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The Tectonic Evolution of the Central Andean Plateau and Geodynamic Implications for the Growth of Plateaus

Carmala Garzione,

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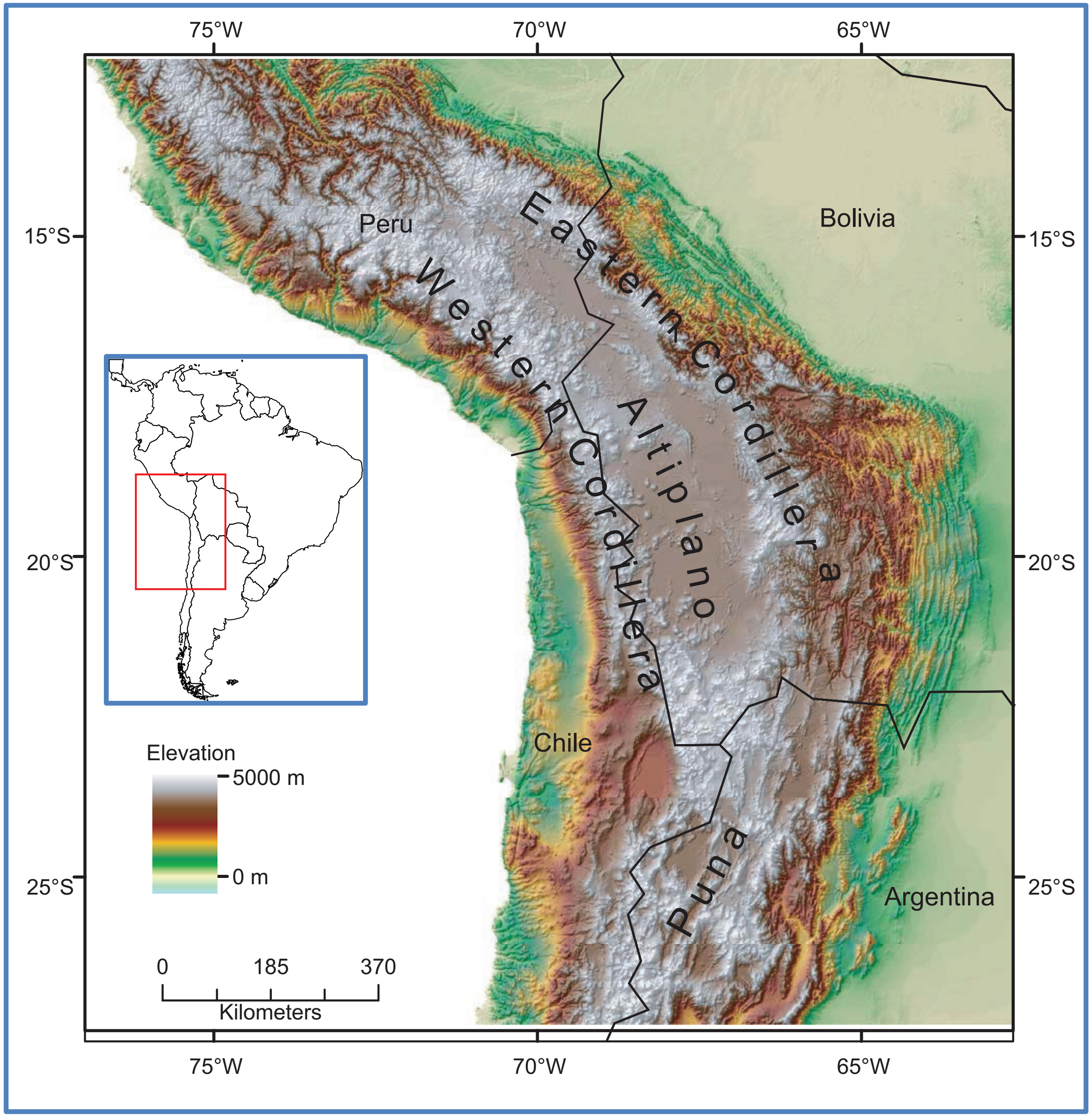
Collaborators:

CAUGHT Continental Dynamics project team Susan L. Beck (U Arizona), Alan D. Chapman (Macalester), Mihai N. Ducea (U Arizona), Todd. A. Ehlers (U Tubingen), Nathan Eichelberger (StructureSolver LLC), Brian K. Horton (UT Austin), Nandini Kar (Wash U), Richard O. Lease (USGS Anchorage), Nadine McQuarrie (U Pittsburgh), Nicholas D. Perez (Texan A&M), Christopher J. Poulsen (U Michigan), Joel E. Saylor (U Houston), Lara S. Wagner (DTM Carnegie Inst), Kevin M. Ward (U Utah), George Zandt (U Arizona)

Acknowledgements:
NSF Tectonics & Continental Dynamics programs

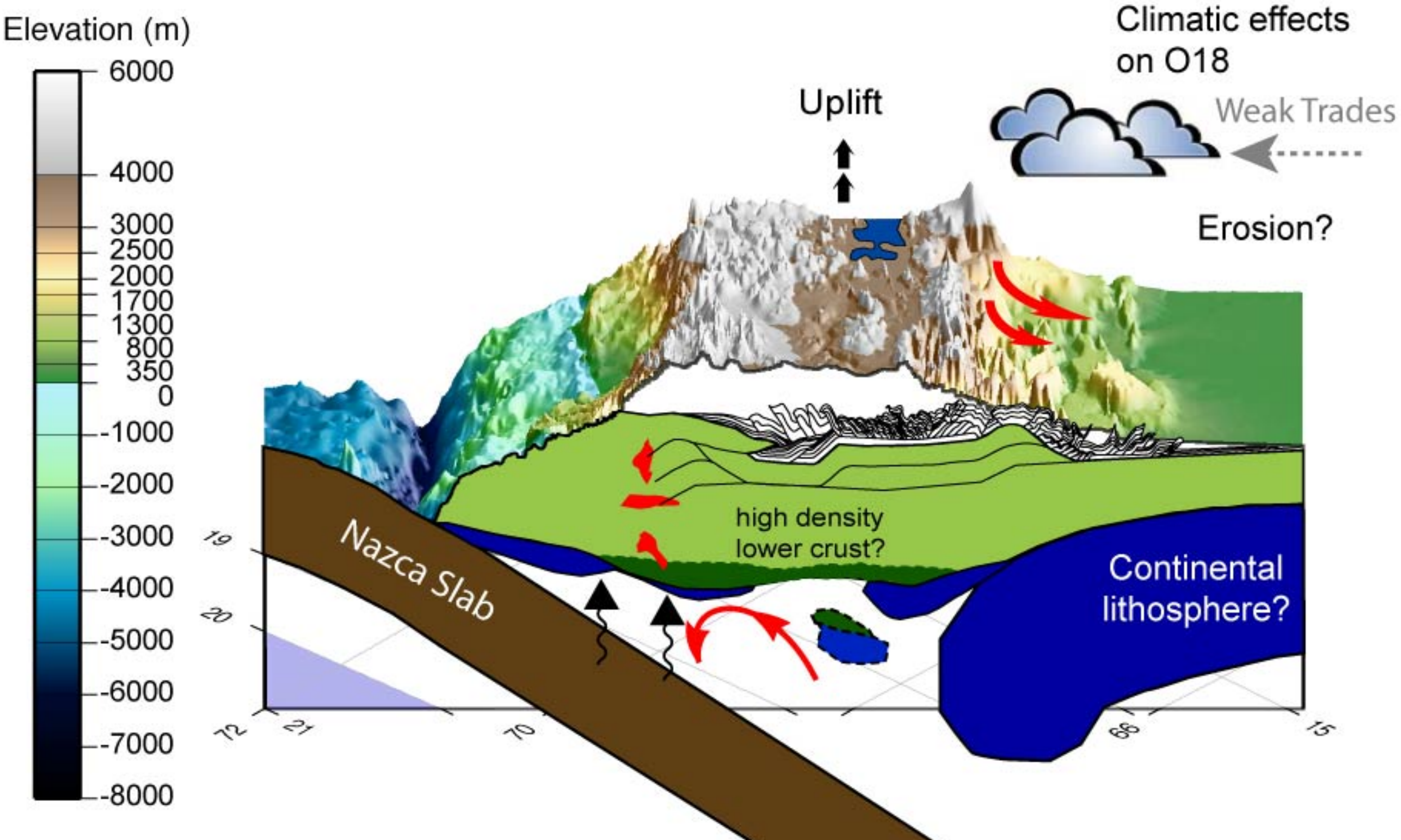
Geologic Setting



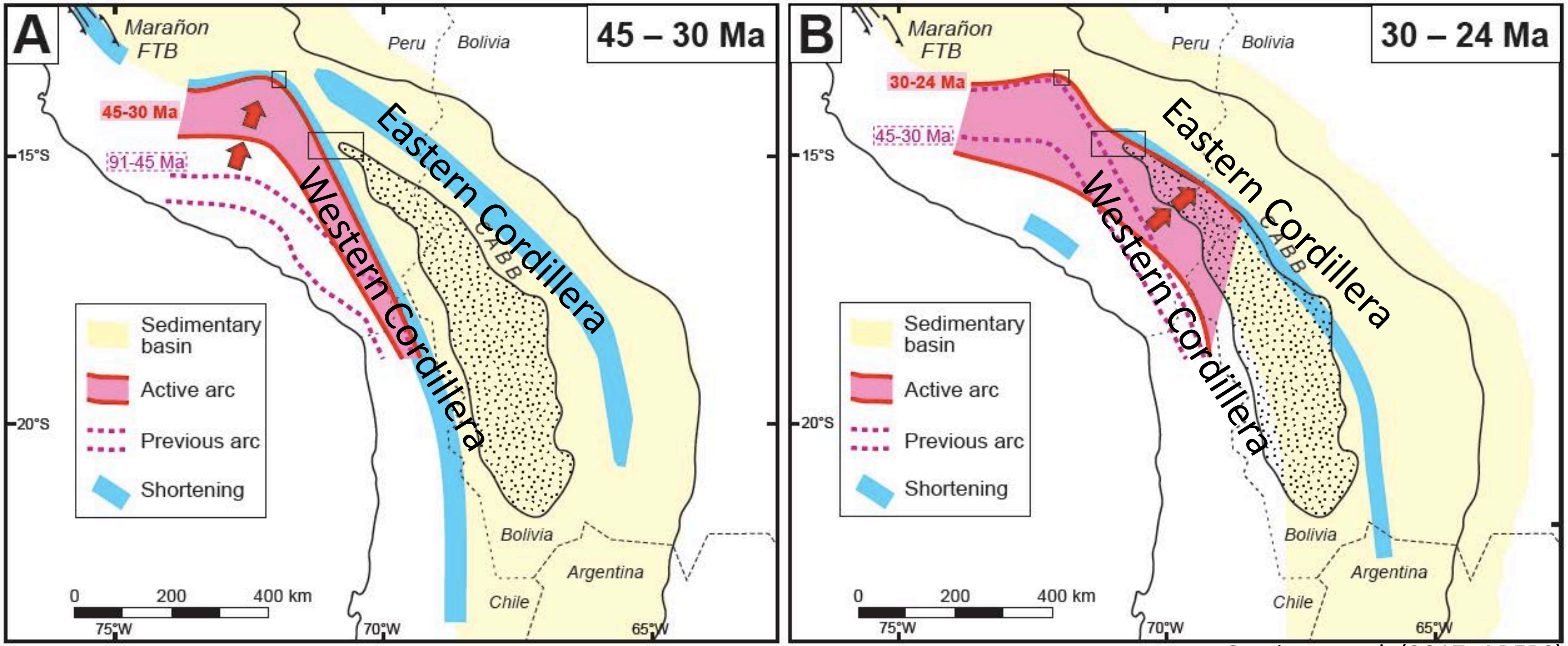
- Altiplano: internally drained with low relief topography and an average modern elevation of ~4km
- Altiplano region: Overlies a zone of normal subduction (~30° dip) of Nazca plate between two zones of flat slab subduction

Key Questions in the Central Andes

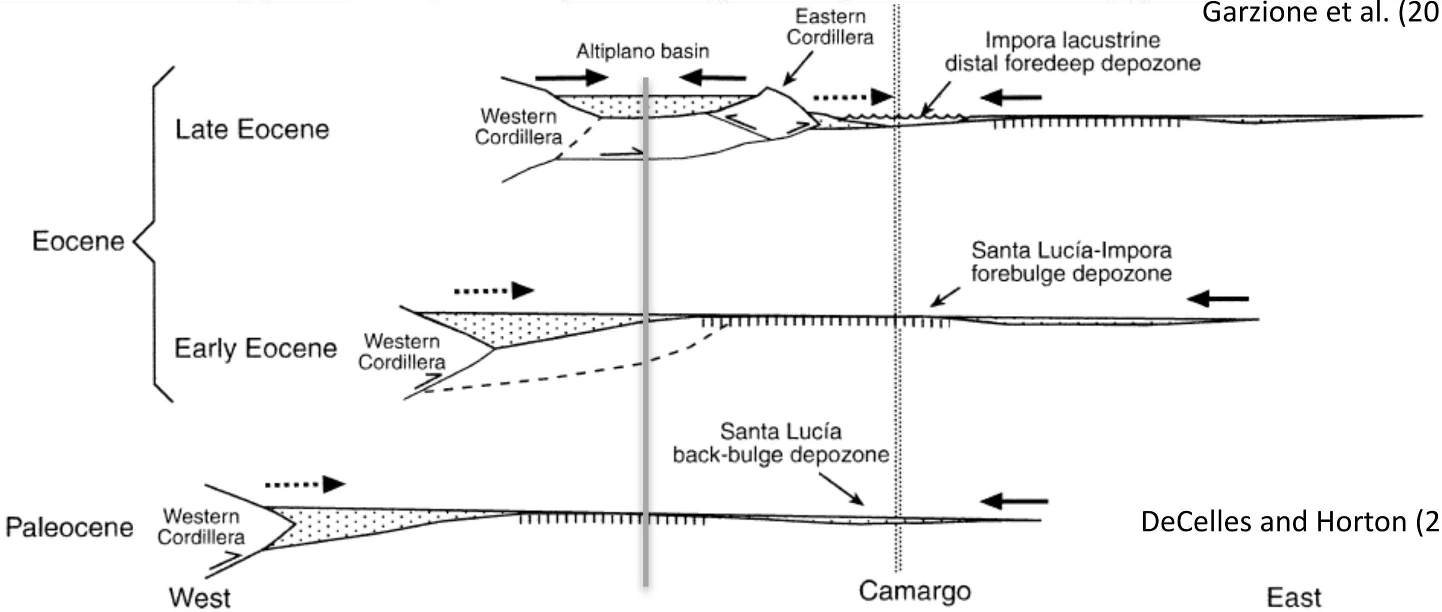
- Geodynamic processes for building the Andean plateau?
  - Long-term crustal shortening/thickening causes gradual isostatic surface uplift
  - Isostatic surface uplift by magmatic addition
  - Surface uplift by delamination/convective removal of dense lower lithosphere
  - Redistribution of crustal material by mid to lower crustal flow



Altiplano basin evolution



Garzione et al. (2017, AREPS)



DeCelles and Horton (2003, GSAB)

Western Cordillera

Altiplano – Corque section

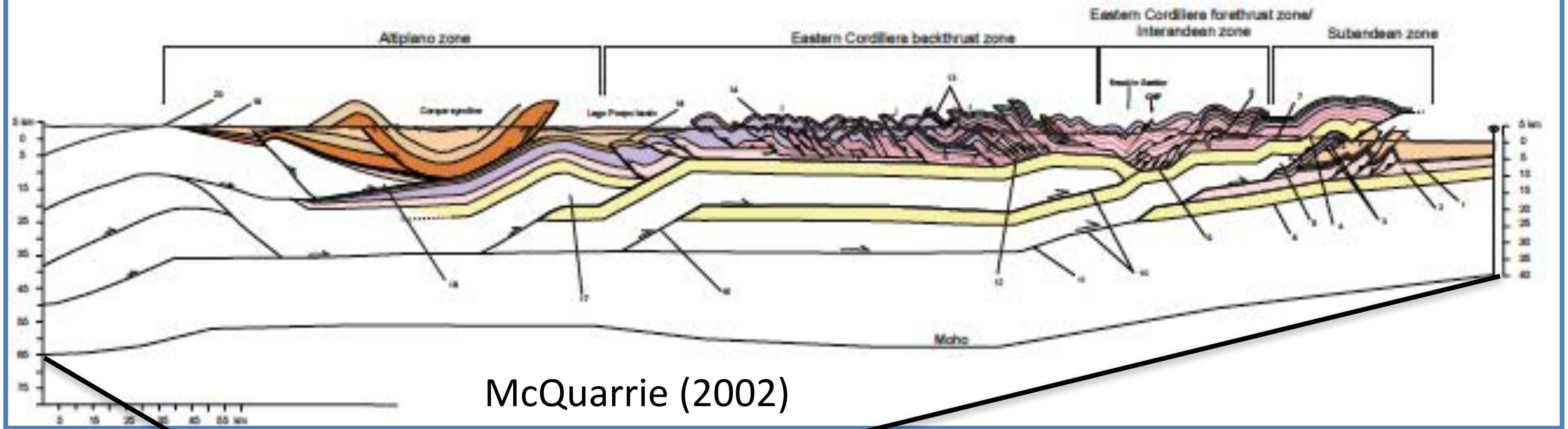
Eastern Cordillera – Salla Formation

End Member Model I

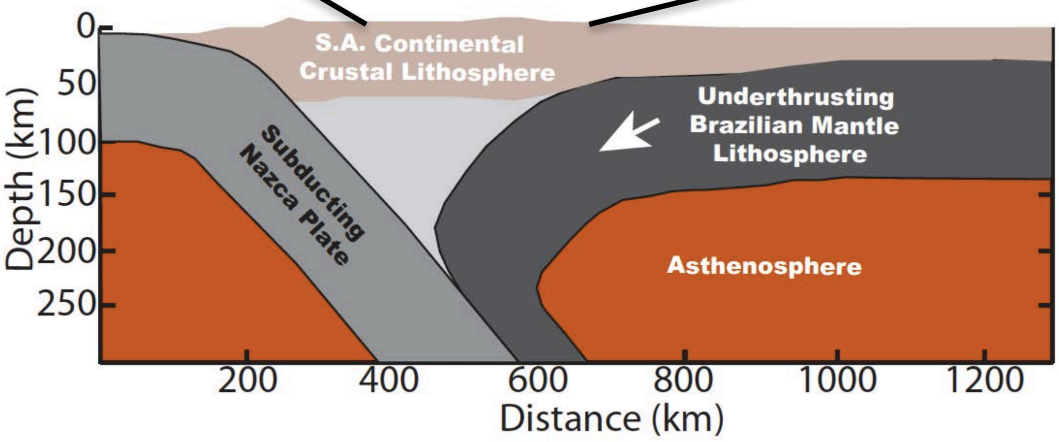
Slow and Gradual Surface Uplift

Surface uplift rates = 0 to 0.25 mm/yr

Crustal thickening/continuous subduction of foreland lithosphere



McQuarrie (2002)



Garzione et al. (2017, AREPS)

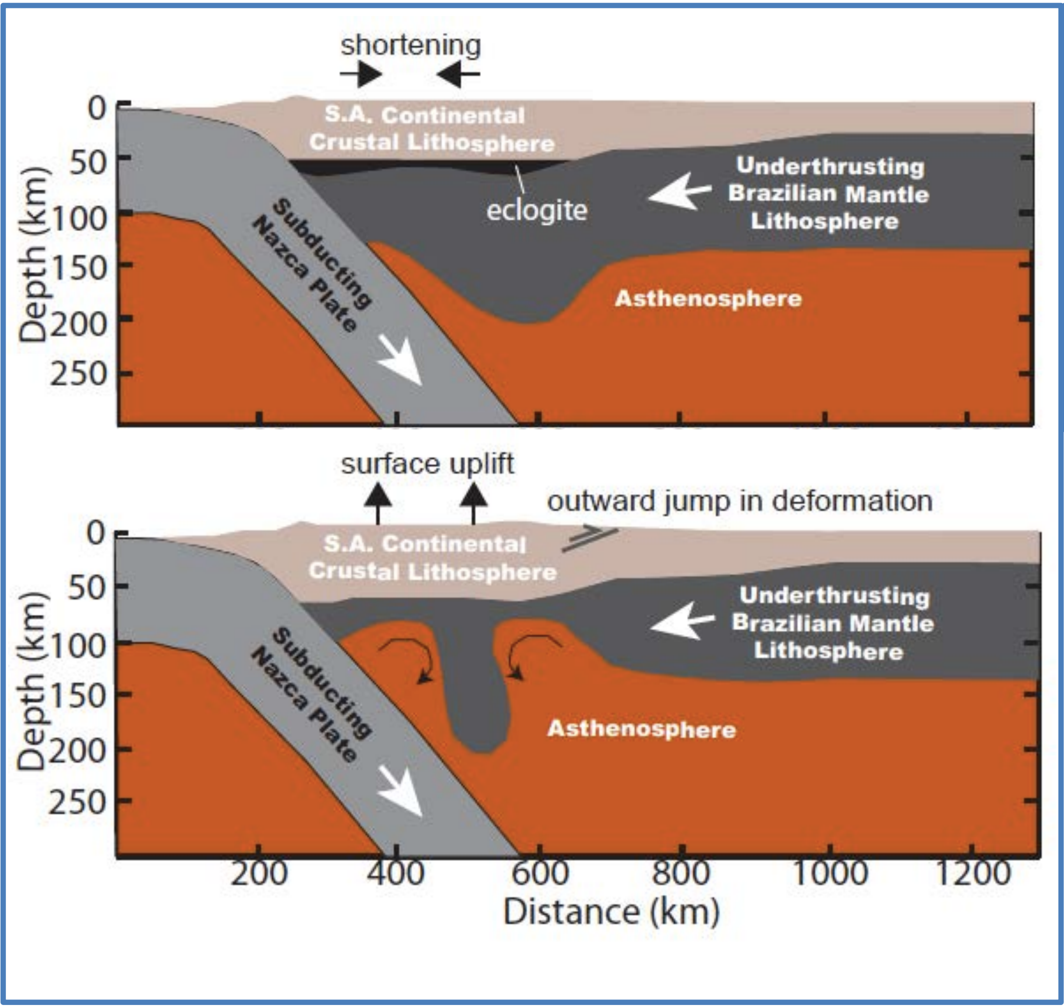
- **MECHANISMS:** Crustal Crustal shortening, Ablative subduction
- **PREDICTIONS:** deformation coupled with surface uplift

End Member Models II

Rapid Pulses of Surface Uplift

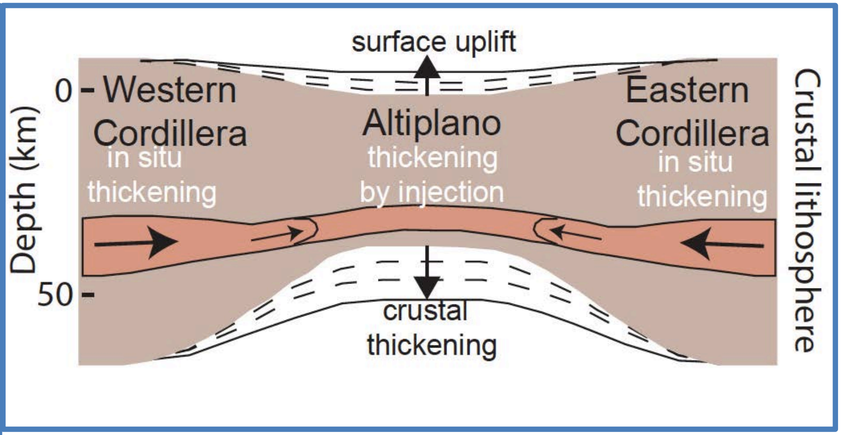
Surface uplift rates >0.4 mm/yr

Removal of lower lithosphere



Garzione et al. (2017, AREPS)

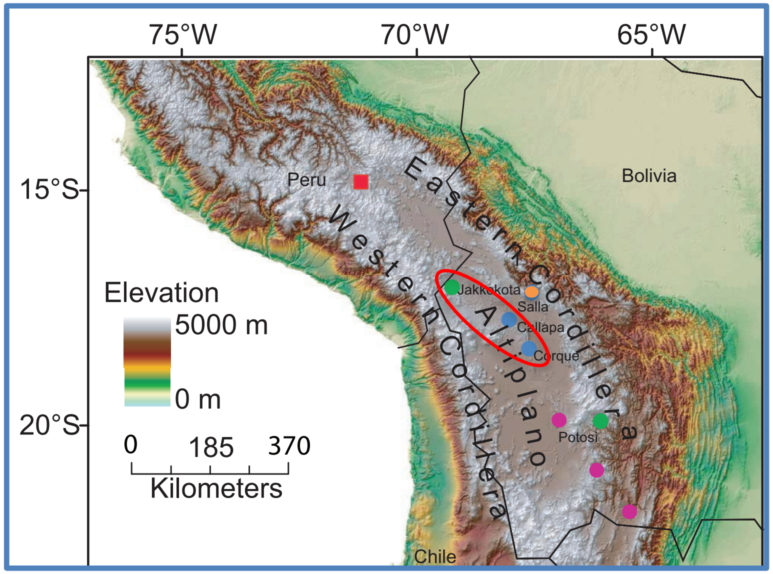
Lower crustal flow



modified from Husson and Sempere, 2003

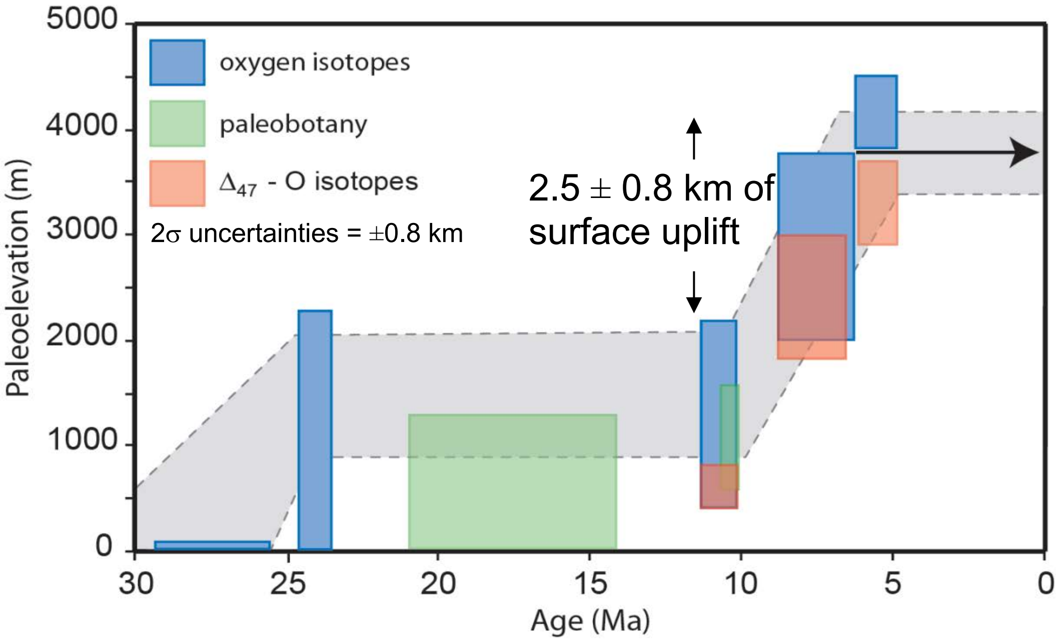
- **MECHANISMS:** Removal of dense lower lithosphere, lower crustal flow
- **PREDICTIONS:** Decoupled deformation and surface uplift

End Member Model II



Rapid Surface Uplift

- Decoupled deformation and surface uplift
- Proposed Mechanisms: Removal of dense lower lithosphere and/or lower crustal flow



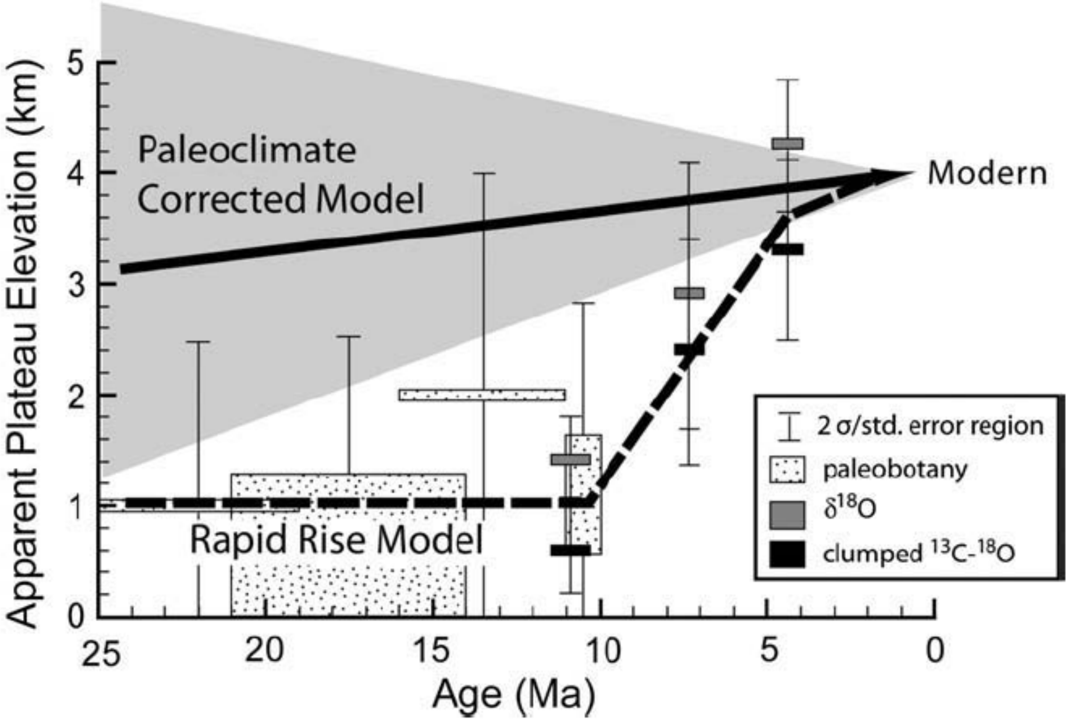
Large magnitude surface uplift of the central Altiplano between 10 and 6 Ma.

Garzione et al. (2006, EPSL; 2008, Science); Ghosh et al. (2006, Science)
Paleobotany: Gregory-Wodzicki (2000)

DEBATE: End Member Model I

Slow and Gradual Surface Uplift

Surface uplift rates = 0 to 0.25 mm/yr

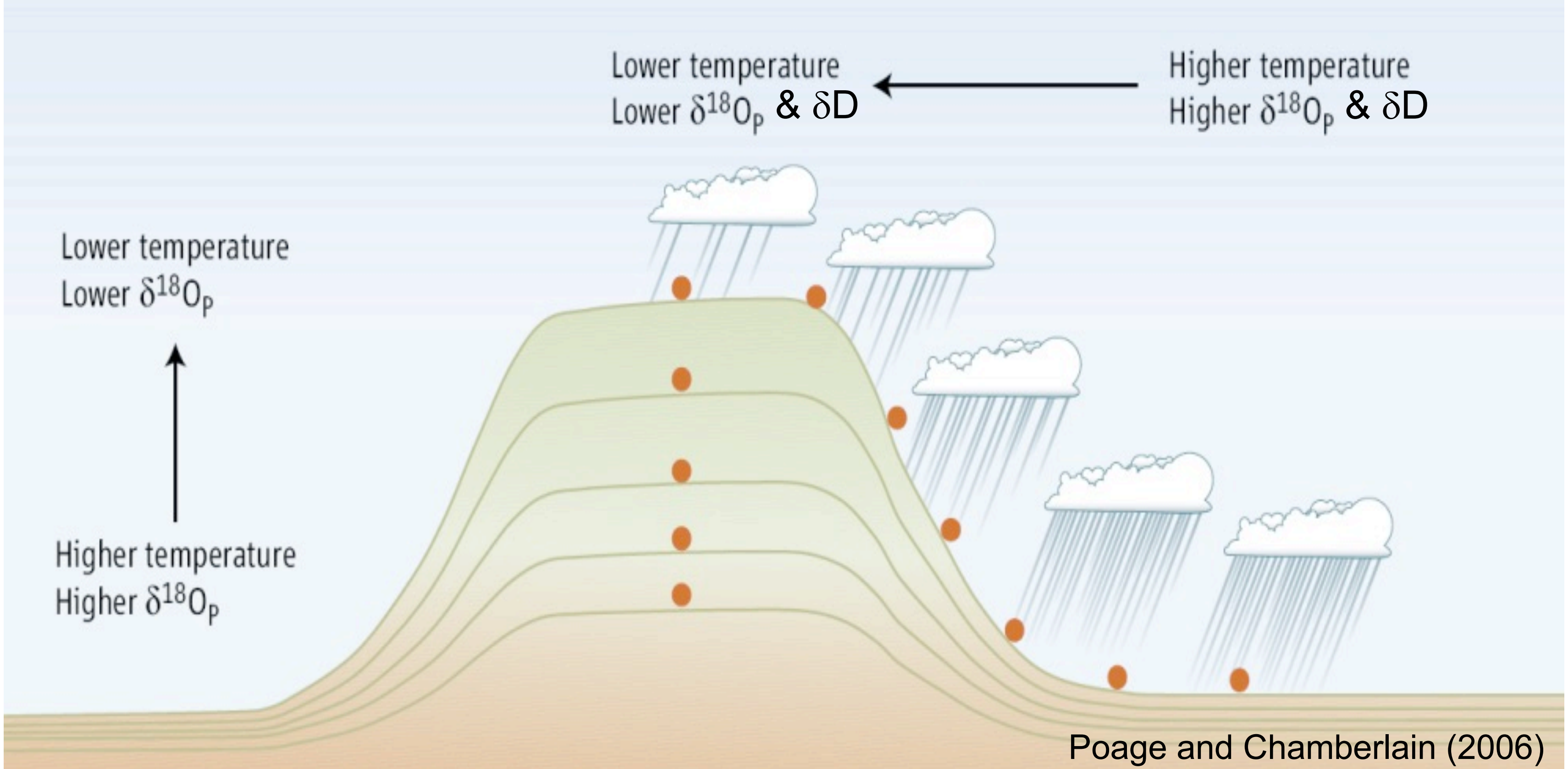


Used climate modeling to show that surface uplift of the Andes causes non-linear cooling of land surface and increase in convective rainfall. Argued that gradual surface uplift is permissible with our data.

- **MECHANISMS:** Crustal shortening, Ablative subduction
- **PREDICTIONS:** deformation coupled with surface uplift

Ehlers and Poulsen (2009, EPSL); Poulsen et al. (2010, Science)

Sedimentary deposits record $\delta^{18}O$ and T of surface water: Used to quantify paleoelevations

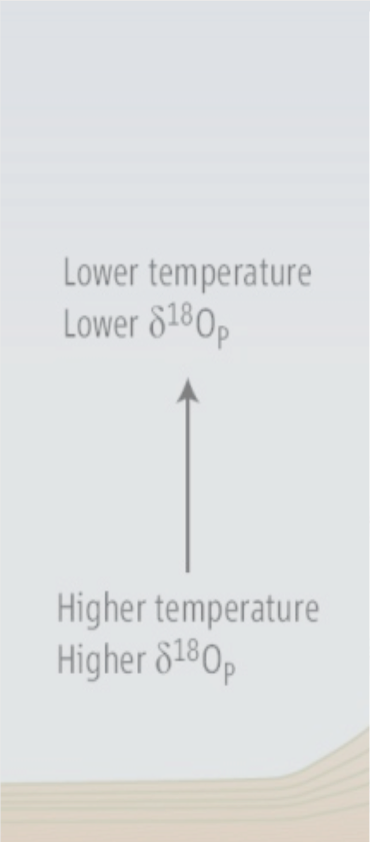


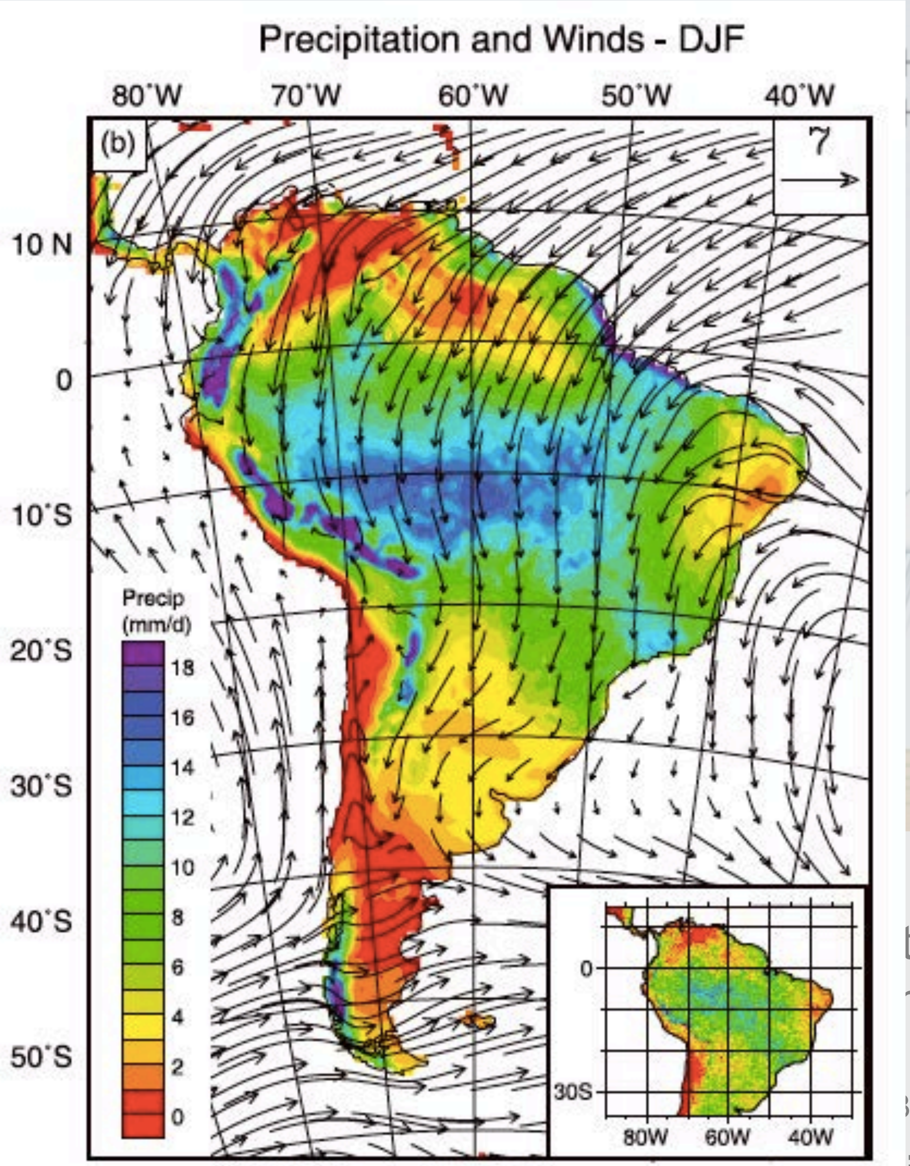
Poage and Chamberlain (2006)

Stable isotope paleoelevation estimates:

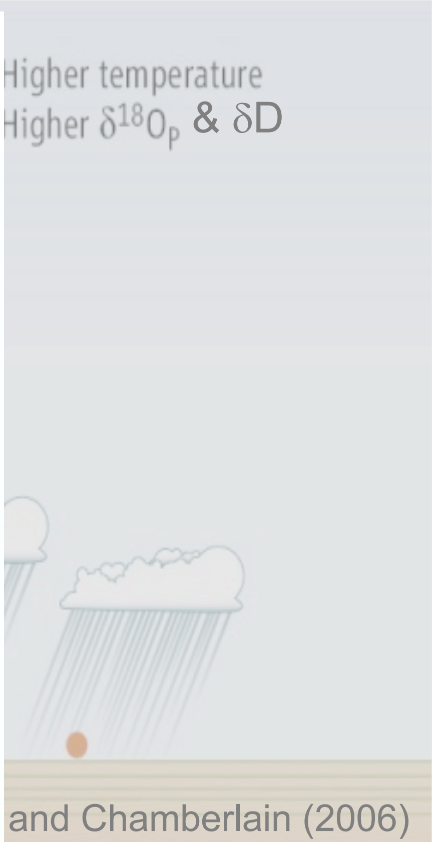
- Ghosh et al. (2006) – ^{13}C-^{18}O clumped isotope thermometer compared paleotemperature and $\delta^{18}O_{mw}$ from authigenic calcite to modern T - $\delta^{18}O_{mw}$ vs. altitude gradients
- Garzione et al. (2006) – $\delta^{18}O$ paleoaltimetry compared $\delta^{18}O_{mw}$- δD_{mw} from authigenic calcite to modern $\delta^{18}O$ vs. altitude gradient

Sedimentary deposits record $\delta^{18}O$ and T of surface water: **Used to quantify Paleoelevations**





Insel et al. (2013)

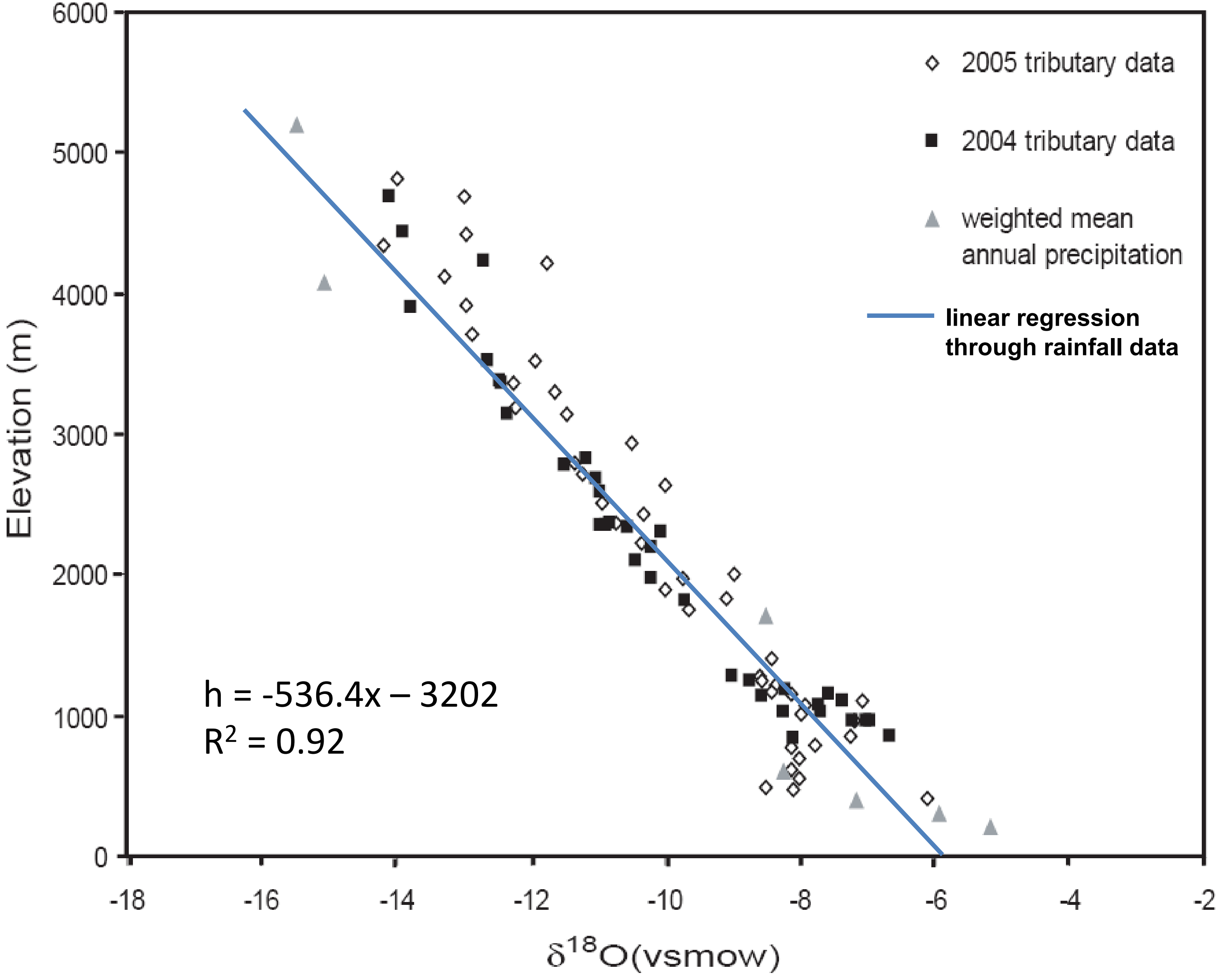


and Chamberlain (2006)

Stable isotope

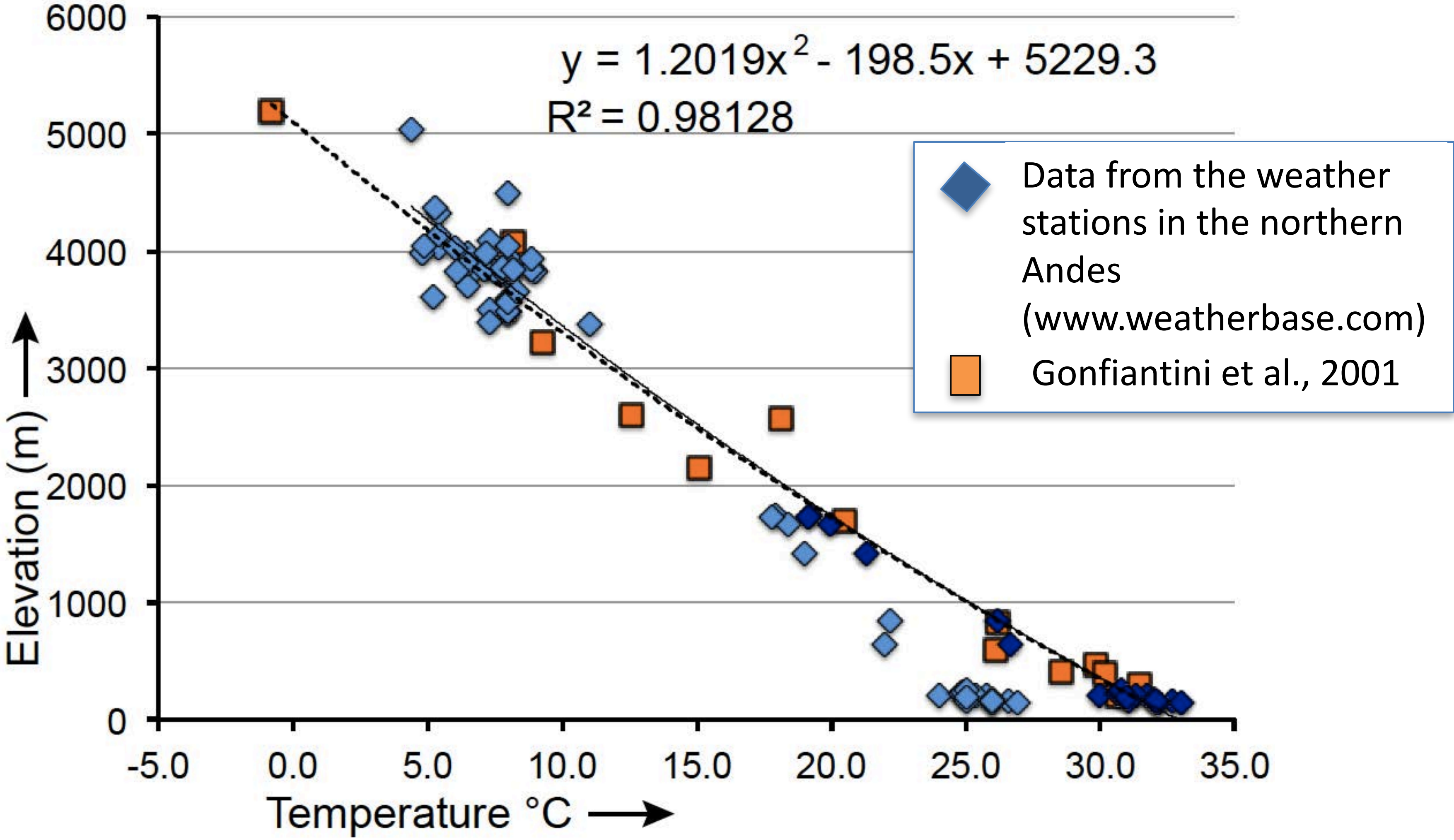
- Ghosh et al. (2 ter compared paleotemperat nodern T - $\delta^{18}O_{mw}$ vs. altitude gra
- Garzione et al. O_{mw}- δD_{mw} from authigenic calc ient

$\delta^{18}O$-Altitude Relationship of Meteoric Waters



data from Gonfiantini et al. (2001); Garzione et al. (2007); Bershaw et al. (2010)

Temperature-Altitude Relationship



Temperature corrected at ≤2 km for warmer conditions under lower Andes scenarios (Ehlers and Poulsen, 2009).

Kar et al. (in review); modified from Garzione et al. (2014)

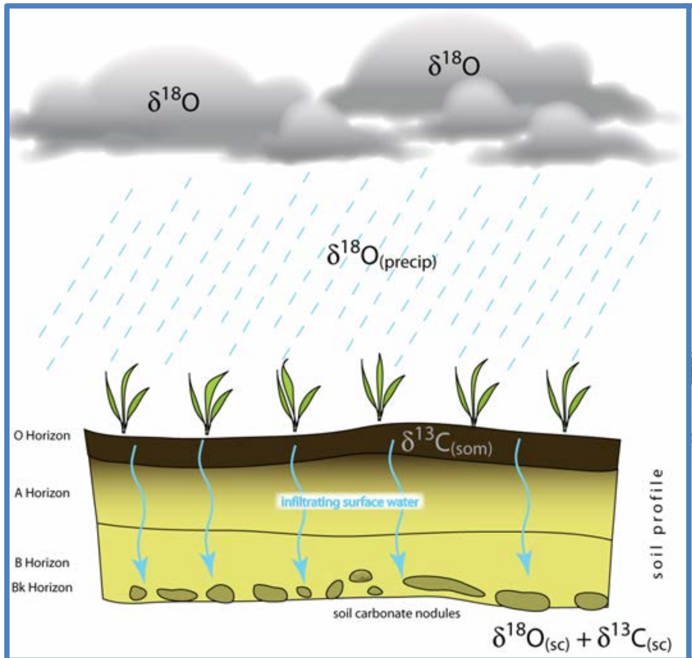
Meteoric Water $\delta^{18}O$

$$\delta^{18}O = \left[\frac{{}^{18}O/{}^{16}O_{sample}}{{}^{18}O/{}^{16}O_{reference}} - 1\right] * 1000 \text{ (per mil)}$$

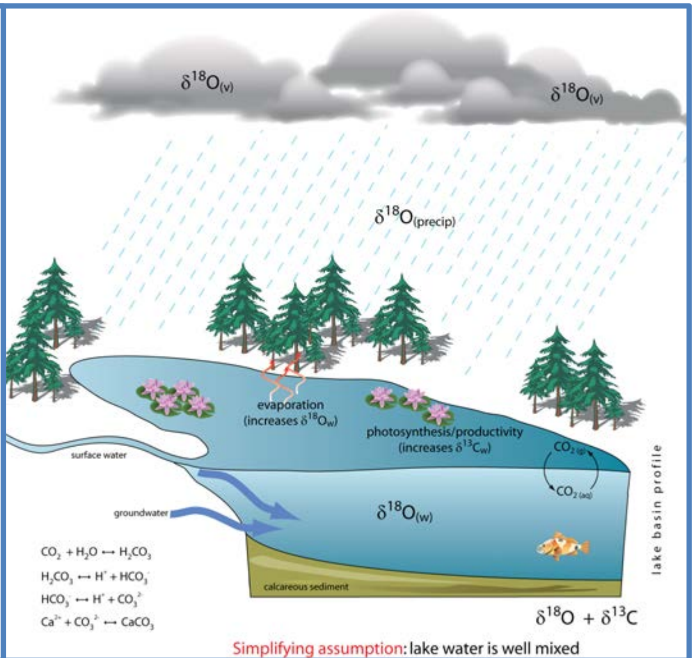
- Sedimentary carbonates: $\delta^{18}O_{carbonate}$ depends on $\delta^{18}O_{\text{meteroric water (mw)}}$, evaporation, and temperature of carbonate precipitation
- Temperature dependent fractionation:

$$1000\ln\alpha_{\text{(Calcite-H20)}} = 18.03\ (10^{3}T^{-1}) - 32.42 \text{ (Kim and O'Neil, 1997)}$$

paleosols

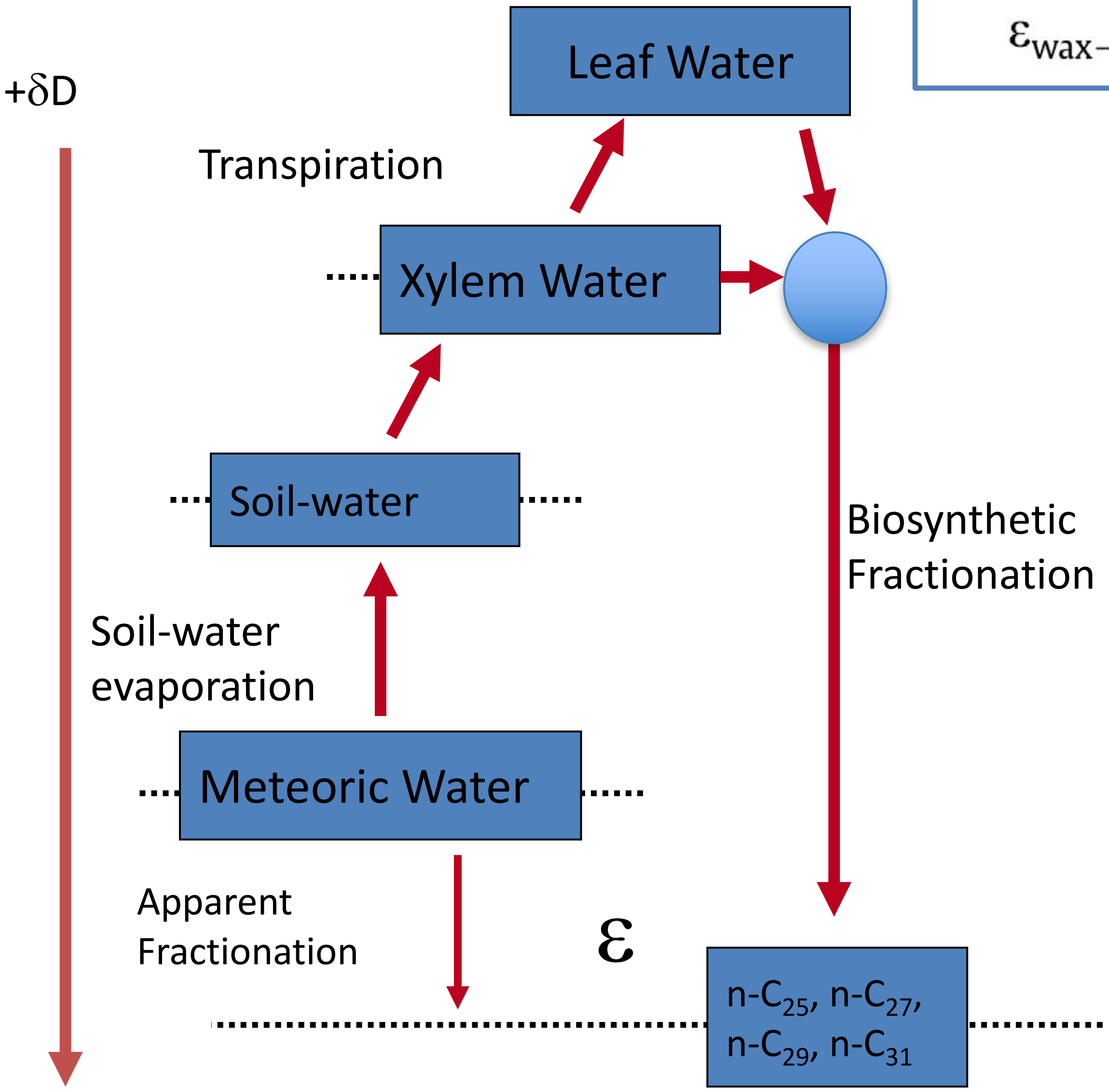


lake carbonates



Plant Waxes: δD of C_{25} to C_{31} n-Alkanes

$$\varepsilon_{wax-p} = (\delta D_{wax} + 1)/(\delta D_p + 1) - 1$$


+δD

Leaf Water

Transpiration

Xylem Water

Soil-water

Soil-water evaporation

Meteoric Water

Apparent Fractionation

Biosynthetic Fractionation

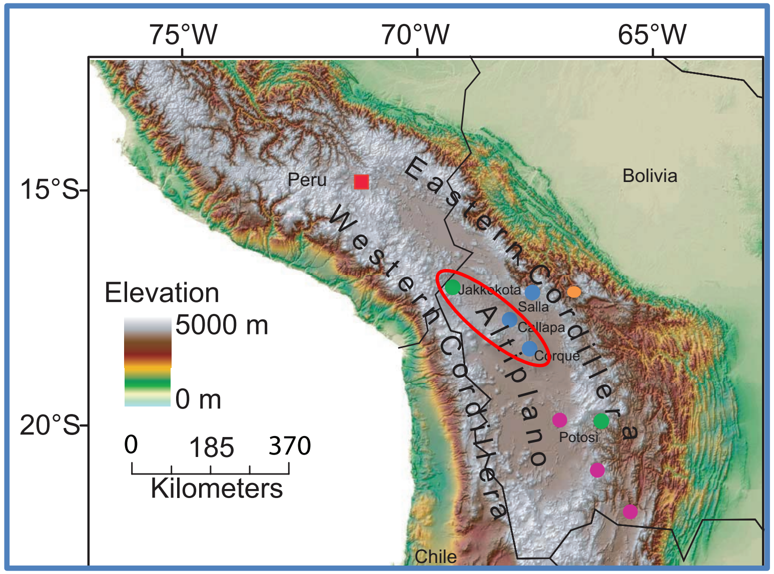
ε

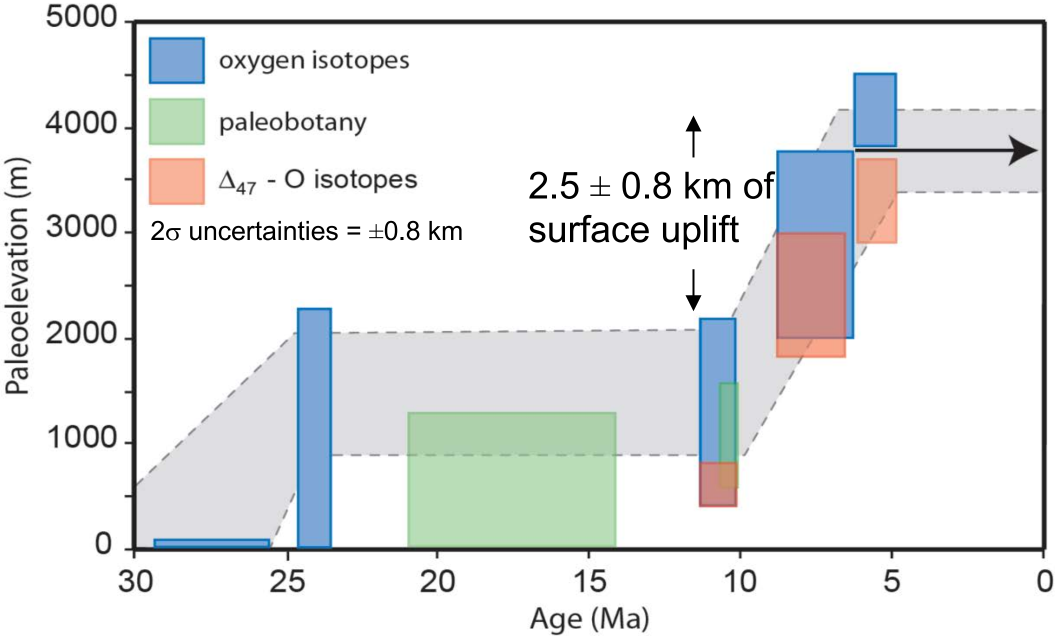
n-C_{25}, n-C_{27}, n-C_{29}, n-C_{31}

-δD

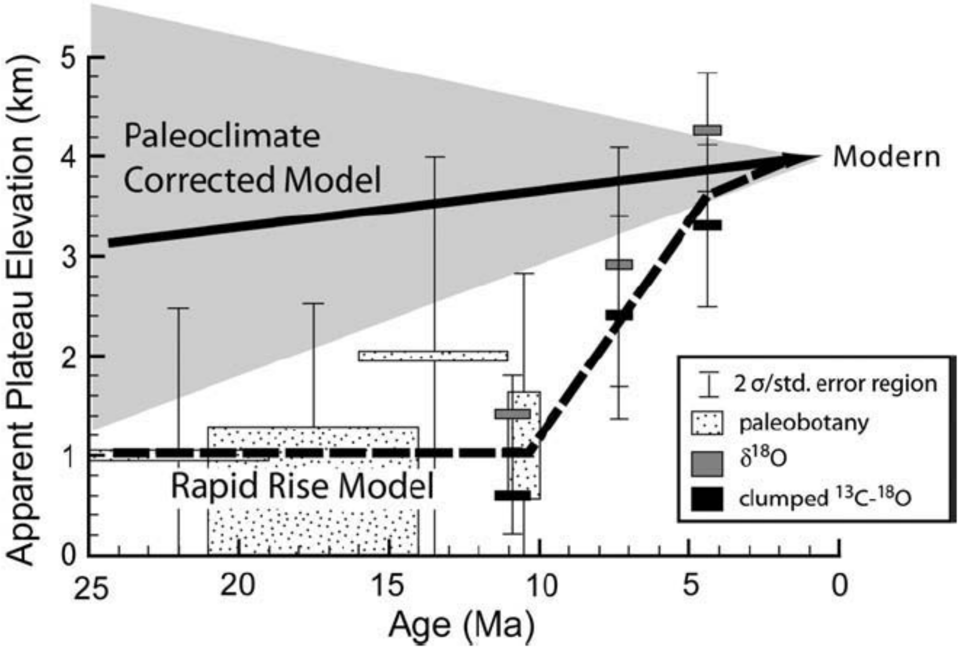
Hren et al. (2014)

Rapid Surface Uplift vs. Gradual Surface Uplift



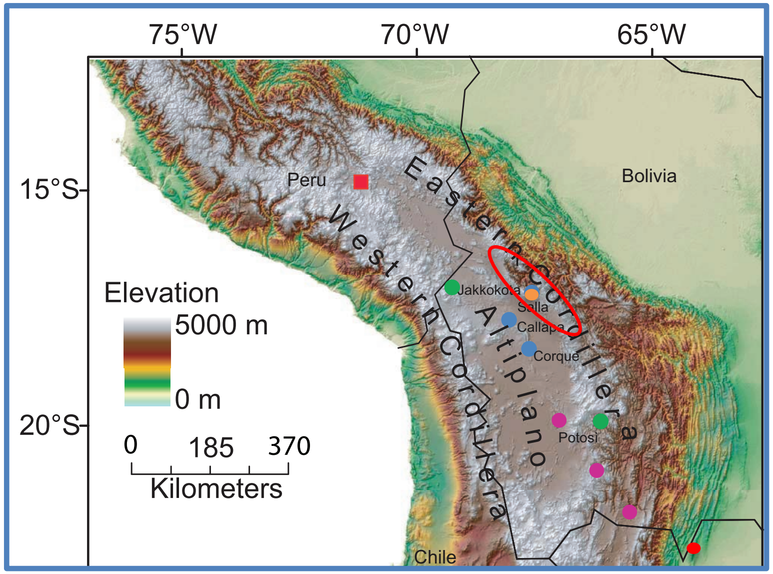


Garzione et al. (2006, 2008);
Ghosh et al. (2006);
Gregory-Wodzicki (2000)



Ehlers and Poulsen (2009)
Poulsen et al. (2010)

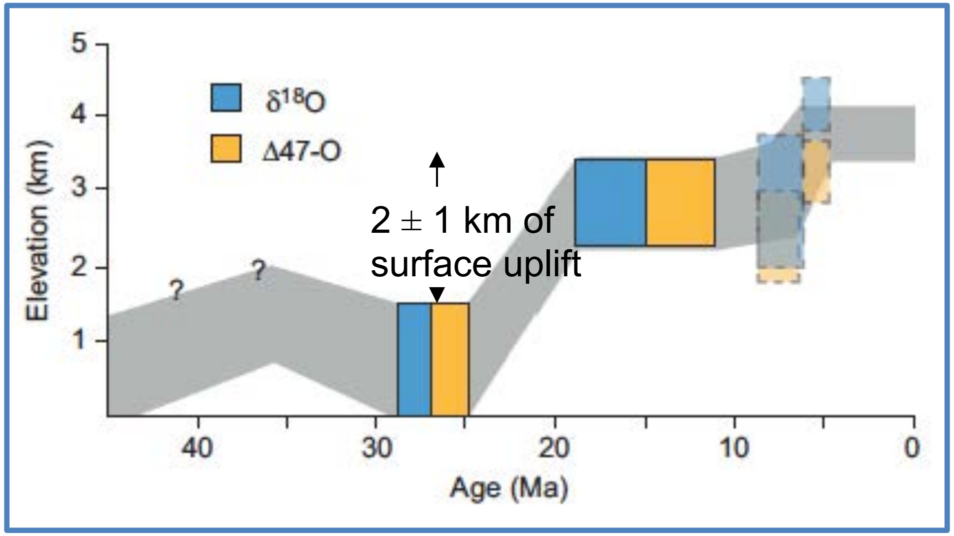
End Member Model II



Rapid Surface Uplift

- Decoupled deformation and surface uplift
- Proposed Mechanisms: Removal of dense lower lithosphere and/or lower crustal flow

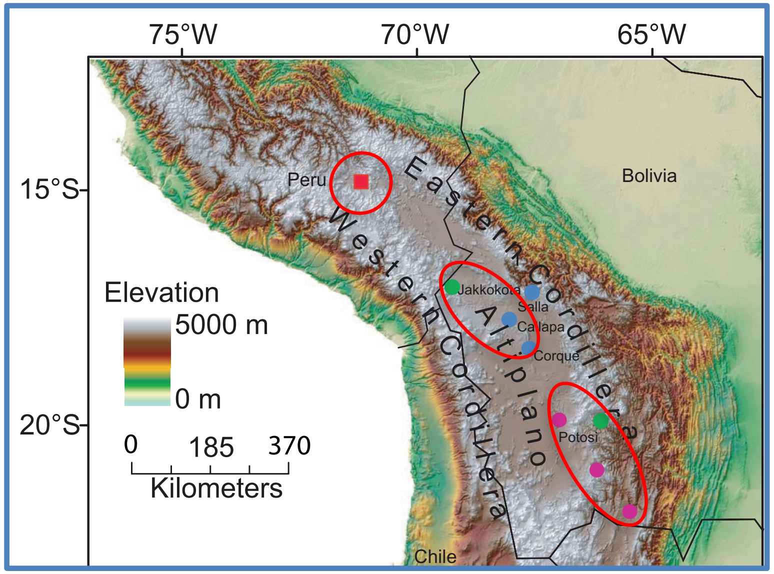
central Eastern Cordillera

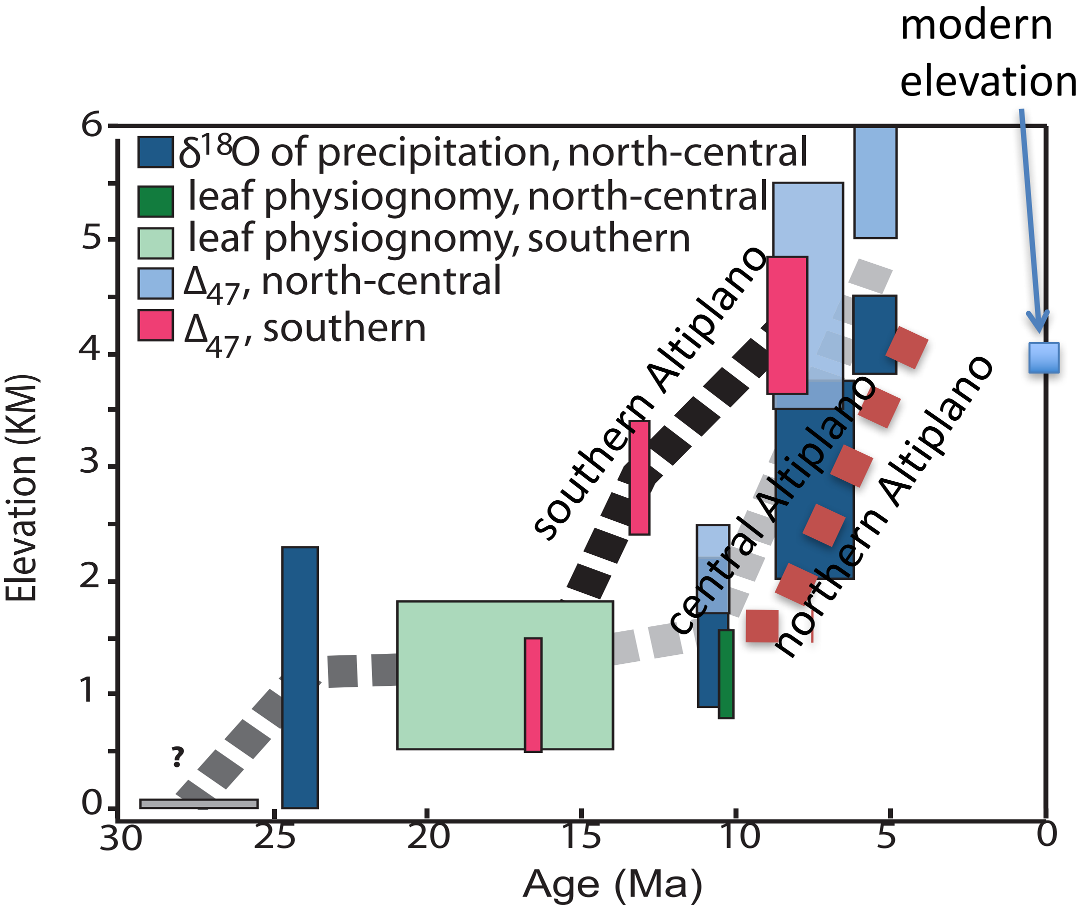


Leier et al.(2013, EPSL)

Large magnitude surface uplift of the central Eastern Cordillera between 24 and 17 Ma.

Along-strike variations in surface uplift

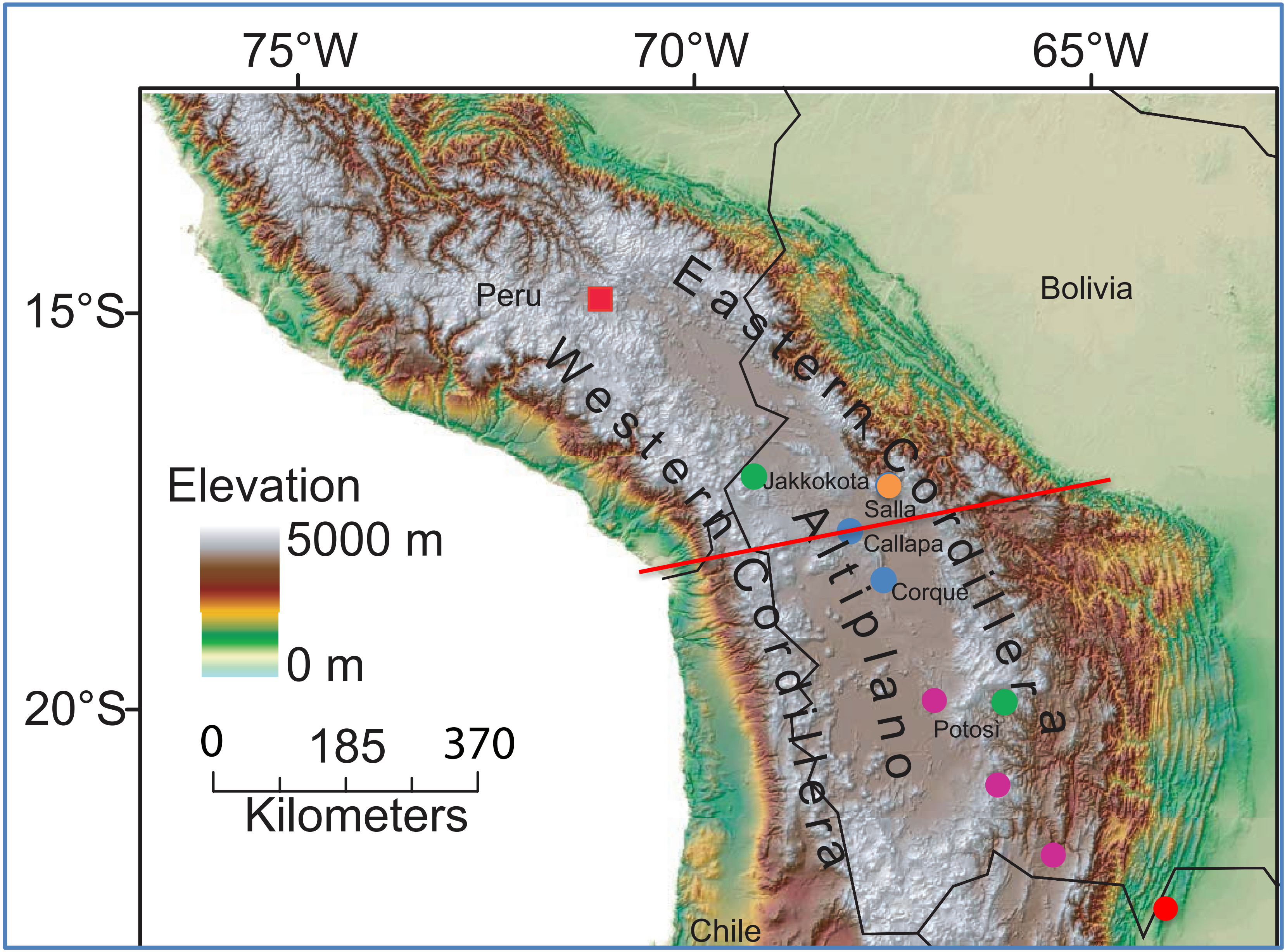




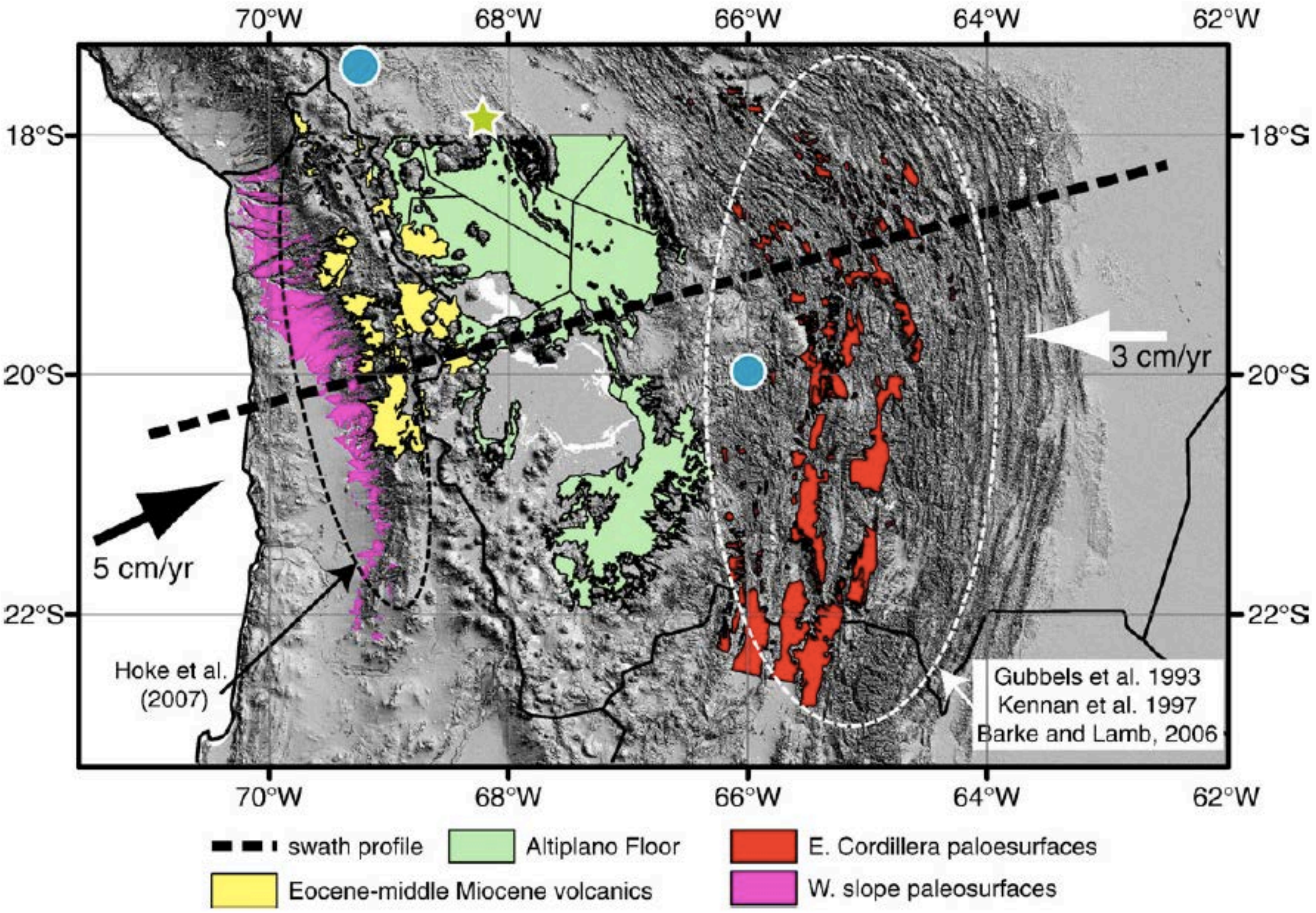
Large magnitude surface uplift of the Altiplano Propagates from S to N from middle to late Miocene time.

modified from Garzione et al. (2014, EPSL) & Kar et al. (2016, EPSL)

Central Andean Plateau Topographic History

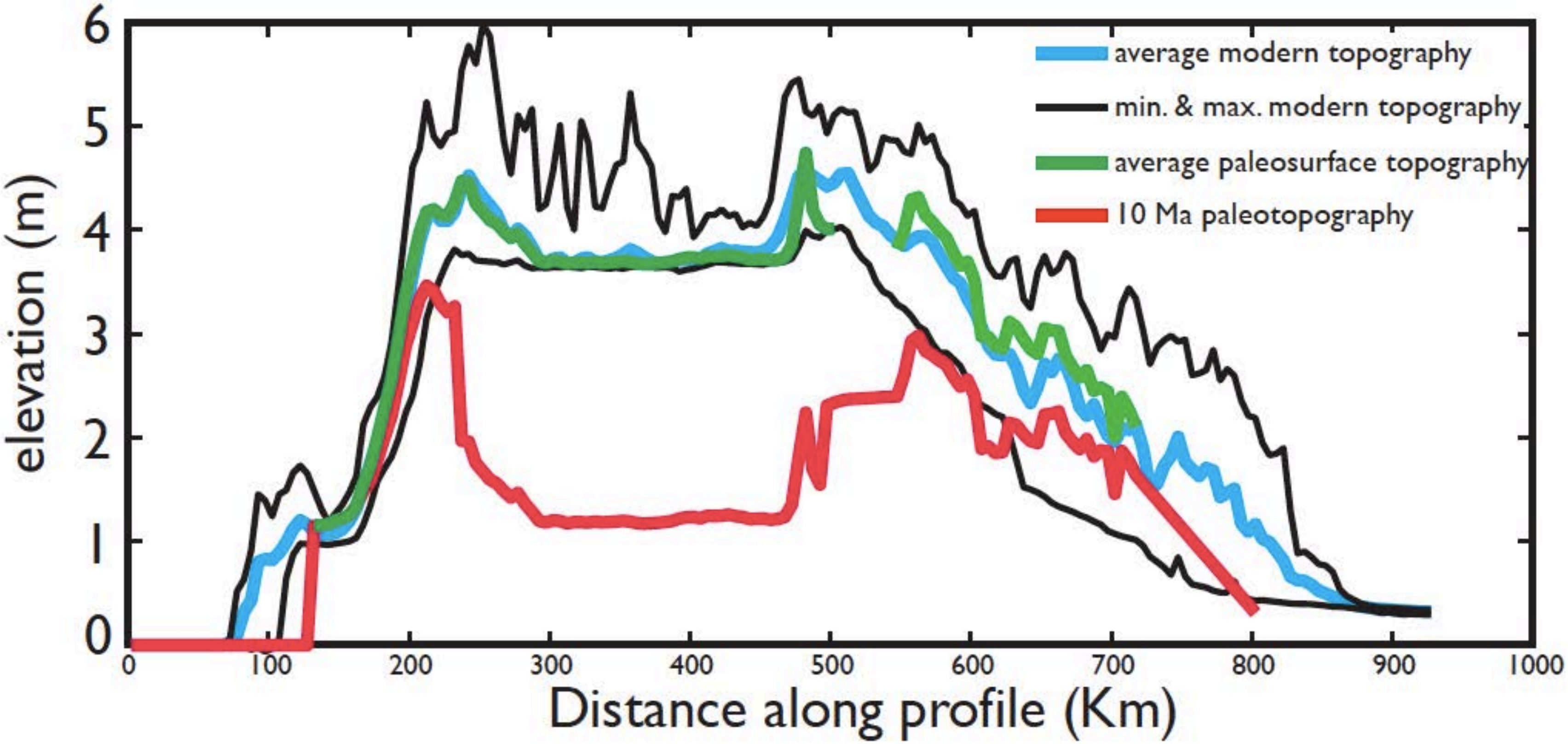


~10 Ma Paleosurface:



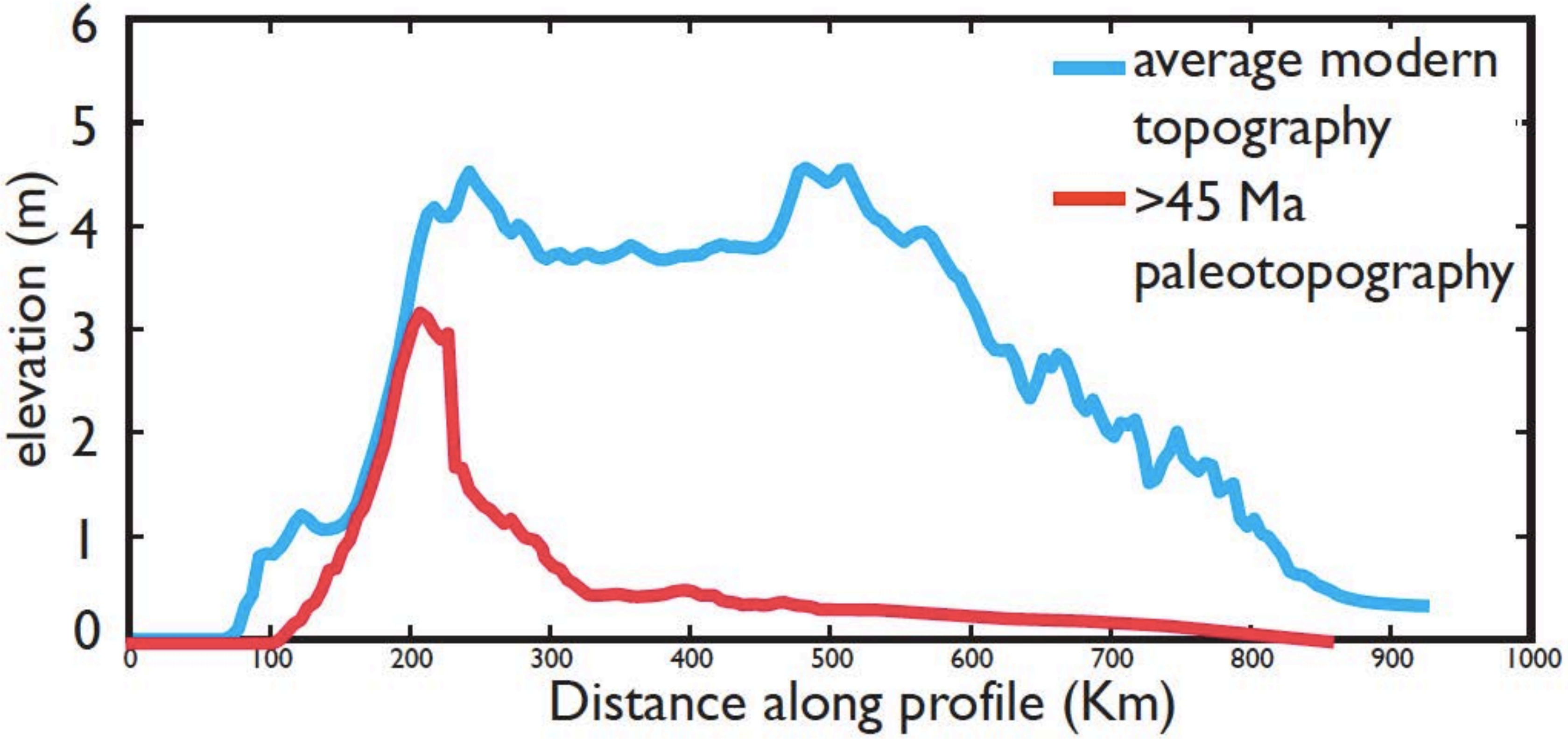
Gubbels et al. (1993); Kennan et al. (1997); Barke and Lamb (2006); Hoke and Garzione (2008)

Central Andean Plateau



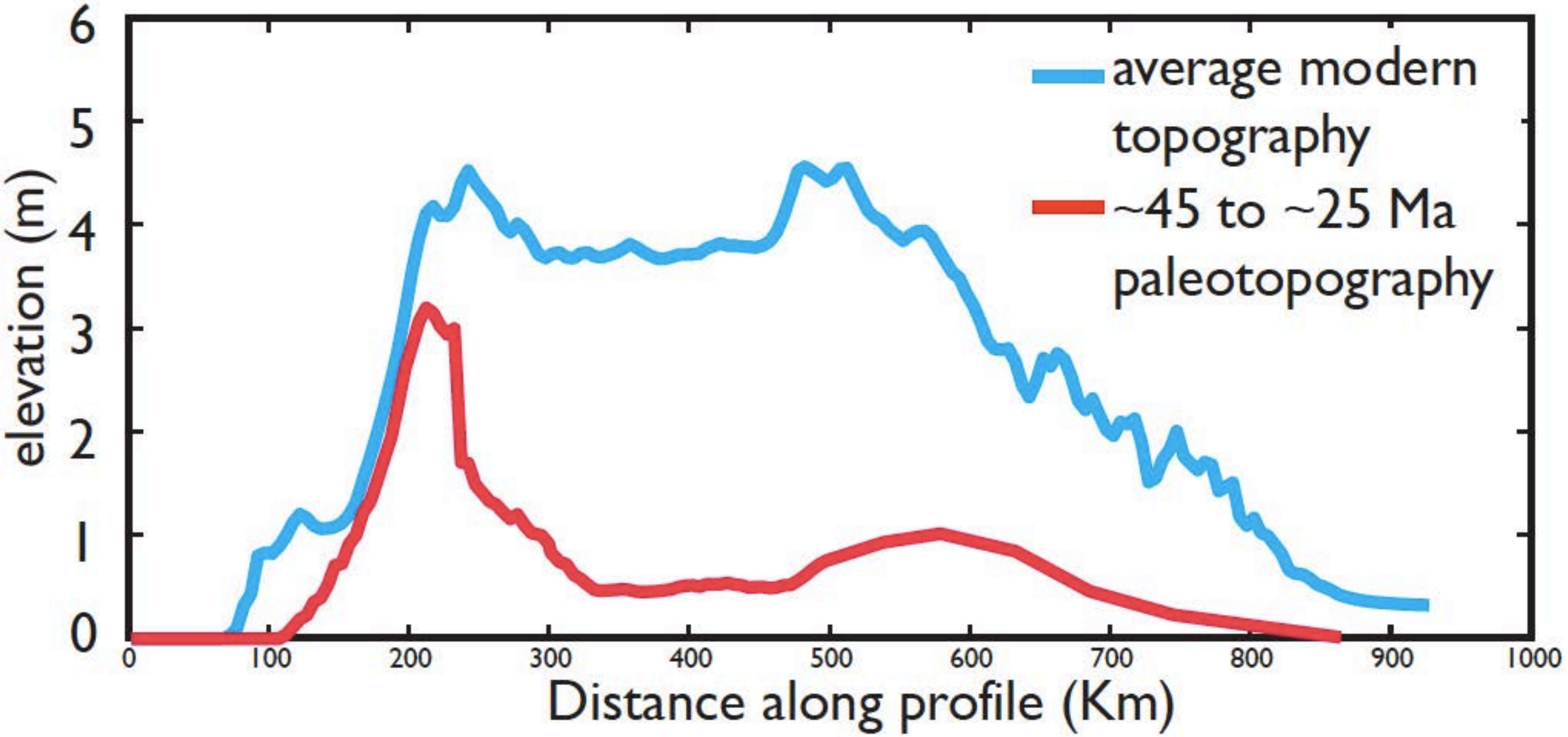
Hoke and Garzione (2008, EPSL)

~45 Ma Paleotopography



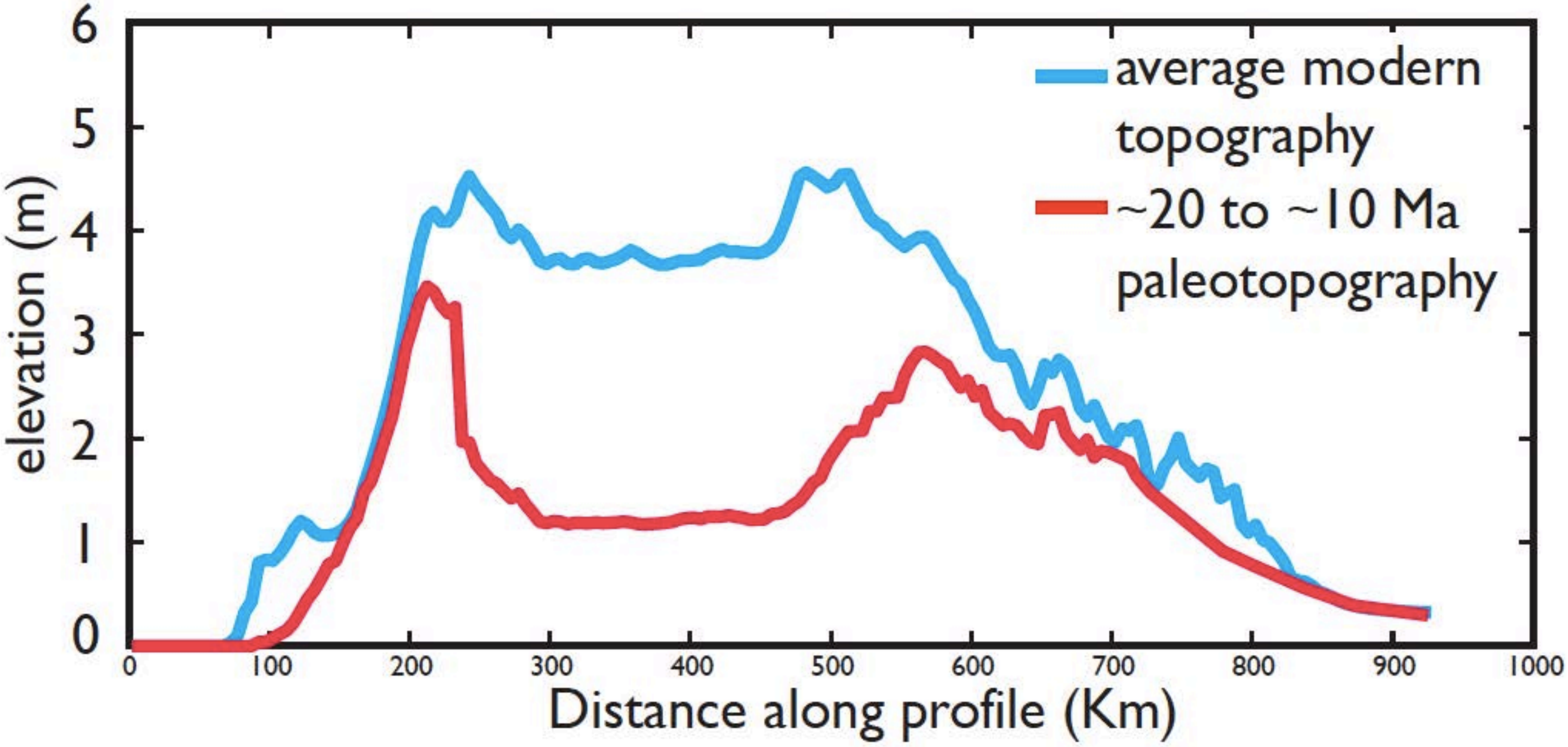
Evidence for a long-lived magmatic arc suggests that there was significant relief in the Western Cordillera; stable isotope evidence – Saylor et al. (2014)

~45 – ~25 Ma Paleotopography



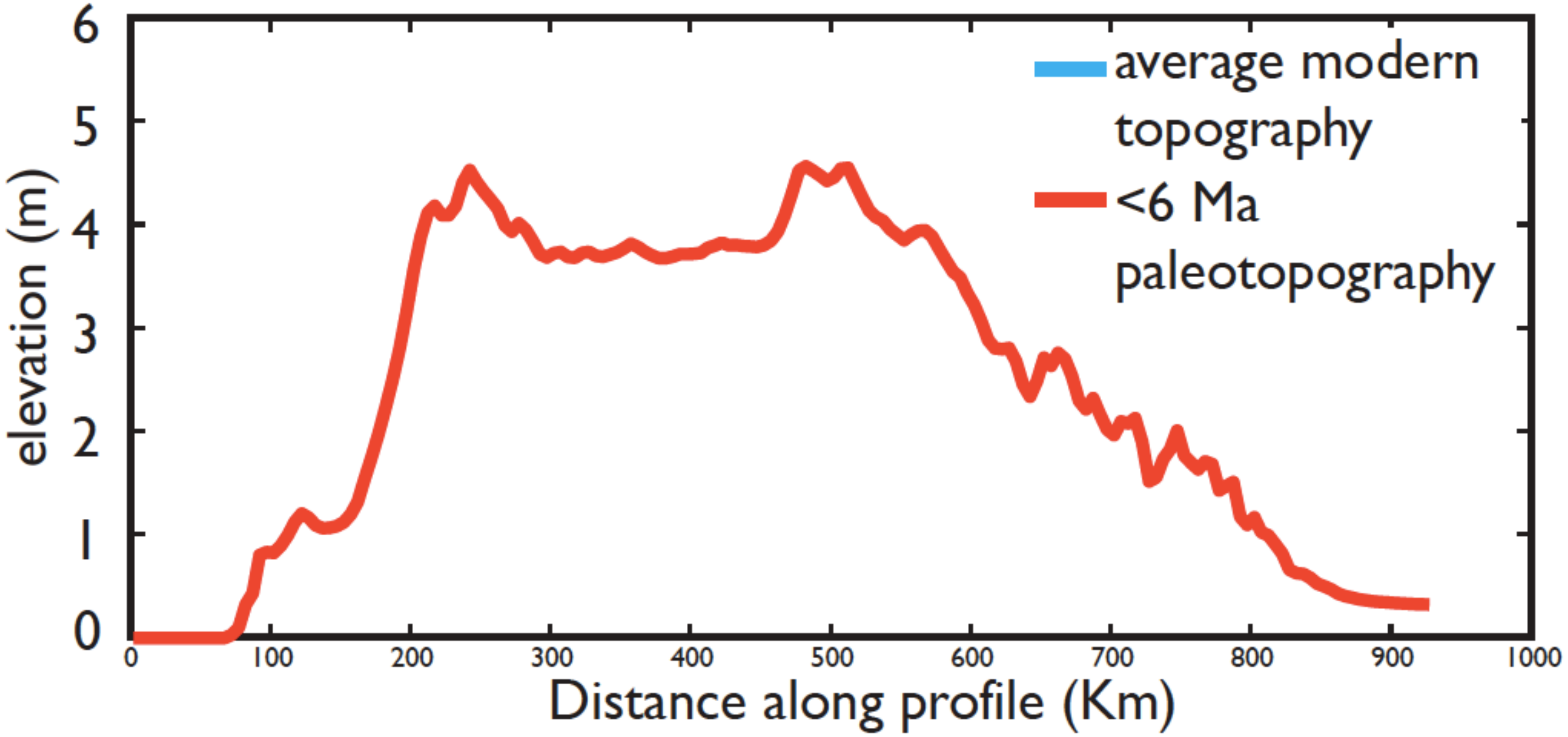
- Basin analysis, structural evidence, and thermochronology indicate that the Eastern Cordillera began to deform by ~45 to 40 Ma (Horton et al., 2001; McQuarrie, 2002; Gillis et al., 2006; Barnes et al., 2008)
- Paleoelevation estimates from Salla Fm (Leier et al., 2013) also support this

~20 to ~10 Ma Paleotopography



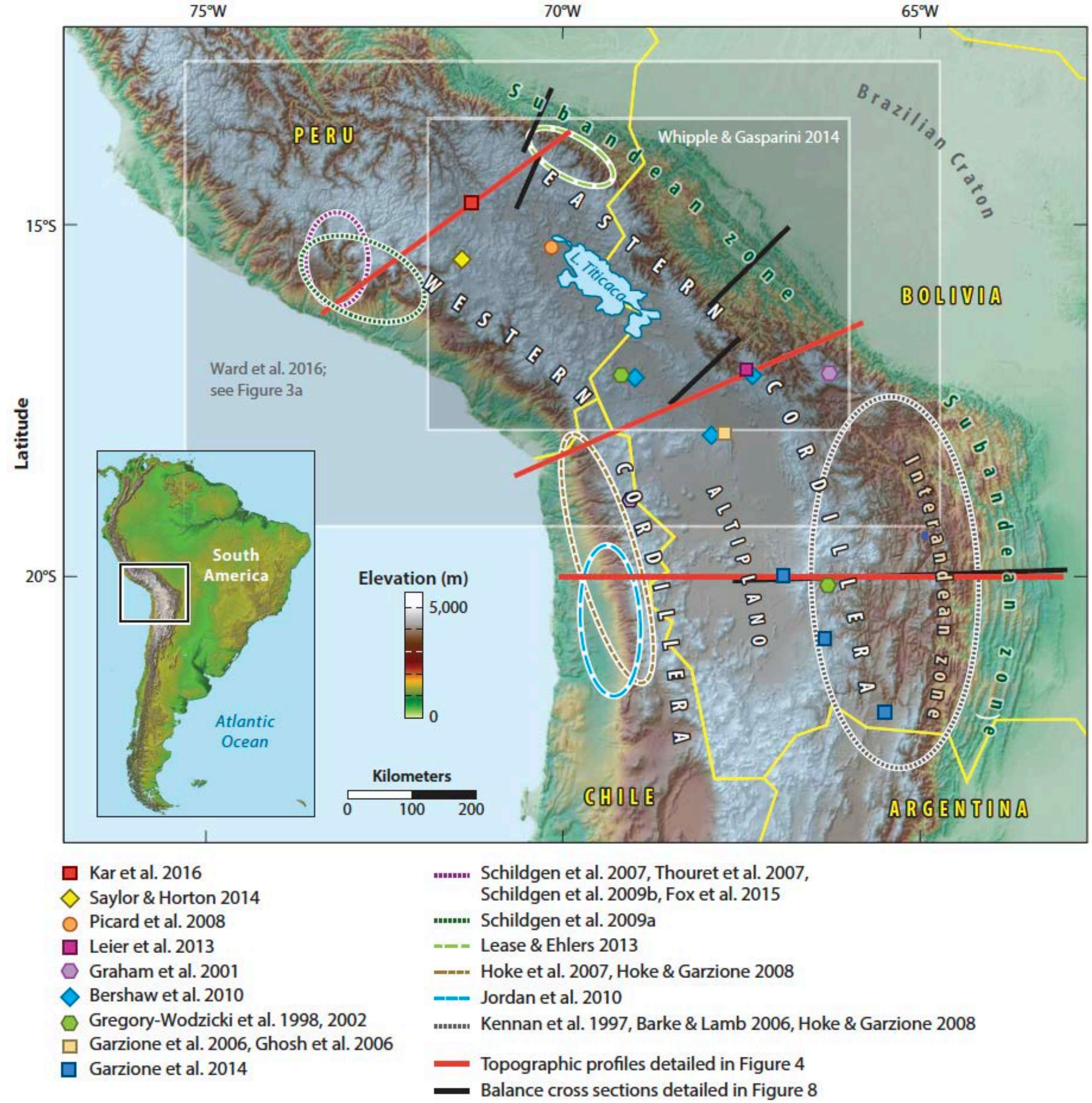
Leier et al. (2013) results suggest that the Eastern Cordillera experiences a rapid pulse of surface uplift between ~24 and 17 Ma.

<6 Ma Paleotopography



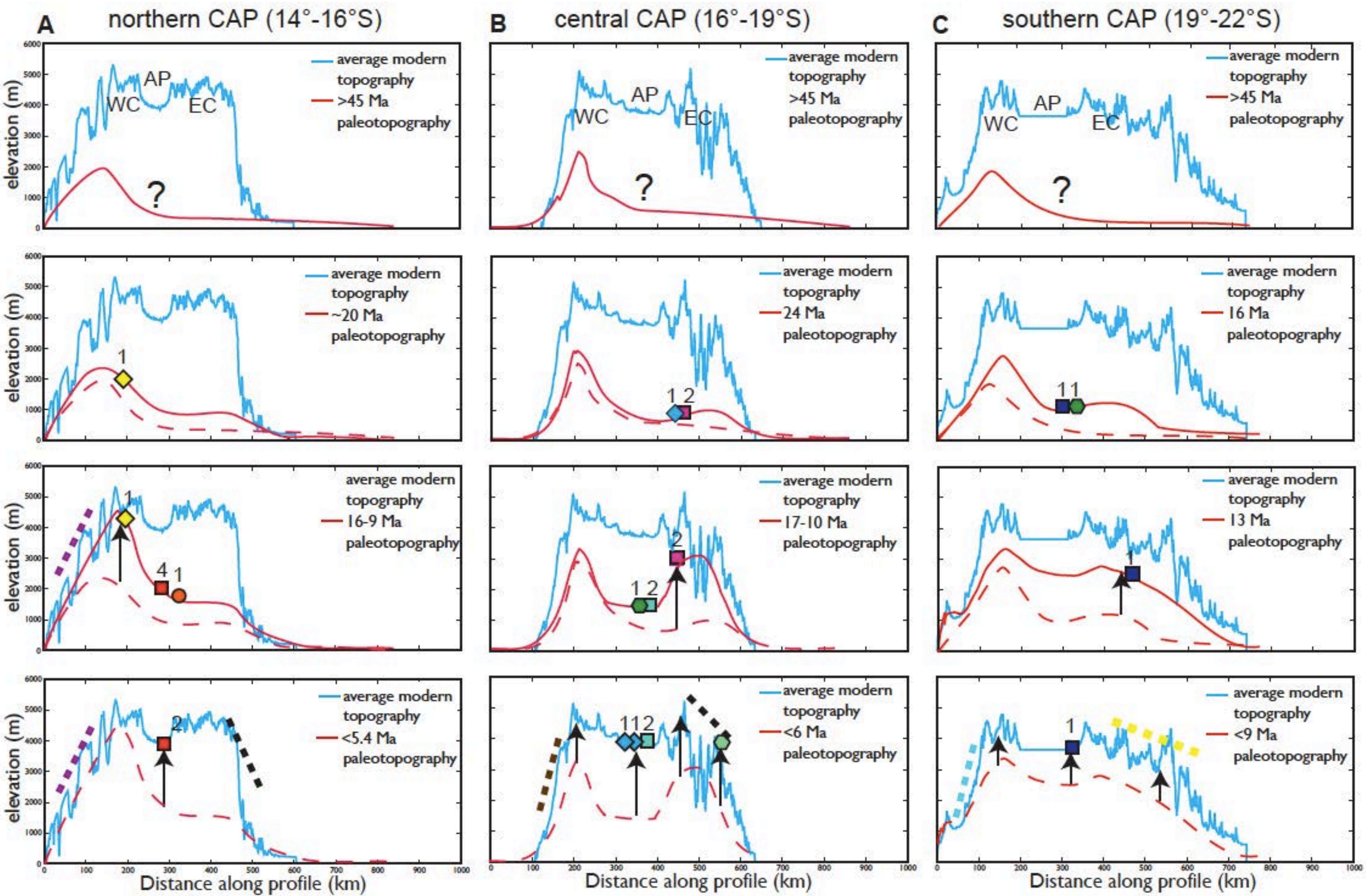
Stable isotope results and incision histories suggest a rapid pulse of surface uplift between 10 and 6 Ma that established the modern topography of the central portion of the Andean plateau.

Along-strike variations in paleotopography



Garzione et al. (2017, AREPS)

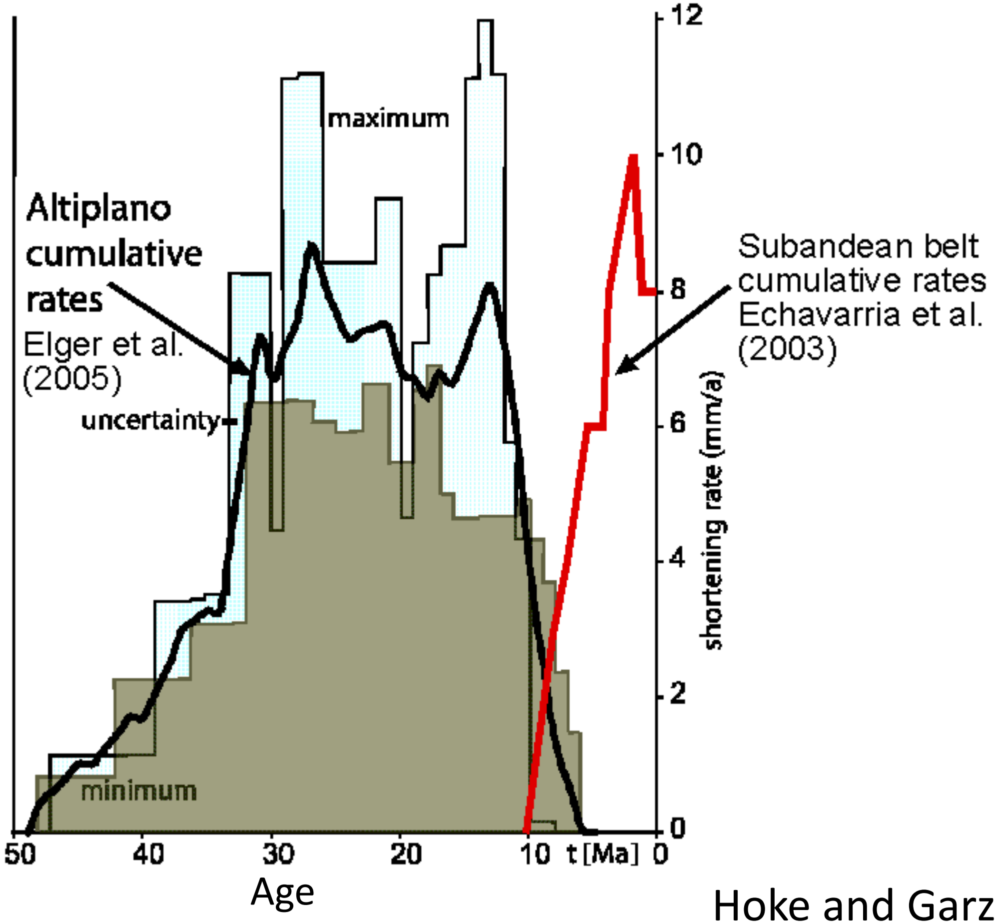
Along-strike variations in paleotopography



Garzione et al. (2017, AREPS)

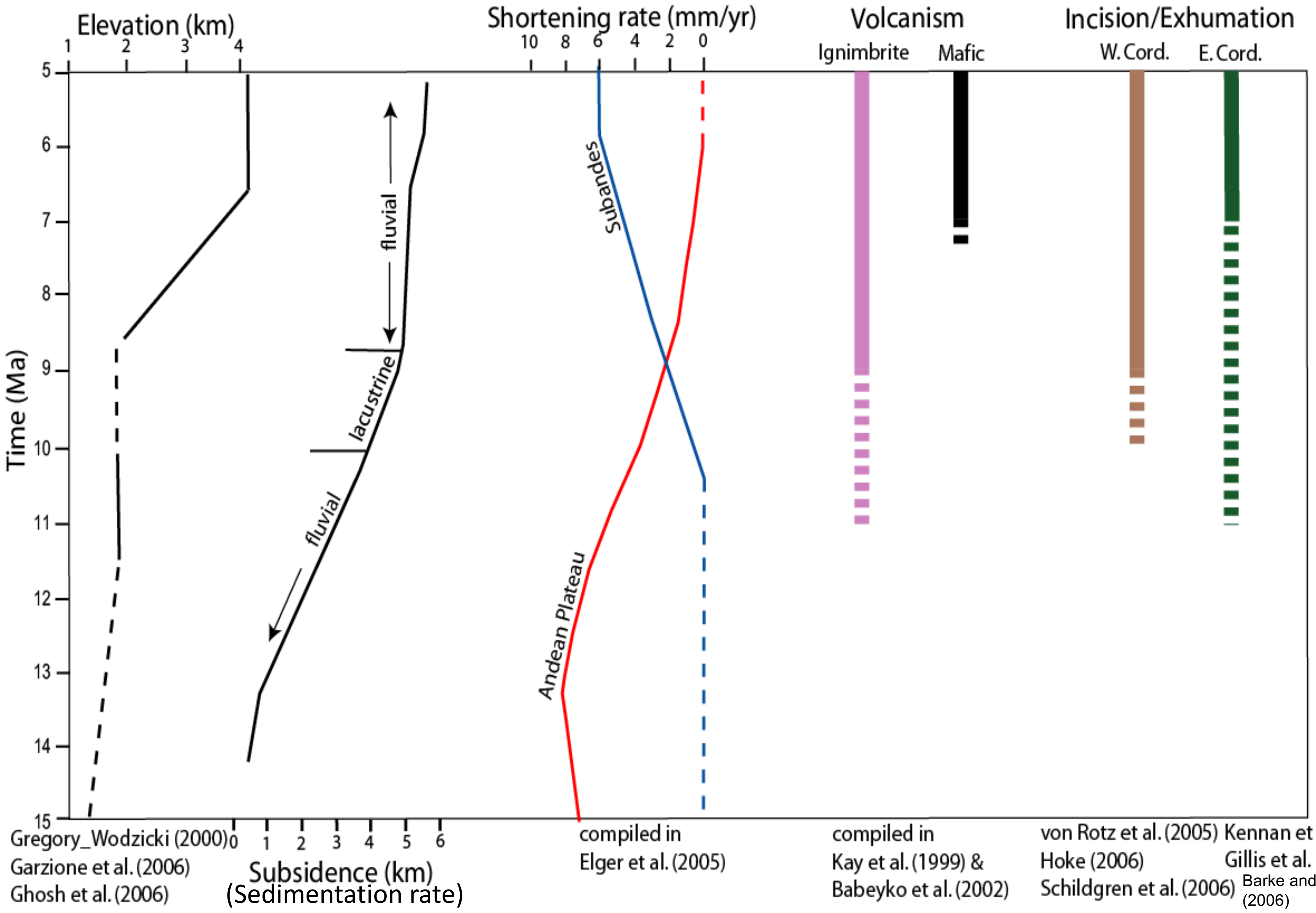
Prediction: Rapid removal of lower lithosphere - surface uplift decreases the horizontal compressive stress in the Andean plateau

Observation: Contractional deformation ceased in the central Altiplano and propagated eastward into the Subandes.



Hoke and Garzione (2008, EPSL)

Middle-late Miocene events in the Andean plateau



Gregory_Wodzicki (2000)
Garzione et al. (2006)
Ghosh et al. (2006)

compiled in
Elger et al. (2005)

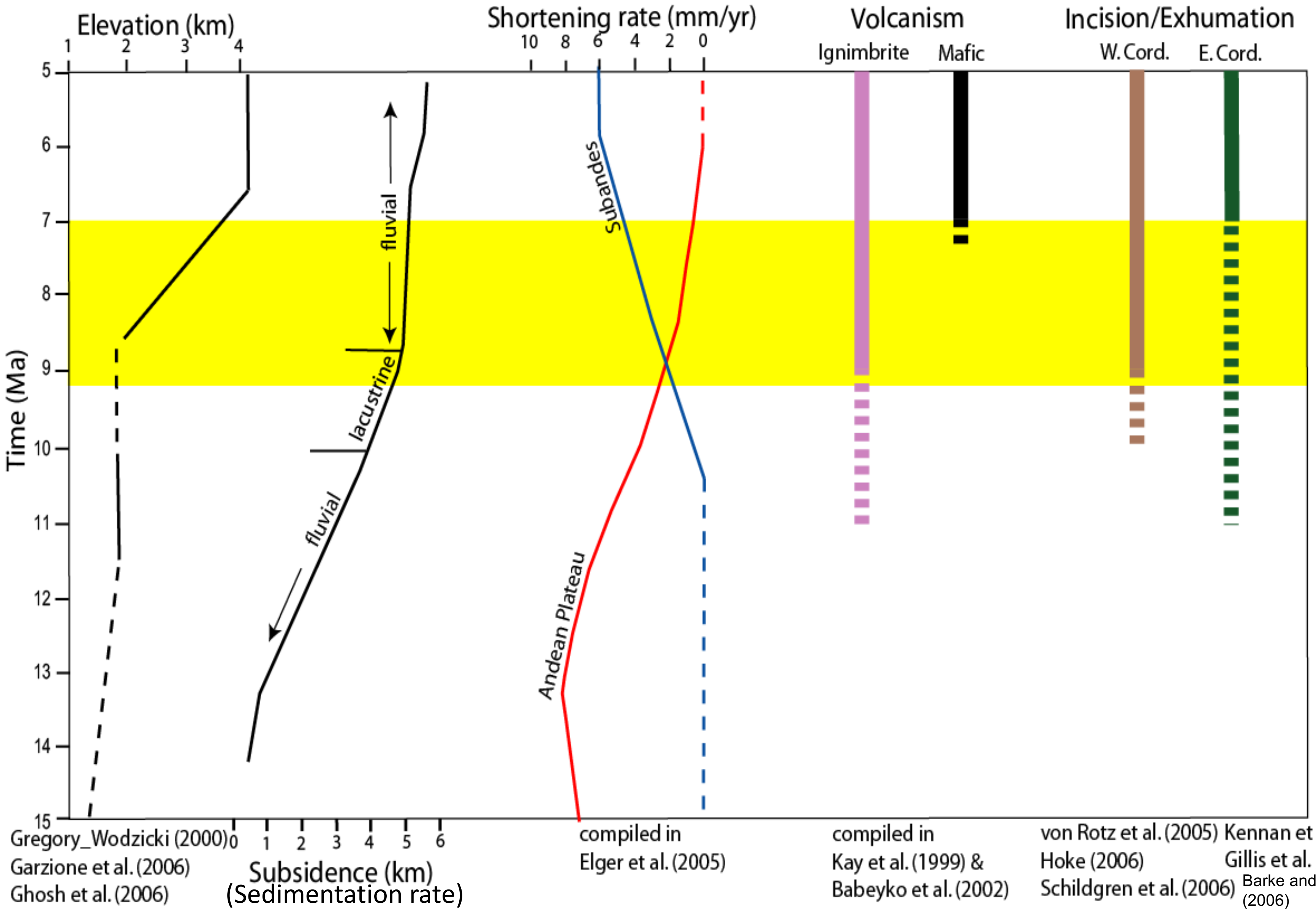
compiled in
Kay et al. (1999) &
Babeyko et al. (2002)

von Rotz et al. (2005)
Hoke (2006)
Schildgren et al. (2006)

Kennan et al. (1997)
Gillis et al. (2006)
Barke and Lamb (2006)

Garzione et al. (2008, Science)

Middle-late Miocene events in the Andean plateau



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Kennan et al. (1997)
(2006)
Gillis et al.
Barke and Lamb
(2006)

Garzione et al. (2008, Science)

What mechanisms form broad, high elevation, low relief orogenic plateaus?

CAUGHT – Central Andean Uplift and the Geodynamics of High Topography

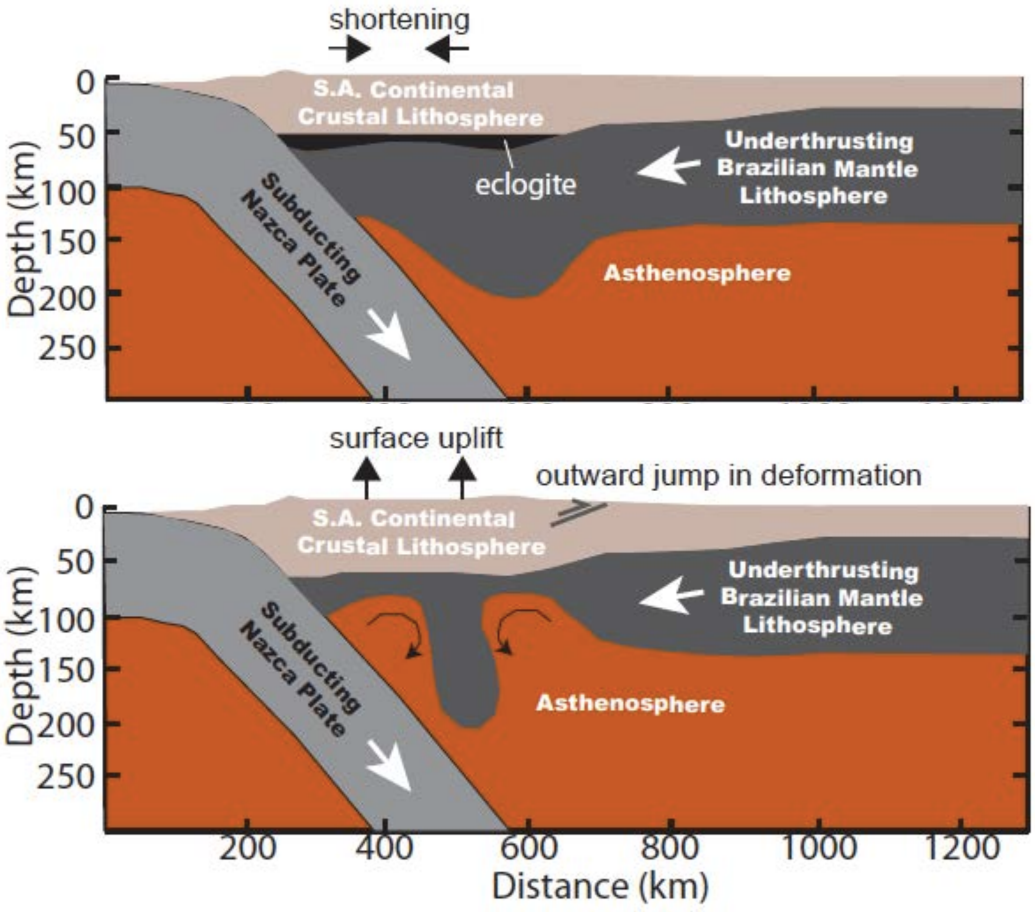
- Incision history
- Crustal structure
- Shortening history
- Volcanics
- Mantle structure

Collaborators:

CAUGHT Continental Dynamics project team Susan L. Beck (U Arizona), Alan D. Chapman (Macalester), Mihai N. Ducea (U Arizona), Todd. A. Ehlers (U Tubingen), Nathan Eichelberger (StructureSolver LLC), Brian K. Horton (UT Austin), Nandini Kar (Wash U), Richard O. Lease (USGS Anchorage), Nadine McQuarrie (U Pittsburgh), Nicholas D. Perez Texan A&M), Christopher J. Poulsen (U Michigan), Joel E. Saylor (U Houston), Lara S. Wagner (DTM Carnegie Inst), Kevin M. Ward (U Utah), George Zandt (U Arizona)

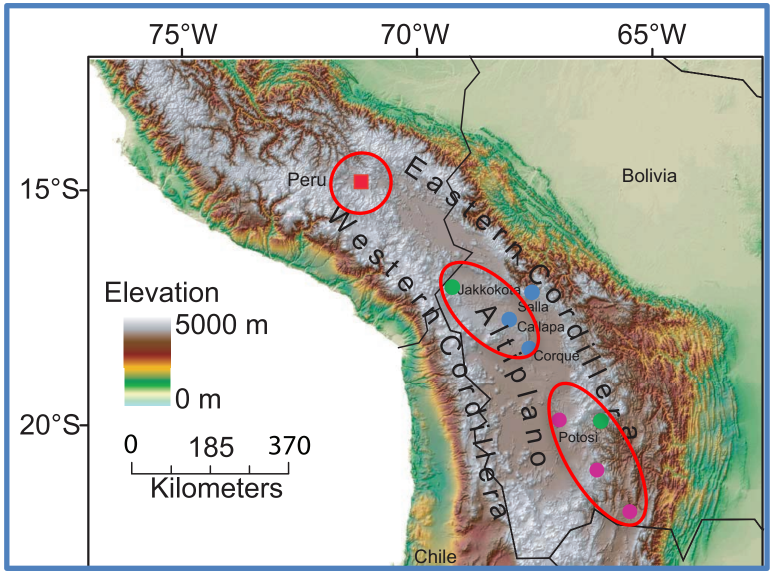
Garzione et al. (2017 – AREPS)

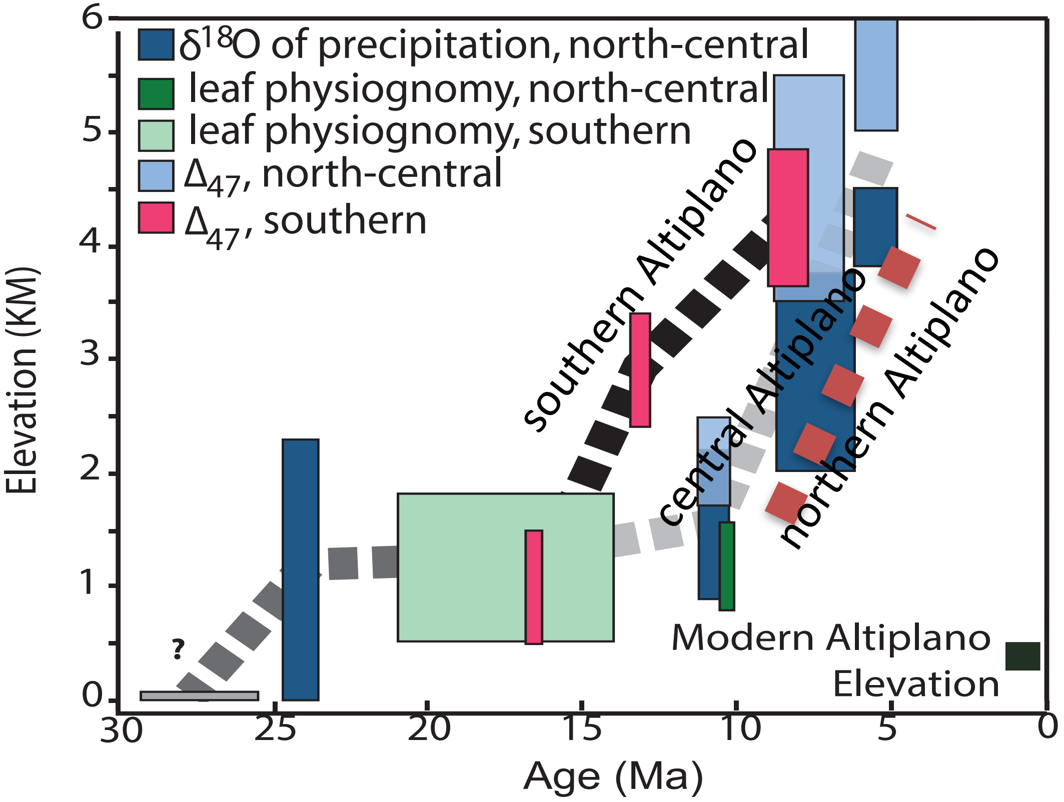
The case for convective removal of the lower lithosphere



- Crustal thickening precedes pulses of surface uplift
- Pulses of surface uplift should correspond with an outward jump in deformation
- If high density eclogitic lower crust drives lower lithosphere removal, then crustal thickening history would predict crustal thickness in excess of modern thickness.
- Crustal and mantle structure may show evidence of recent or ongoing convective removal of lower lithosphere.

Along-strike variations in surface uplift

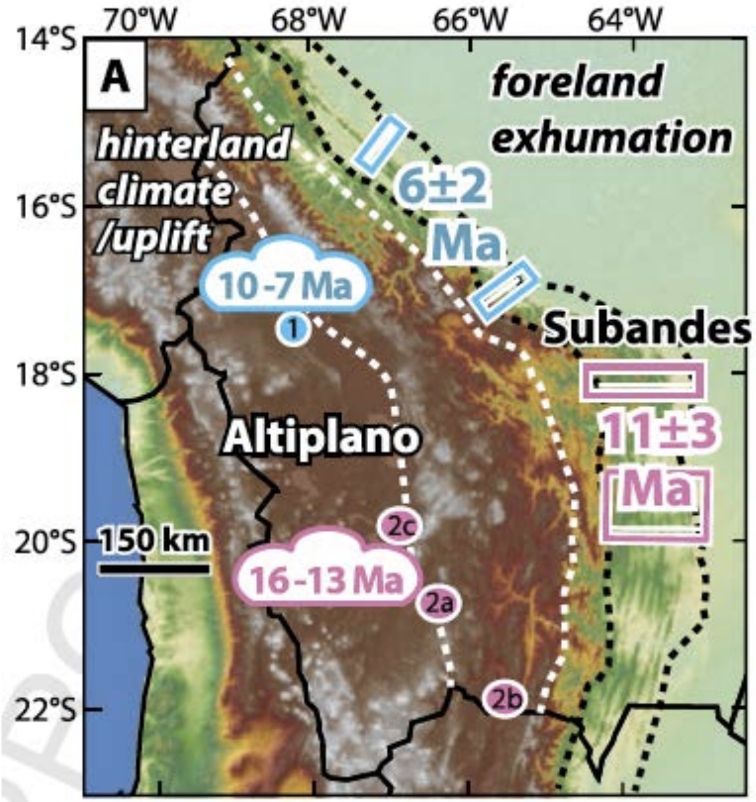


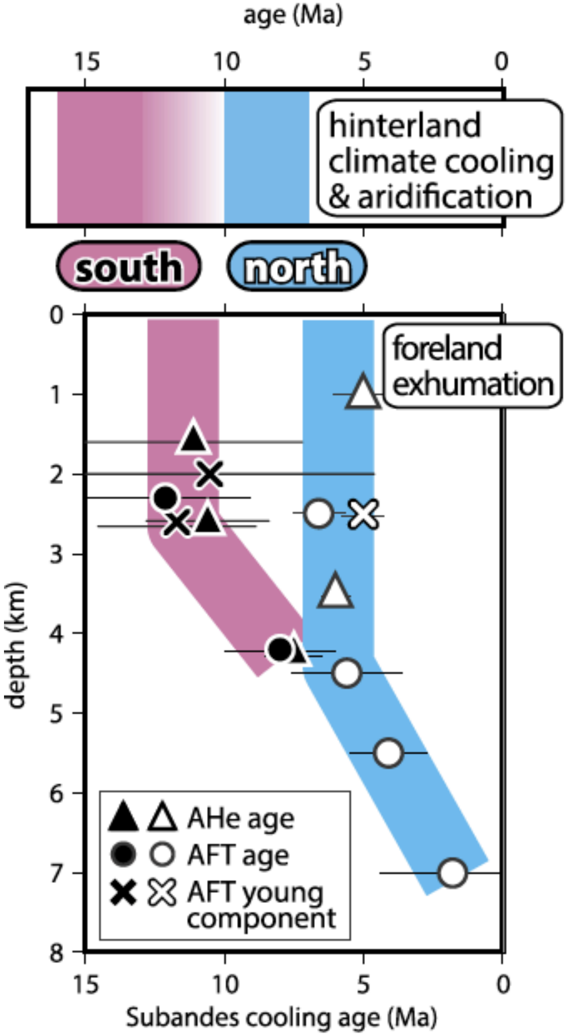


Large magnitude surface uplift of the Altiplano Propagates from S to N from middle to late Miocene time.

modified from Garzione et al. (2014, EPSL) & Kar et al. (2016, EPSL)

Along-strike variations in the outward jump in deformation & aridification of the Altiplano

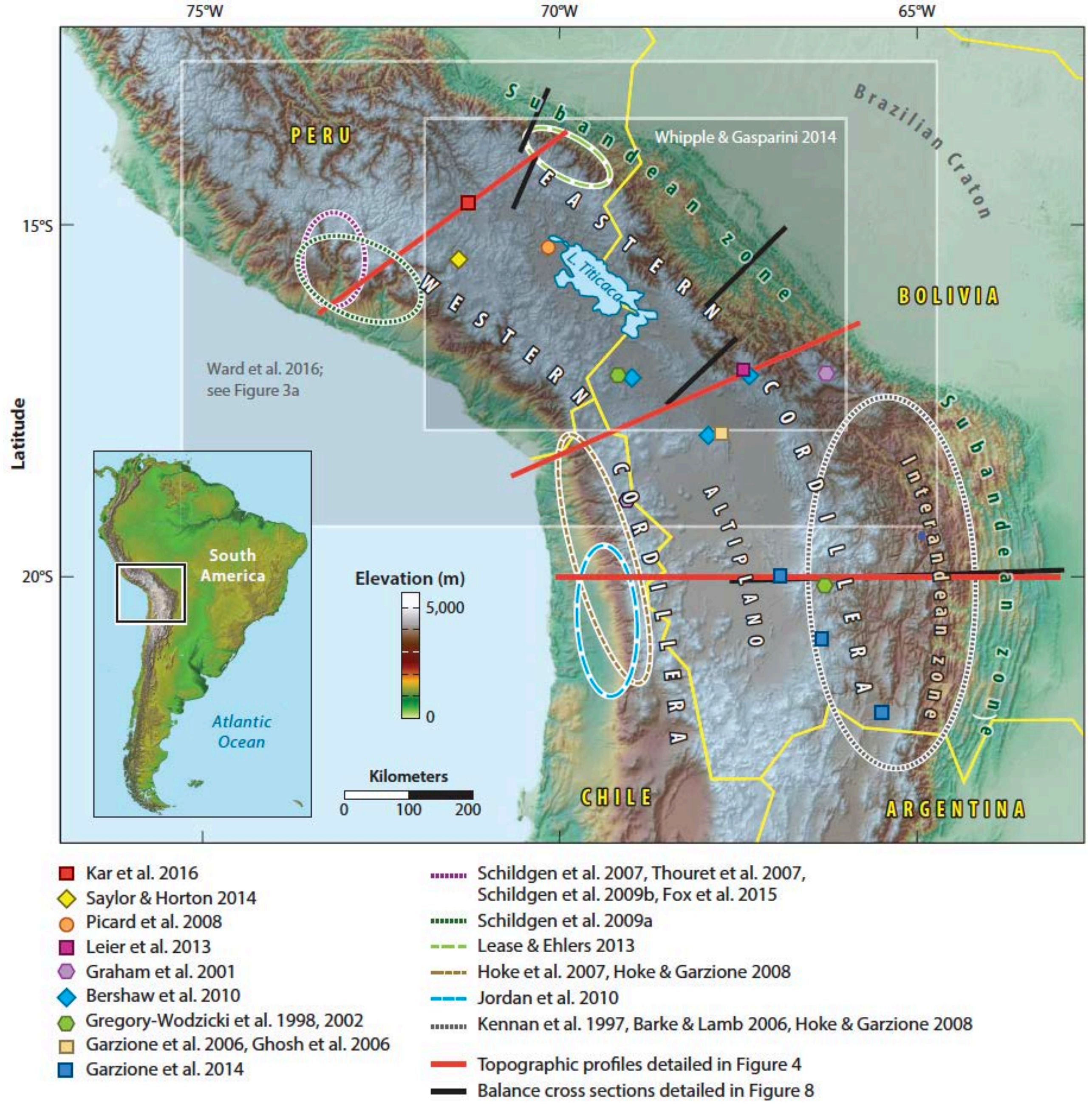




- Middle Miocene aridification of the southern Altiplano and western slope versus late Miocene aridification of the northern Altiplano
- Middle Miocene onset of southern Subandean deformation versus late Miocene onset of southern Subandean deformation

Lease et al. (2016)

Along-strike variations in crustal shortening

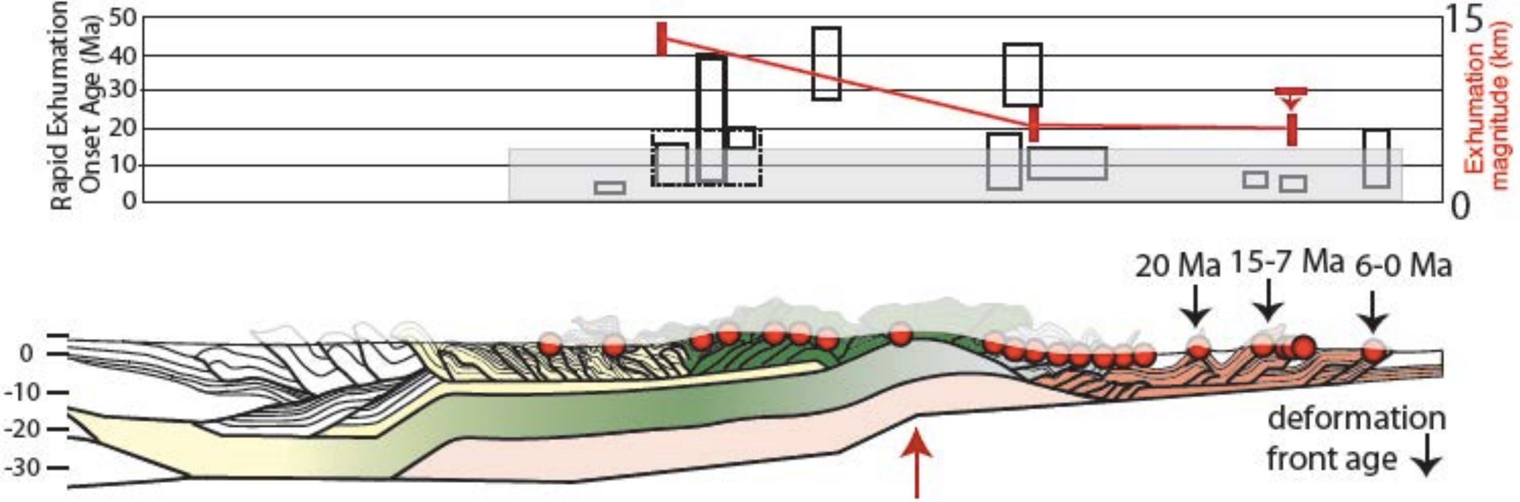


Garzione et al.
(2017, AREPS)

Crustal shortening history

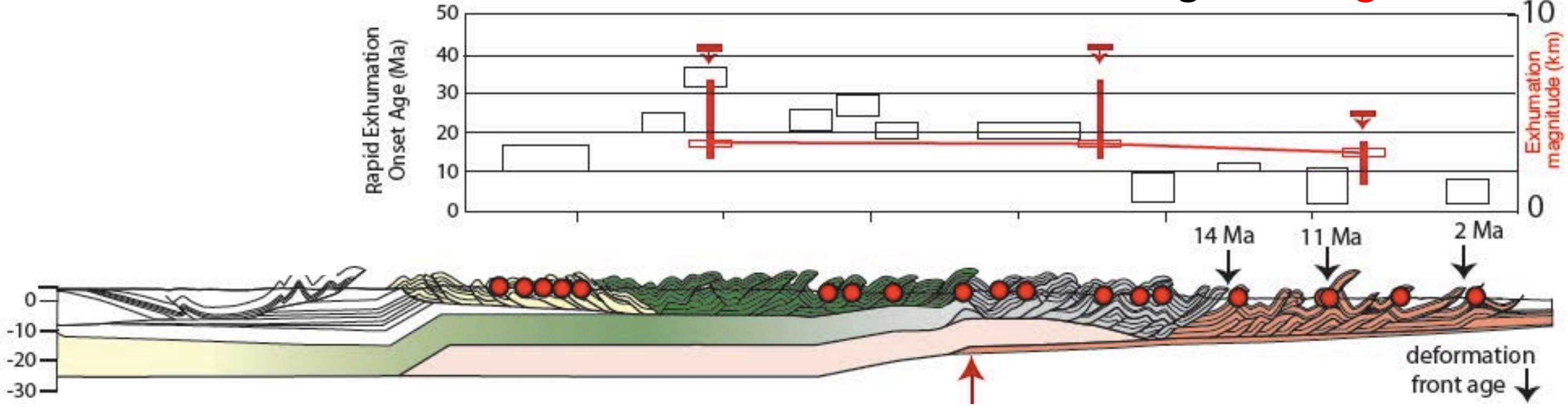
Central Central Andean Plateau

Exhumation timing and magnitude



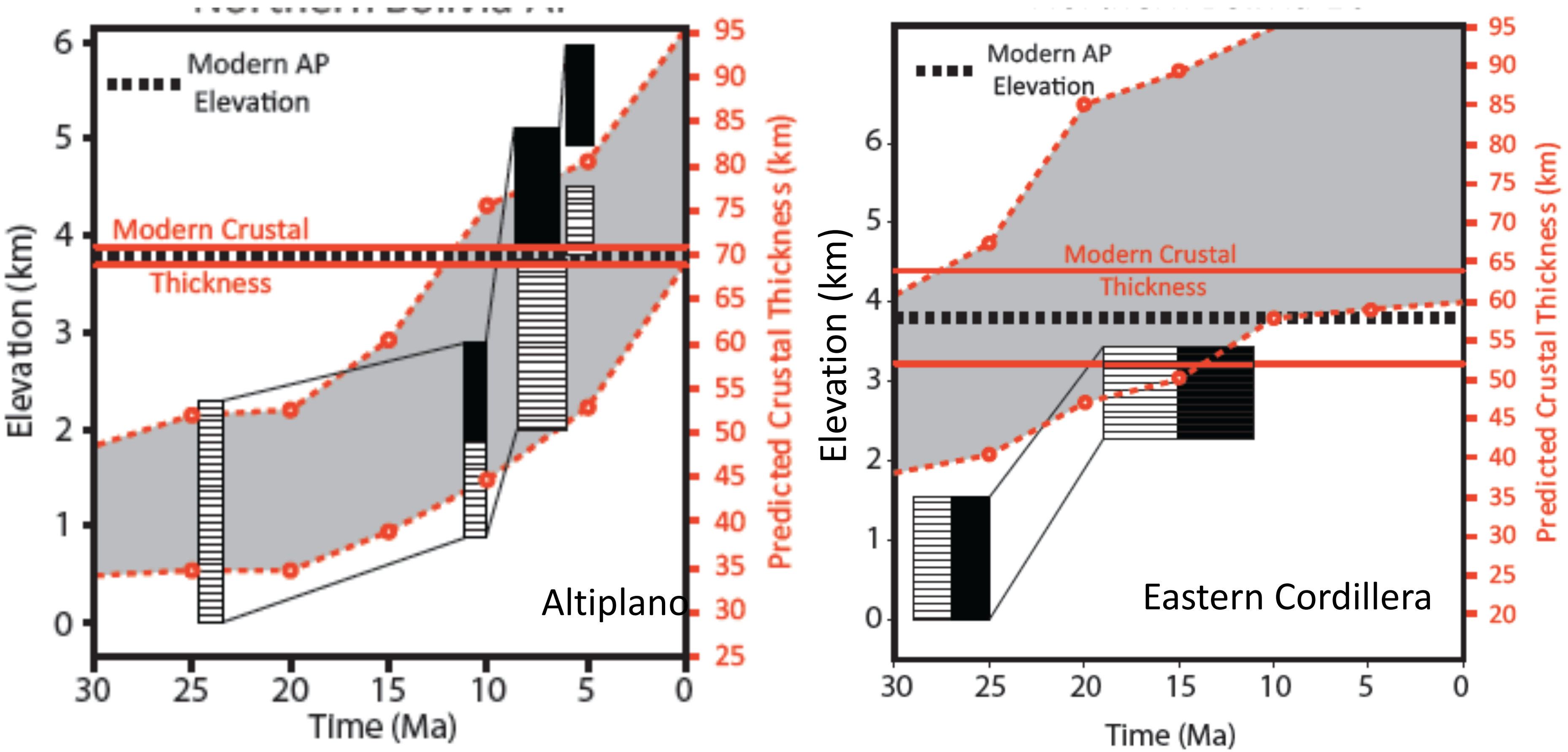
Southern Central Andean Plateau

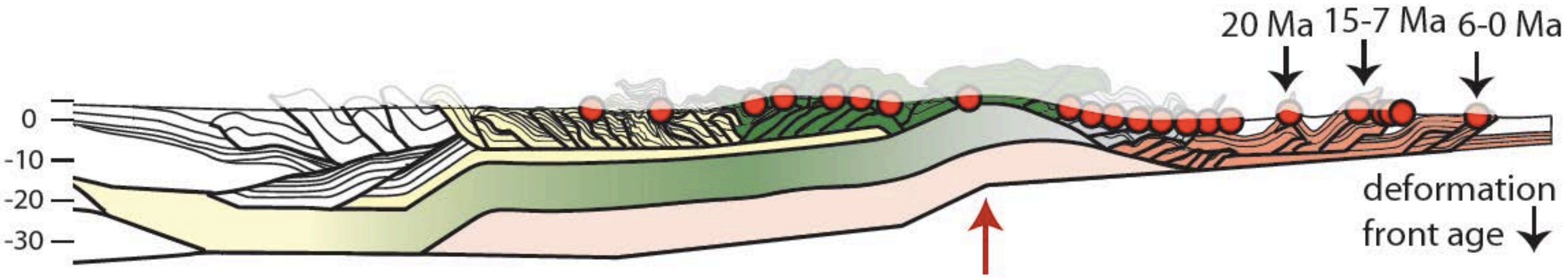
Exhumation timing and magnitude



Garzione et al. (2017, AREPS), from McQuarrie et al. (2002, 2008), Barnes et al. (2012)

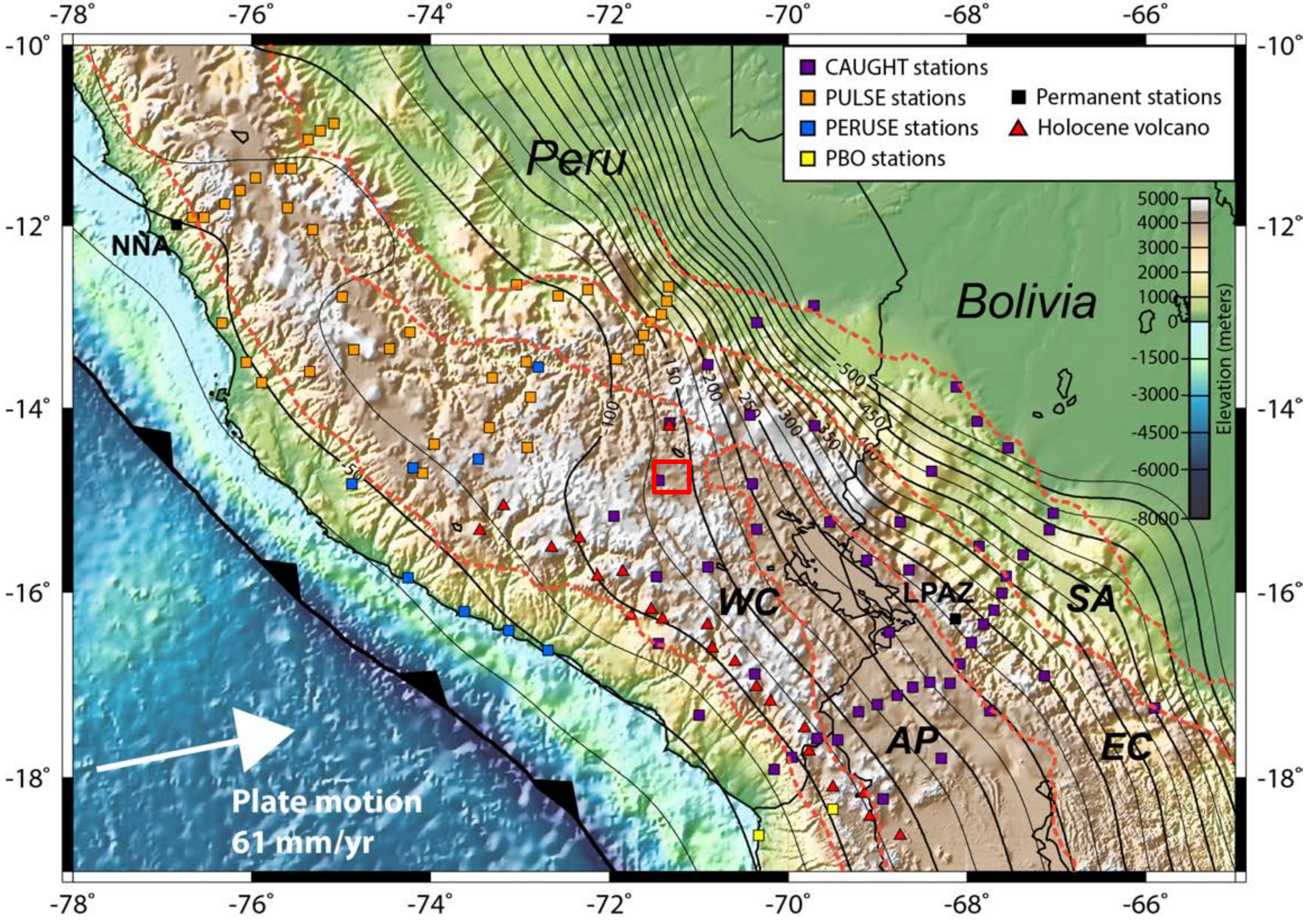
Crustal thickening versus surface uplift - Central Plateau



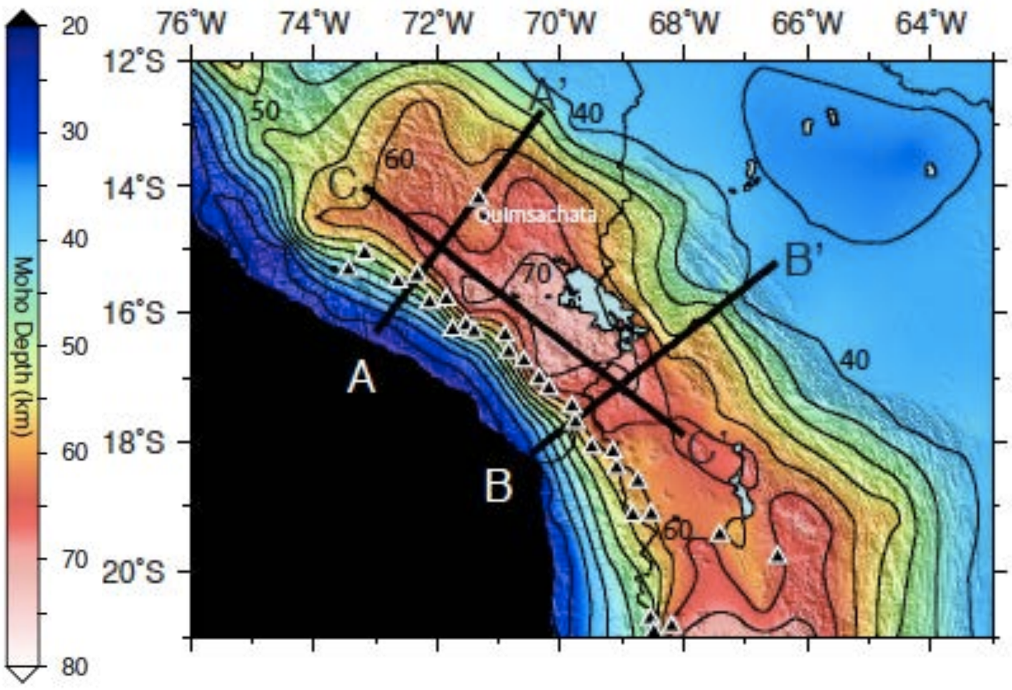


Garzione et al. (2017, AREPS), from Eichelberger et al. (2015), Garzione et al. (2006, 2008), Leier et al. (2013)

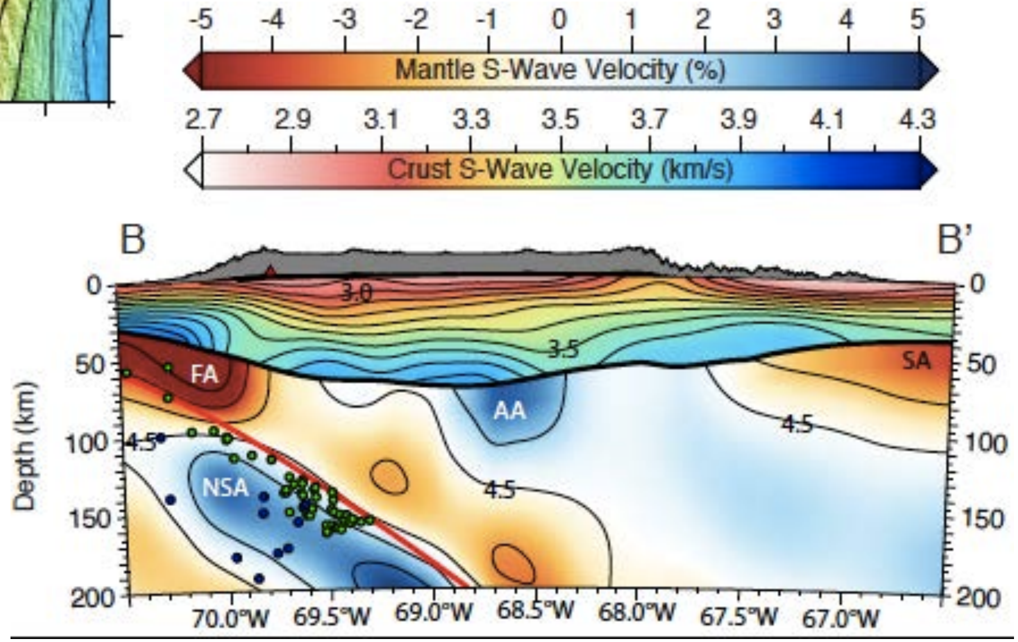
CAUGHT-PULSE broadband station map



Crustal thickness map (receiver functions) & Crustal/mantle structure



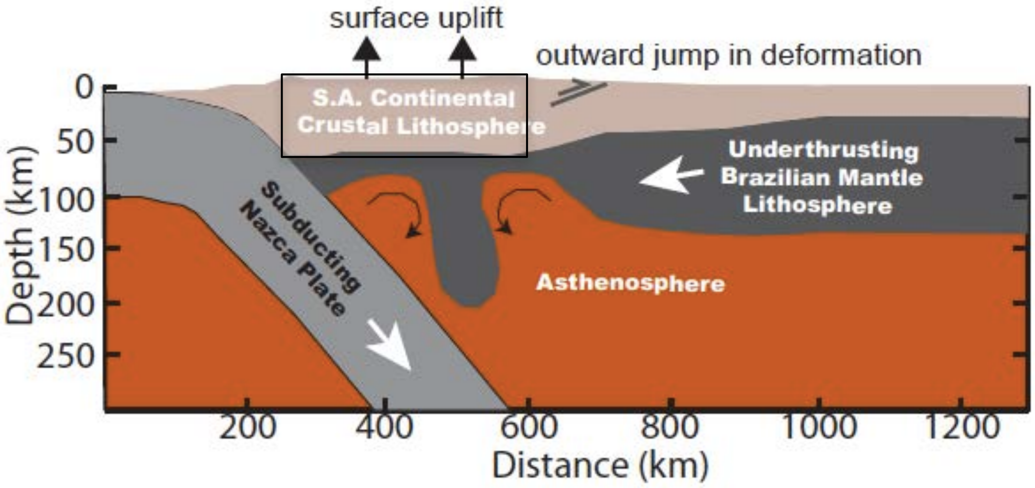
- Large step in Moho beneath Eastern Cordillera, suggesting that lower crust (eclogite) has been removed
- This region is associated with highest elevations and greatest magnitude of crustal thickening

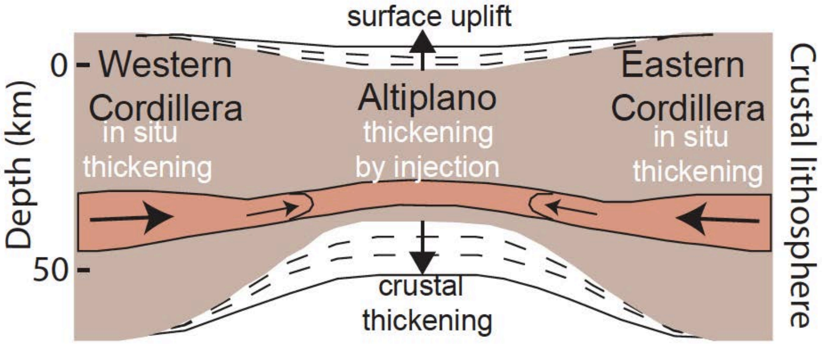


- High velocity AA anomaly suggests a portion of the lower lithosphere is still attached
- This region is associated with the lowest Altiplano elevations

Garzione et al. (2017, AREPS), from Ward et al. (2013, 2016) & Ryan et al. (2016)

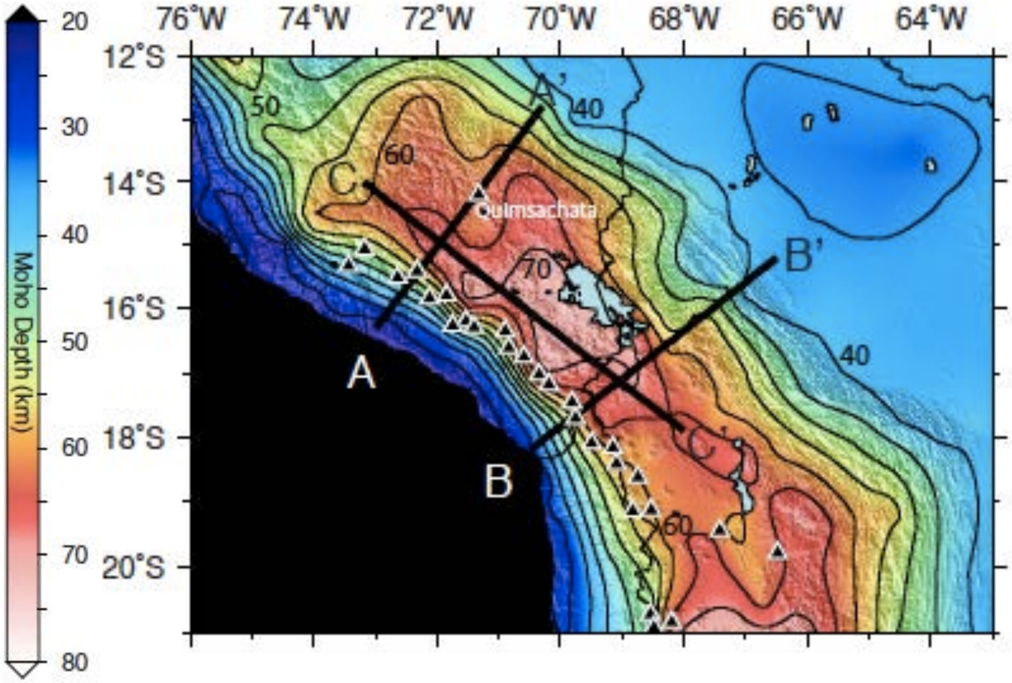
The case for lower crustal flow





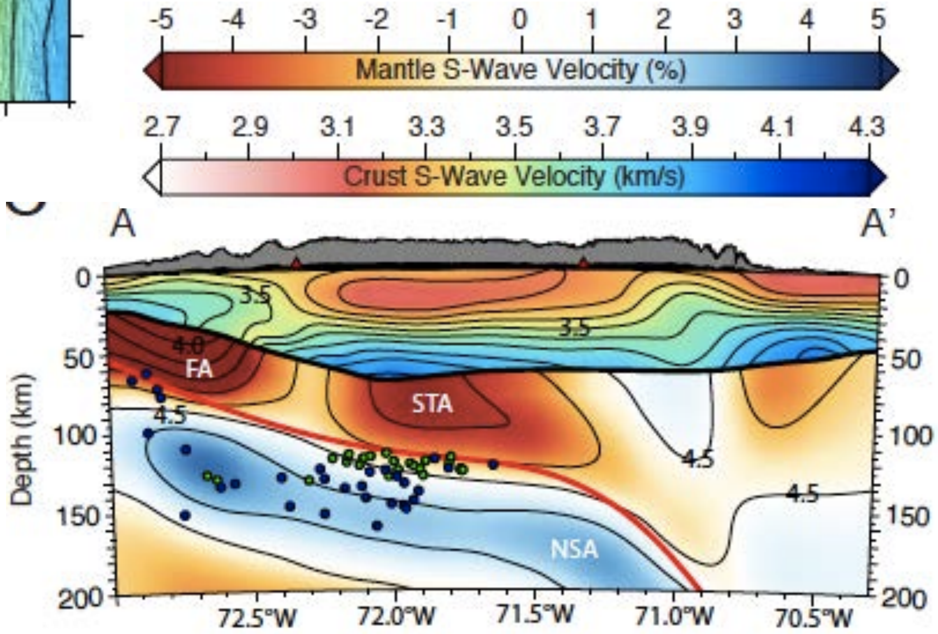
- Rapid surface uplift during time periods of crustal thickening that is decoupled from crustal shortening
- Modern crustal thickness exceeds that which can be accounted for by crustal shortening
- Trace element evidence for rapid crustal thickening in the absence of shortening
- Exhumation/incision events track both crustal thickening and surface uplift in the absence of shortening

Crustal thickness map (receiver functions) & Crustal/mantle structure



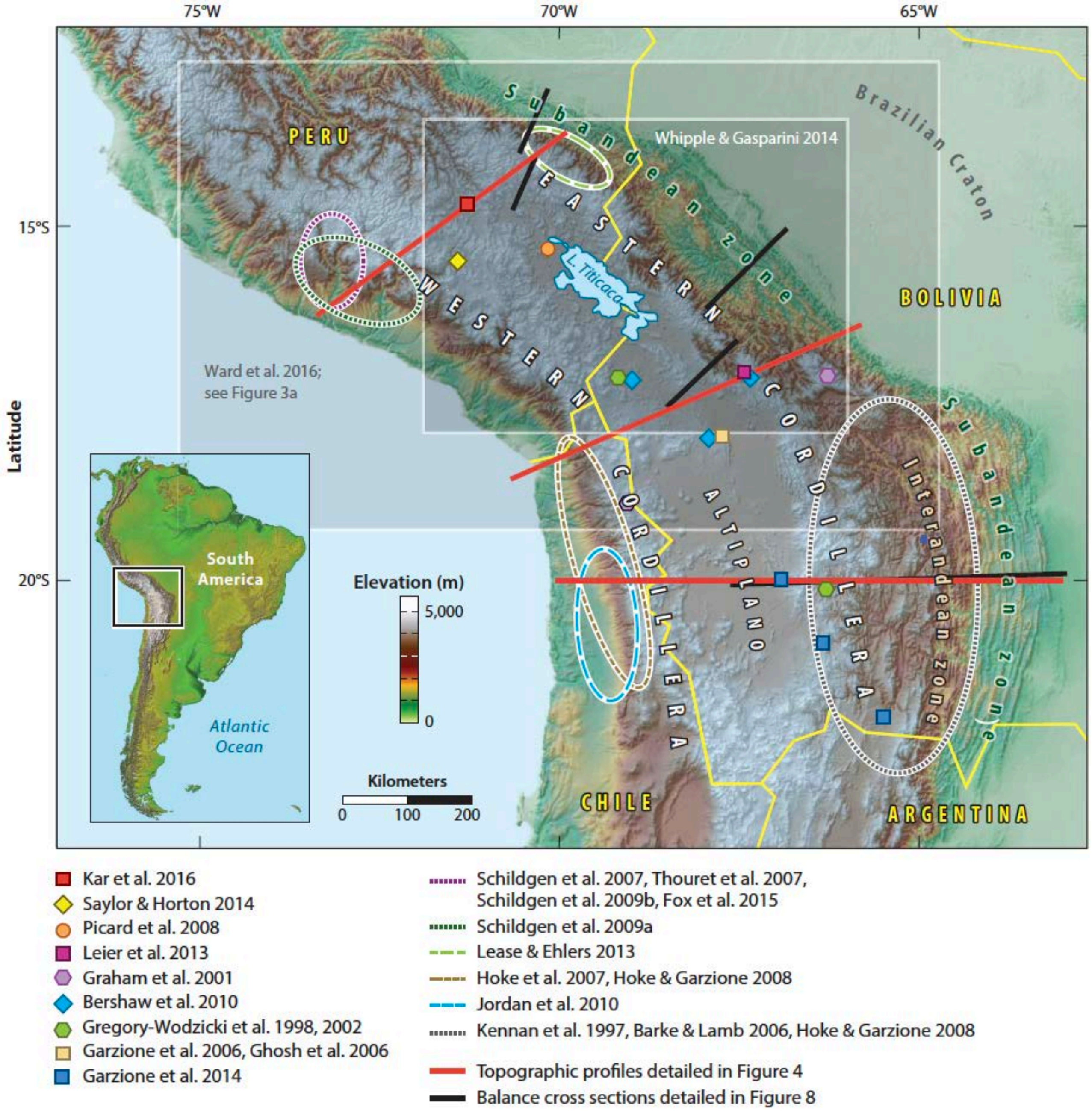
- Northern Altiplano shows greatest crustal thicknesses in excess of 70 km
- This region is associated with high elevations, but low magnitude of crustal shortening

- This region is associated with a mid. crustal low velocity zone



Garzione et al. (2017, AREPS), from Ward et al. (2013, 2016) & Ryan et al. (2016)

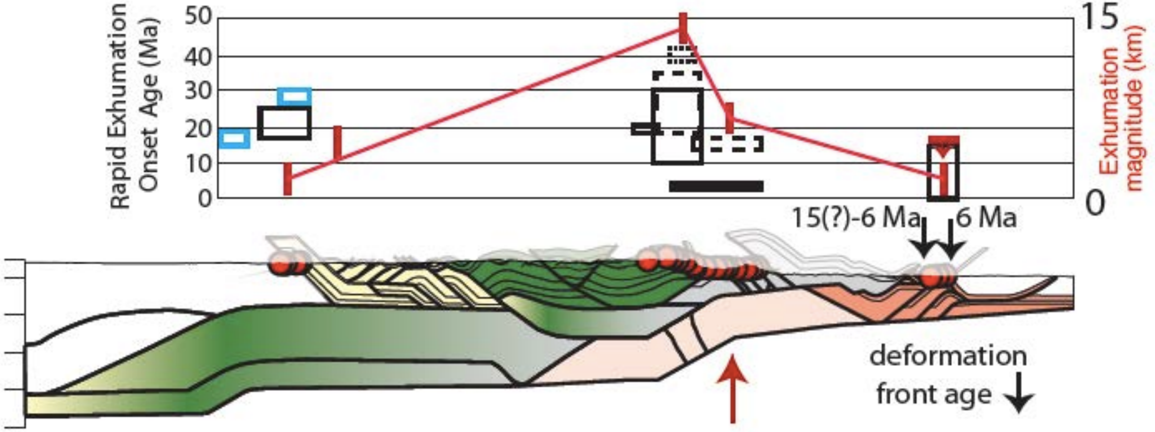
Along-strike variations in crustal shortening



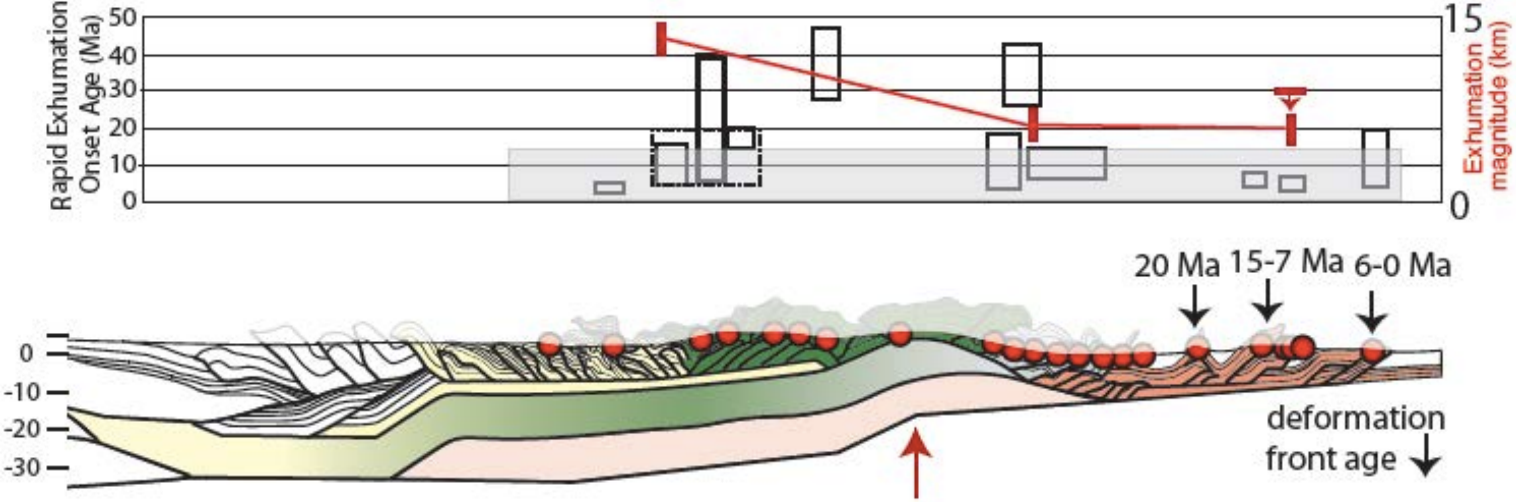
Garzione et al.
(2017, AREPS)

Crustal shortening history

Northern Central Andean Plateau

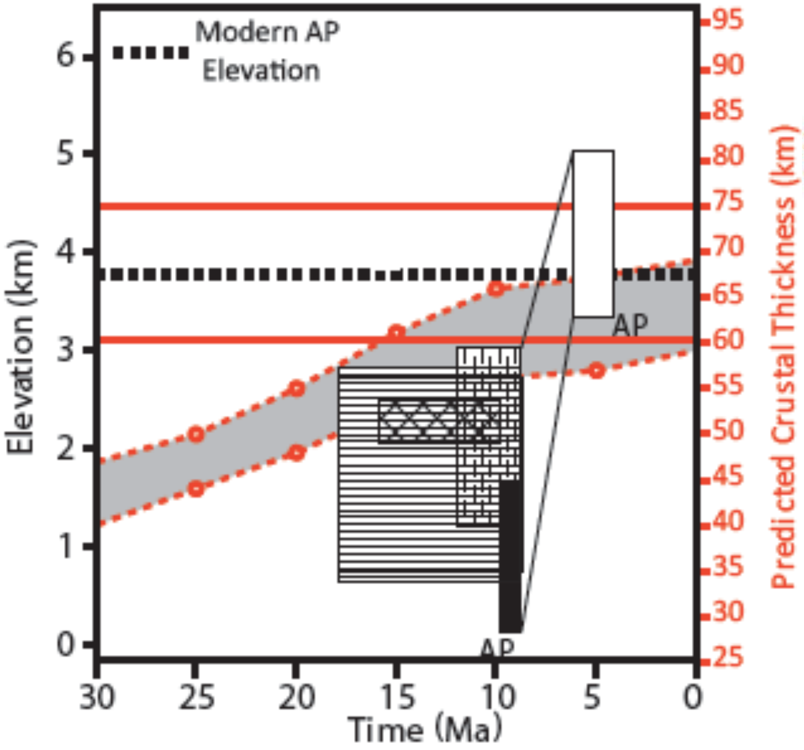

Exhumation timing and magnitude

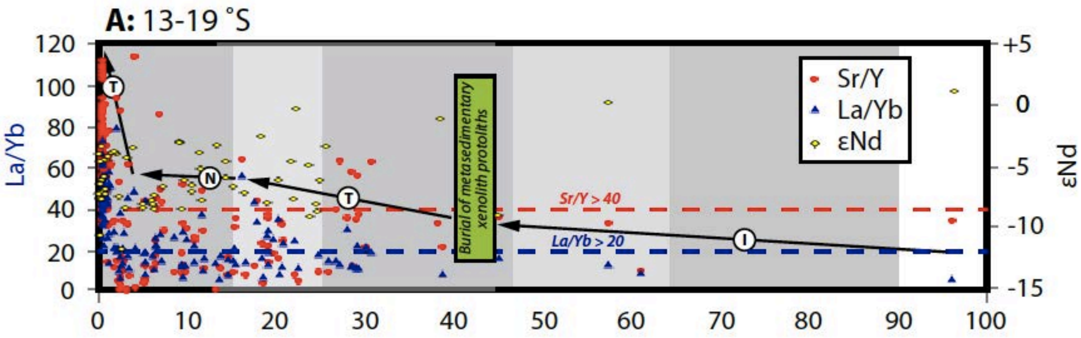
Central Central Andean Plateau


Exhumation timing and magnitude

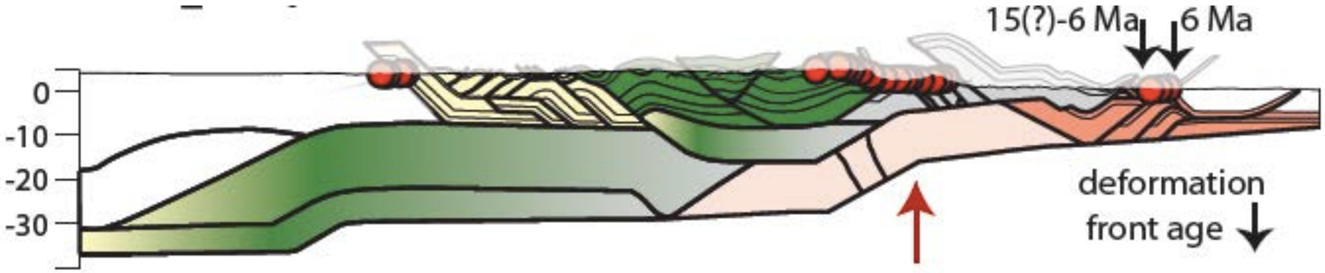
Garzione et al. (2017, AREPS), from McQuarrie et al. (2002), Barnes et al. (2012), Perez et al. (2016)

Crustal thickening versus surface uplift



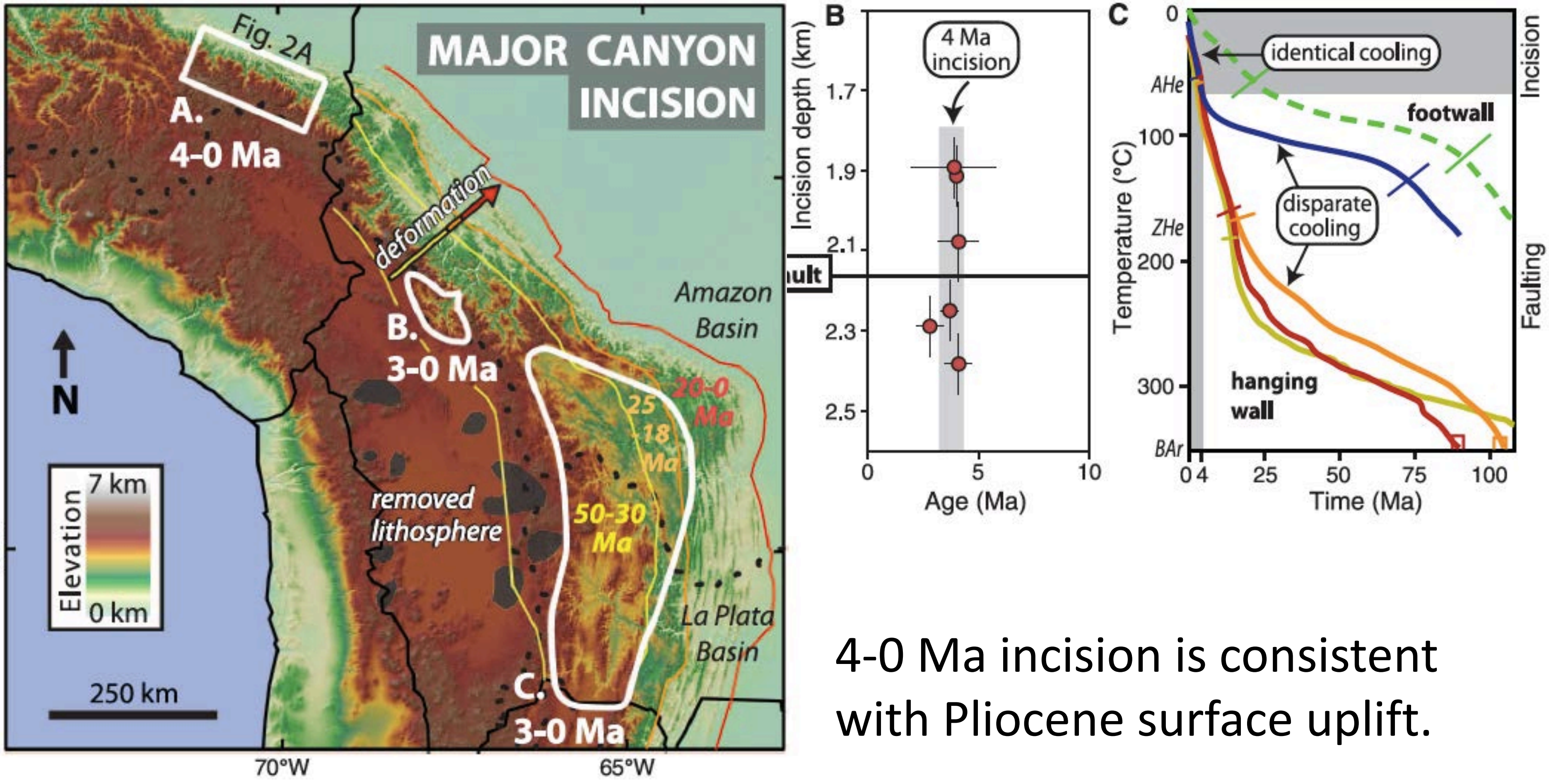


- Crustal shortening cannot account for the modern crustal thickness in this region
- Trace element ratios show that dramatic crustal thickening occurs after shortening ceased
- Simultaneous crustal thickening and surface uplift implicate crustal flow



Garzione et al. (2017, AREPS), from Eichelberger et al. (2015), Kar et al. (2016), Perez et al. (2016)

Pliocene–recent incision of the NE Andean plateau



4-0 Ma incision is consistent with Pliocene surface uplift.

Lease and Ehlers (2013)

Summary – Pulsed nature of surface uplift

- The central Central Andean Plateau shows at least two pulses of rapid surface uplift: early Miocene Eastern Cordillera and late Miocene Eastern Cordillera and Altiplano.

- In the Altiplano, rapid surface uplift propagates from south to north from middle Miocene to late Miocene/Pliocene time.

Evidence for lower lithosphere removal & lower crustal flow

- Crustal thickening predictions from balanced cross sections show thickness excess in regions that have experienced multiple pulses of surface uplift → suggests convective removal of eclogitic lower crust

- The northernmost portion of the Andean plateau lacks the magnitude of crustal shortening required to account for the modern crustal thickness → suggests crustal flow into this region

- In the northernmost portion of the Andes, HREE depletion (i.e., high La/Yb) over past ~5 Ma suggests crustal thickening in the absence of crustal shortening over the same time period as surface uplift →suggests crustal flow into this region