The Taiwan Arc-Continent Collision
Not-So-Old Orogen

Many collaborators: Ruey-Juin Rau, Yuan-Hsi Lee, Hao Kuo-Chen, Hsin-Hua Huang,
Huang and many others...

Support from NSF, NSC and UConn Research Foundation

Active Dehydration, Detachment and Exhumation of Thinned Continental Crust in an Arc-Continent Collision, Taiwan

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Yuan-Hsi Lee, Hao Kuo-Chen, Hsin-Hua
Huang,
Huang and many others...

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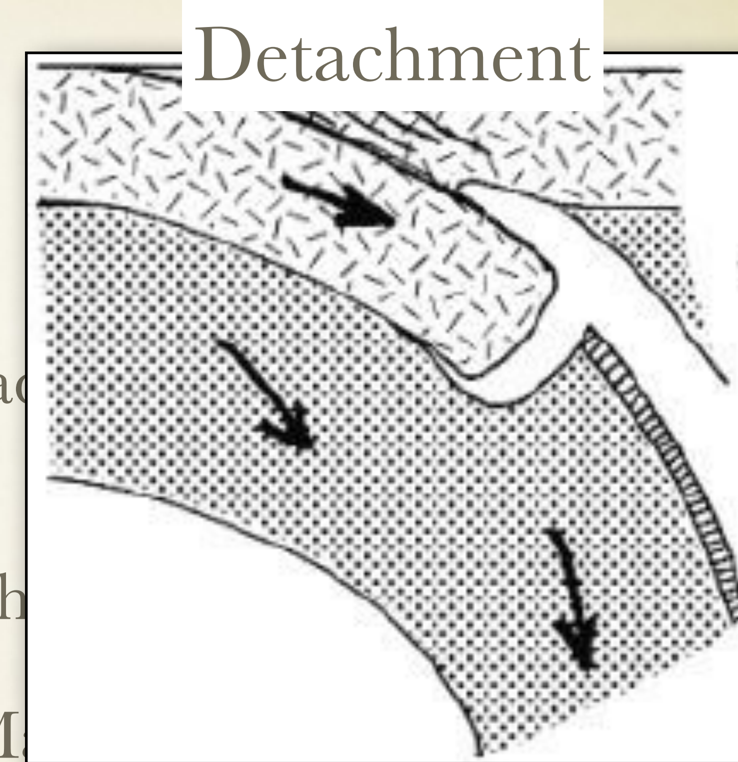
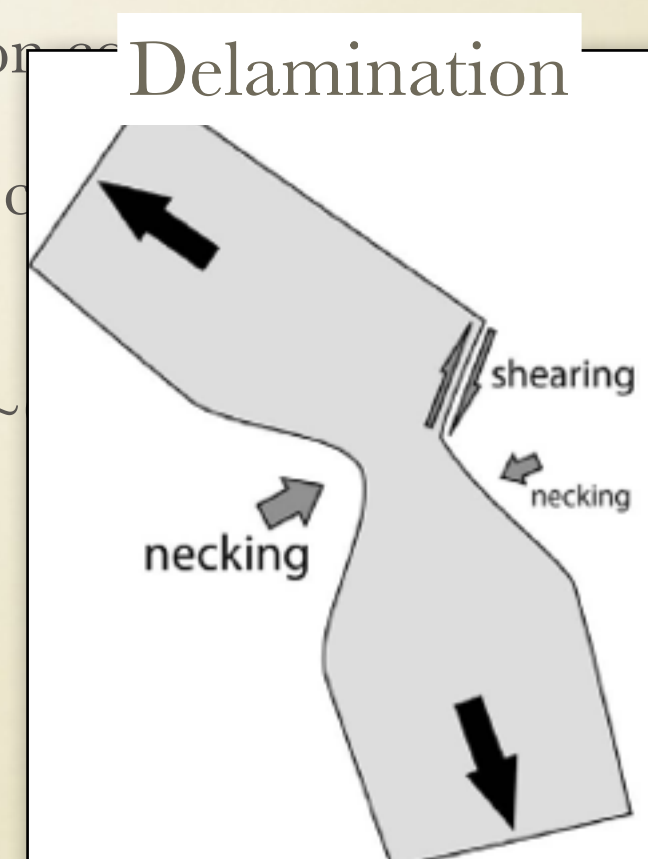
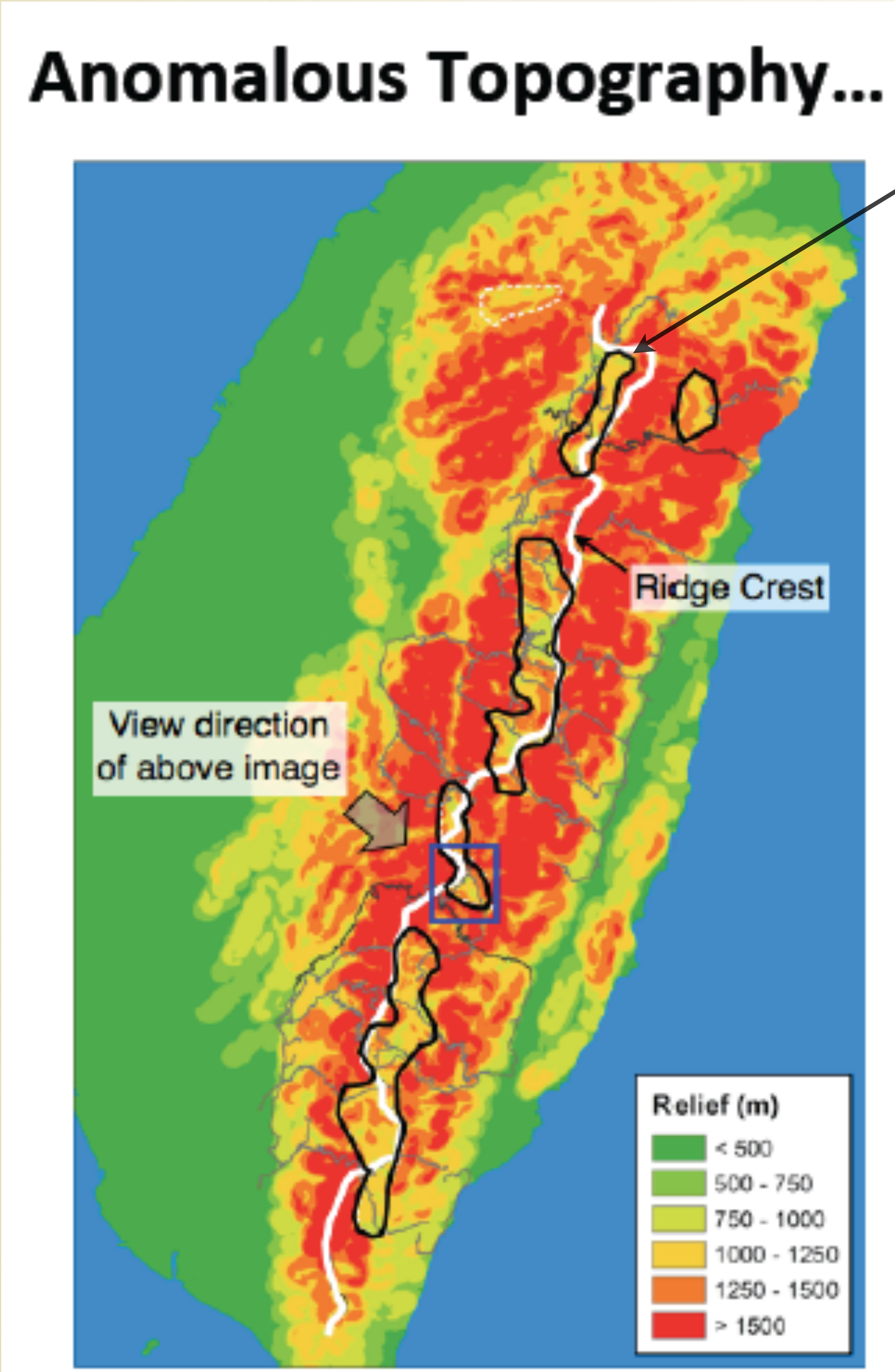
Outline

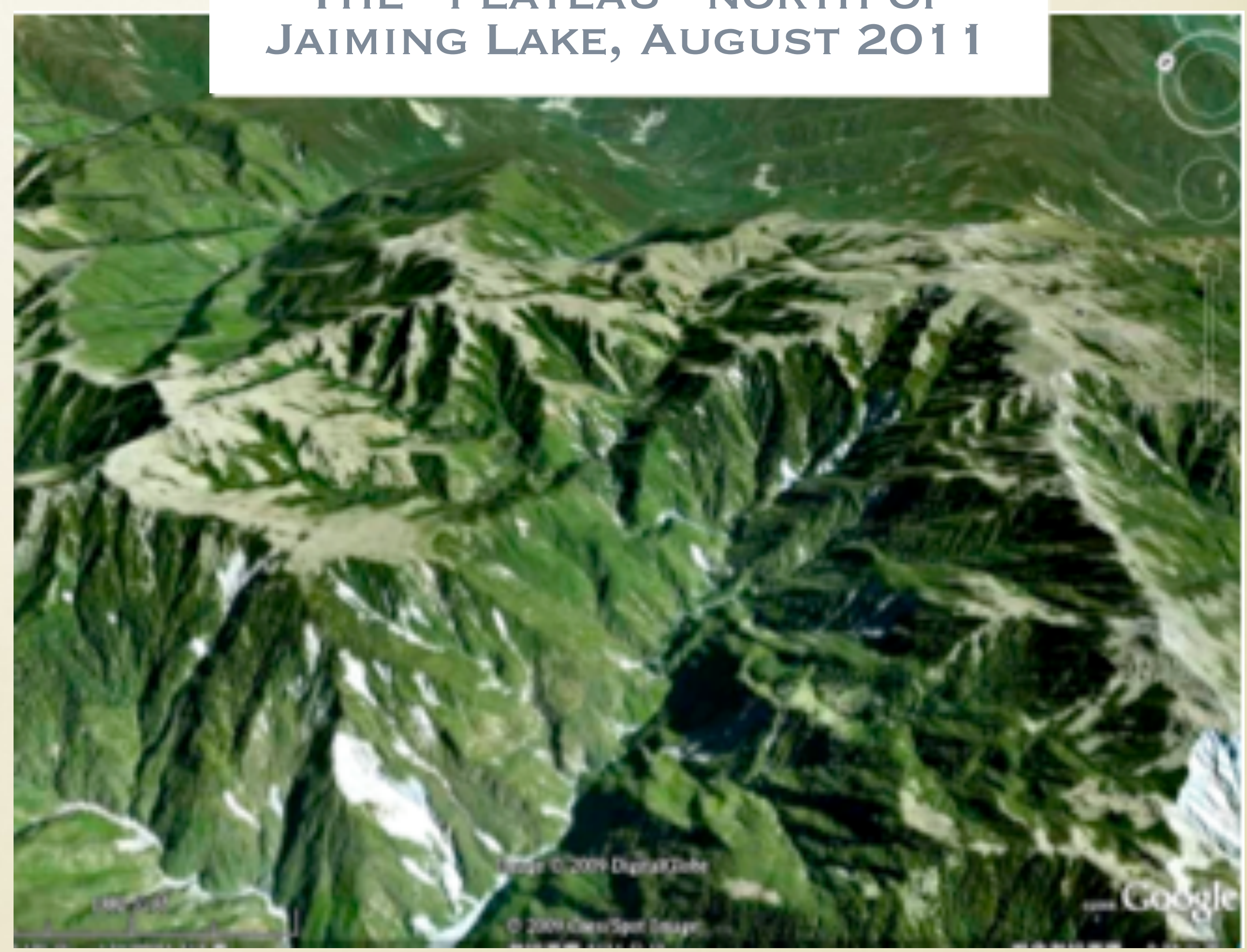
1. Arc-continent collision - classic example of a subaerial, stead
   prism… maybe not…
   - ✦ Areas of anomalous - Low Relief - topography at high
   - ✦ “Parallel” collision with stretched continental at ~5 M
2. More recent research
   - ✦ Age-elevation transects show acceleration in exhumation
   - ✦ Seismic tomography shows crustal imbrication along a d
     marked by seismic tremors
   - ✦ Plate reconstructions for PSP - doubling of PC vector ~
3. Are lithospheric scale processes needed? For example:
   - ✦ Crustal detachment or   Today
   - ✦ Lithospheric delamination





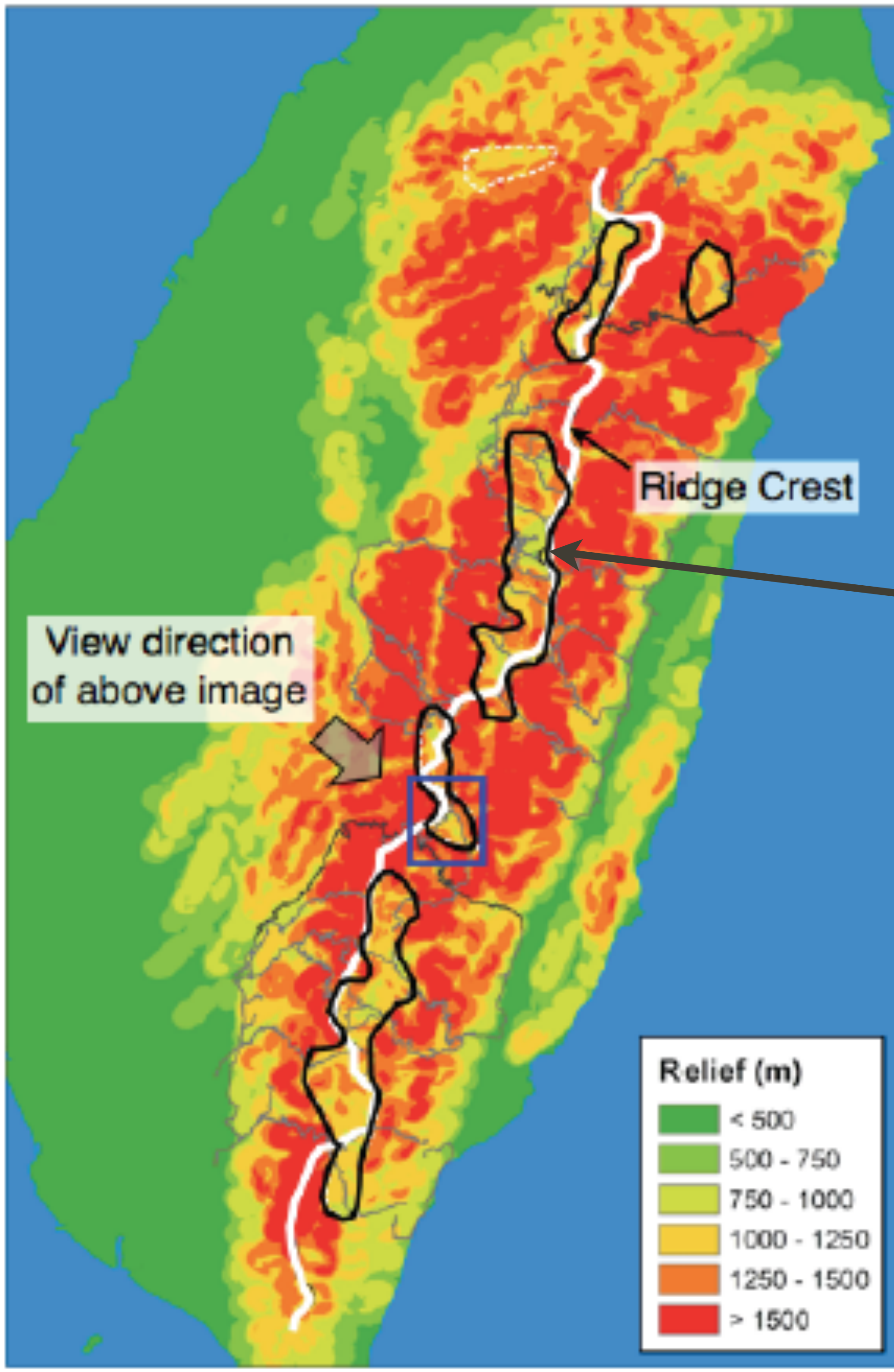


Large areas (20-100 sq km) of anomalously low relief in the higher elevations of the Central Range



THE "PLATEAU" NORTH OF JAIMING LAKE, AUGUST 2011

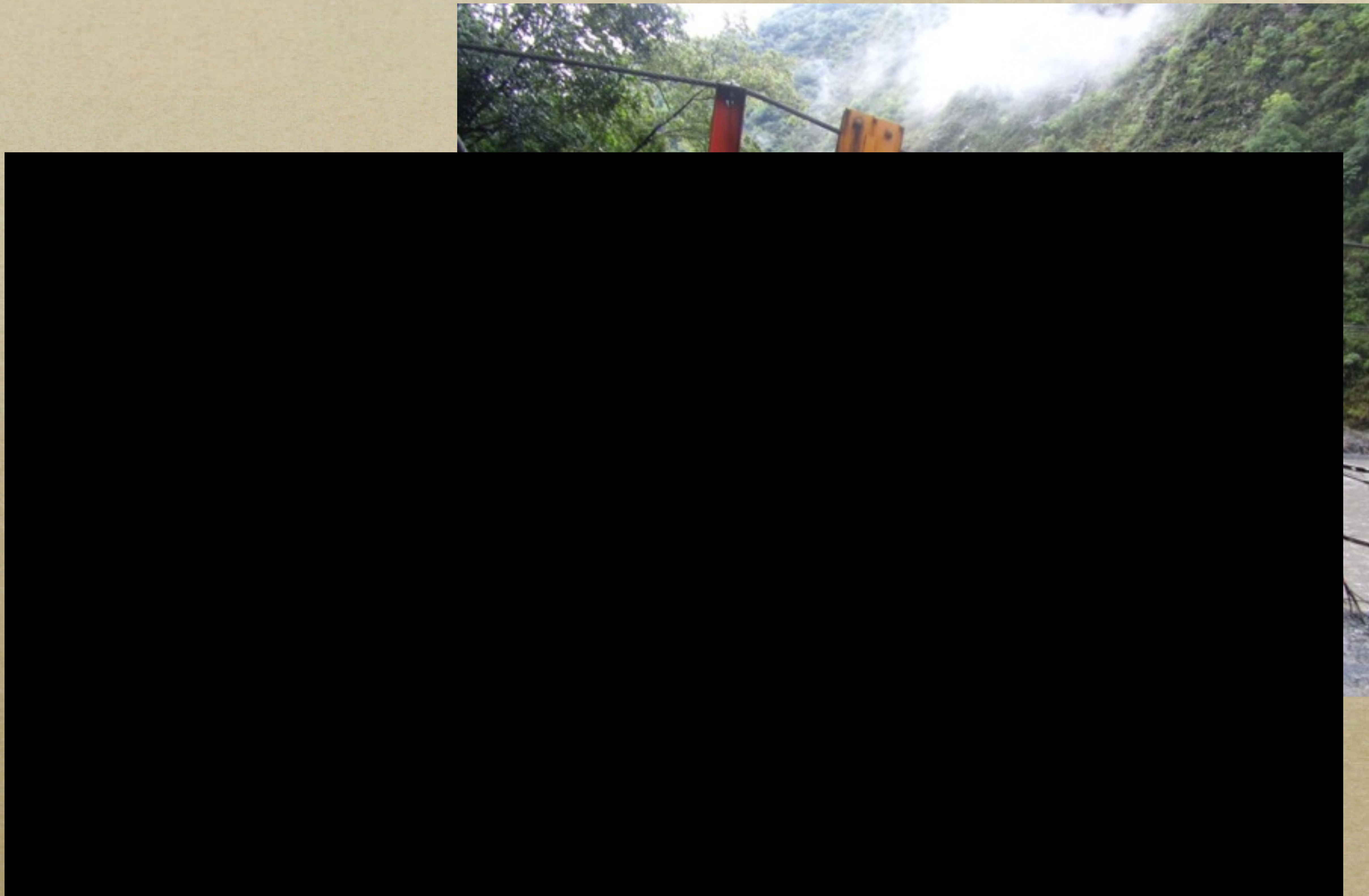
Anomalous Topography...



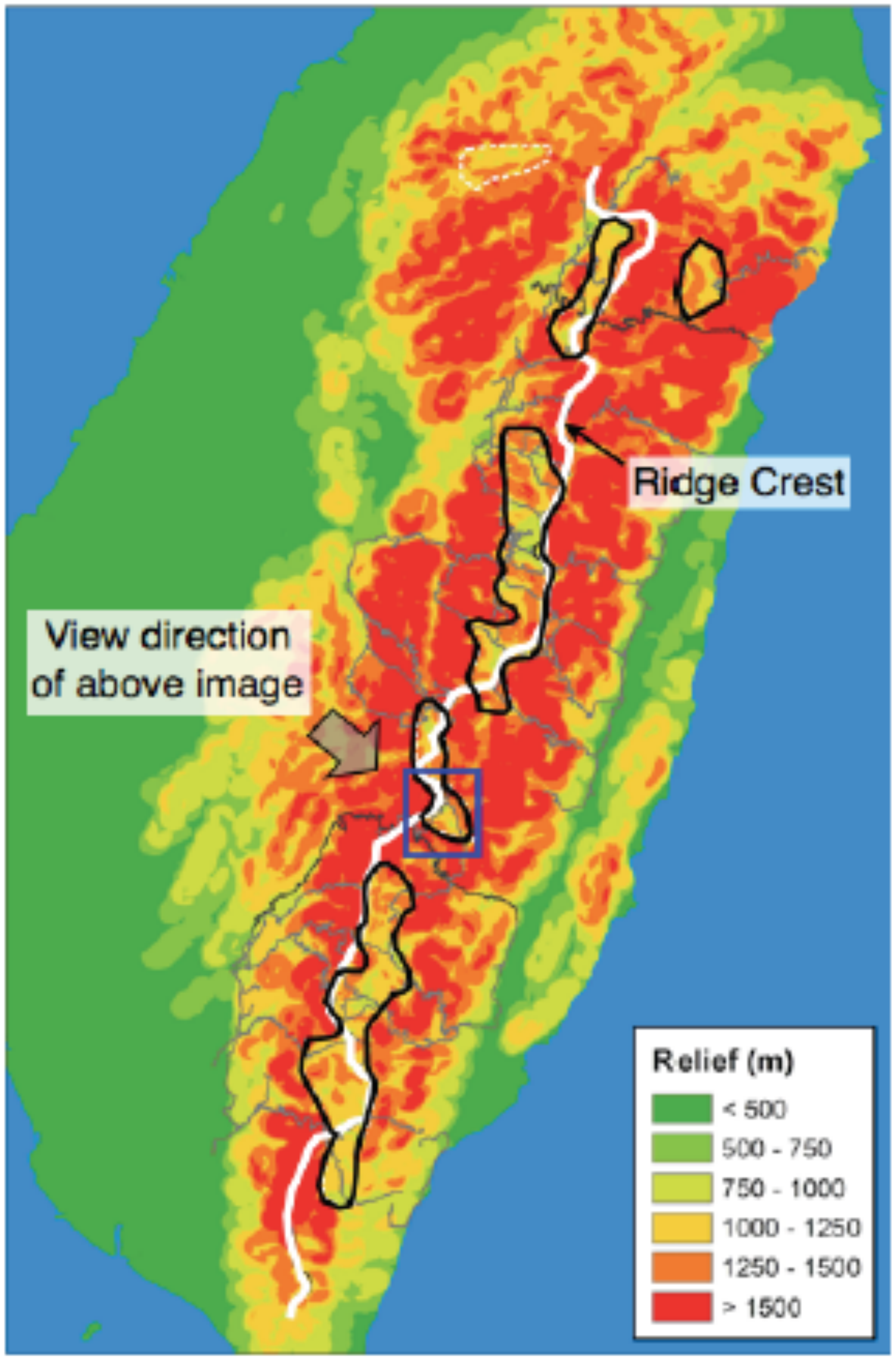
Most recent field expedition:

Seven Colors Lake area
April-May, 2013


Image Landsat
Image © 2013 DigitalGlobe
© 2013 Cnes/Spot Image
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google earth
Imag 2010 Date: 9/10/2013
23°46'19.41" N 121°12'13.52" E elev 8921 ft
eye alt 22778 ft

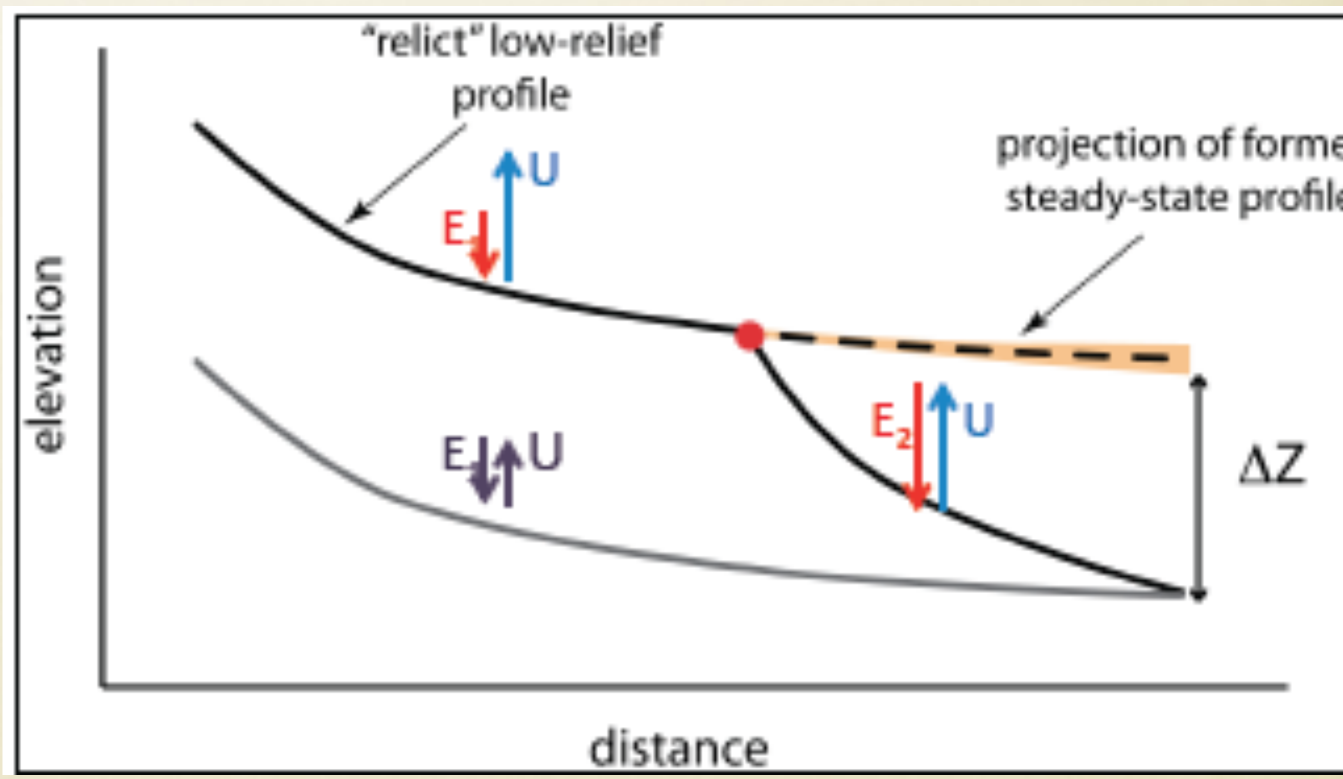



Anomalous Topography…

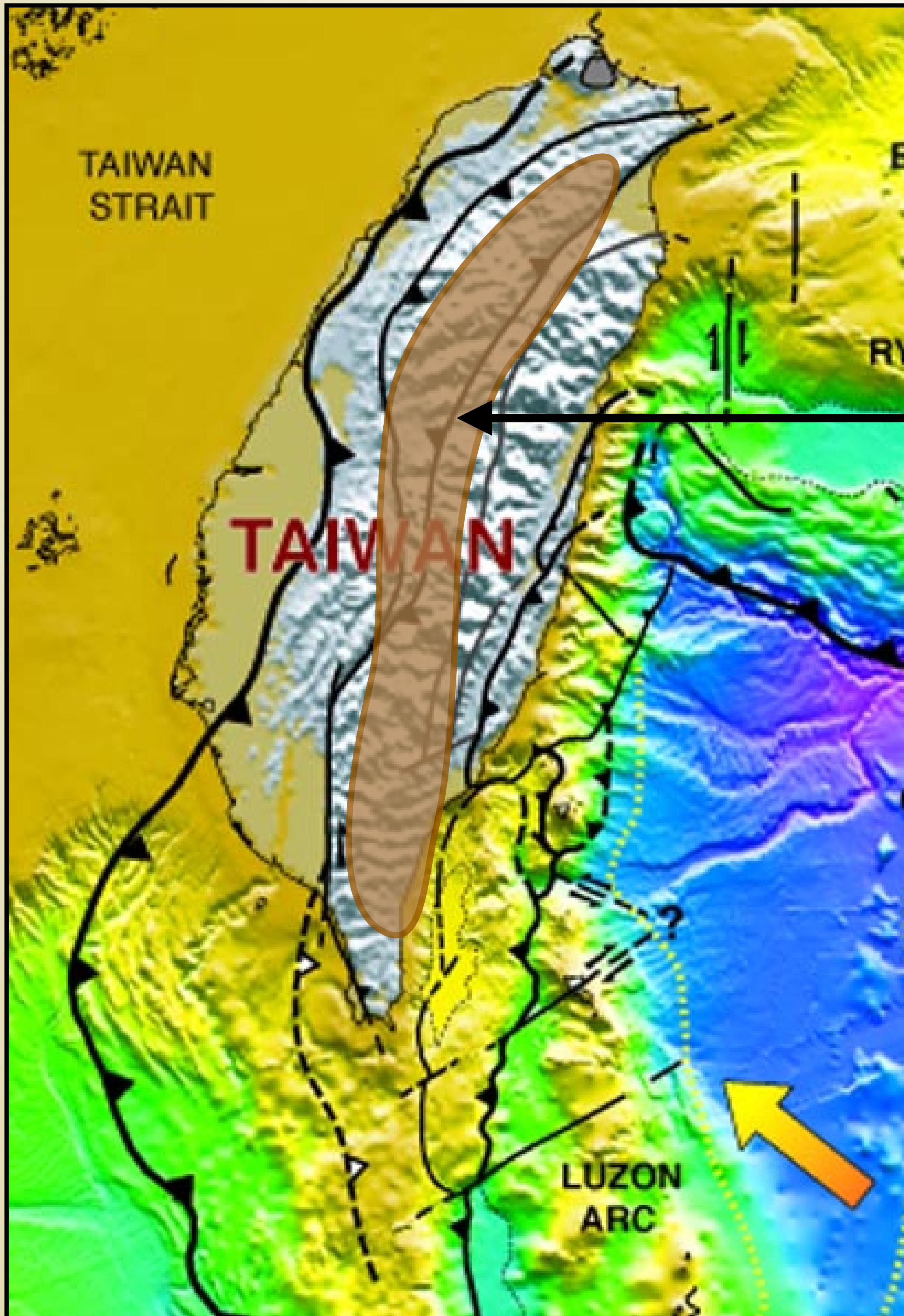


Hypothesis:

Areas of subdued, low slope topography are eroding slowing and represent a relict landscape that formed prior to a recent acceleration in rock uplift rate



When did the collision start and did it propagate?



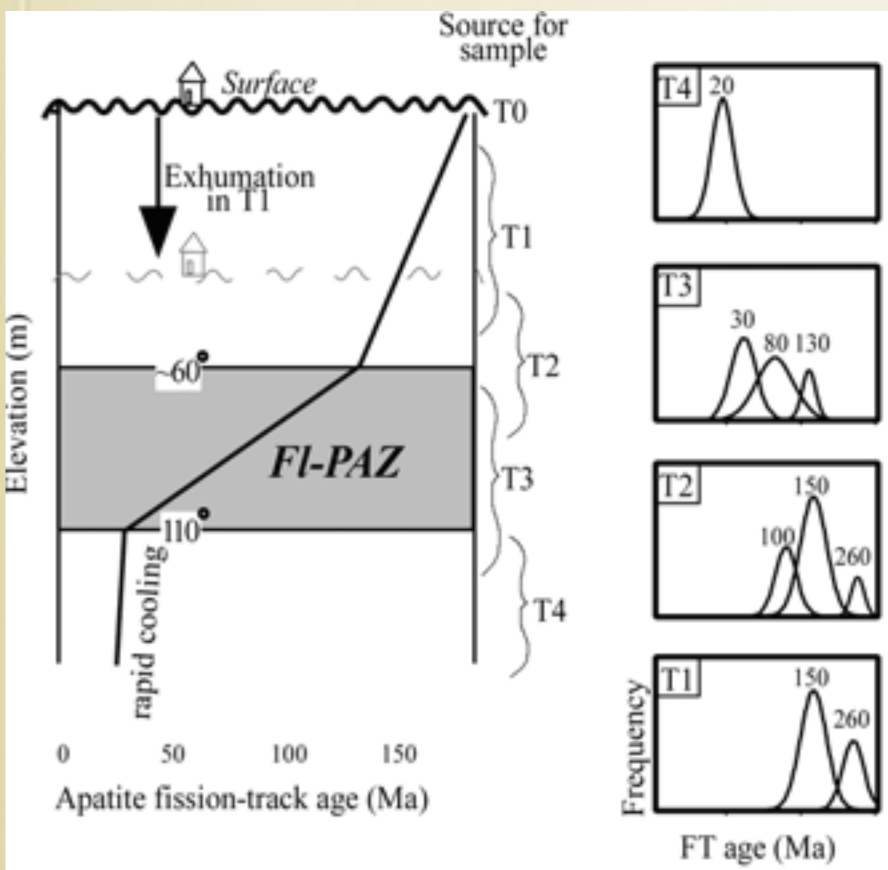
Collected sandstone samples from the highest peaks in the Hsuehshan and southern Cenral Range

- looking for detrital zircon grains with totally reset fission track ages

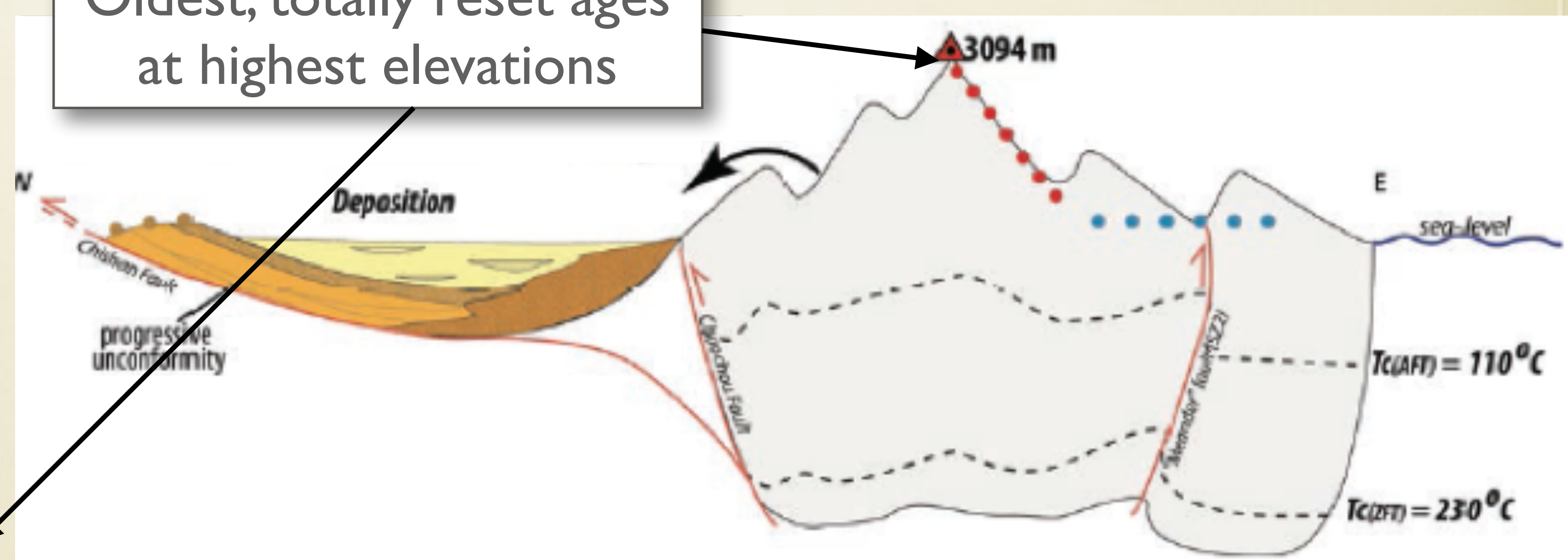
Table 2 Closure parameters for He and FT dating

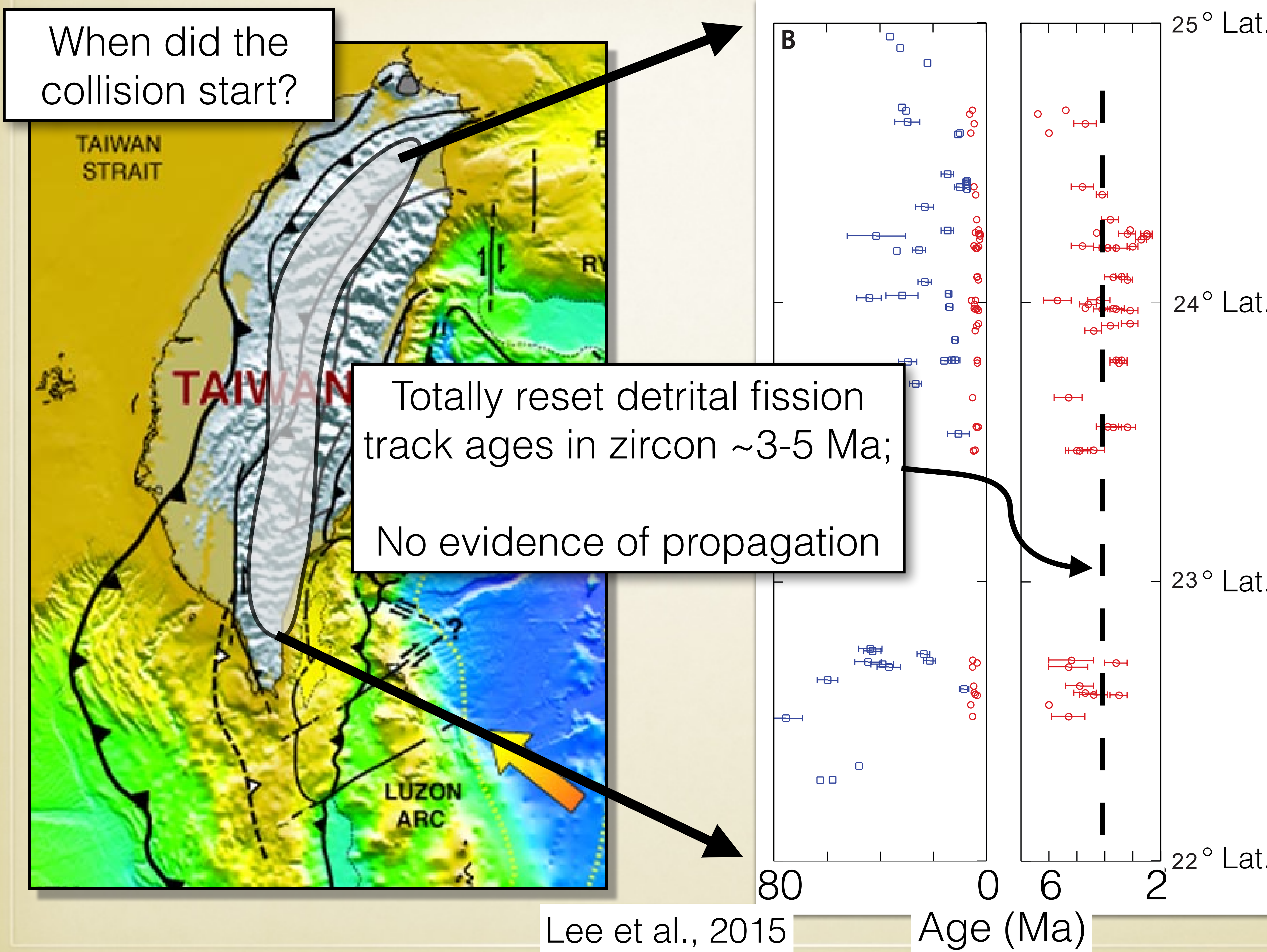
Method (references)	E_a (kJ mol^{-1})	D_0 (cm^2 s^{-1})	a_s[1] (μm)	Ω[2] (s^{-1})	$T_{c,10}$[3] (C)
(U-Th)/He apatite (Farley 2000)	138	50	60	7.64×10^7	67
(U-Th)/He zircon (Reiners et al. 2004)	169	0.46	60	7.03×10^5	183
(U-Th)/He titanite (Reiners & Farley 1999)	187	60	150	1.47×10^7	200
FT apatite[4] (average composition[5]) (Ketcham et al. 1999)	147	—	—	2.05×10^6	116
FT Renfrew apatite[6] (low retentivity) (Ketcham et al. 1999)	138	—	—	5.08×10^5	104
FT Tioga apatite[6] (high retentivity) (Ketcham et al. 1999)	187	—	—	1.57×10^8	177
FT zircon[4] (natural, radiation damaged) (Brandon et al. 1998)	208	—	—	1.00×10^8	232

Reiners and Brandon, 2006

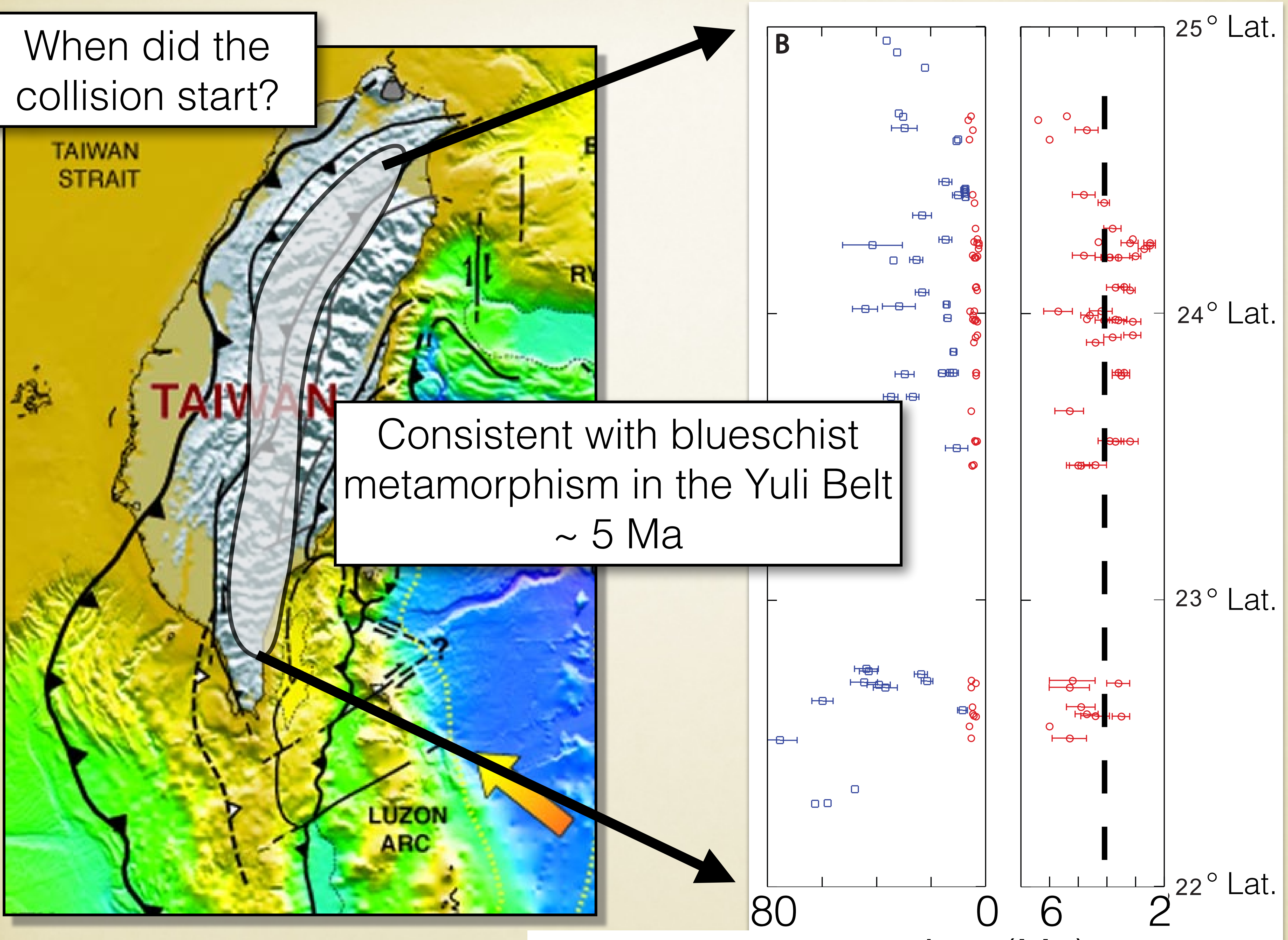


Oldest, totally reset ages at highest elevations




When did the collision start?
TAIWAN STRAIT
TAIWAN
LUZON ARC
Totally reset detrital fission track ages in zircon ~3-5 Ma;
No evidence of propagation
B
25° Lat.
24° Lat.
23° Lat.
22° Lat.
80
0
6
2
Age (Ma)
Lee et al., 2015

When did the collision start?

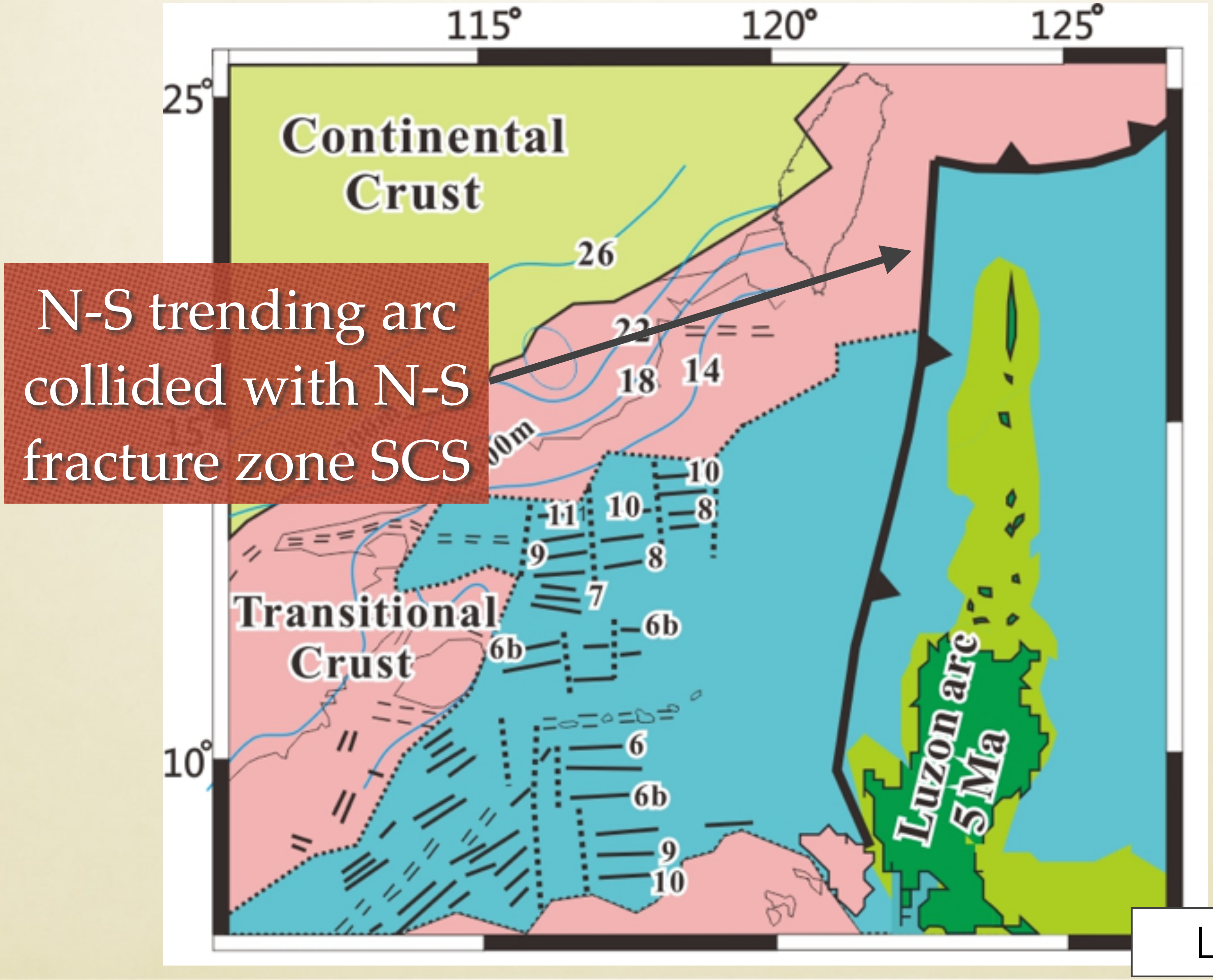


Consistent with blueschist metamorphism in the Yuli Belt ~ 5 Ma

Lee et al., 2015

Alternative Tectonic Setting:

Arc collided with, and partially consumed, a wide zone of thinned continental crust that probably contained N-S trending fracture zones

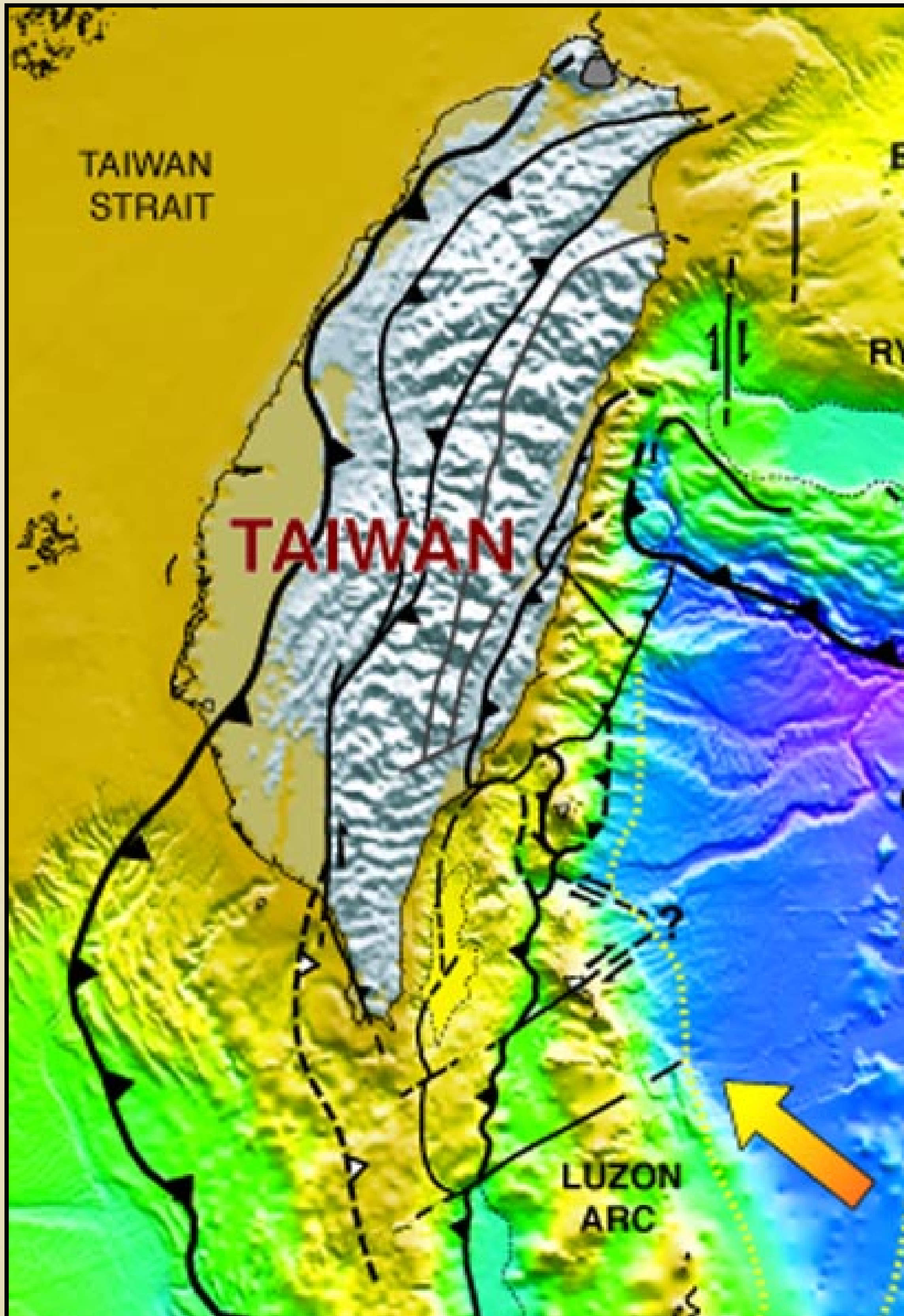


Lee et al., 2015

Recent Observations

- Age-elevation transects show acceleration, up to 5 km/Ma, in exhumation cooling ~2 Ma in both northern and southern Taiwan
  - Yuli Belt metamorphosed to blueschist facies ~5 Ma => some form of tectonic exhumation
- Seismic tomography shows crustal imbrication along a crustal-scale shear zone marked by seismic tremors
- Plate reconstructions for PSP suggest doubling of the rate of convergence < 1 Ma
  - AHe and leveling data suggest 2nd acceleration in uplift/exhumation ~0.5 Ma

Exhumation Cooling



Fission track and (U-Th)/He ages of totally reset detrital zircon and apatite grains - as a proxy for uplift:

- When did th
  — Oldest
  track ages

4-5 Ma
(Lee et al., 2015)

- History of exhumation?
  — Age-elevation plots along the length of the orogen

Table 2 Closure parameters for He and FT dating

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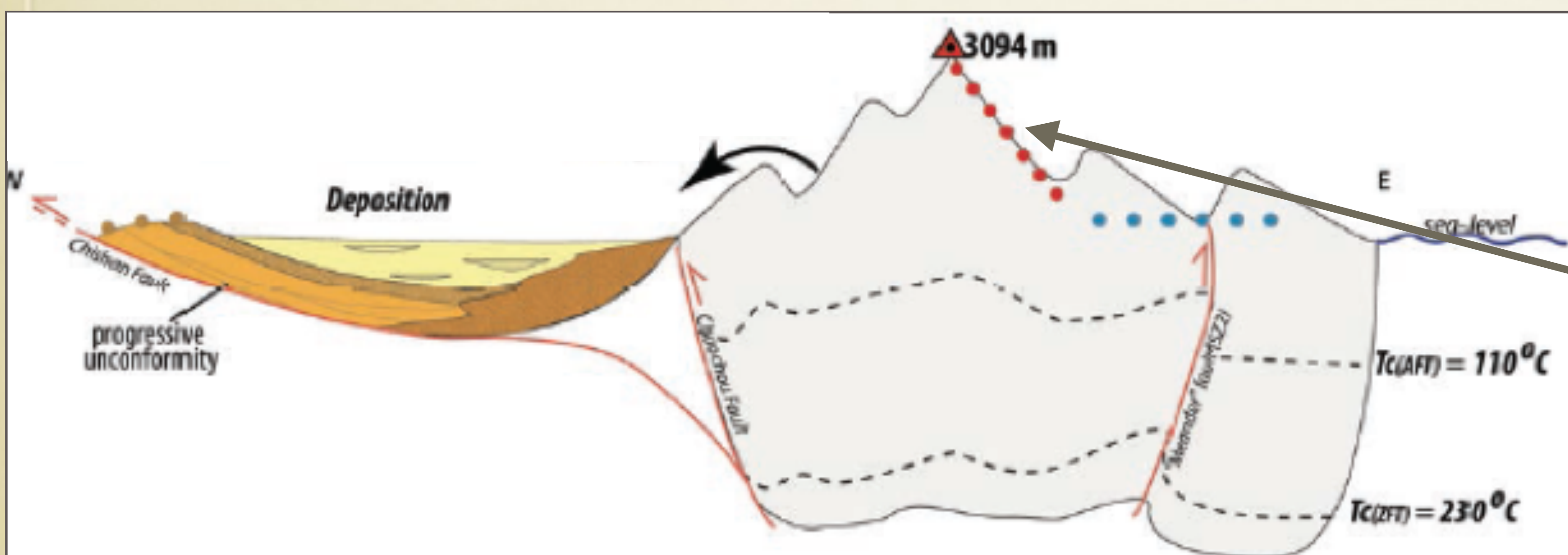
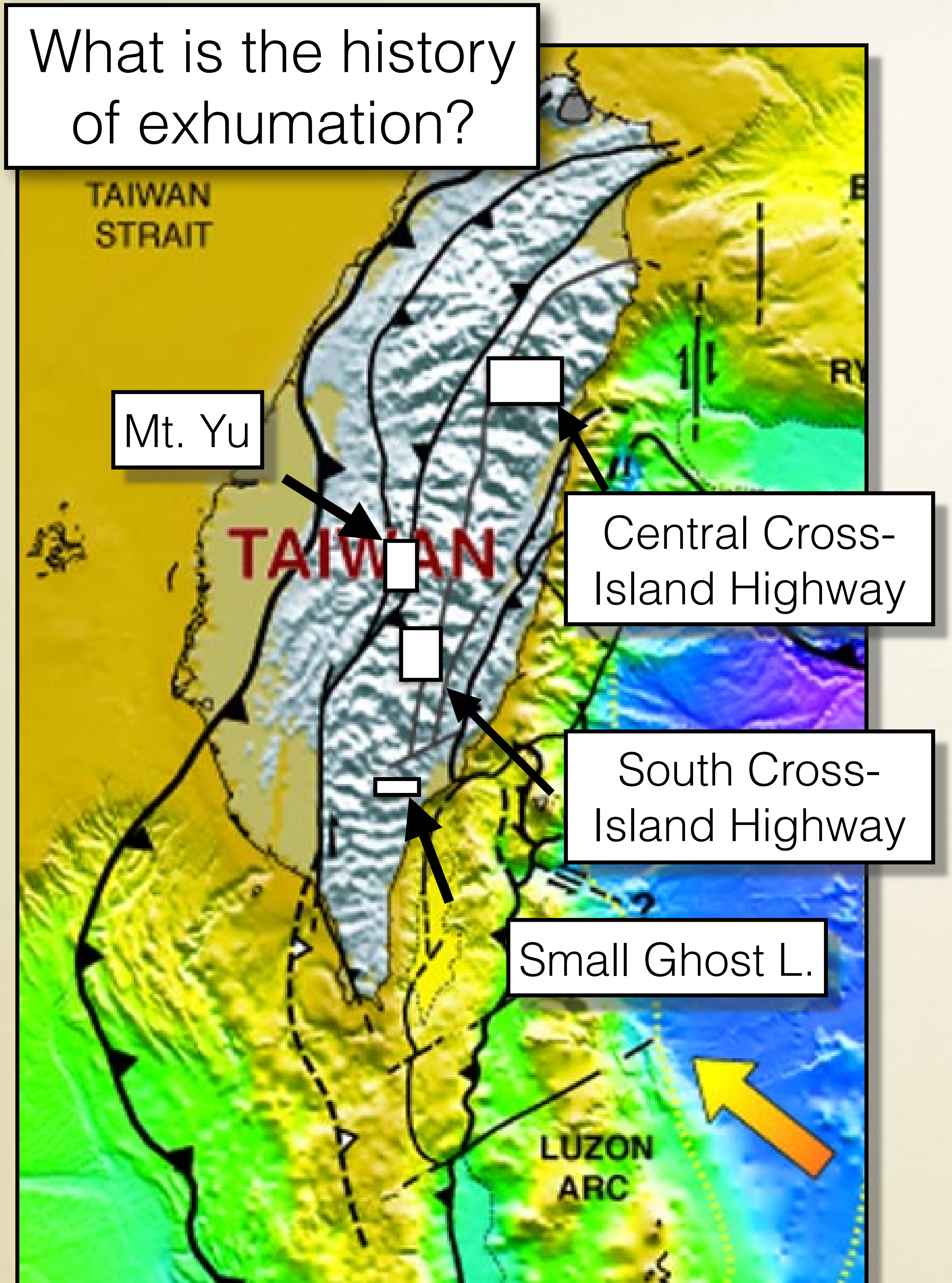
Reiners and Brandon, 2006



Vertical transect should have older ages at higher elevations and younger ages at lower elevation

Yield: rate of exhumation cooling independent of geothermal gradient

Age-elevation Transects

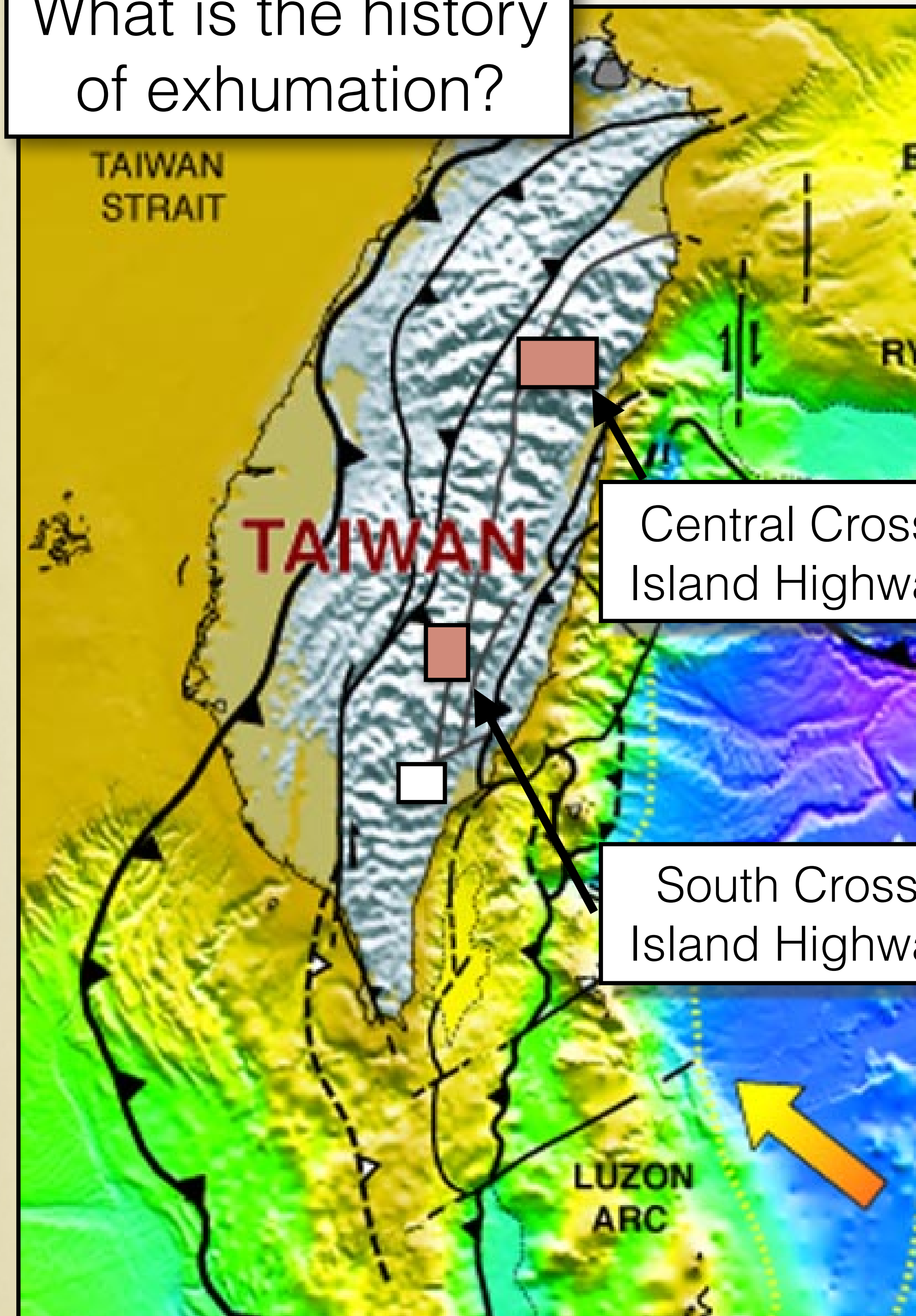


Four new age-elevation transects along strike in the eastern Central Range constrain exhumation cooling

Hsu et al., 2016, *Geology*
—Tsao et al., 1992, *Acta Geological Taiwanica*;
— Beyssac et al., 2007, *Tectonics*

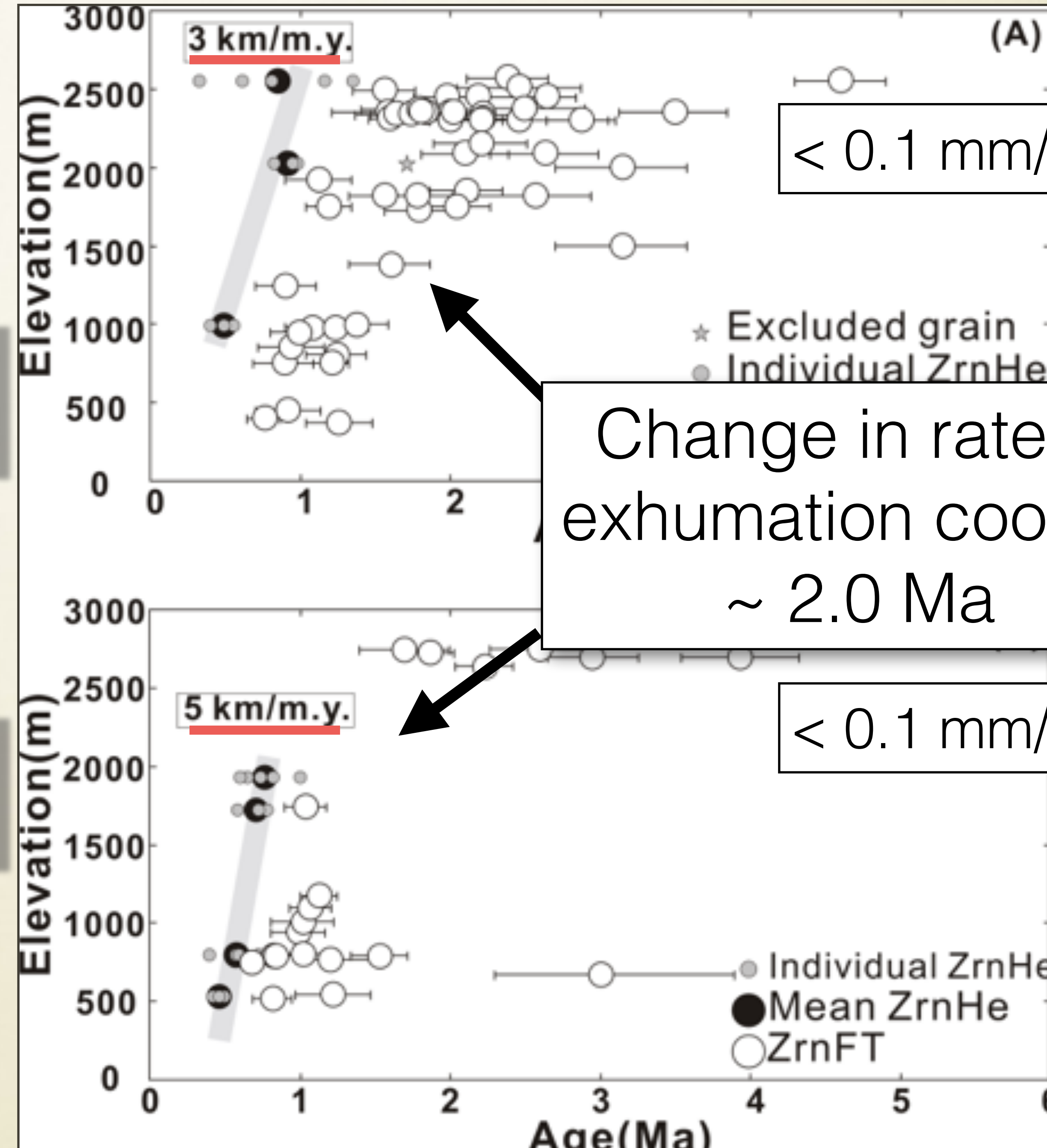
Age-elevation Transects

What is the history of exhumation?



Central Cross-Island Highway

South Cross-Island Highway



< 0.1 mm/yr

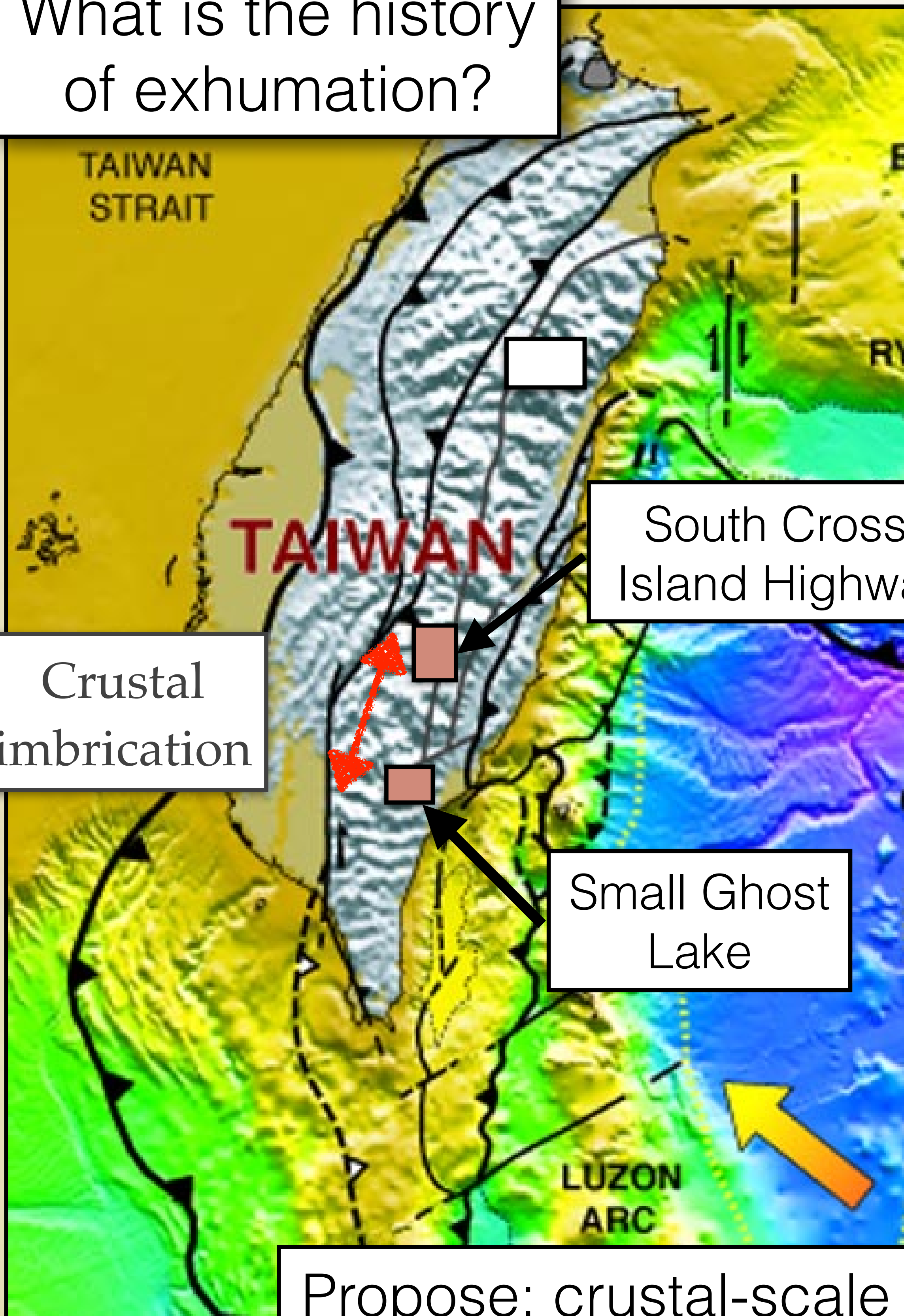
Change in rate of exhumation cooling ~ 2.0 Ma

< 0.1 mm/yr

Hsu et al., 2016;
ZFt from Tsao et al., 1992;
ZHe from Beyssac et al., 2007

Age-elevation Transects

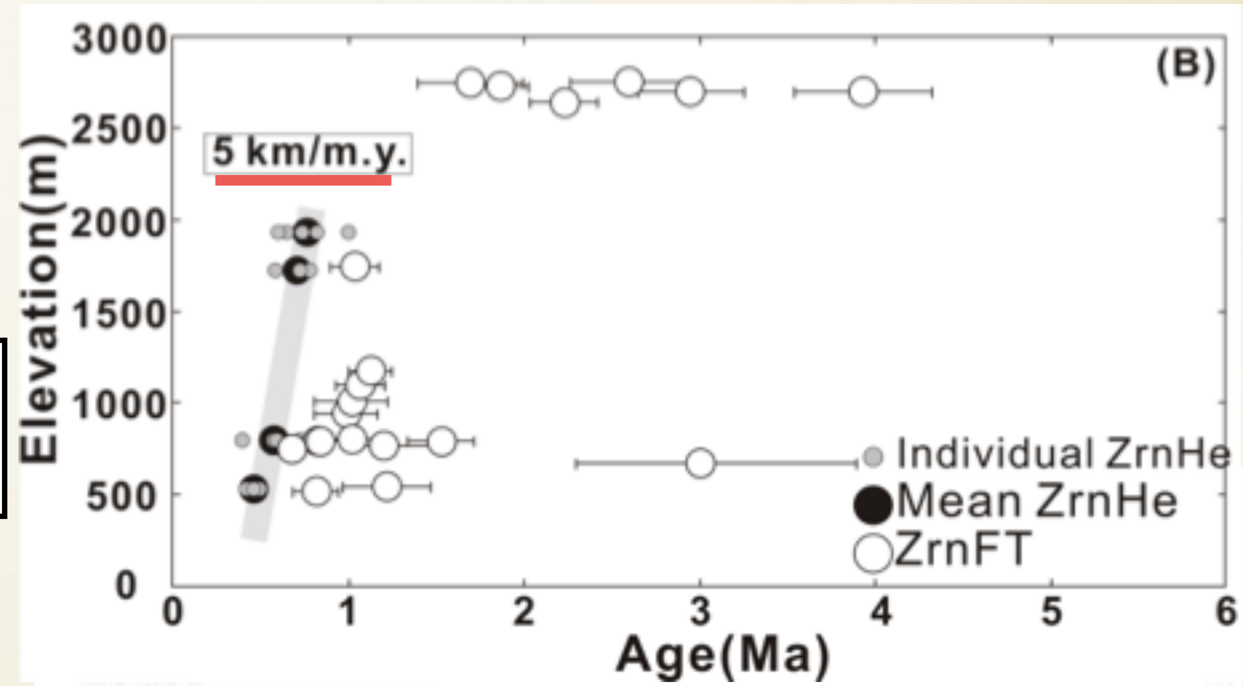
What is the history of exhumation?

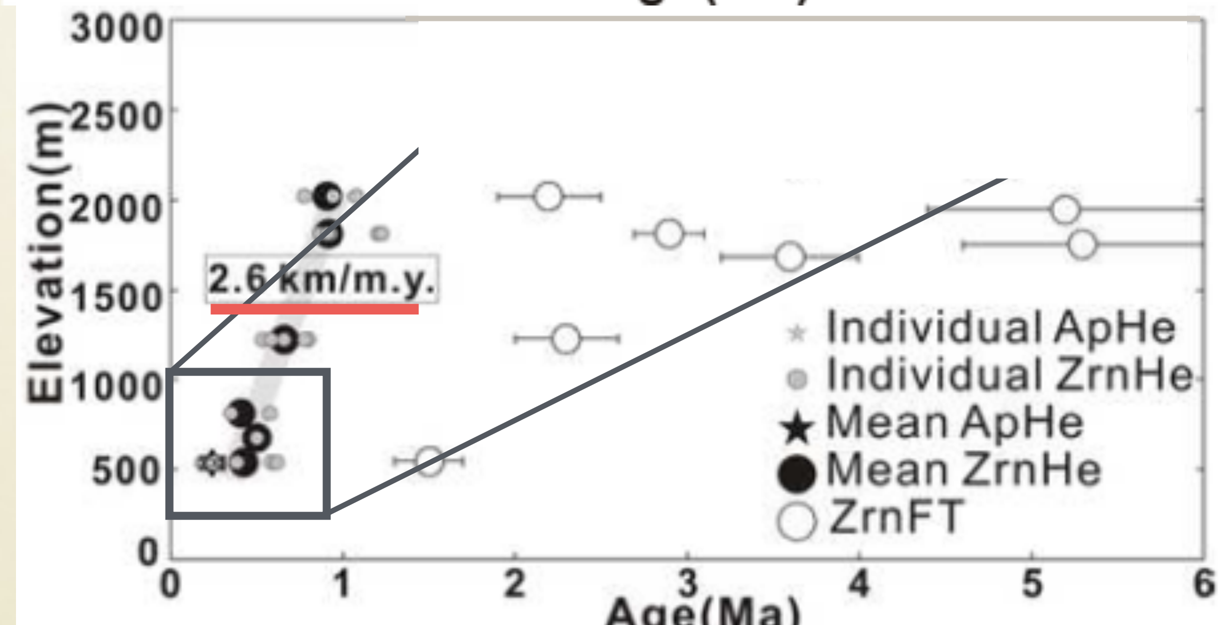


South Cross-Island Highway

Crustal imbrication

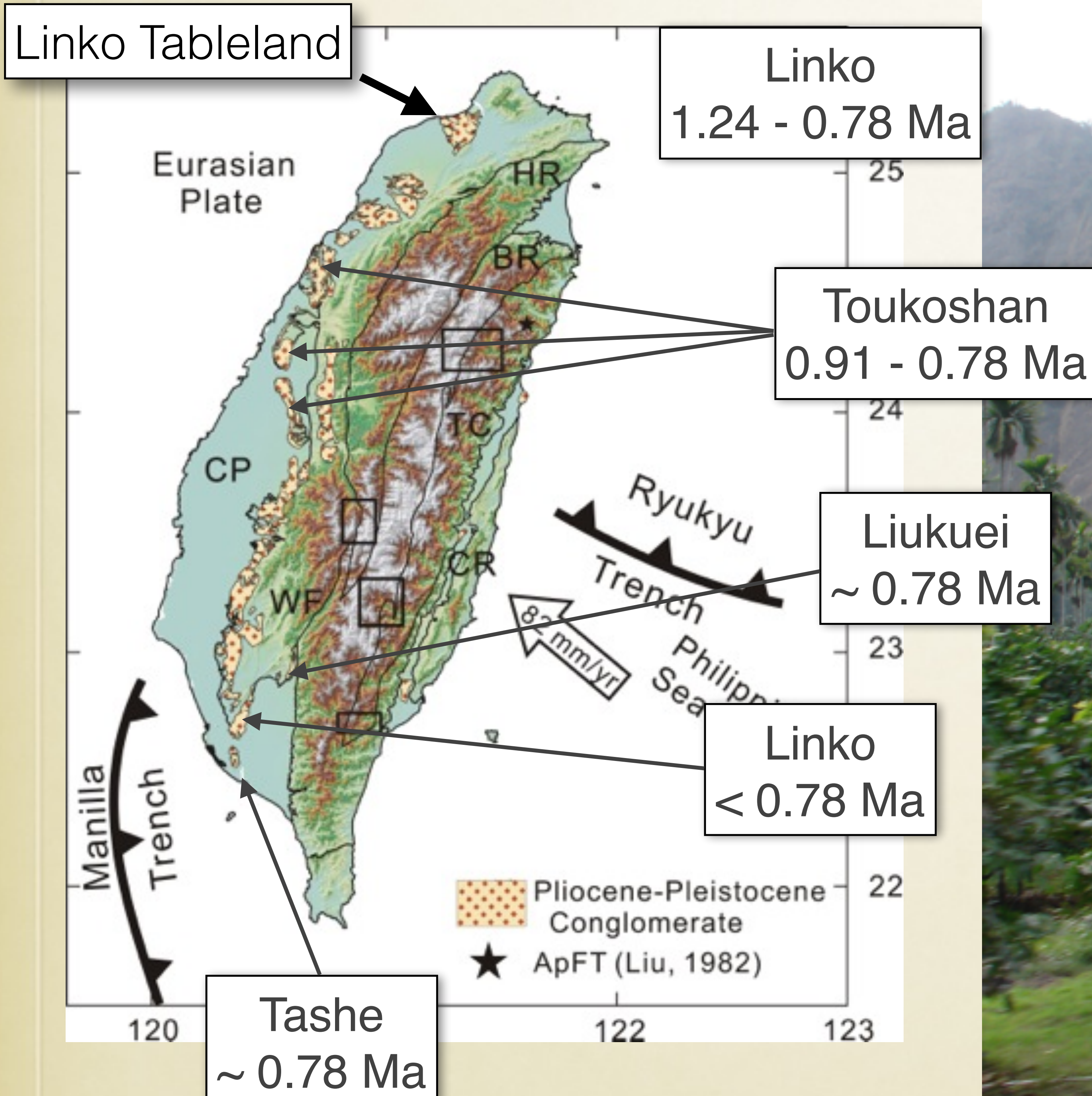
Small Ghost Lake

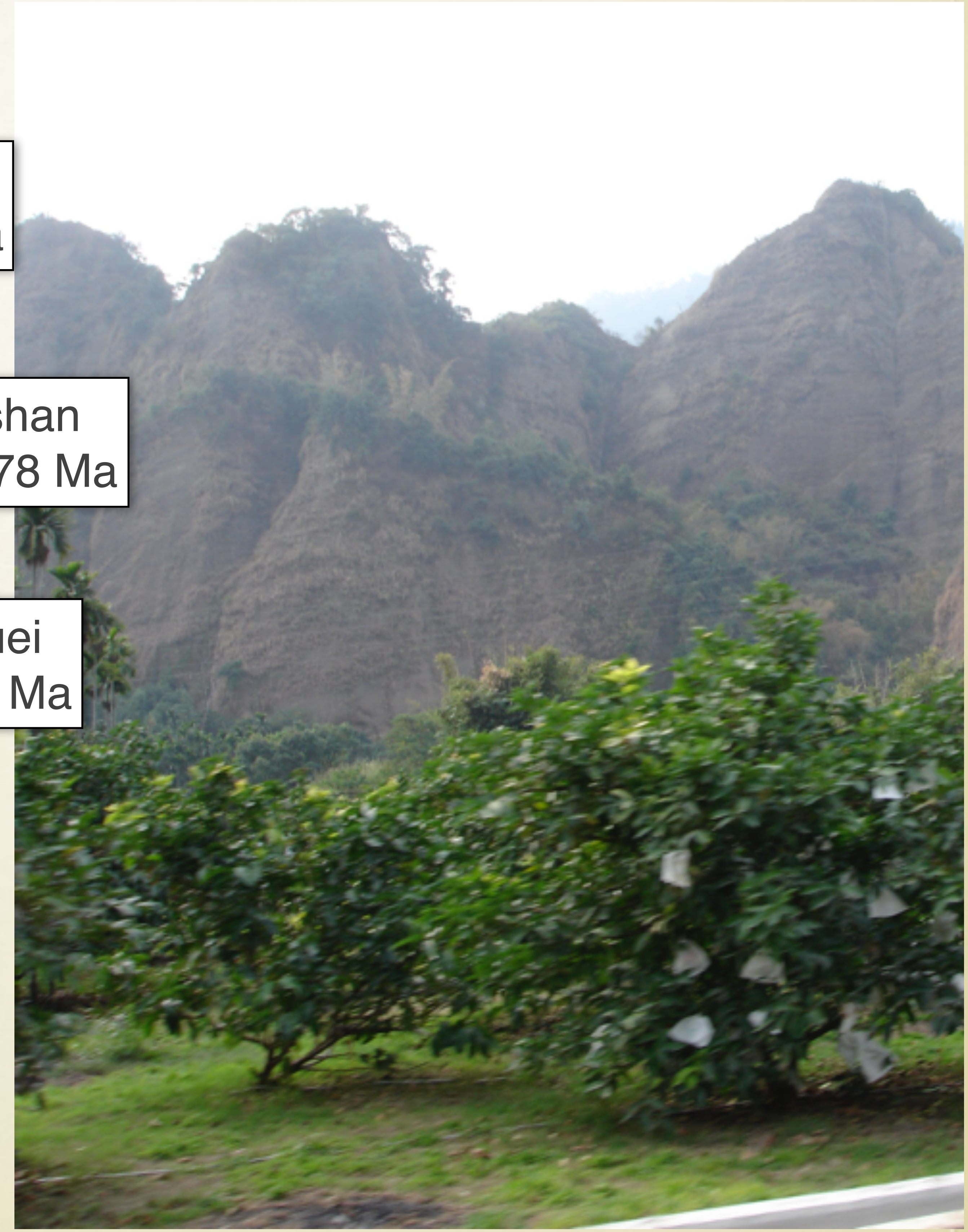




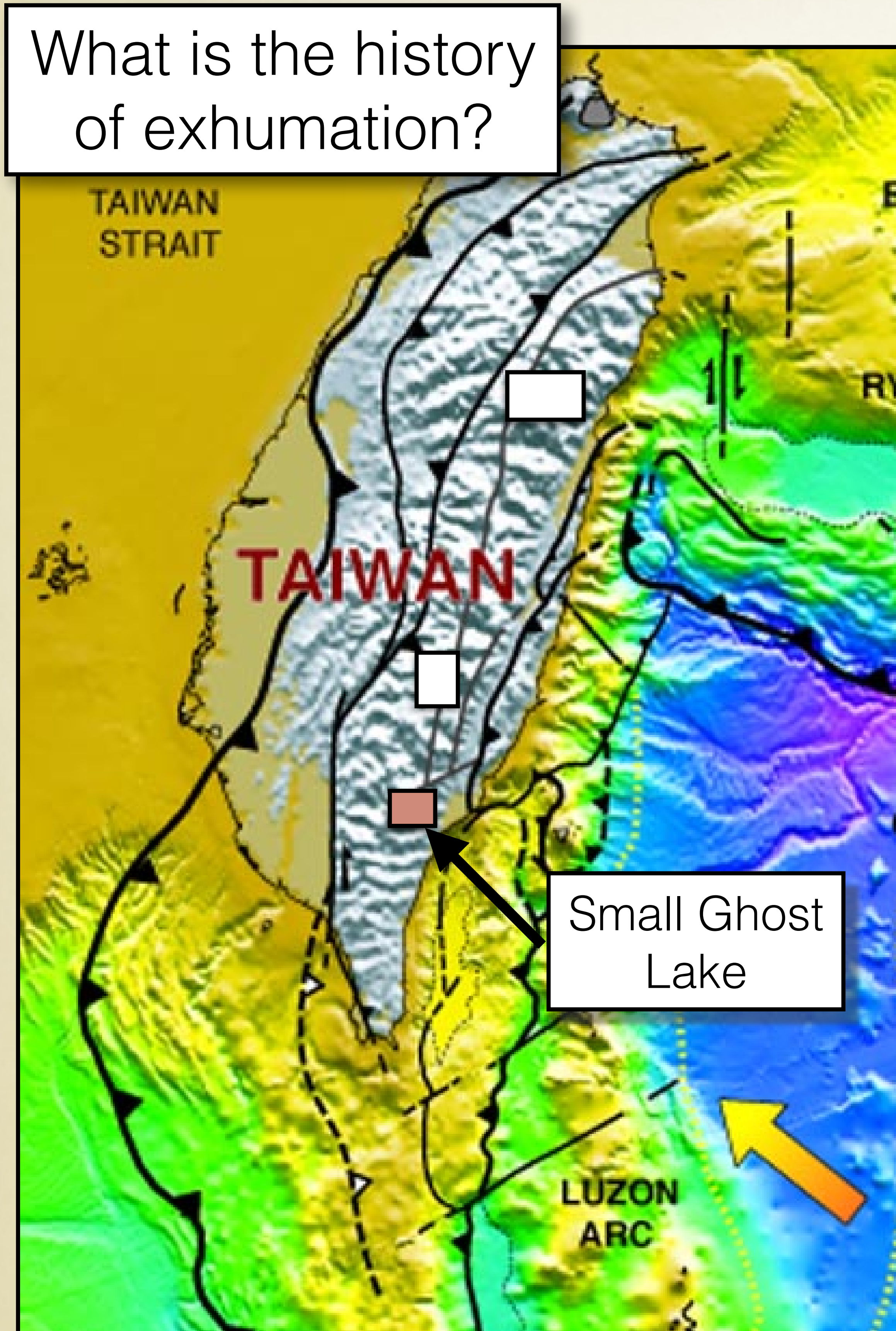
Propose: crustal-scale imbrication is driving exhumation of subducted continental crust.

Pleistocene Conglomberates

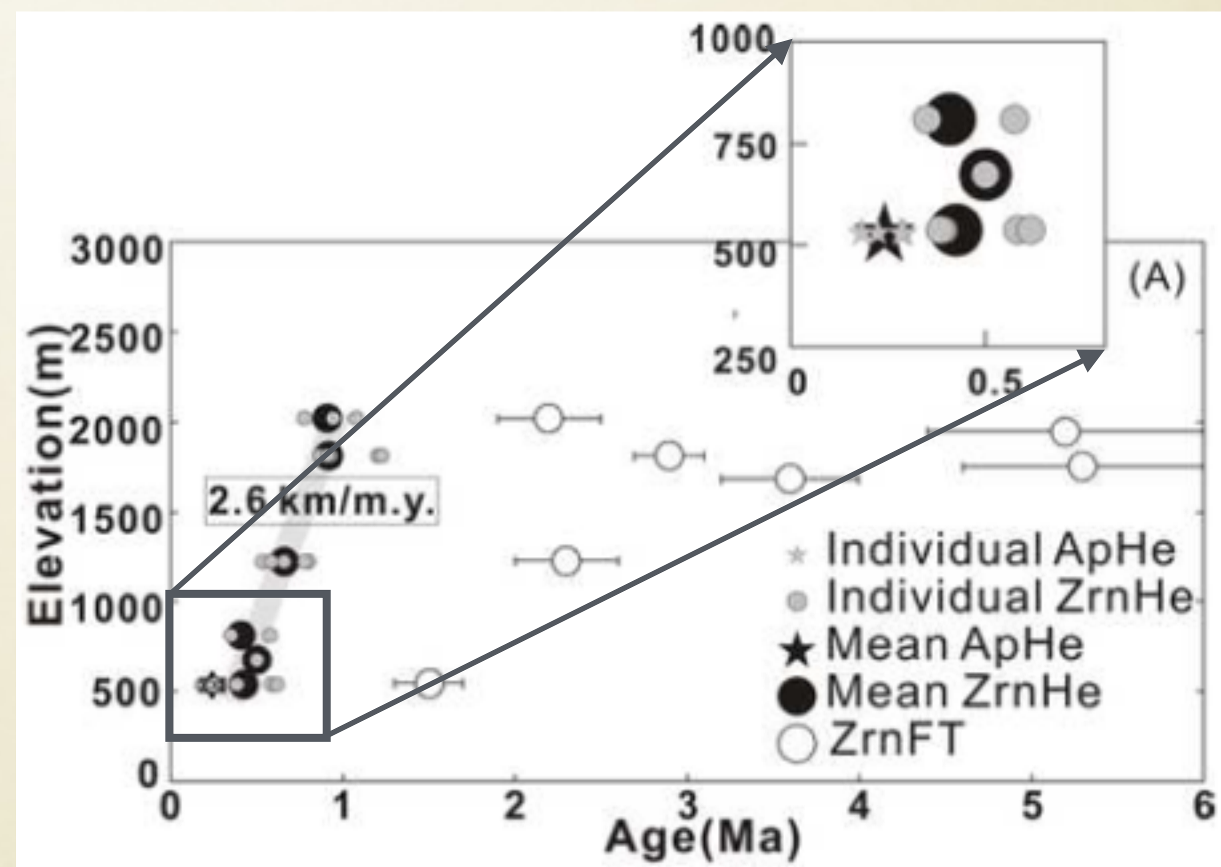




Age-elevation Transects



Very young apatite (u-Th)/He ages (0.25 Ma) suggest acceleration to 4-5 km/m.y. from ~ 0.5 Ma



Hsu et al., 2016, Geology

Subduction and imbrication of stretched continental crust

Crustal-scale P-wave velocity models:

1. Rau and Wu, 1995
2. McIntosh et al., 2005 (TaiCrust)
3. Kao-Chen et al., 2012 (TAIGER)
4. Huang et al., 2014

Ambient tremors

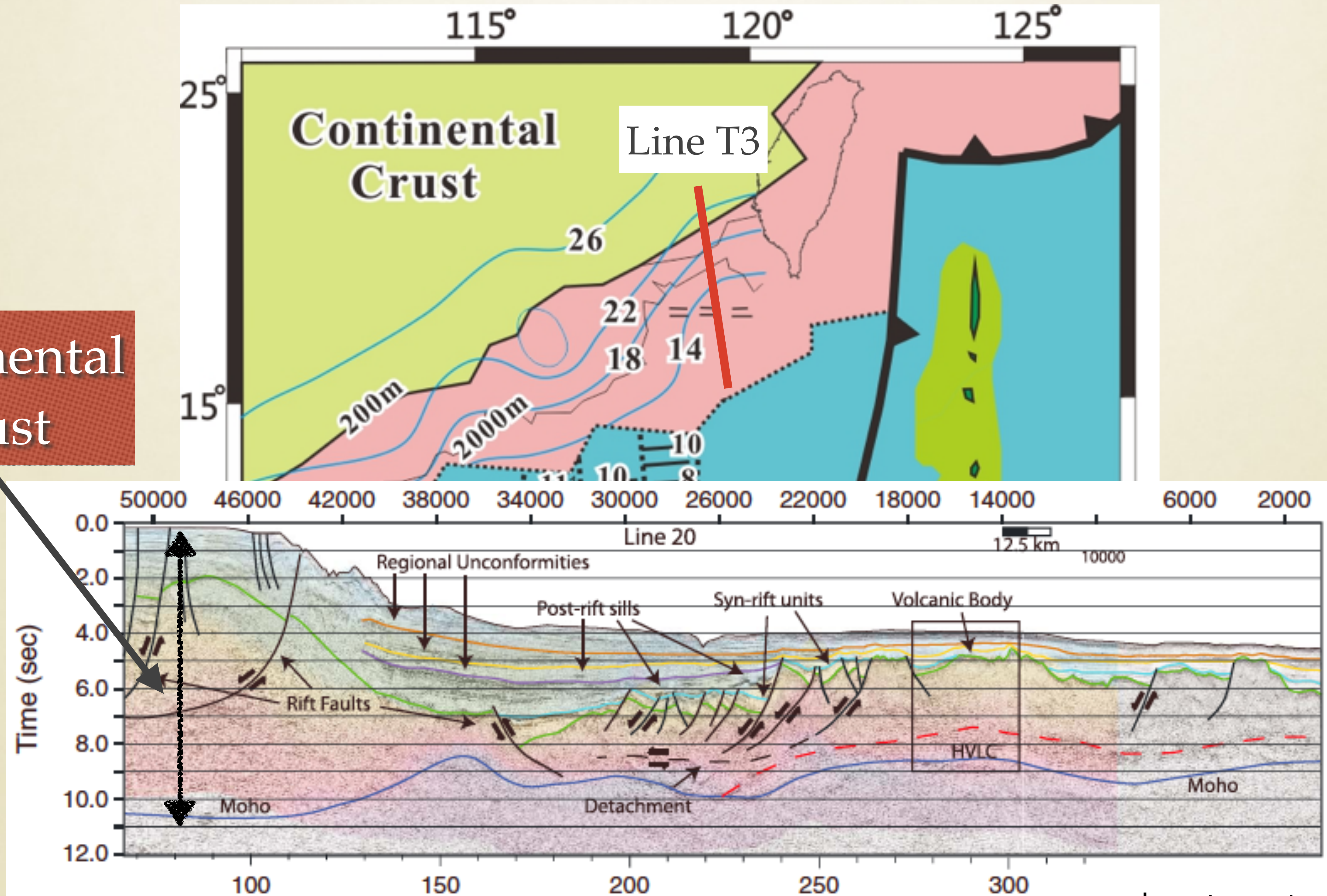
1. Chuang et al., 2014
2. Chen, pers. comm., 2016

Evaluate interpretation with geological observations:

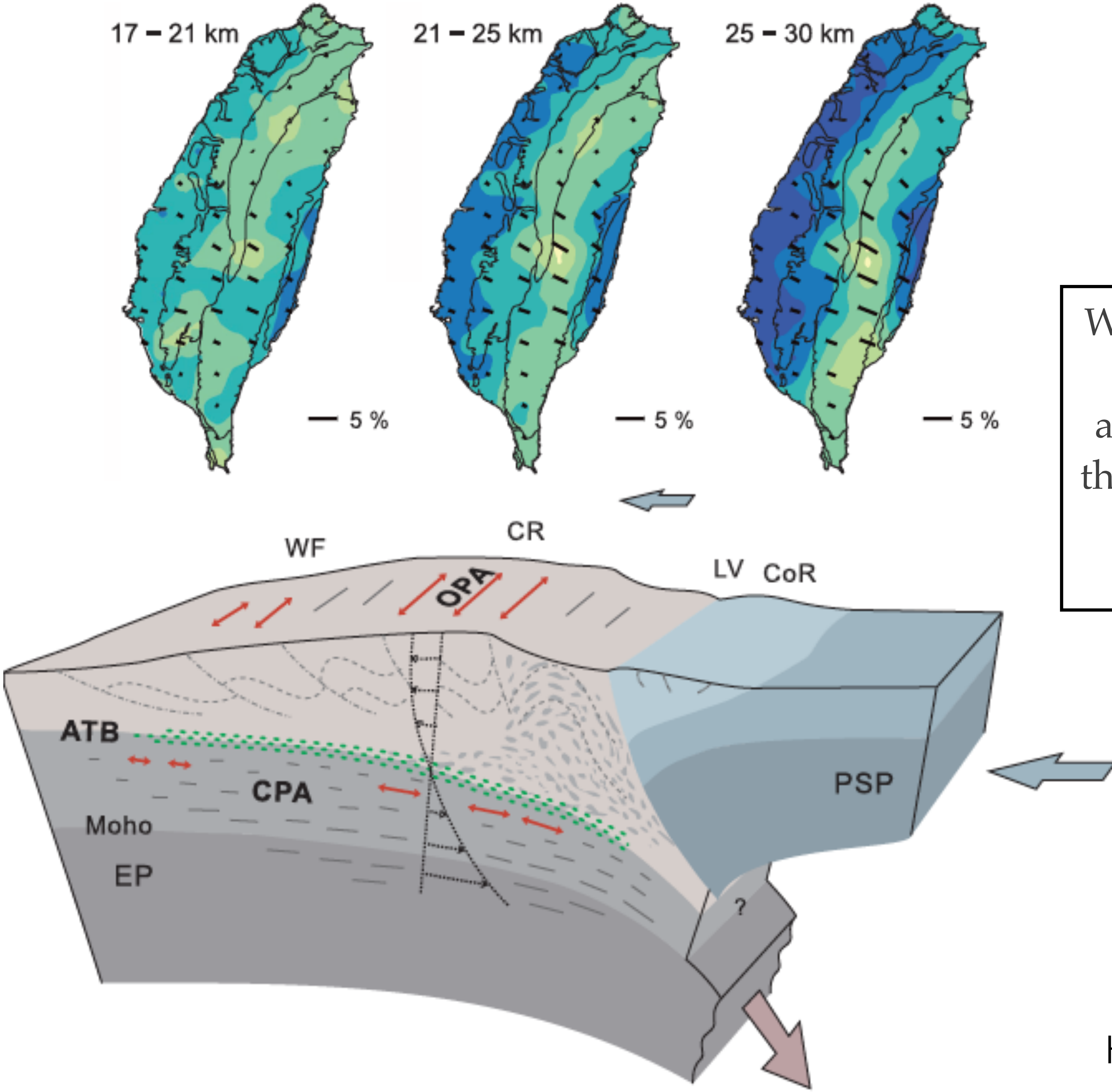
Alternative Tectonic Setting:

Arc collided with, and partially consumed, a wide zone of thinned continental crust that probably contained N-S trending fracture zones

Continental Crust

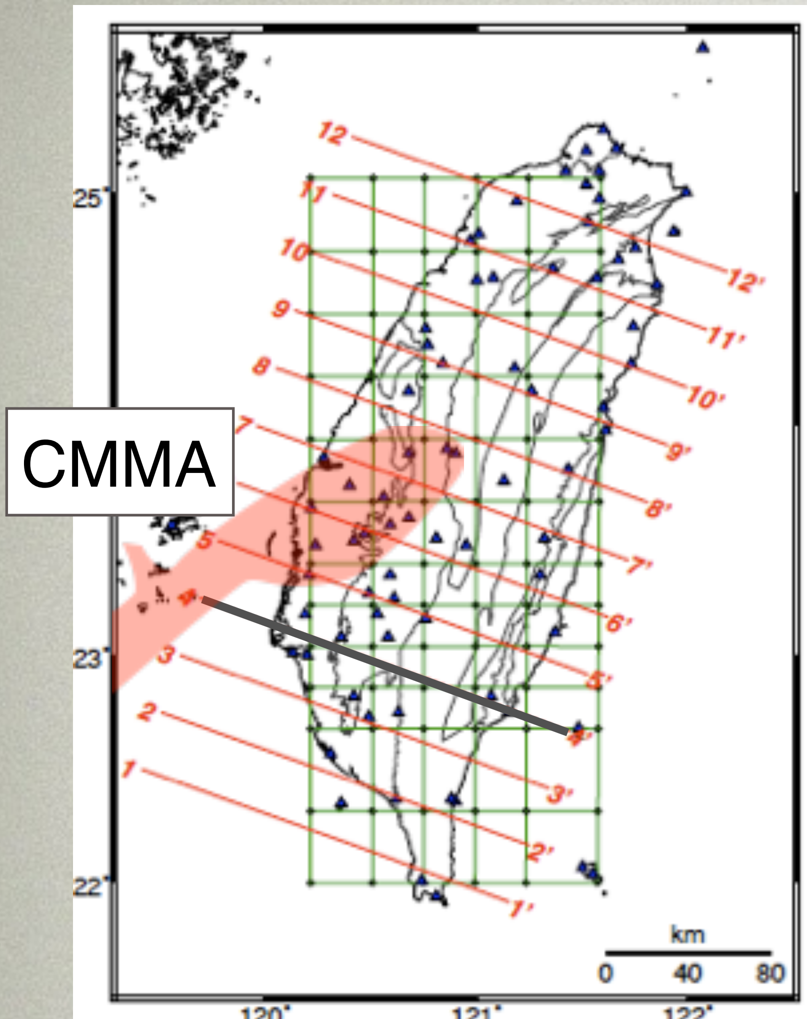


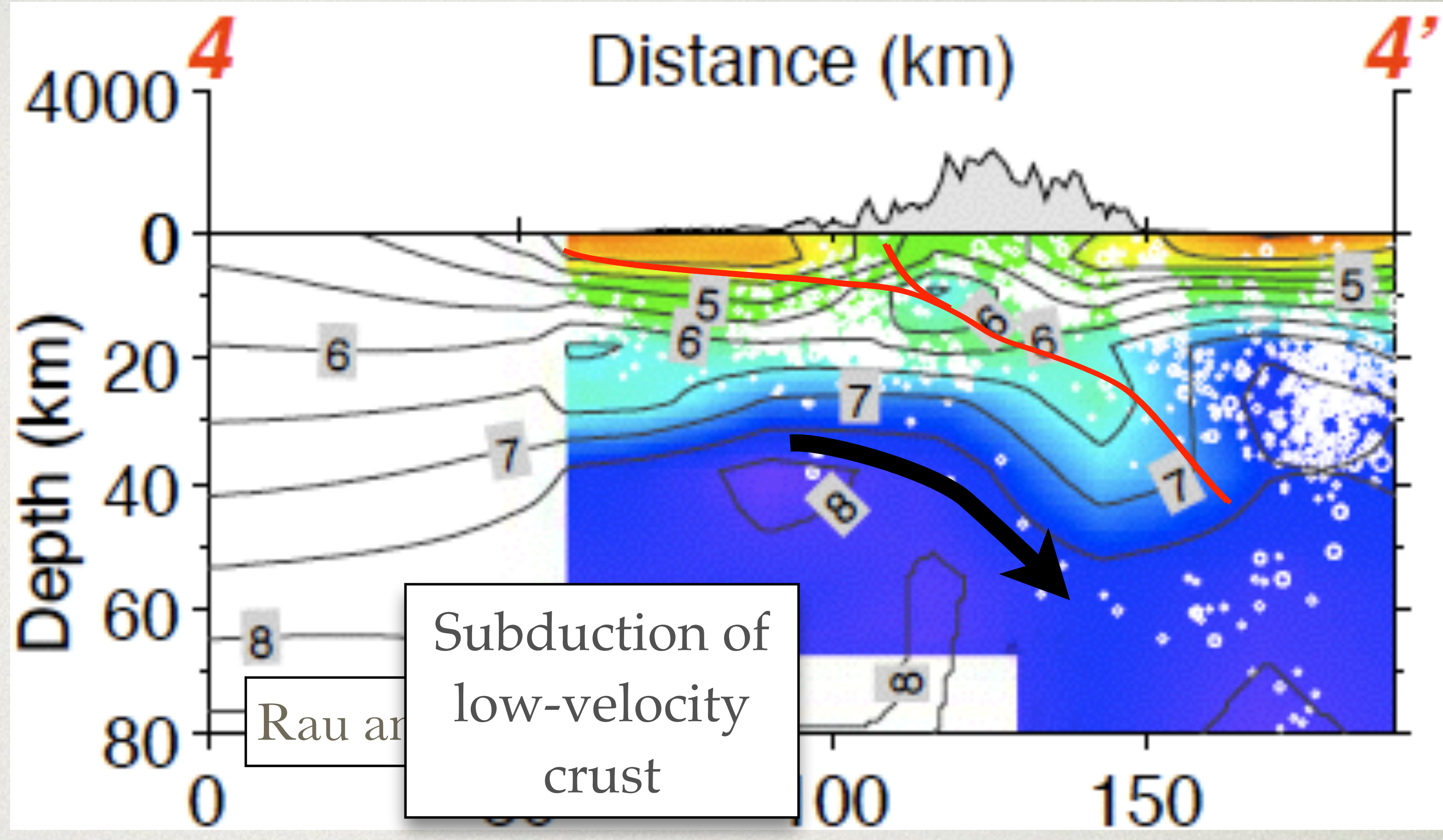
Lester et al., 2014

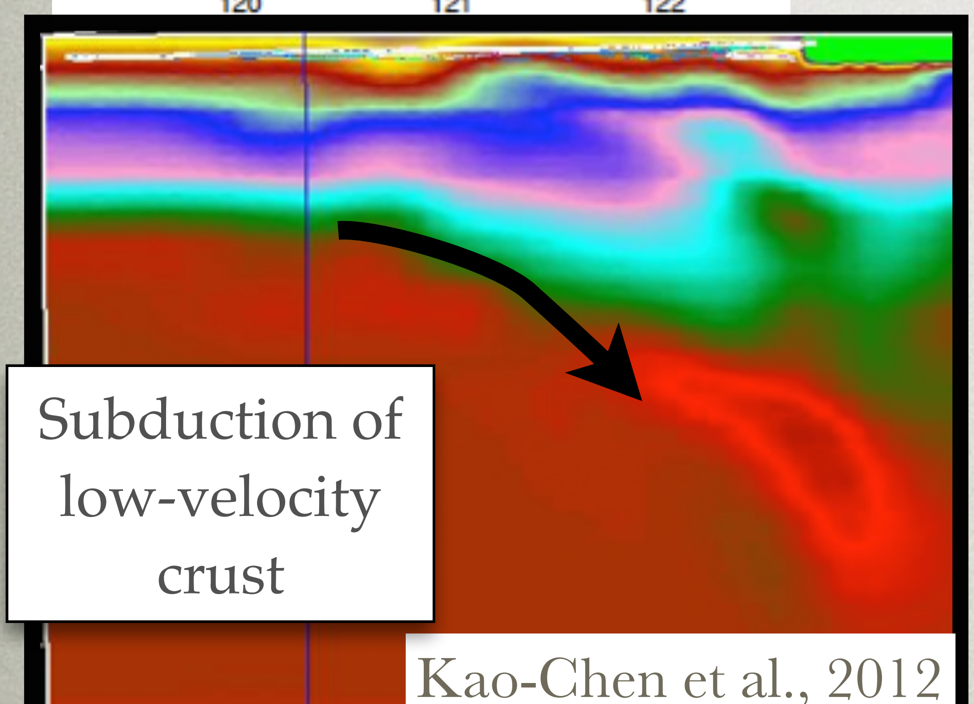


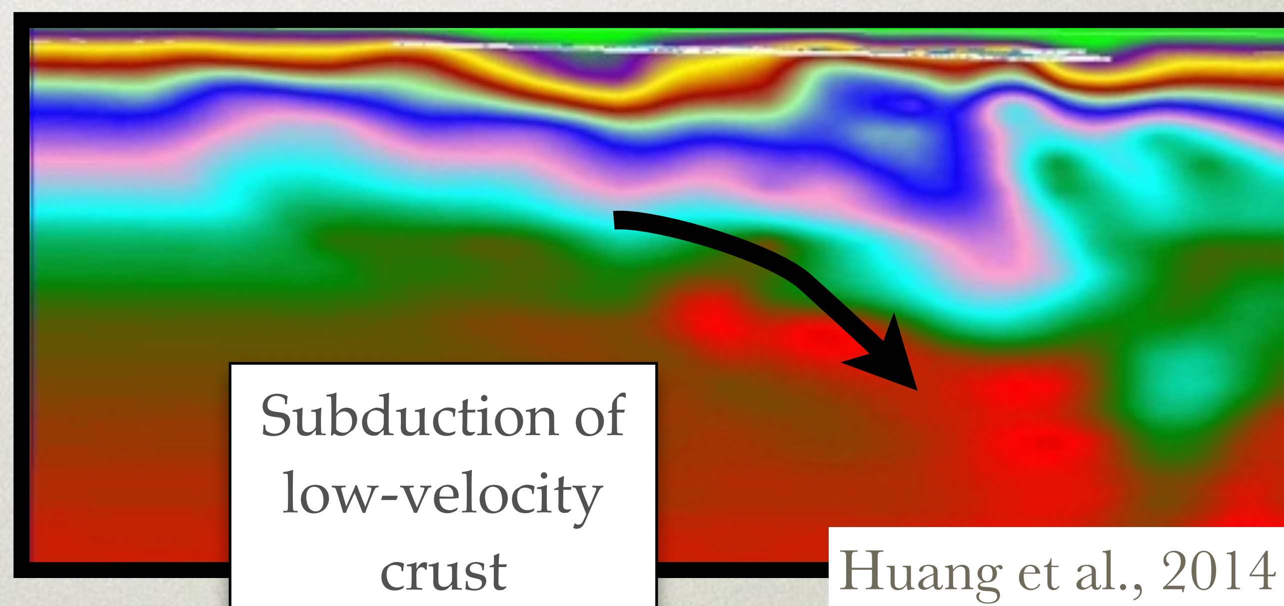
Well developed plate motion parallel anisotropy (CPA) in the middle and lower crust in southern Taiwan

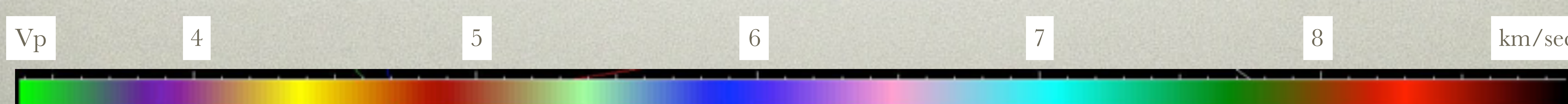
Huang et al., 2015

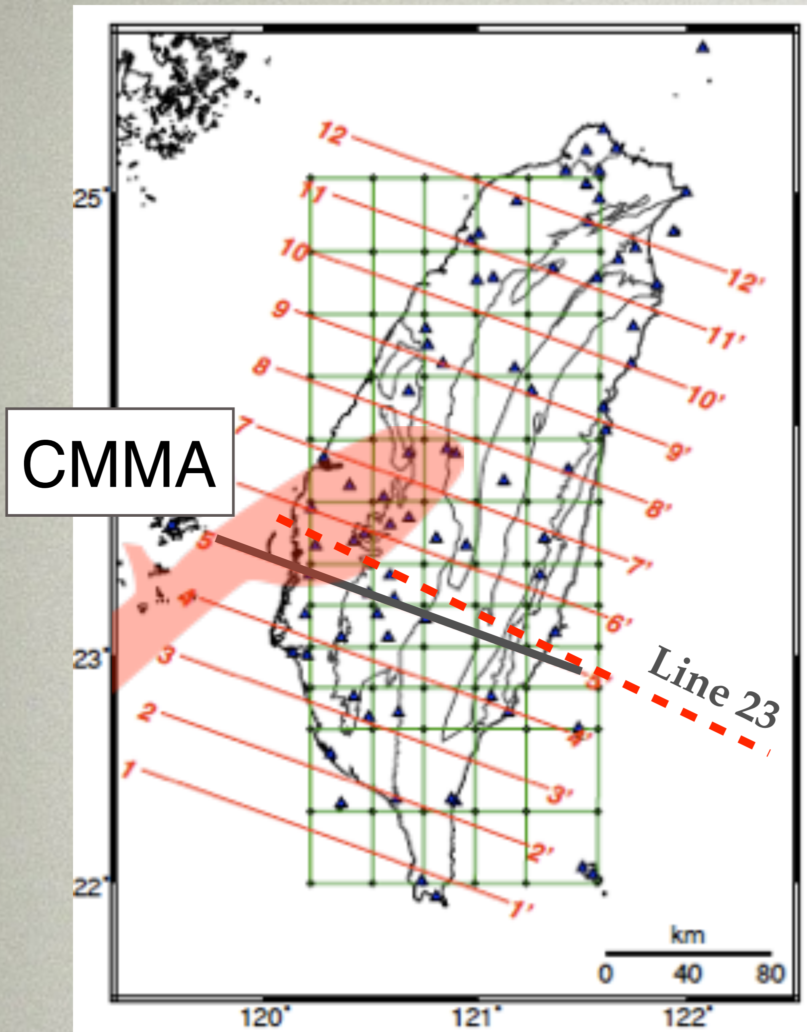

CMMA
km
0 40 80
25°
23°
22°
120°
121°
122°

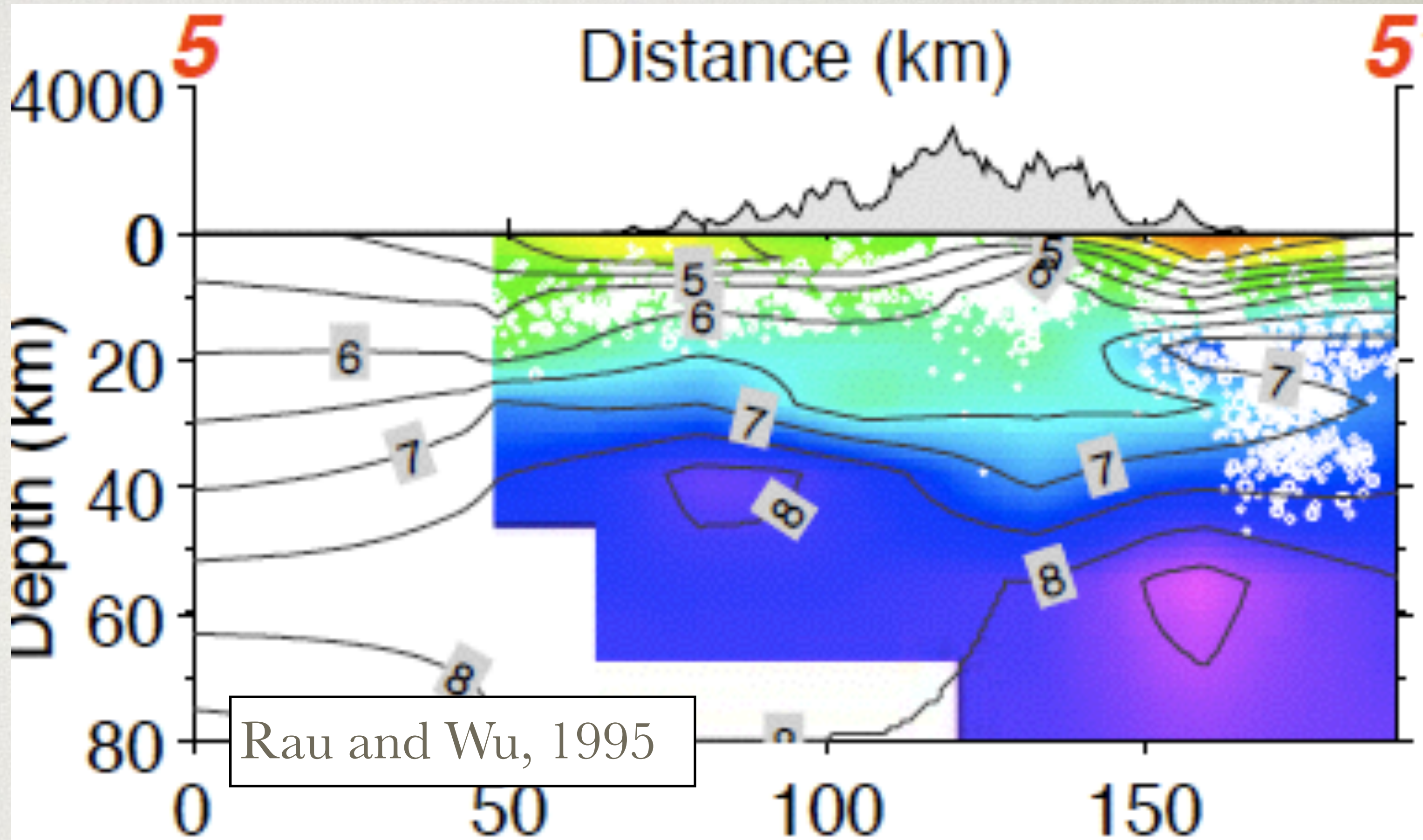

4
Distance (km)
4'
Depth (km)
4000
0
20
40
60
80
0
100
150
Subduction of low-velocity crust
Rau ar


Subduction of low-velocity crust
Kao-Chen et al., 2012

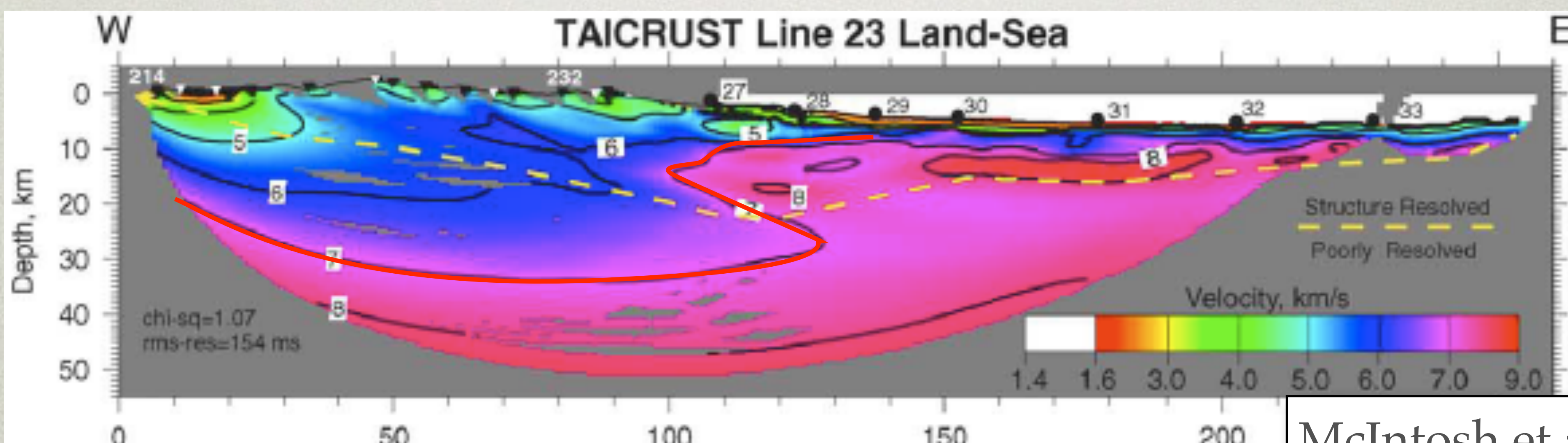

Subduction of low-velocity crust
Huang et al., 2014


Vp
4
5
6
7
8
km/sec

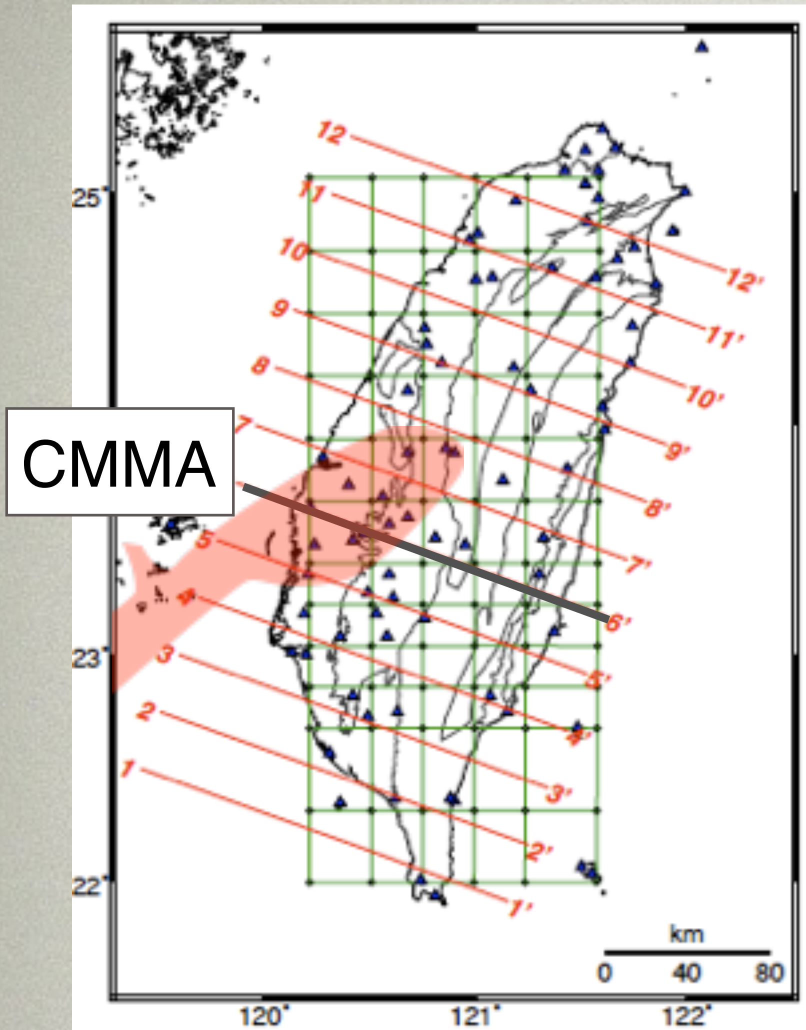


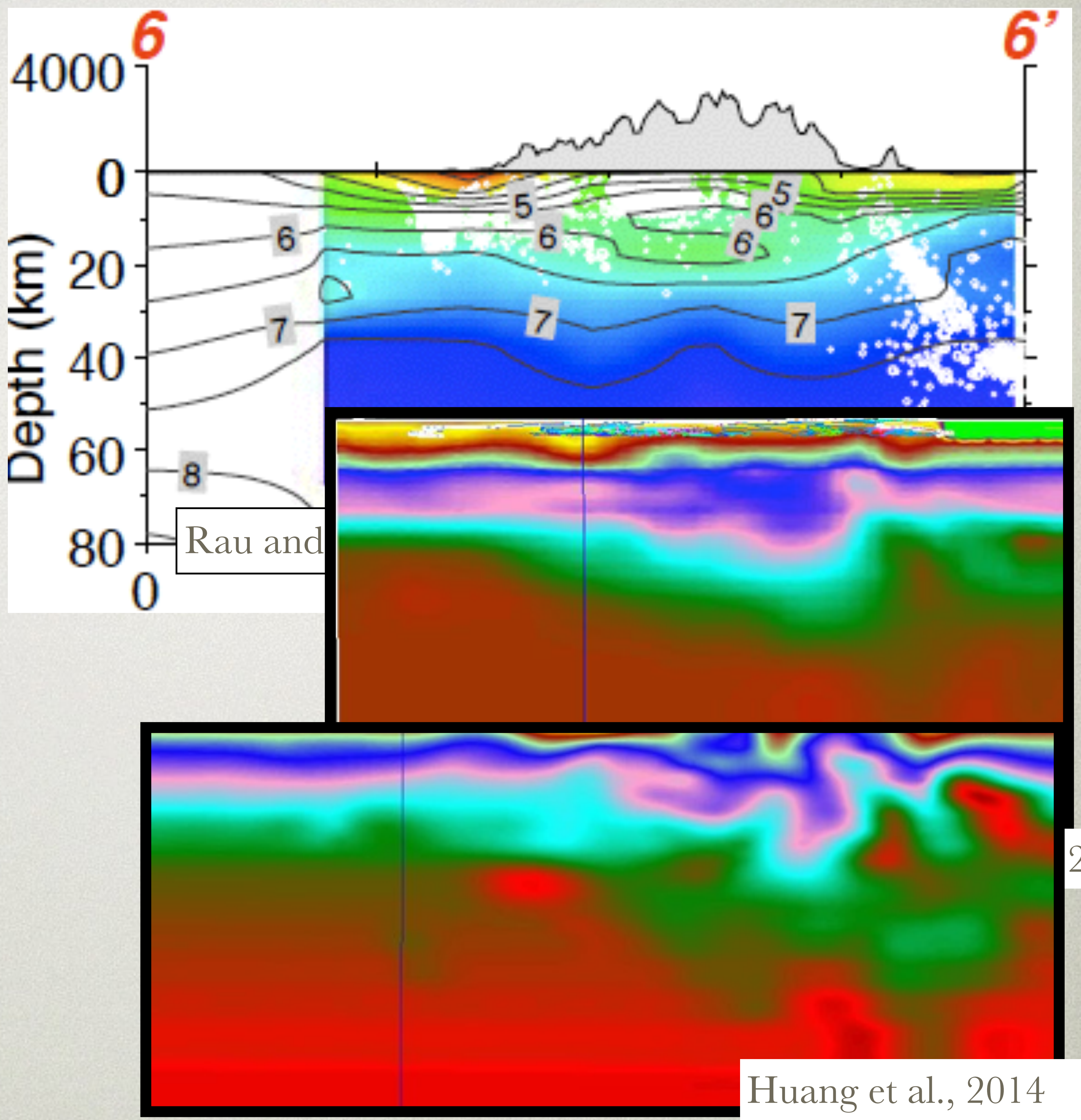


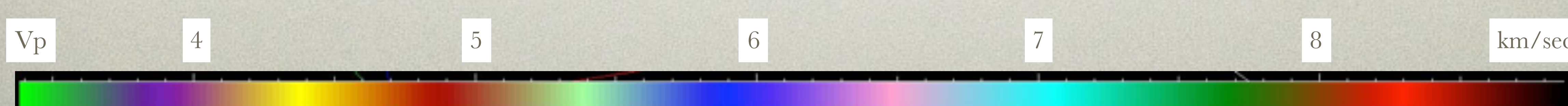
Rau and Wu, 1995

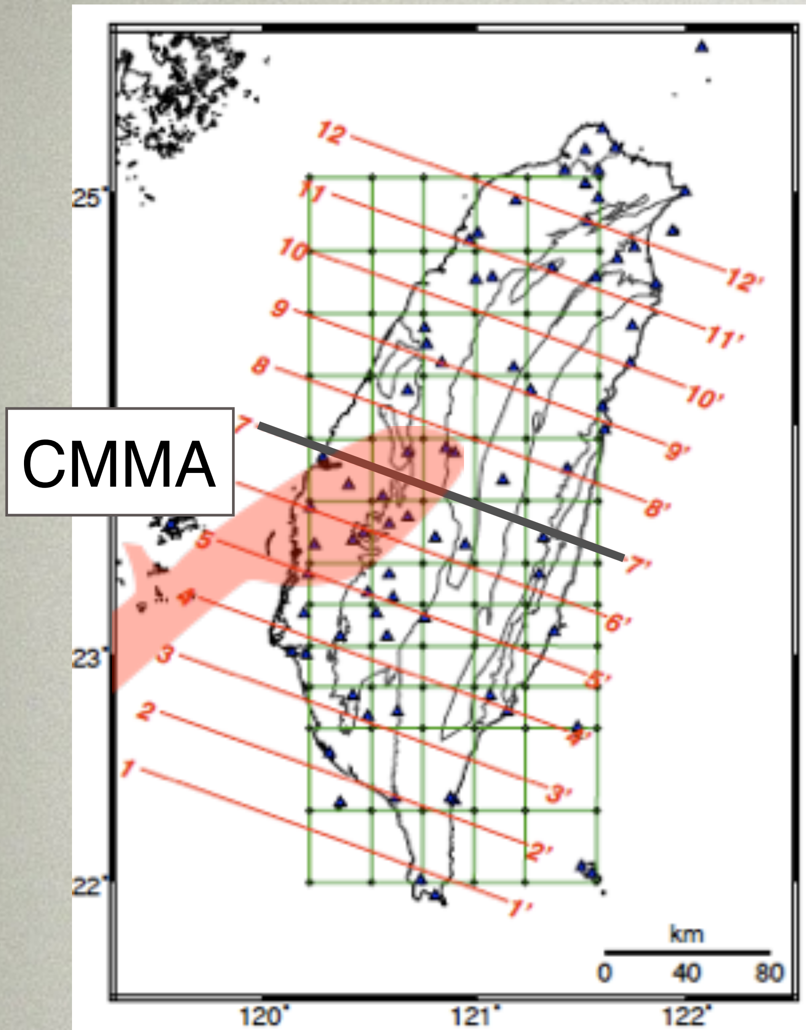


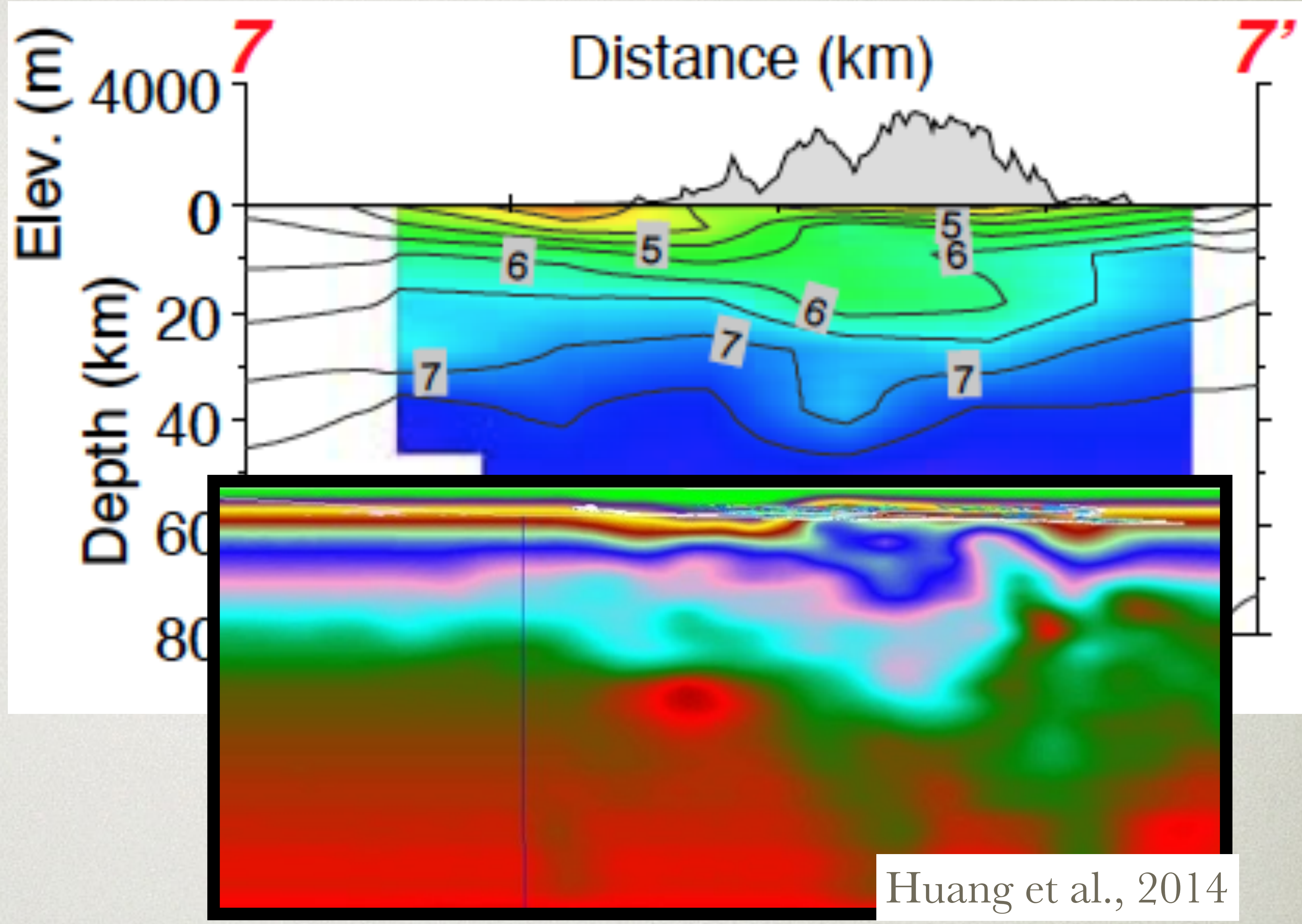
McIntosh et al., 2005


CMMA
12
11
10
9
8
7
5
3
2
1
12'
11'
10'
9'
8'
7'
6'
5'
4'
3'
2'
1'
25°
23°
22°
120°
121°
122°
km
0
40
80

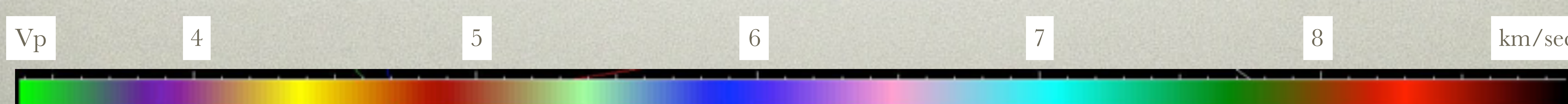

6
6'
4000
0
20
40
60
80
0
Depth (km)
5
6
7
8
Rau and
2
Huang et al., 2014

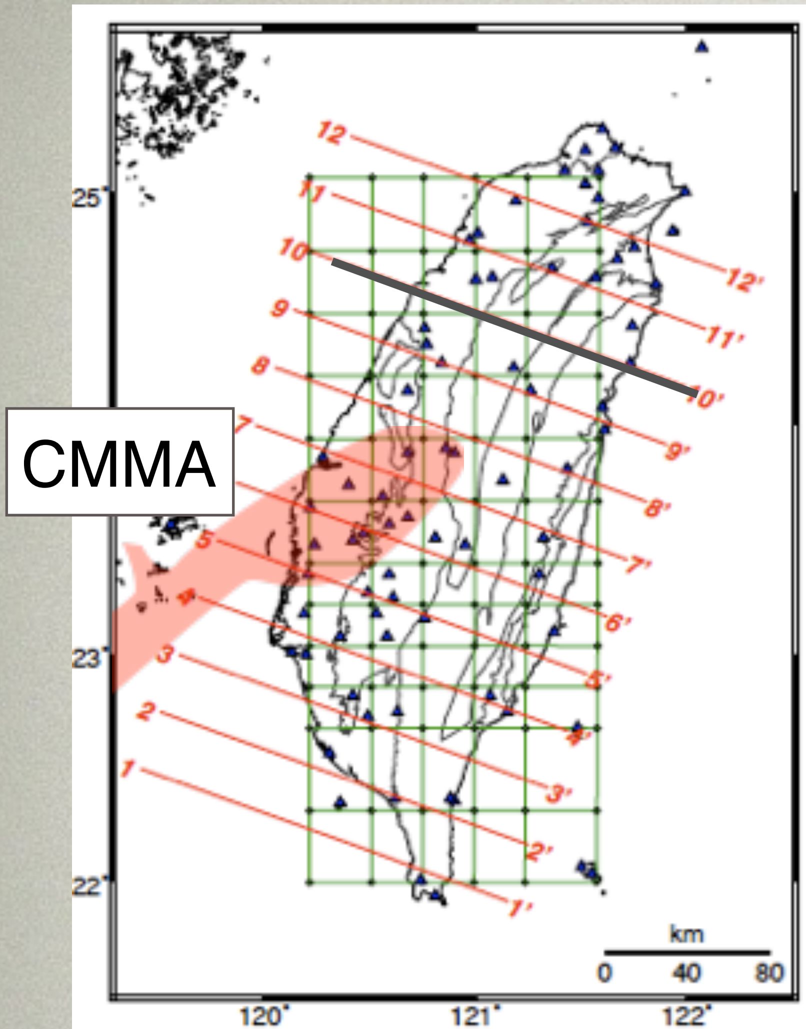

Vp
4
5
6
7
8
km/sec

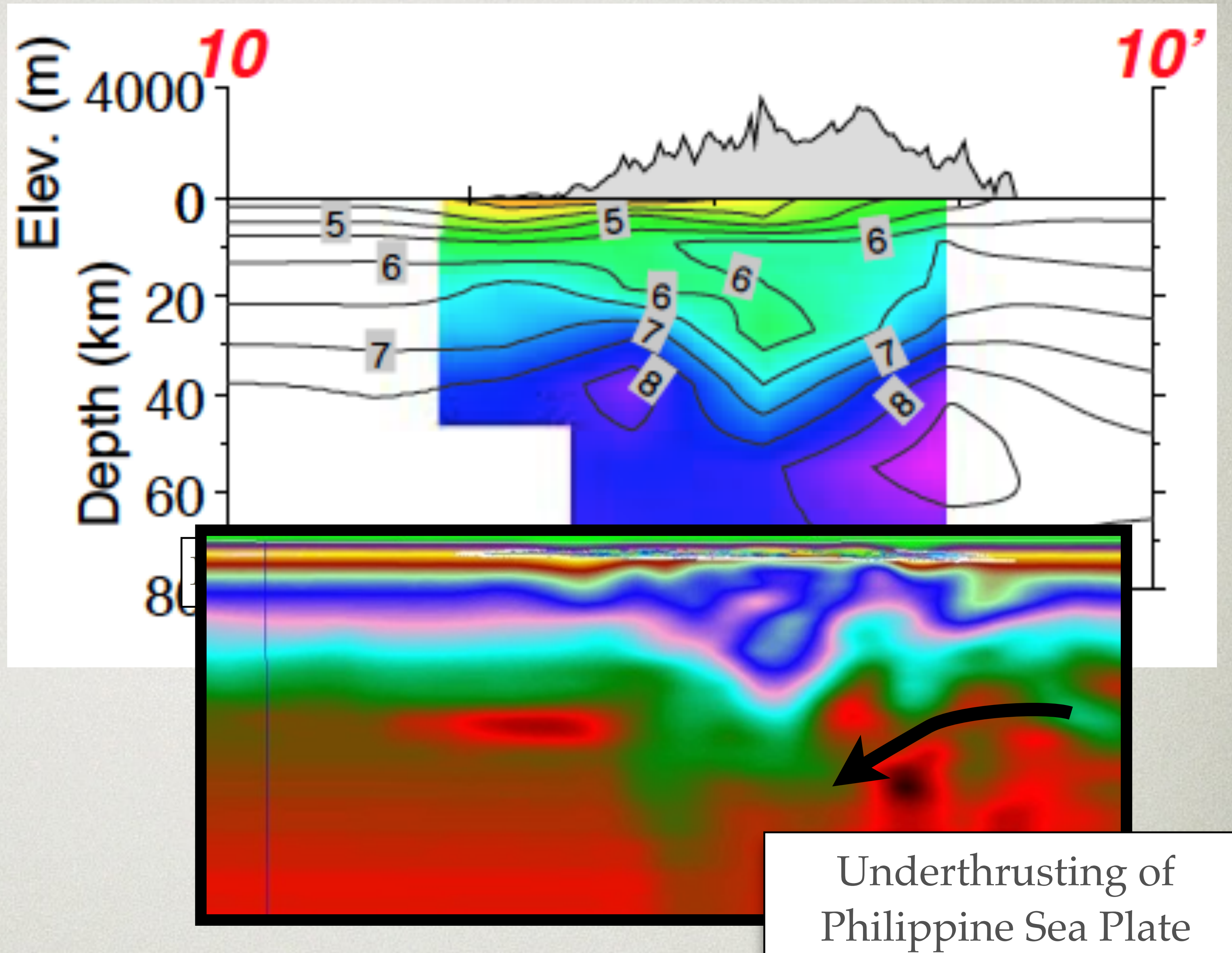


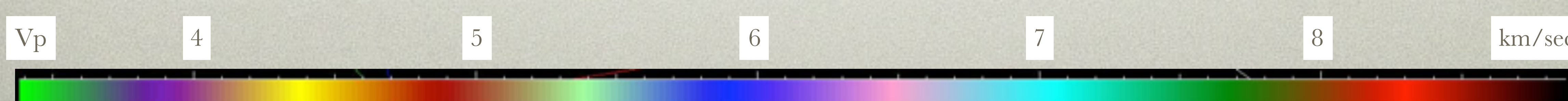


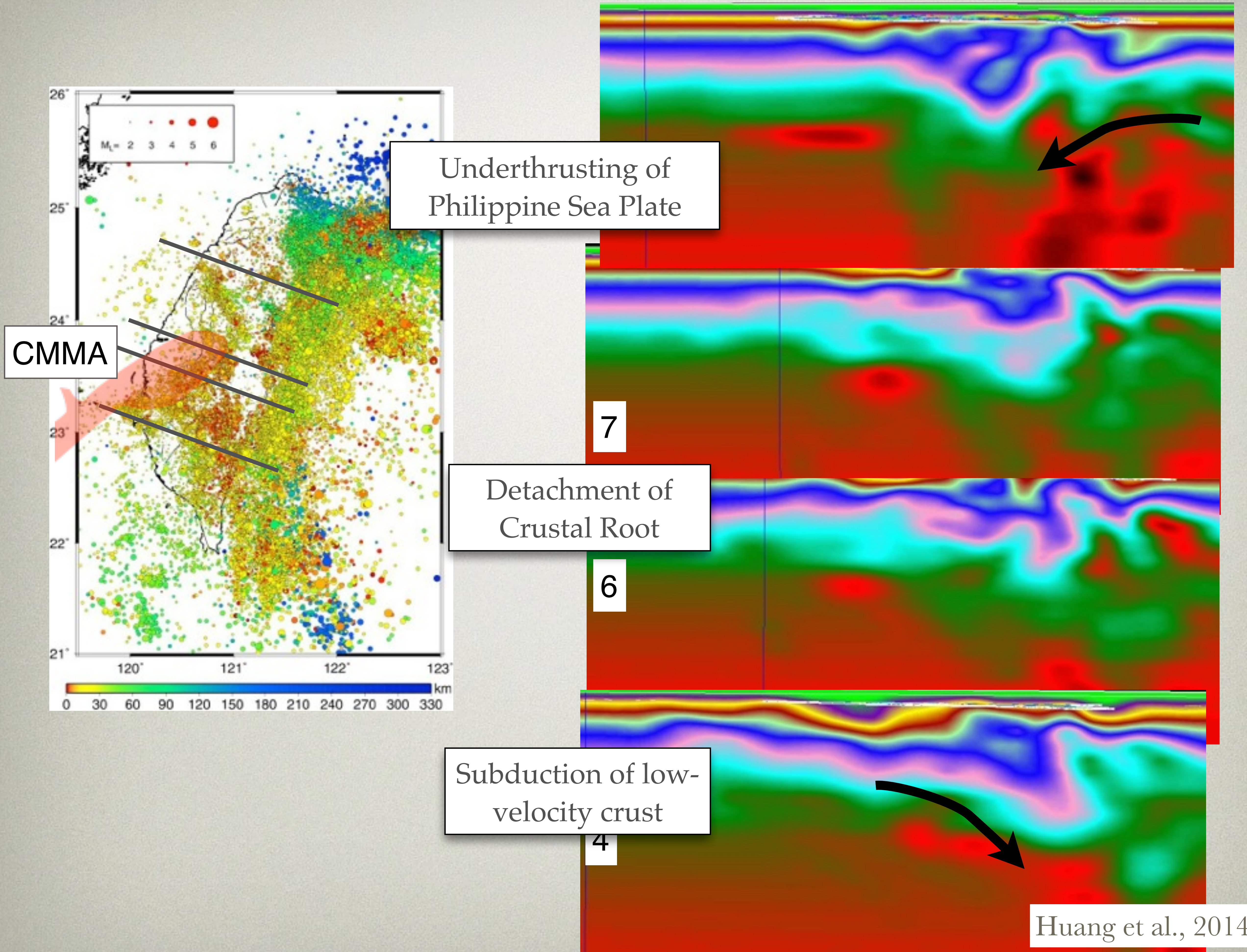
Huang et al., 2014

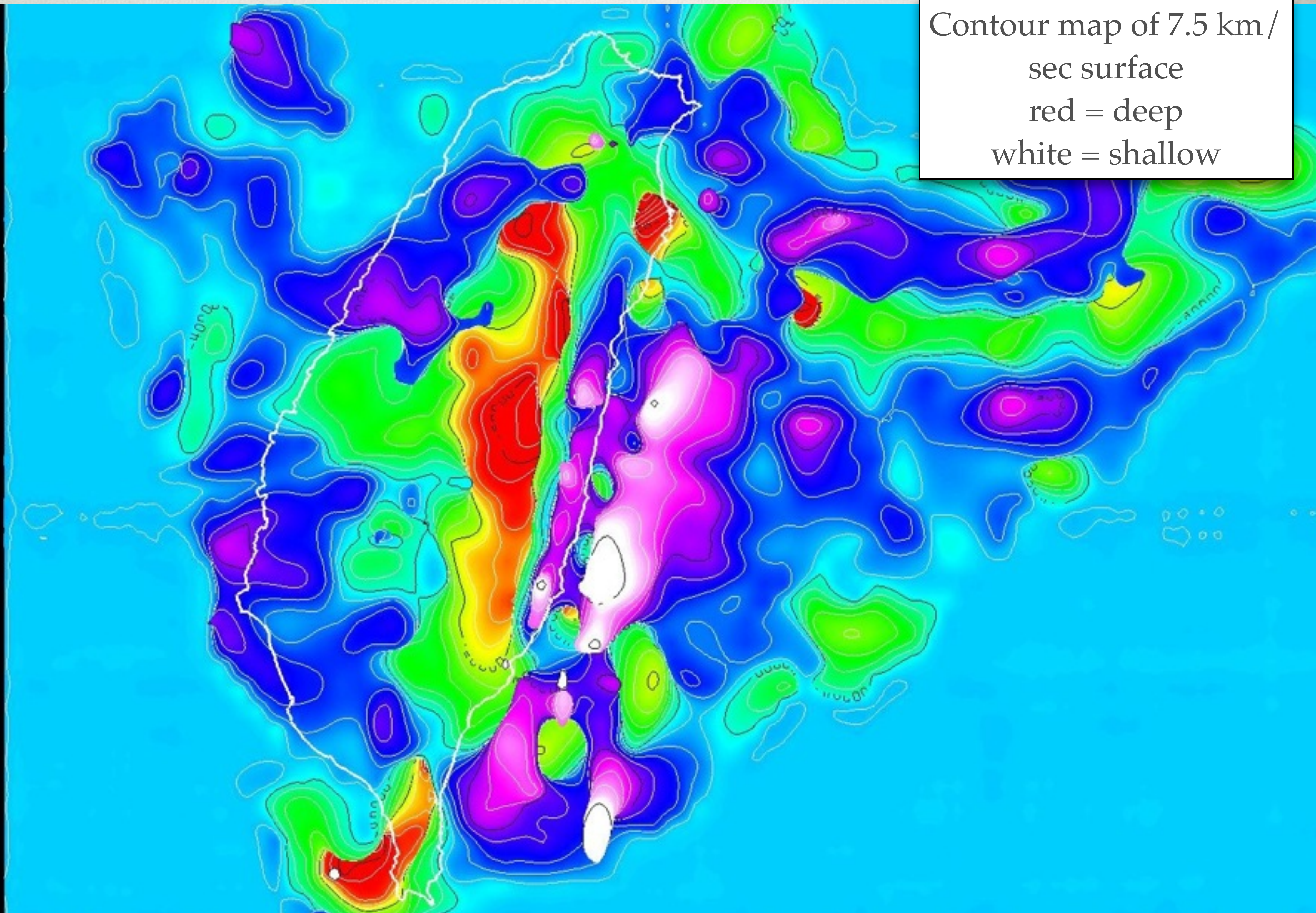


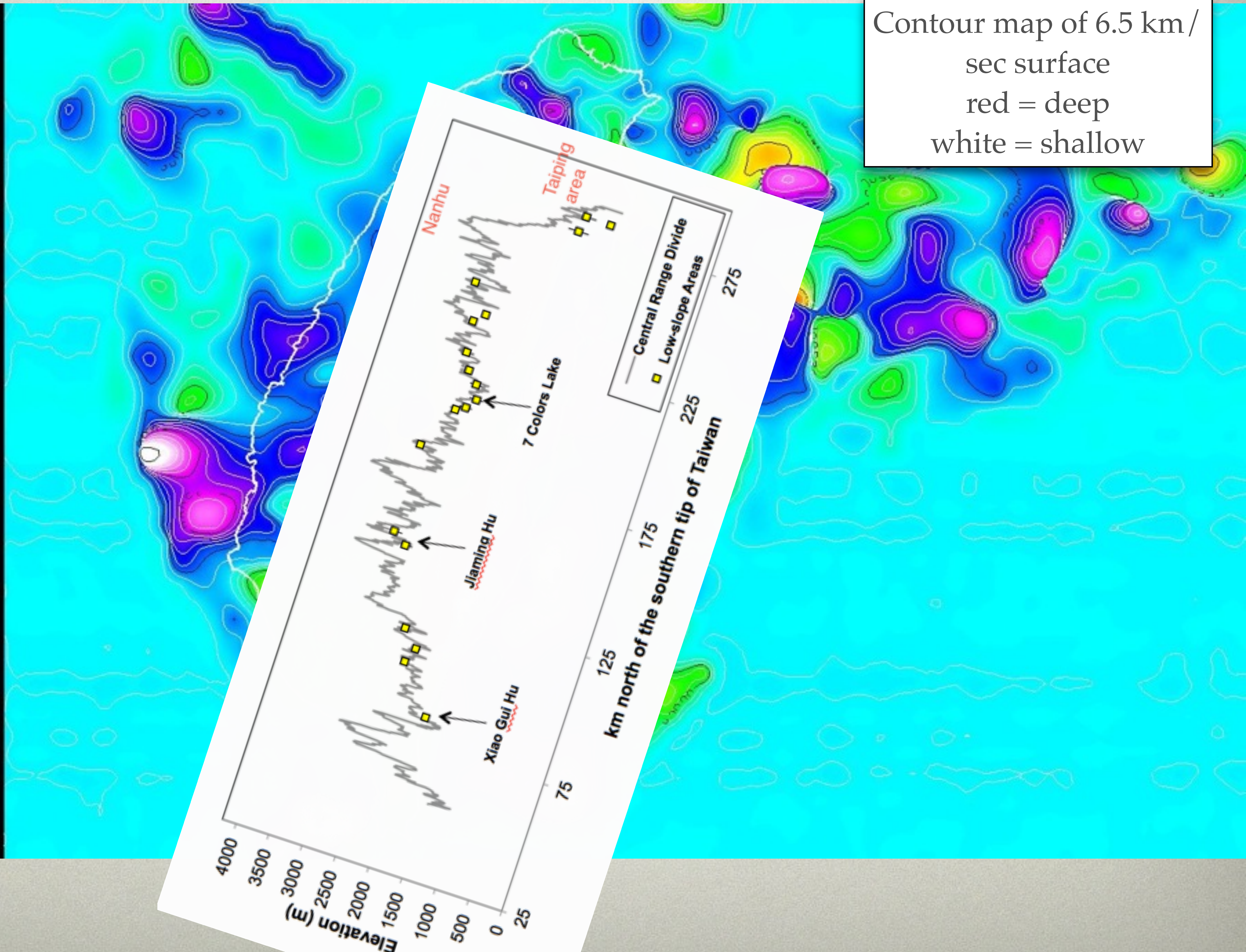

CMMA
25°
23°
22°
120°
121°
122°
km
0 40 80


10
10'
Elev. (m)
4000
0
Depth (km)
20
40
60
80
Underthrusting of Philippine Sea Plate


Vp
4
5
6
7
8
km/sec

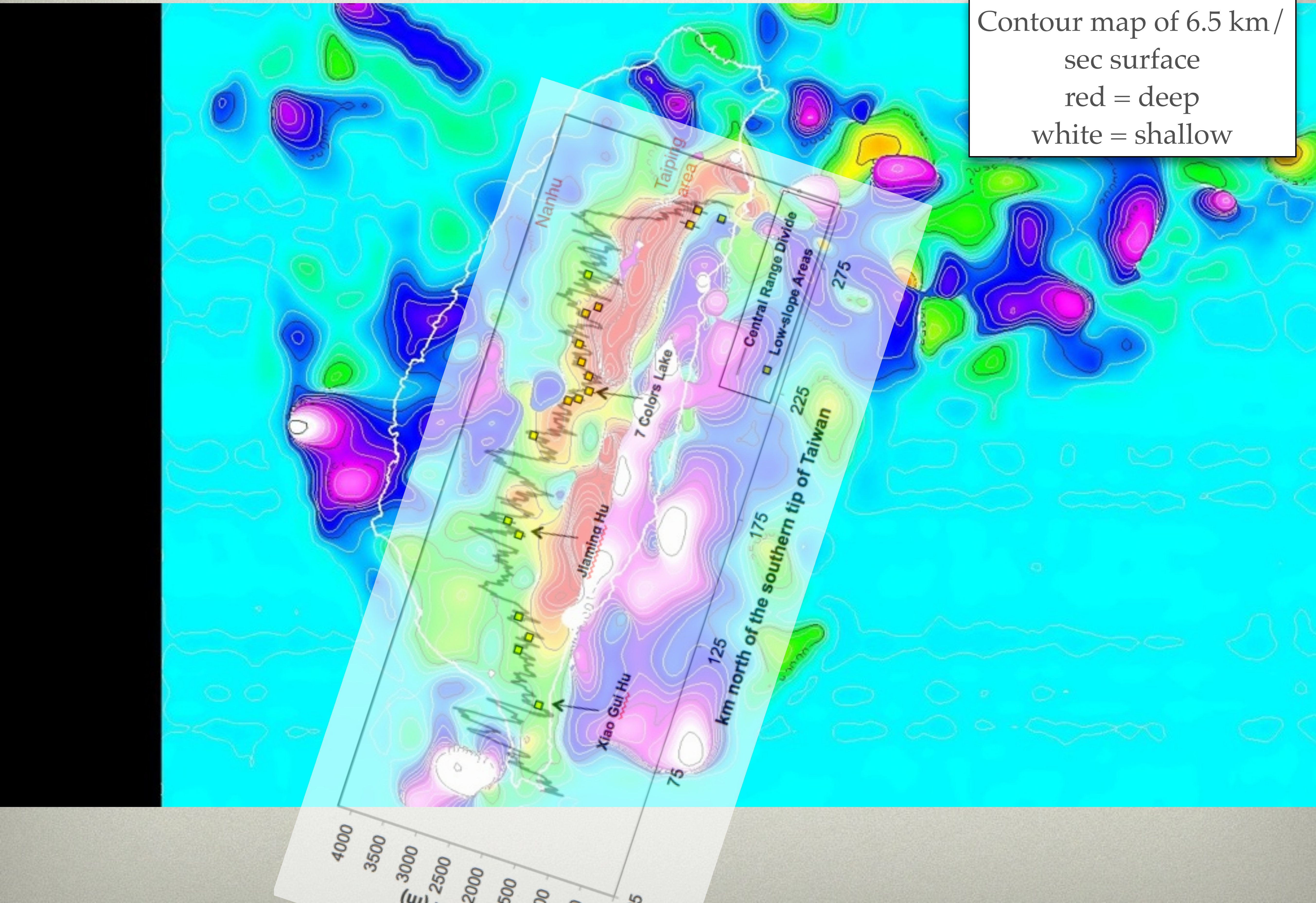

Underthrusting of Philippine Sea Plate
CMMA
Detachment of Crustal Root
Subduction of low-velocity crust
7
6
4
26˚
25˚
24˚
23˚
22˚
21˚
120˚
121˚
122˚
123˚
M_L = 2 3 4 5 6
km
0 30 60 90 120 150 180 210 240 270 300 330
Huang et al., 2014

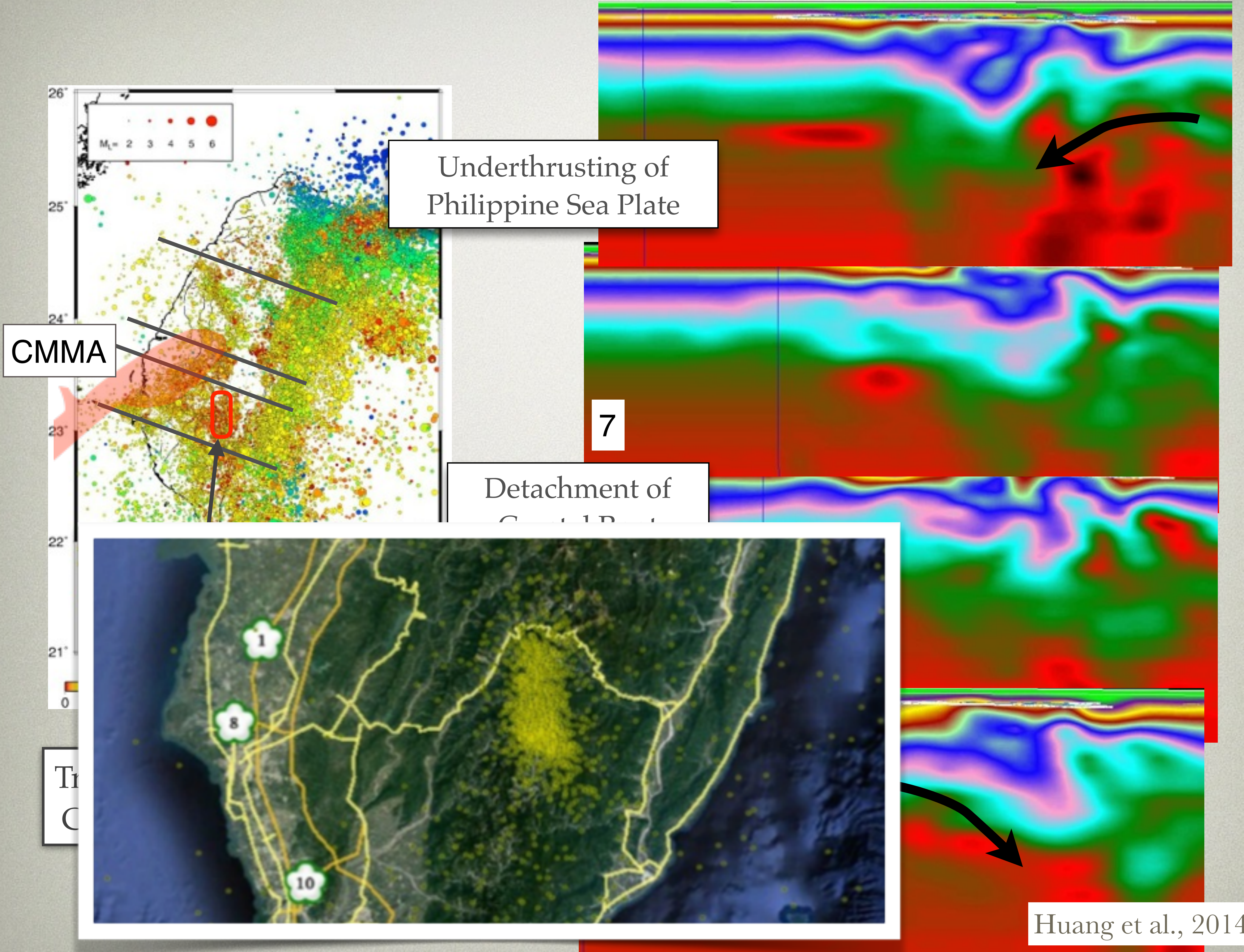

Contour map of 7.5 km/
sec surface
red = deep
white = shallow

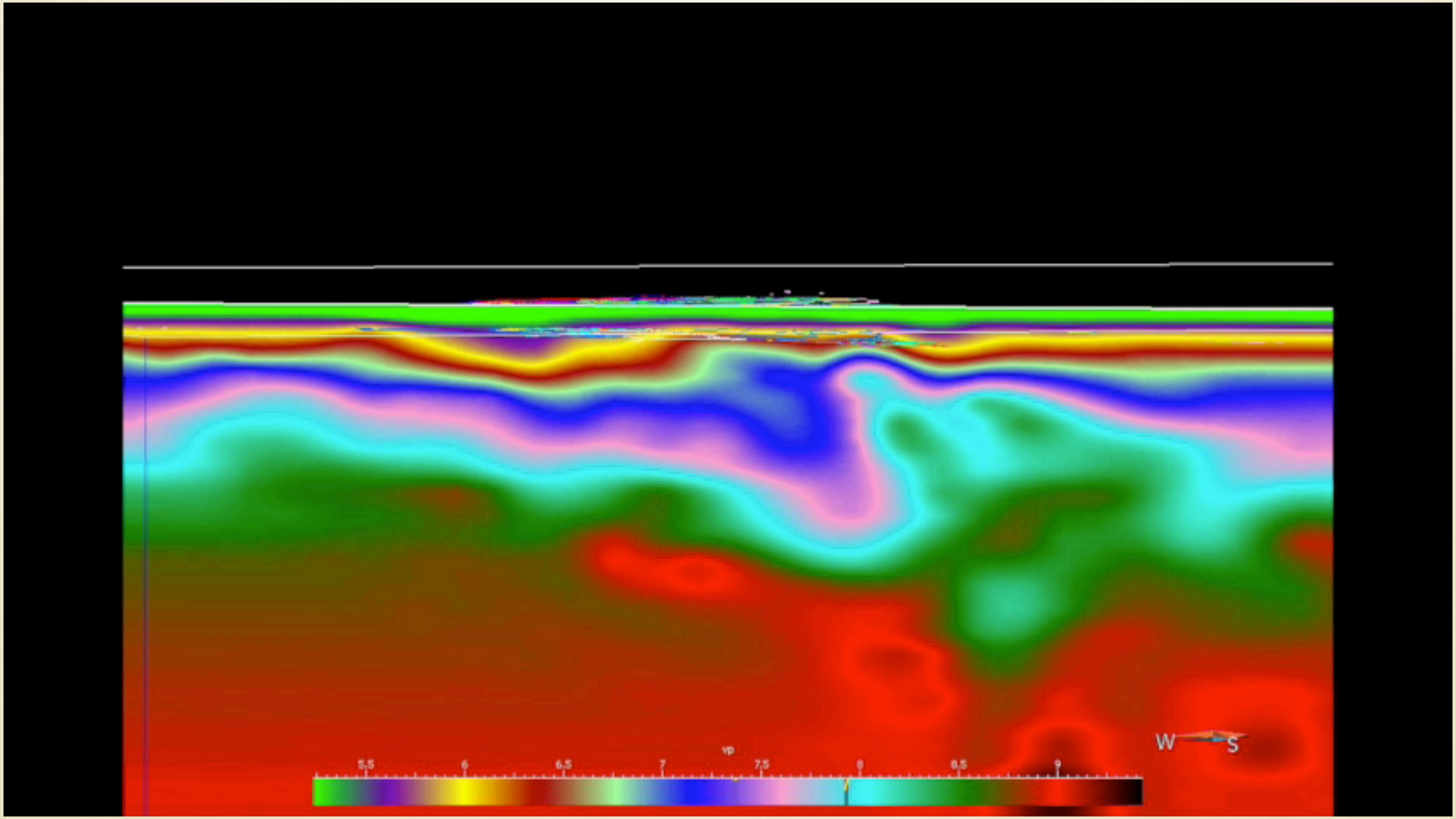


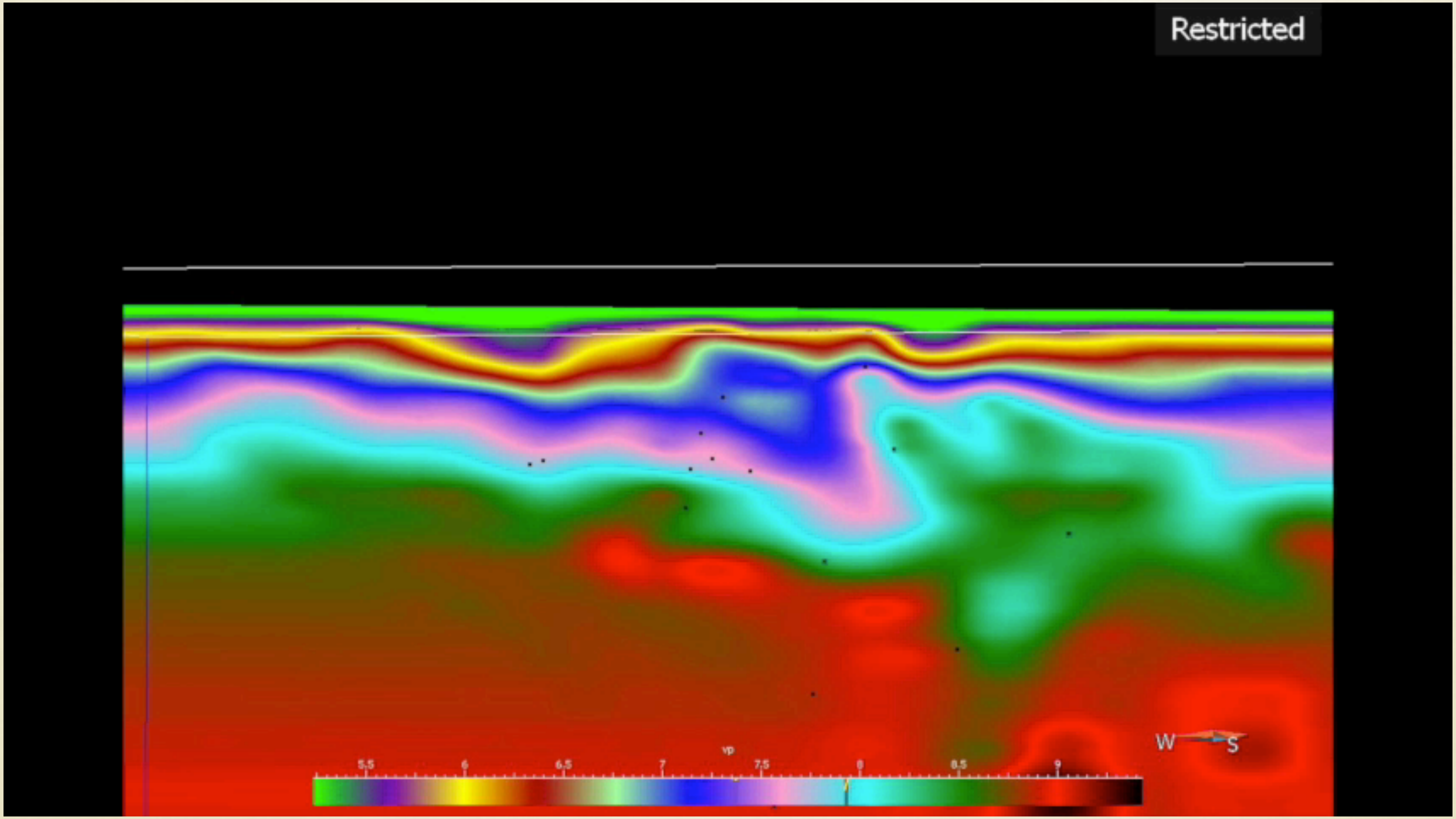
Contour map of 6.5 km/
sec surface
red = deep
white = shallow

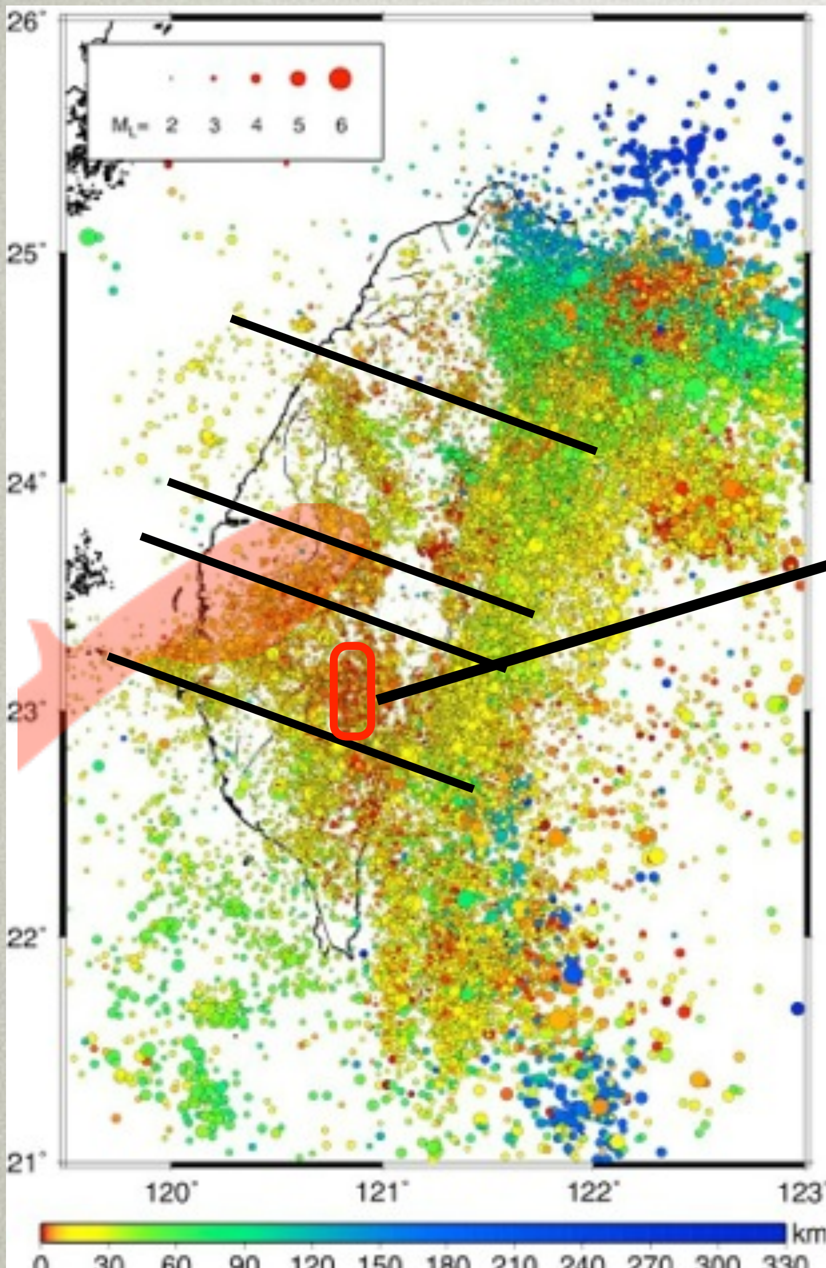
Contour map of 6.5 km/sec surface
red = deep
white = shallow



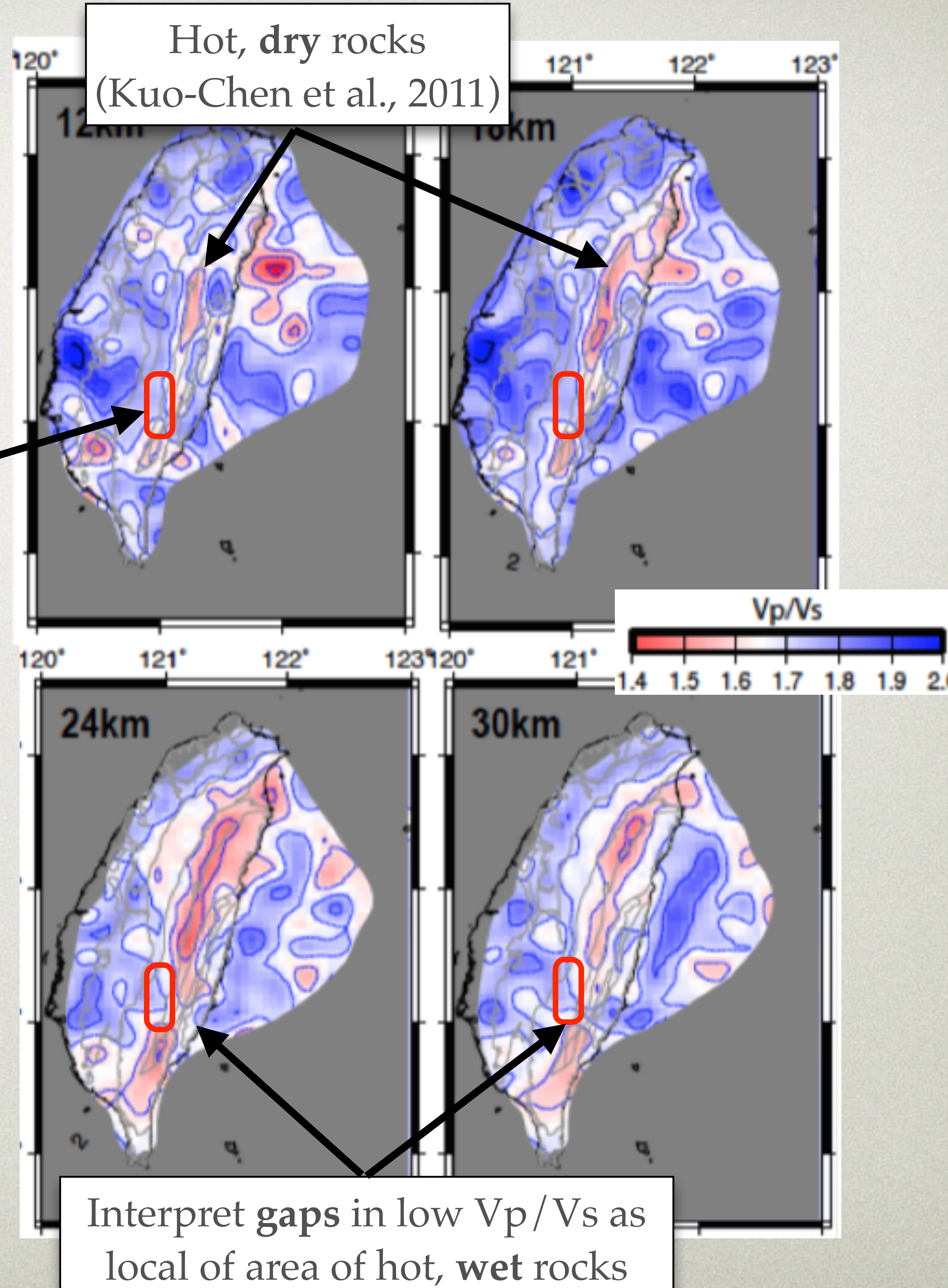

Underthrusting of
Philippine Sea Plate
CMMA
7
Detachment of
Huang et al., 2014
26°
25°
24°
23°
22°
21°
ML= 2 3 4 5 6
1
8
10

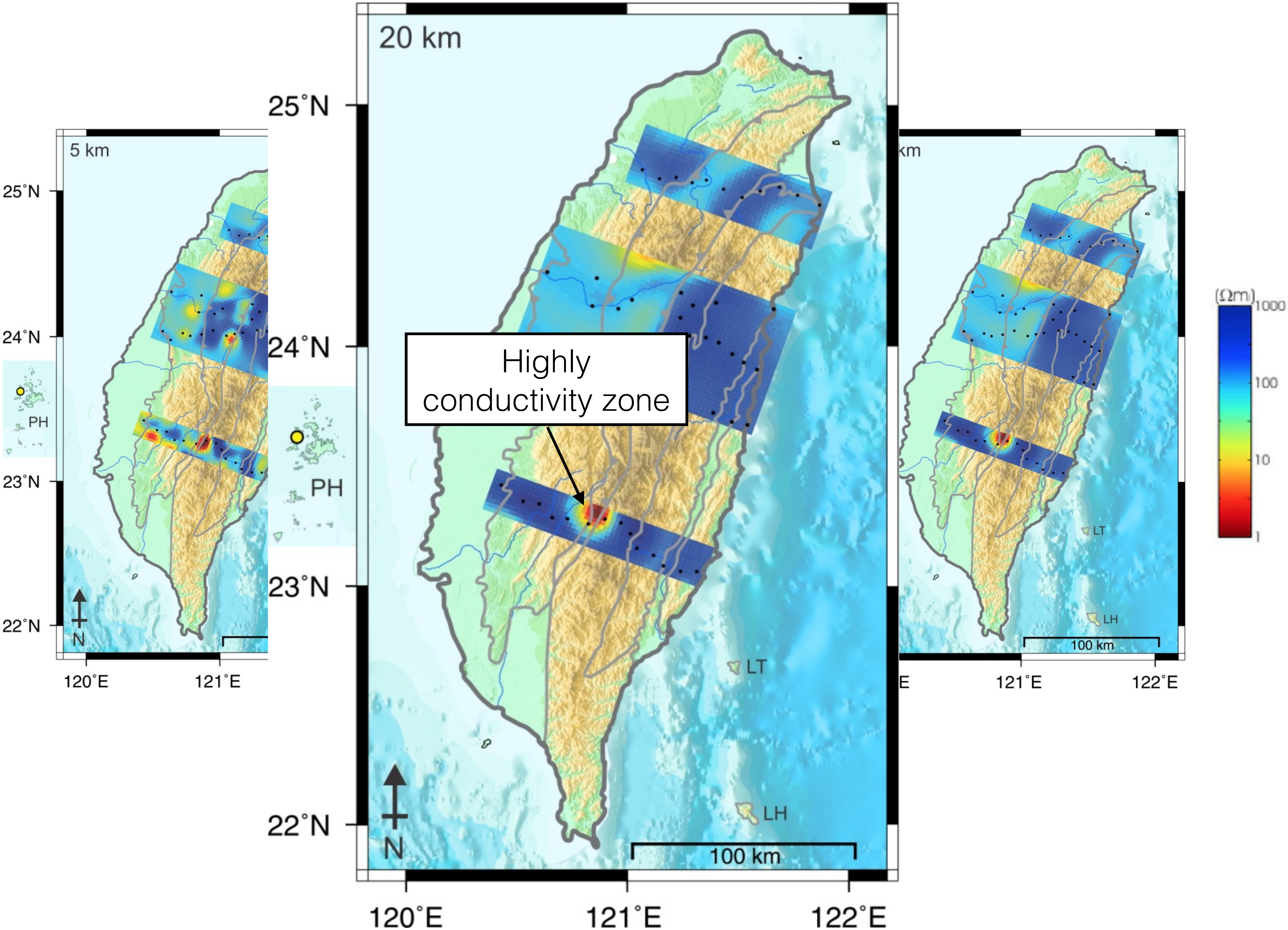

vp
5.5
6
6.5
7
7.5
8
8.5
9
W
S


Restricted
vp
5.5
6
6.5
7
7.5
8
8.5
9
W
S

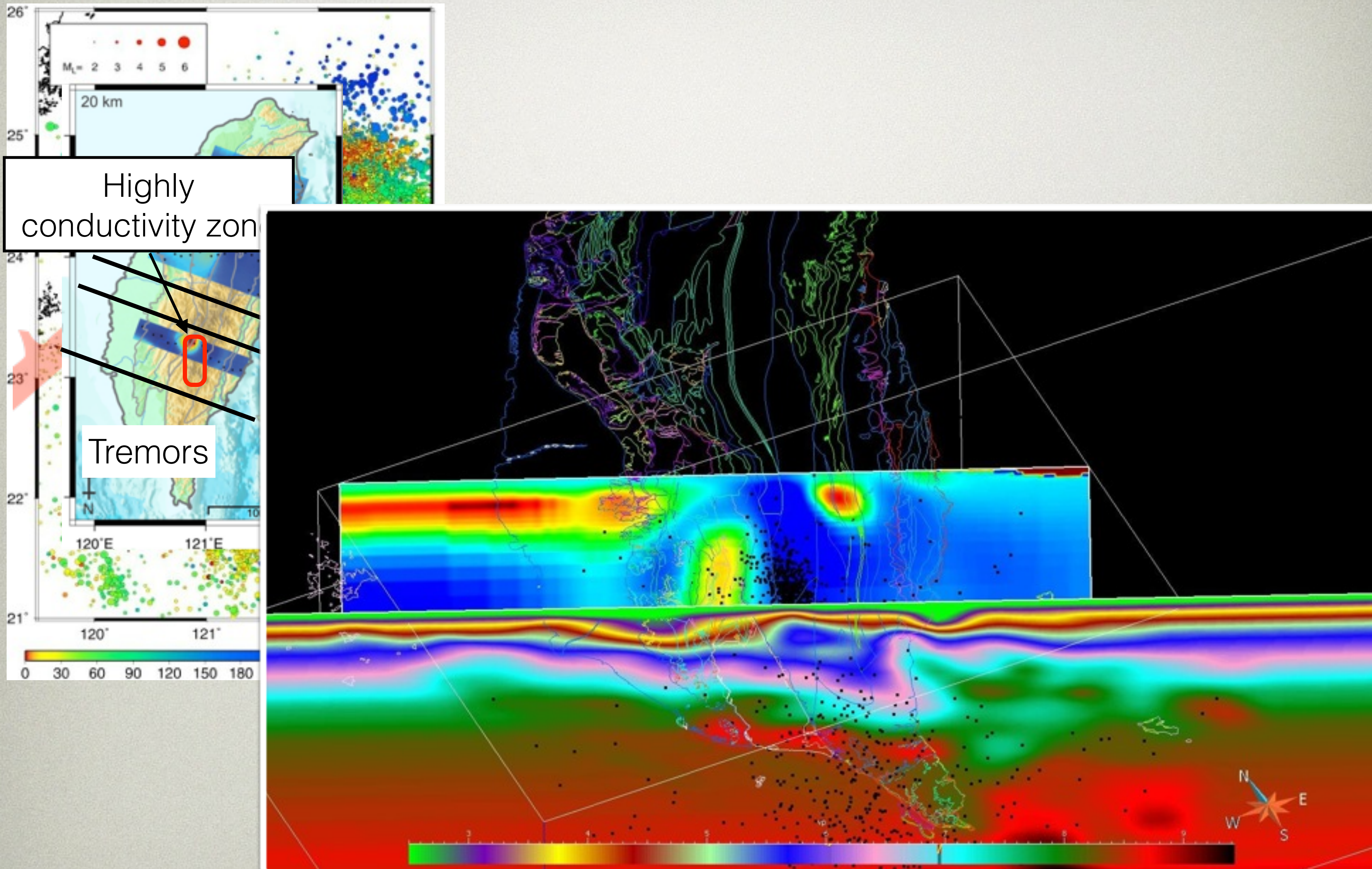


Gaps correlate with area of ambient tremors consistent with tremors associated with fluids

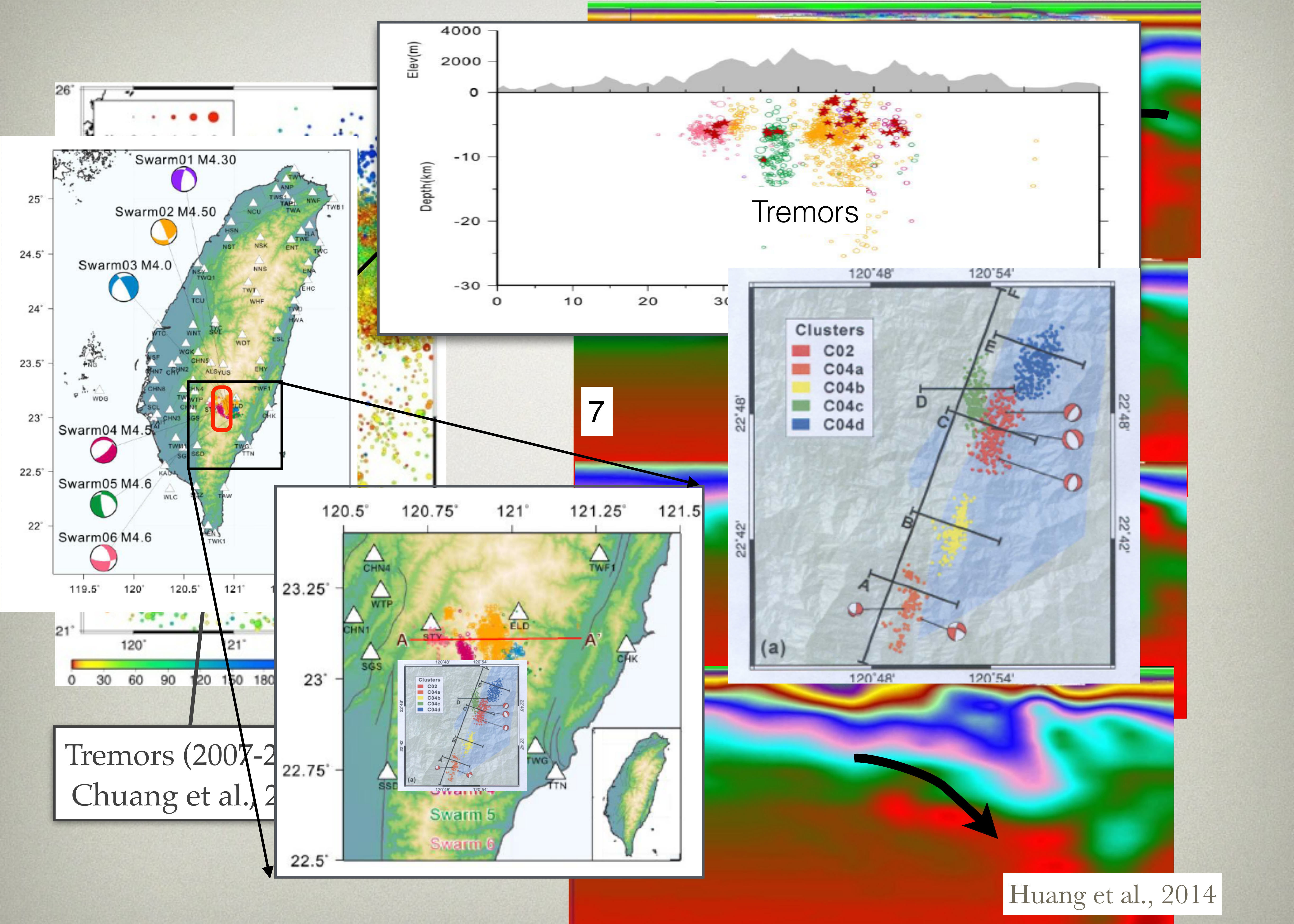




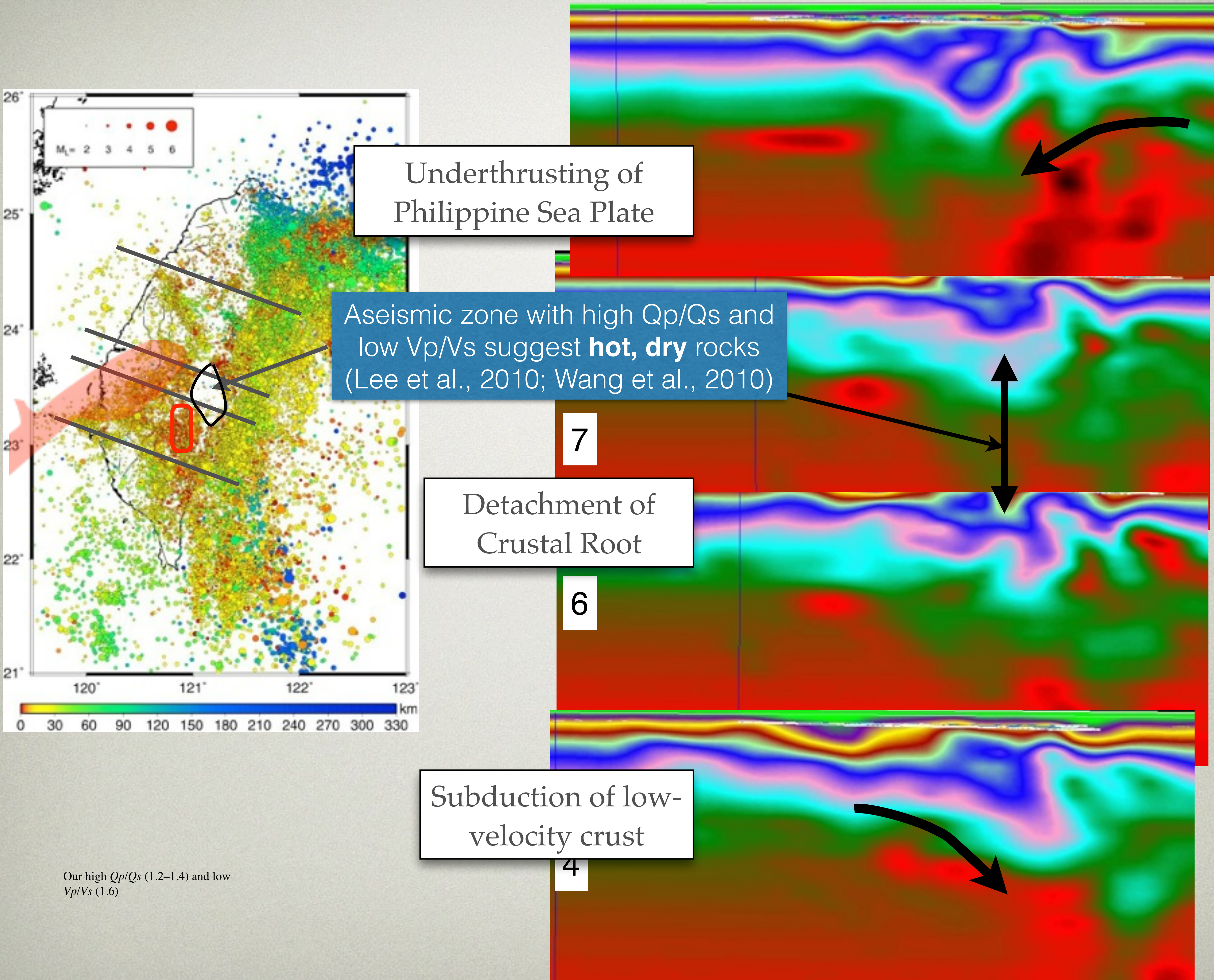
5 km
25°N
24°N
23°N
22°N
PH
N
120°E
121°E
20 km
25°N
24°N
23°N
22°N
Highly conductivity zone
PH
LT
LH
N
100 km
120°E
121°E
122°E
km
LT
LH
100 km
E
121°E
122°E
(Ωm)
1000
100
10
1



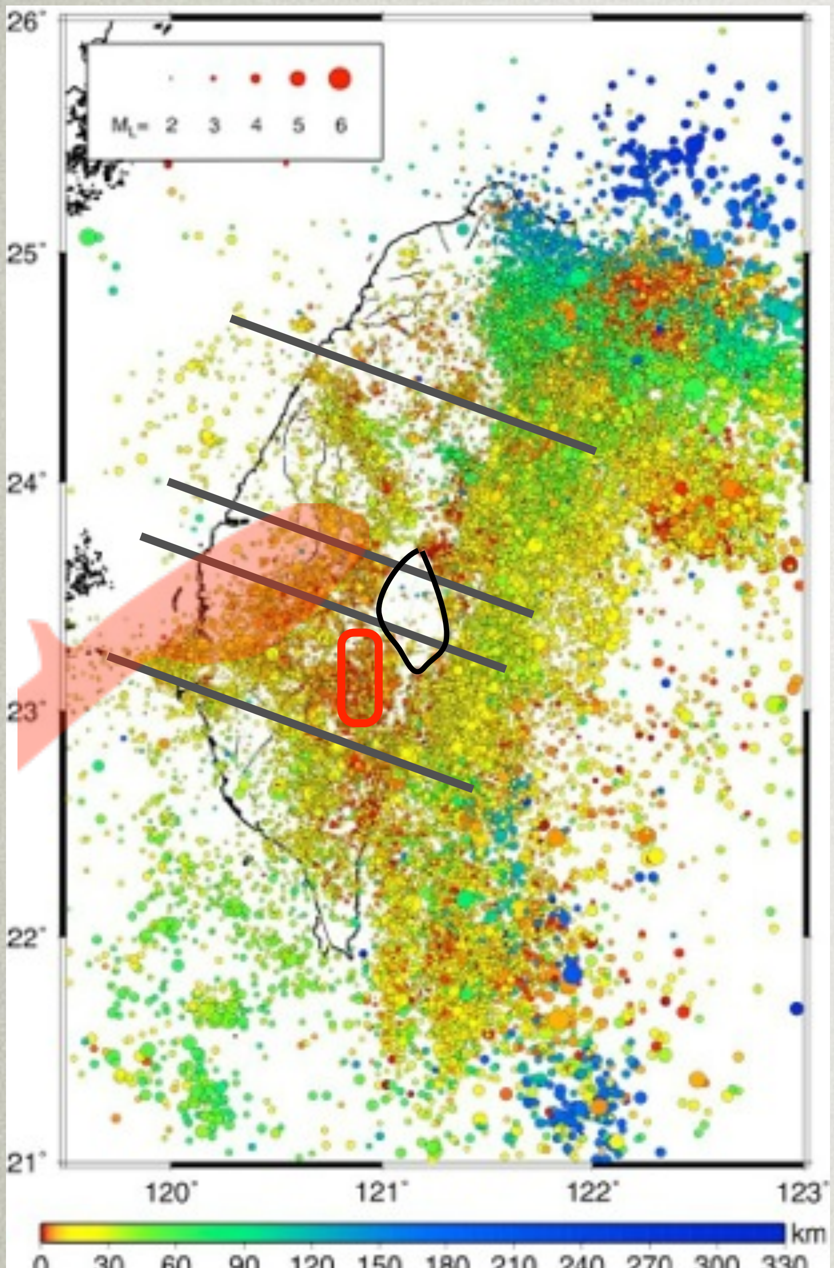
Highly
conductivity zon
Tremors
20 km
M_L= 2 3 4 5 6
26°
25°
24°
23°
22°
21°
120°E
121°E
120°
121°
0 30 60 90 120 150 180
N
E
W
S



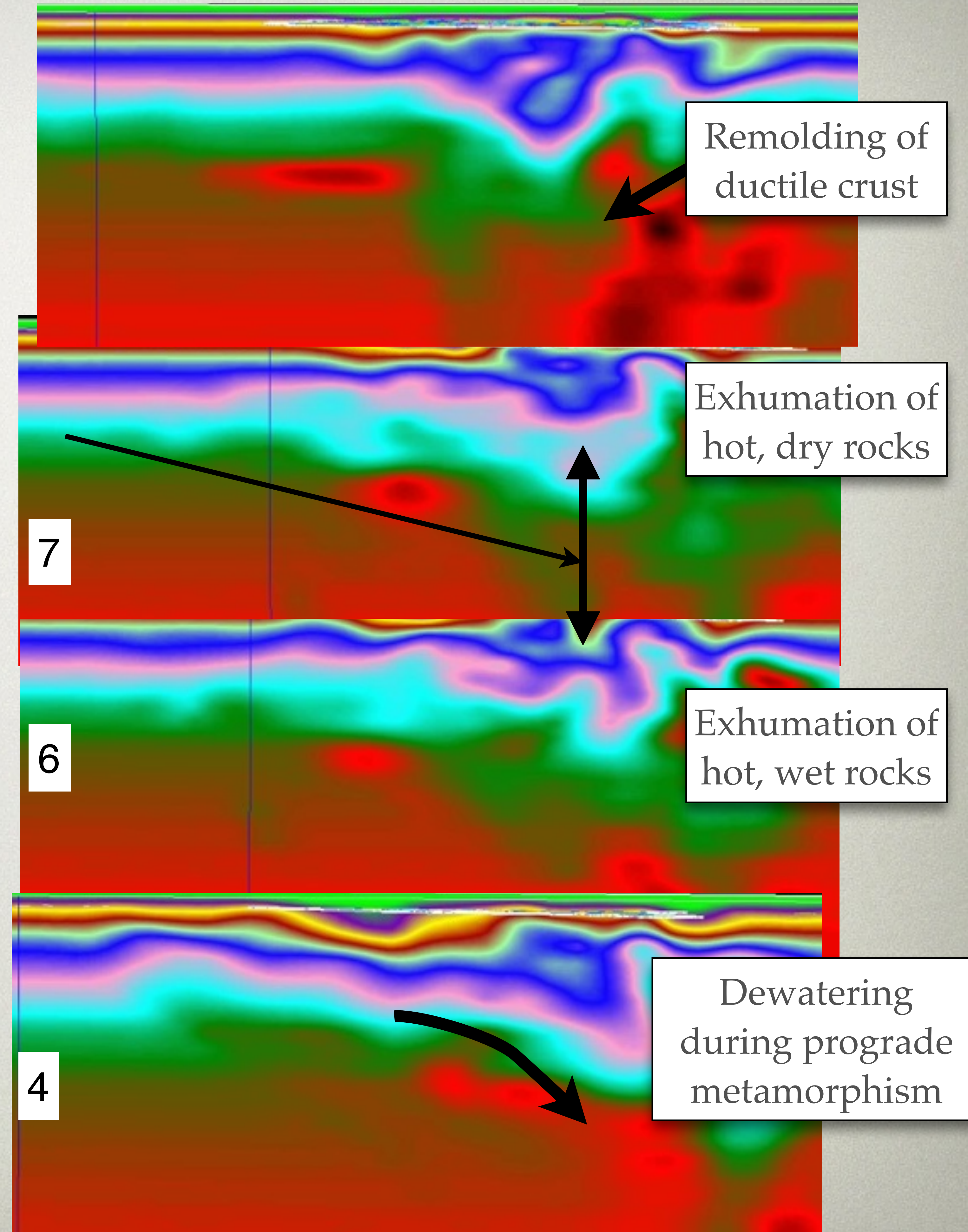
Swarm01 M4.30
Swarm02 M4.50
Swarm03 M4.0
Swarm04 M4.5
Swarm05 M4.6
Swarm06 M4.6
Elev(m)
Depth(km)
Tremors
Clusters
C02
C04a
C04b
C04c
C04d
(a)
7
A
A'
Swarm 5
Swarm 6
Tremors (2007-2
Chuang et al., 2
Huang et al., 2014



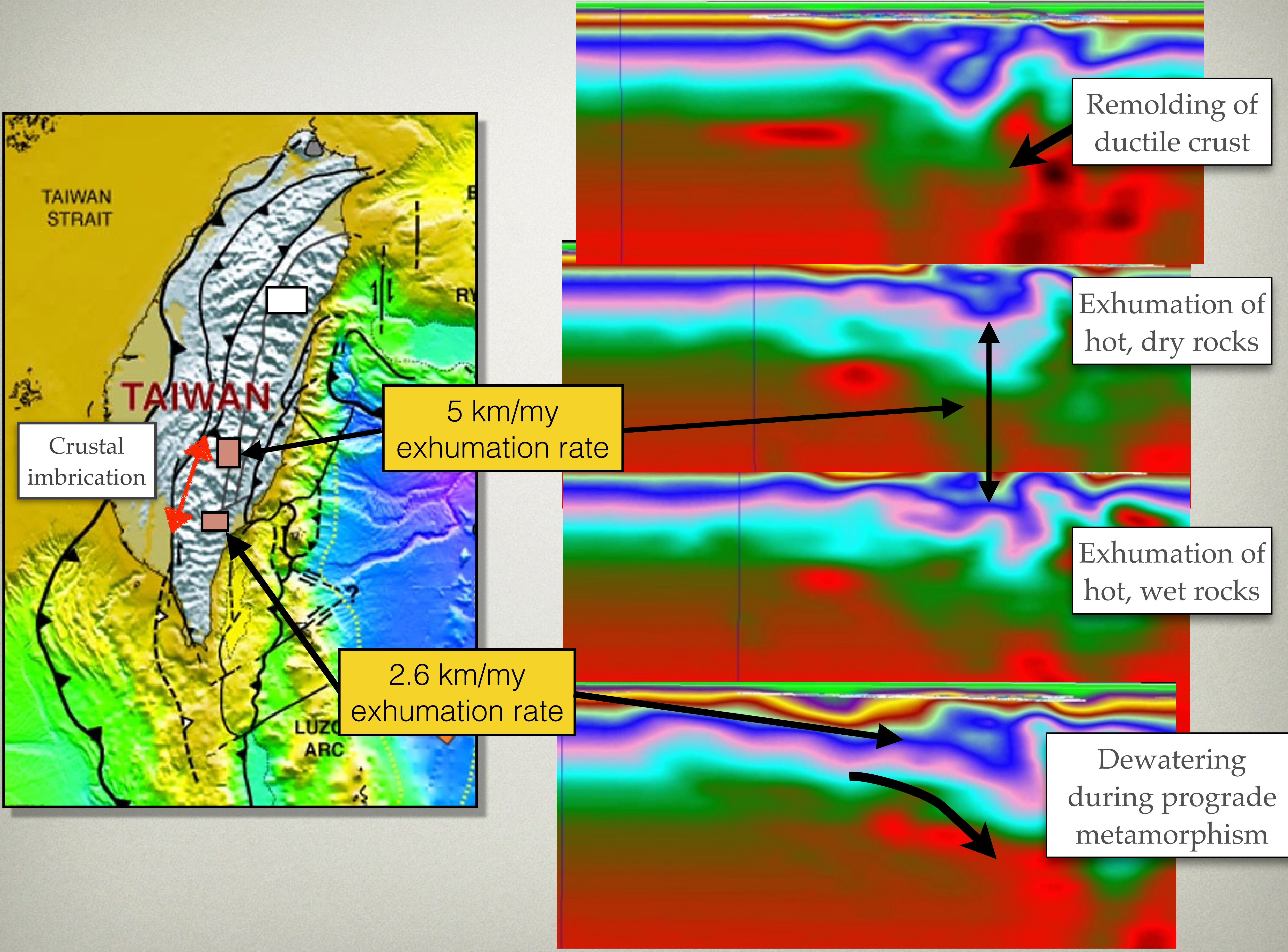
Our high *Qp*/*Qs* (1.2–1.4) and low *Vp*/*Vs* (1.6)



M_L= 2 3 4 5 6
26°
25°
24°
23°
22°
21°
120°
121°
122°
123°
km
0 30 60 90 120 150 180 210 240 270 300 330

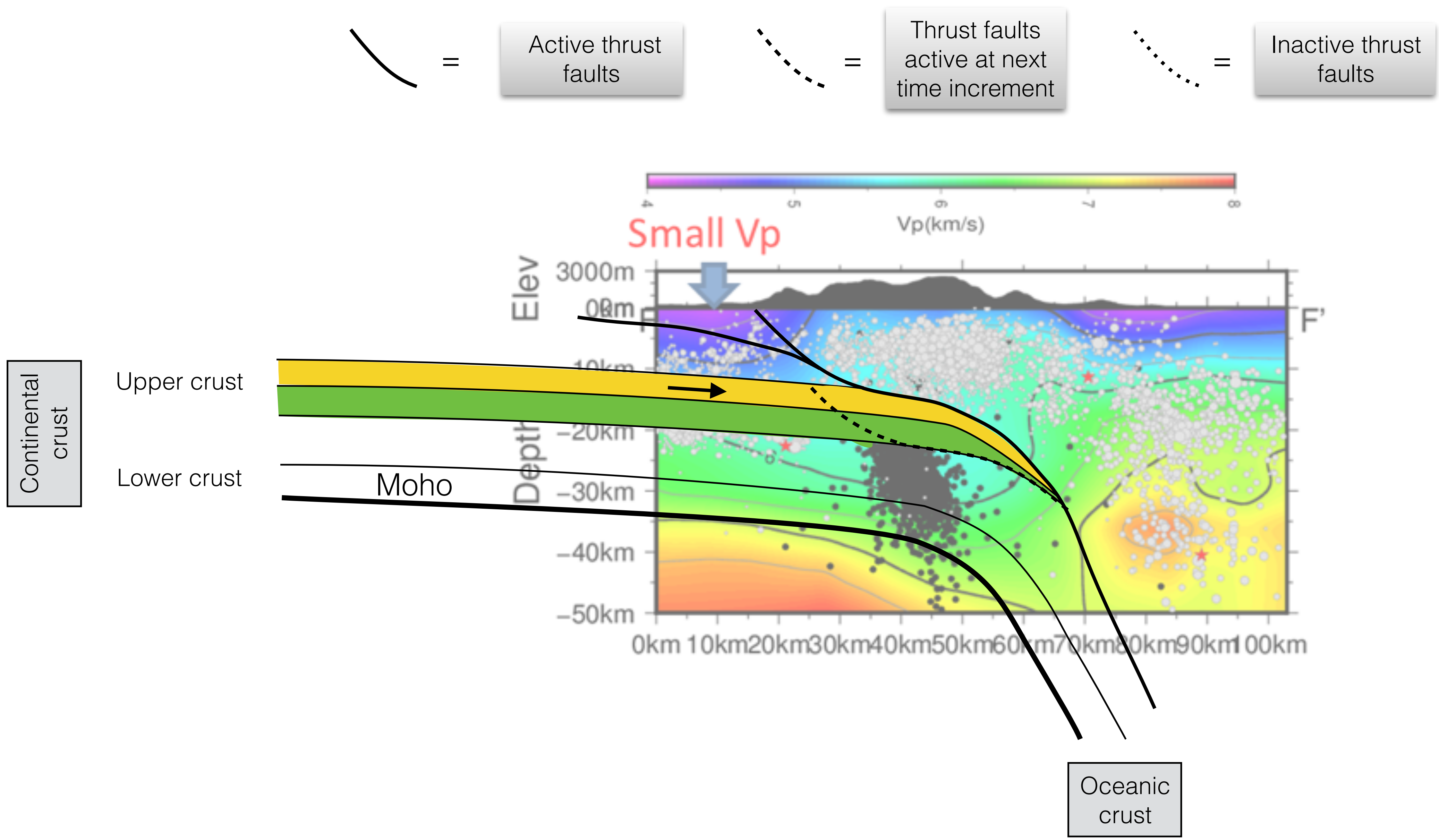


Remolding of ductile crust
Exhumation of hot, dry rocks
7
6
Exhumation of hot, wet rocks
4
Dewatering during prograde metamorphism



TAIWAN
STRAIT
TAIWAN
Crustal imbrication
5 km/my exhumation rate
2.6 km/my exhumation rate
ARC
Remolding of ductile crust
Exhumation of hot, dry rocks
Exhumation of hot, wet rocks
Dewatering during prograde metamorphism

Time 1: Subduction of stretched continent crust

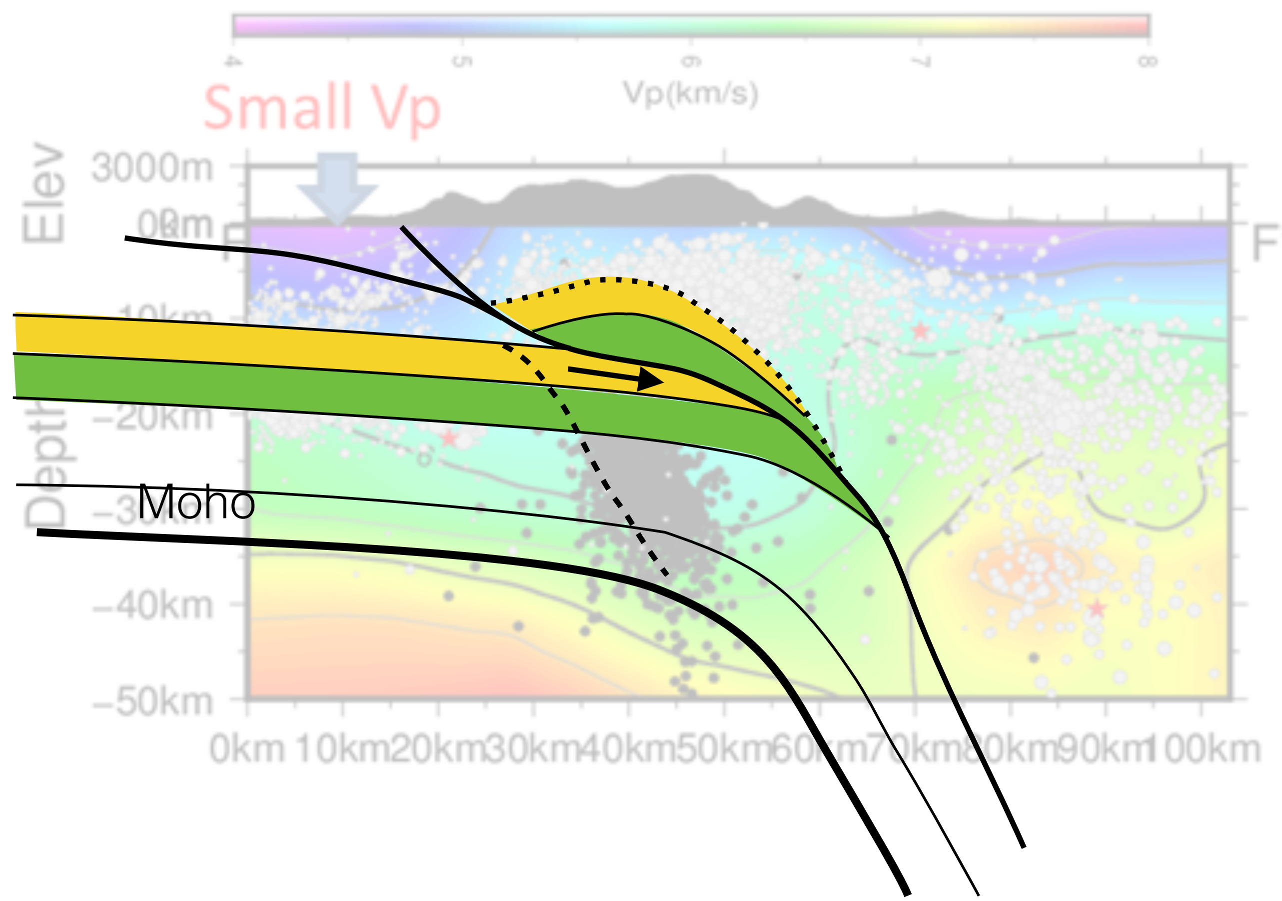


Time 2: Imbrication of upper continental crust

= Active thrust faults

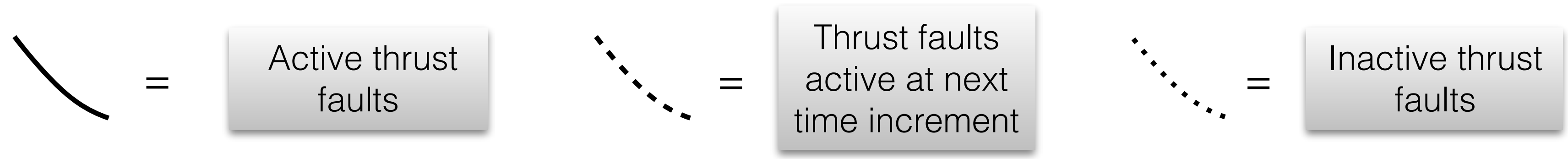
= Thrust faults active at next time increment

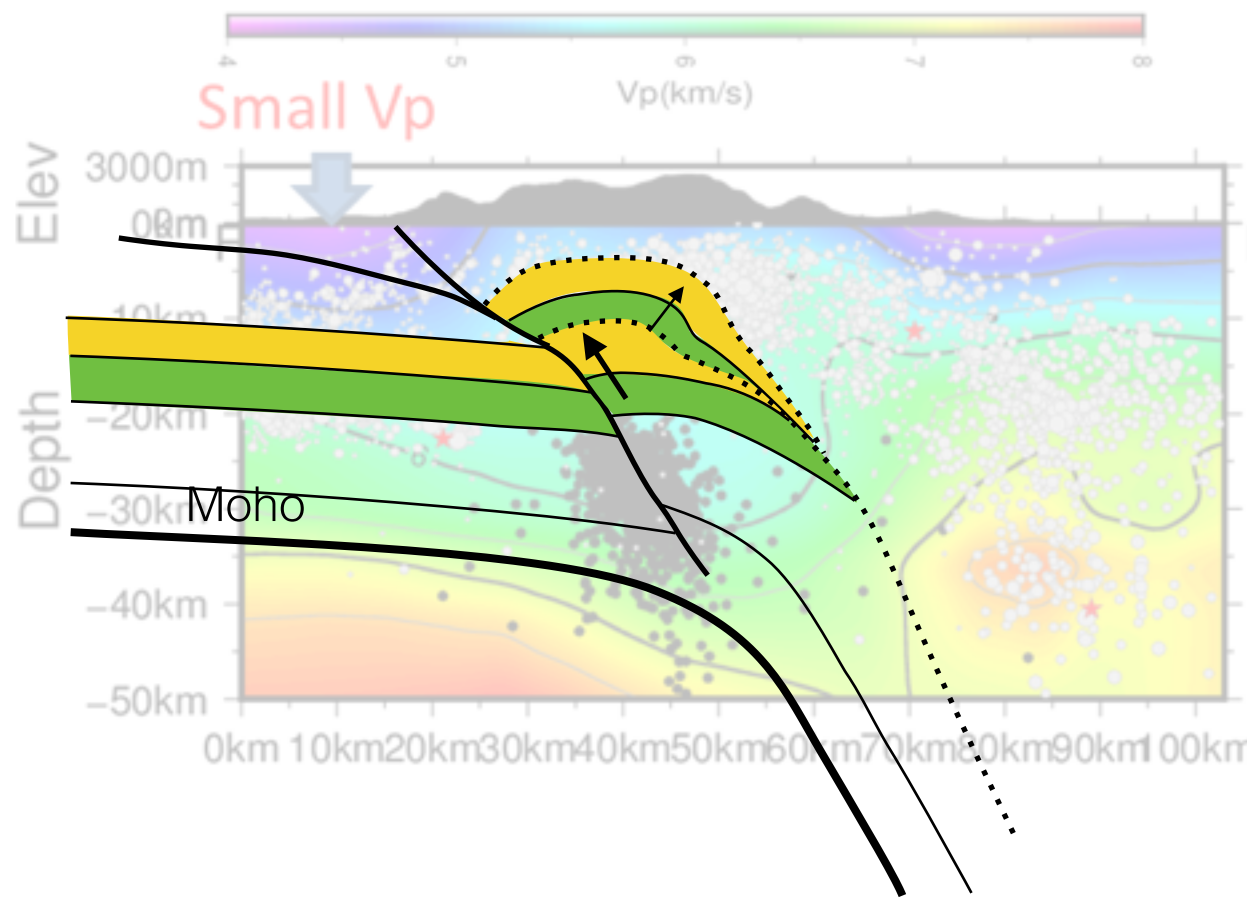
= Inactive thrust faults



Uplift driven by thickening in the upper crust (note shown: subduction of forearc and exhumation of blueschist belt)

Time 3: Detachment of middle and upper continental crust





Uplift driven by thickening of the middle and upper crust (and buoyancy?)