The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA

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Advanced School on Direct and Inverse Problems of Seismology

27 September - 8 October, 2010

Multi-disciplinary TAIGER Experiments to Explore the Science of Mountain Building

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Multi-disciplinary TAIGER Experiments to Explore the Science of Mountain Building

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Hao Kuo-Chen, SUNY Binghamton

David Okaya, USC

US TAIGER Team

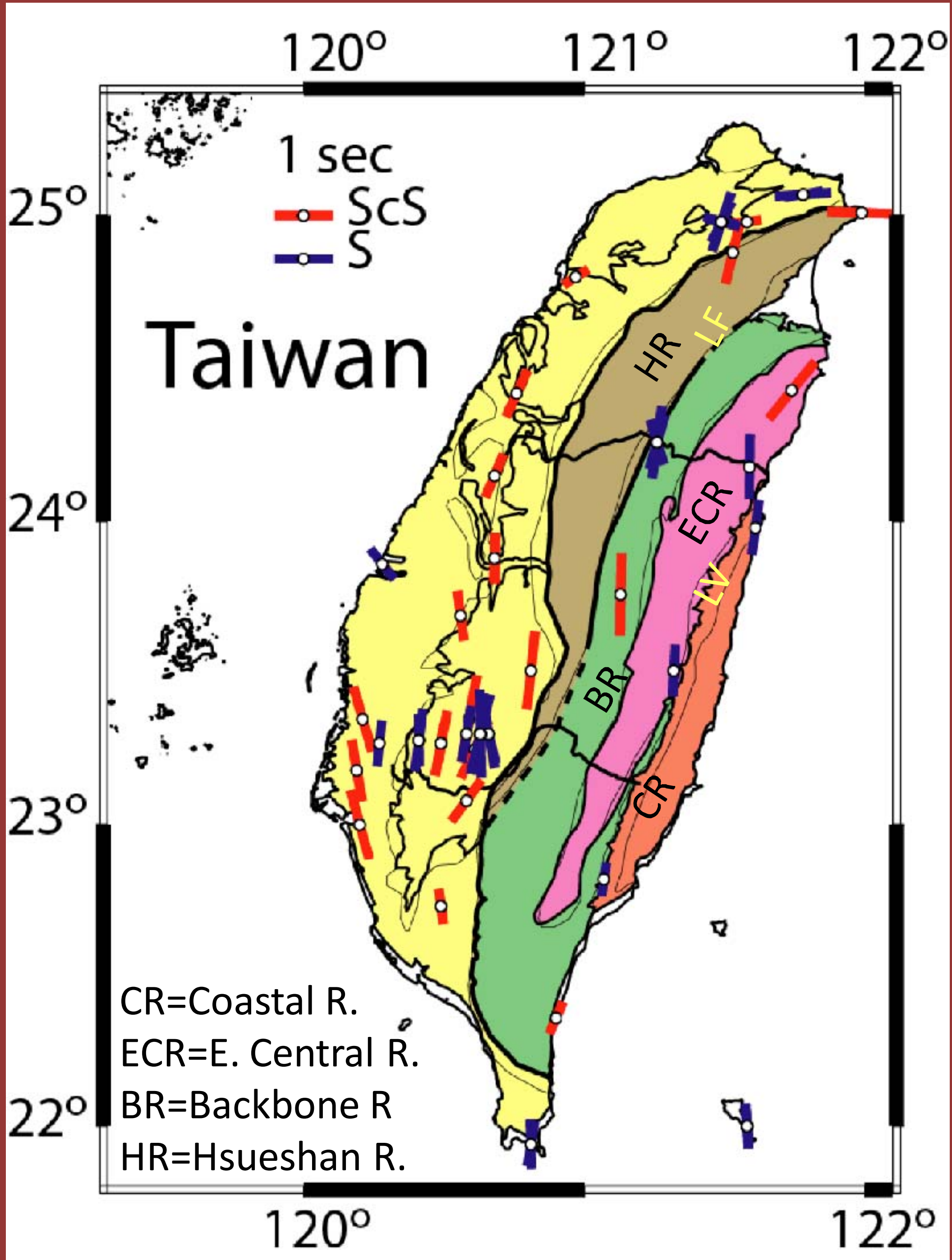
Taiwan TAIGER Team

Fallacies of Observations – R. W. Van Bemelen, 1954

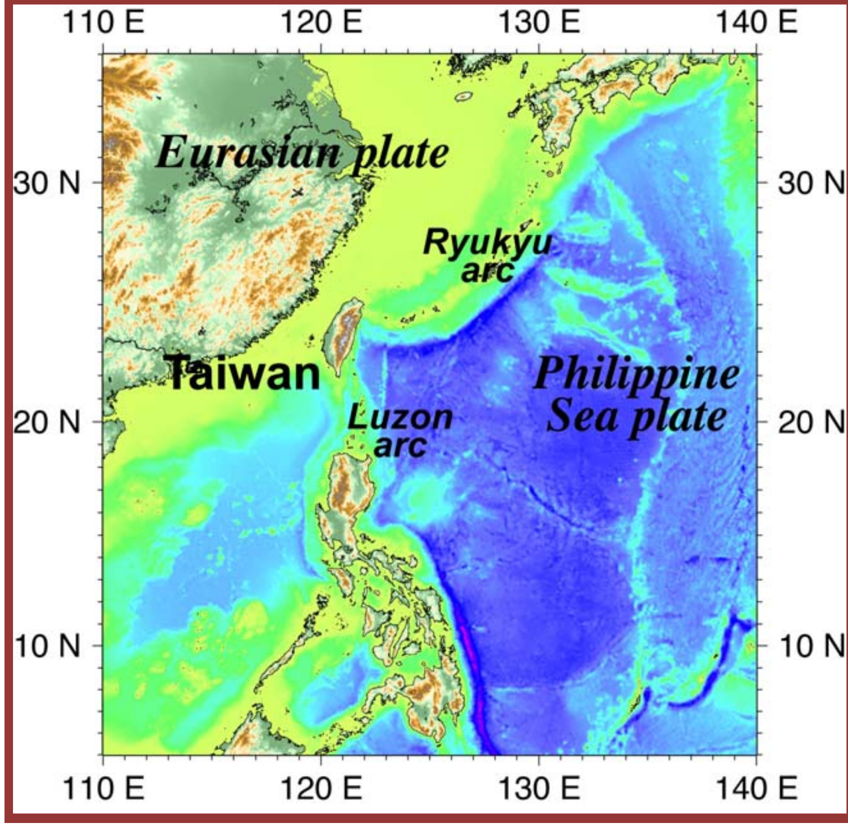
However there is always the danger that our observations are no longer primary data objectively gathered, but are unconsciously influenced by theoretical conceptions. The latter may assume a dogmatic character, being no longer mere working hypothesis providing the guiding principles of our research; they may become rigid axioms, assuming in our mental processes the same value as the facts of observation. In such a situation some scientists are apt to be prejudiced in their observations by theory, which means frustration of research. Then if discrepancies between theoretical prognoses and observational diagnoses become apparent, it is often not the theory that is revised; instead, the observations are sometimes dogmatically reinterpreted and incorrect values may be assigned to them.

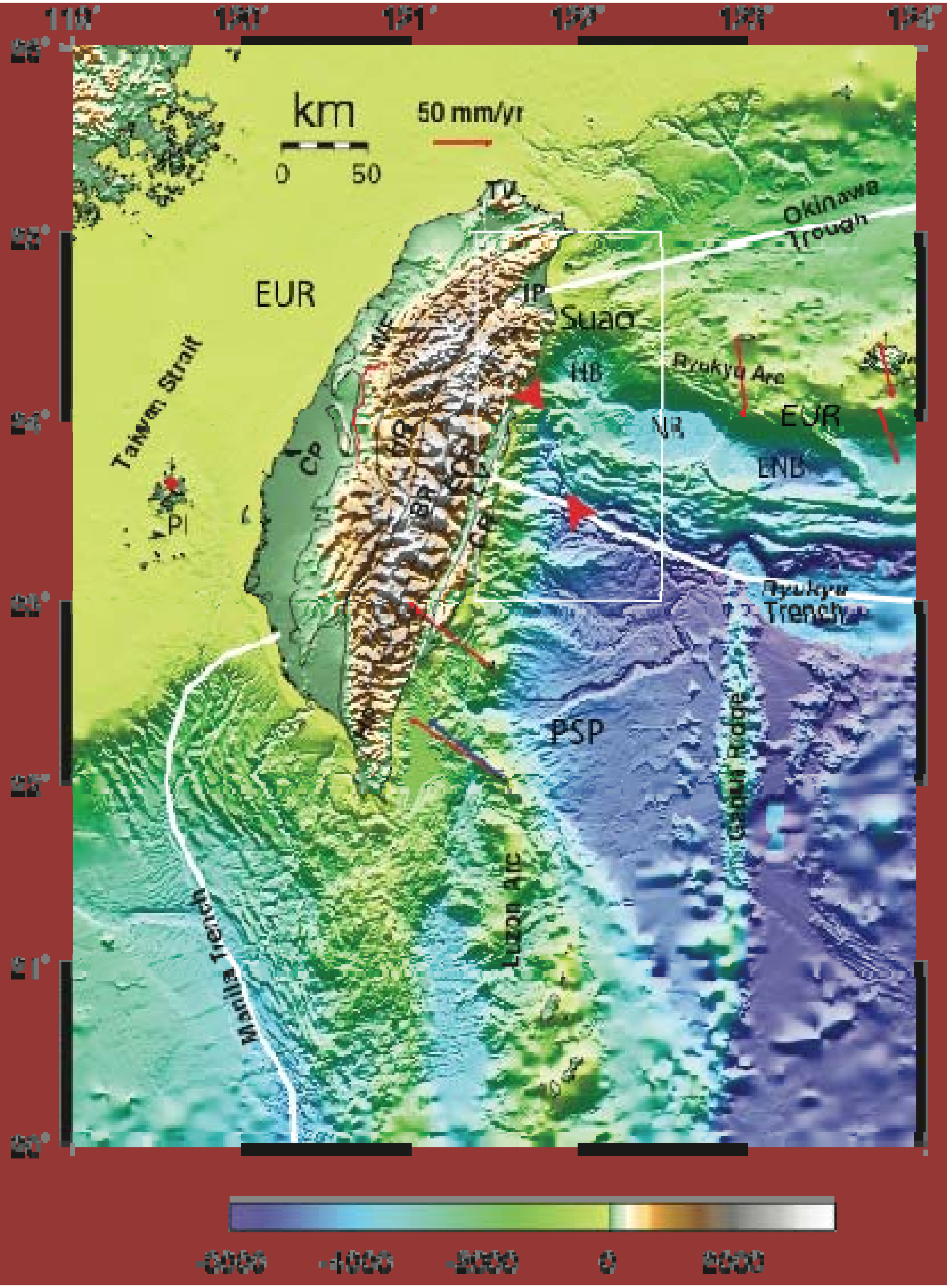
Geology

- Taiwan orogeny began ~5 million years ago
- ~3952 m Jade Mountain; ~280 km long mountachain
- One of the fastest rising mountains in the world (>1cm/year or 10 km/myr)
- Also has one of the highest erosion rates (>0.5cm/yr short term; long term?)

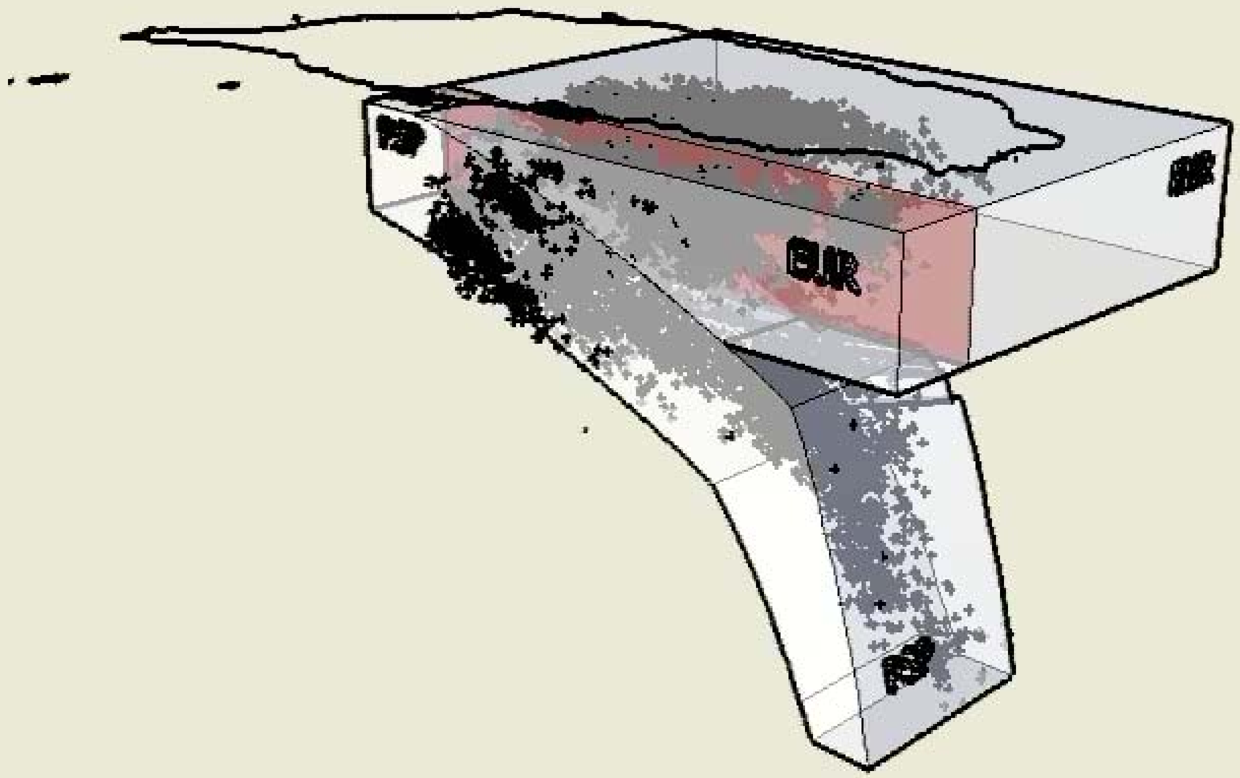


Regional Setting and Plate Tectonic Environment of Taiwan

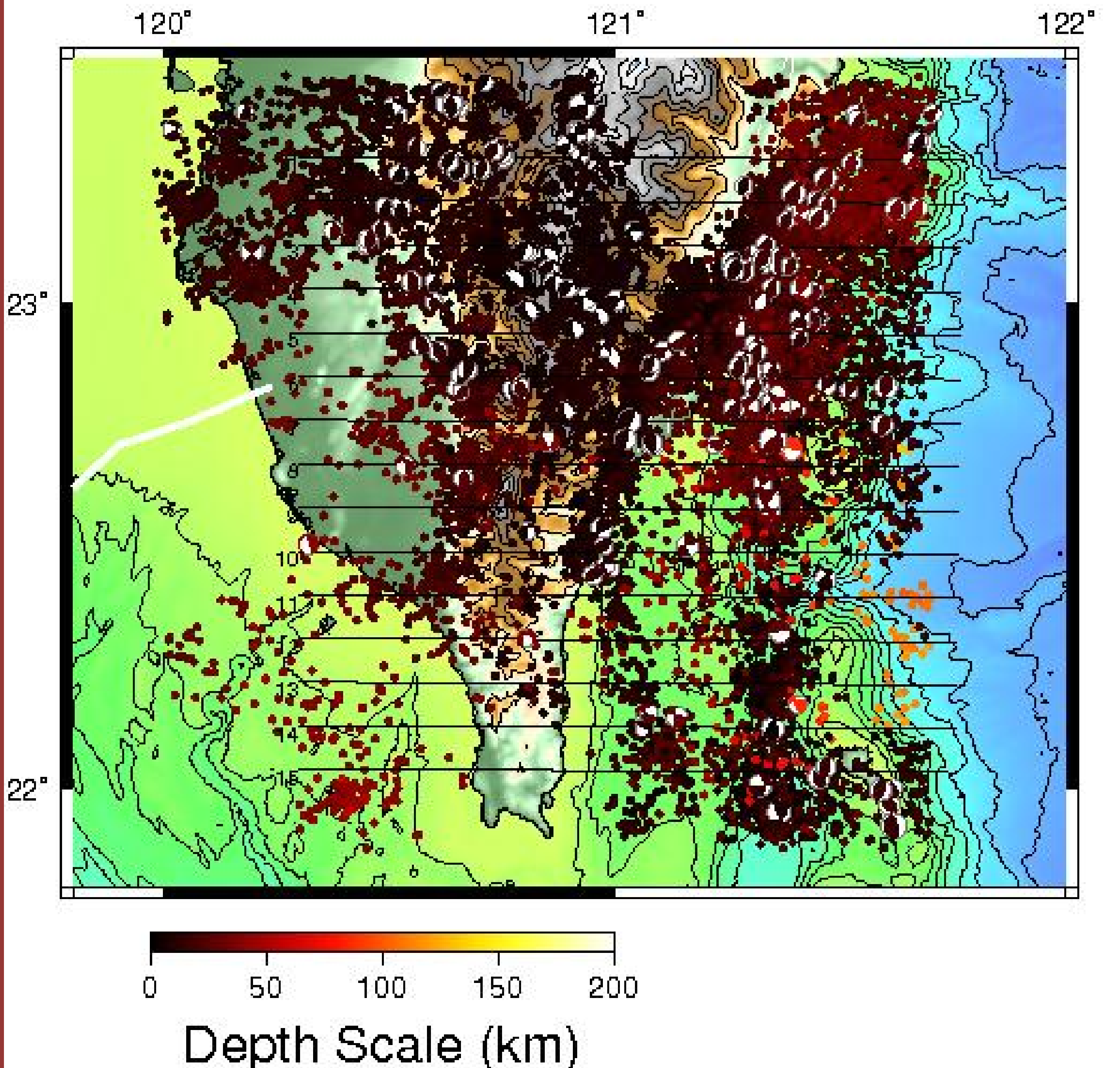


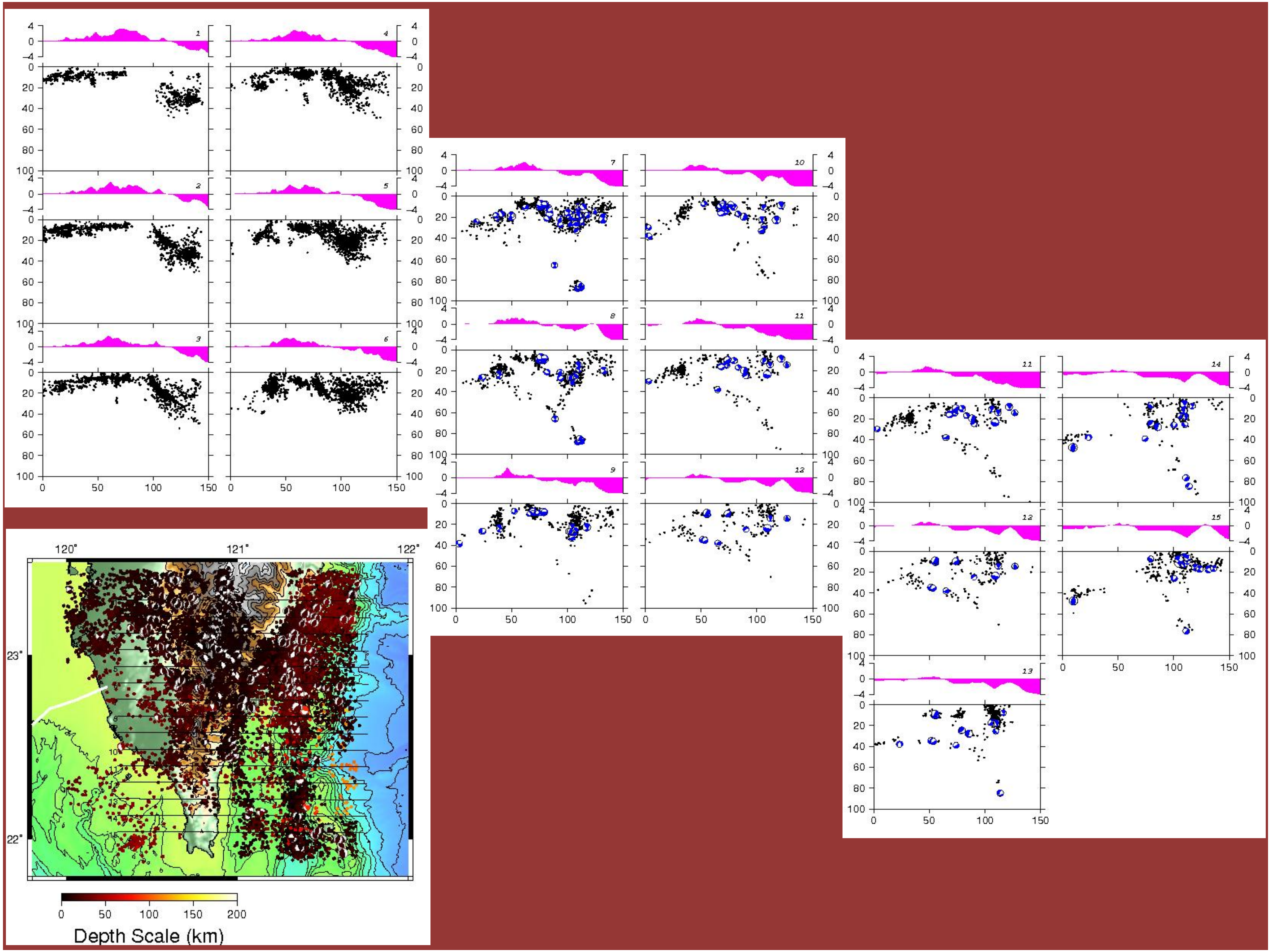


3-D View of N. Taiwan Plate Structure



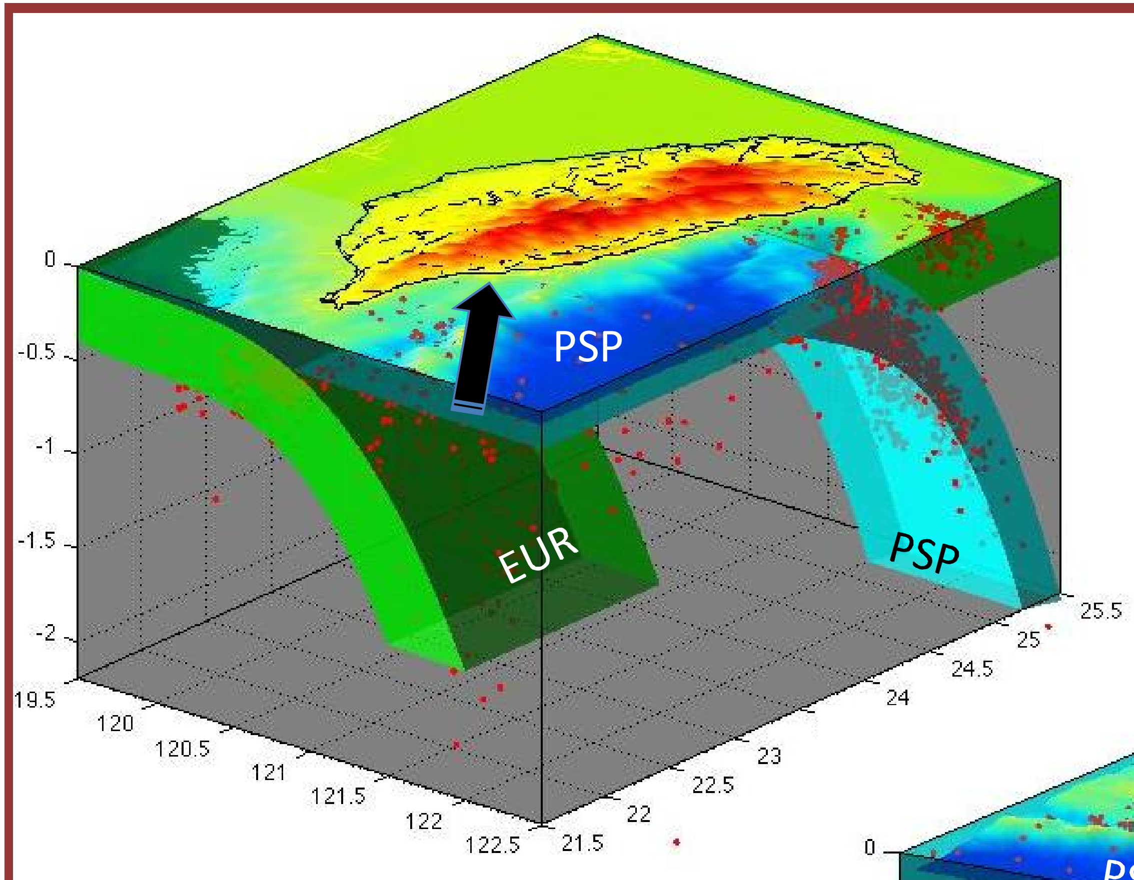
Seismicity and Plate Structure in S. Taiwan

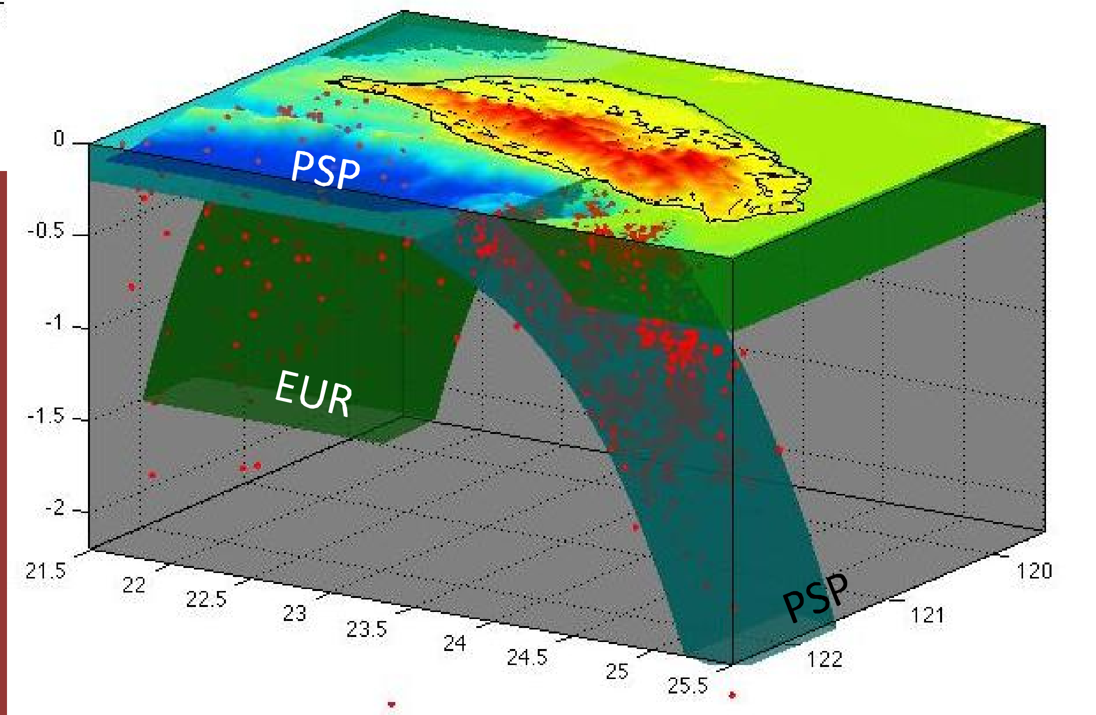




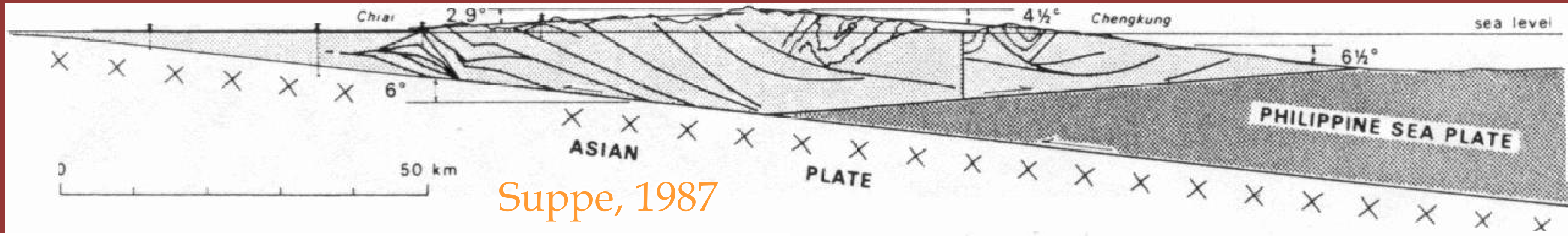
120°
121°
122°
23°
22°
0
50
100
150
200
Depth Scale (km)

Active subduction zones under Taiwan

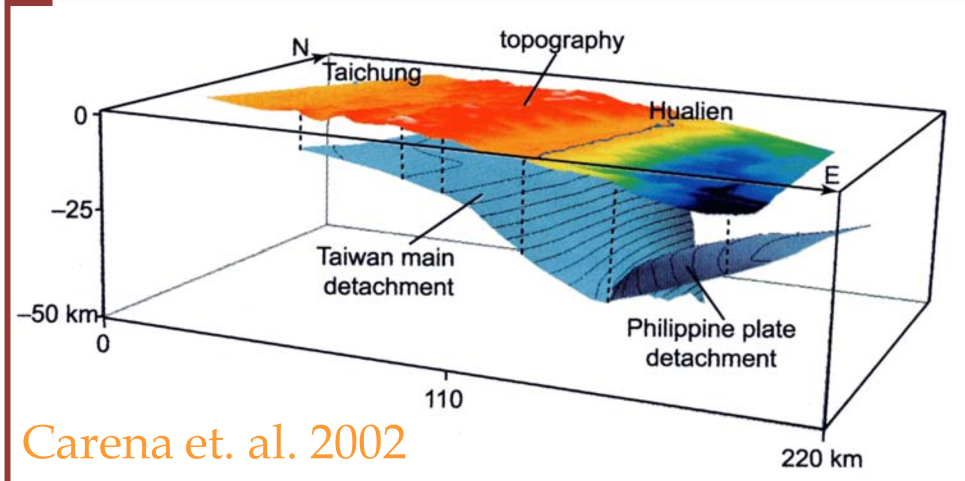




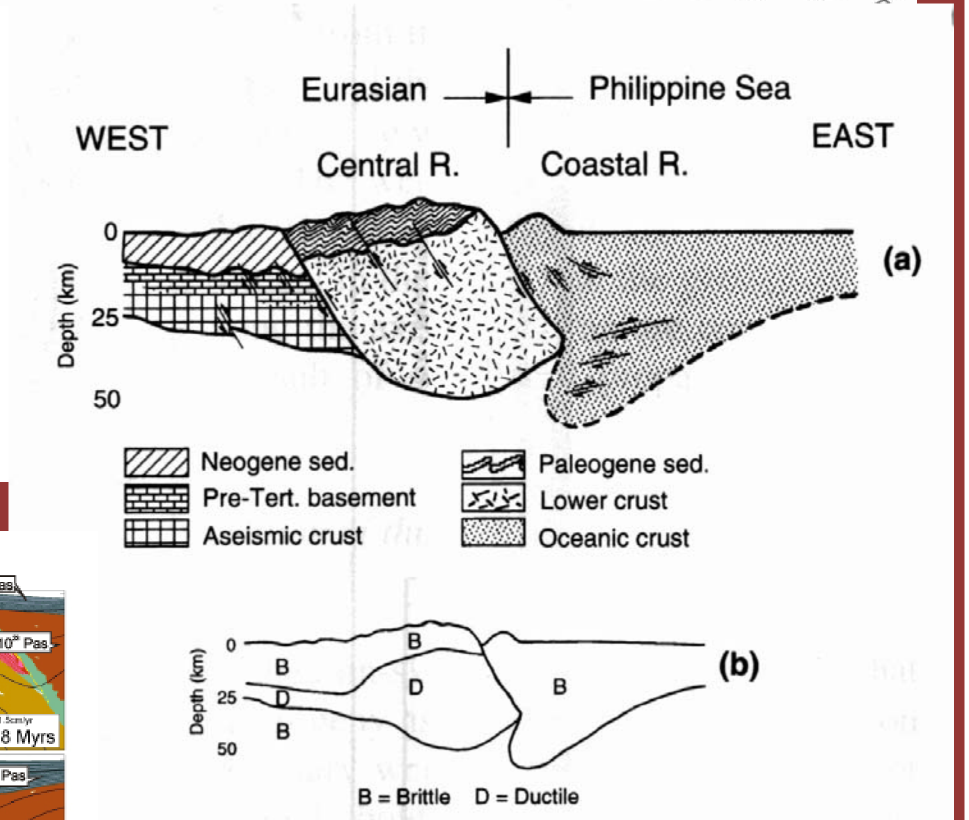
Some Proposed “End Member” models

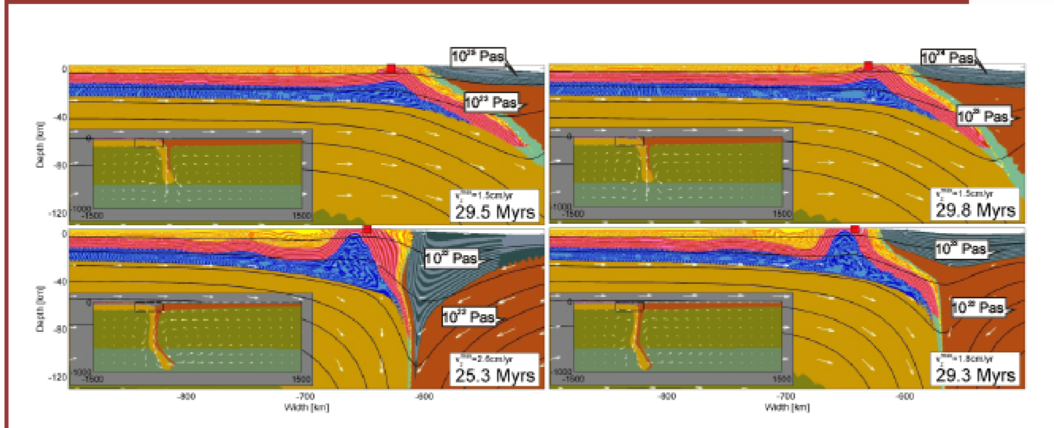


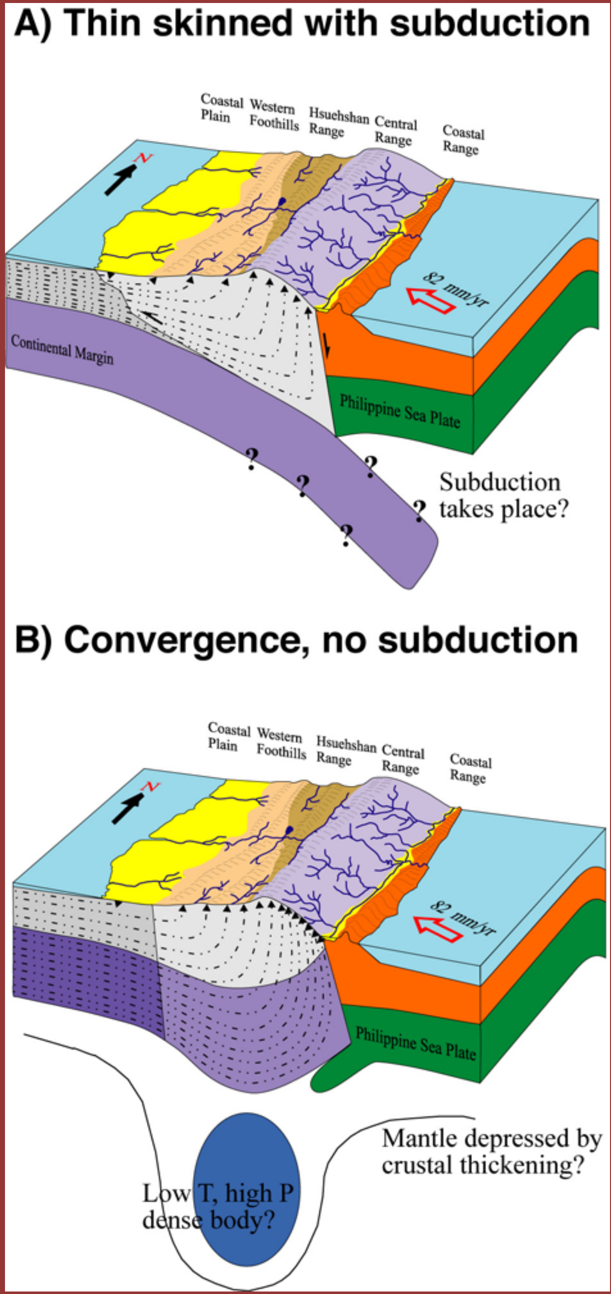
Suppe, 1987



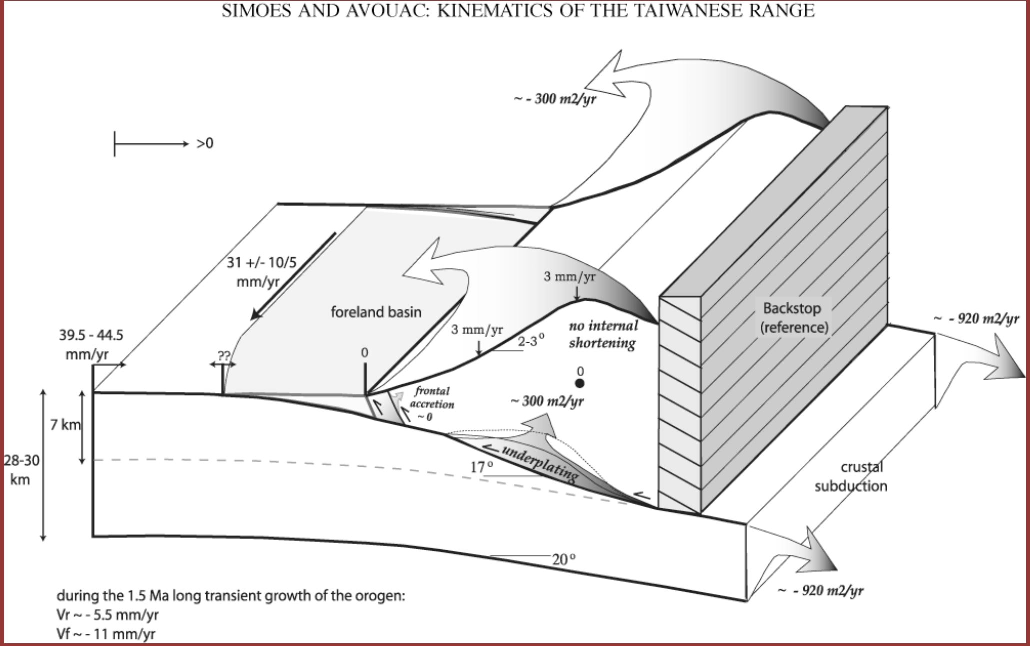
Carena et. al. 2002







Dahlen-Davis-Suppe thin-skinned thrusting



Taiger Teams

USA

Francis Wu , Steve Roecker
David Okaya, Larry Brown
Kirk McIntosh, Yosio Nakamura
Nik Christensen
Martyn Unsworth
Luc Lavier

Japan

Naoshi Hirata, Hiroshi Sato

Taiwan

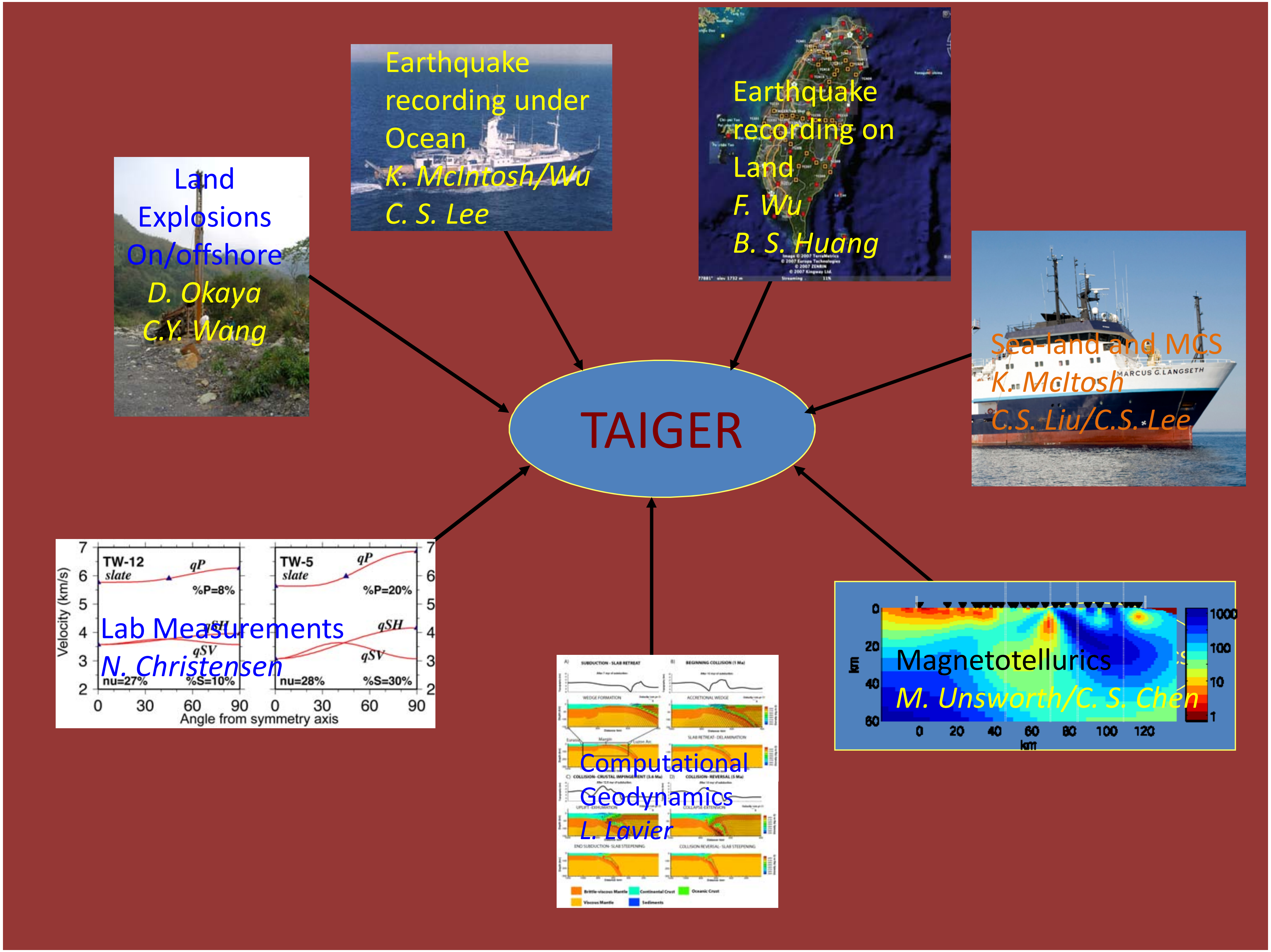
C.Y.Wang, Bor-shouh Huang, K. F. Ma
Char-Shine Liu, C.S. Lee,
Shukun Hsu
W.T. Liang
H.Y. Yen, W.H. Wang, C.H. Chen, R.J. Rau

France

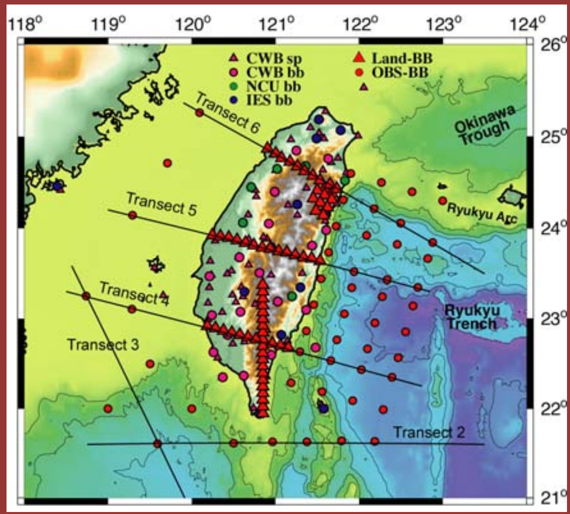
Serge Lallemand

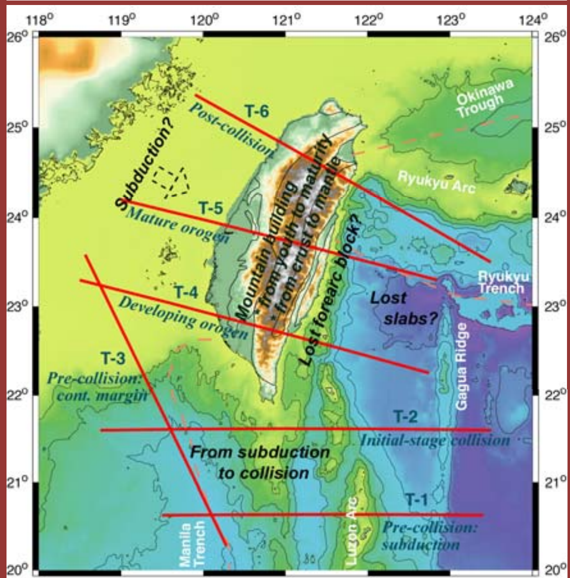
China

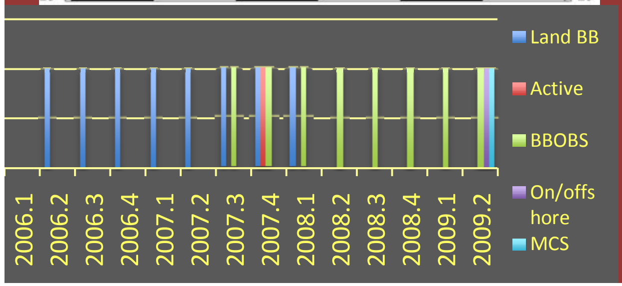
Gao Rui


TAIGER
Land Explosions On/offshore
D. Okaya
C.Y. Wang
Earthquake recording under Ocean
K. McIntosh/Wu
C. S. Lee
Earthquake recording on Land
F. Wu
B. S. Huang
Sea-land and MCS
K. McItosh
C.S. Liu/C.S. Lee
MARCUS G. LANGSETH
Lab Measurements
N. Christensen
TW-12 slate
TW-5 slate
qP
qSH
qSV
%P=8%
%P=20%
nu=27%
%S=10%
nu=28%
%S=30%
Velocity (km/s)
Angle from symmetry axis
Computational Geodynamics
L. Lavier
Magnetotellurics
M. Unsworth/C. S. Chen
km

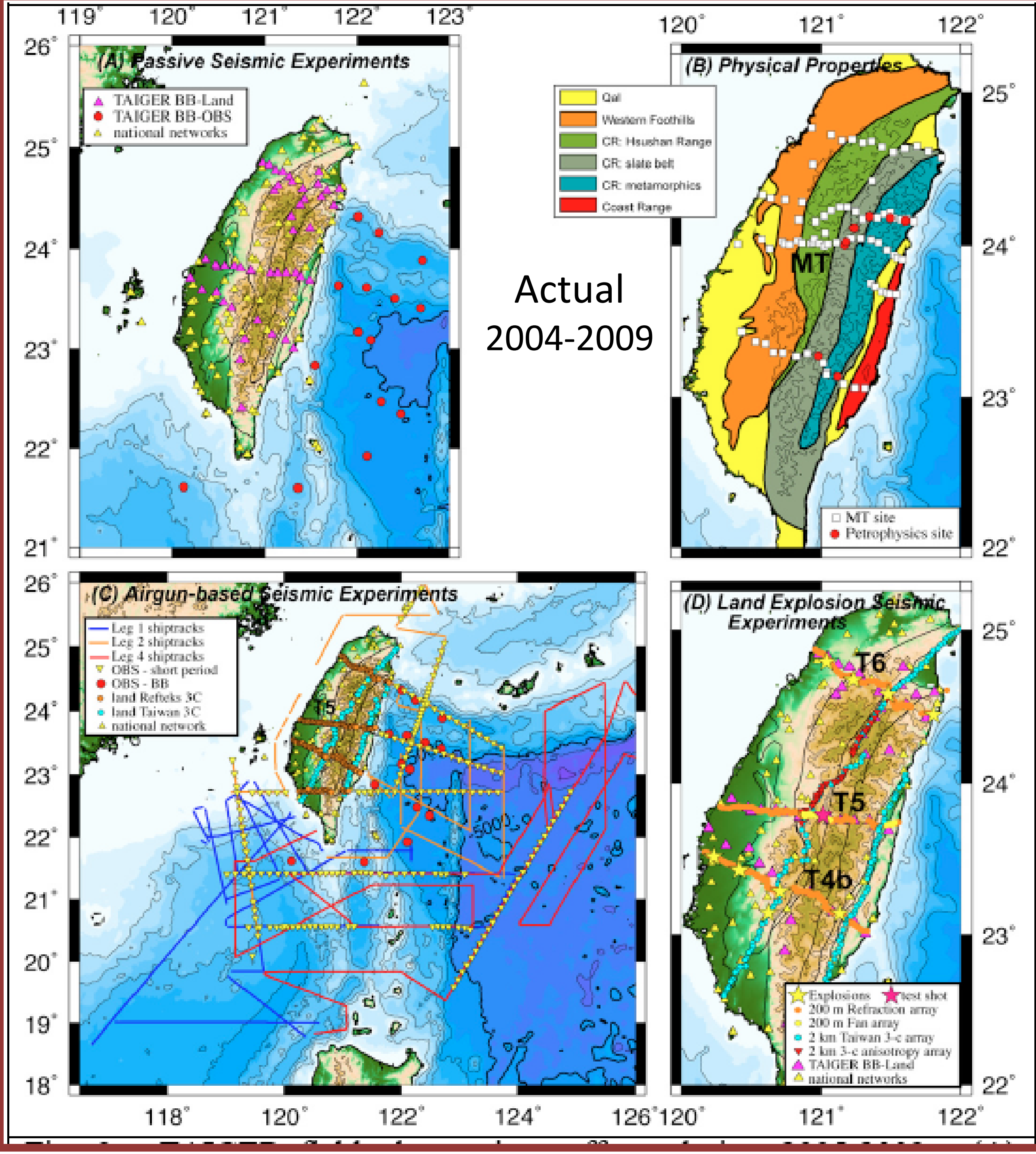
Proposed (2003)







Actual
2004-2009



TAIGER Fleet

Joys of True International Scientific Cooperation

- Joint planning and execution of experiments
- Share of facilities and cost of experiments
- Establish mirror databases in the US and in Taiwan
- Availability of auxilliary data in Taiwan (permanent broadband seismic data, GPS, CWB network data, map data)

Importance of Built-in Redundancy

Even with careful tests of field techniques and most demanding negotiations with multiple agencies we have to replace one set of critical active source experiments with a different set

Resulting Dataset

- 600 Gbytes of land broadband data
- 185 Gbytes of broadband OBS data
- ~3000 texans recording sites in windowed and continuous mode (450 sites) during active source work
- ~300 off/onshore stations in continuous mode for 3 months (2 km spacing along transects) – 2 TB
- ~10,320 km of R/V Langseth MCS data acquisition
- ~300 SPOBS drops

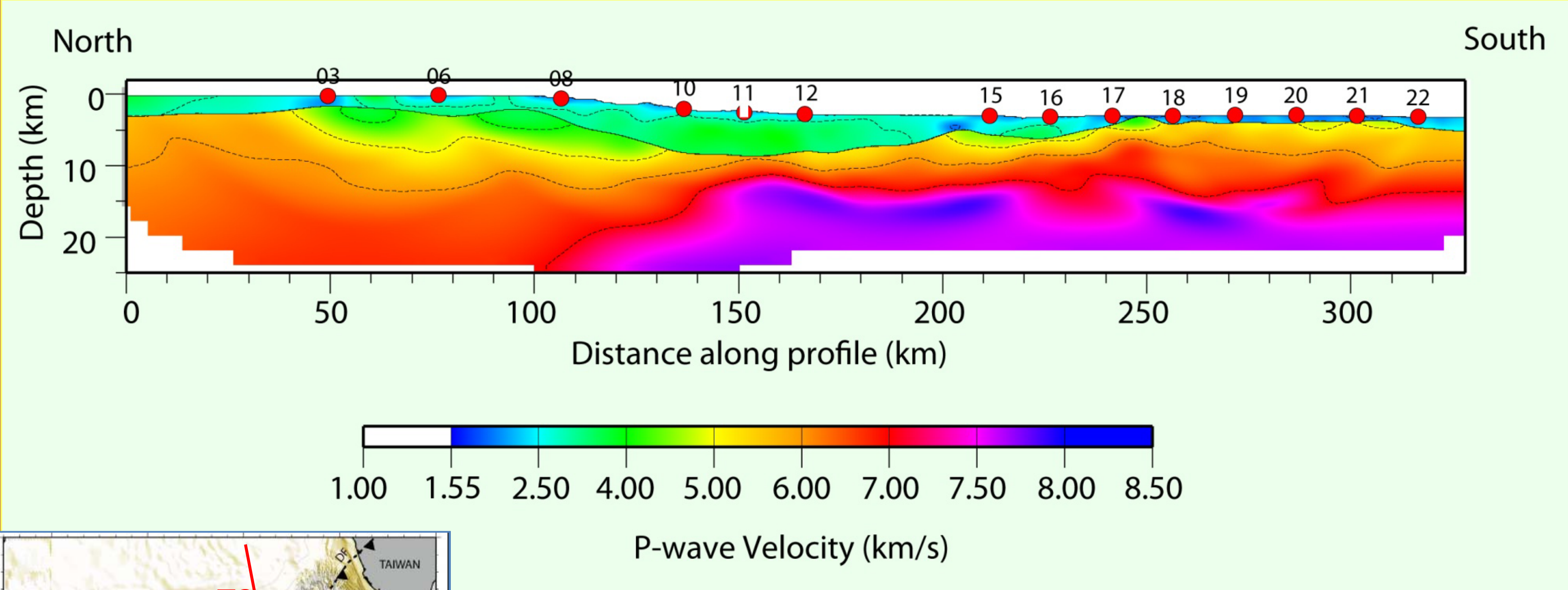
Current Research

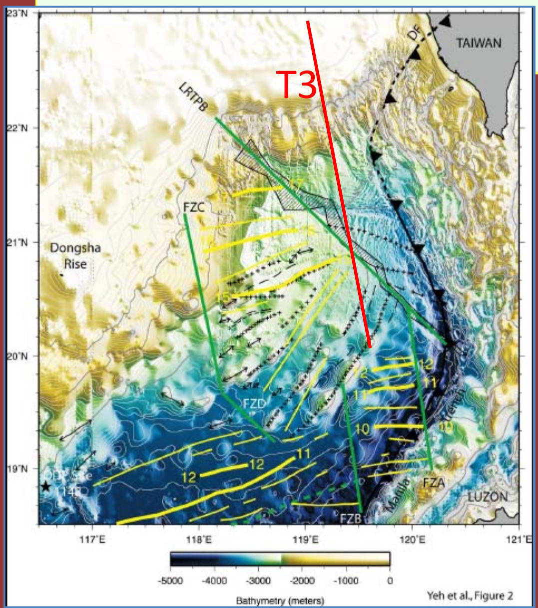
- Currently US and Taiwan scientists carry out different analyses after initial coordination in 2009
- Some cross-over data (active source stations recording earthquake and passive stations recording active sources) are already benefiting research and more expected.
- A geodynamic “sandbox” was designed by Luc Lavier for TAIGER team to test models using new results
- More coordination to be conducted after initial results obtained

Highlights on the US Side

- Search for intracrustal reflector (Quiros and Brown)
- Offshore/onshore active source and earthquakes profiling (Okaya, Kuo-Chen and Wu)
- SPOBS/MCS mapping of the continental shelf SW of Taiwan – hints of the “initial conditions” of collision (Lester, McIntosh, Avendonck et al.)
- S-splitting (Kuo-Chen, Wu and Okaya)
- Tomographic imaging of crust and mantle with TAIGER and other broadband data (Kuo-Chen and Wu)
- Joint analysis of MT, Seismicity, velocity and geology of Central Range (Wu, Bertrand et al.)

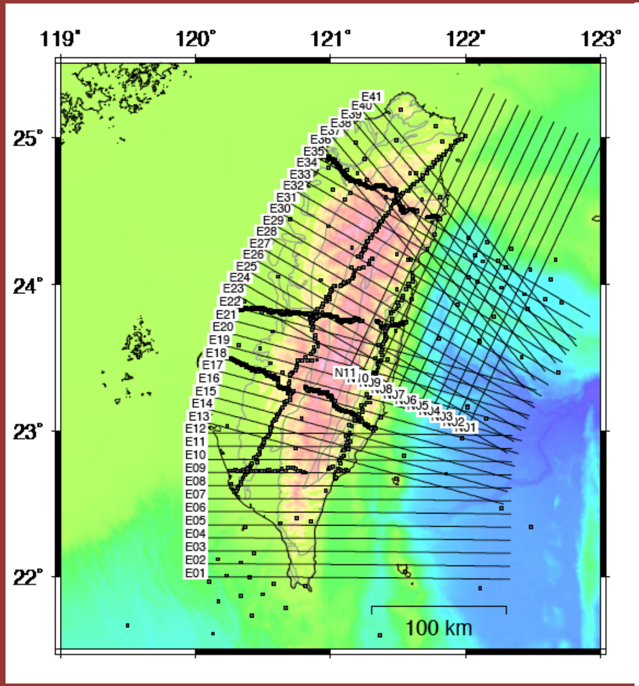
T3 – Velocity Model

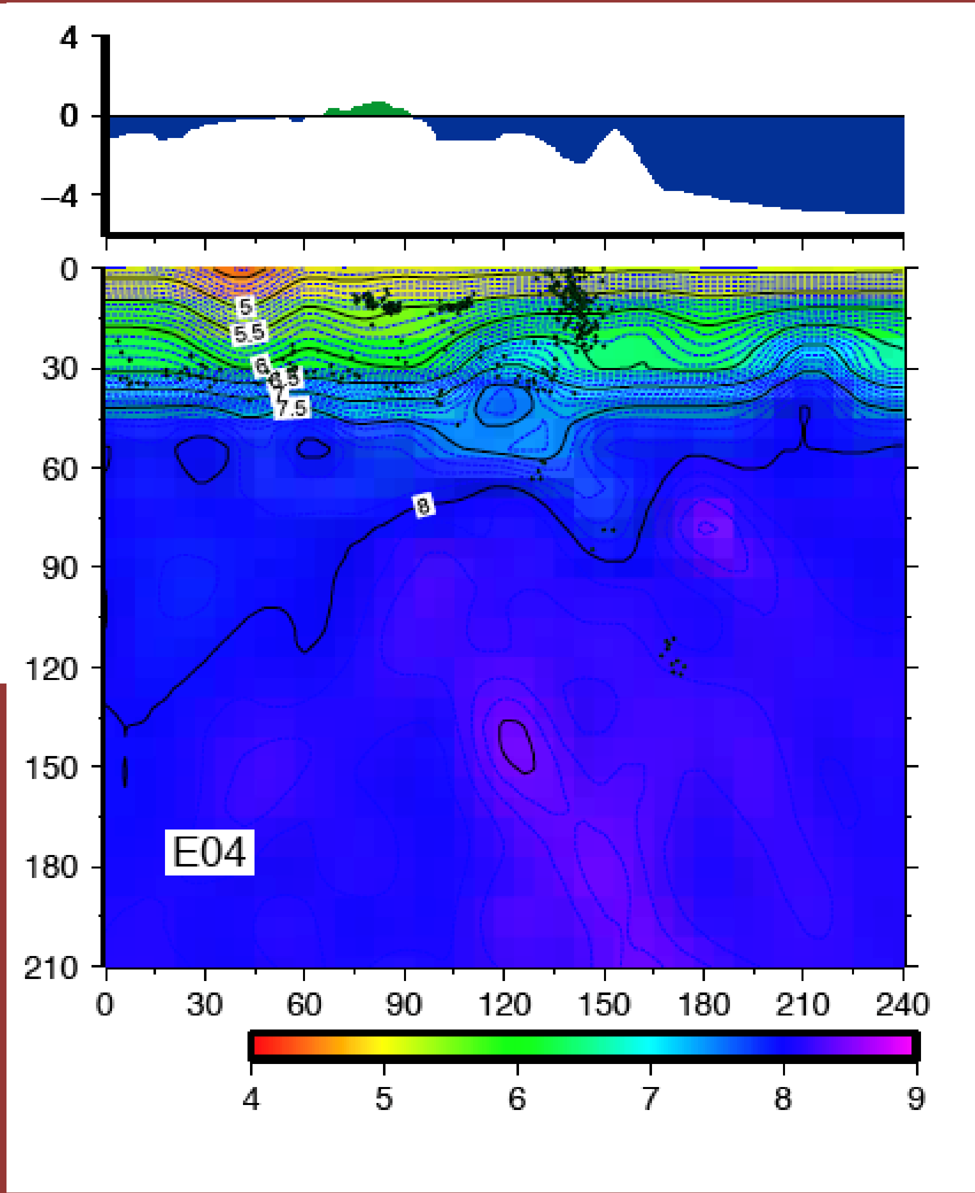




- Key observed features in the model include:
  - Thick (> 20 km) presumably continental crust at the shelf overlain by 2-3 km of sediments
  - Sediment thickness maximum (~6 km) underlain by thin (~ 4 km) crust and shoaling Moho
  - Crust thickening away from this point to the south (crust ~ 10 km thick)

Main Features of TAIGER Tomography





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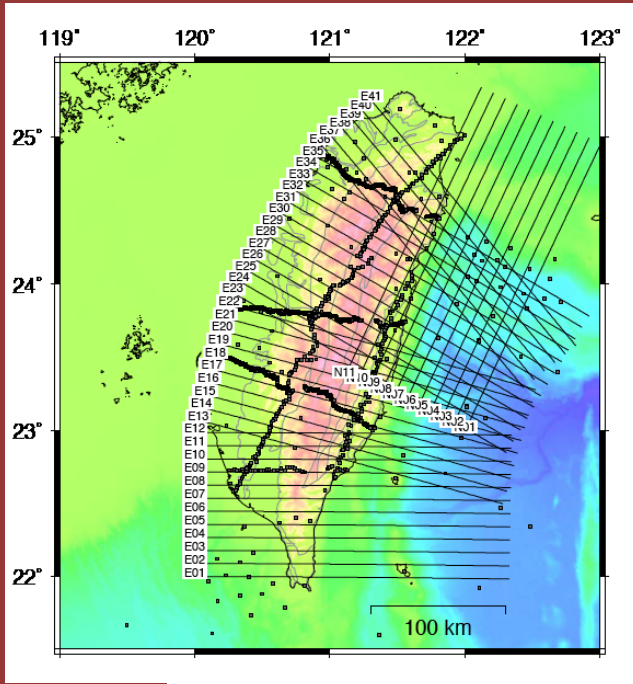
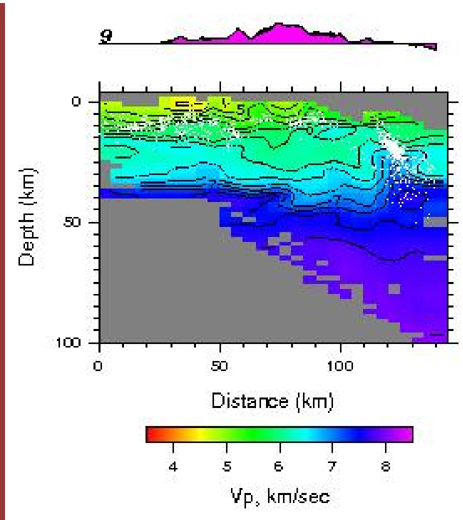
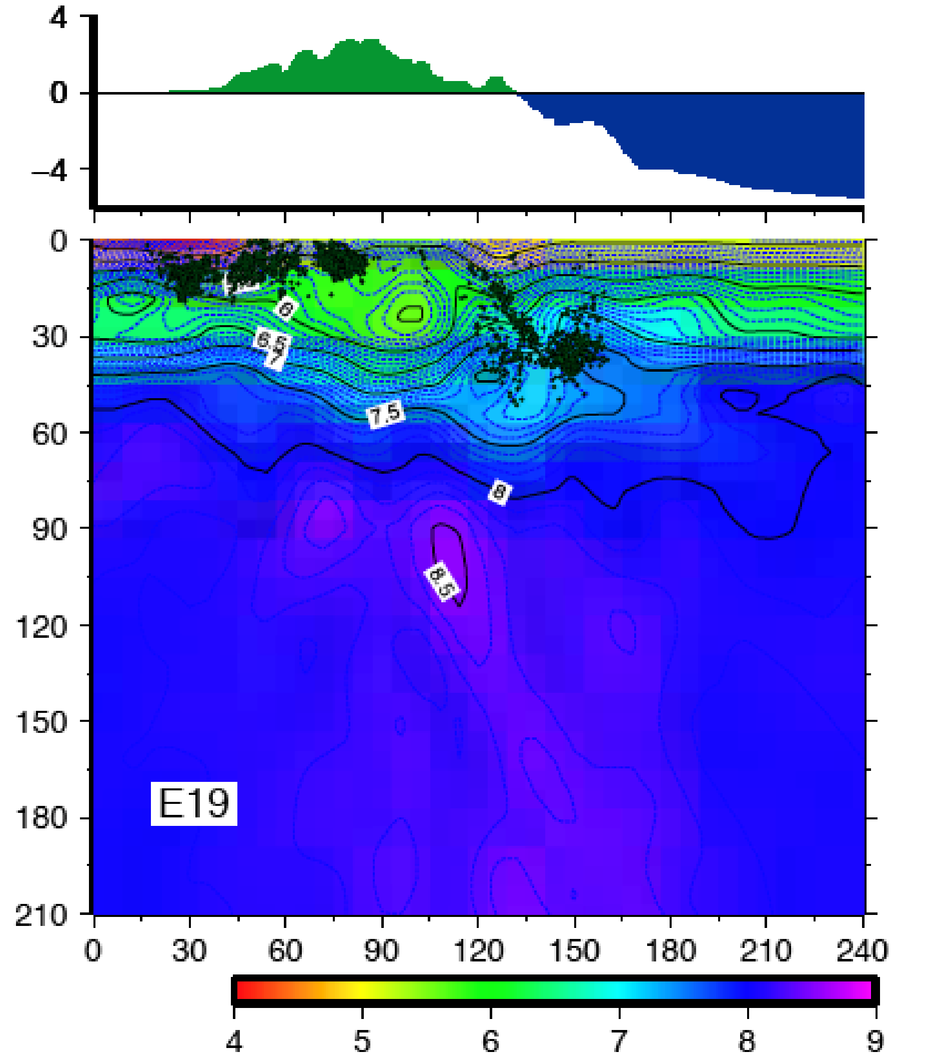


119°
120°
121°
122°
123°
25°
24°
23°
22°
100 km

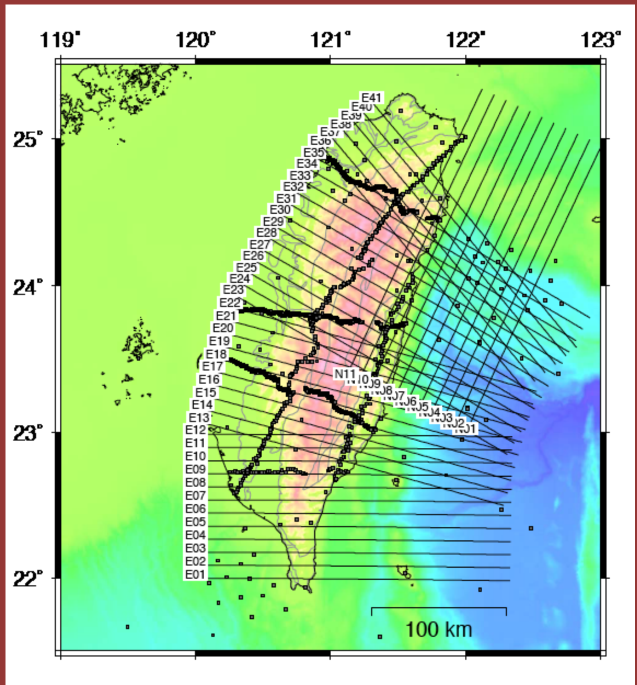


Depth (km)
Distance (km)
Vp, km/sec

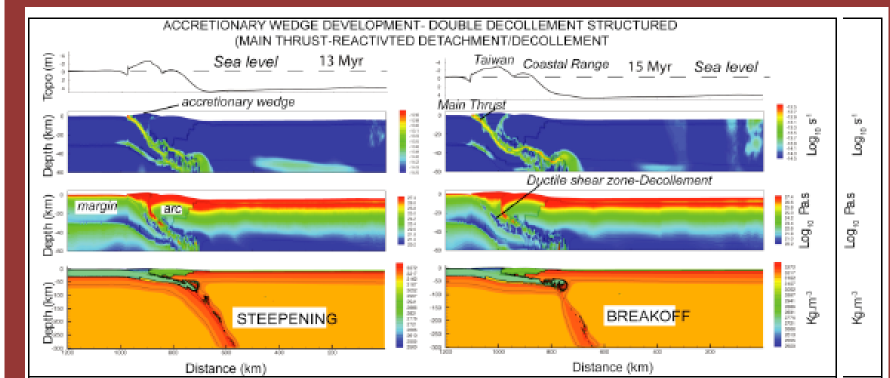


E19

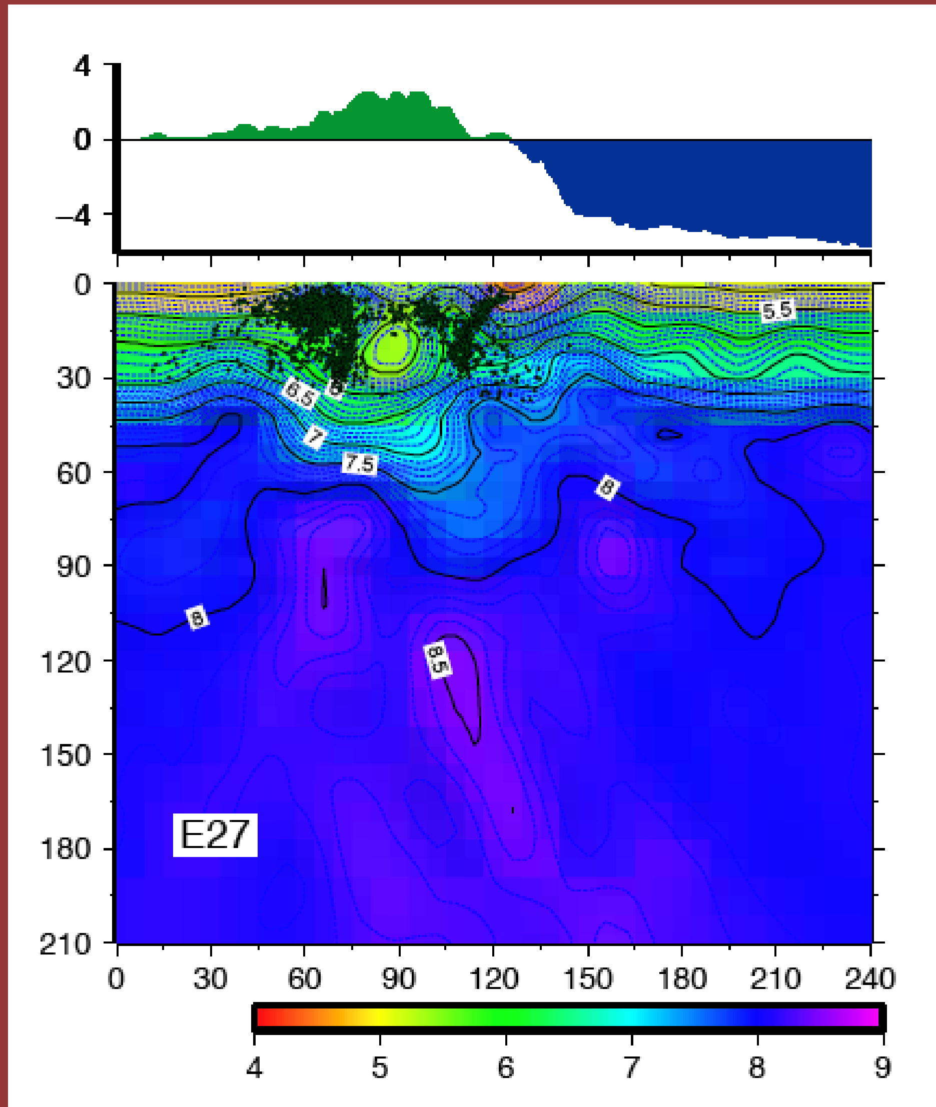
Continued



119° 120° 121° 122° 123°
25°
24°
23°
22°
E01 E02 E03 E04 E05 E06 E07 E08 E09 E10 E11 E12 E13 E14 E15 E16 E17 E18 E19 E20 E21 E22 E23 E24 E25 E26 E27 E28 E29 E30 E31 E32 E33 E34 E35
E39 E40 E41
N11
100 km

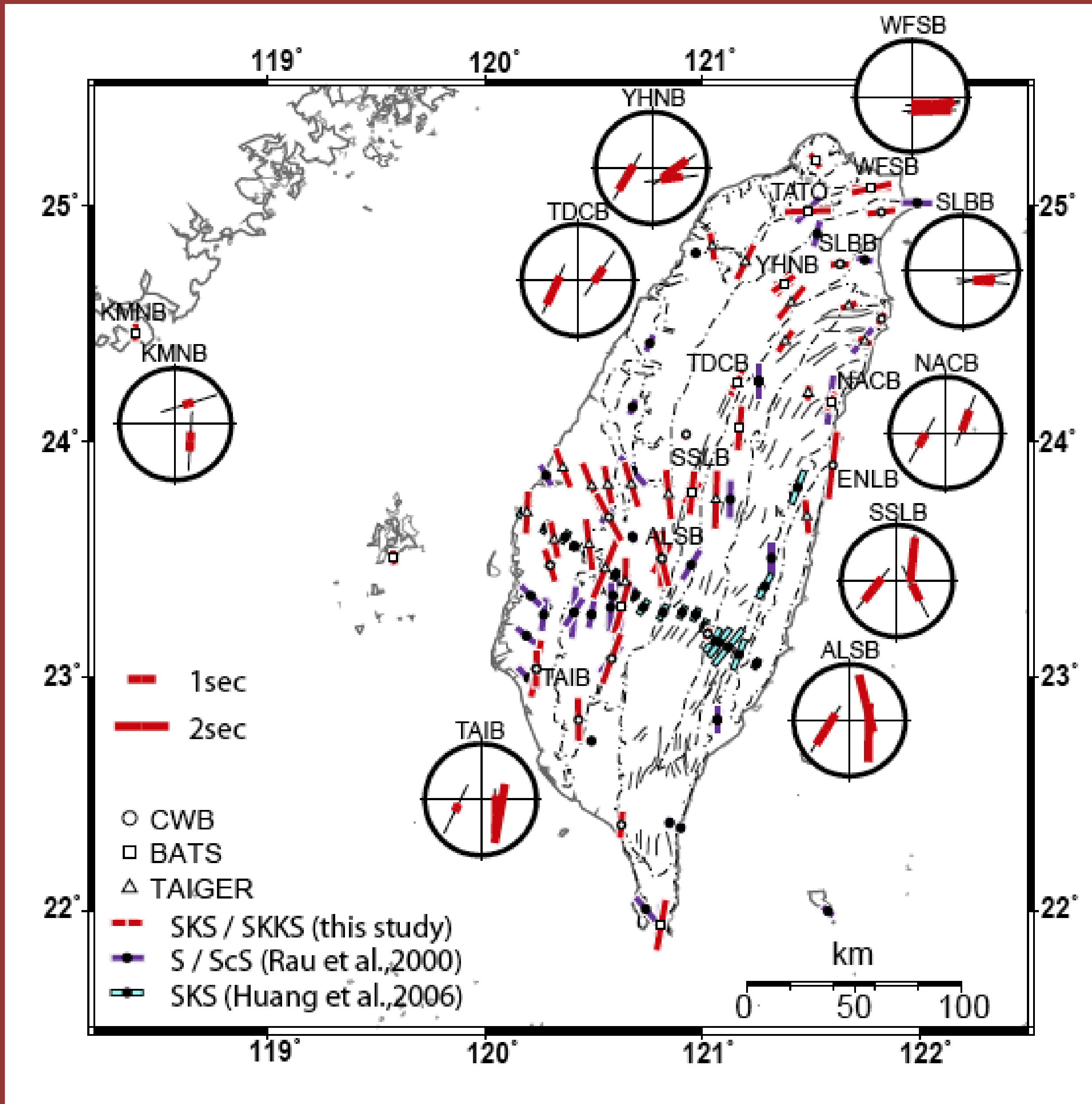


ACCRETIONARY WEDGE DEVELOPMENT- DOUBLE DECOLLEMENT STRUCTURED
(MAIN THRUST-REACTIVTED DETACHMENT/DECOLLEMENT
Topo (m)
Sea level
13 Myr
Taiwan
Coastal Range
15 Myr
Sea level
accretionary wedge
Main Thrust
Depth (km)
Ductile shear zone-Decollement
margin
arc
STEEPENING
BREAKOFF
Distance (km)
Distance (km)



4
0
−4
0
30
60
90
120
150
180
210
5.5
6.5
6
7
7.5
8
8
8
8.5
E27
0 30 60 90 120 150 180 210 240
4 5 6 7 8 9

S-splittng and Tectonics



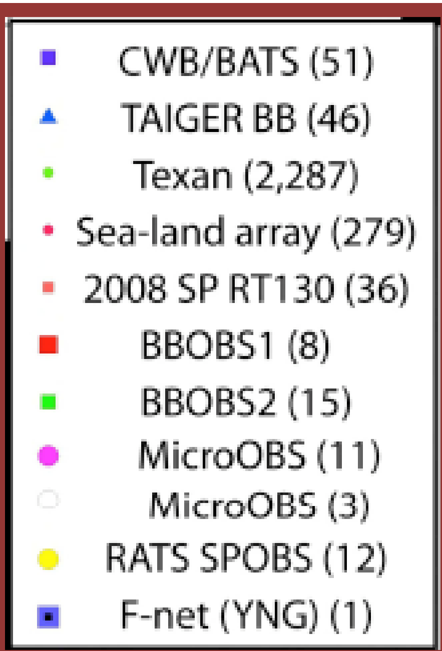
Summary

- δt: <1 sec - ~2 sec.
- Nearly parallel to local strike
- Large δt for SE eq.
- Small δt for W eq.

Interpretation

- Anisotropy of aligned minerals is the cause of S-splitting
- The sources probably are in the upper mantle down to a few hundred kilometers
- Vertical coherence

Local/Teleseismic Tomography



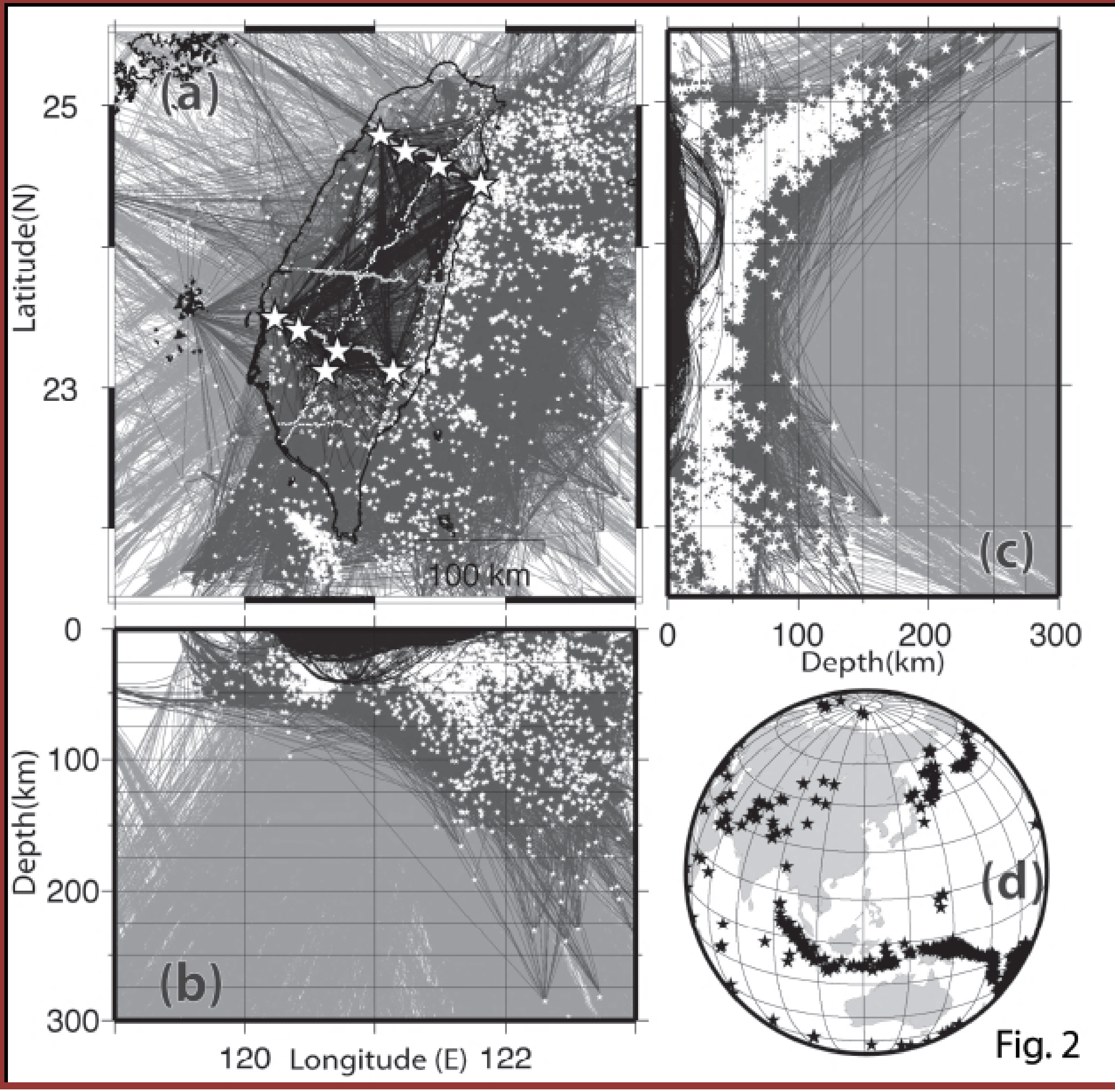
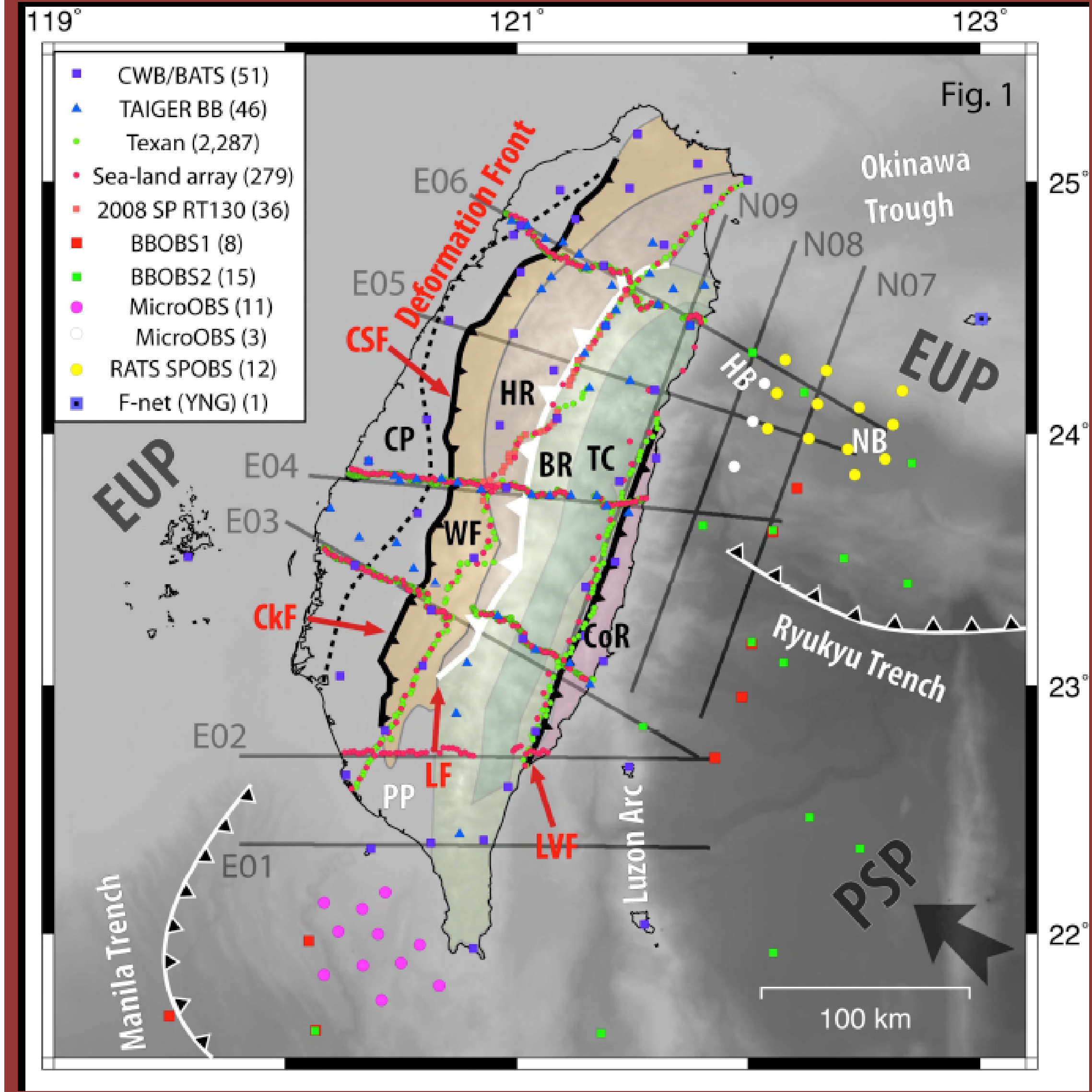
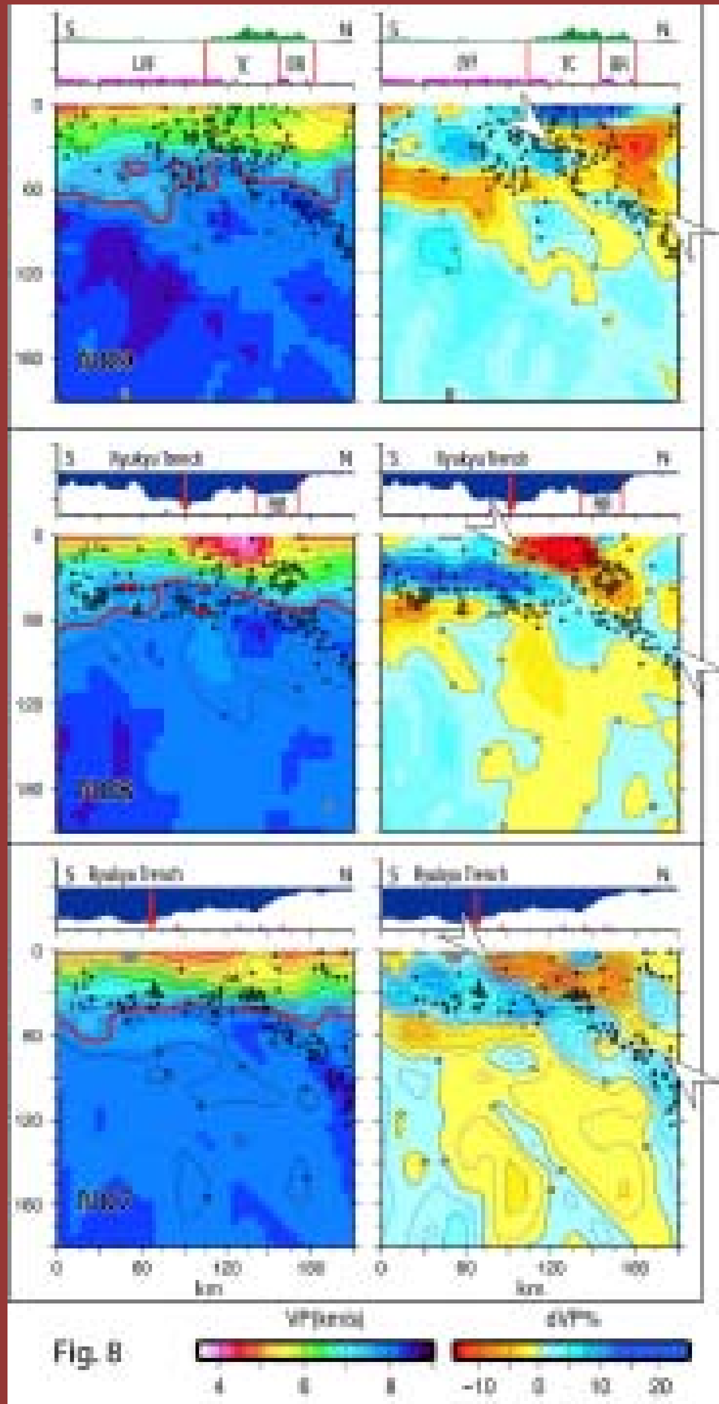


Fig. 2

Vertical Tomographic Sections - NS





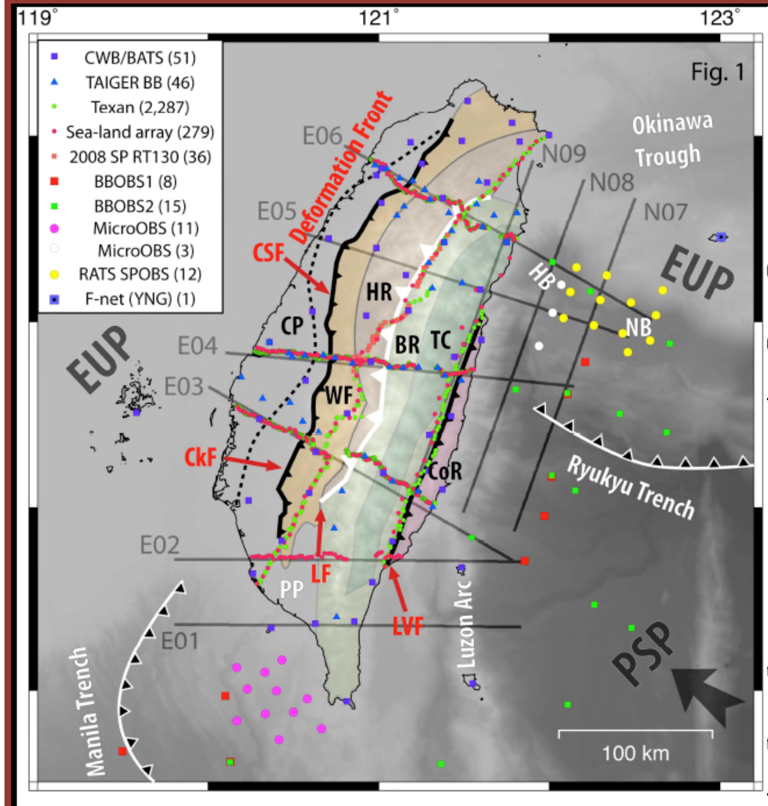

119°
121°
123°
CWB/BATS (51)
TAIGER BB (46)
Texan (2,287)
Sea-land array (279)
2008 SP RT130 (36)
BBOBS1 (8)
BBOBS2 (15)
MicroOBS (11)
MicroOBS (3)
RATS SPOBS (12)
F-net (YNG) (1)
Deformation Front
Okinawa Trough
E06
E05
E04
E03
E02
E01
N09
N08
N07
CSF
CkF
LF
LVF
HR
CP
BR
TC
WF
CoR
PP
HB
NB
EUP
EUP
PSP
Ryukyu Trench
Manila Trench
Luzon Arc
100 km

Fig. 1

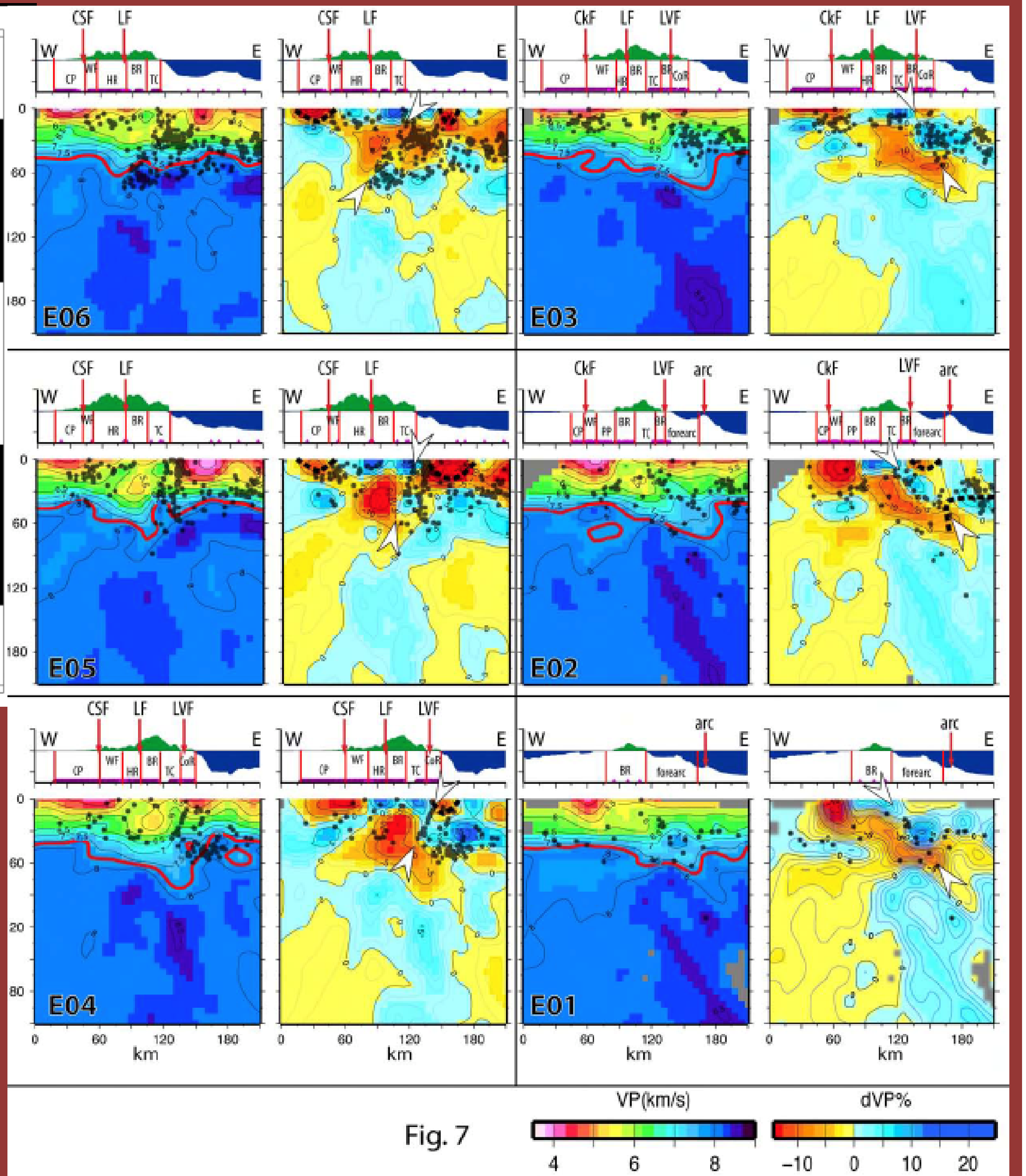
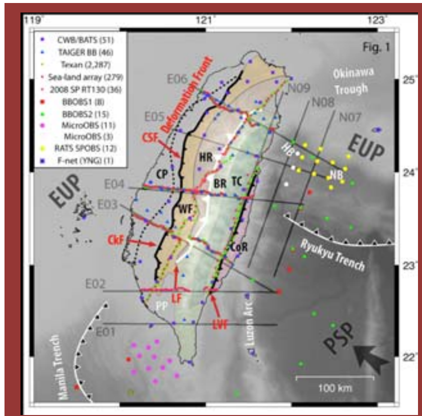
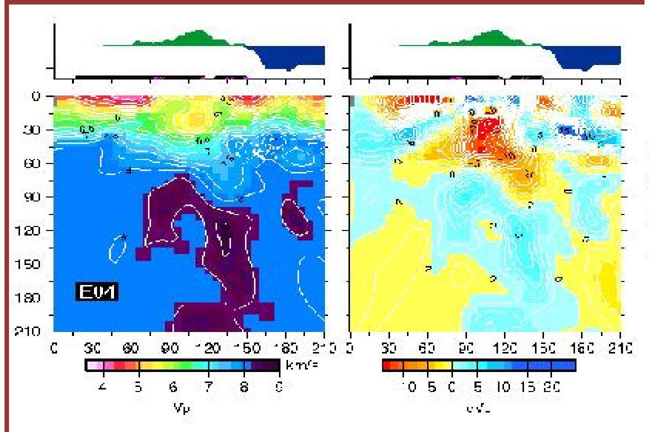
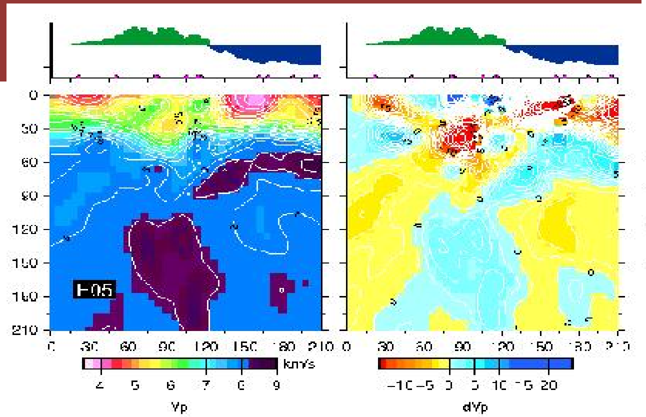

E06
E05
E04
E03
E02
E01
CSF
LF
CkF
LVF
arc
W
E
CP
WF
HR
BR
TC
CoR
PP
forearc
0
60
120
180
km
VP(km/s)
4
6
8
dVP%
−10
0
10
20

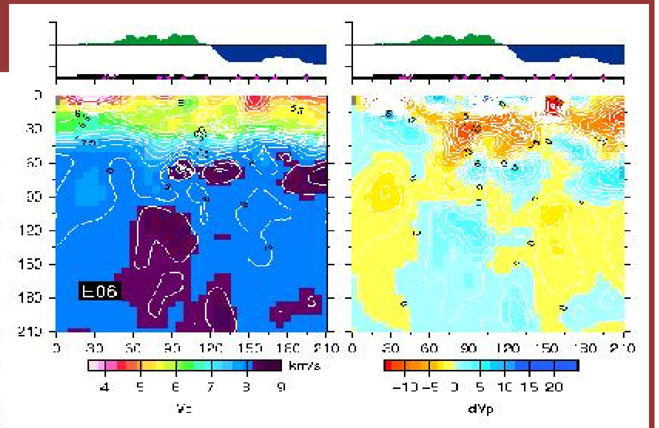
Fig. 7

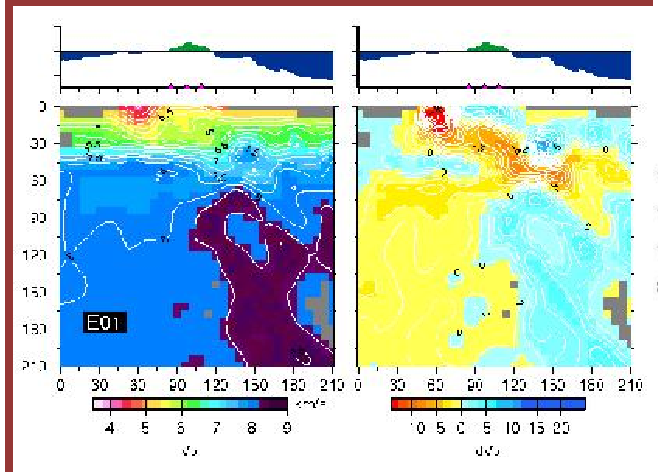
Tomographic sections – Perp. to Trend

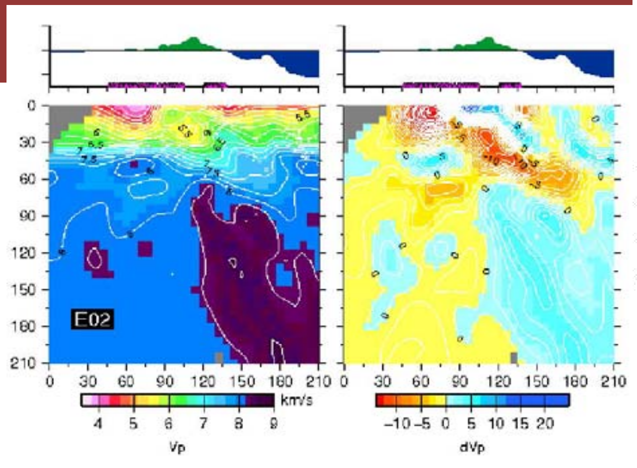


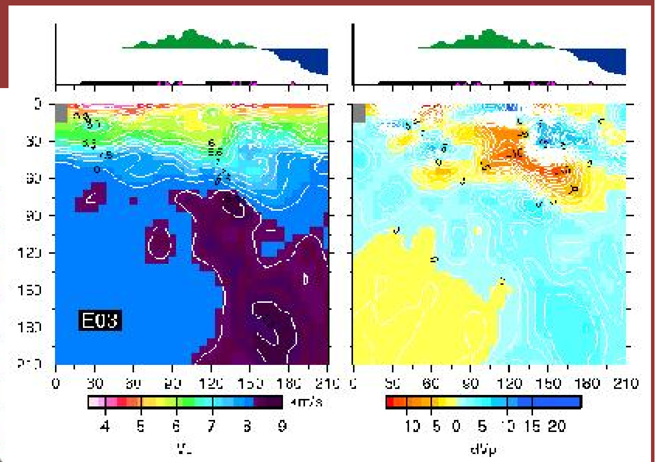




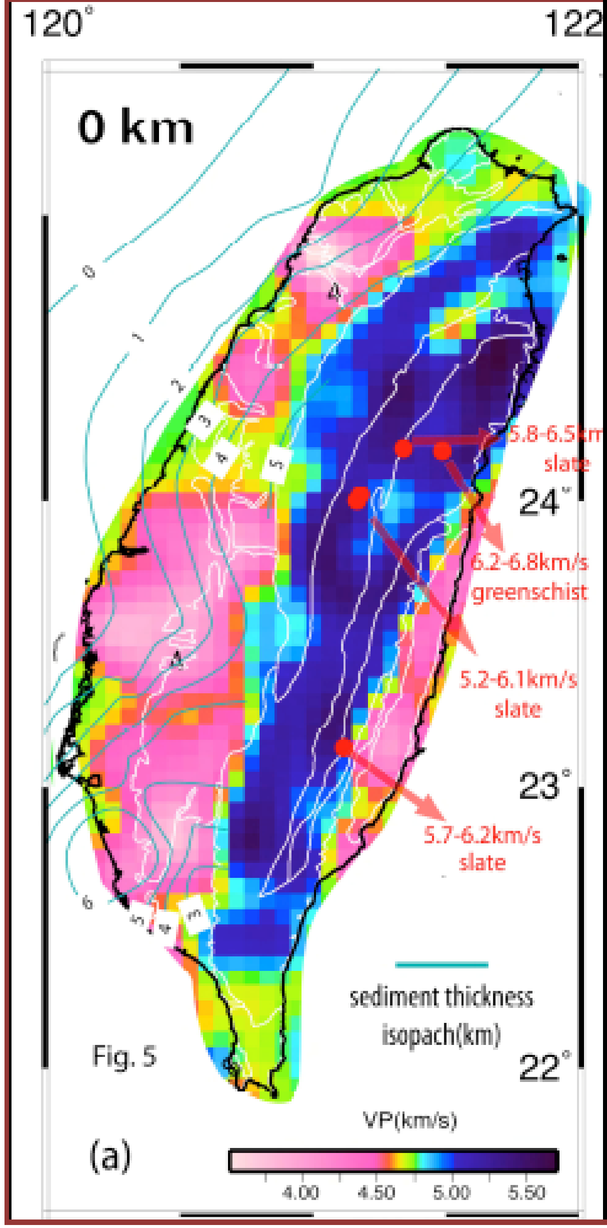








Map View



120°
122
0 km
5.8-6.5km
slate
24°
6.2-6.8km/s
greenschist
5.2-6.1km/s
slate
23°
5.7-6.2km/s
slate
sediment thickness
isopach(km)
22°
Fig. 5
(a)
VP(km/s)
4.00
4.50
5.00
5.50

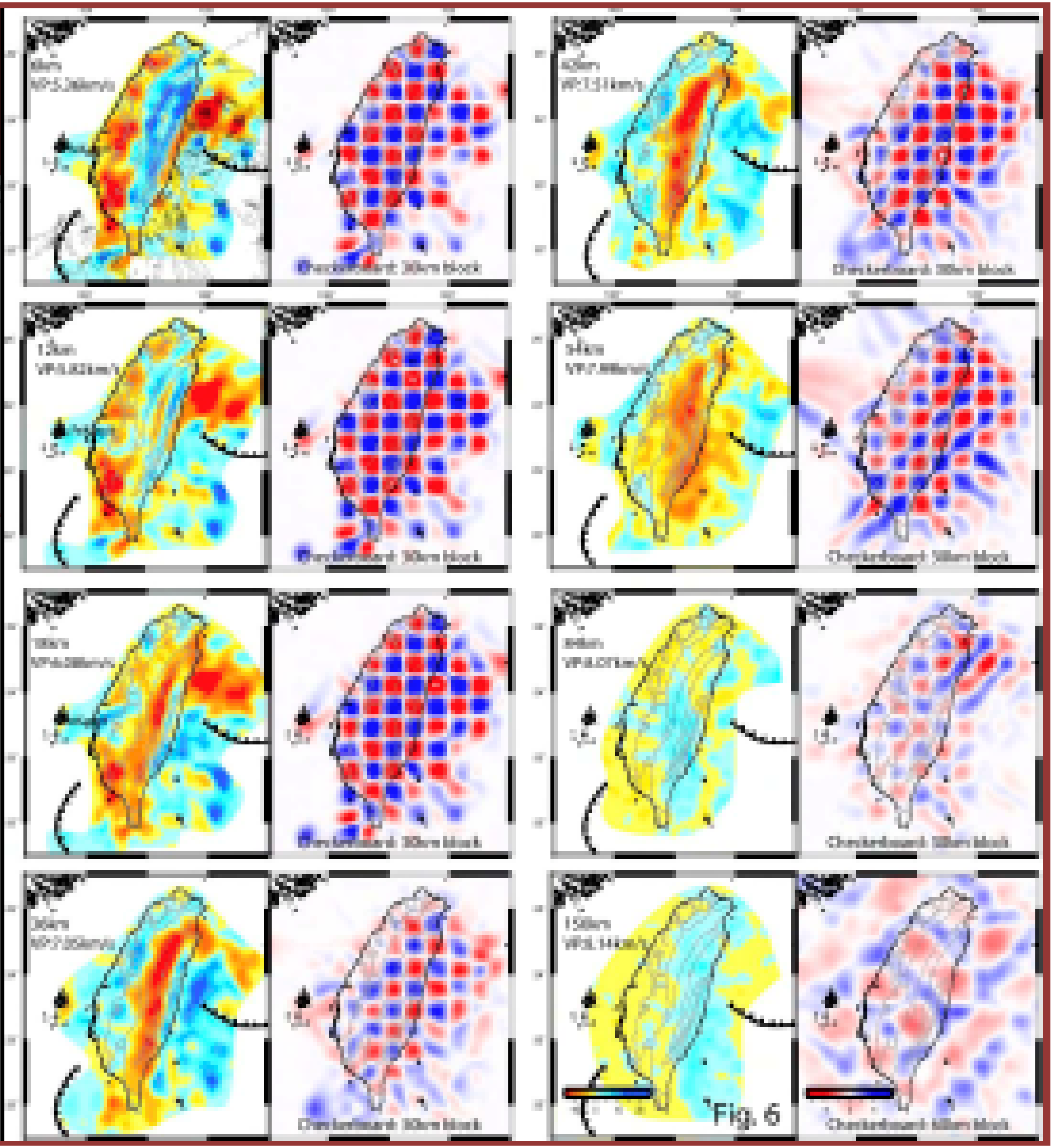
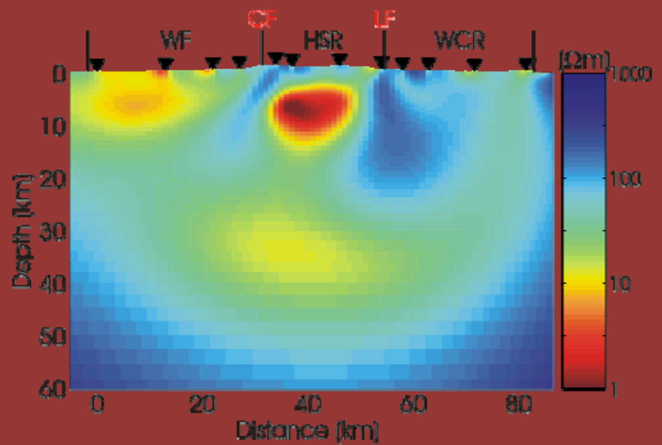


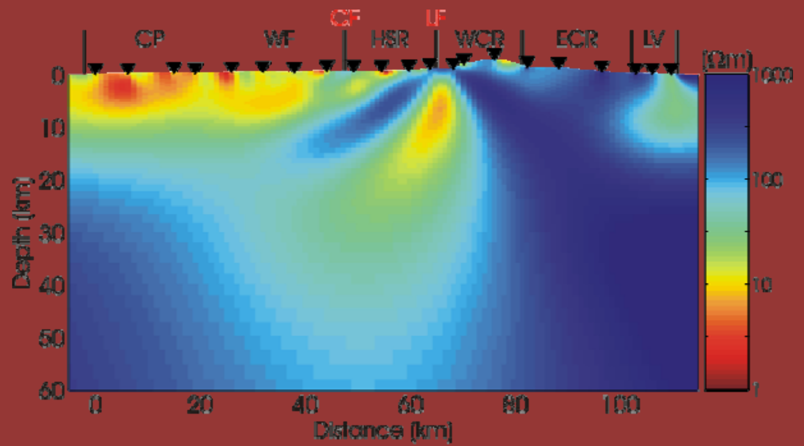
Fig. 6

Resistivity, Seismicity, Deformation and Mountain Building

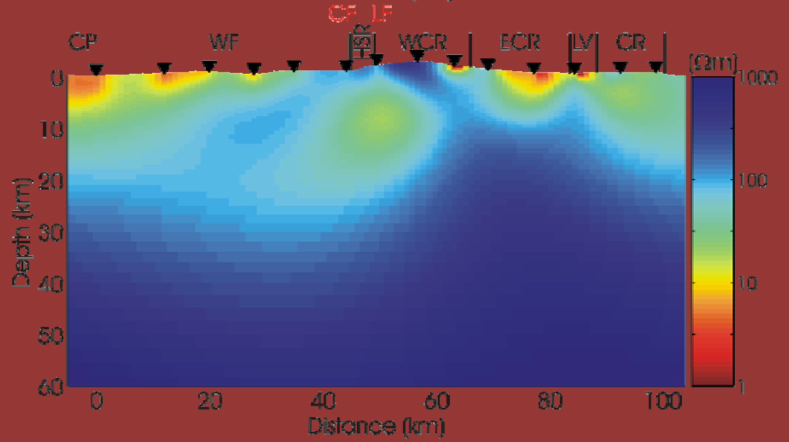
north

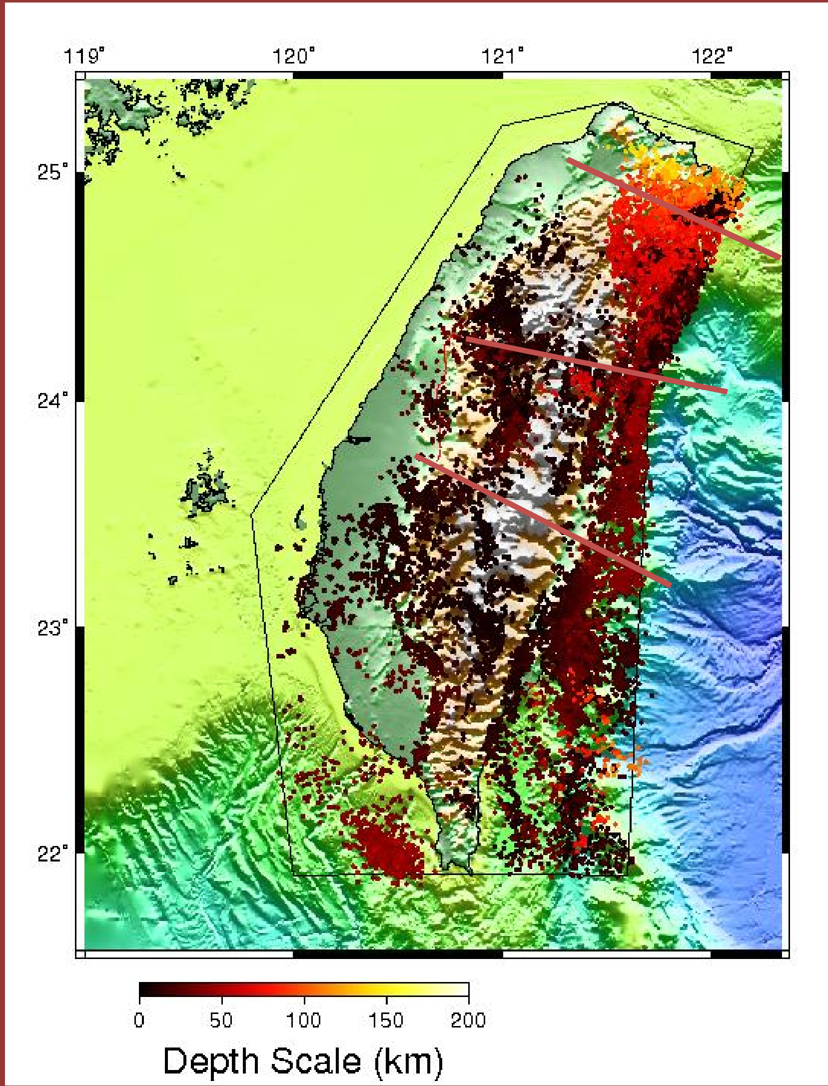


central

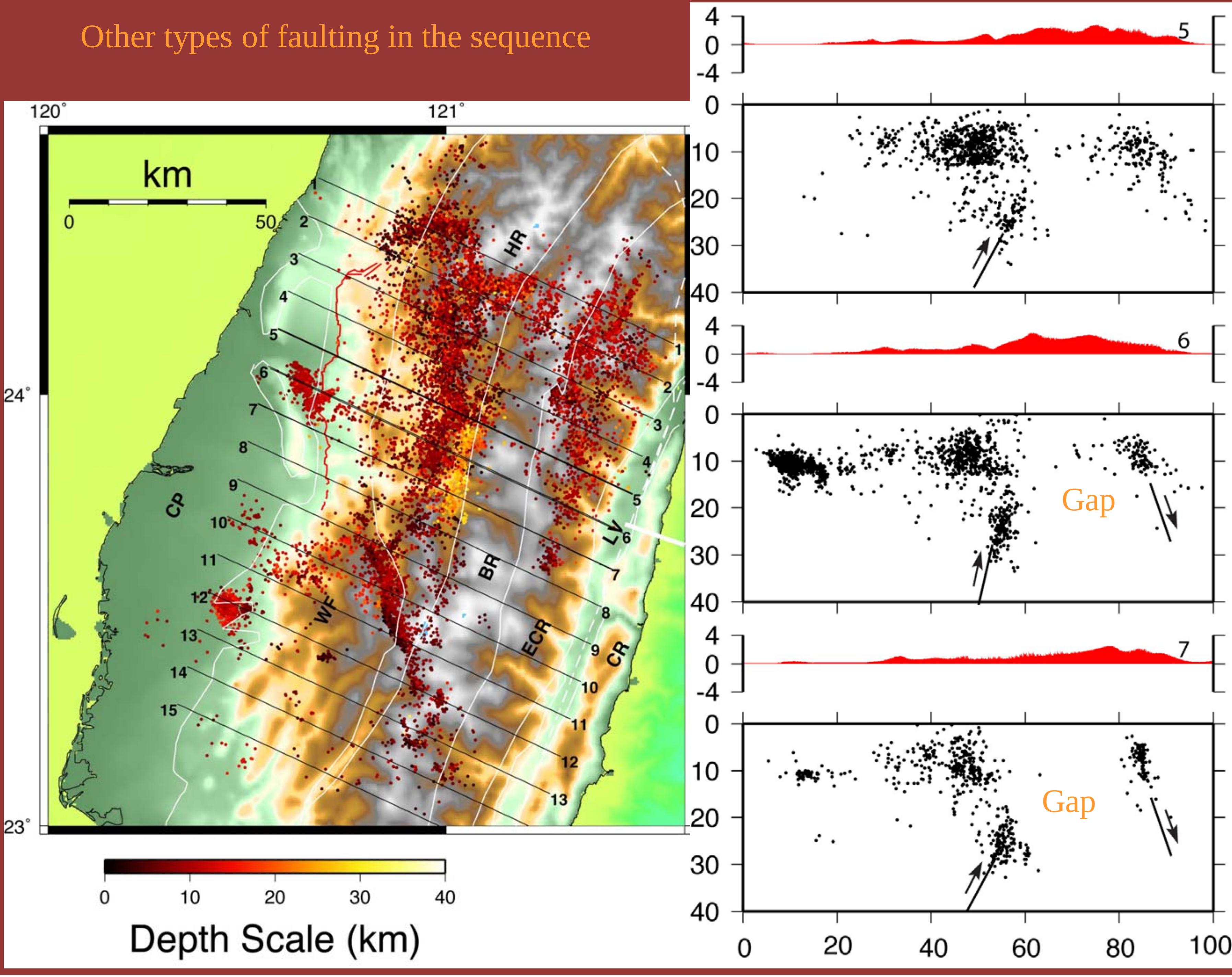


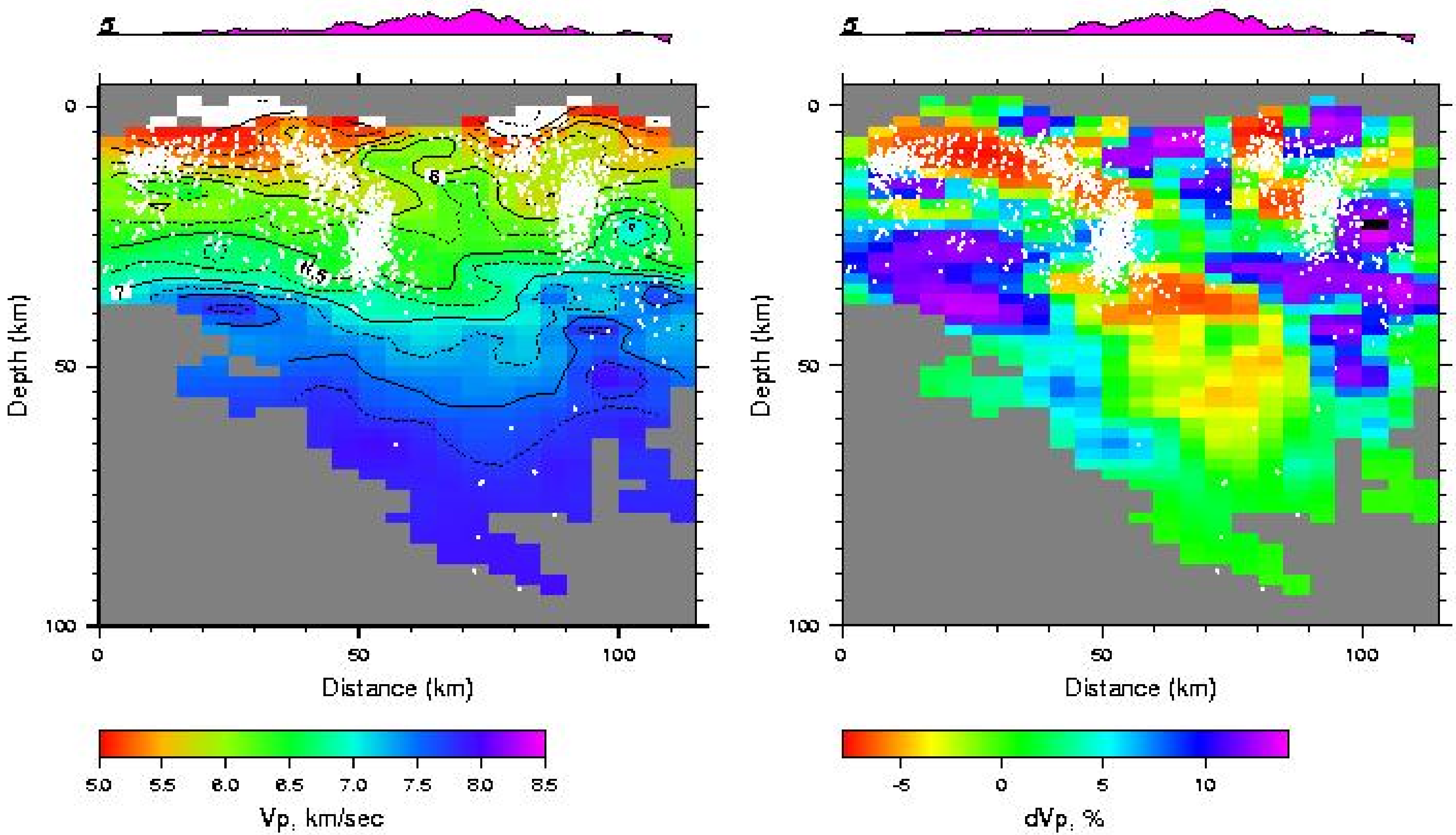
south





Other types of faulting in the sequence



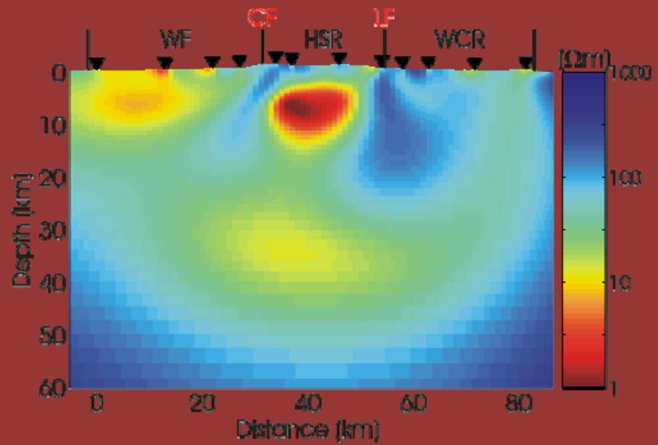


5
Depth (km)
0
50
100
Distance (km)
0
50
100
6
6.5
7
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
Vp, km/sec
5
Depth (km)
0
50
100
Distance (km)
0
50
100
-5
0
5
10
dVp, %

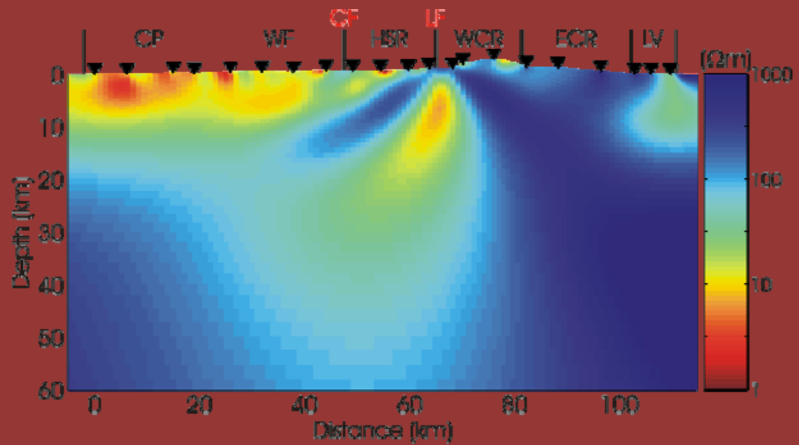
Resistivity Across Taiwan Orogen (Bertrand et al. 2009)

- Central Taiwan (~24^{O}N)
  - Central Range east of Lishan Fault is largely a region of high resistivity (500-1000 Ohm-m) 0-40+ km deep
  - Under the Lishan trace is a west-dipping conductive zone to at least 20 km depth
- Southern Taiwan (S. Cross Isl. Hwy.)
  - WCR conductive (<100 Ω-m) above 15 km; less conductive under ECR

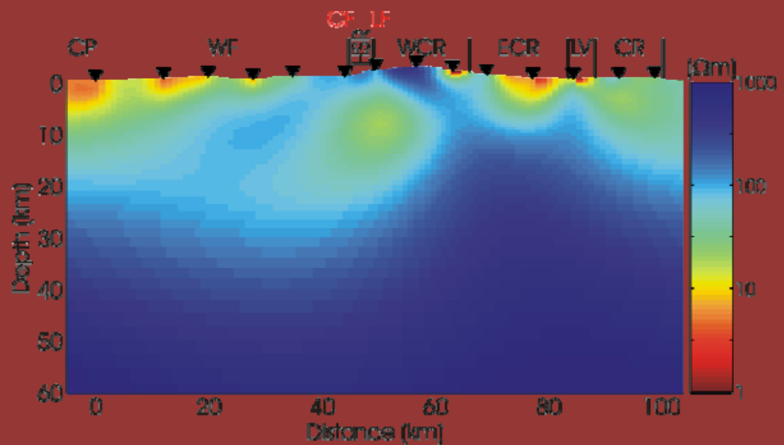
north

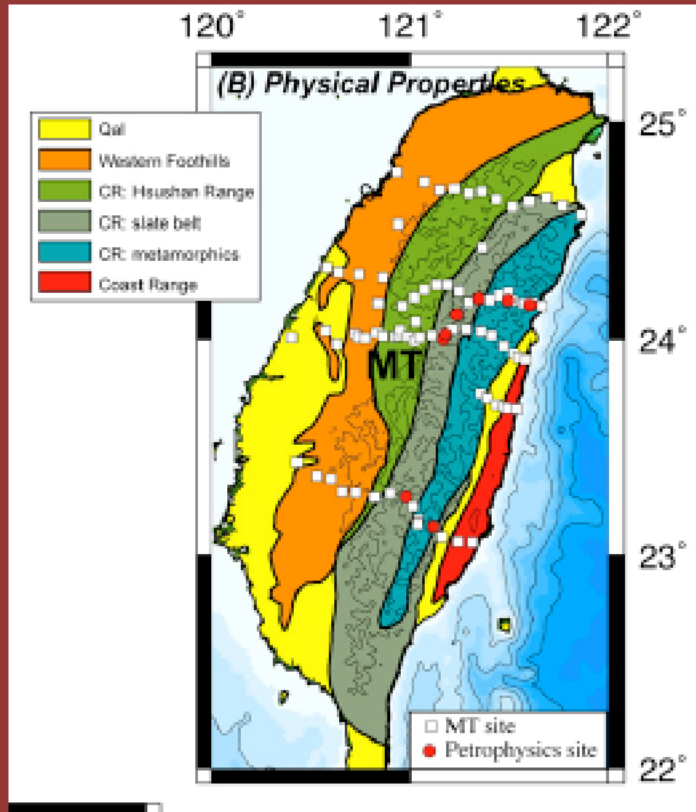


central



south





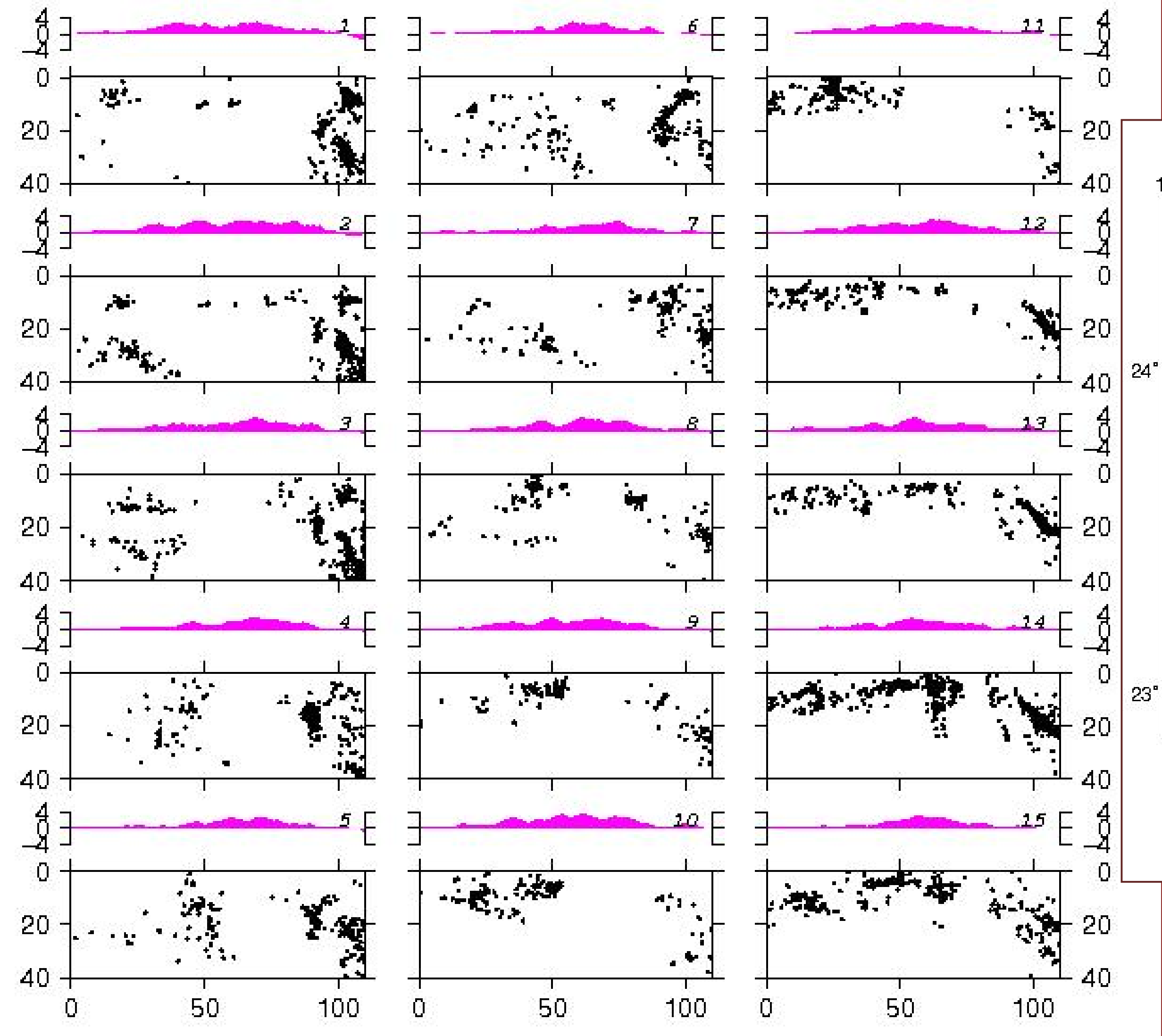
Seismicity (Wu et al., 1987; 2004)

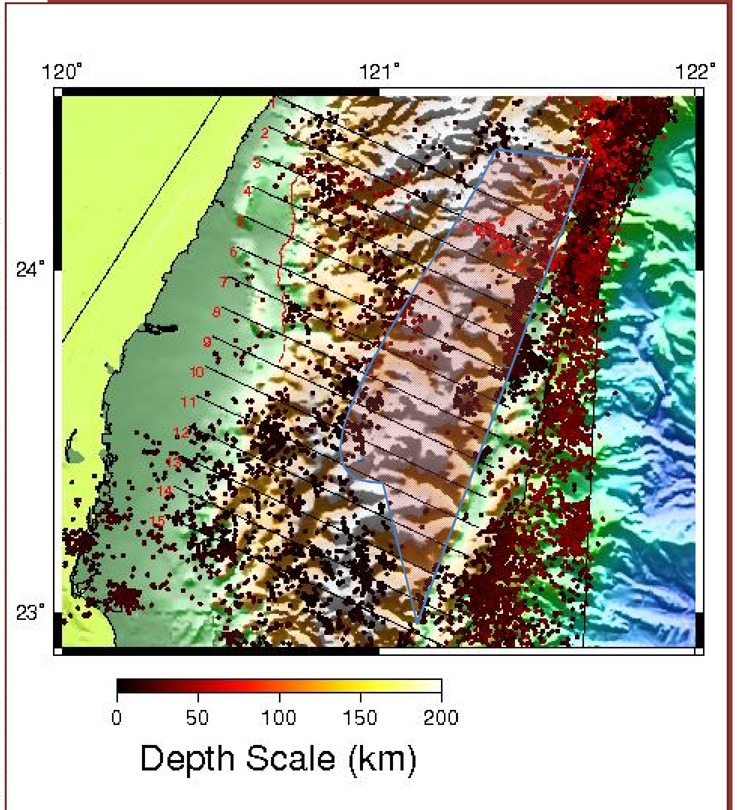
- 1973-1999.9.20: nearly aseismic Central Range east of Lishan Fault below 10 km from ~23.5^{O}N-24.5^{O}N; sparse seismicity above 10 km

- This quiescence resumed ~2007

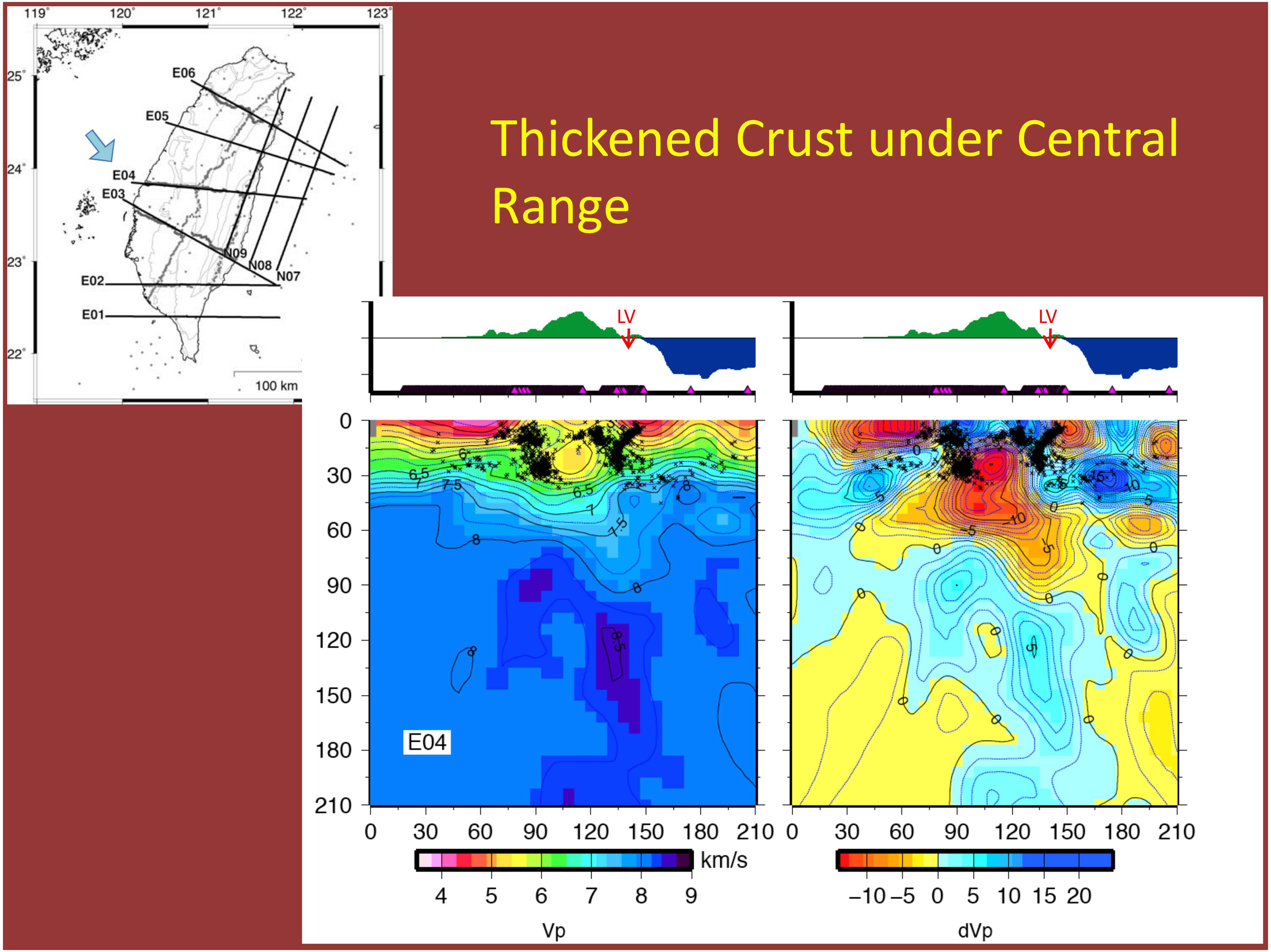
- South of 23.5^{O}N shallow seismic zone active and widens southward

Seismicity of Central Taiwan





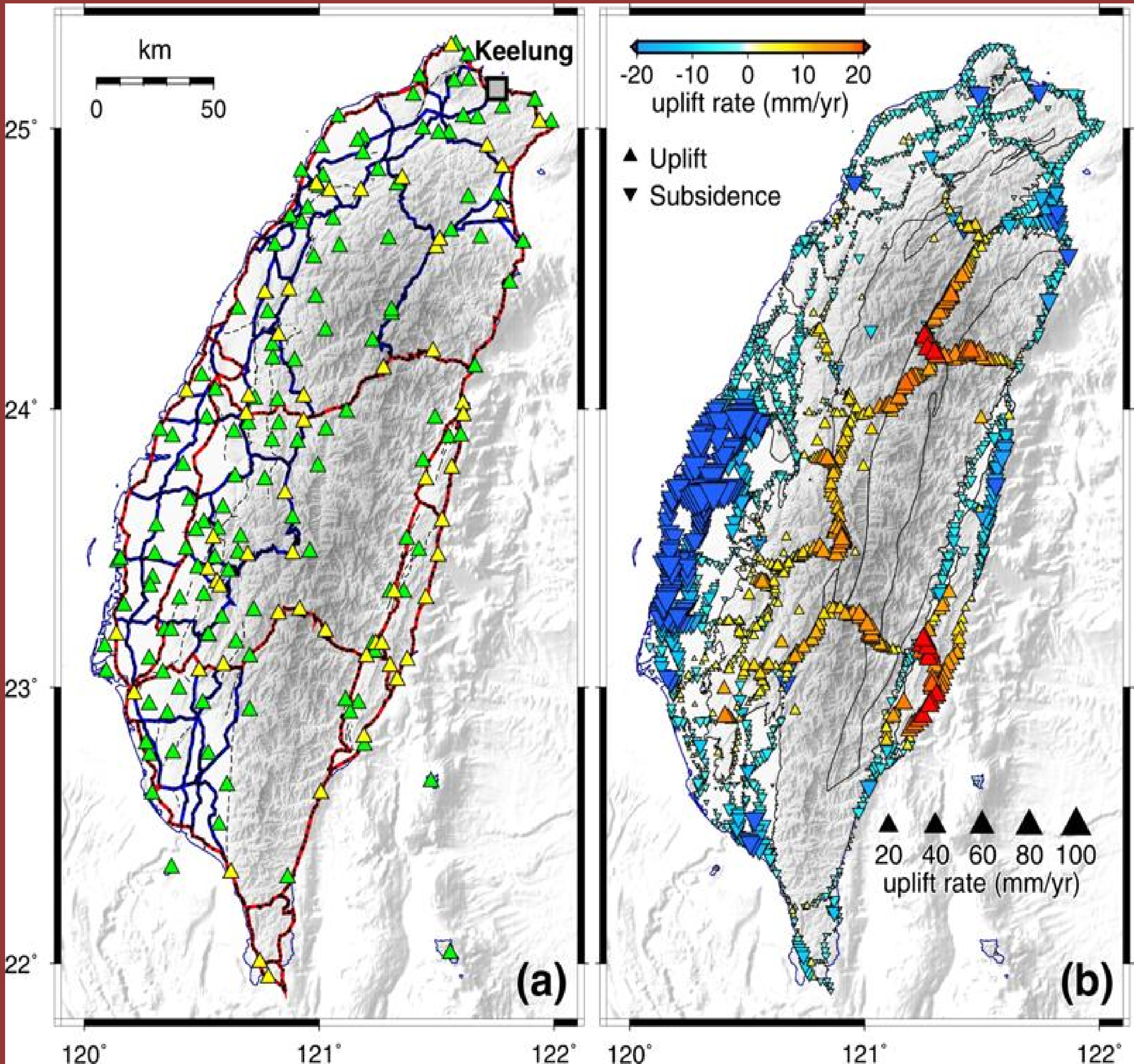
Thickened Crust under Central Range



Vertical Deformation of Taiwan

- Repeated leveling shows that Central Range is the most rapidly rising area of Taiwan (C.C. Liu, 1977; J.C. Hu, 2009; Ching et al., 2009) with a rate of ~2 cm/yr
- The above short term rate is higher than the longer term rate shown by fission-track data (Li et al., 2007) but the distribution patterns of rapid uplift are similar

Vertical Uplift (Ching et al. 2010)



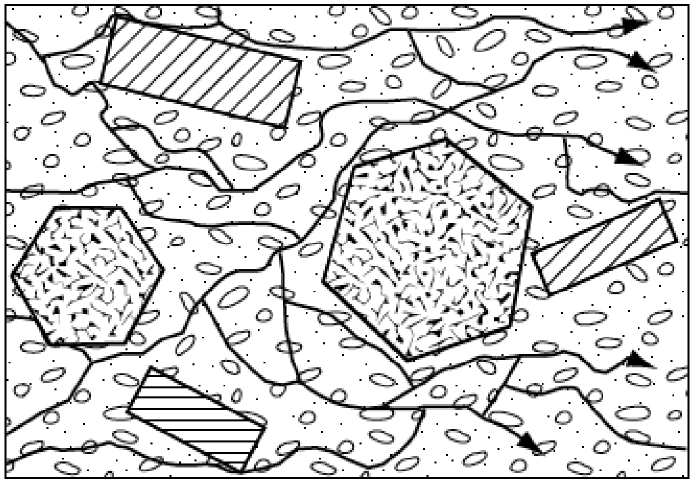
Interpretation of Observations

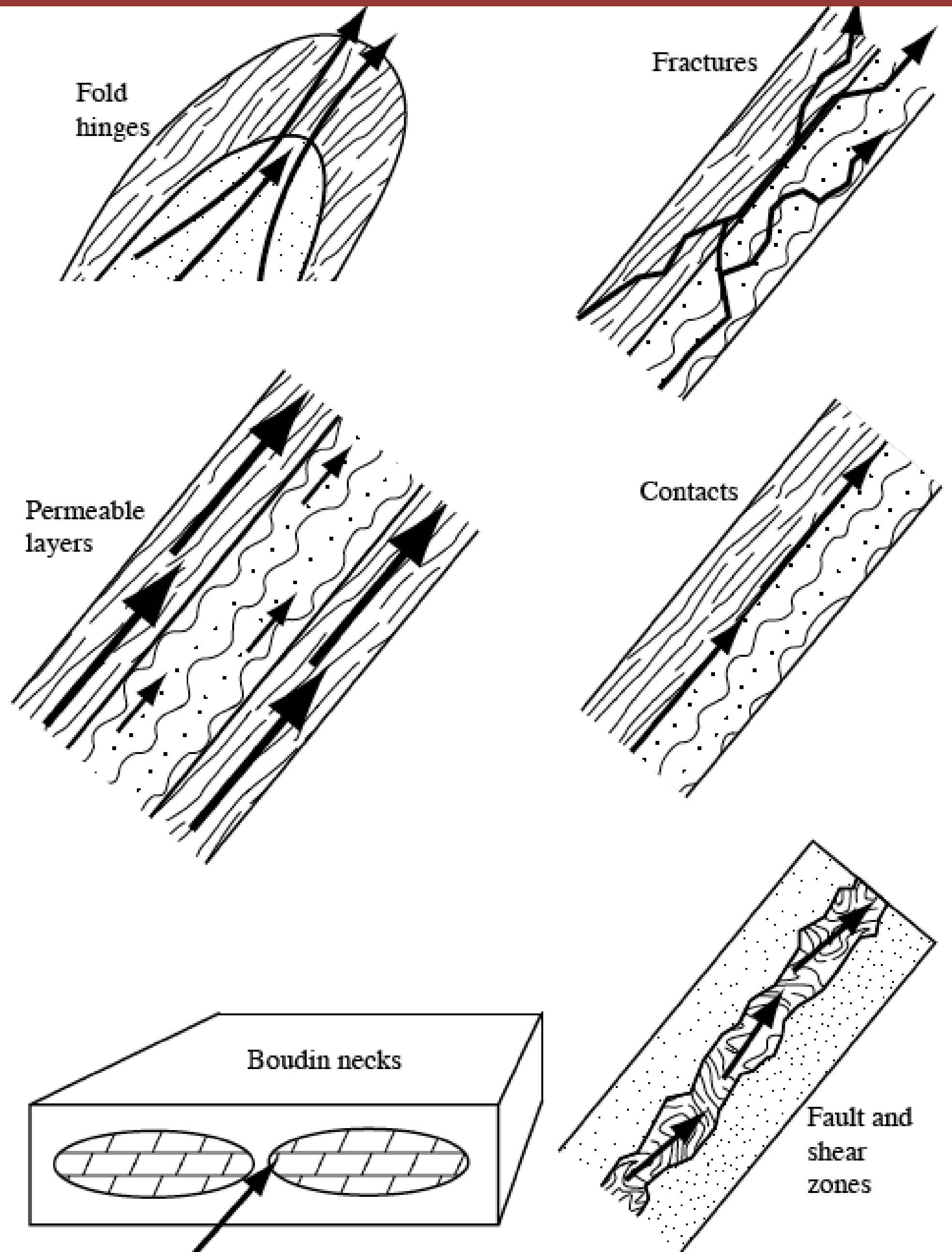
- A part of the Central Range is ductile and mechanically weak
- Surprisingly, this part of CR is also relatively dry; lacking the common weakening agent of water
- In this part of the CR we have mostly the pre-Tertiary metamorphic lower crustal rocks
- Dehydration during metamorphism comes to the rescue……

Metamorphism and Dehydration

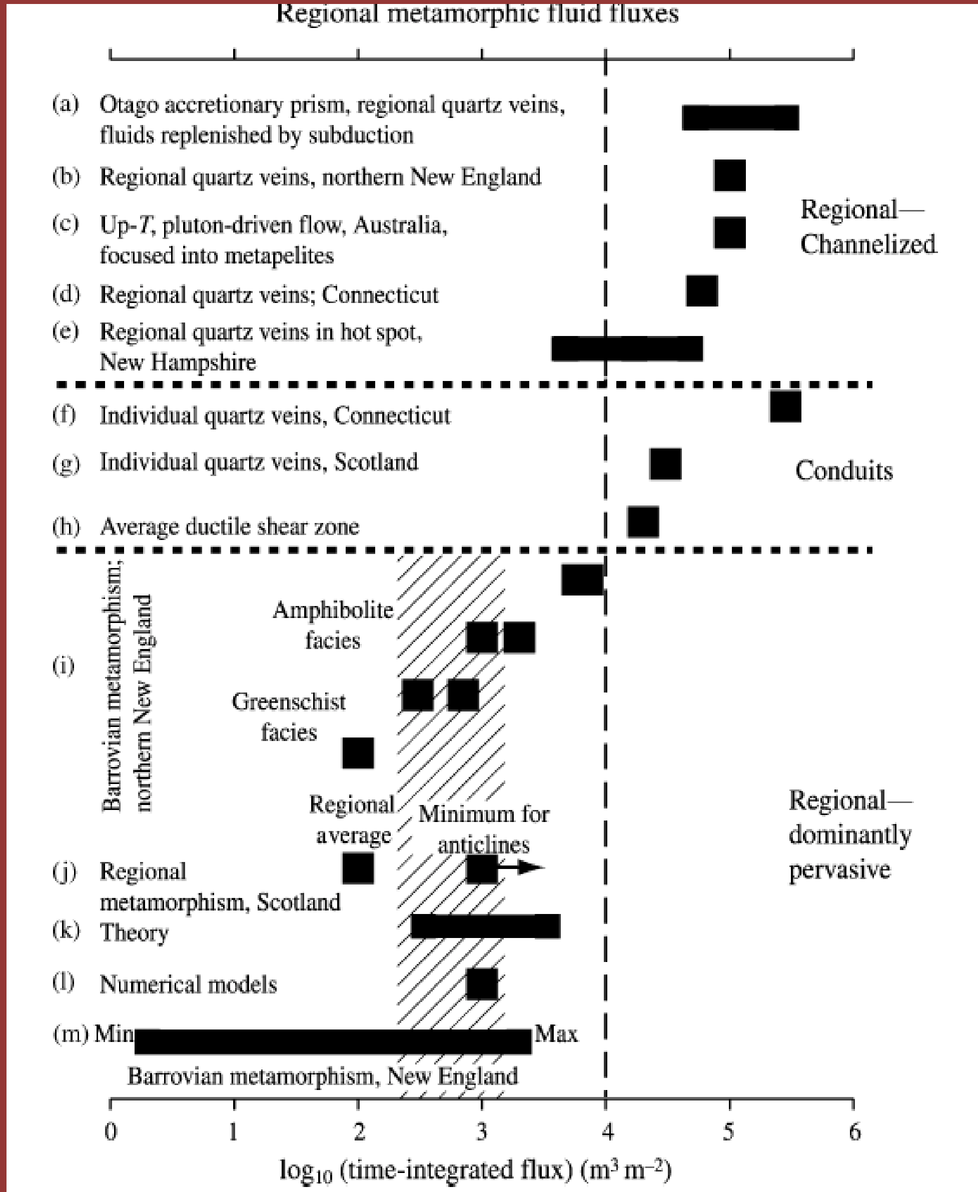
- In the Central Range: two sets of quartz veins, one associated with pre-Miocene tectonics and one with the current orogeny
- To form these veins a large amount of fluids carrying disolved quartz to go through the rock
- They form as a result of metamorphism
- The first set formed probably during buriel
- The second set during rapid ascent
- Cyclic hydrofracturing may have happened

Pervasive or channelized flow

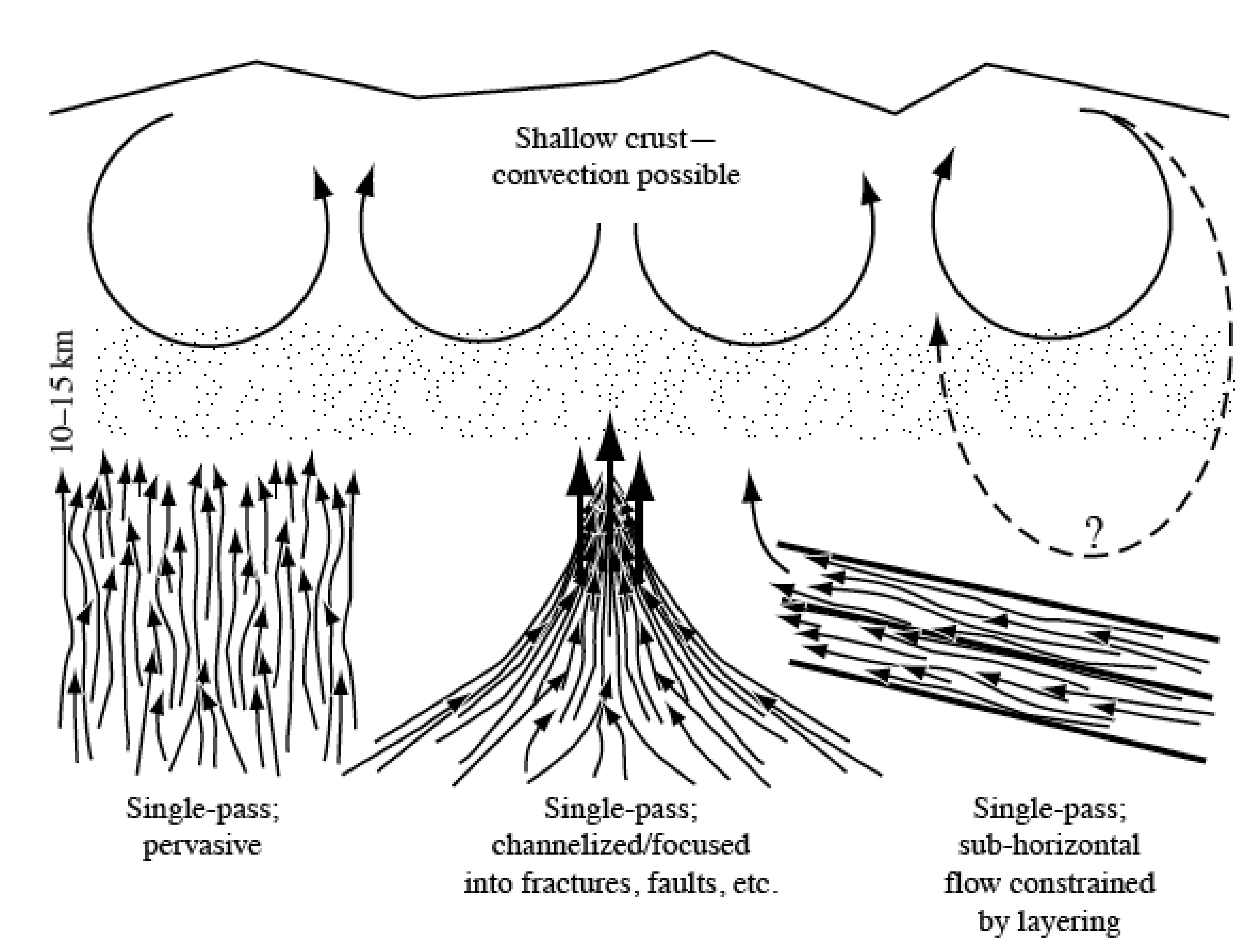




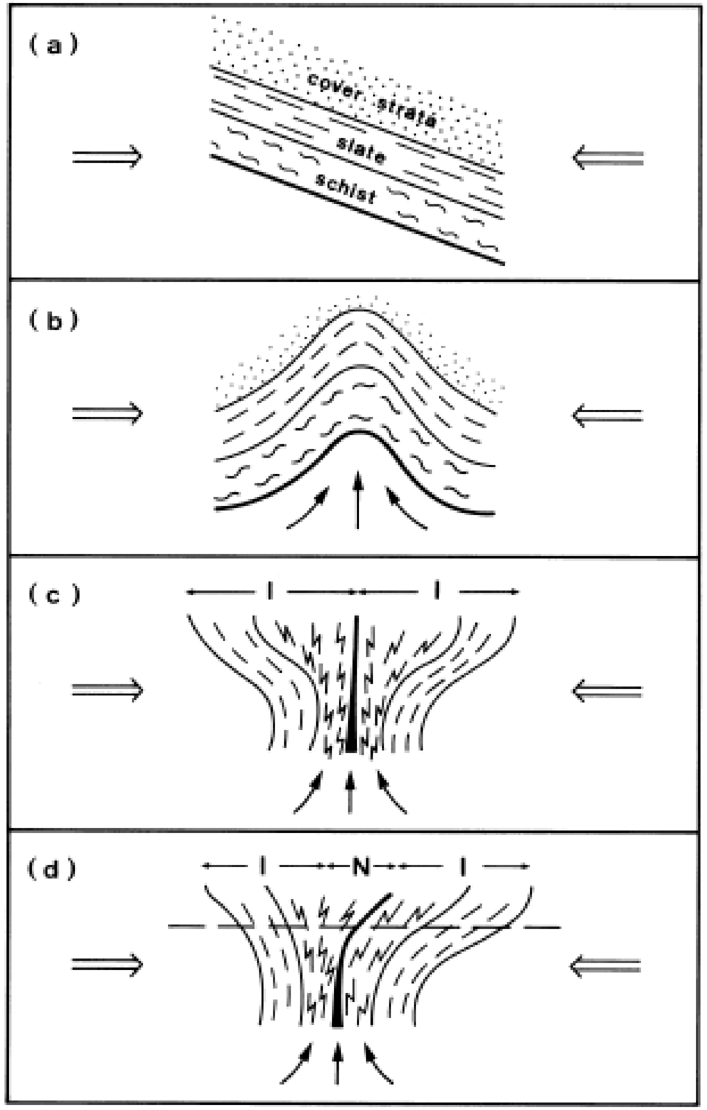
Fluid Flow in Metamorphism

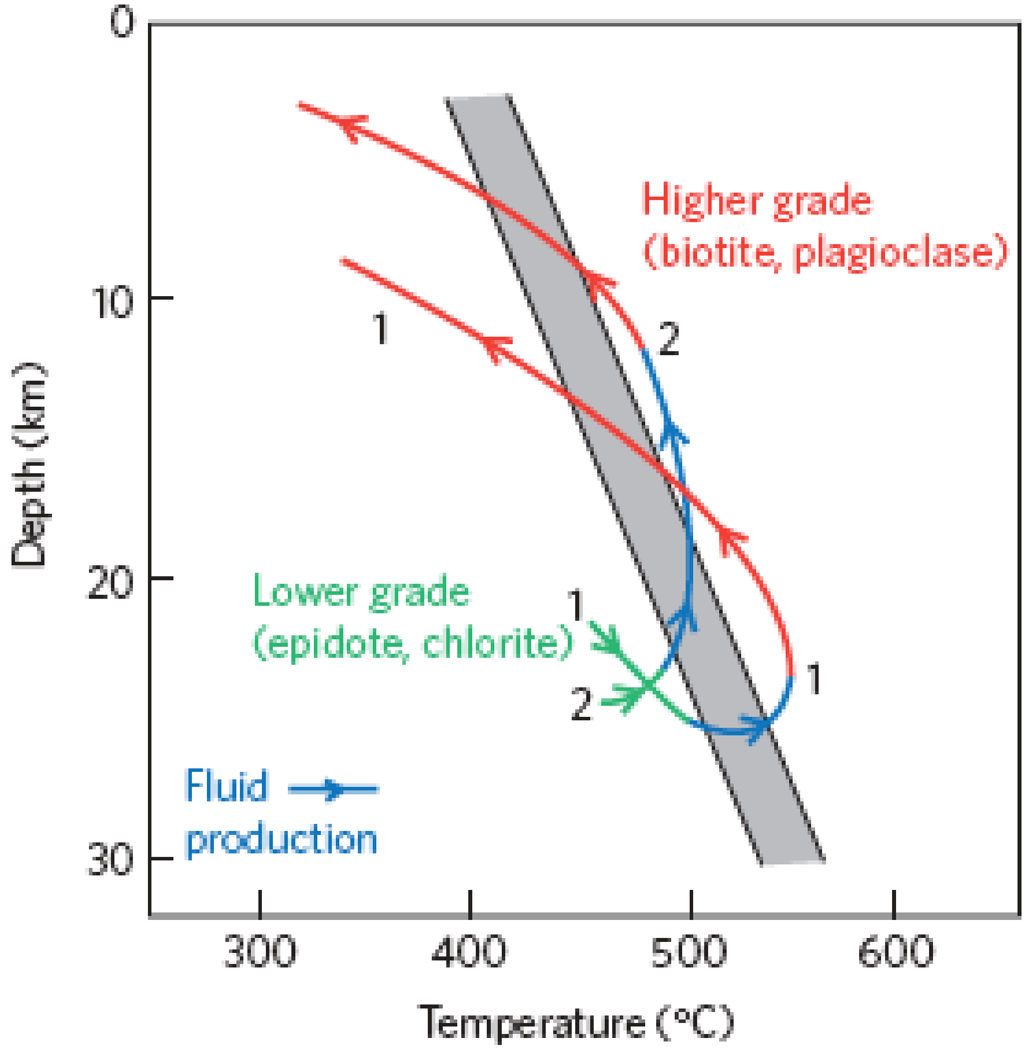


Fluid Transport in the Crust



Mode of deformation and dehydration



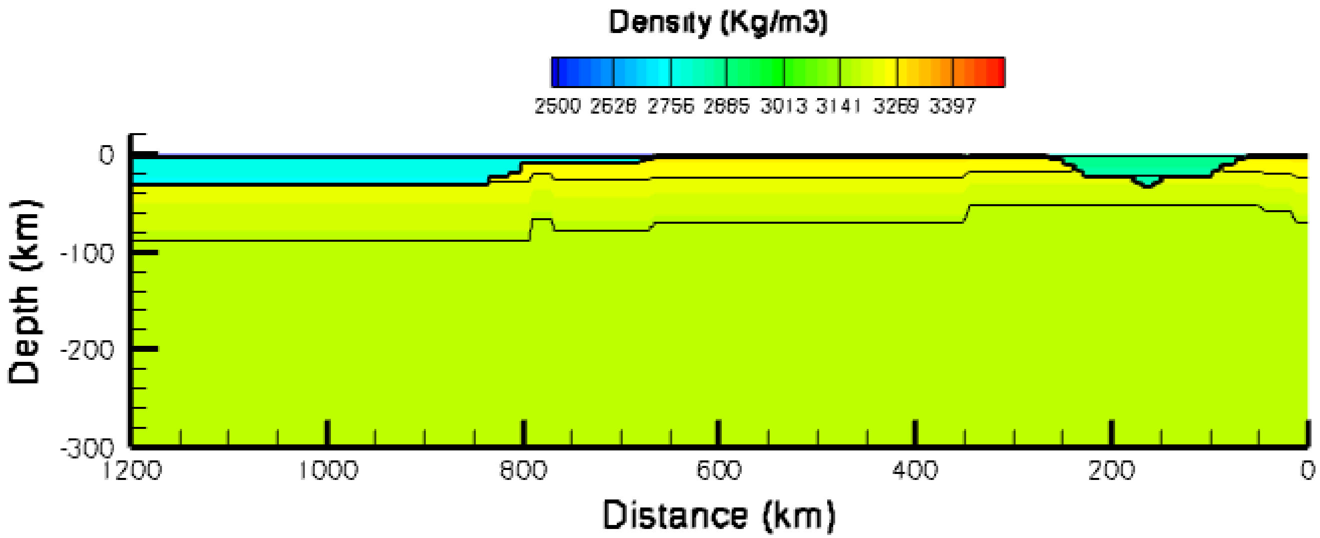


Metamorphism, Mobilization and Orogeny

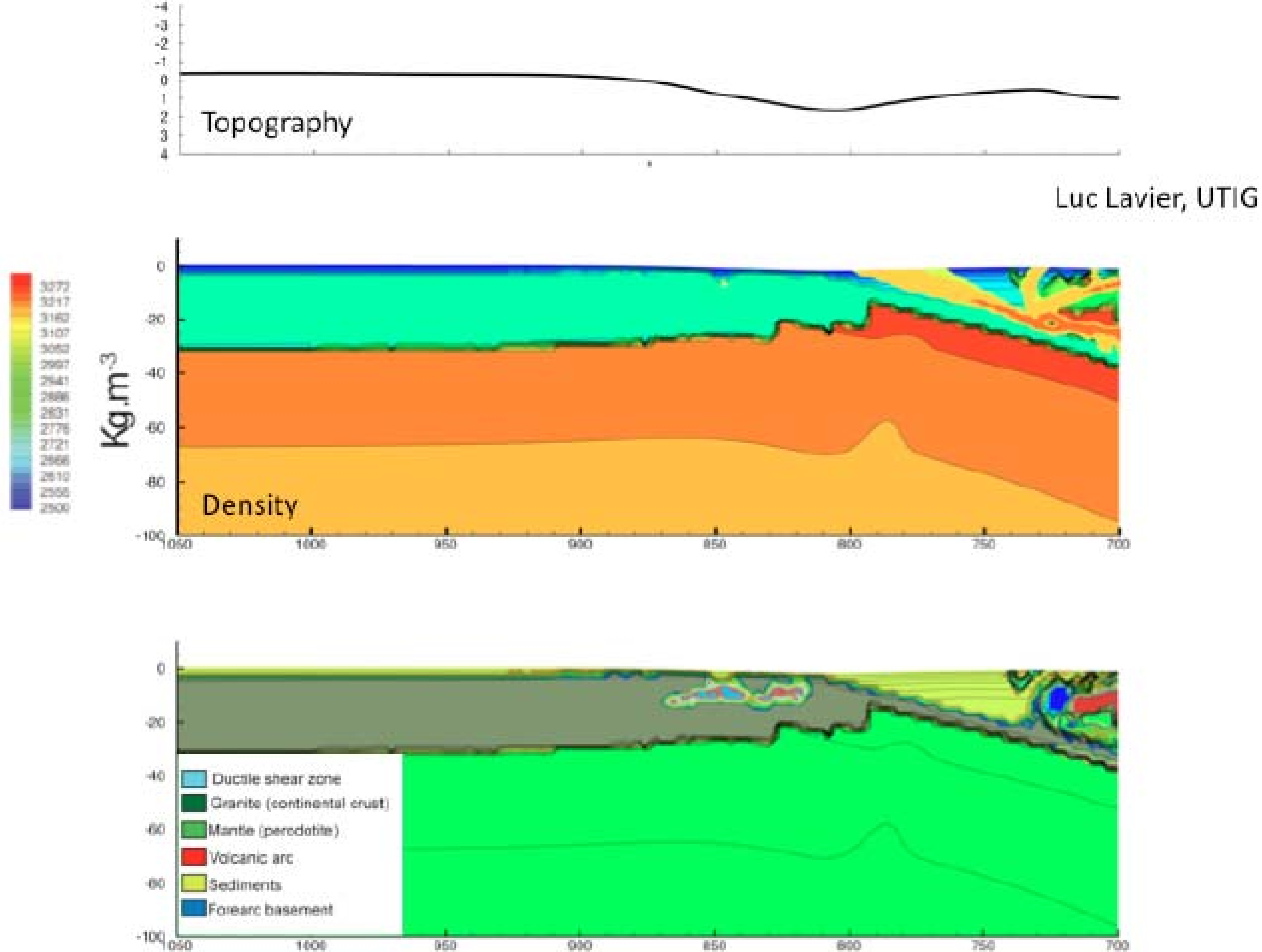
- Although dehydrated, the foliated and carbonate rocks are ductile and weak (e.g. Groom and Johnson, 2006)
- These rocks came from lower crust of Taiwan (Jahn, Yesterday)
- The zone has been “mobilized” in orogeny
- It must have widened as orogeny progressed
- Is it still widening?
- Is the Lishan conductive zone the current locus of dehydration? The “metamorphic front”?

Geodynamics of Mountain Building

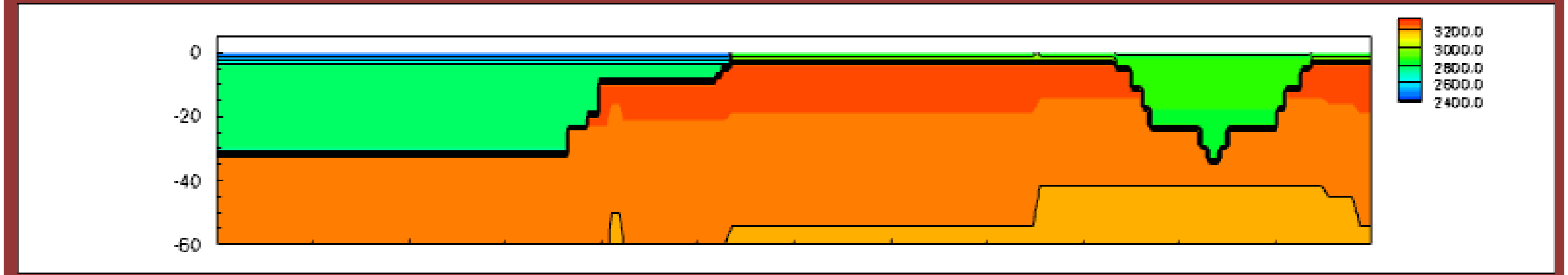
- Metamorphism and mobilization enabled by weathering (removal of materials at top)
- The exhumation pushes upward and sideways
- The sideways motion enables thrusting and deformation of western Taiwan crust
- The mobilized belt may grow or stop growing as orogeny continues or halts



Density (Kg/m3)
2500 2628 2756 2885 3013 3141 3269 3397
0
-100
-200
-300
Depth (km)
1200
1000
800
600
400
200
0
Distance (km)


Topography
Luc Lavier, UTIG
Kg.m^3
Density
Ductile shear zone
Granite (continental crust)
Mantle (peridotite)
Volcanic arc
Sediments
Forearc basement

Geodynamics of arc/continent collision
- directed by Luc Lavier -



Conclusion

- TAIGER data acquisition exceeded expectation
- Enhanced subsurface imaging is achieved with new data
- Data analyses and interpretation still in an early stage
- Fundamental issues of mountain building in Taiwan arise