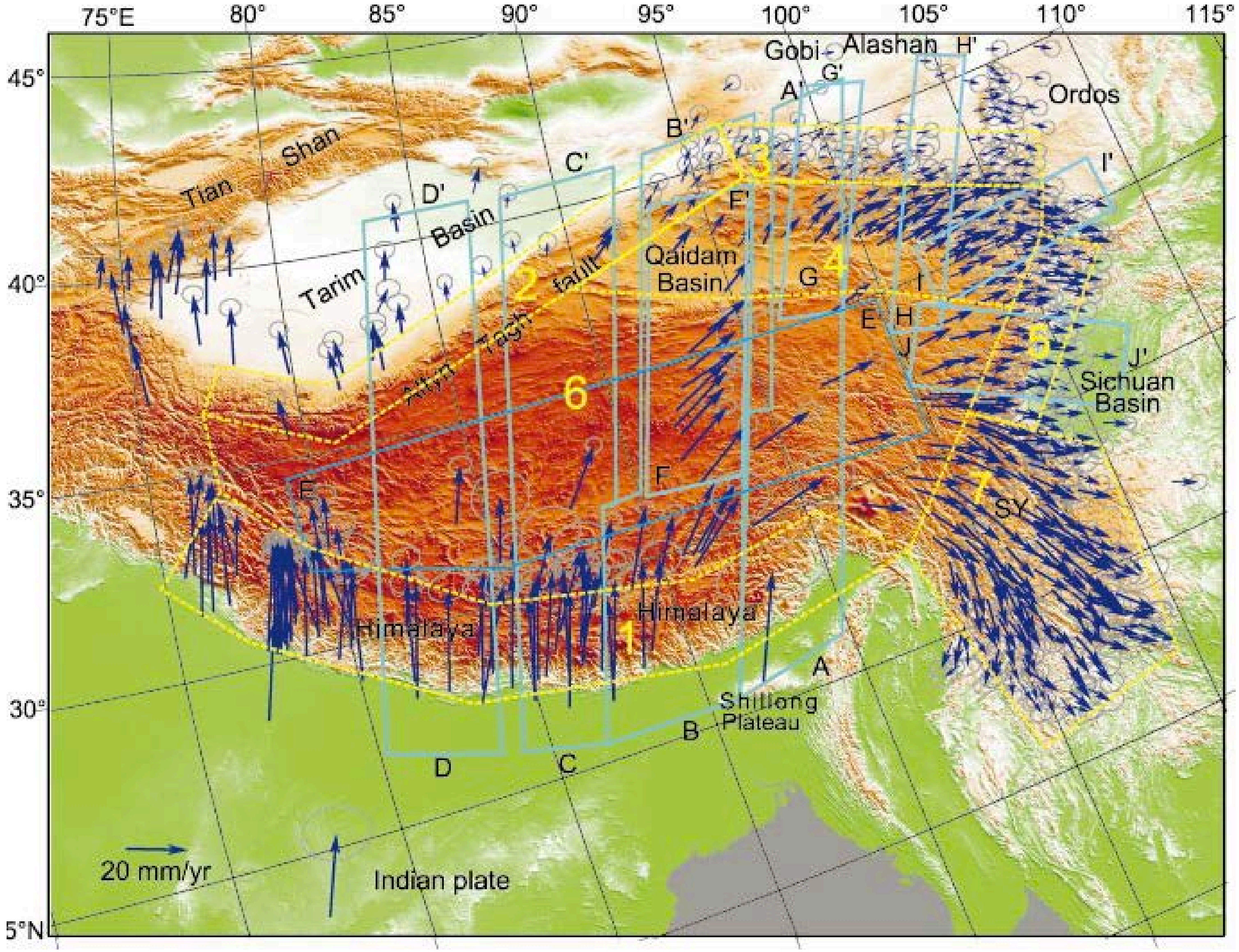
Folds Drilled by the Ocean Drilling Project

[Cochran, 1990]

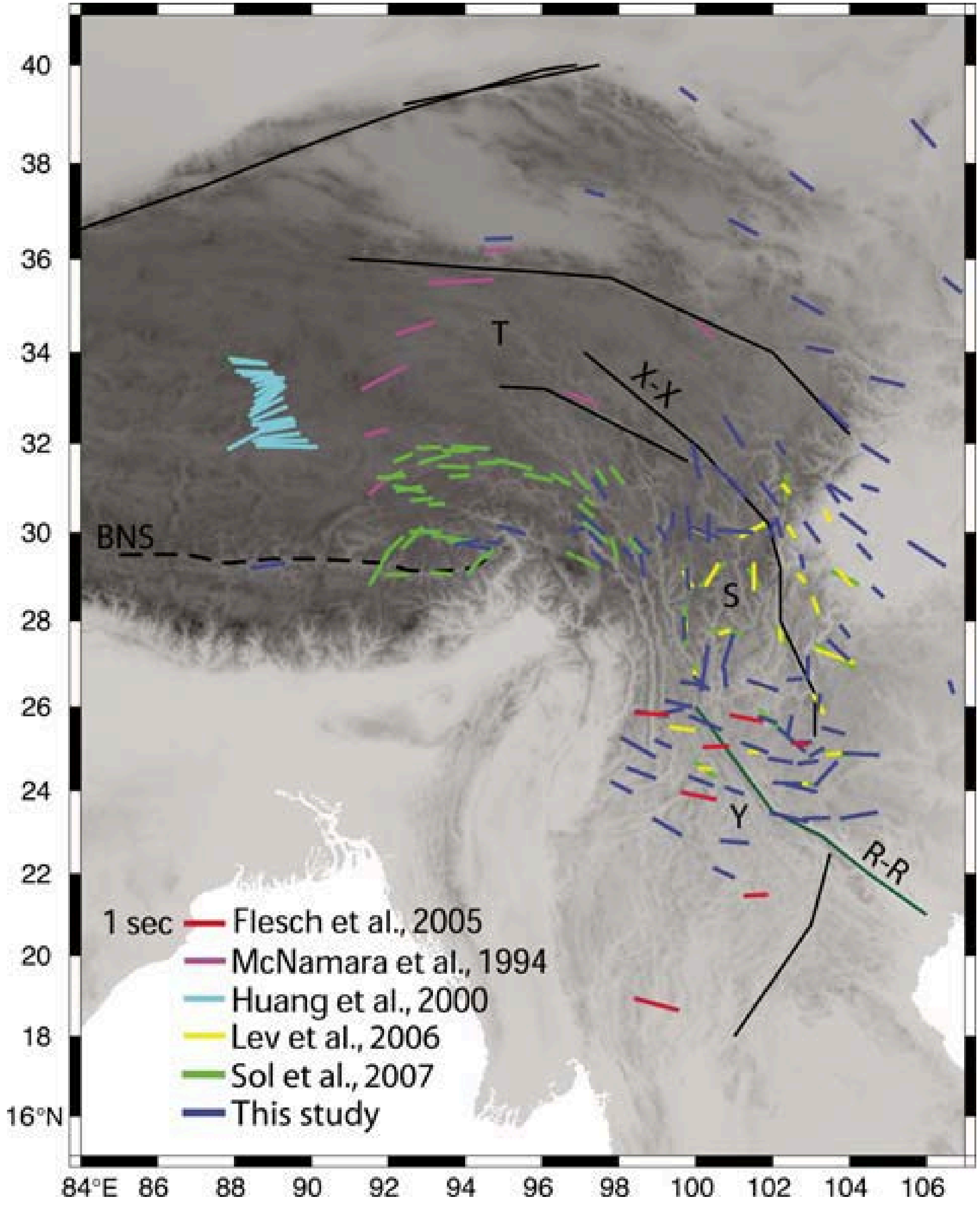
Horizon A has been dated at ~7.6 Ma



Present-day GPS Velocities



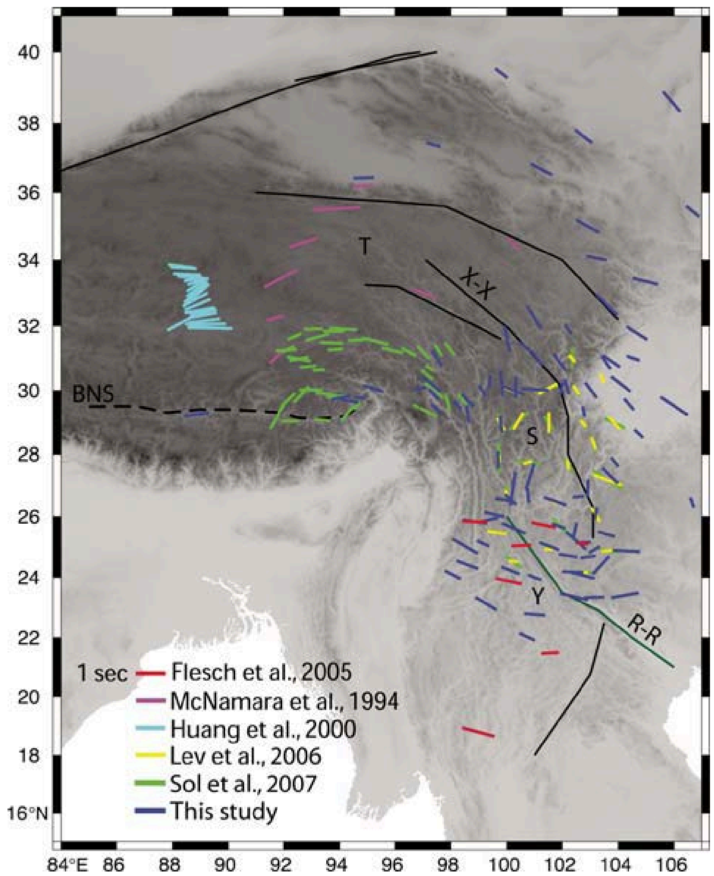
[*Zhang et al.*, *Geology*,2004]

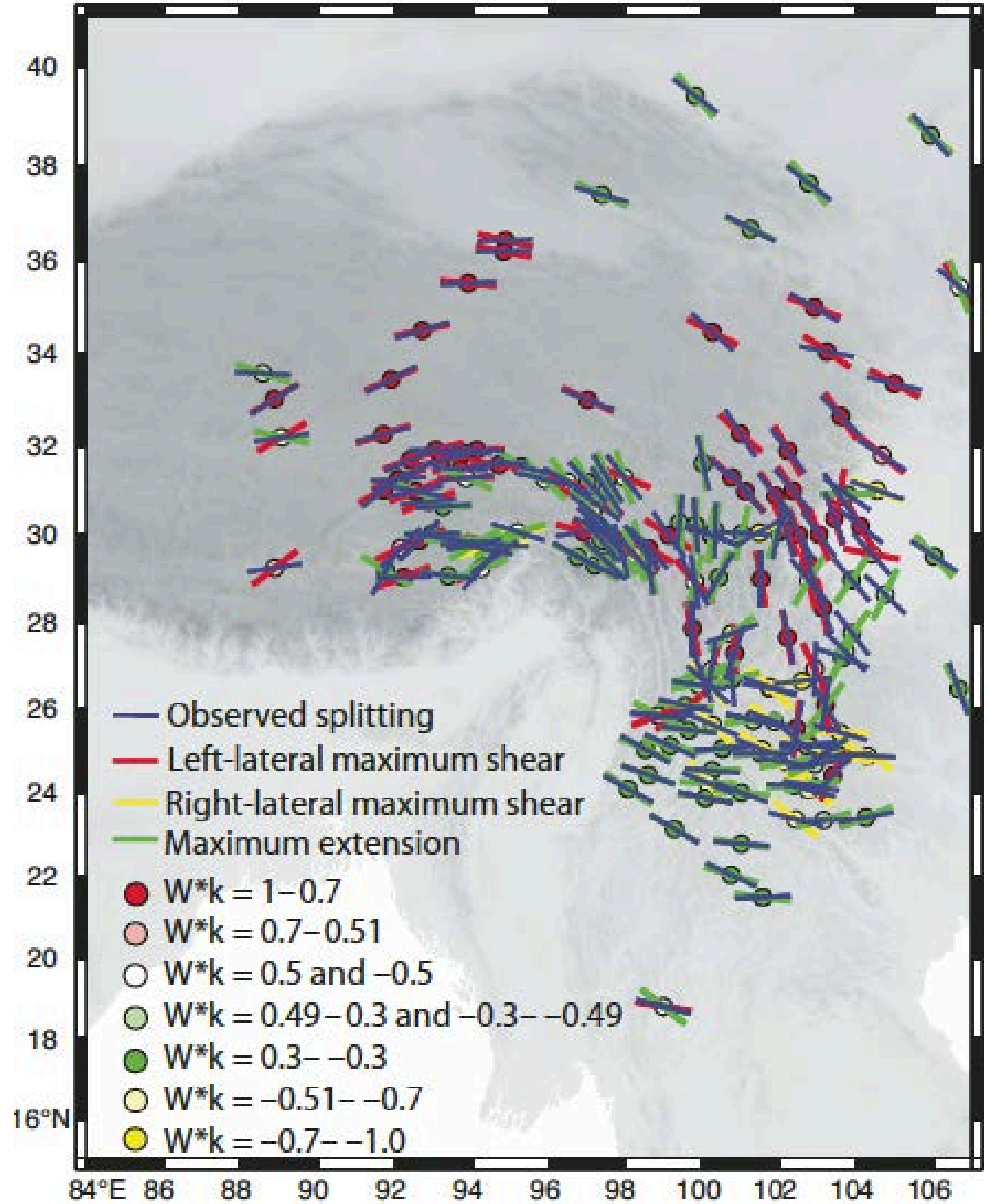


Brief Digression: Shear-wave splitting and anisotropy

[Wang et al., Geology, 2008]

Shear-wave splitting and anisotropy



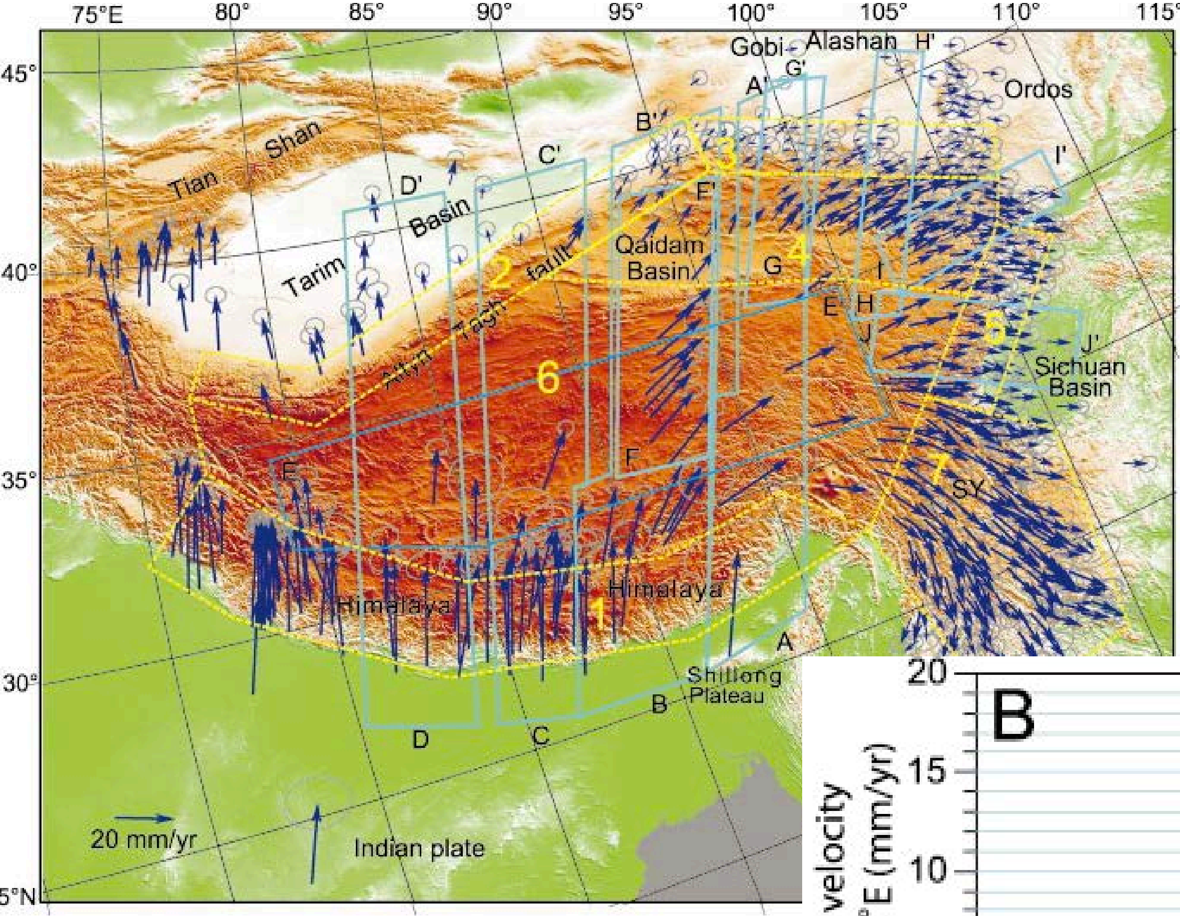


Brief Digression: Shear-wave splitting and anisotropy

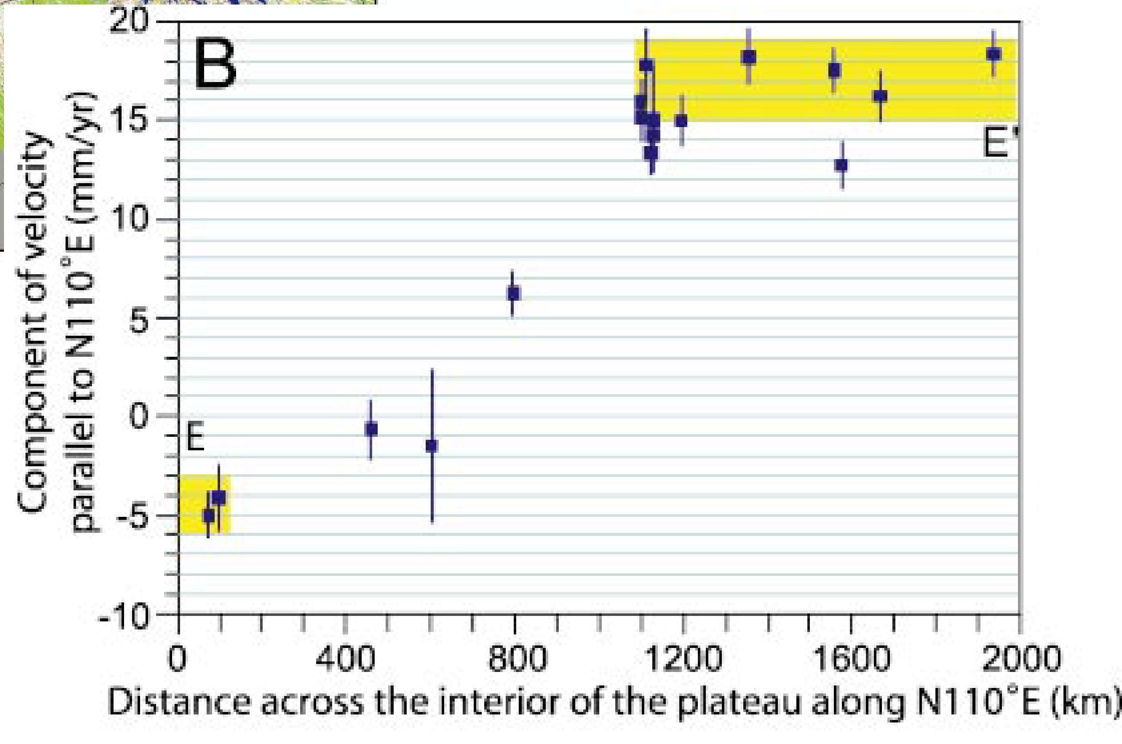
Orientations of present-day strain rates match orientations of fast quasi-S waves in shear wave splitting.

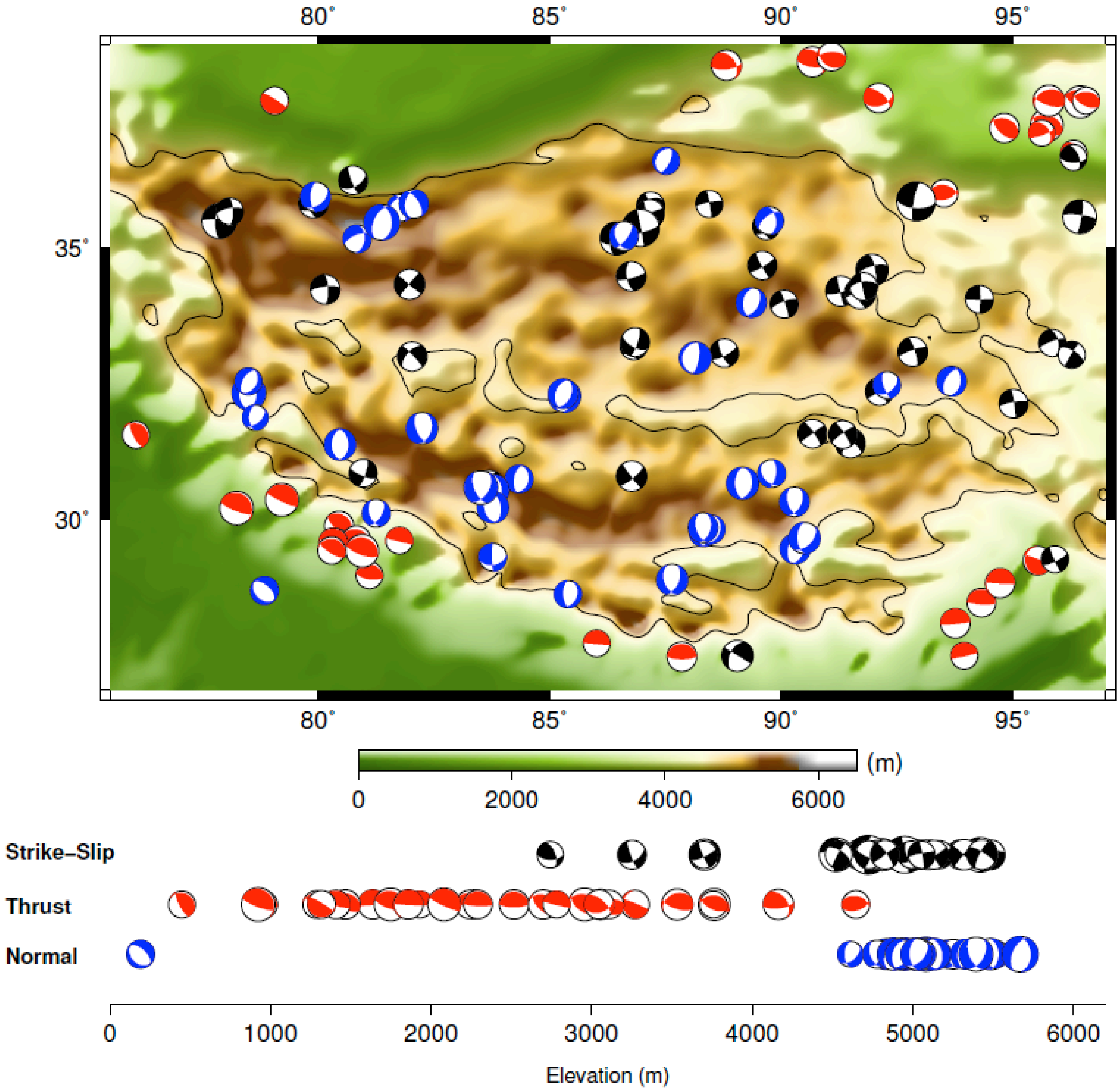
Thus, the uppermost crust and the upper mantle seem to deform together.

Present-day GPS Velocities



[*Zhang et al., Geology*,2004]



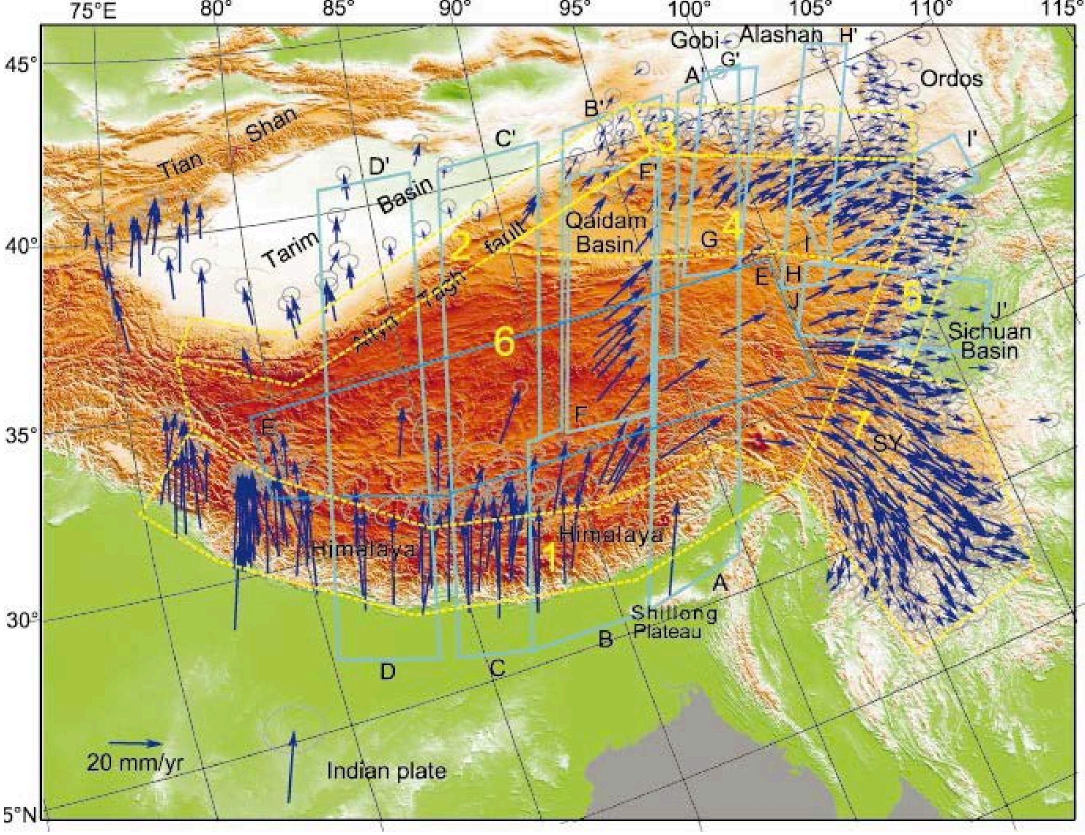


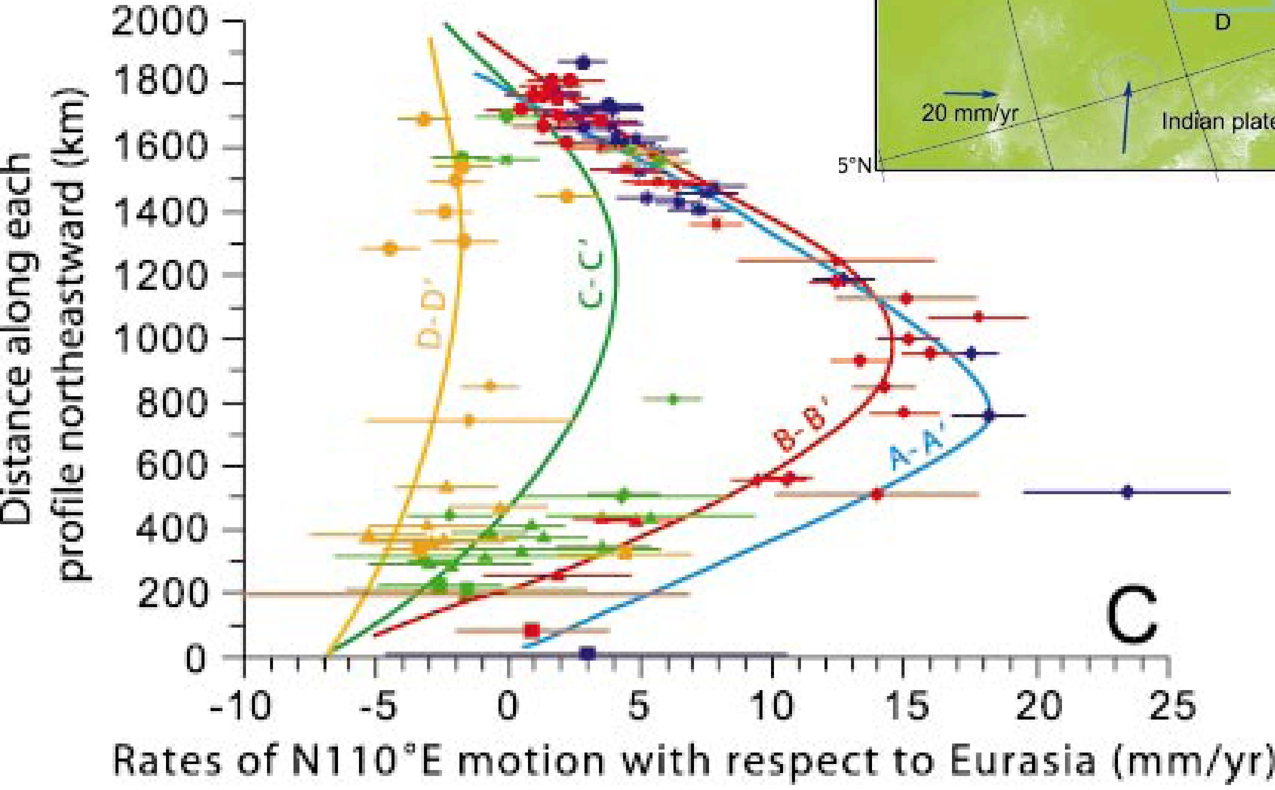
[*Elliott, Walters, England, Jackson, Li, and Parsons* 2010]

Normal faulting and E-W crustal extension occur throughout Tibet; thrust faulting and crustal shortening occur on the surrounding flanks.

*A high plateau **cannot** be built by normal faulting. Some **change** must have occurred.*

Present-day GPS Velocities

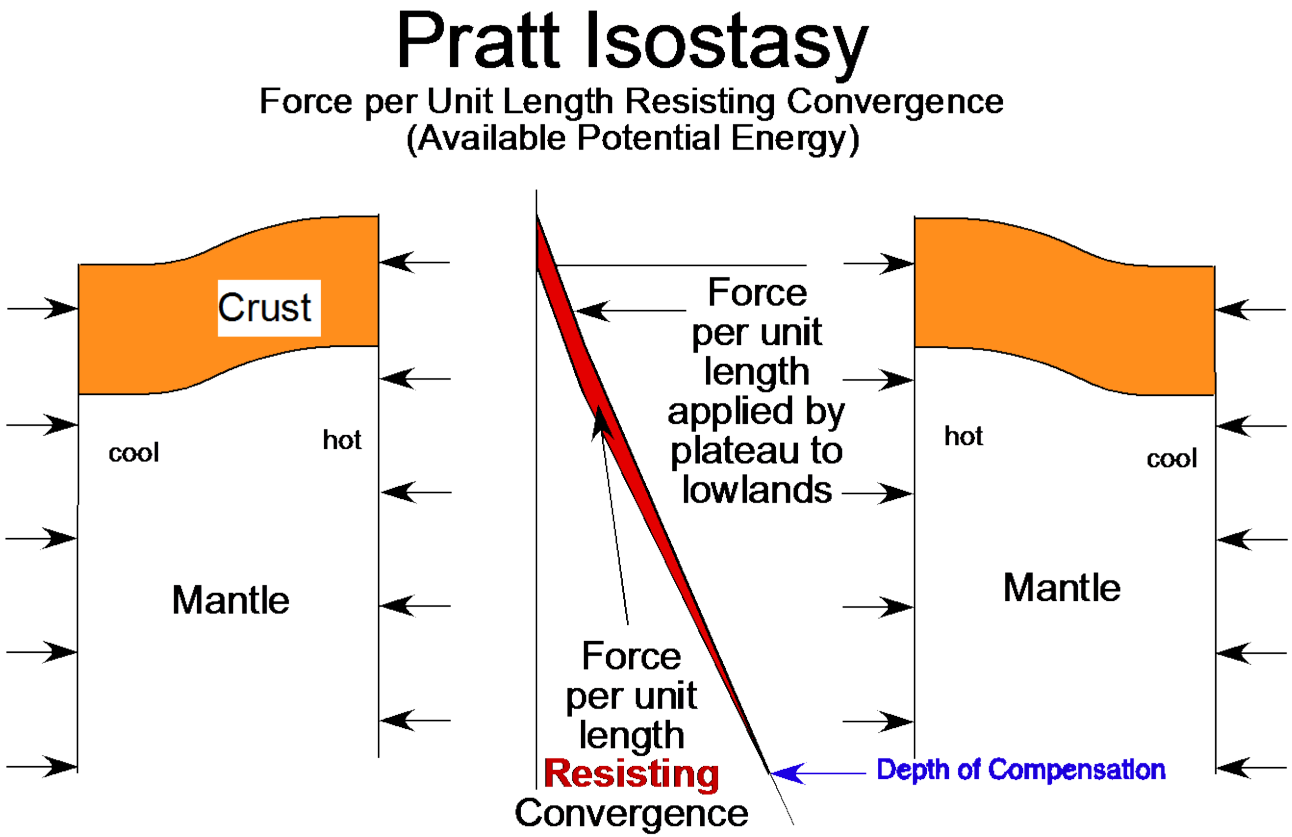




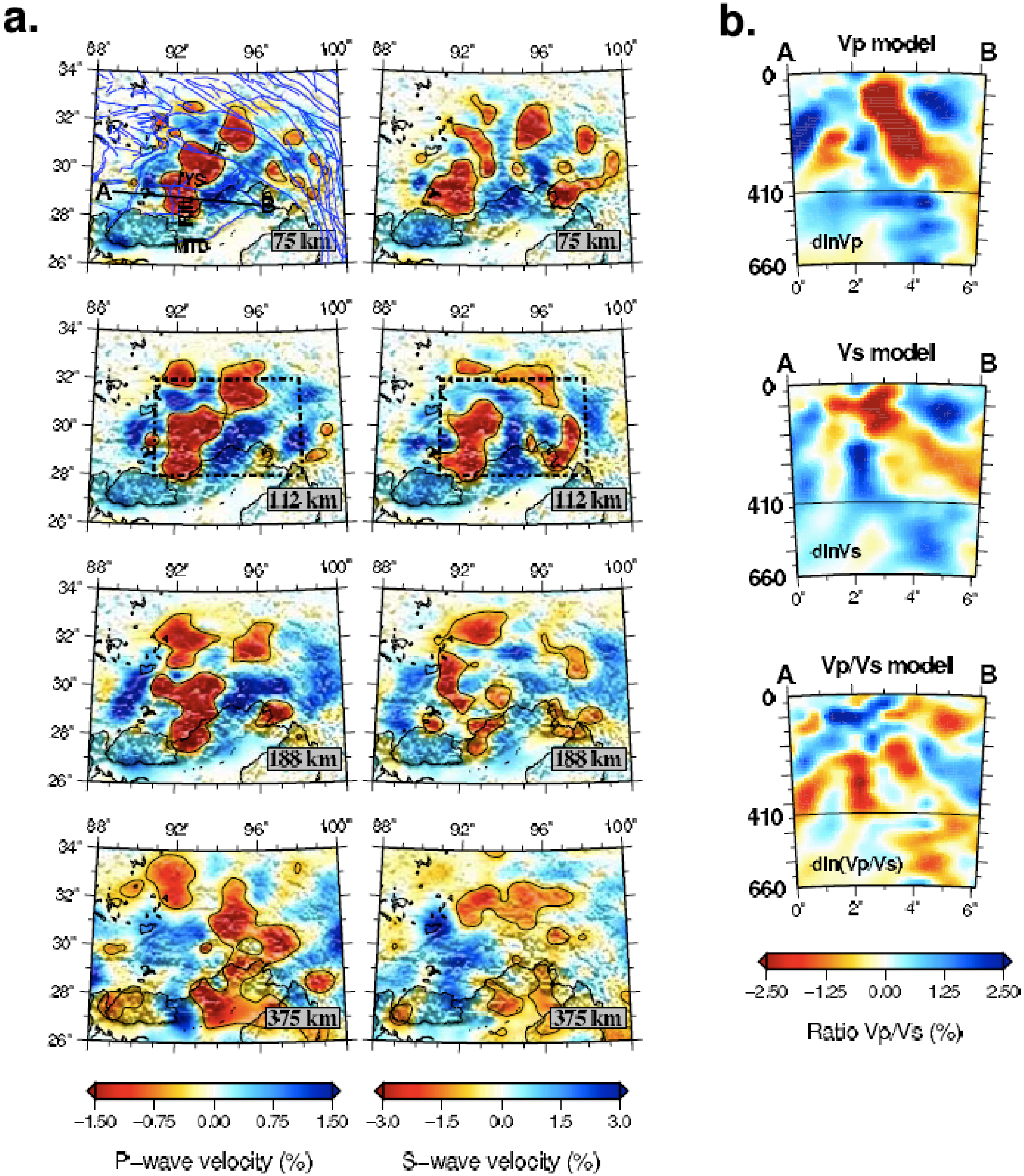
East-Southeast components of velocity

[*Zhang et al.*, *Geology*, 2004]

Lithostatic Pressure, Available Potential Energy, and Force per unit length

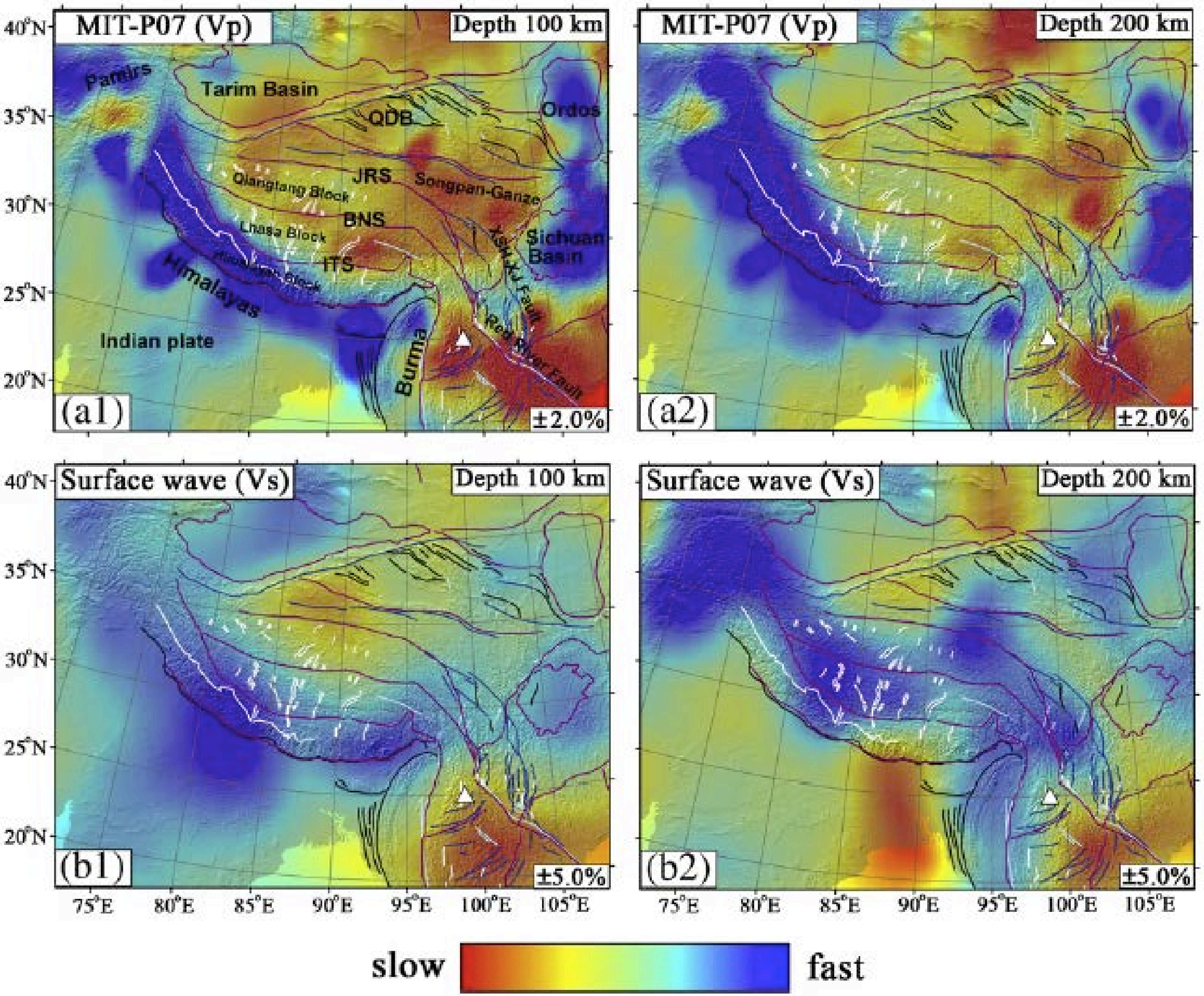


Upper mantle seismic wave speeds



from *Ren and Shen* [2008]

Upper mantle seismic wave speeds

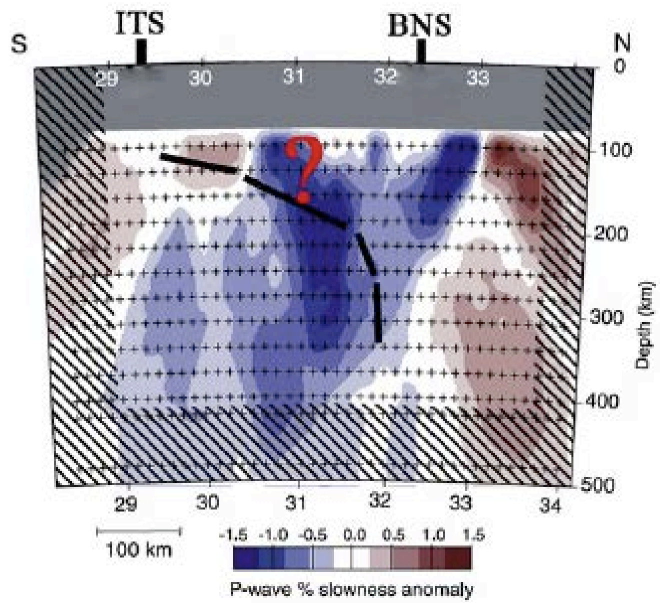


Low speeds beneath Tibet at 100 km associated with warm material

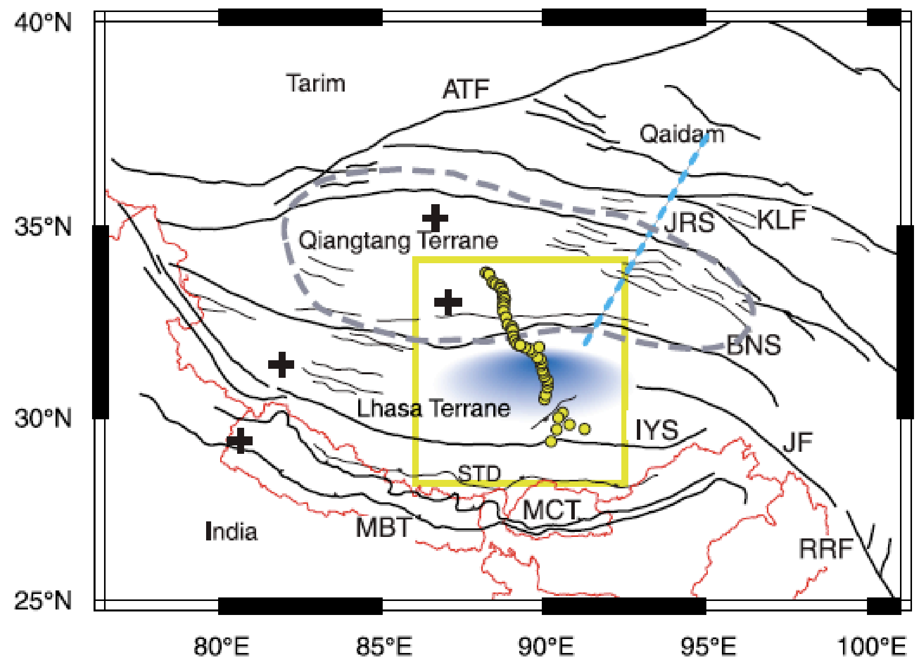
High speeds beneath the edges of Tibet at 200 km associated with cold material

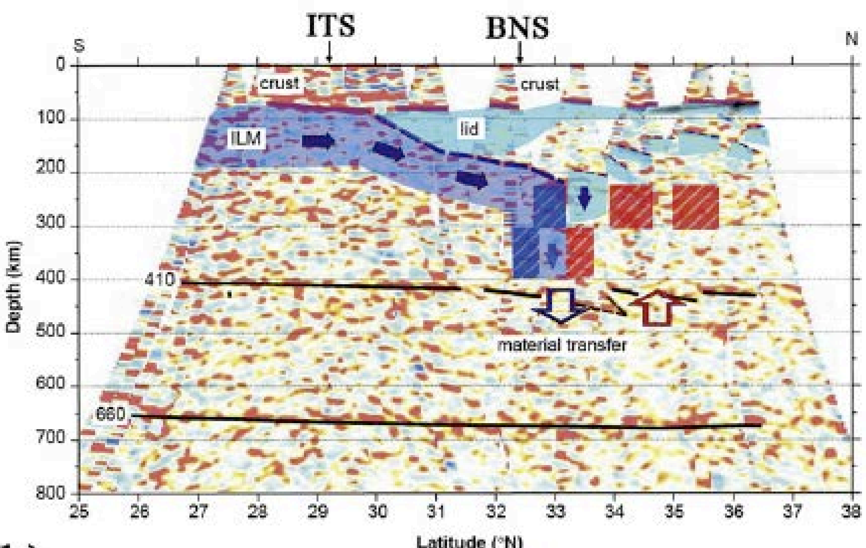
[*Li, van der Hilst, Meltzer, and Engdahl*, 2008]

Upper mantle seismic wave speeds



(a)

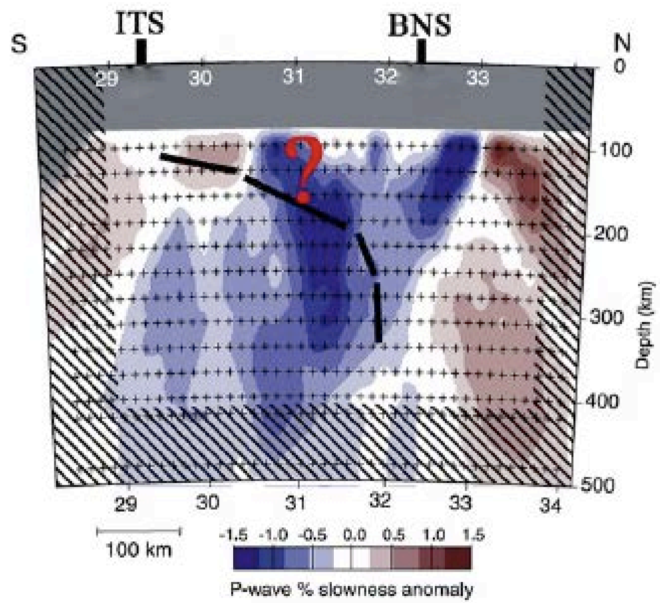




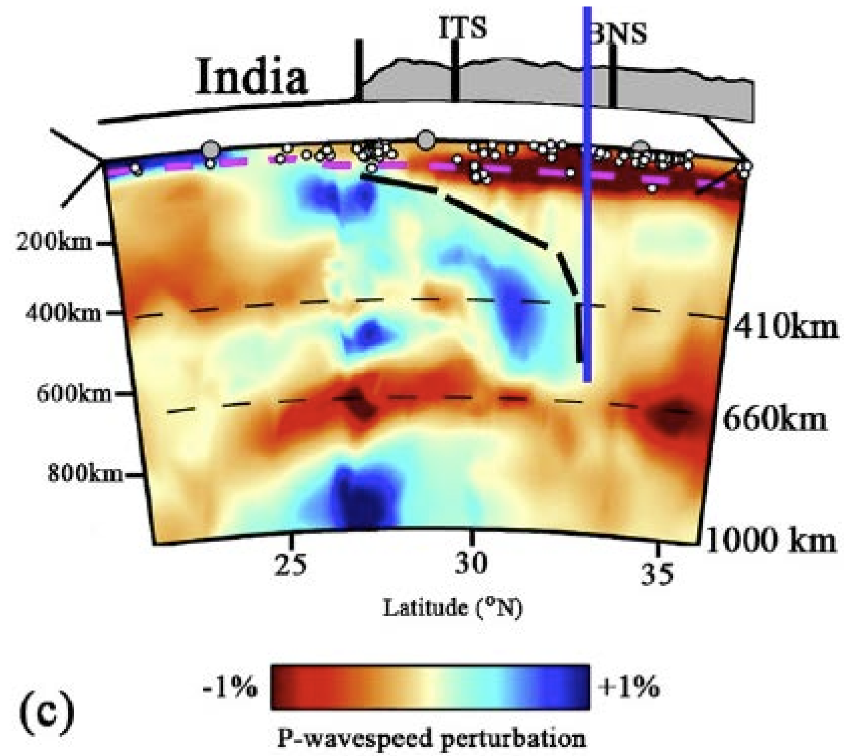
(b)

from *Tilmann, Ni, et al*. [2003]

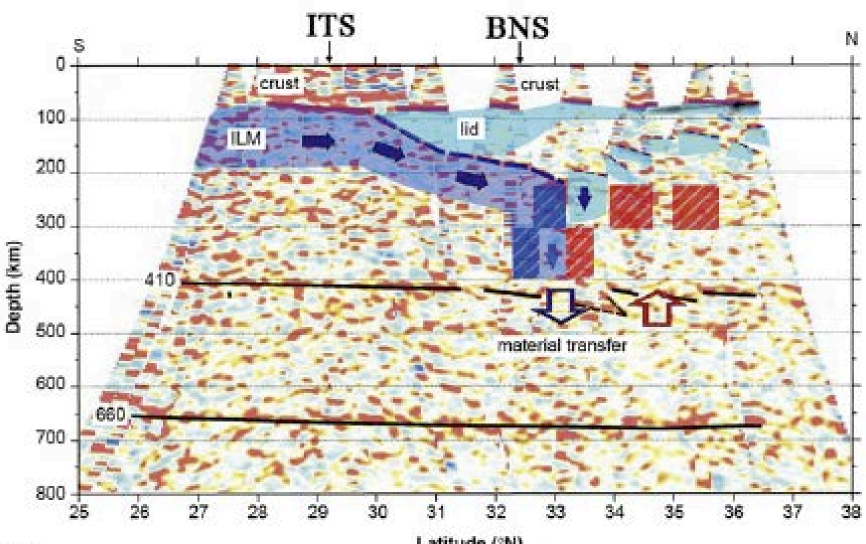
Upper mantle seismic wave speeds



(a)



(c)



(b)

Above: from *Li, van der Hilst, Meltzer, and Engdahl* [2008]

How does Tibet affect the South Asian Monsoon?

It **blocks flow**, from the north, of **cold, dry air**, and hence with low moist static energy $\boldsymbol{h}$ or low subcloud moist entropy $\boldsymbol{s_b}$. Tibet prevents that air from mixing with the **hot, moist air** over India.

Thus, Tibet (the Himalaya) enables a local maximum in $\boldsymbol{h}$ or $\boldsymbol{s_b}$ to develop over India.

[*Boos and Emanuel* 2009; *Boos and Kuang* 2010; *Chakraborty et al.* 2006; *Plumb* 2007; *Privé and Plumb* 2007]

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Thus, Tibet (the Himalaya) enables a local maximum in $\boldsymbol{h}$ or $\boldsymbol{s_b}$ to develop over India.

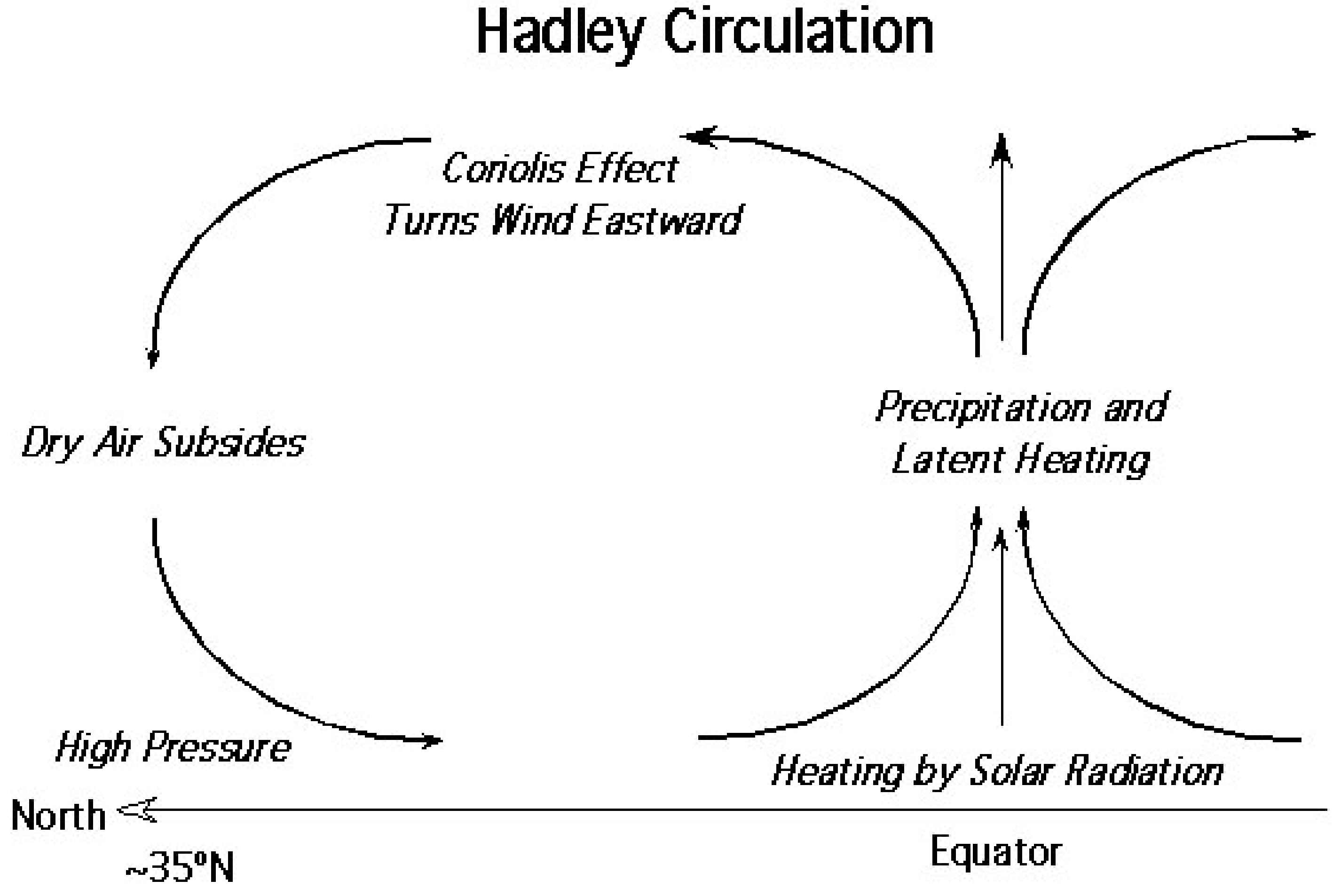
The Himalaya is **necessary** for a strong South Asian Monsoon, but a **high wide Tibetan Plateau** is **not necessary**; a long, **narrow mountain range**, the Himalaya (if not a punier range) would **suffice**.

[*Boos and Emanuel* 2009; *Boos and Kuang* 2010; *Chakraborty et al.* 2006; *Plumb* 2007; *Privé and Plumb* 2007]

Heating near the equator, evaporation, and latent heating lead to meridional circulation

Cooler (but not cold) upper troposphere

Hot upper troposphere



Francis Birch,

Elasticity and constitution of the Earth's interior,
Journal of Geophysical Research, 57, 227-286, 1952.

"Unwary readers should take warning that ordinary language undergoes modification to a high-pressure form when applied to the interior of the earth; a few equivalents follow:

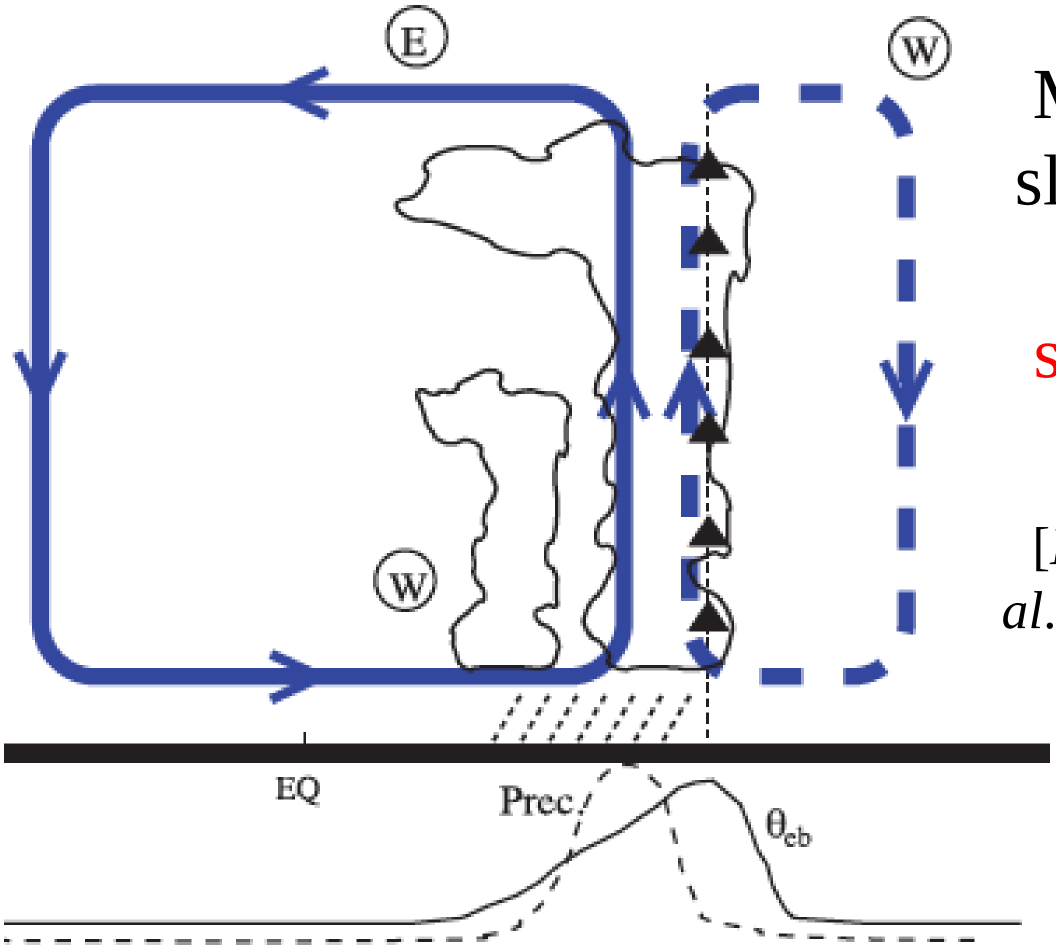
High-pressure form:	**Ordinary meaning:**
Certain	**Dubious**
Undoubtedly	**Perhaps**
Positive Proof	**Vague Suggestion**
Unanswerable Argument	**Trivial Objection**
Pure Iron	**Uncertain Mixture of all of the Elements**

5 Ma = 10 Ma = 15 Ma

Growth of Tibet and South Asian climate

1. Tibet apparently grew steadily since collision with India at ca. 45 Ma, but underwent a **change near 15-10 Ma**, when it abruptly began to grow outward, especially eastward, **may have risen ~1000 m**, and then began to collapse.
2. **Paleoclimate** data suggest changes in South Asian climate at approximately the **same time** (or **a little more recently**).
3. Recent work suggests that the **Tibetan Plateau** plays a **minor role** in effecting a strong South Asian monsoon; only a narrow mountain range, the Himalaya is necessary.
4. By analogy with *Rodwell and Hoskins's* [1996] suggestion that diabatic heating over the Bay of Bengal induces subsidence and warming over the Sahara, perhaps the **growth of eastern Tibet at ca. 10 Ma induced subsidence over NW India and aridification** there (**a weaker monsoon**).
5. Maybe heating over Tibet does affect the strength of the monsoon, but apparently only in the early and late seasons.

Elementary monsoon theory: quasi-equilibrium



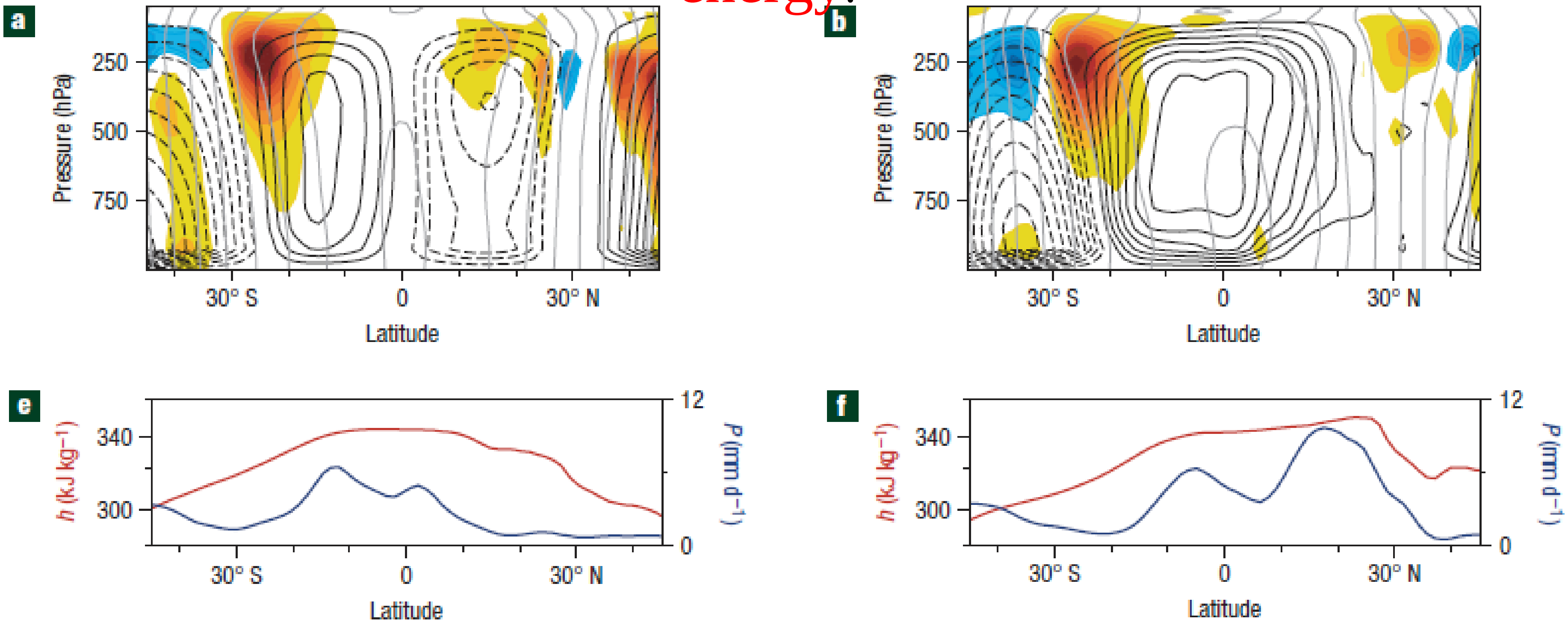
Maximum ascent rate lies slightly equatorward of the locus of **maximum** subcloud specific entropy or moist static energy.

[*Emanuel*, 1995, 2007; *Emanuel et al.*, 1994; *Neelin*, 2007; *Plumb*, 2007; *Privé and Plumb*, 2007].

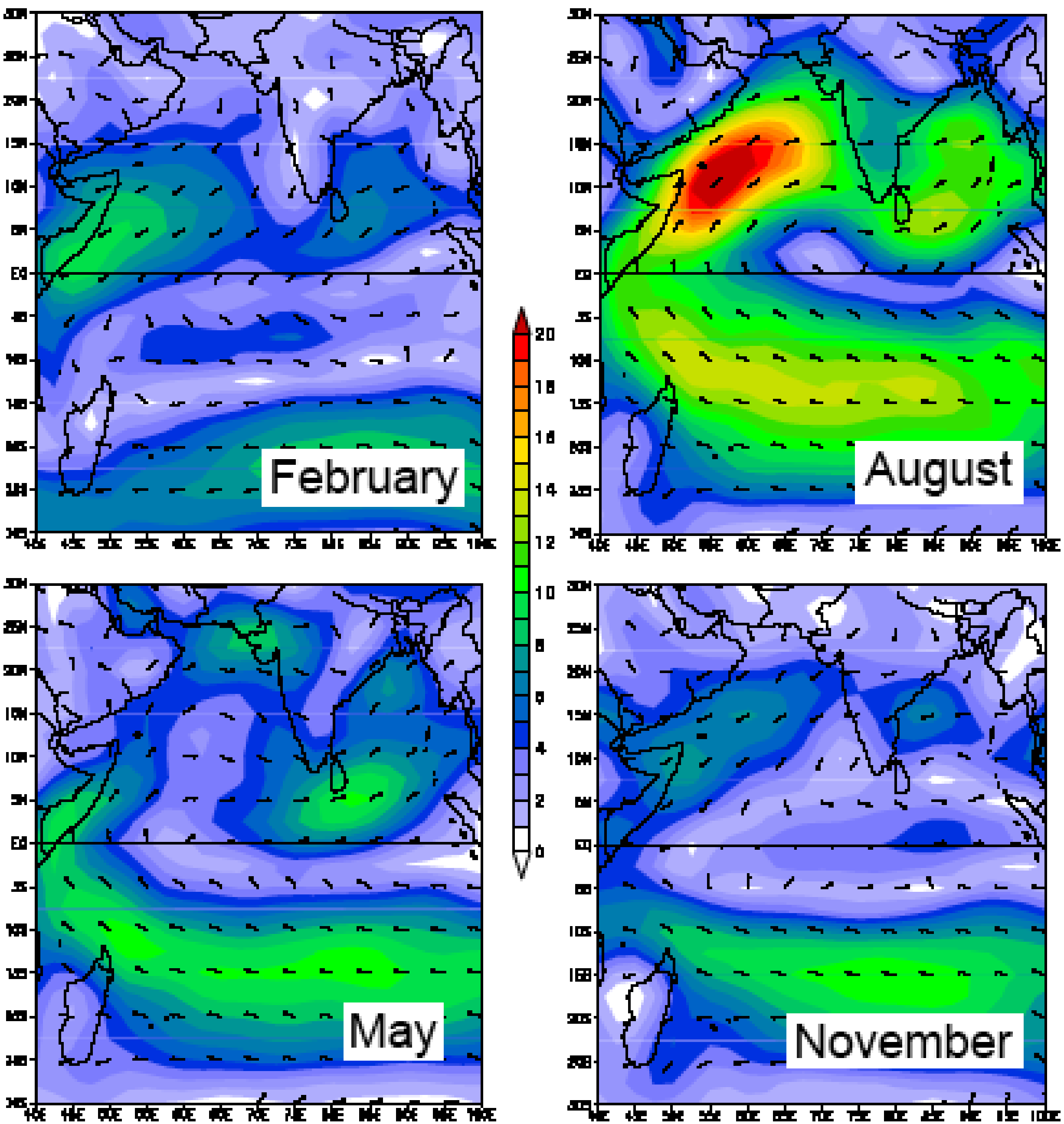
(from *Nie, Boos, and Kuang* [*Journal of Climate*. 2010])

Elementary monsoon theory

Maximum ascent rate lies slightly equatorward of the locus of **maximum** subcloud specific entropy or moist static energy.

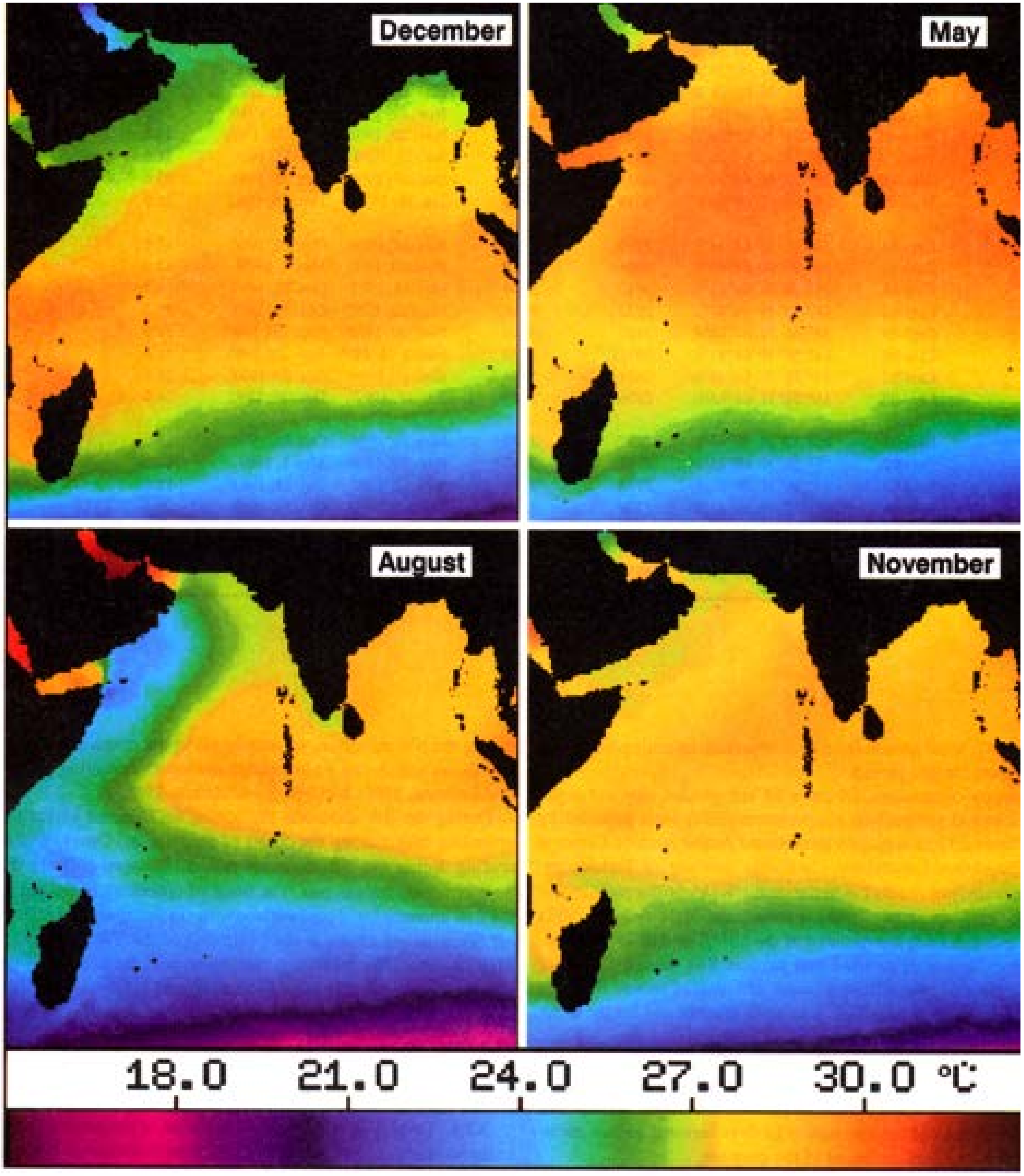


Most static energy, ***h***, in **red**: is maximum near poleward edge of cross-equatorial circulation. (Precipitation in **blue**)   [*Bordoni and Schneider, Nature Geosci*. 2008]



Seasonal Differences in Winds over the Indian Ocean:

in summer (winter) monsoons, winds blow toward the NE (SW)



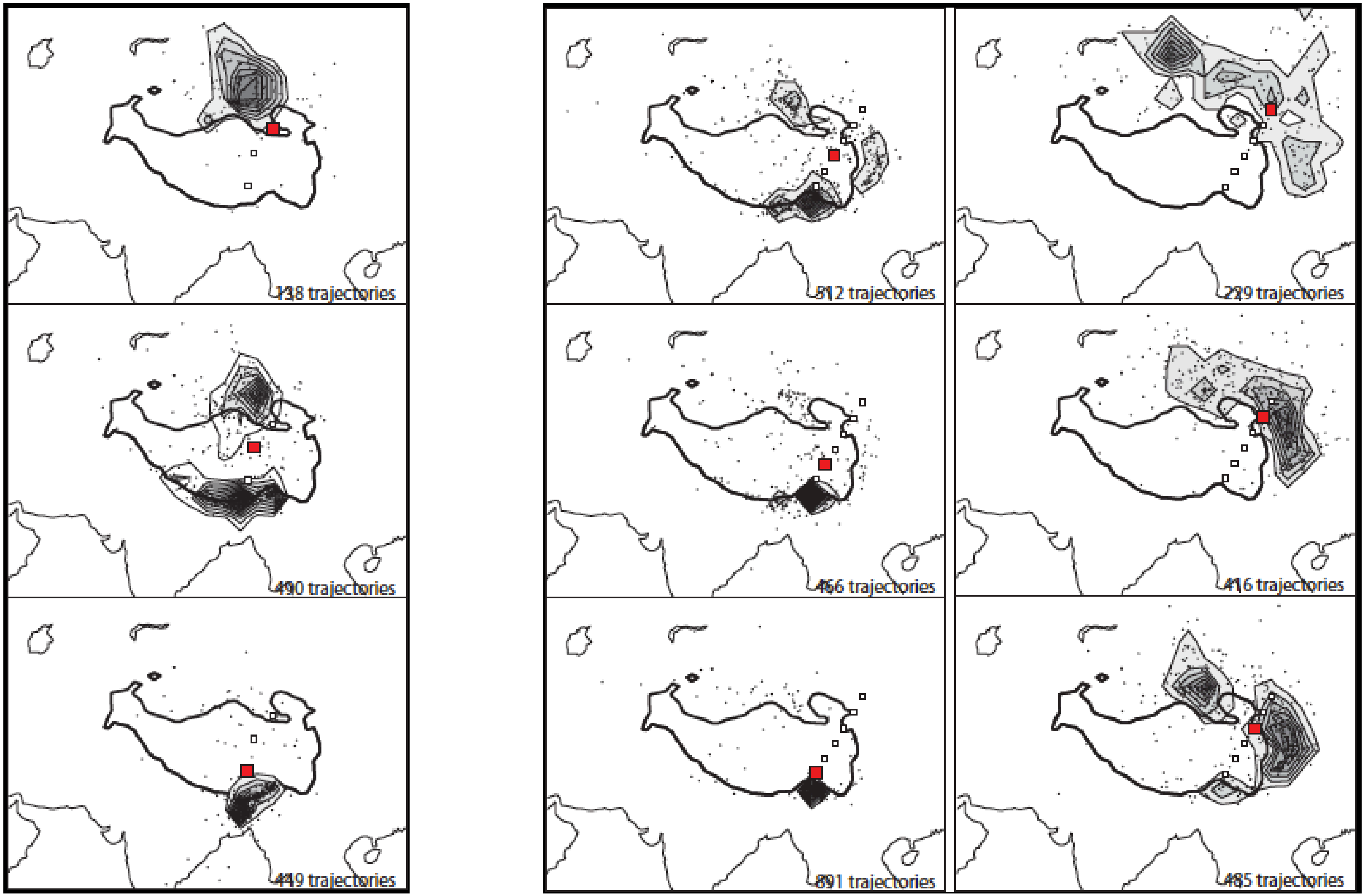
Indian Ocean Sea-Surface Temperature

During summer monsoons (June-August), northeastward (southeasterly) winds blow the surface water away from the coast and draw deep, cold, nutrient-rich water to the surface

[*Rixen, Haake, & Ittekot* 2000]

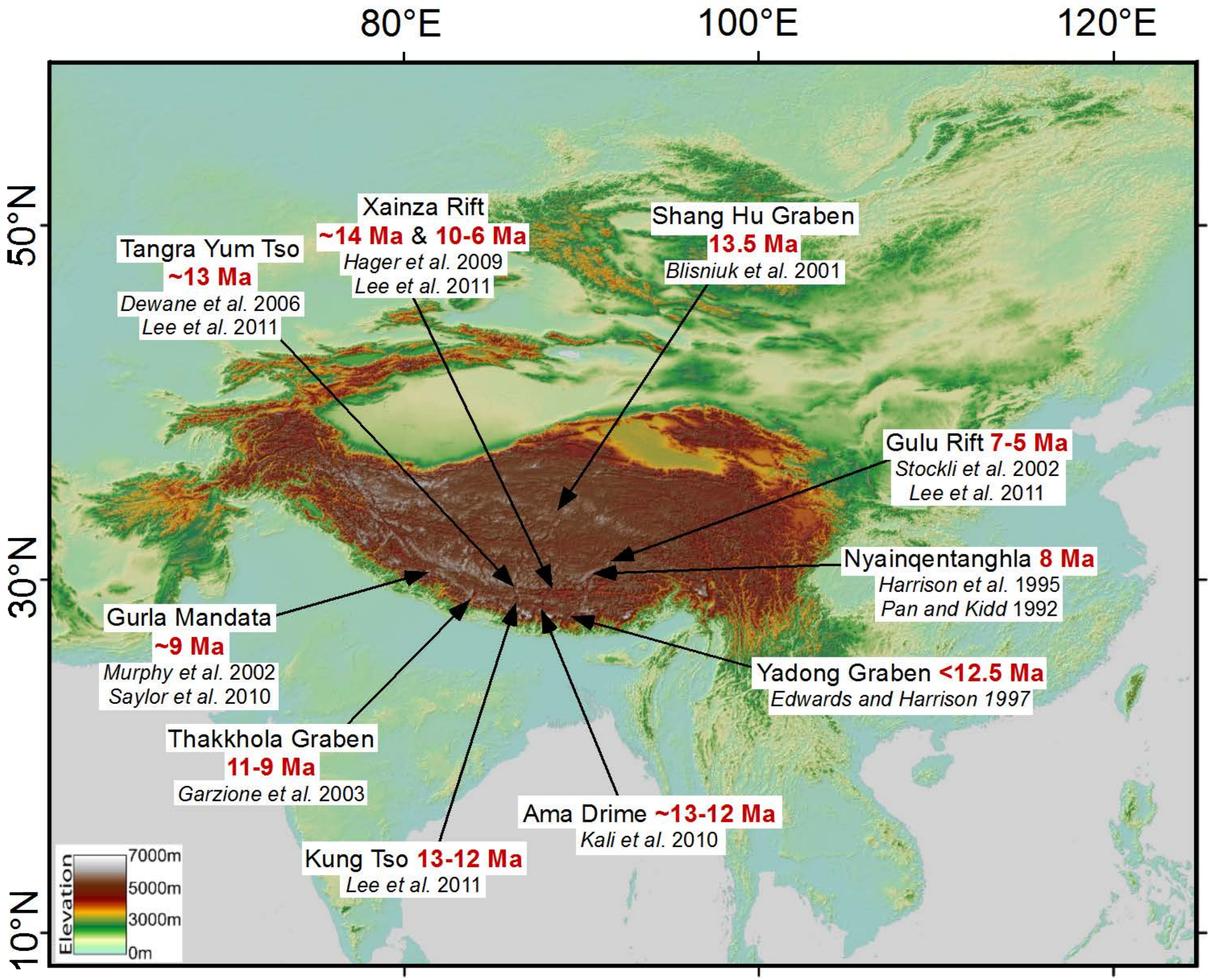
Sources of water:

Half of $\delta^{18}O$ in northern Tibet comes from the north!



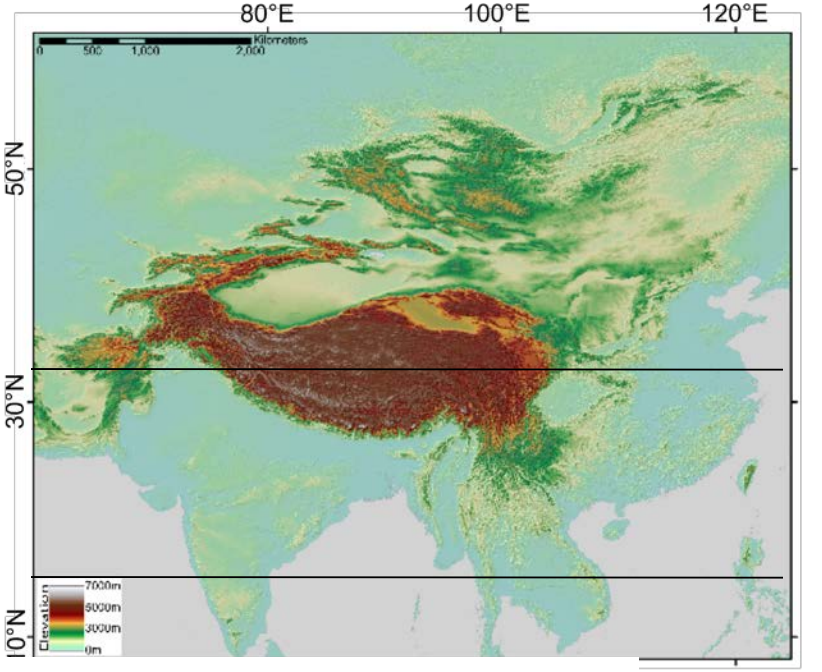
[*Bershaw, Penny, and Garzione* 2012]

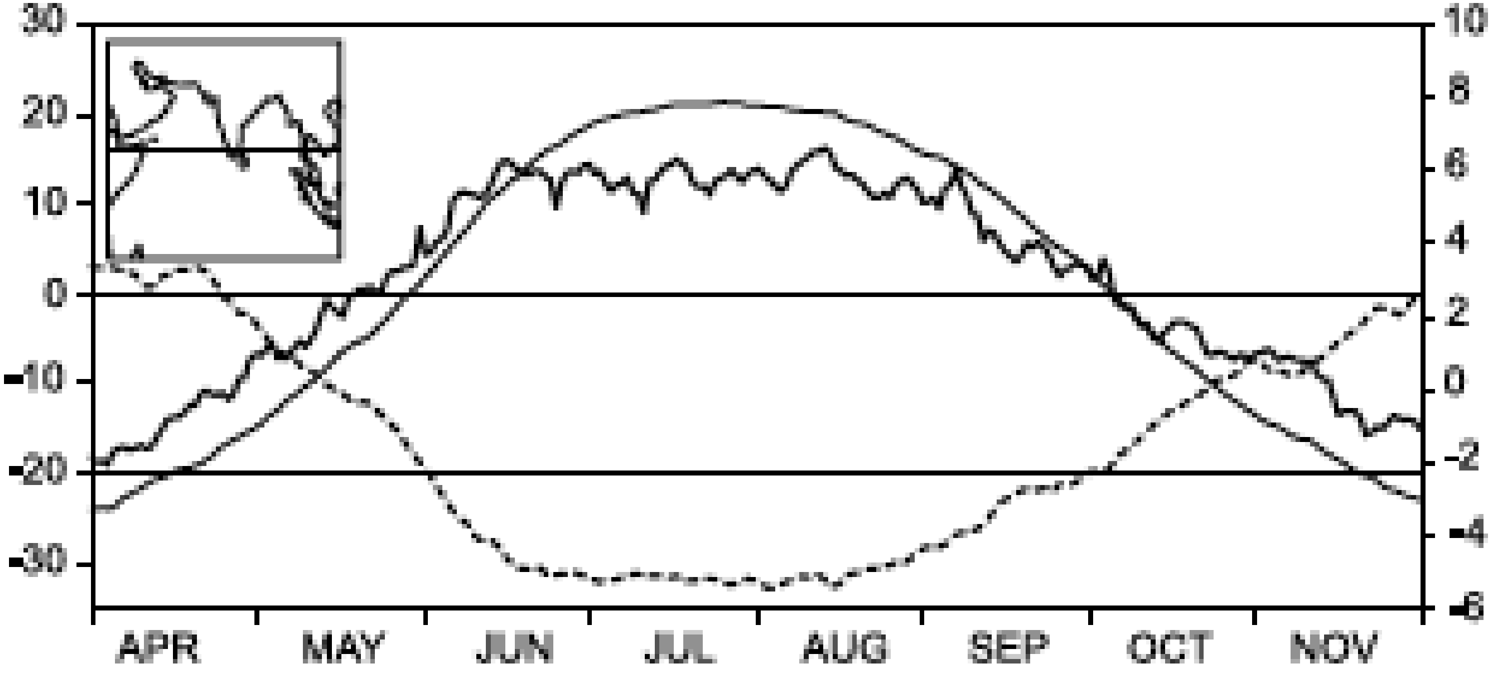
An extrapolation of present-day strain rates to 15-10 Ma gives a **drop** of ~500 m in the mean elevation of Tibet



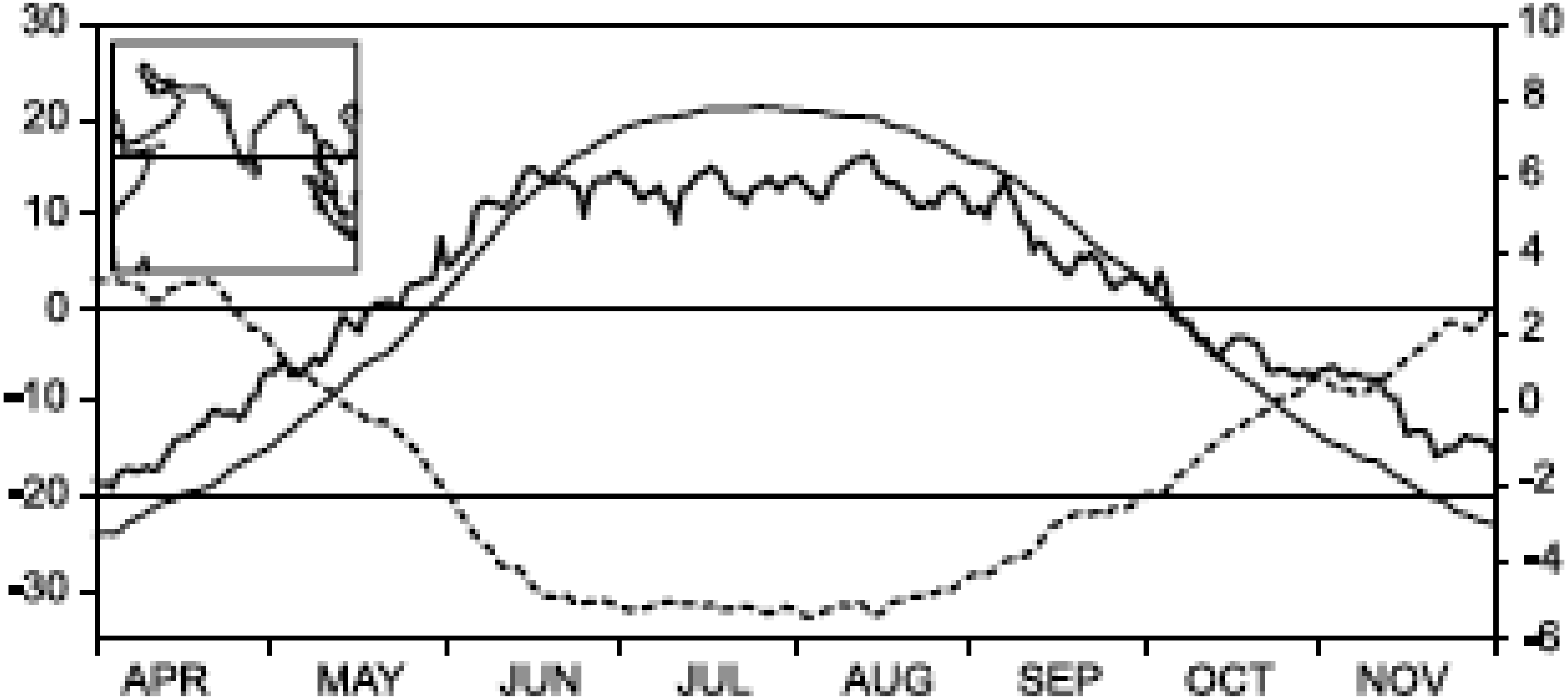
Heating over Tibet and Northern India

Thin solid line: Temperature difference, 10-35°N – 10°N-15°S
[Goswami and Xavier, *GRL*, 2005]





Monsoon onset and withdrawal



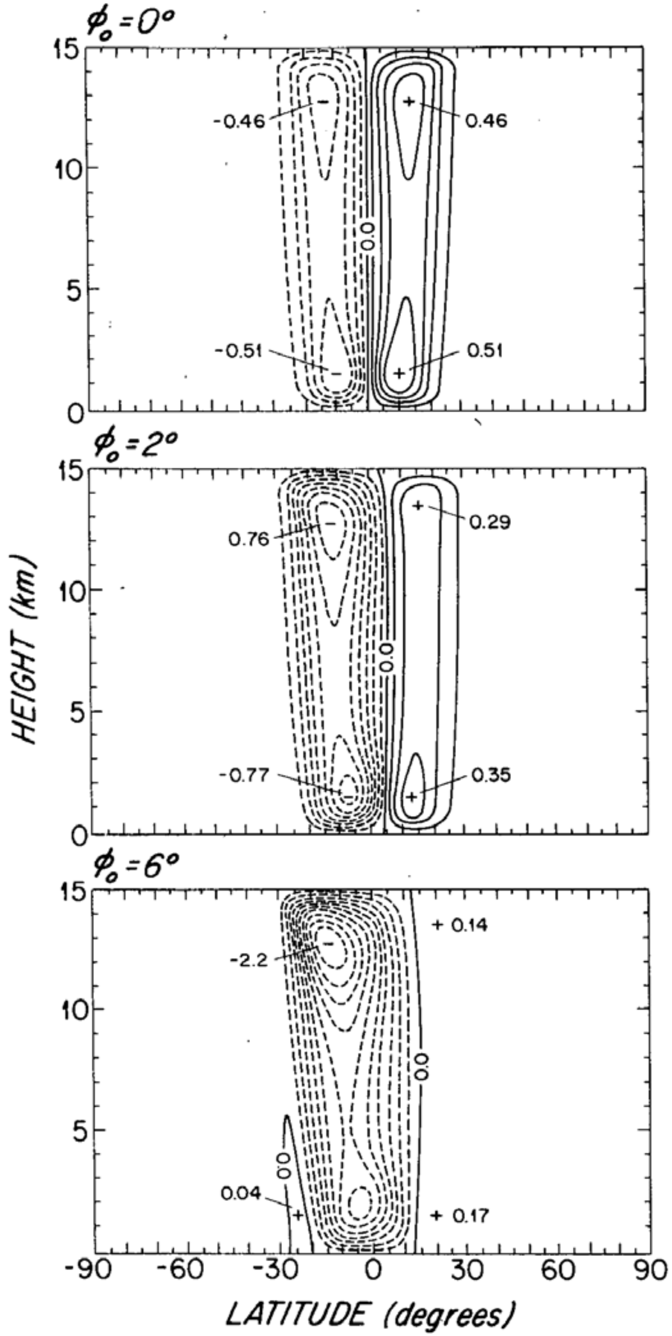
Thin solid line: Temperature difference, 10-35°N – 10°N-15°S

Thick solid line: latitude of zero vorticity

Dashed line: wind shear, 200 mb – 850 mb, 0–15°N

[Goswami and Xavier, *GRL*, 2005]

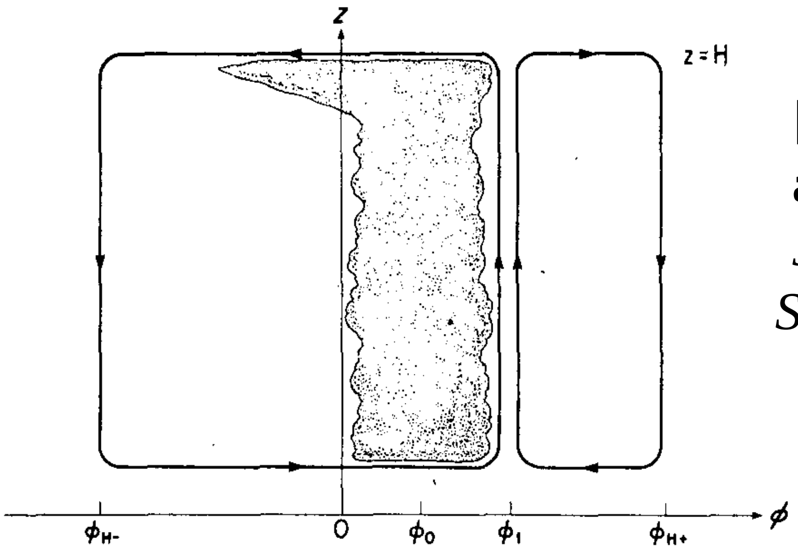
Elementary monsoon theory: 1



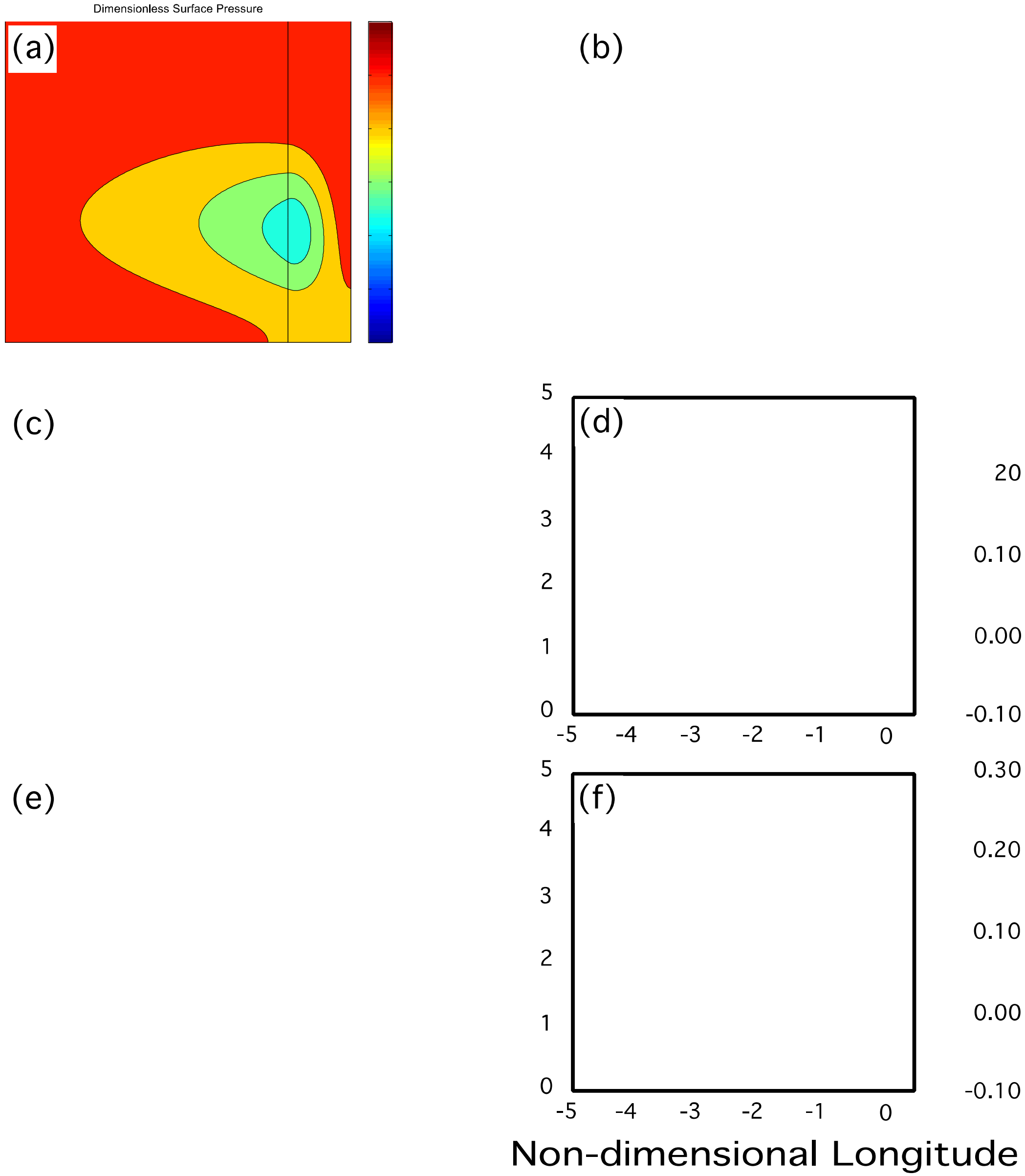
Ascent occurs poleward, at ϕ_1, of the locus of heating, at ϕ_0.

Hottest air aloft overlies the equatorward edge of ascent.

Strength of circulation increases with latitude of heating.



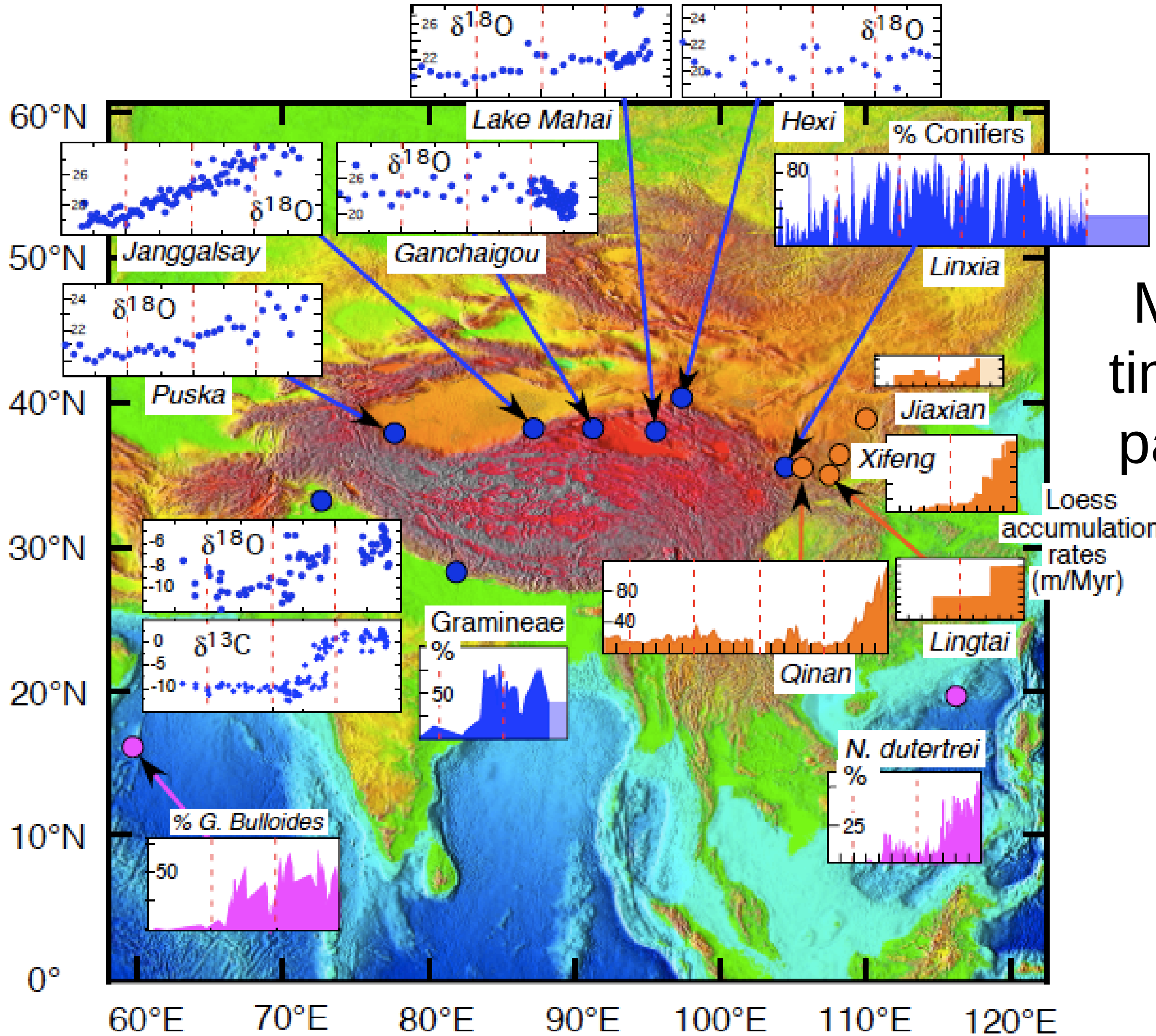
[Lindzen and Hou, *J. Atmos. Sci.*, 1988]



Gill model calculations, based on zillions of assumptions, of surface pressure and vertical components of velocity forced by heat sources at three different latitudes:

at 1, 2, and 3 Rossby radii of deformation (~10°, ~20°, and ~30°) from the equator.

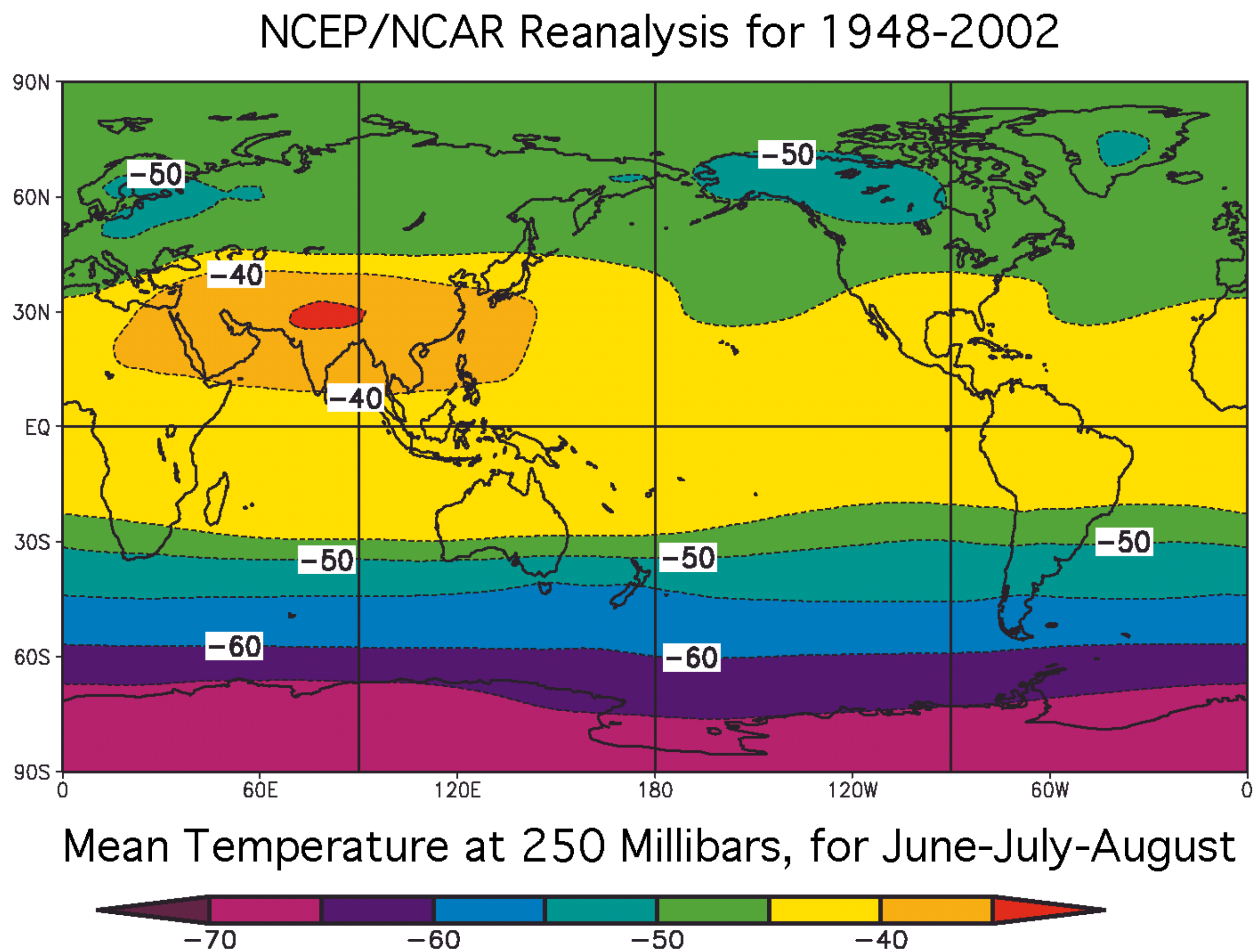
Based on *Gill* [1980], from *Molnar and Rajagopalan* [2012]



Million-year time series of paleoclimate

Compiled by *Molnar, Boos, and Battisti* [20101]

In Summer, Tibet and surroundings comprise the hottest place on earth (at 250 millibars)



The idea that Tibet rose ~1000 m (*after already having reached 4000 m*) and then began to collapse at ~10 Ma passes several tests, but maybe fails a more important one.

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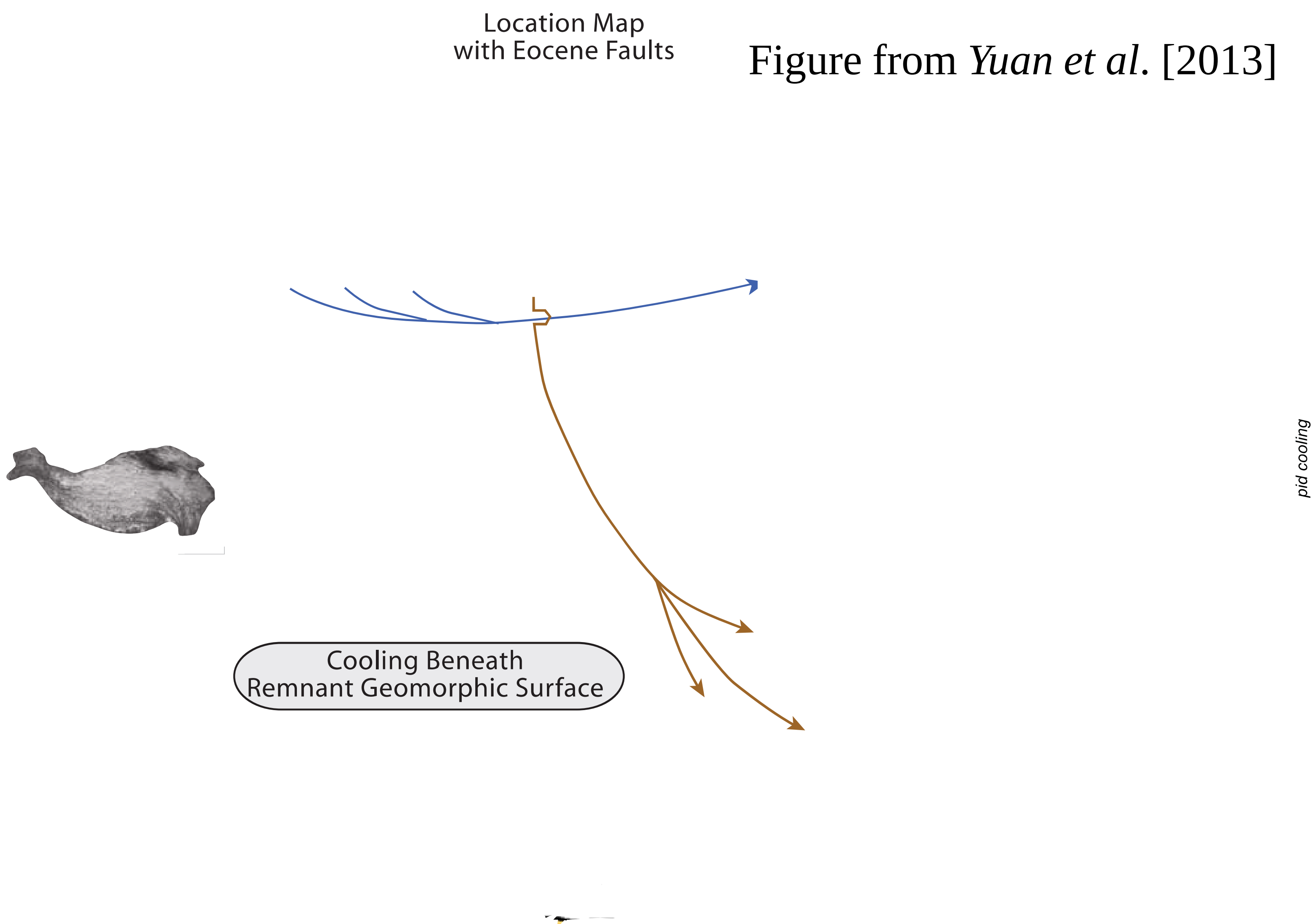
So, how might Tibet, and its growth, affect climate and paleoclimate?

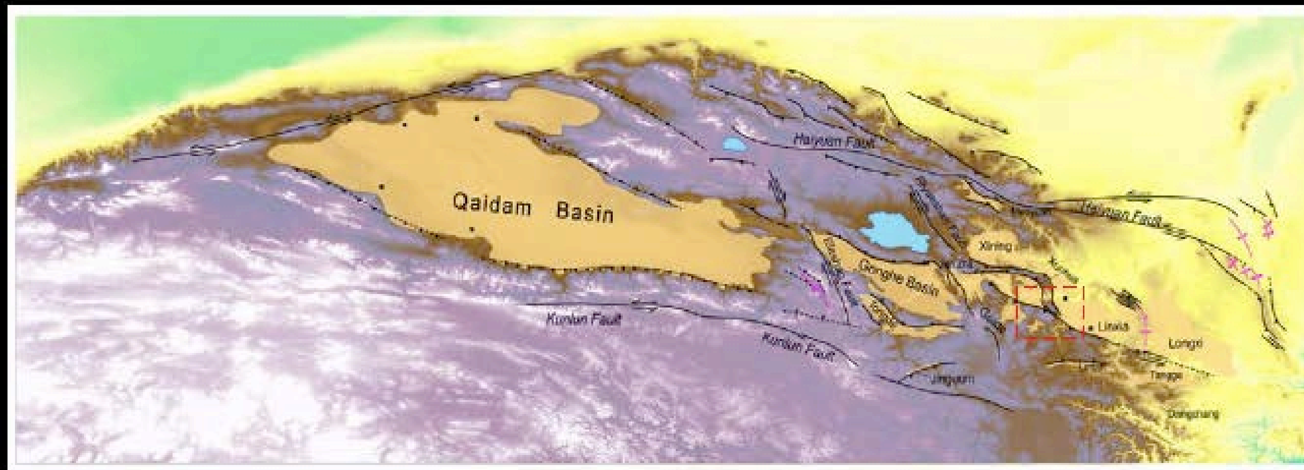
Figure from *Yuan et al*. [2013]

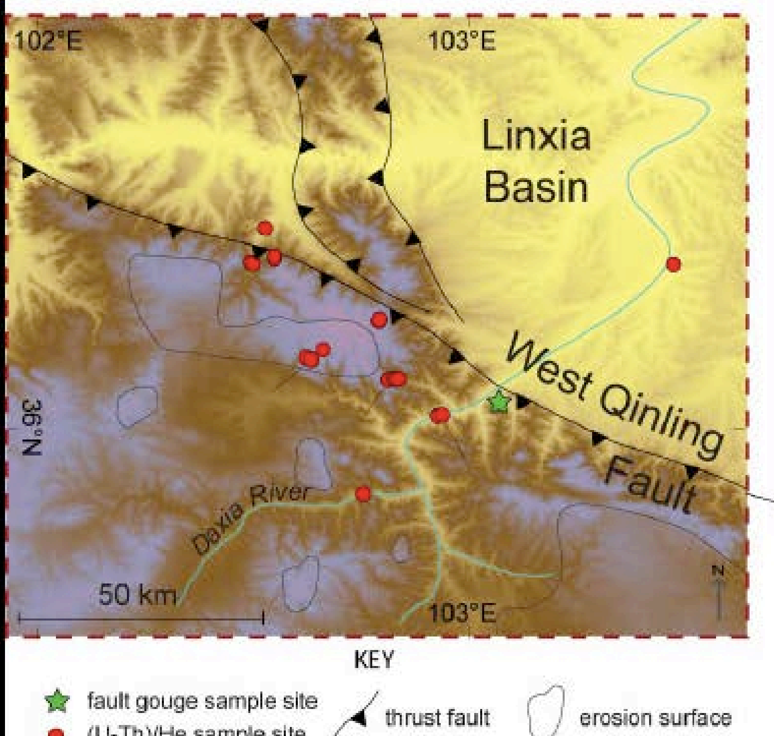


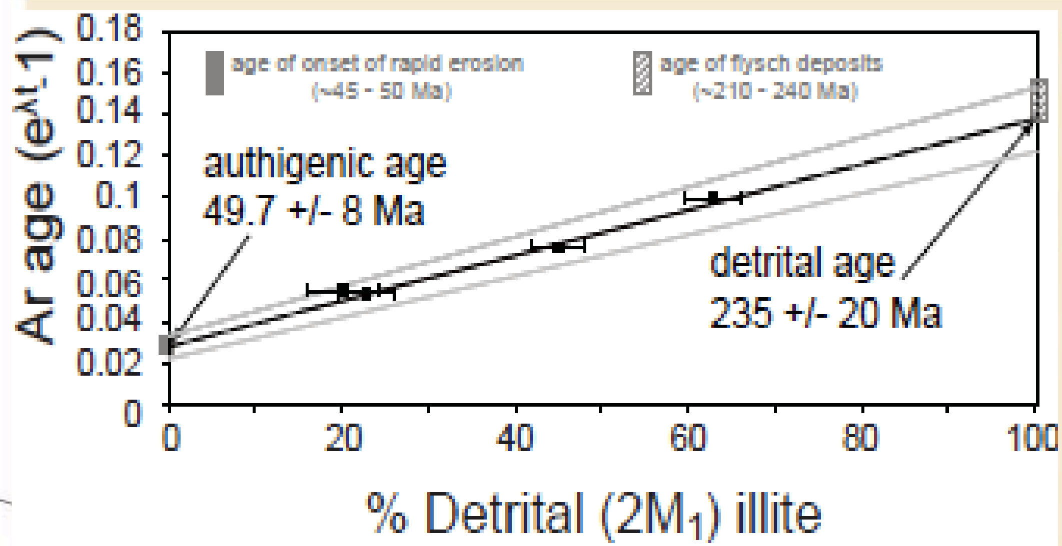
Work of *Marin Clark, Ken Farley, Zheng Dewen, Wang Zhicai, and Alison Duvall* [2010]

Direct dating of faulting: West Qinling Fault site

[Duvall, Clark, van der Pluijm, and Li, 2011]





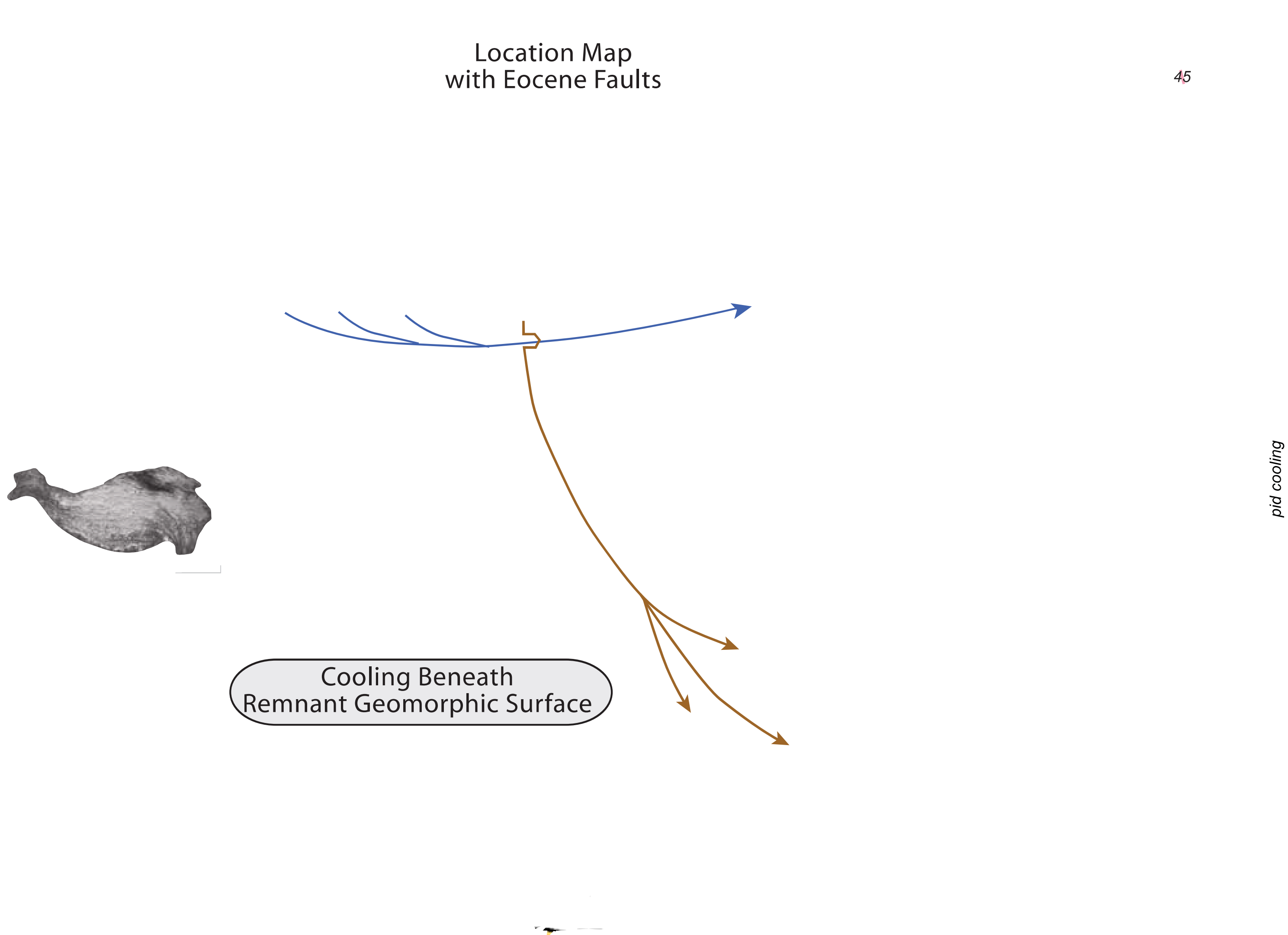


Coupled Approach:

- Clay dating of fault gouge at West Qinling fault site
- Apatite (U-Th)/He in hanging wall rocks

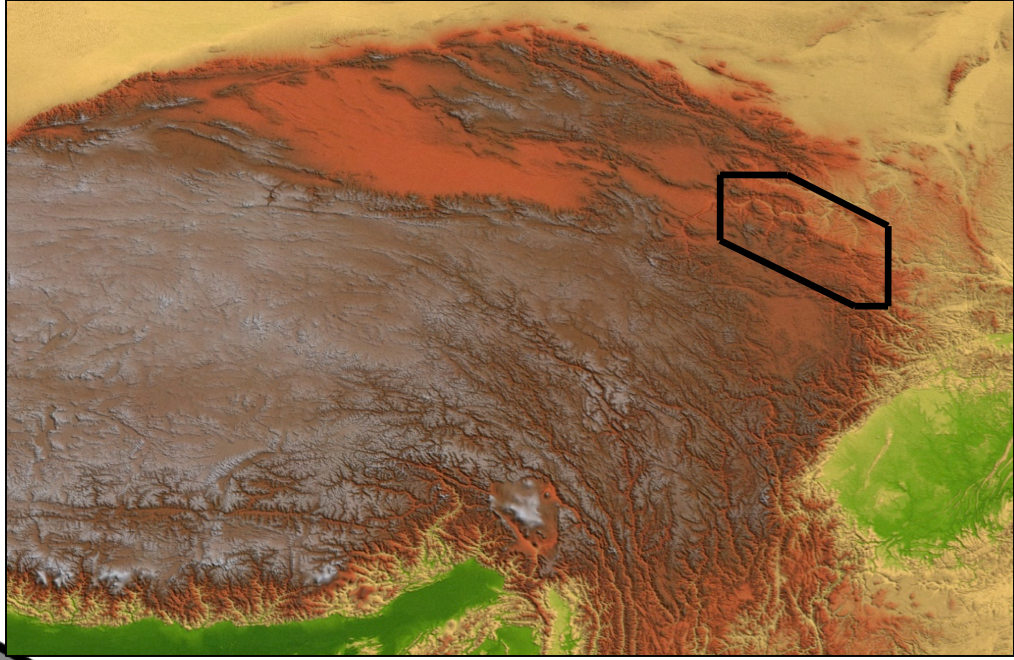
Figure from *Yuan et al*. [2013]

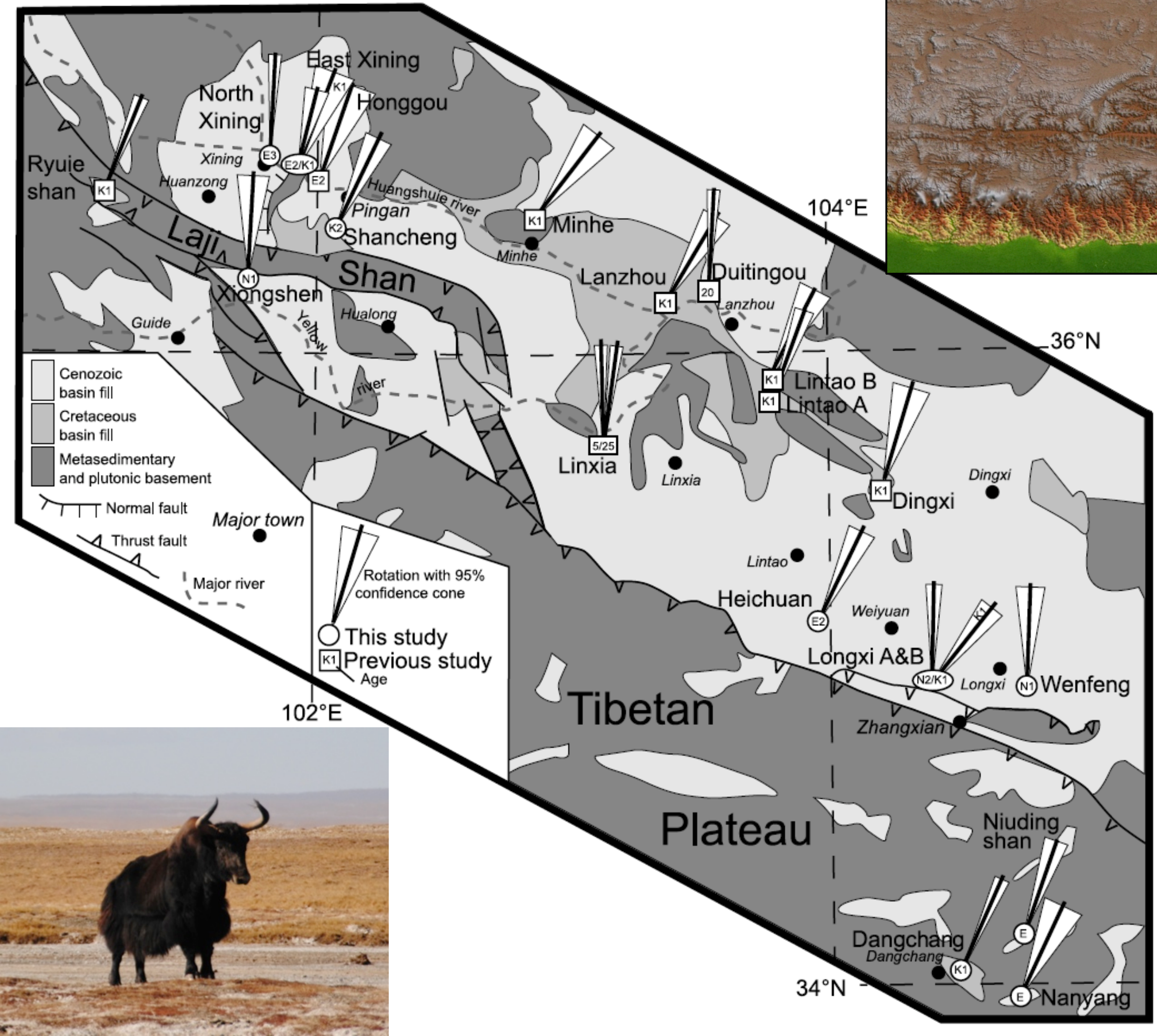
Thermochronology Transects



Work of *Marin Clark, Ken Farley, Zheng Dewen, Wang Zhicai, and Alison Duvall* [2010] and *Alison Duvall, Marin Clark, Ben van der Pluijm, and Li Chuanyou* [2011]

[*Dupont-Nivet et al*., *Tectonics*, 2004]



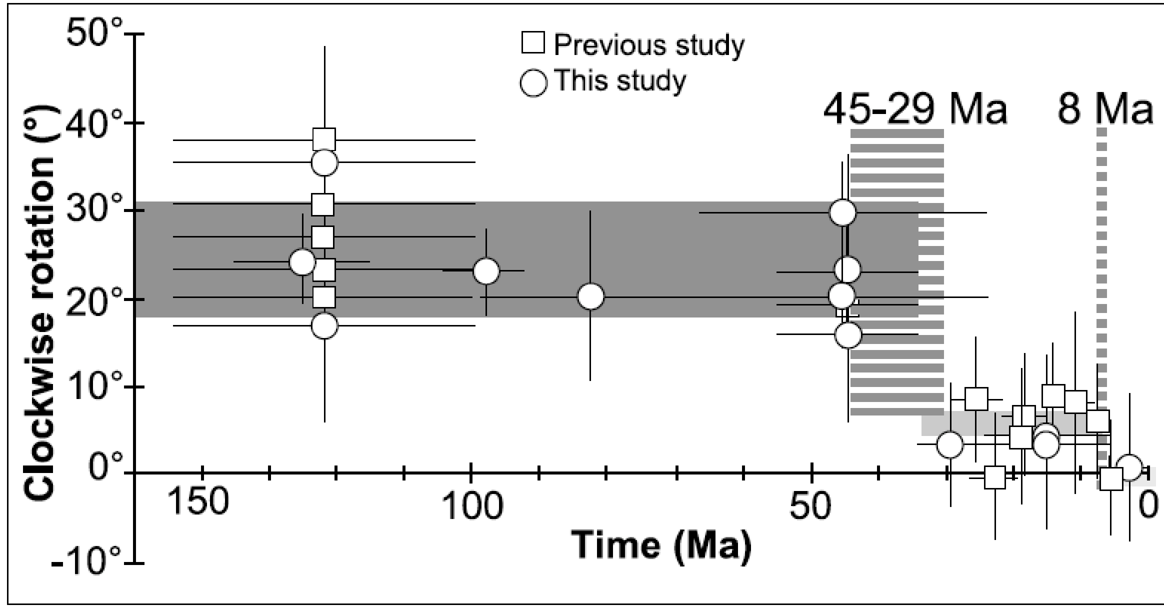


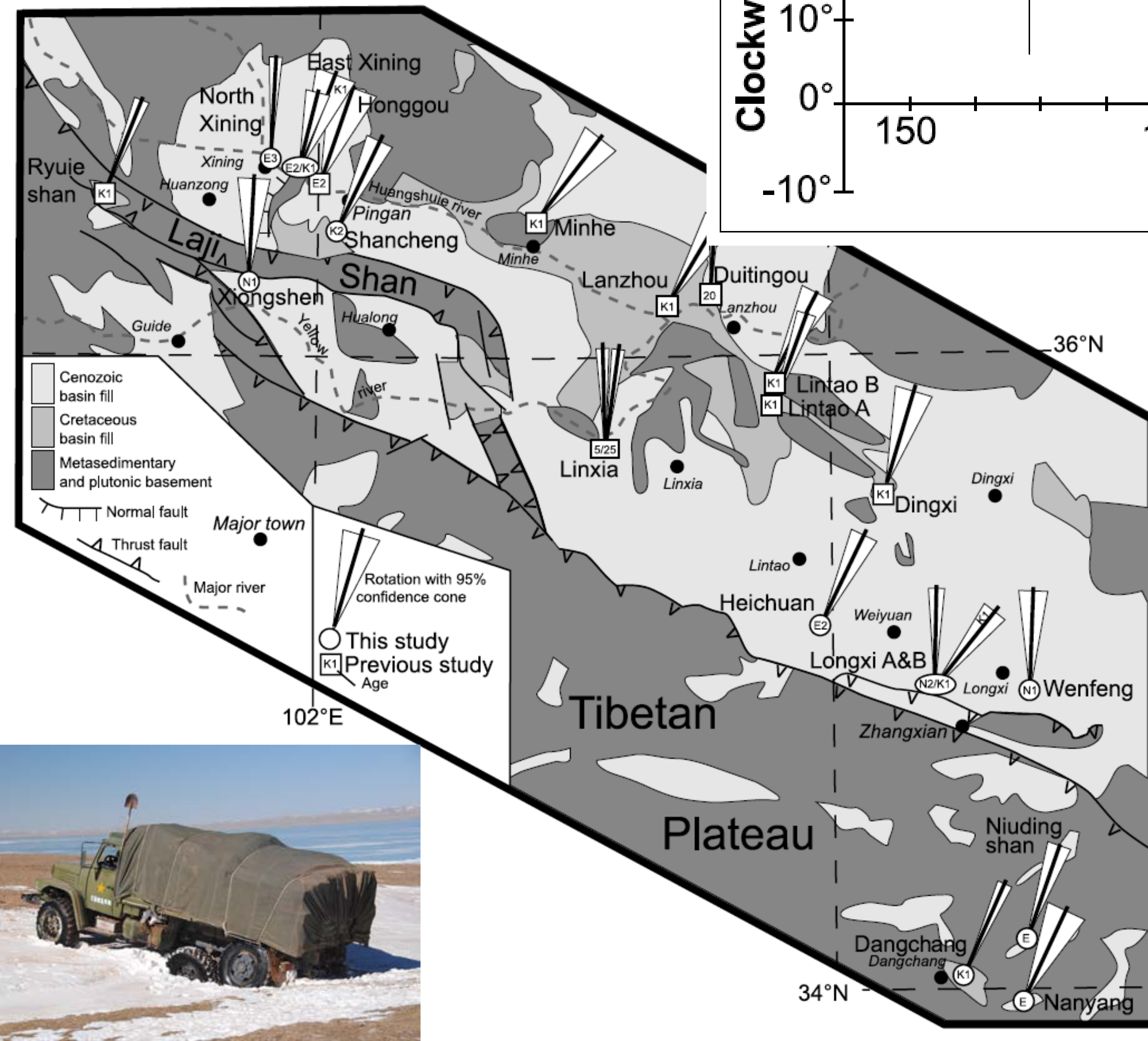
Clockwise rotation

up to ~20° to 30° ?

(Right-lateral simple shear)

[*Dupont-Nivet et al*. *Tectonics*, 2004]

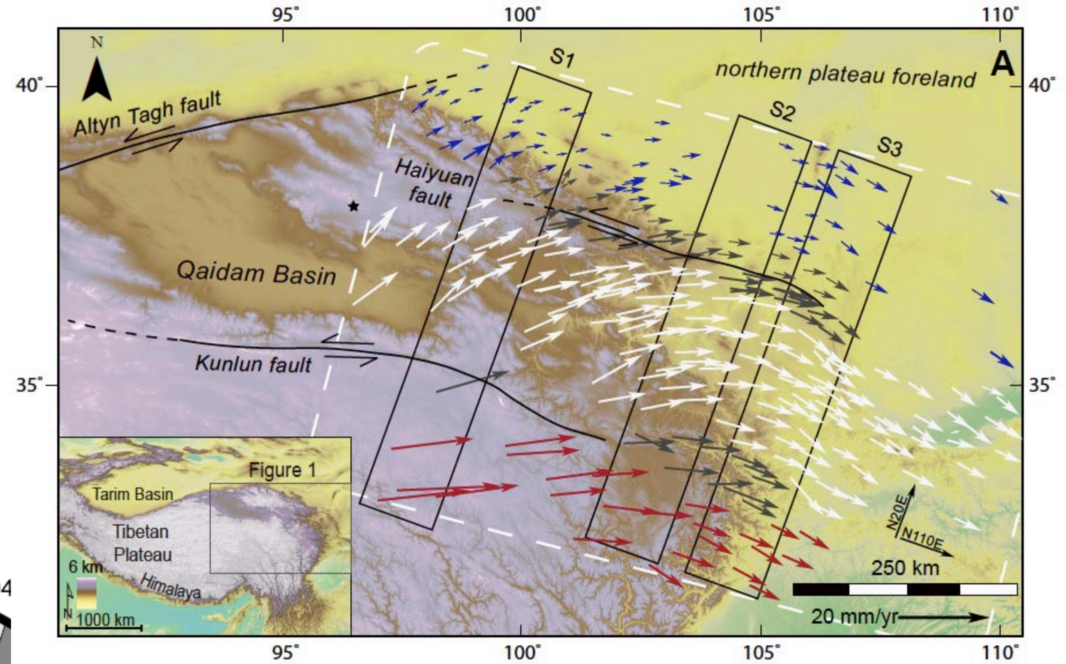


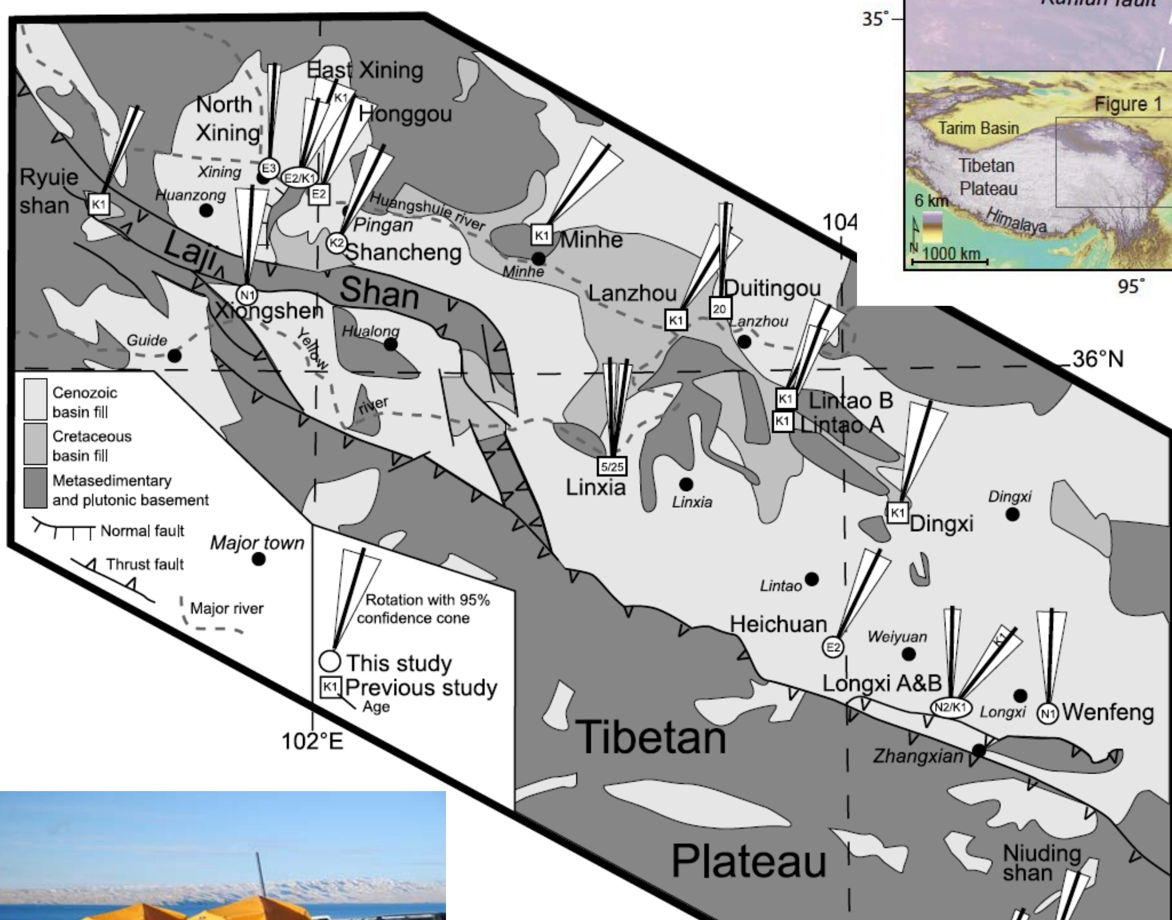


Clockwise rotation
~20° to 30°
Since 45-30 Ma
and ~5° since 30 Ma
and before 8 Ma.

Right-lateral simple shear

Duvall and Clark, Geology [2010], based on GPS data of *Zhang et al.* [2004] and *Gan et al.* [2007]





Clockwise rotation

since ~30 Ma

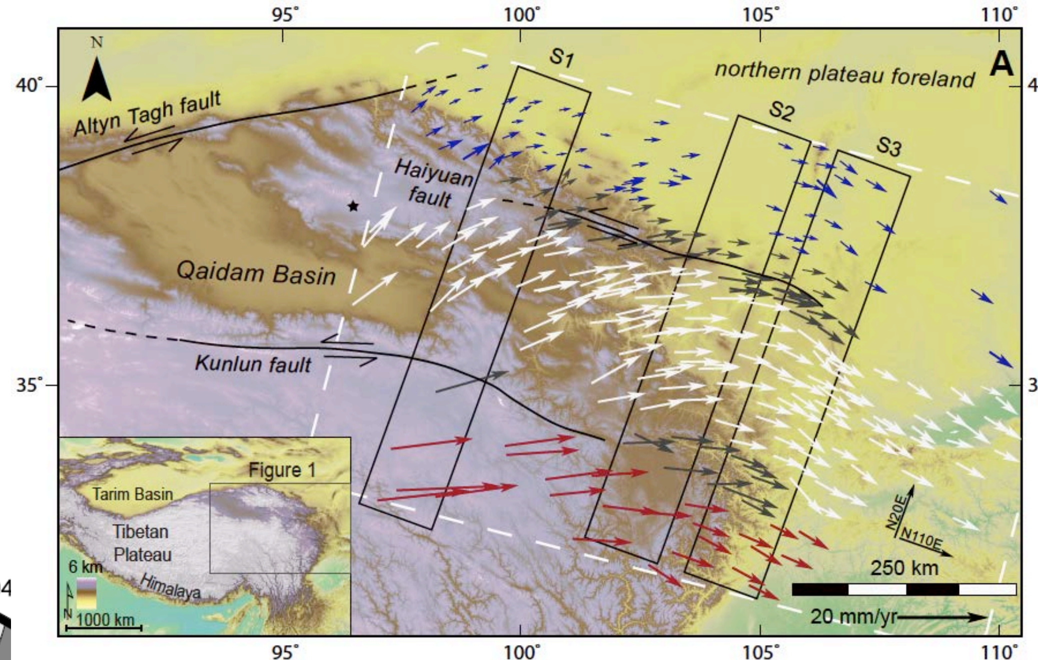
and before ~8 Ma

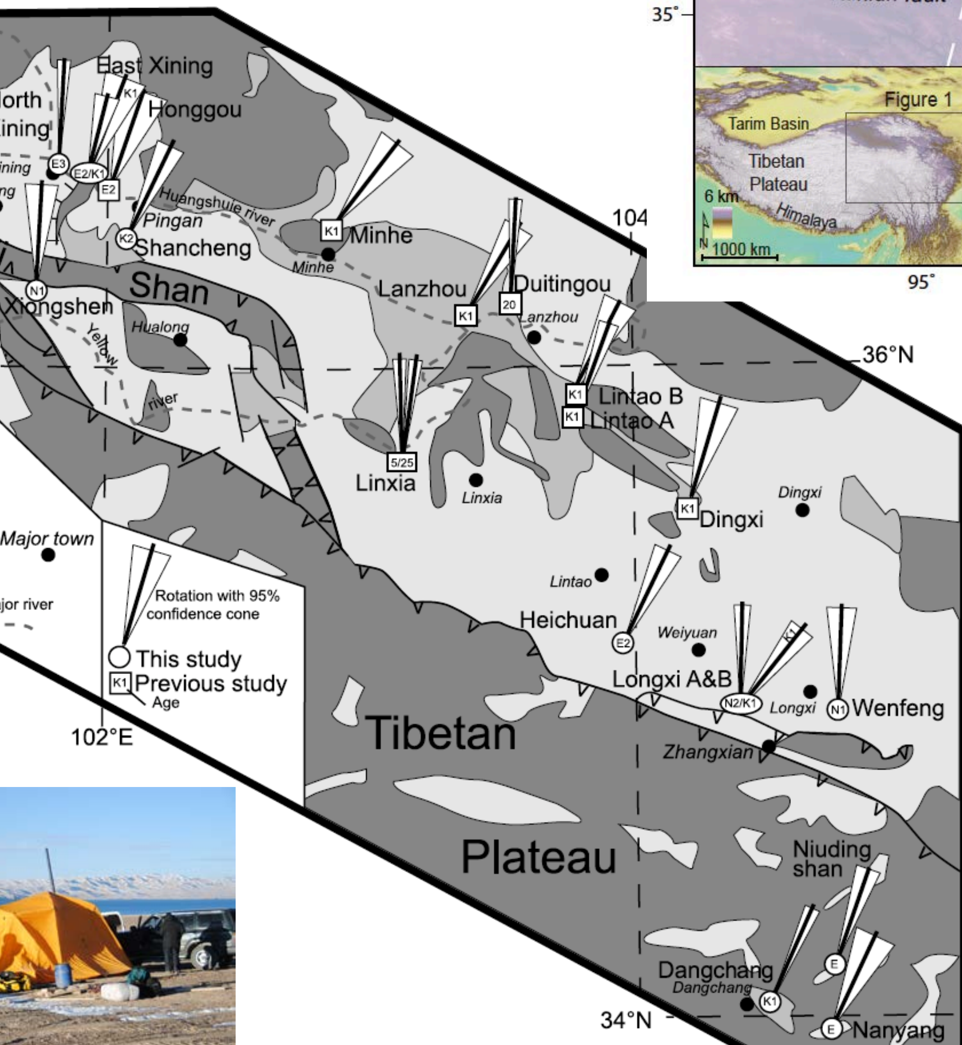
Right-lateral simple shear

[*Dupont-Nivet et al.*, *Tectonics*, 2004]

Present-day: **left-lateral shear** on ~east-west planes

Duvall and Clark, Geology [2010], based on GPS data of *Zhang et al.* [2004] and *Gan et al.* [2007]





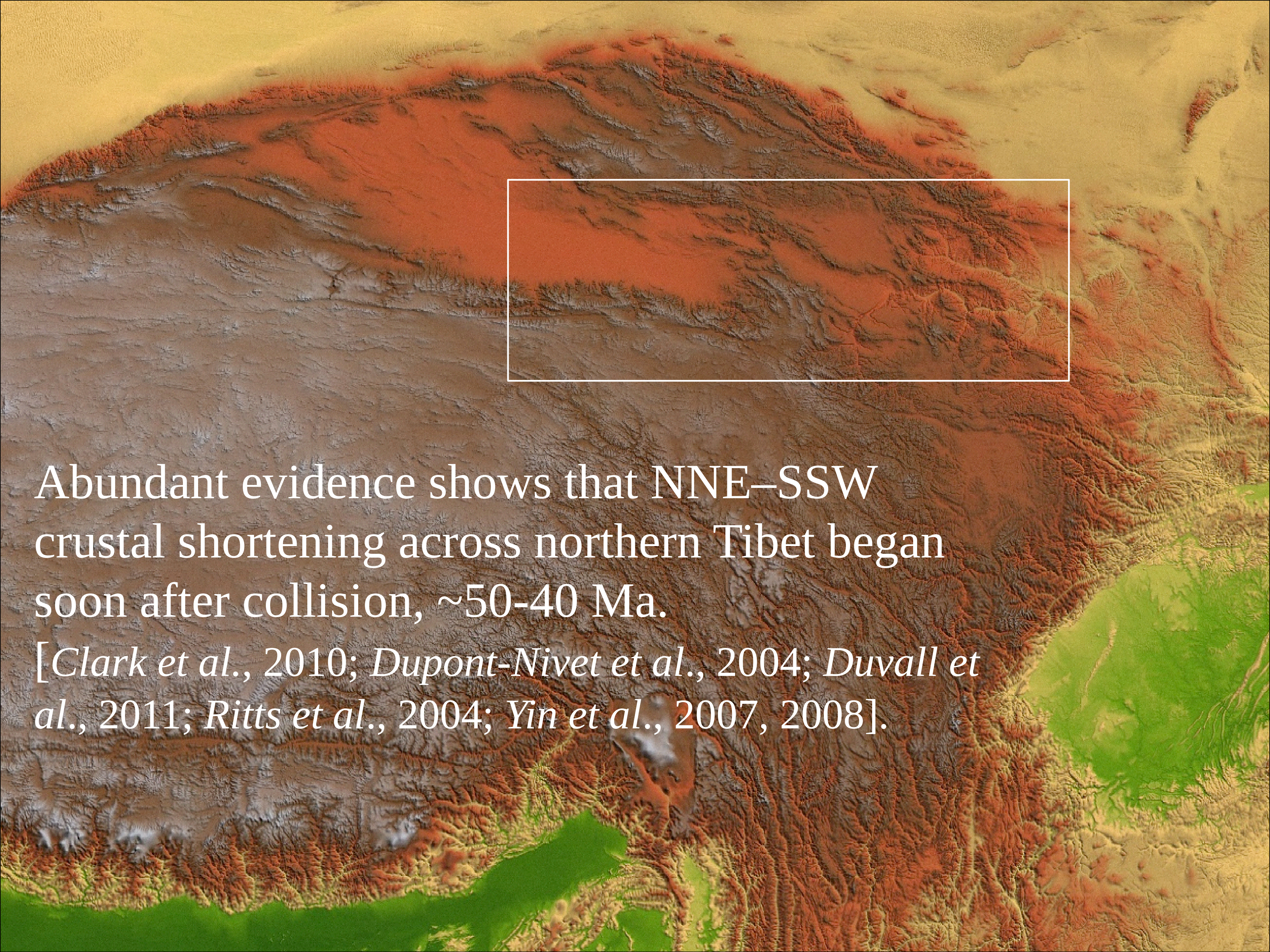
Clockwise rotation

since ~30 Ma

and before ~8 Ma

Right-lateral simple shear

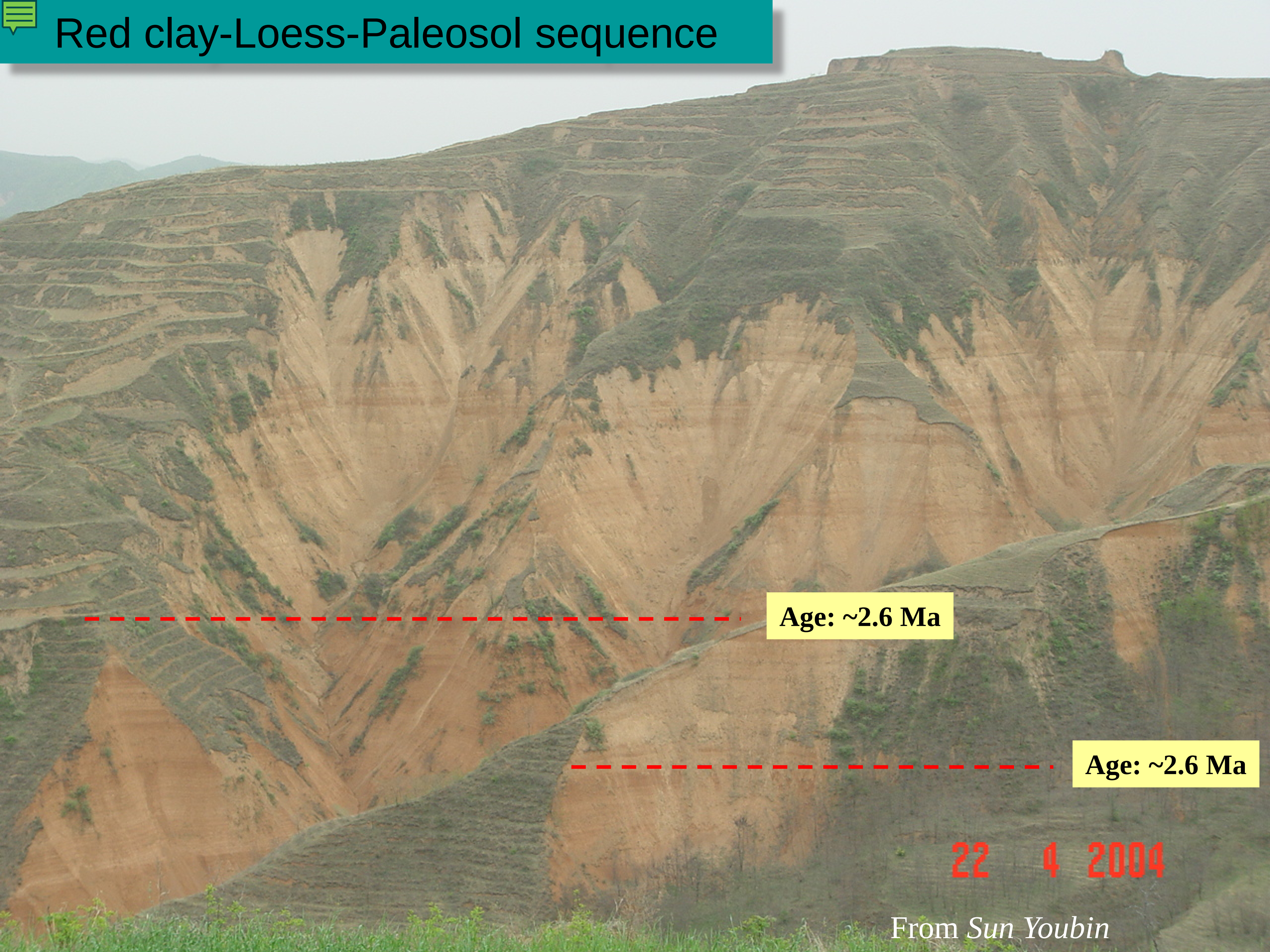
[*Dupont-Nivet et al.*, *Tectonics*, 2004]



Abundant evidence shows that NNE–SSW crustal shortening across northern Tibet began soon after collision, ~50-40 Ma.

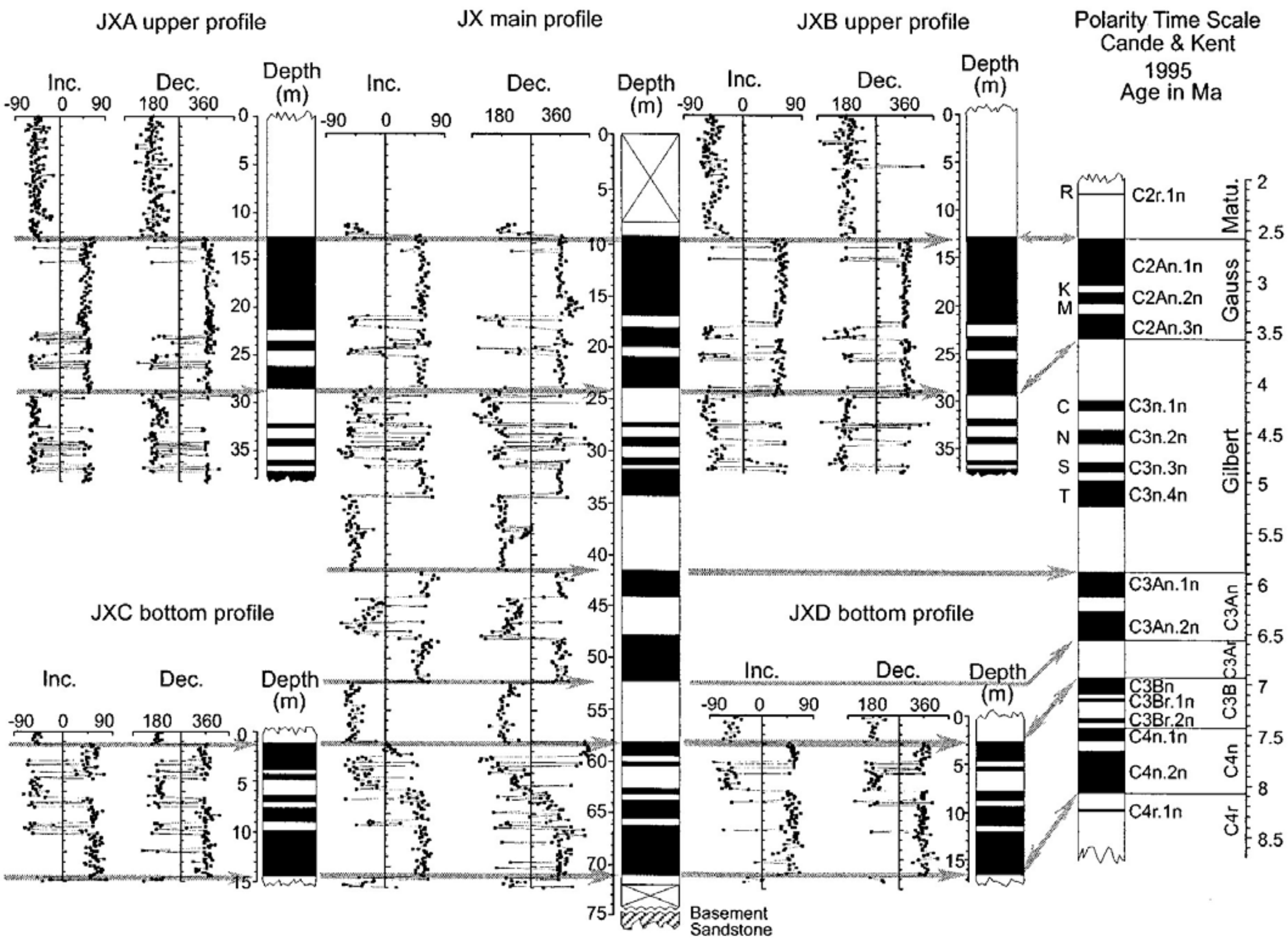
[*Clark et al.*, 2010; *Dupont-Nivet et al.*, 2004; *Duvall et al.*, 2011; *Ritts et al.*, 2004; *Yin et al.*, 2007, 2008].

Red clay-Loess-Paleosol sequence



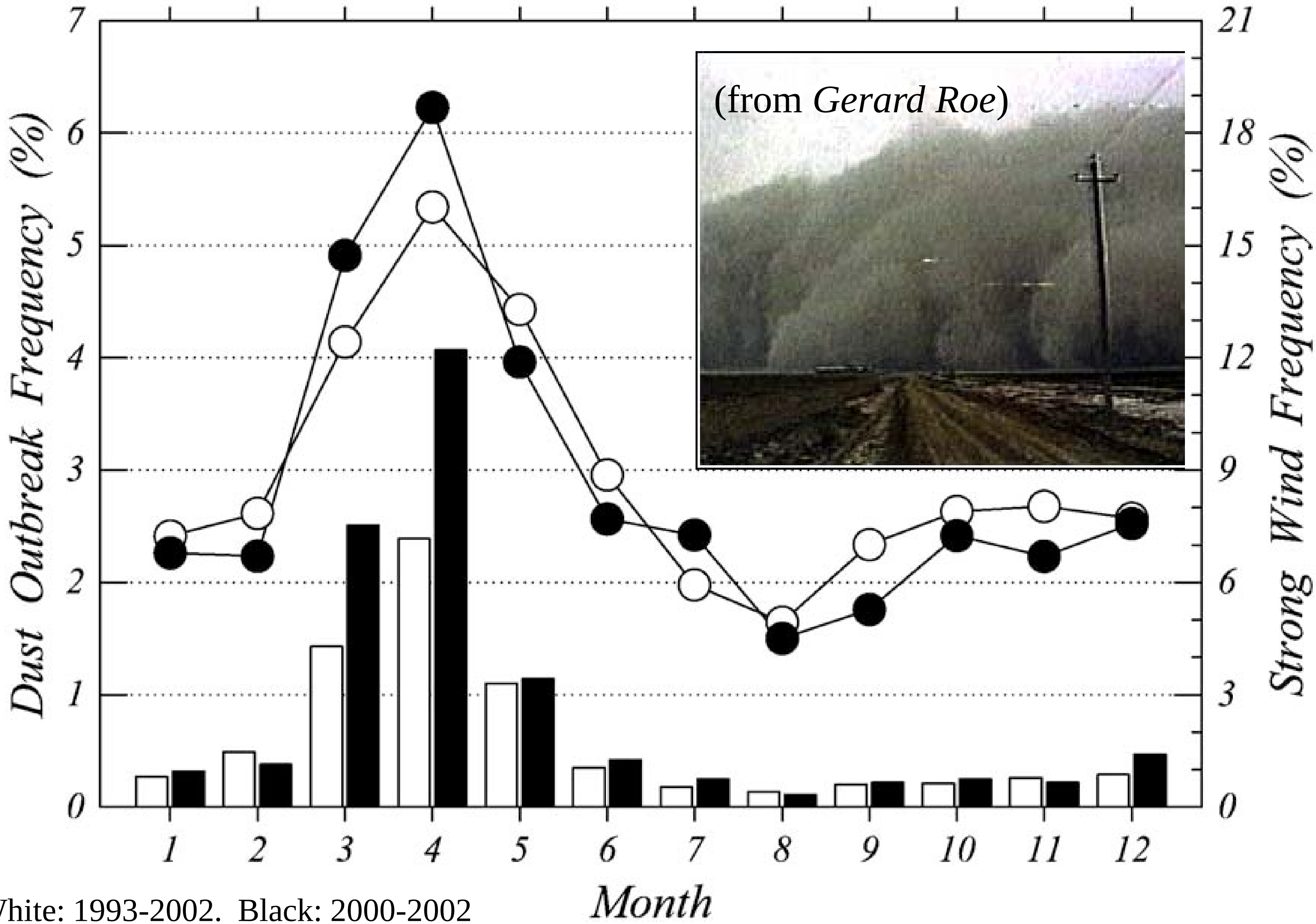
From *Sun Youbin*

Loess Magnetostratigraphy: Beginning of deposition at ~8 Ma



[*Qiang Li, Powell, and Zheng* 2001]

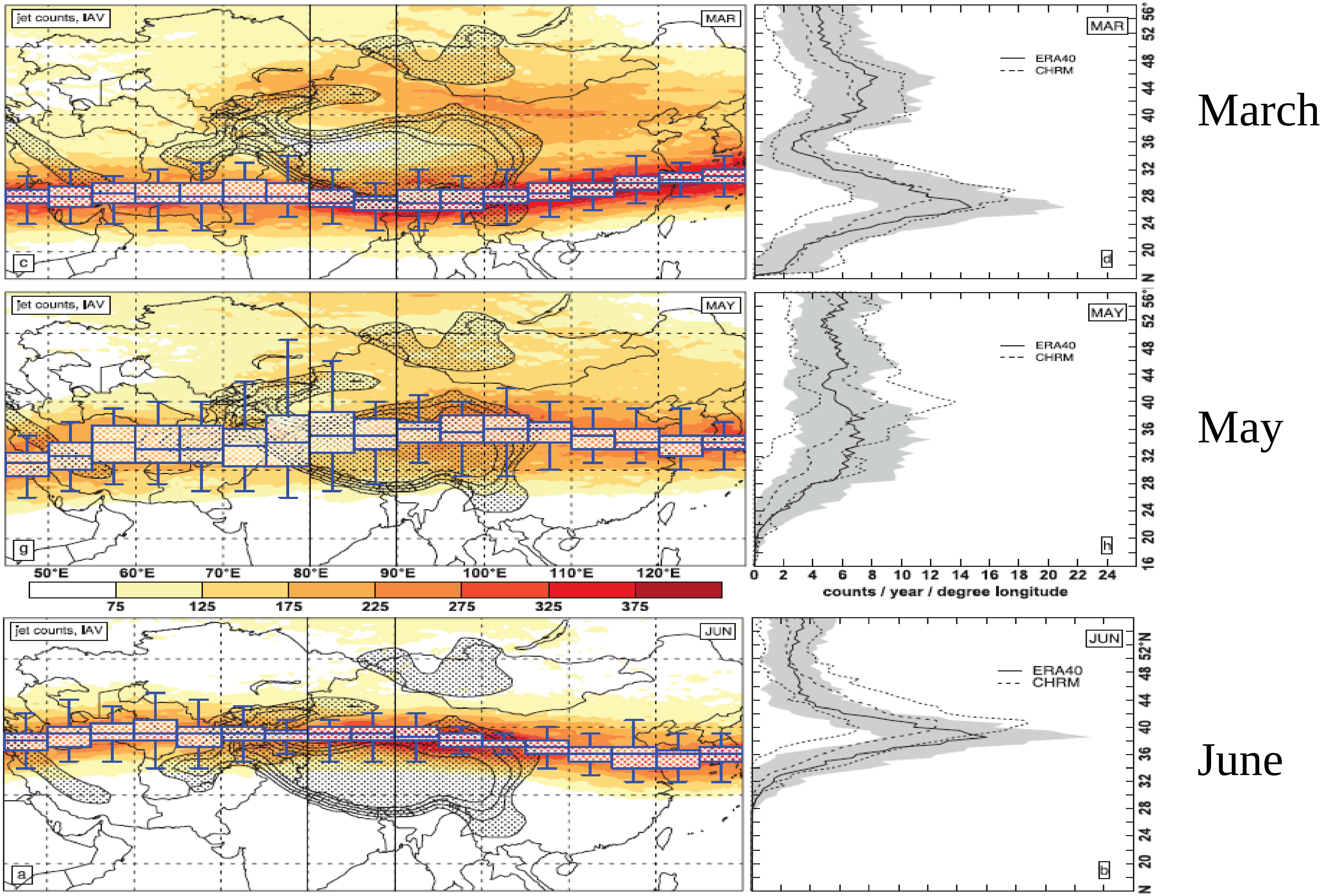
Dust-storm and strong wind frequency in northern China: Spring is the season (not winter or summer)



White: 1993-2002. Black: 2000-2002
Dust outbreak: bars. Strong winds: circles.

[*Kurosaki and Mikami* 2003; *Roe* 2009]

Jet speed and position



[*Schiemann, Lüthi, and Schär* 2009]

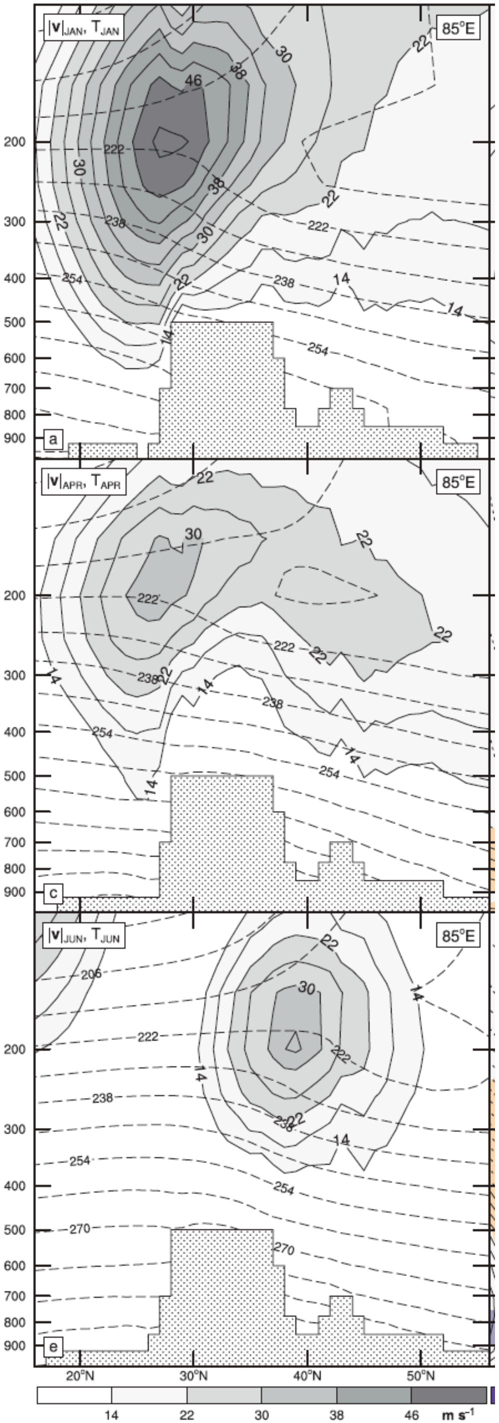
Profiles of jet speeds

January

April

June

South



North

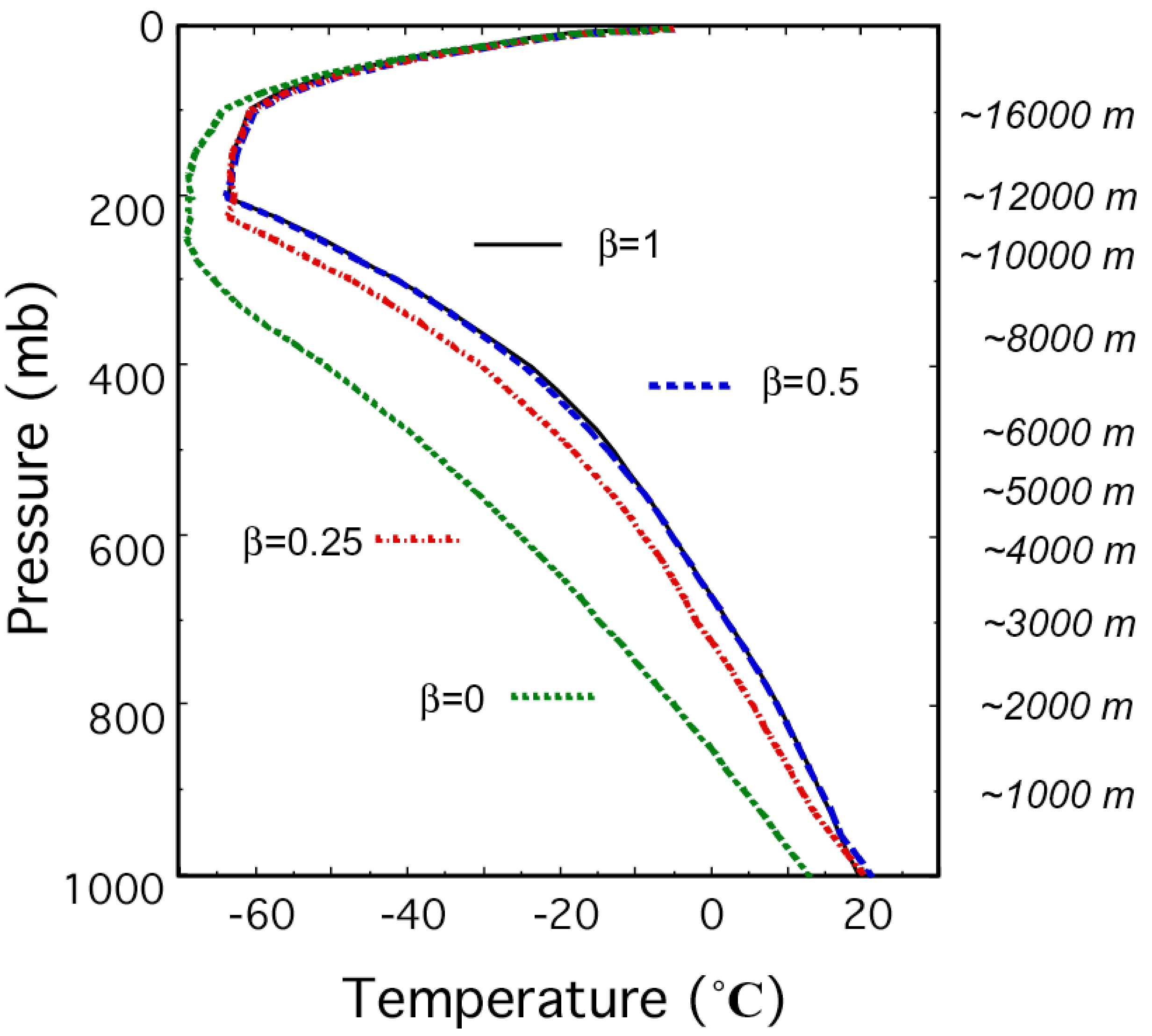
[*Schiemann, Lüthi, and Schär* 2009]

How might the growth of Tibet have affected paleoclimate in Asia, at least insofar as we can measure it and assign Tibet an unimpeachable role?

1. Maybe not at all.
2. Alternatively, maybe as we thought (*increased temperature over Tibet leads to a stronger meridional temperature gradient aloft, and stronger cross-equatorial circulation*), but we cannot measure consequences of this yet (except maybe *G. bulloides* and strong winds over the western Arabian Sea).
3. Perhaps in subtle ways that are clearer with paleoclimate proxies sampled on Milankovitch timescales (and therefore hard to discern).
4. Perhaps removal of mantle lithosphere increased potential energy (per unit area) and hence the force per unit length that Tibet applies to is surroundings, so that crust thickened and mountains grew north of Tibet (which enhanced *lee cyclogenesis in Mongolia*).
5. Somehow (?).

Stages in the Growth of Tibet

1. Before collision, at ~45 Ma, a narrow high range like the present-day ***Andes*** (apparently) bounded southern Eurasia.
2. The **Himalaya** has been built by slices of Indian crust thrust atop the Indian subcontinent.
3. Since Collision, India has penetrated steadily into Eurasia, **shortening and thickening Asian crust** to build the wide **high Tibetan Plateau**.
4. Near **~15-10 Ma**, a change took place; the Plateau started to **collapse**, **spread apart**, and (presumably) **subside** slowly (**perhaps** because of *removal of mantle lithosphere that took a load off the bottom*)**.**

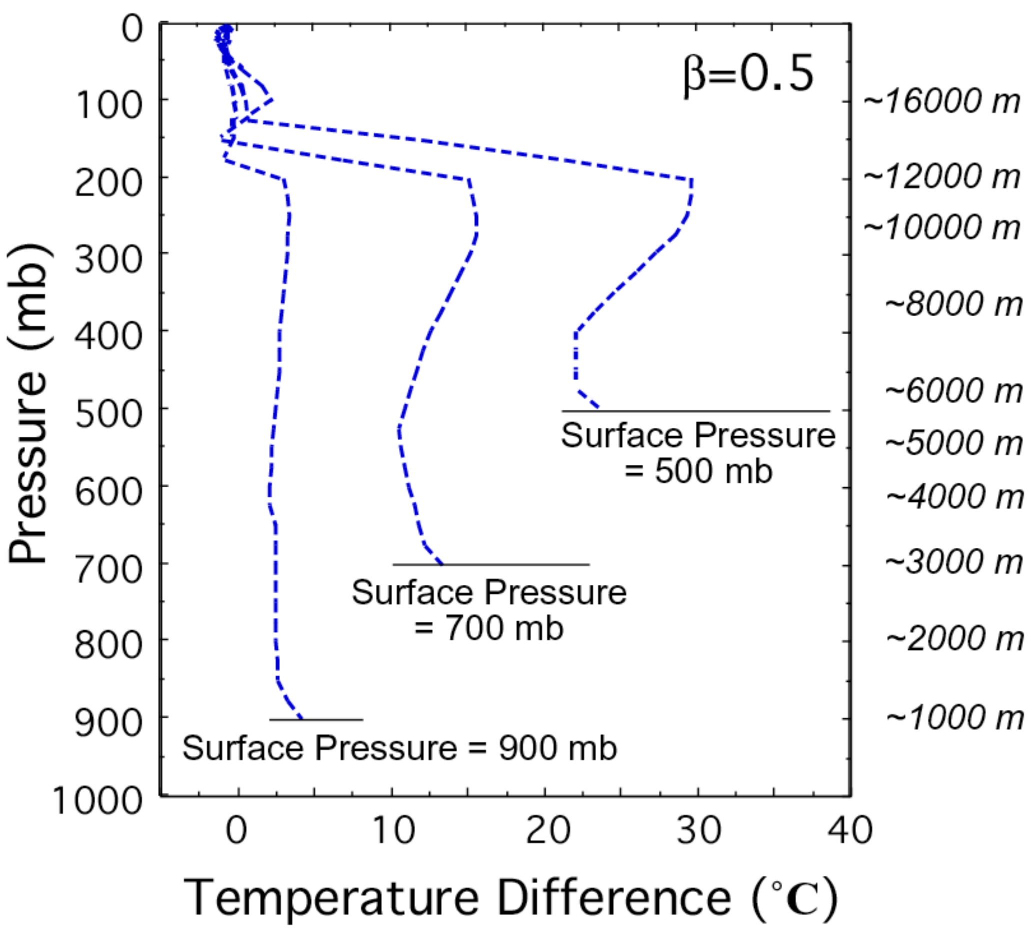


Radiative-Convective Equilibrium

β = fraction of surface water available for evaporation

[*Molnar and Emanuel* 1999]

Differences between calculated air temperatures (for radiative-convective equilibrium) above *elevated surfaces* from those above a surface at *sea level*



If a surface lay at ~4000 m, and then rose to ~5000 m, the calculated difference between temperatures in the upper troposphere over the high surface and over that near sea level wound increase by

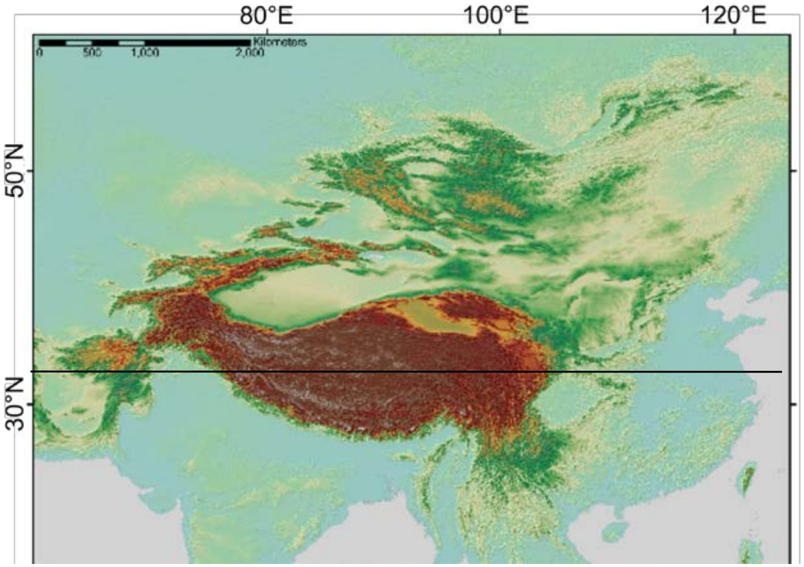
~6°C.

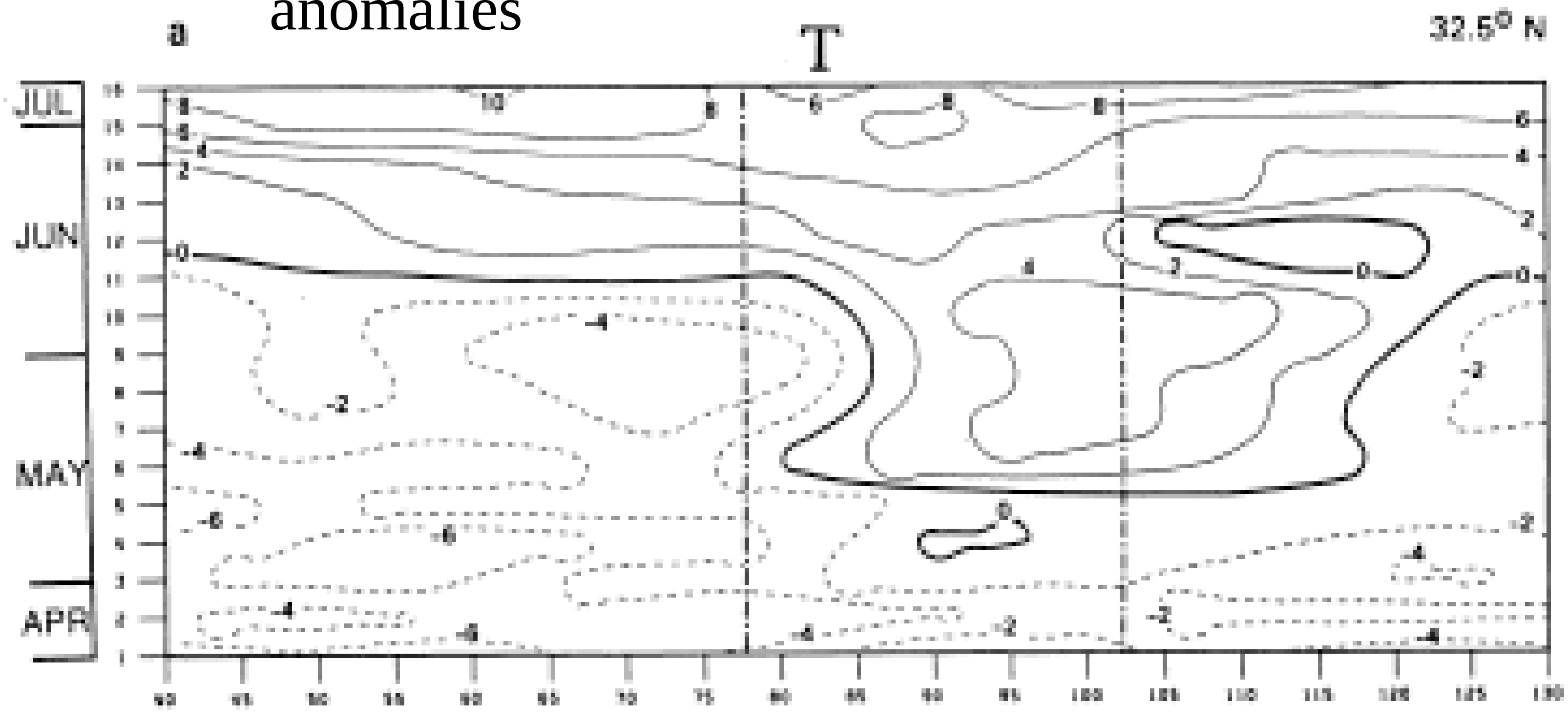
[*Molnar and Emanuel* 1999]

Heating over Tibet

[Yanai, Li, and Song,
J. Meterol. Soc. Japan, 1992]

T = 200-500 mbar temperature anomalies





40°E 80°E 110°E 130°E

Basic theory (buttressed by calculations) suggests

Maximum ascent rate, should lie slightly equatorward of the maximum subcloud moist static energy, *h* [e.g., *Neelin* 2007],

$$h = C_P T + L_v q + gz$$

or **equivalently** the maximum subcloud moist entropy, s_b [*Emanuel*, 1995],

$$s_b = \left(C_{Pd} + qC_{Pl}\right)\ln\theta_{eb}; \quad \theta_e = T\left(\frac{P_0}{P}\right)^{\frac{R}{C_P}} \exp\left(\frac{L_v q}{C_P T}\right)$$

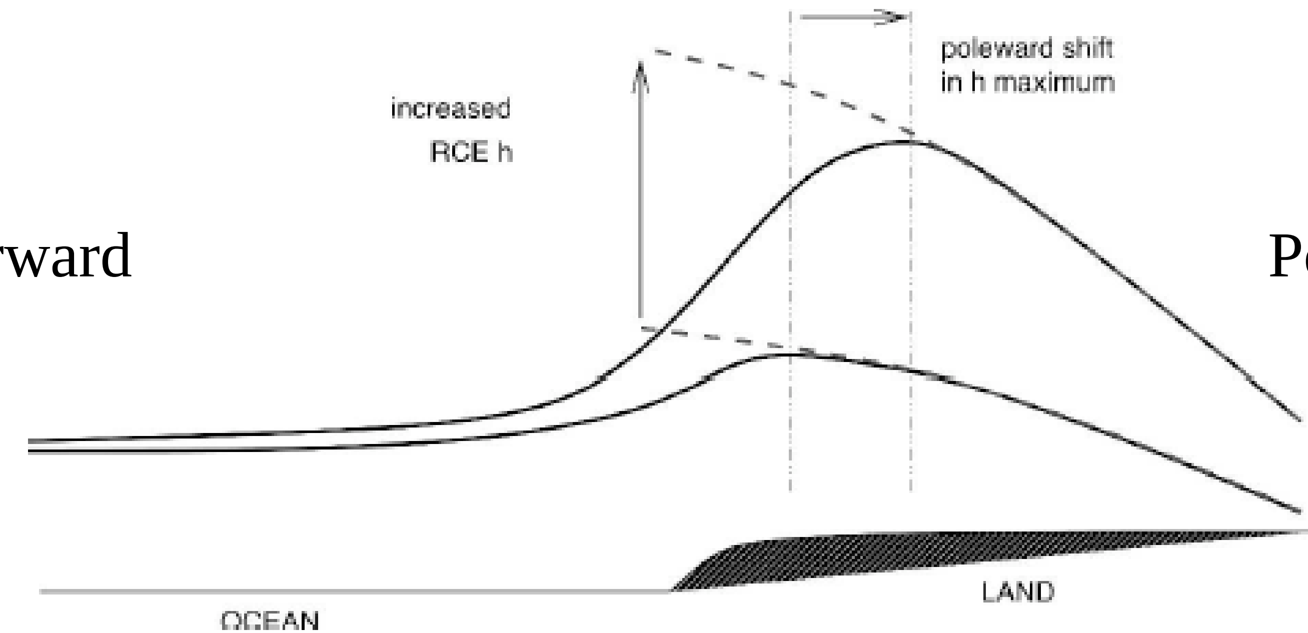
or, simply potential temperature for a dry atmosphere [*Lindzen and Hou*, 1988].

Moist static energy and moist entropy vary together.

Interaction of radiative heating over land and advection of moisture from ocean

Equatorward

Poleward

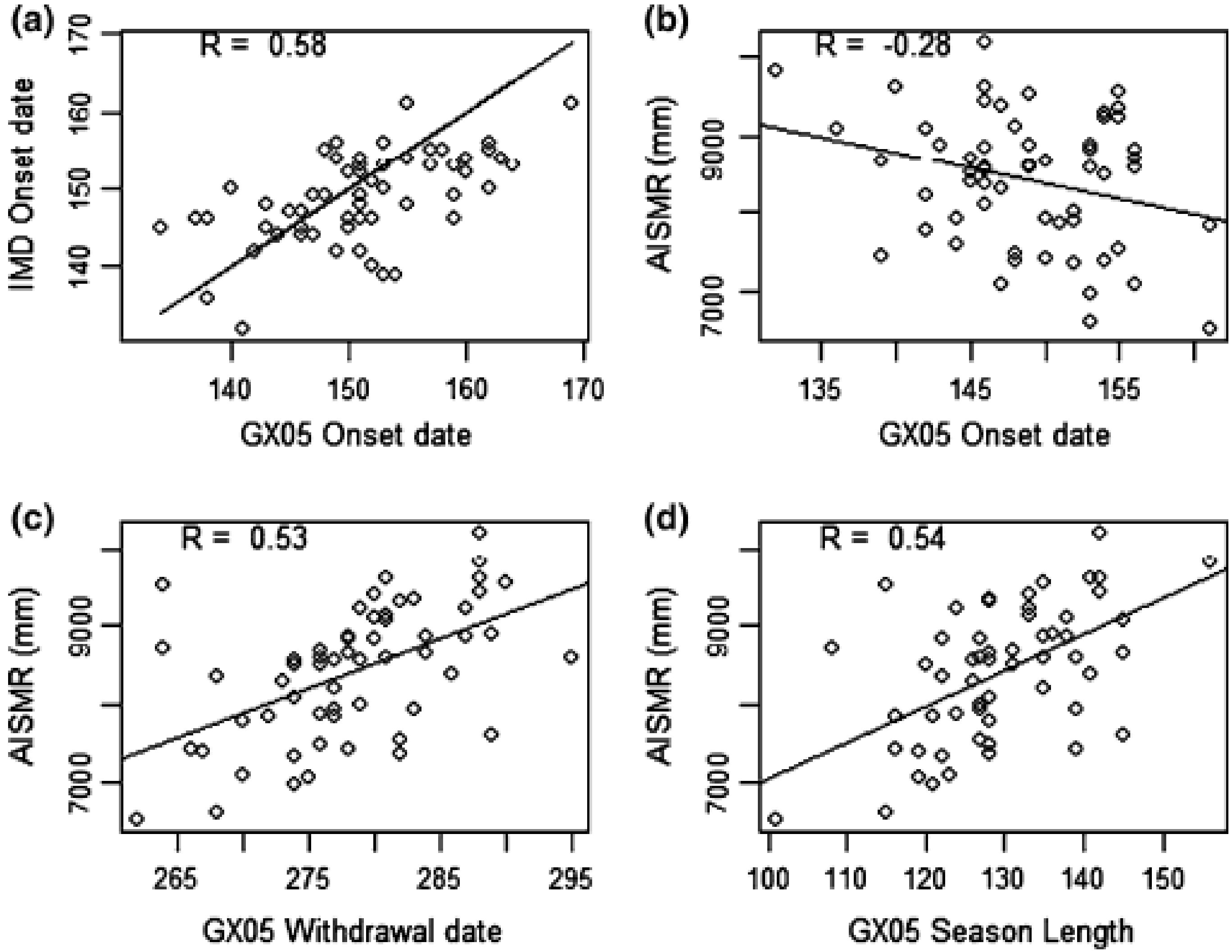


Heating over land increases subcloud **moist static energy, *h*,** (or moist entropy) rapidly in Radiative Convective Equilibrium (RCE). Advection of cooler, but moist, air from the ocean creates a maximum in ***h*** over the land.

$$h = C_p T + L_v q + gz$$

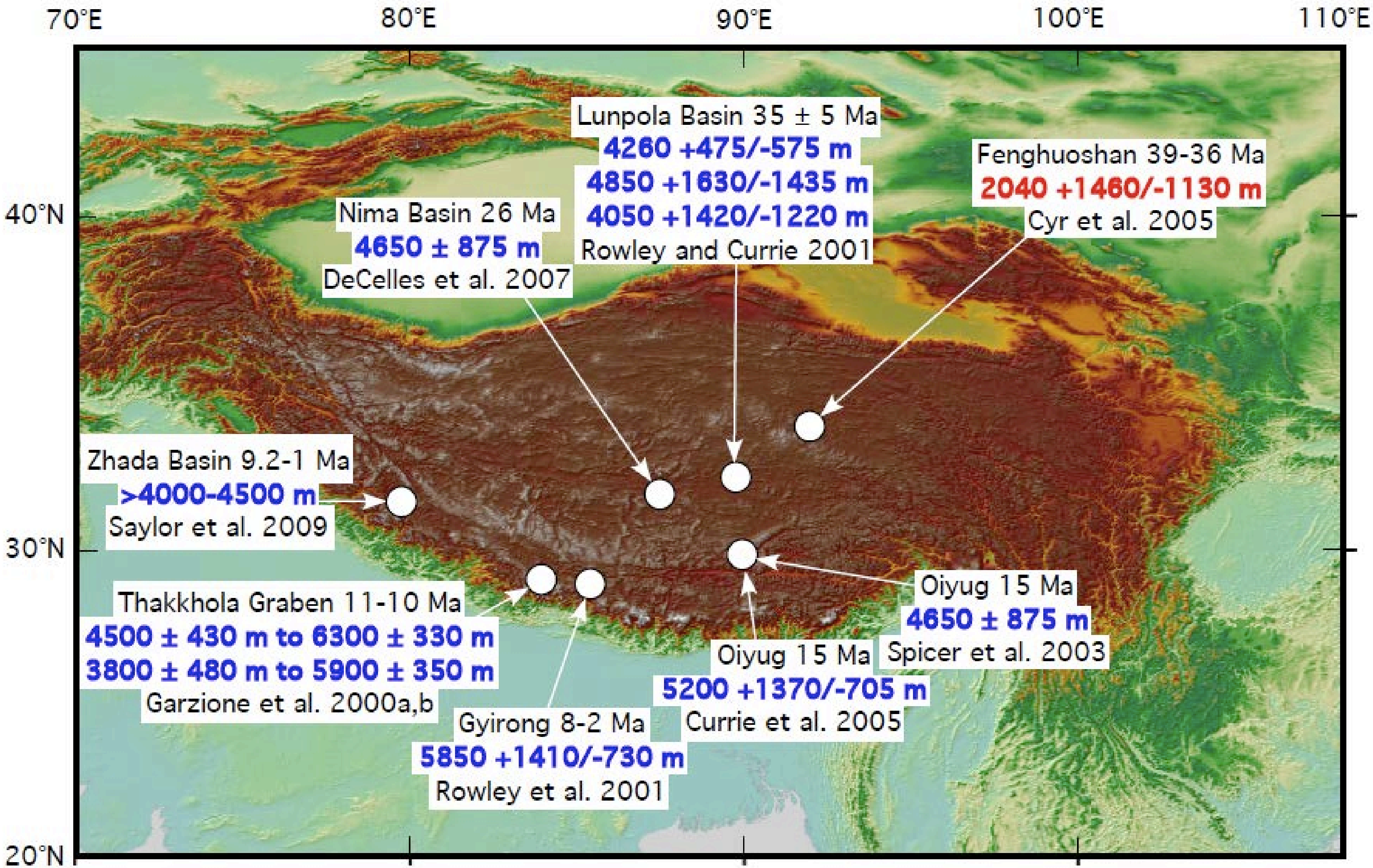
[*Privé and Plumb* 2007]

Goswami and Xavier's onset and withdrawal dates and the monsoon



[Rajagopalan and Molnar, *Climate Dynamics*, 2012]

Tibet Paleo-elevations



Little change (± 1000 m) in southern Tibet; (but no constraint on the elevation of northern Tibet.


View southeast from Ulugh
Muztagh, in northern Tibet

The idea that Tibet rose ~1000 m and then started to collapse at ~10 Ma passes a test.

So, how might Tibet, and its growth, affect climate, and paleoclimate?

1. Loess plateau – dust
2. Rainfall over South China
3. Rainfall (aridification) over NW India
4. Monsoon winds over the Arabian Sea

Interim Summary

1. Widespread accelerated exhumation, incision, and sedimentation near 15-10 Ma.

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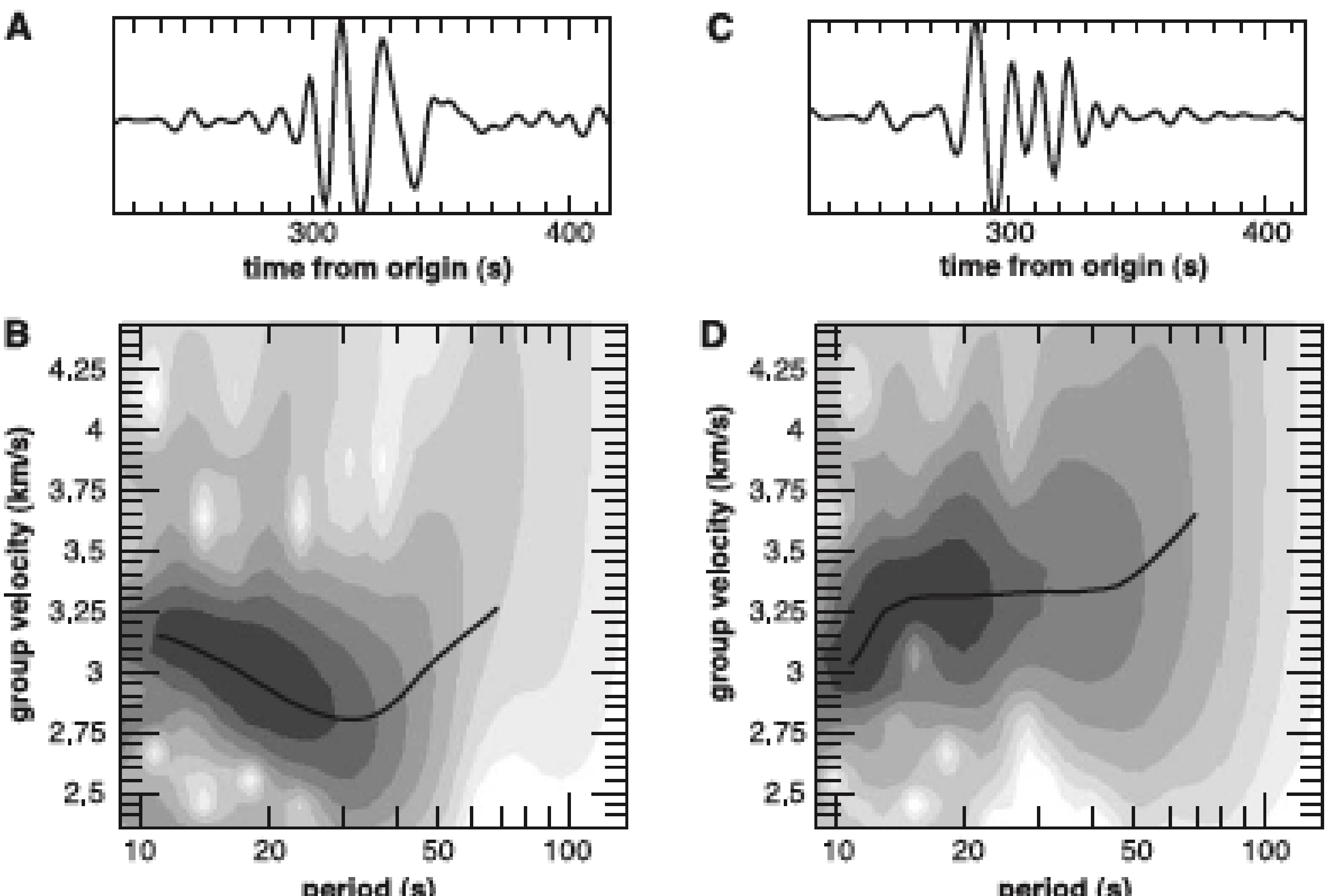
3. For northeast Tibet, a reorientation of deformation at 15-10 Ma.

Radial anisotropy in the crust supports the idea that lateral flow within the crust redistributes mass (channel flow).

[Shapiro et al., 2004]

Let's return to convective removal of mantle lithosphere

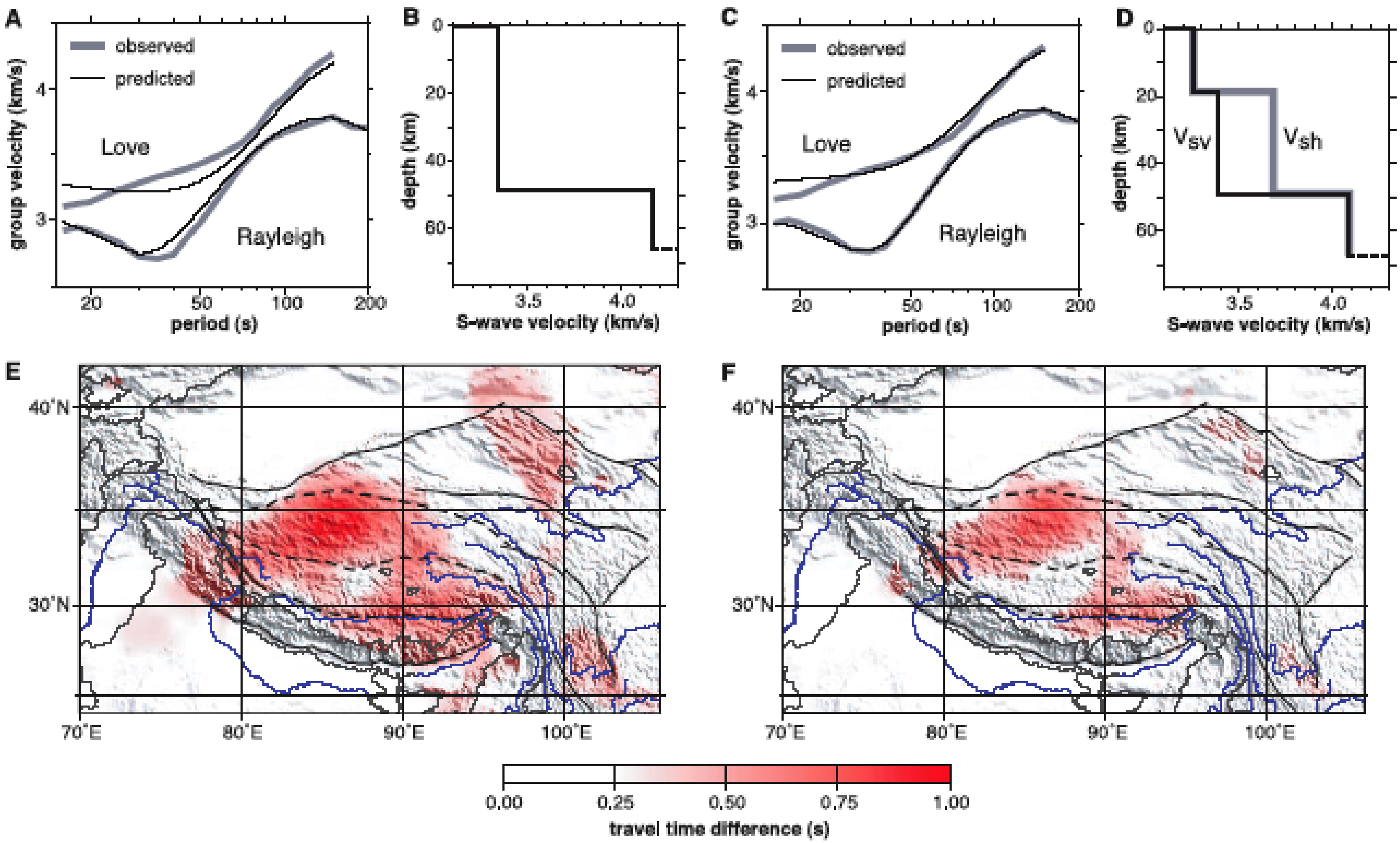
Rayleigh (left) and Love (right) wave dispersion



Note inverse branch for Rayleigh but not for Love waves.

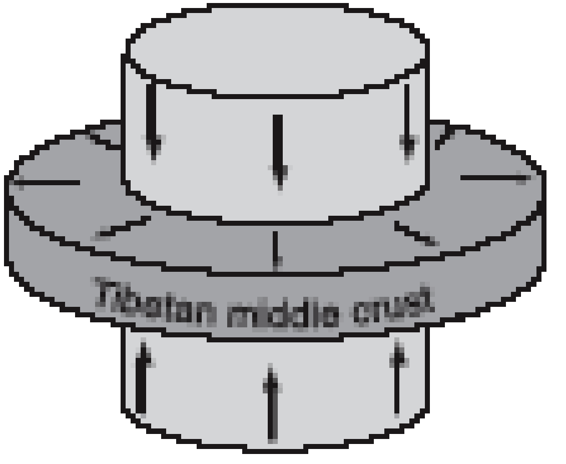
Rayleigh-Love wave difference

In red areas, Love waves require the higher speeds.



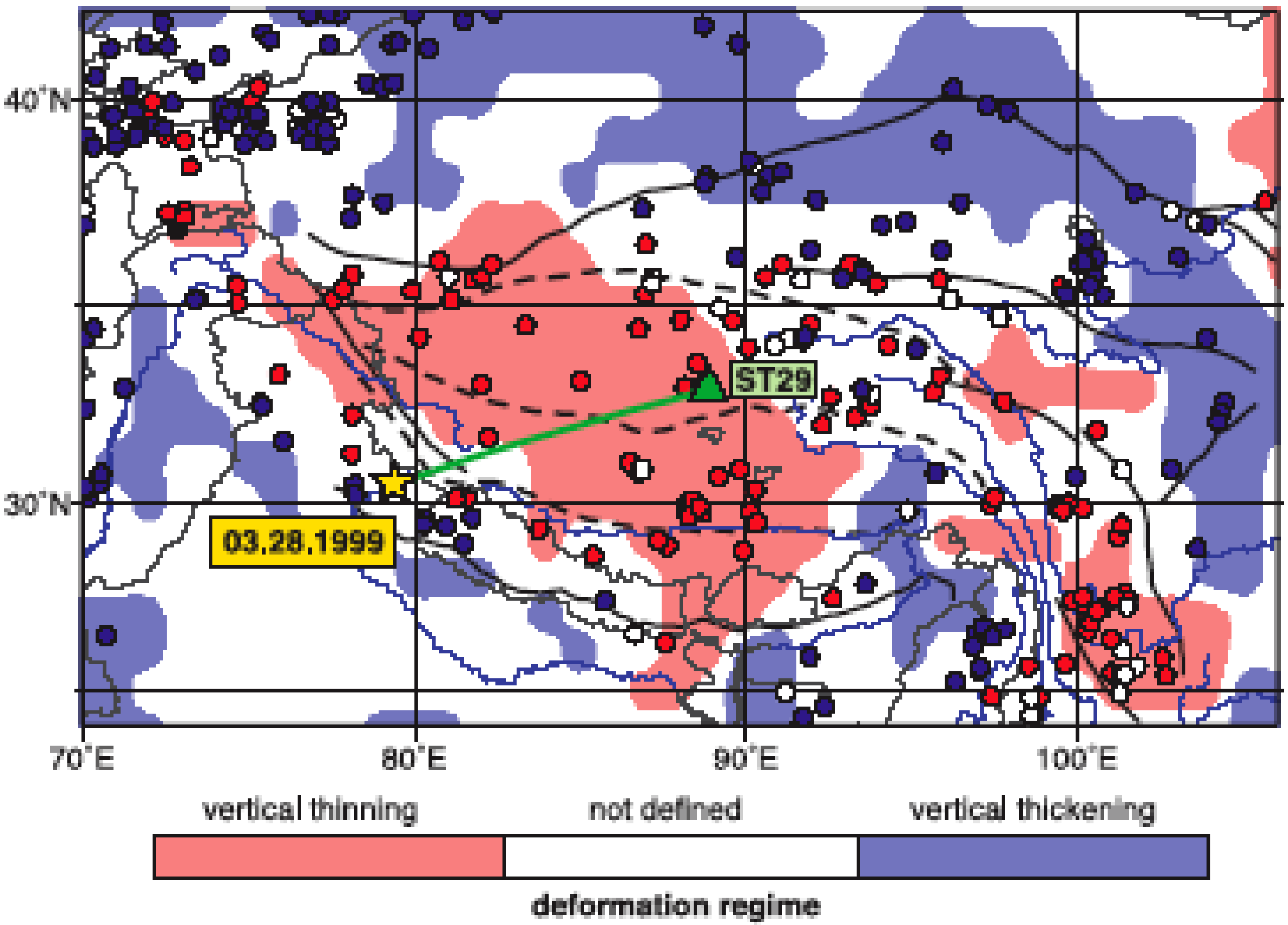
Reorientation of anisotropic crystals

- Surface wave dispersion suggests radial anisotropy: SH propagates faster than SV.
- If anisotropic crystals, like mica were preferentially oriented so that more of them were flat than vertical, SH would propagate faster than SV.
- Horizontal extension and crustal thinning could induce such a preferred orientation.

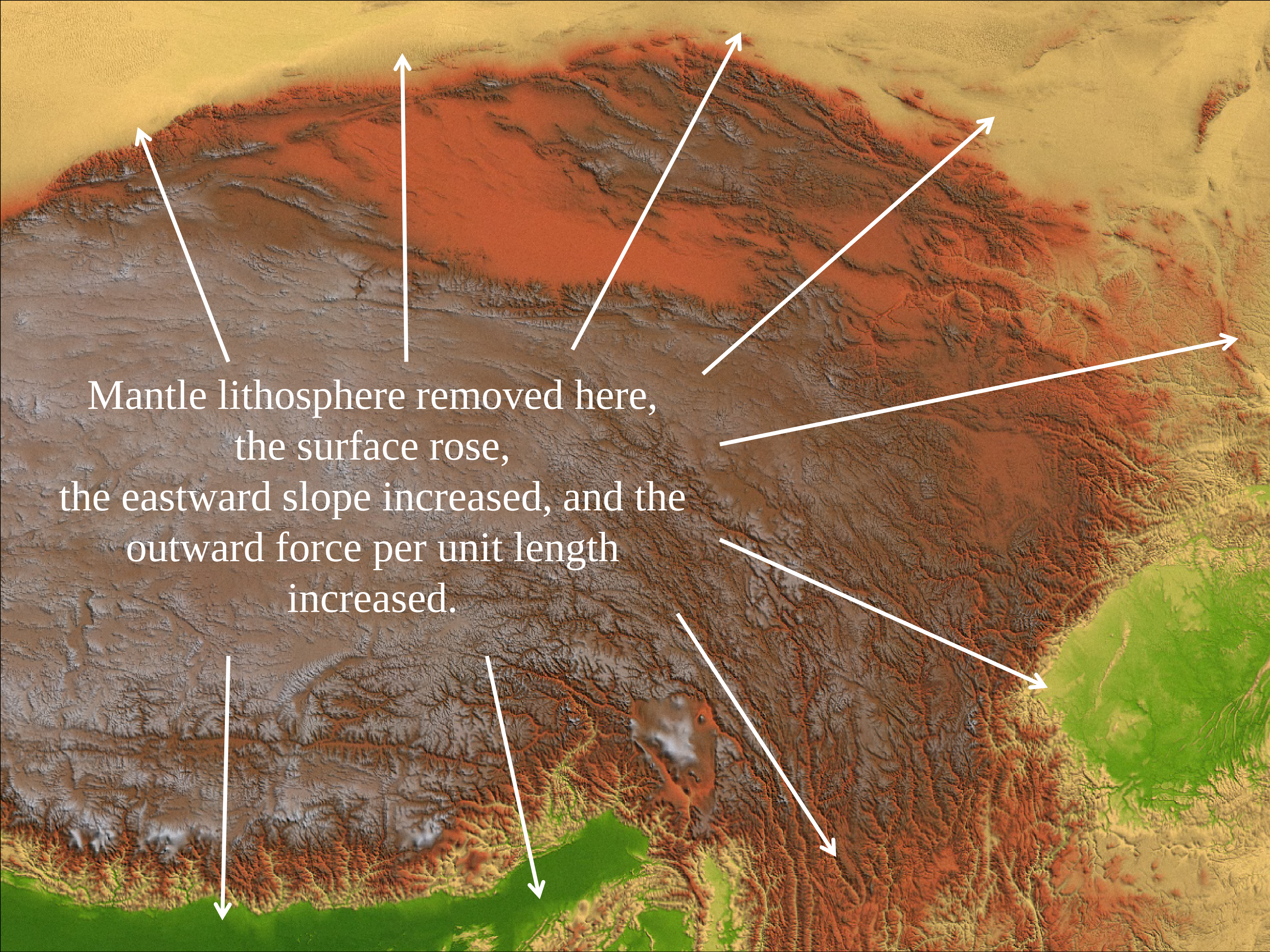


[Shapiro et al., 2004]

Radial anisotropy where SH is faster than SV (red areas)



Normal faulting dominates where dots are red; thrust faulting where dots are blue.


Mantle lithosphere removed here,
the surface rose,
the eastward slope increased, and the
outward force per unit length
increased.

Convective Removal of mantle lithosphere

1. **Passes one test**: predicts an *increased outward force* per unit length, which leads both to a *switch* from crustal *thickening* to crustal *thinning* and to an *outward growth* of plateau.

The deep structure of Tibet

Tibetan deep structure

1. Thick crust everywhere (*Airy isostasy*).
2. but, thicker in the **south** (**70-75 km**) than in the **north** (**60-65 km**)
3. and lower P- and S-wave speeds in the mantle of northern than southern Tibet.
4. Therefore, **hotter** in the **north** than **south**.
5. and part of the high elevation of northern Tibet is due to a **hot** uppermost mantle,
6. consistent with removal of mantle lithosphere.

Convective Removal of mantle lithosphere

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2. **Passes a second test**: also predicts **marked lateral variations in upper mantle structure.**

Convective Removal of mantle lithosphere

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3. Removal of mantle lithosphere also **predicts** an **increase in surface elevation of ~1000 m** (not the whole 5000-m present day mean elevation) of the plateau.

Convective Removal of mantle lithosphere

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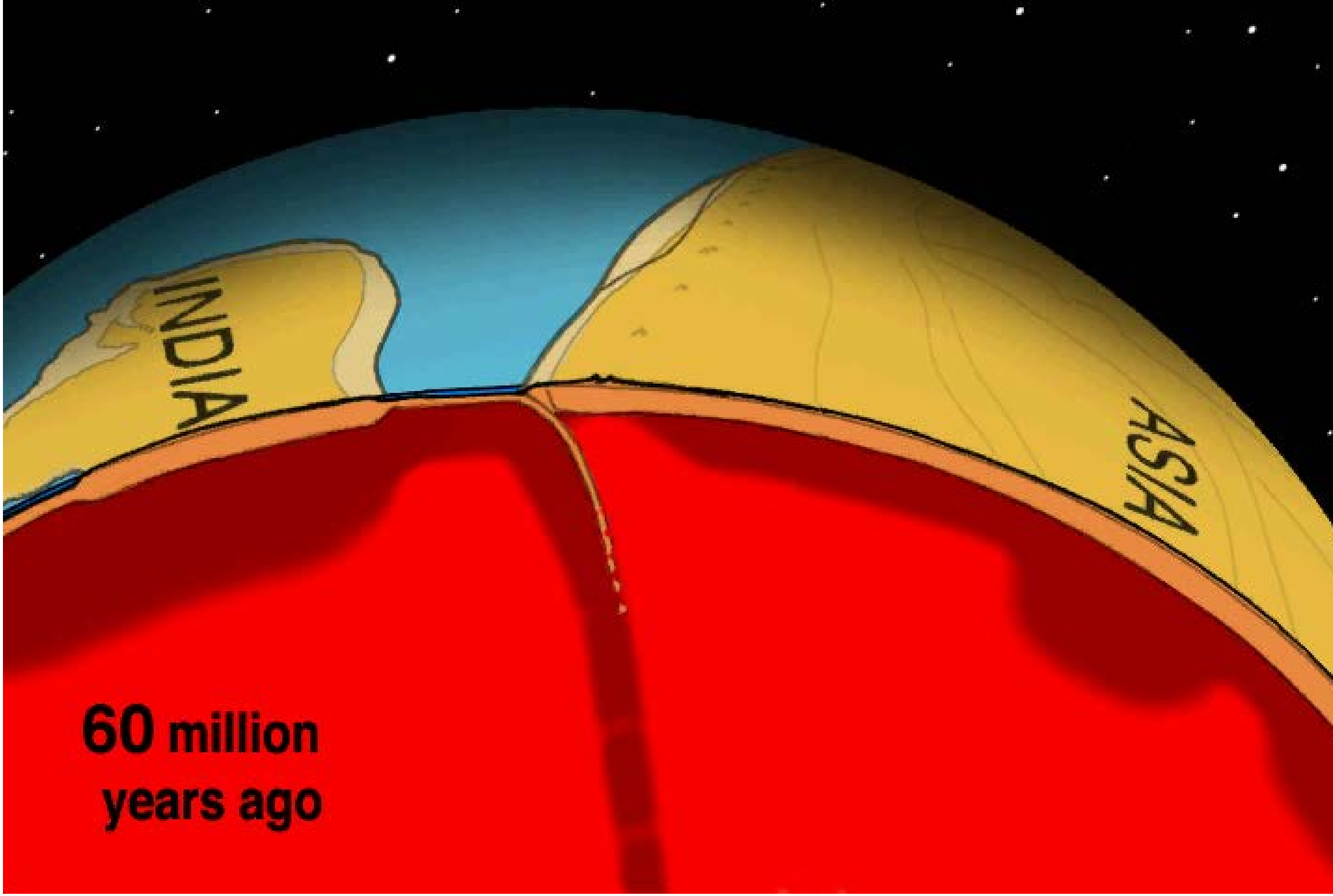
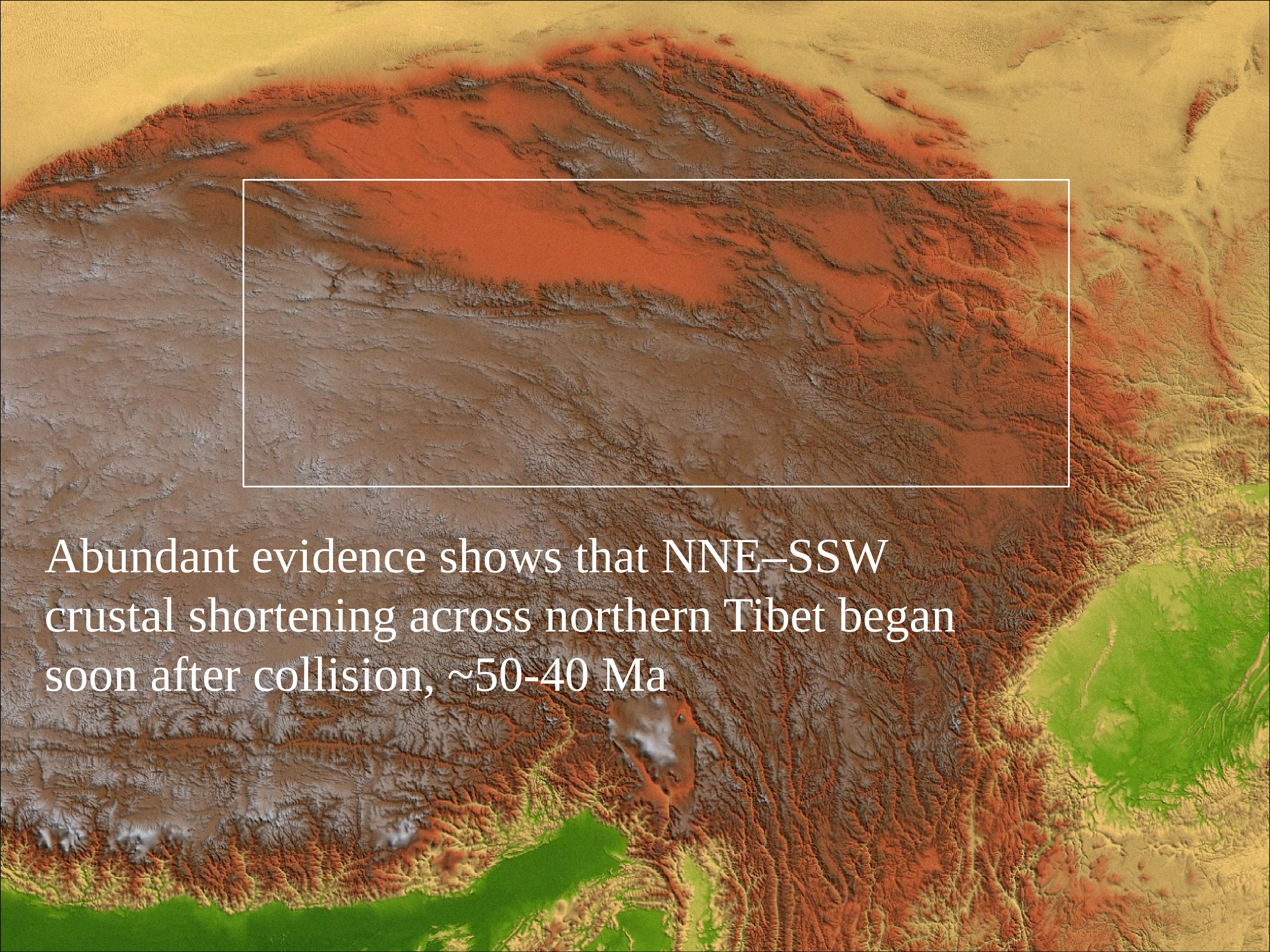
2. **Passes a second test**: also predicts **marked lateral variations in upper mantle structure.**

3. Removal of mantle lithosphere **also predicts** an **increase in surface elevation of ~1000 m** (not the whole 5000-m mean elevation) of the plateau. Ignoring uncertainties of 1000 m, removal of lithosphere **fails this test**, at least for southern Tibet. *Maybe northern Tibet rose 1000 m since 15 Ma.*

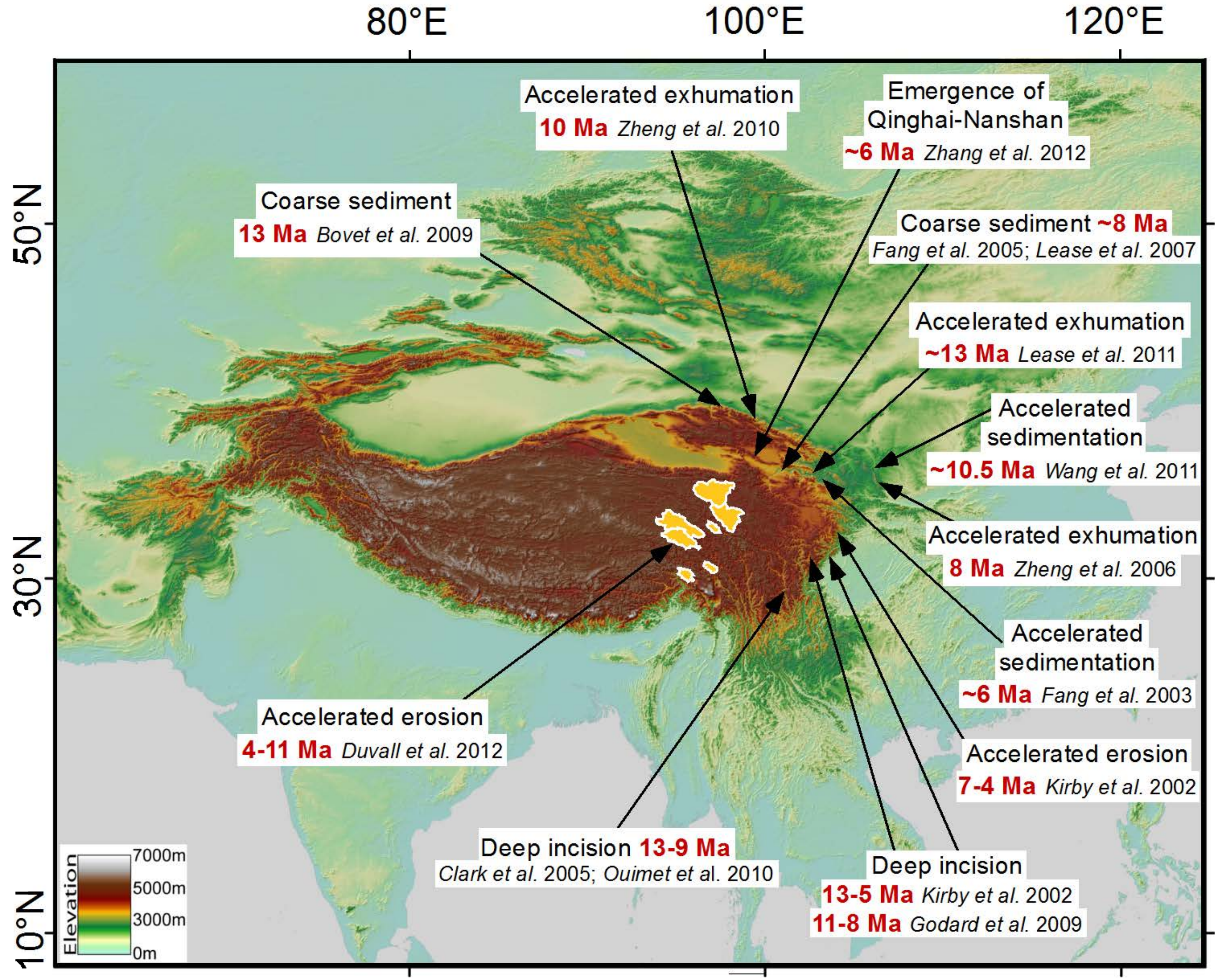


Animation by Tanya Atwater

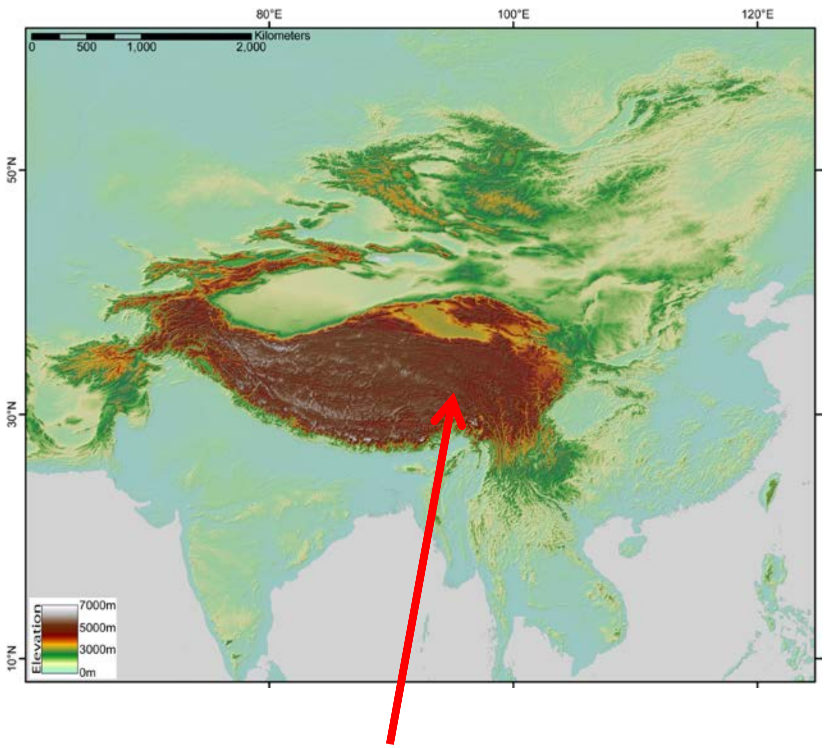
(given to me for my 60^{th} birthday, and hence honoring all of my prejudices, but not necessarily all of the facts)


Abundant evidence shows that NNE–SSW crustal shortening across northern Tibet began soon after collision, ~50-40 Ma

Upward and outward growth of high Tibetan terrain since 15-10 Ma

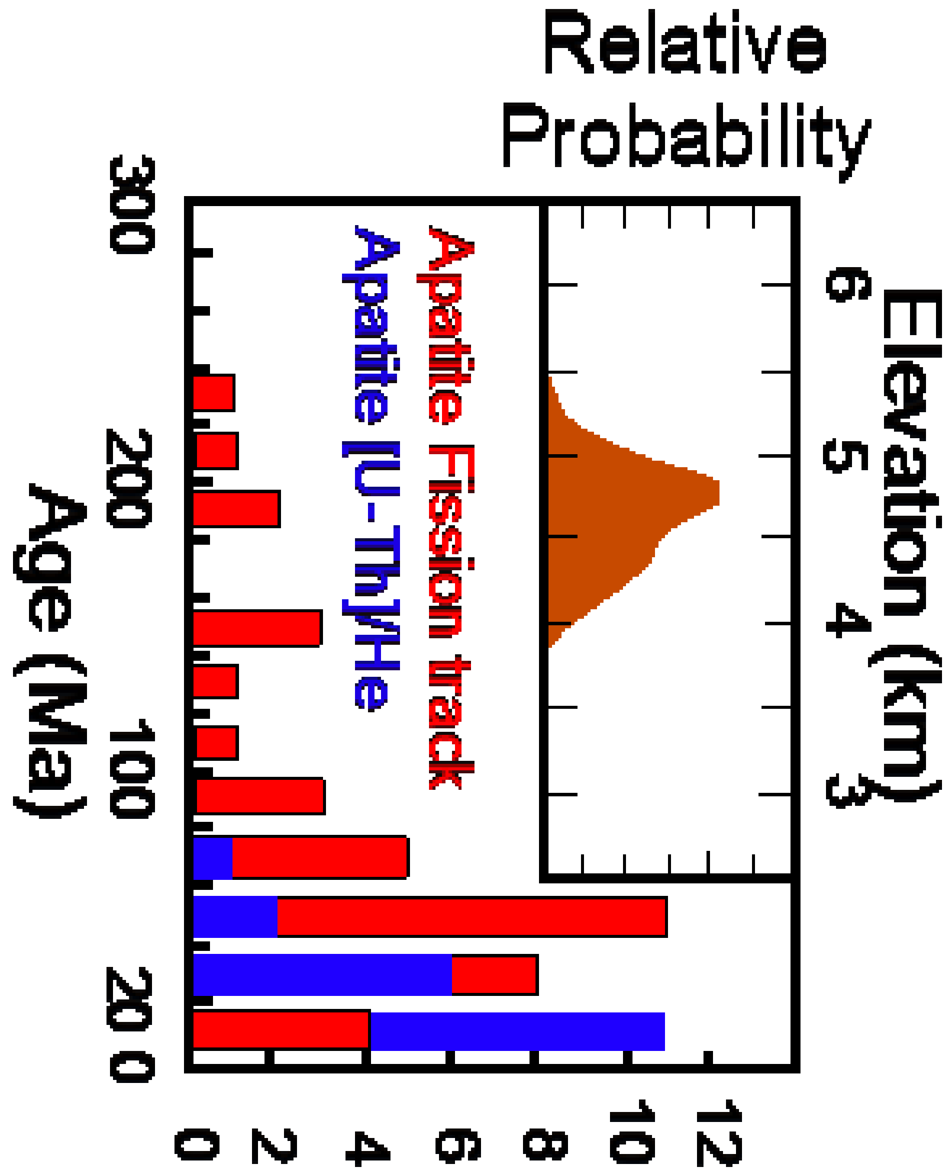


Basin-average erosion rate from detrital ages: Fission tracks (~110°C) and [U-Th]/He (~70°C)



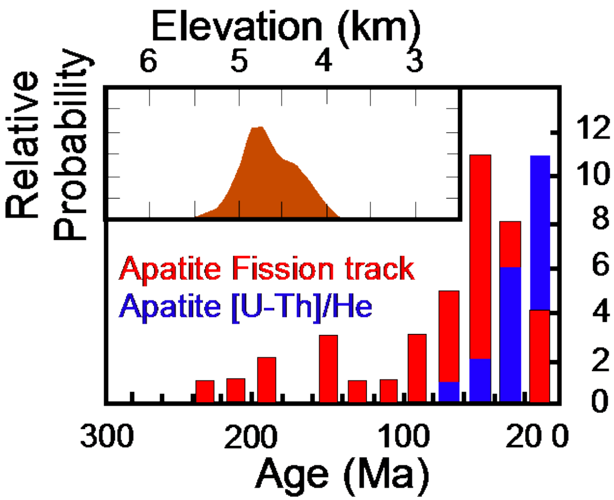
Upper Mekong

[Duvall, Clark, Avdeev, Farley, and Chen, *Tectonics*, 2012]

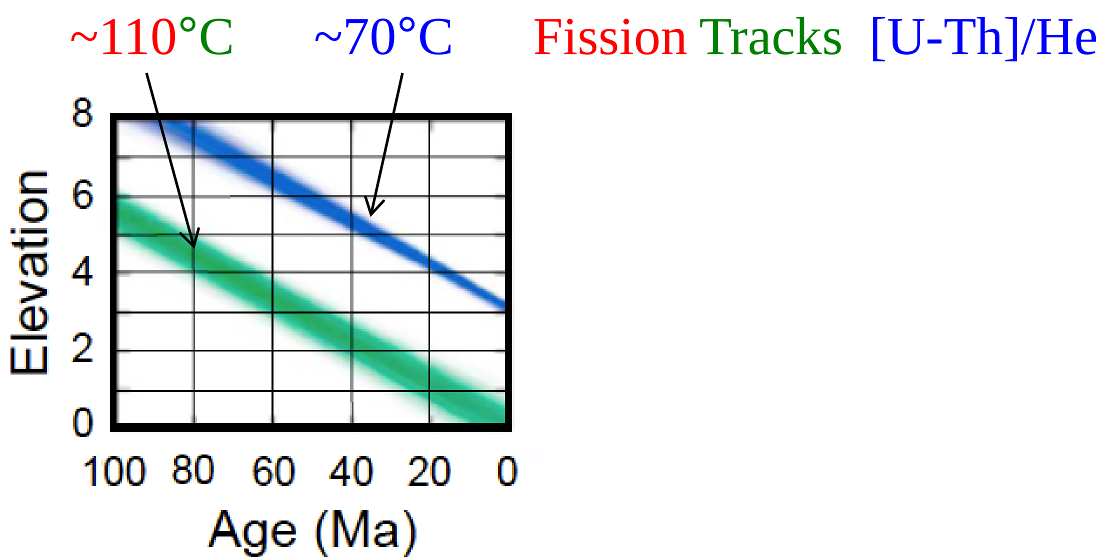


Basin-average erosion rate from detrital ages: Fission tracks and [U-Th]/He

Upper Mekong

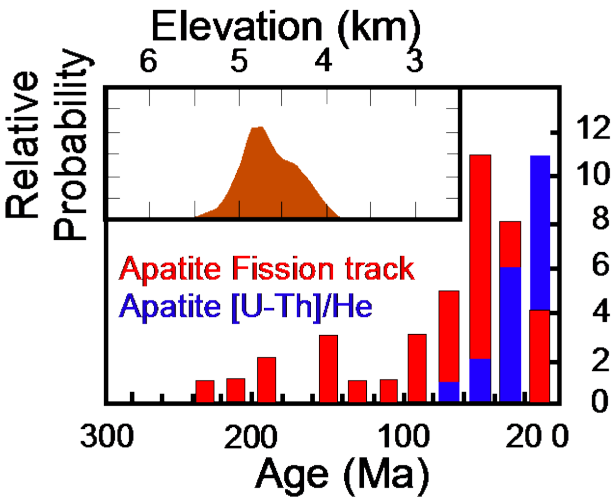


Steady cooling



[Duvall, Clark, Avdeev, Farley, and Chen, *Tectonics*, 2012]

Upper Mekong



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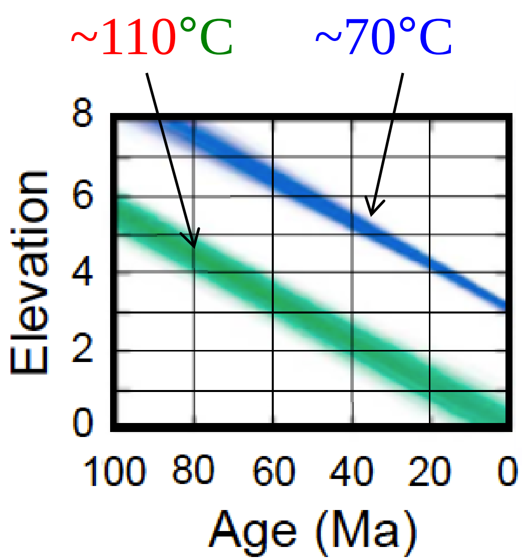

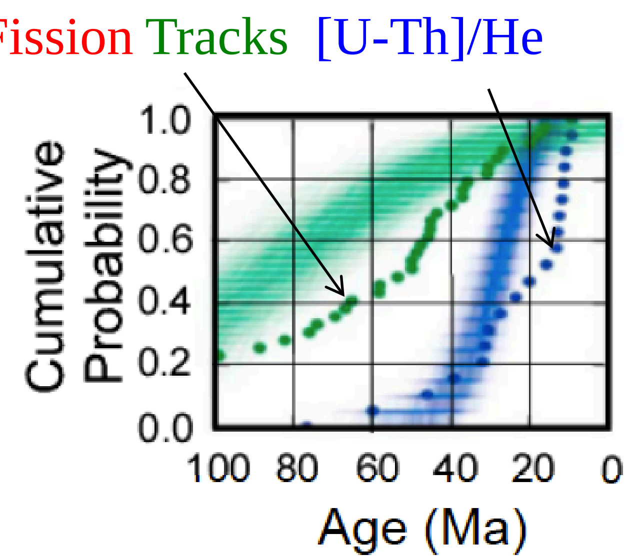

[Duvall, Clark, Avdeev, Farley, and Chen, *Tectonics*, 2012]

Basin-average erosion rate from detrital ages: Fission tracks and [U-Th]/He

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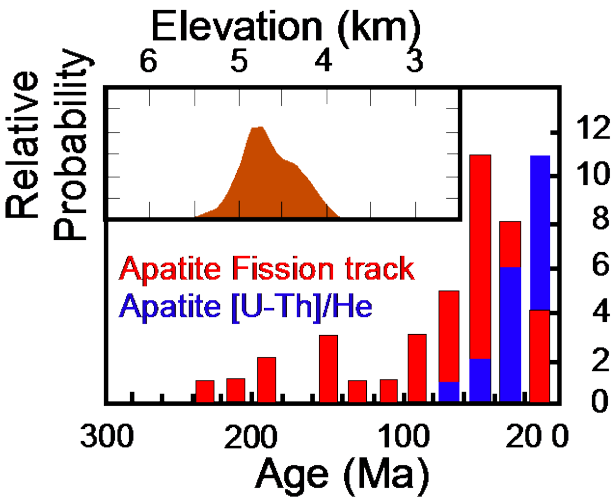
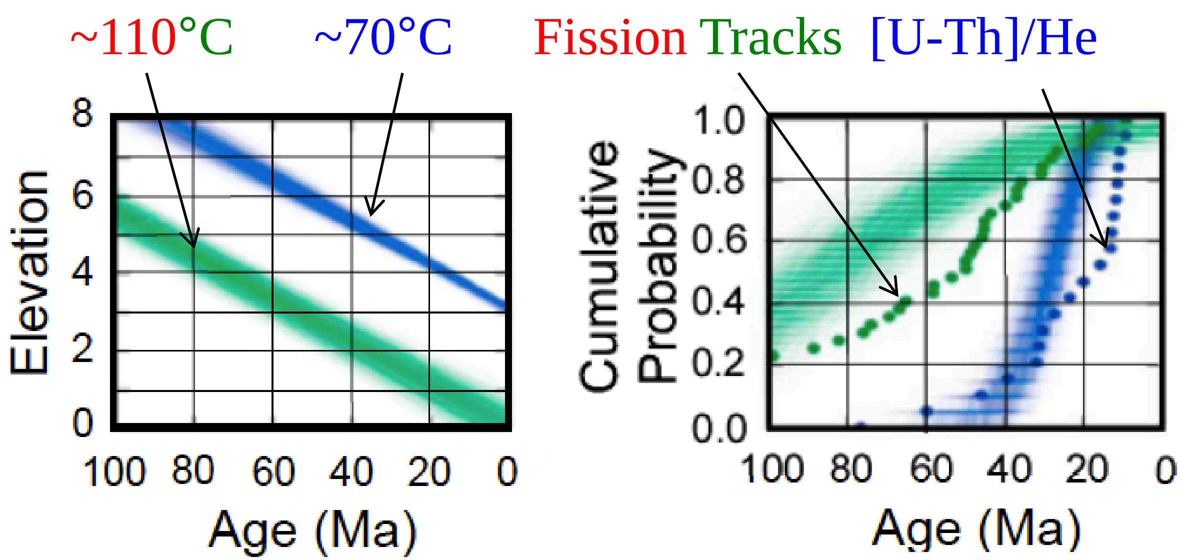
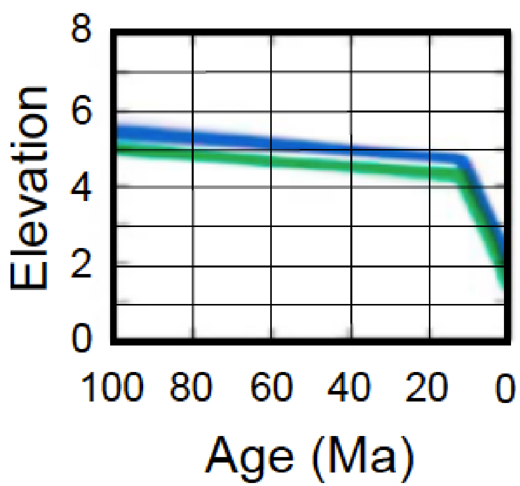


Steady cooling



Abrupt increase in cooling rate



[Duvall, Clark, Avdeev, Farley, and Chen, *Tectonics*, 2012]

Upper Mekong

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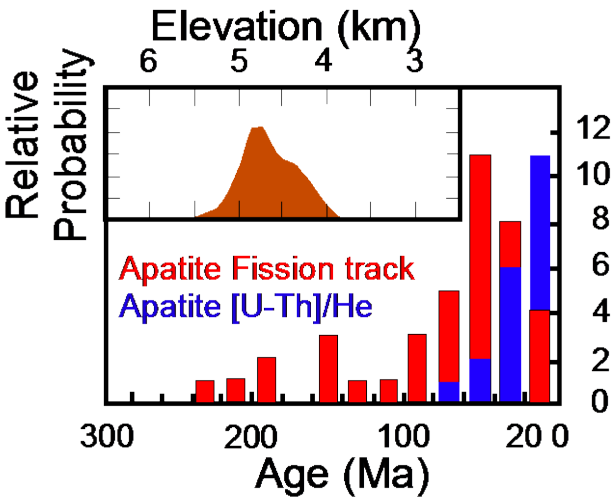
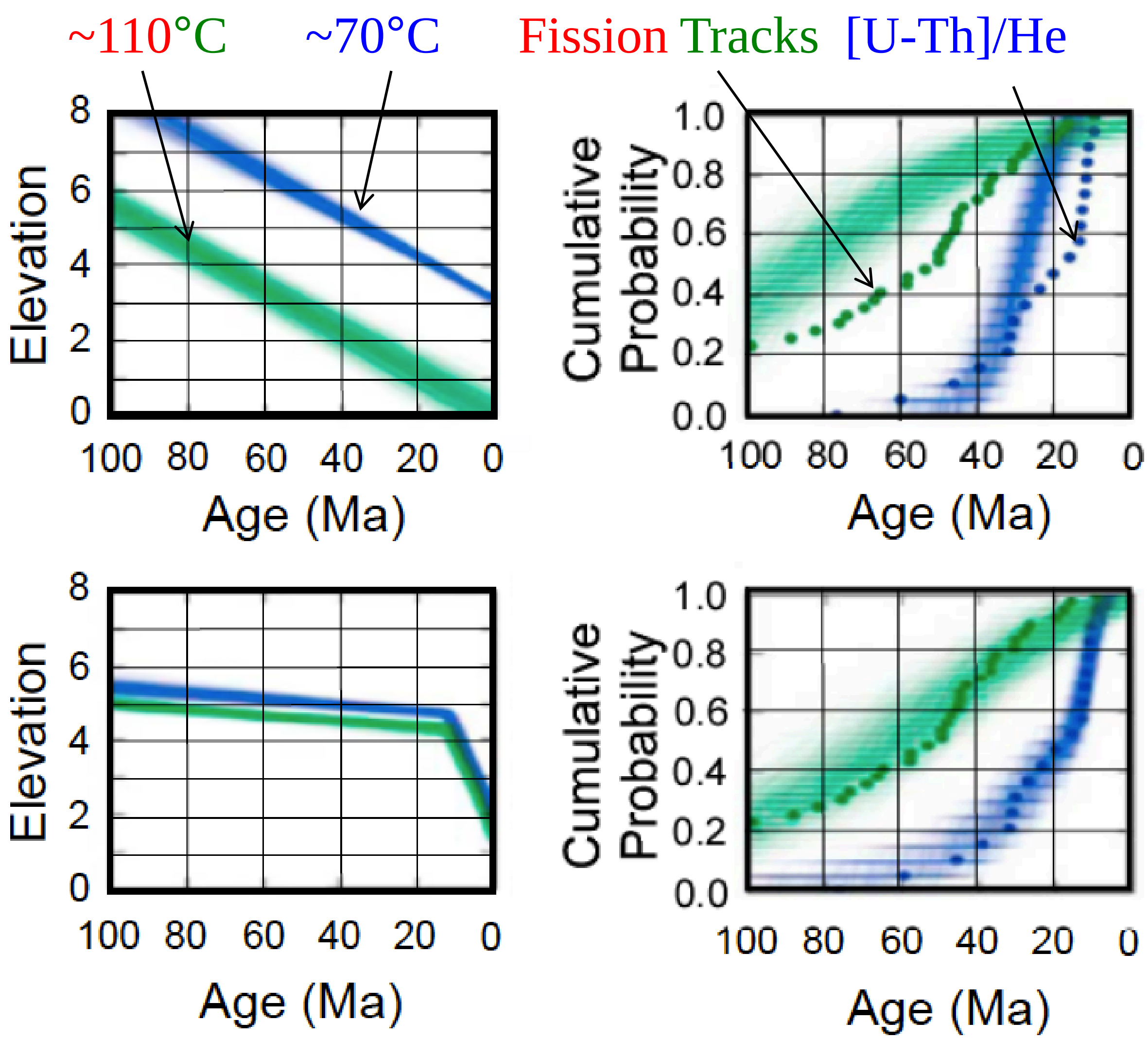


Steady cooling

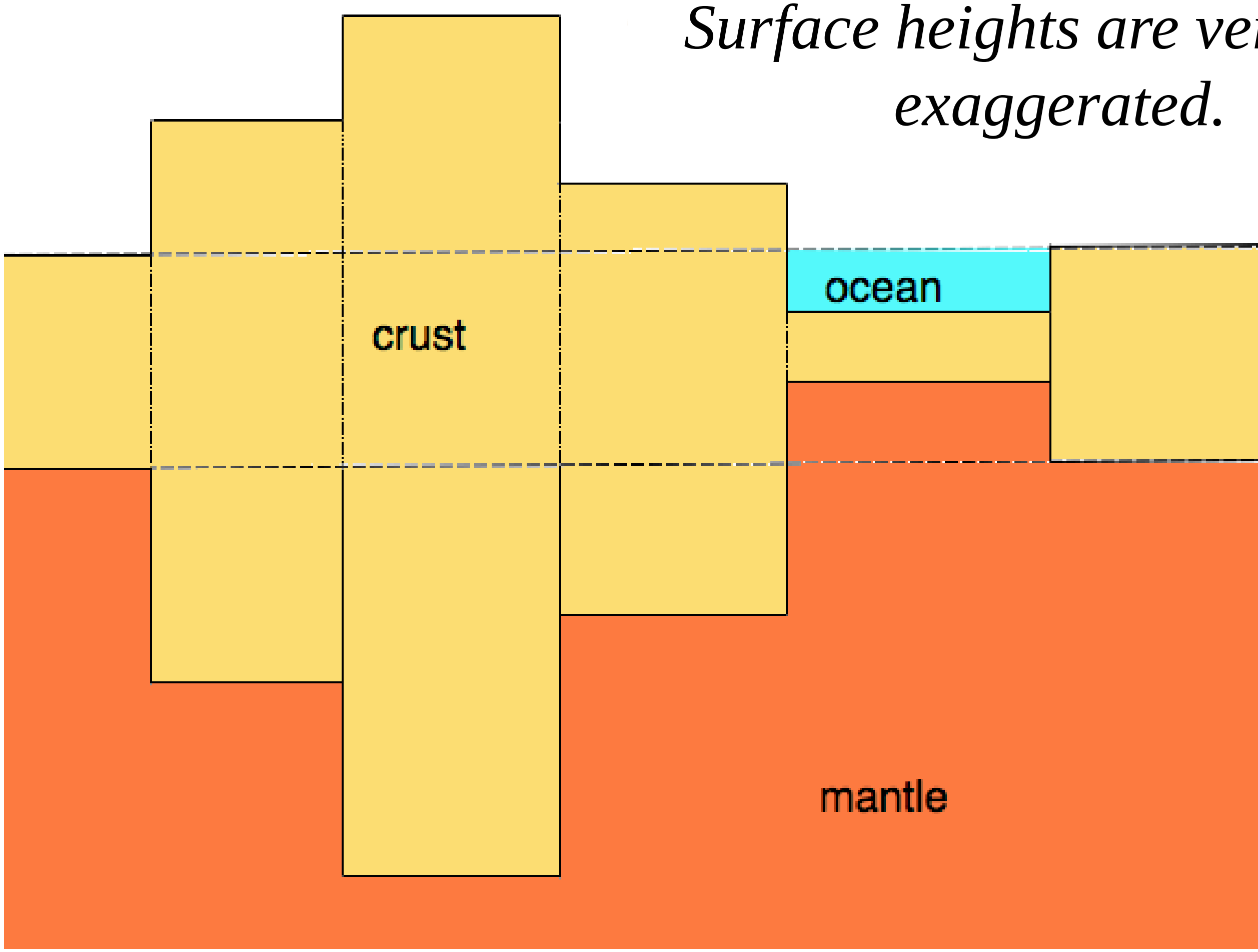
Abrupt increase in cooling rate

[Duvall, Clark, Avdeev, Farley, and Chen, *Tectonics*, 2012]



Isostasy: Archimedes' Principle applied to the Earth's lighter crust over its heavier mantle

Surface heights are vertically exaggerated.



Densities:
Water: 1.0 g/cc
Crust 2.8 g/cc
Mantle 3.3 g/cc

http://deepearthscience.blogspot.com/2013/09/regional-isostasy-supporting-volcano.html

Interim Summary

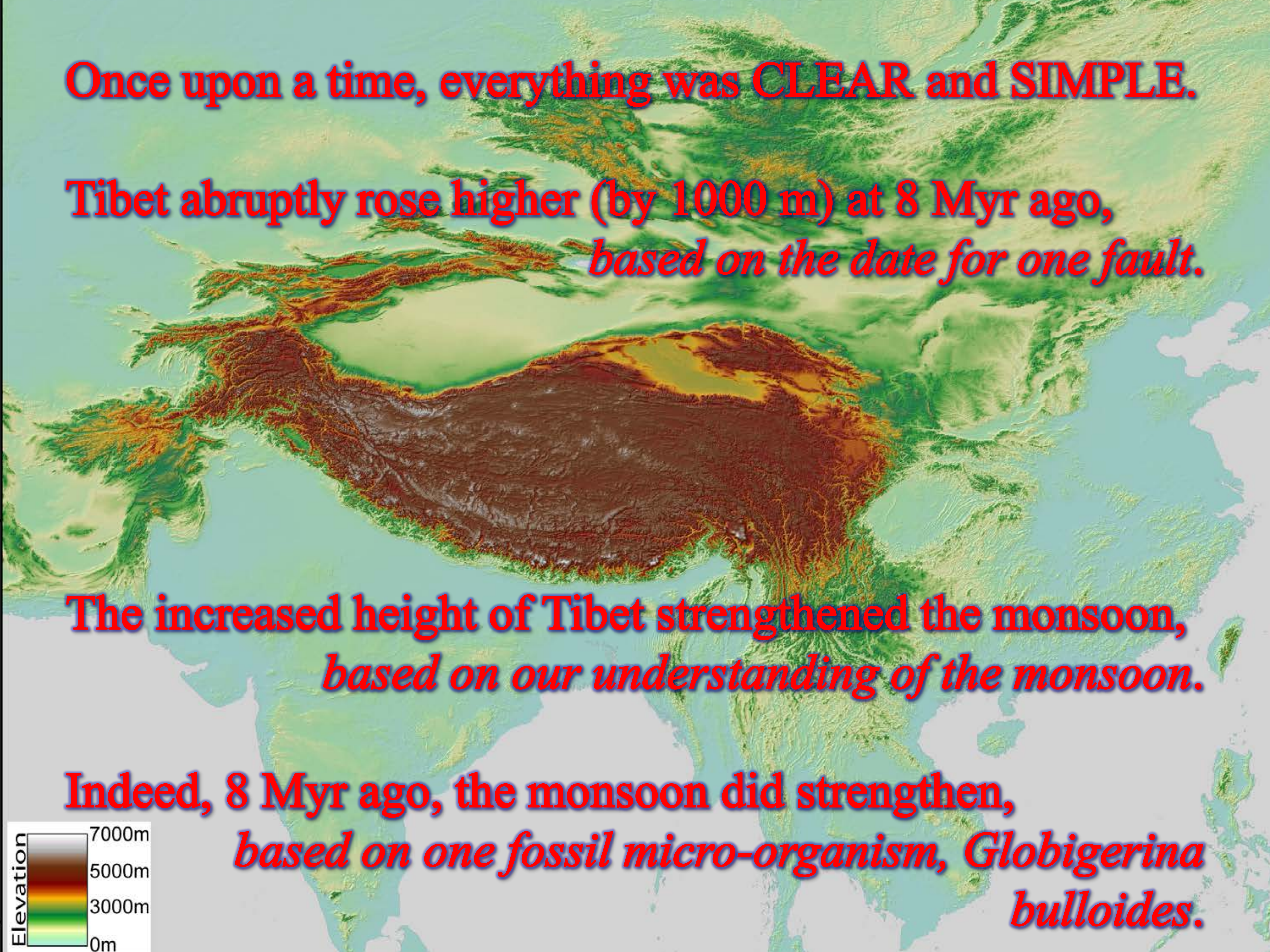
1. High terrain has existed in Asia for > 50 Myr.
2. At ~15-10 Ma, Tibet rose, maybe ~1000 m.
3. Since ~15-10 Ma, high terrain in surrounding regions – Tien Shan, Qilian Shan, Mongolian Altay, etc. – has risen.
4. Since ~15-10 Ma, the surface of the Tibetan Plateau has dropped ~1000 m (as the E-W dimension of the Plateau has grown wider).

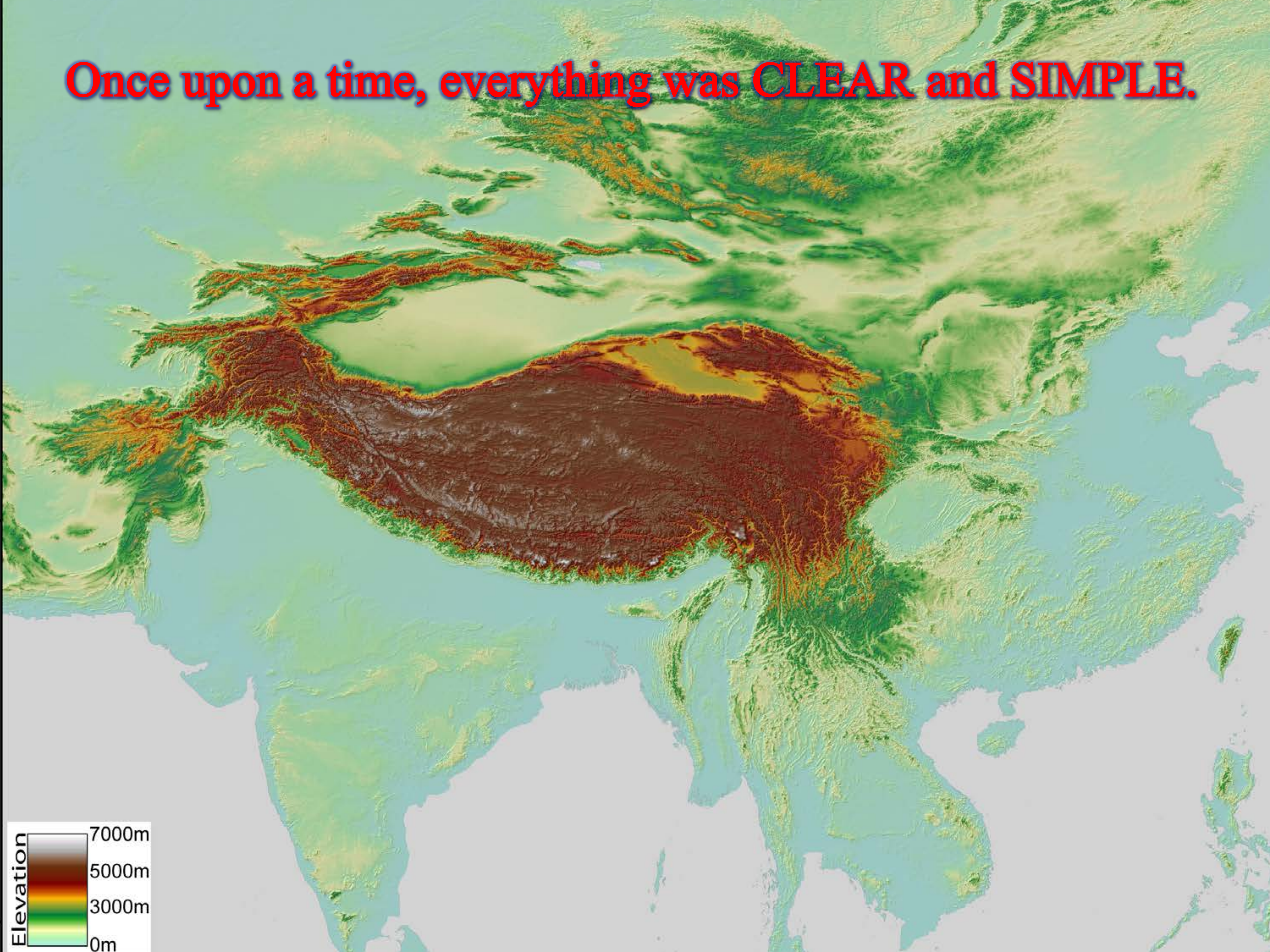
Once upon a time, everything was CLEAR and SIMPLE.

Tibet abruptly rose higher (by 1000 m) at 8 Myr ago,
based on the date for one fault.

The increased height of Tibet strengthened the monsoon,
based on our understanding of the monsoon.

Indeed, 8 Myr ago, the monsoon did strengthen,
based on one fossil micro-organism, Globigerina bulloides.




Once upon a time, everything was CLEAR and SIMPLE.
Elevation
7000m
5000m
3000m
0m

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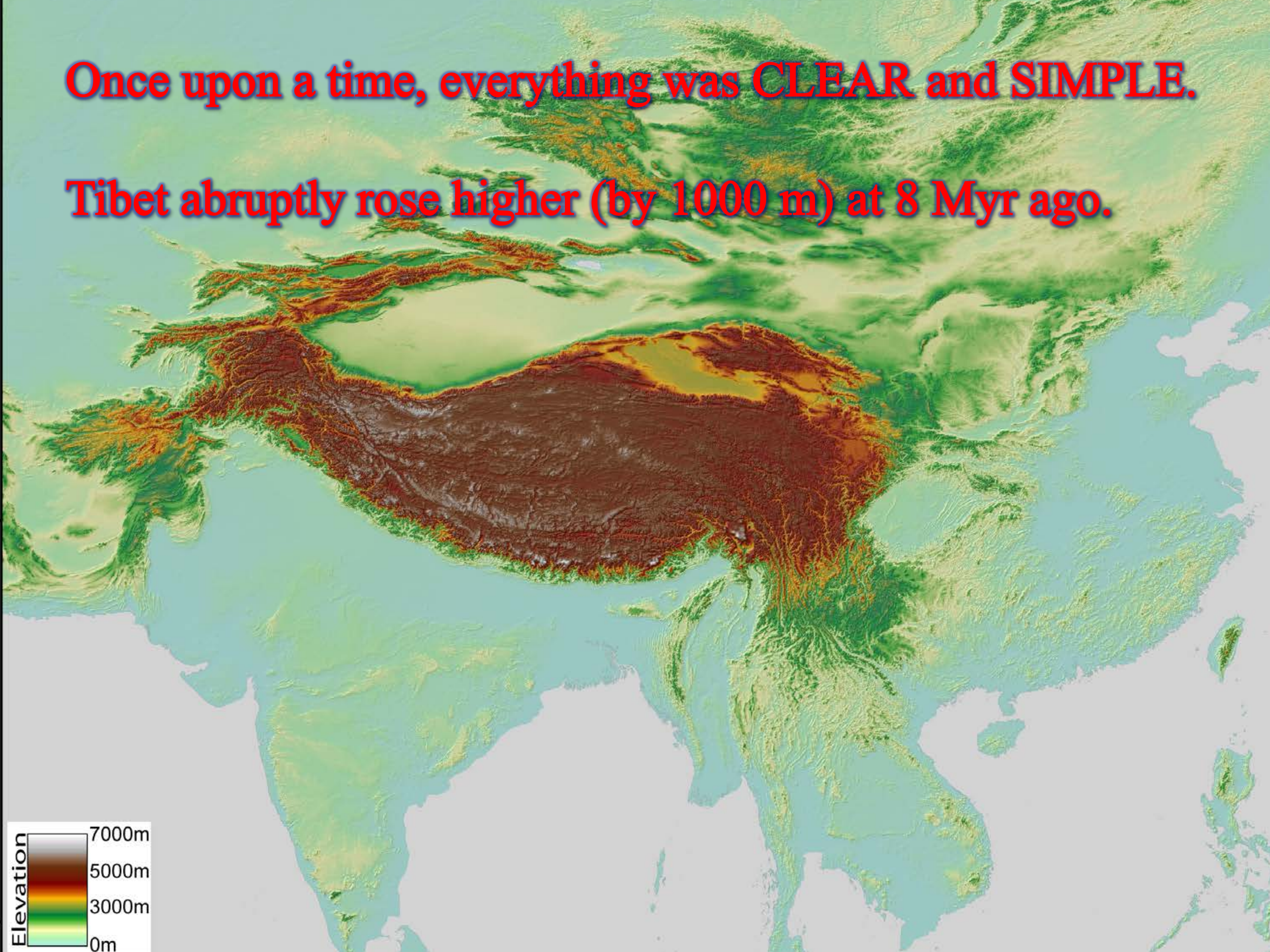

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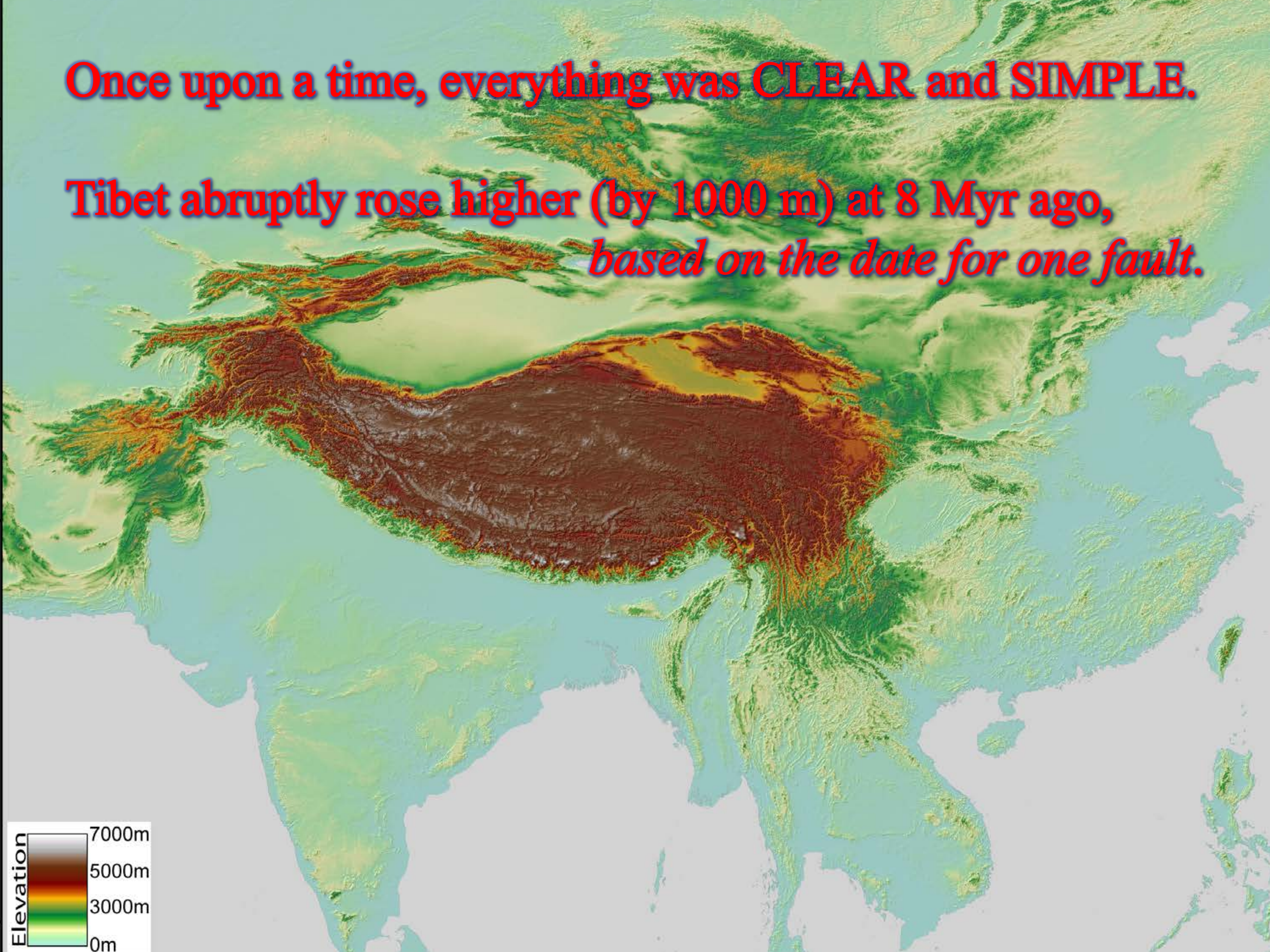

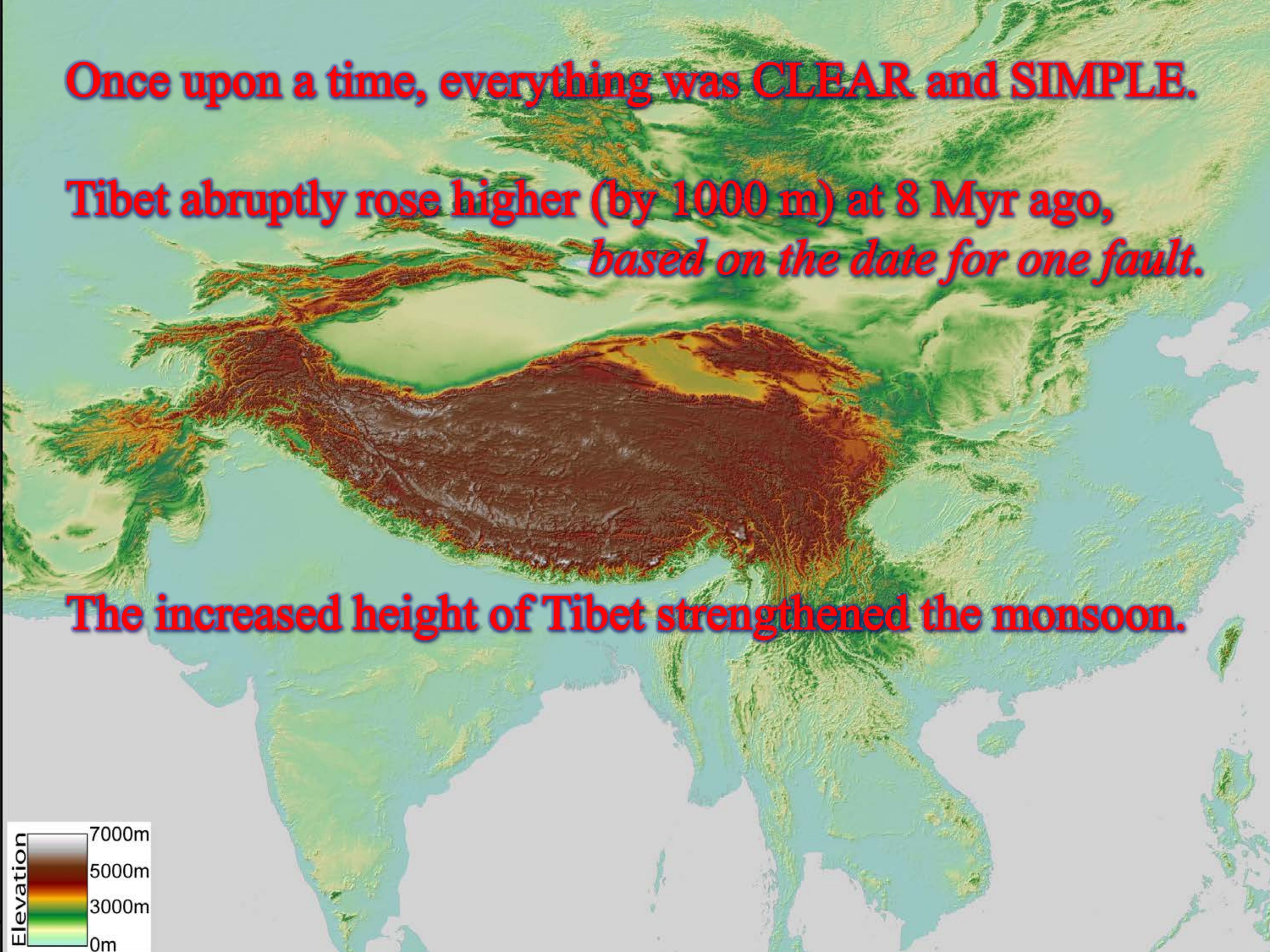
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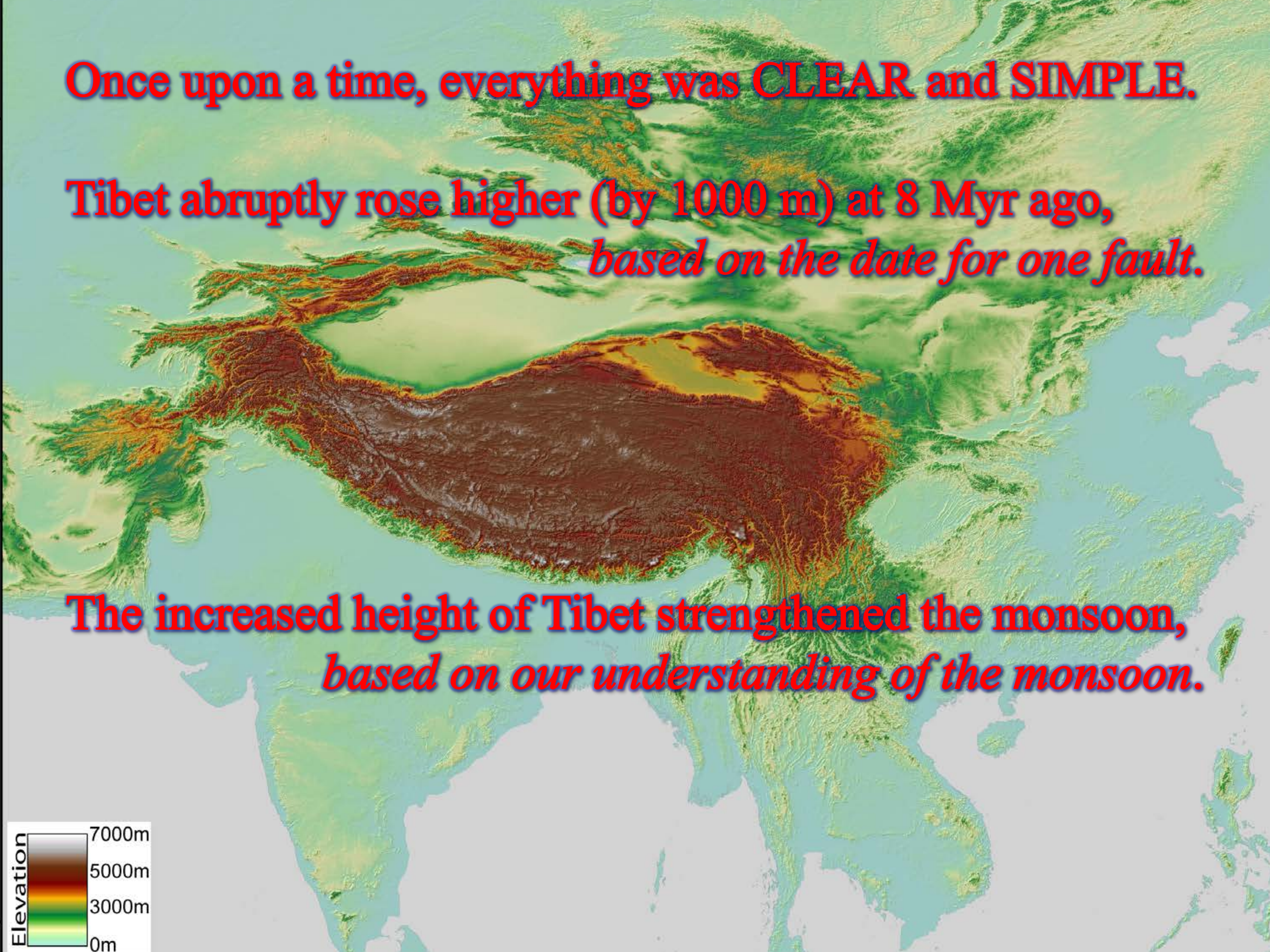
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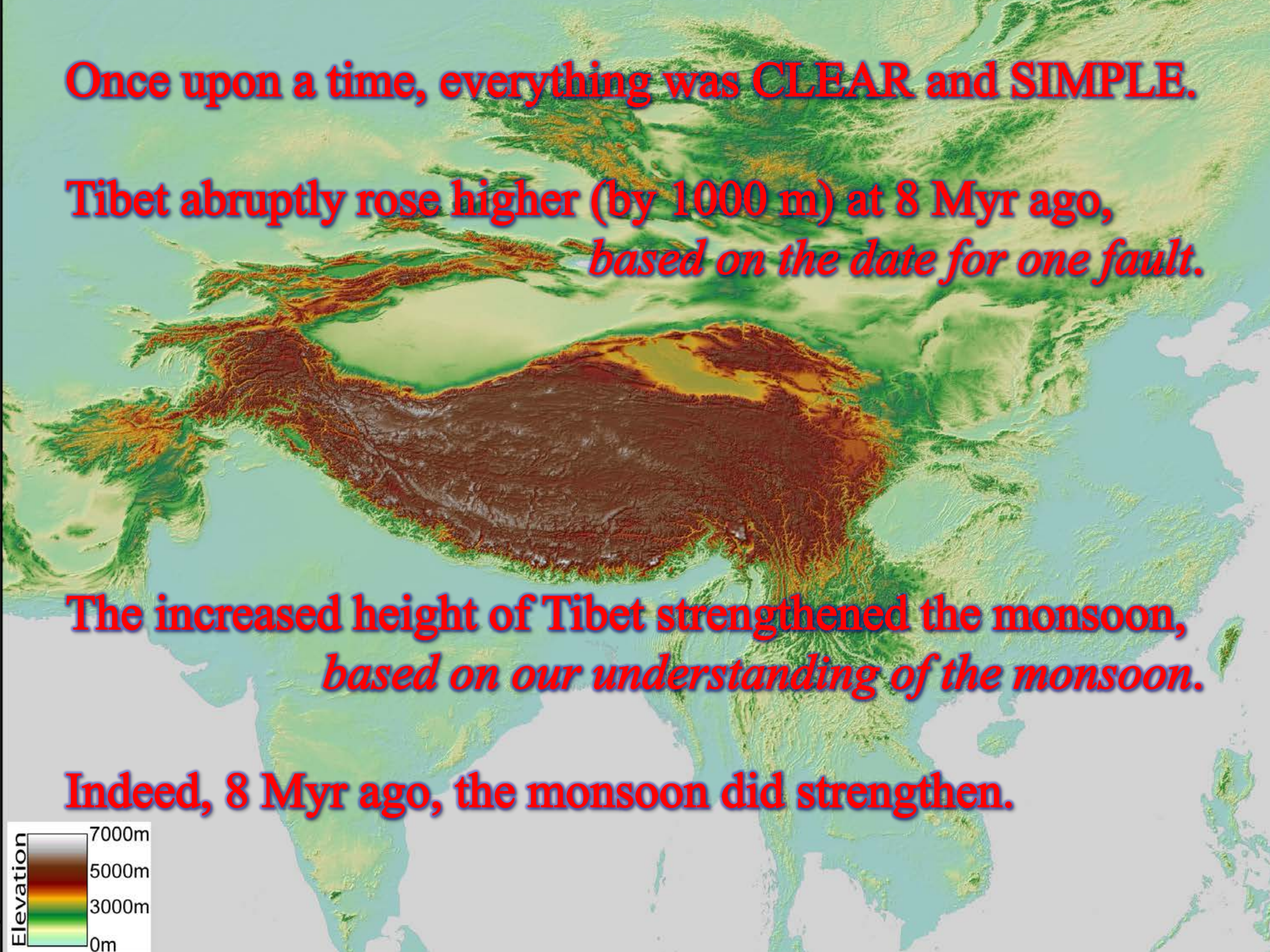

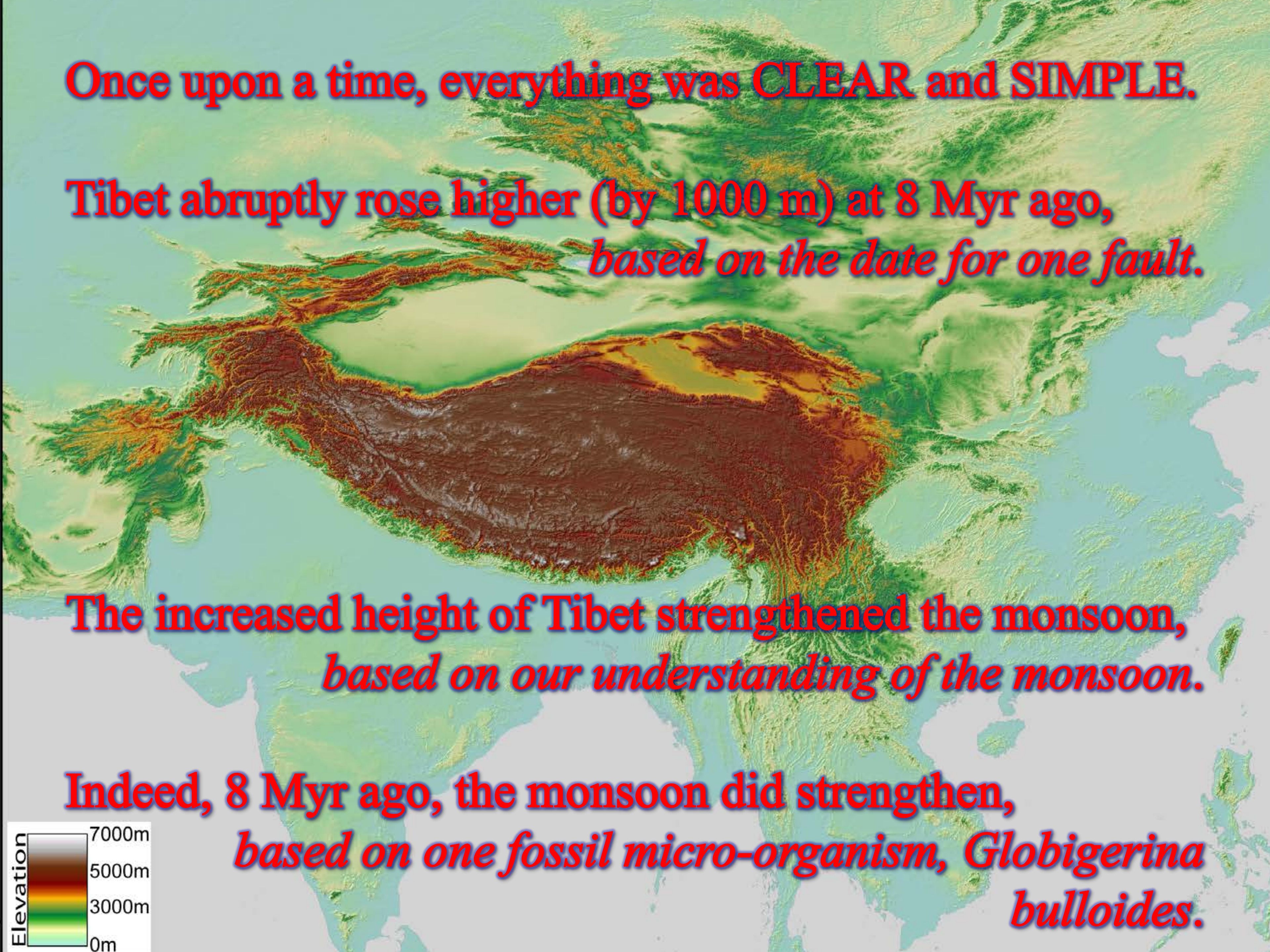

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***based on the date for one fault*.**

The increased height of Tibet strengthened the monsoon,
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Indeed, 8 Myr ago, the monsoon did strengthen,
***based on one fossil micro-organism, Globigerina bulloides*.**

How might Tibet, and its growth, affect climate, and paleoclimate?

1. Monsoon rainfall, in general, over India? ***Weakly***, only in early and late seasons.
2. Loess plateau – dust? *Maybe, but **only** via a **geodynamic teleconnection**.*
3. Rainfall (aridification) over NW India? Maybe, and if so, *via a **Gill-Model teleconnection***. But, this means the monsoon (*sensu lato*) became weaker, not stronger, at ~10 Ma.