Structure of the south-central Taiwan fold-and-thrust belt

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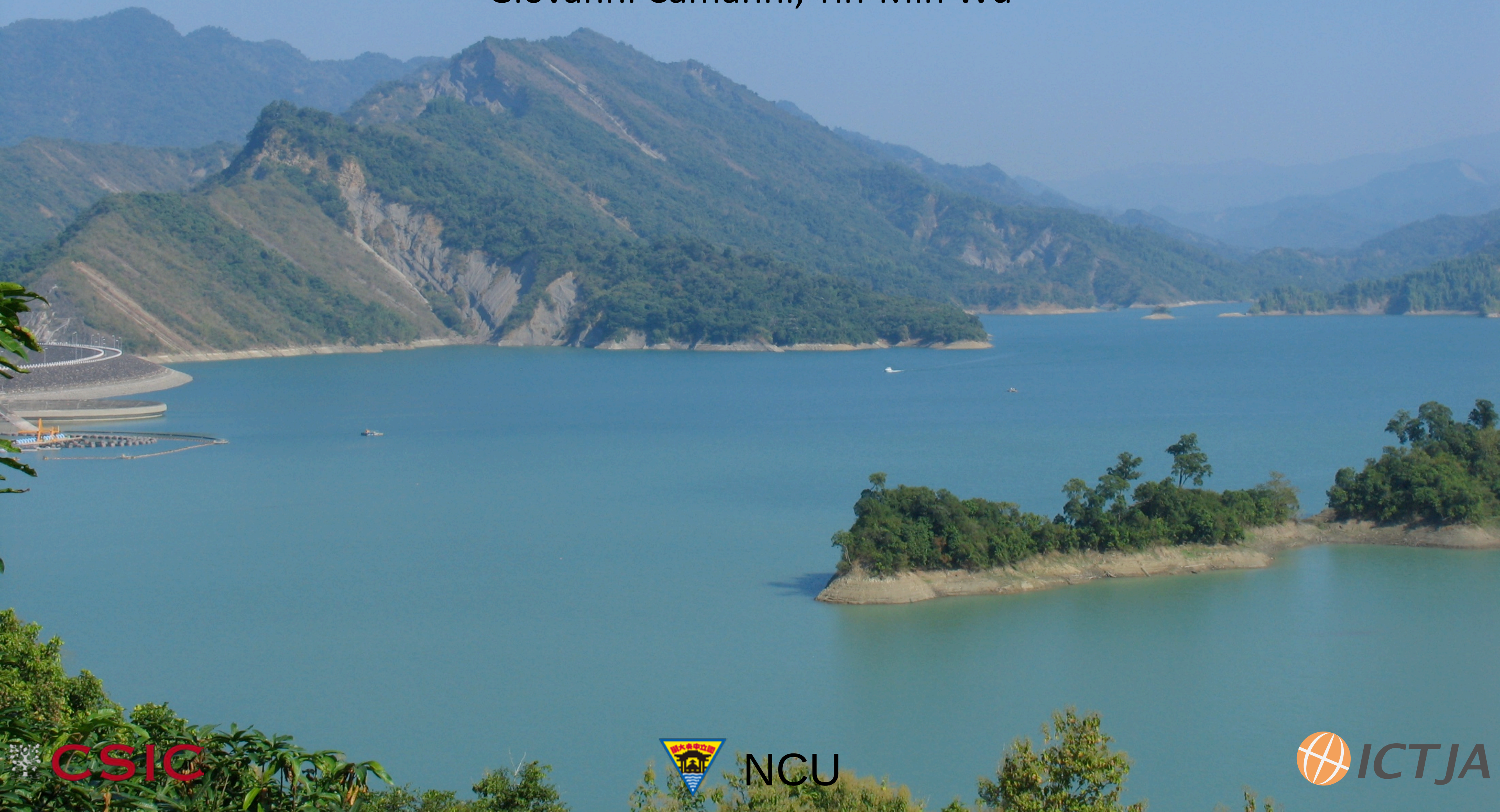

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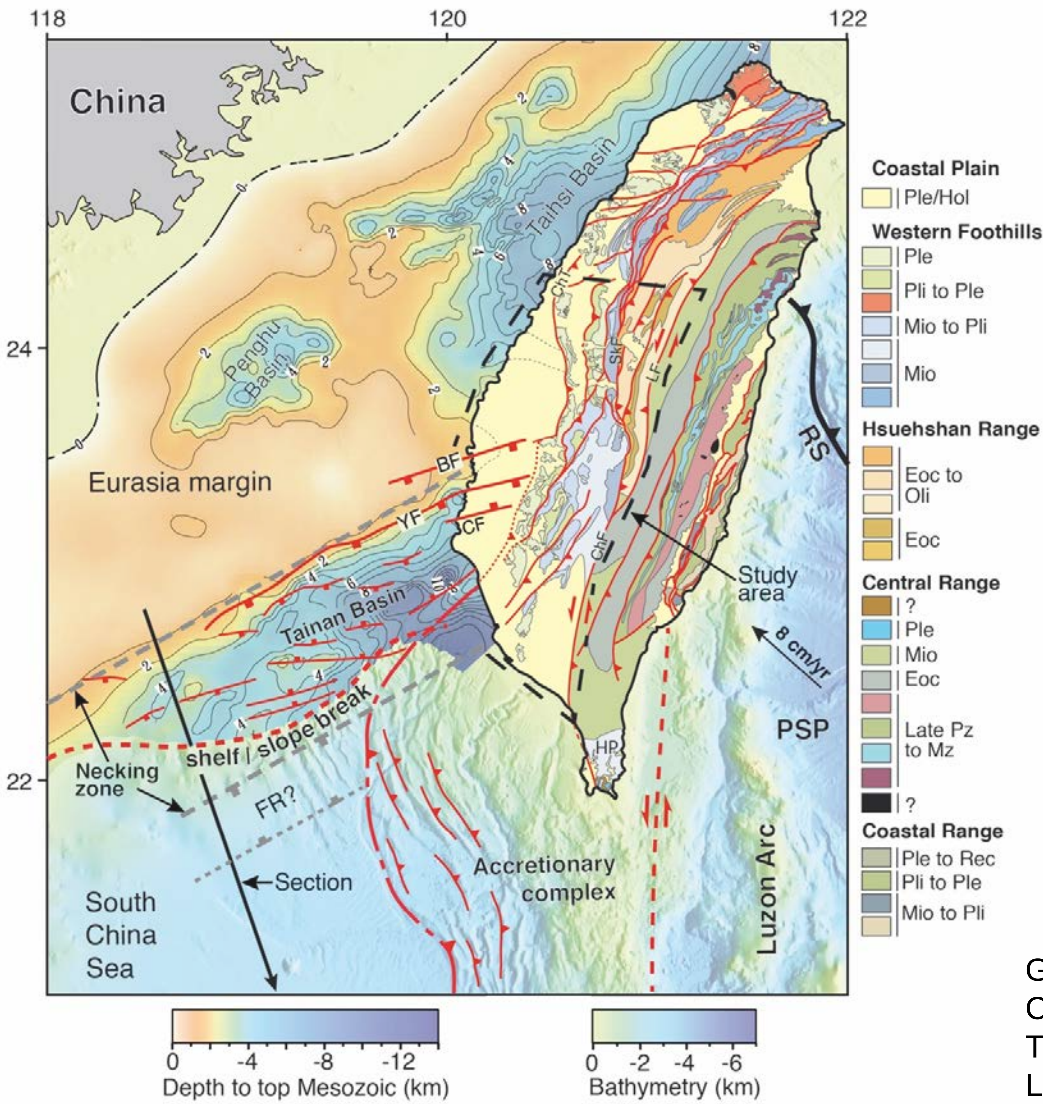
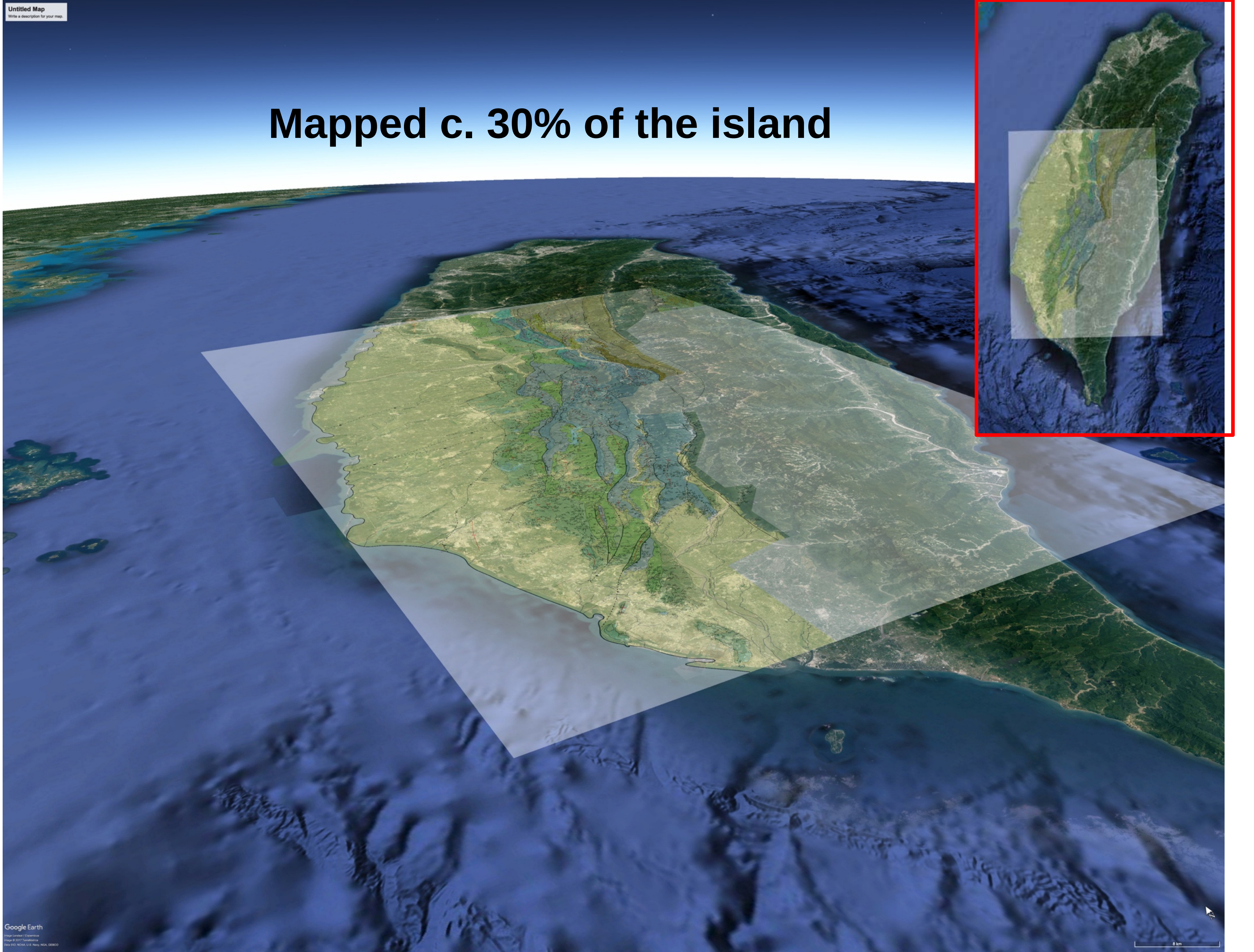
Question: Is the structure, seismicity, stress and strain fields, and topography of the south-central Taiwan fold-and-thrust belt affected by the structure and morphology of the margin?



Geological map revised from Chen et al. (2000 CGS)
Top Mesozoic basement from Lin et al. (2003 BR)

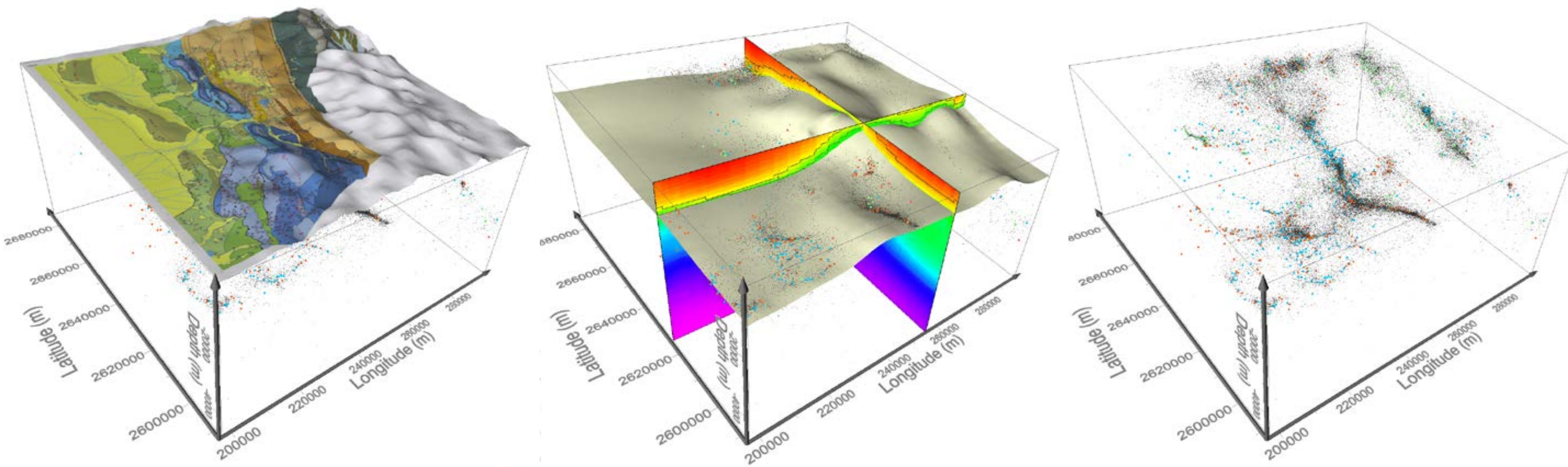
Geological database

- **11 field campaigns: c. 3 person years of mapping**
- **Mapping done at 1:50,000 and 1:25,000 scales**
- **C. 3000 data points**
- **> 6000 structural data**


Untitled Map
Write a description for your map.
Mapped c. 30% of the island
Google Earth
Image Landsat / Copernicus
Image © 2017 TerraMetrics
Data SIO, NOAA, U.S. Navy, NGA, GEBCO

Geophysical database: The search for deep structure

- Integrate surface geology with geophysical and geodetic data



- Vp model of Kuo-Chen et al. (2012)
- c. 60,000 Hypocenters (1994 to 2015) relocated using Hypo-DD 3D
- > 2400 focal mechanisms relocated in the same way
- Invert focal mechansims for the contemporaneous stress field
- GPS data for surface displacement and strain rates

First, some explanations

For the Miocene and younger rocks, we use a chronostratigraphic framework. For simplicity in describing the geology, we assign formation names.

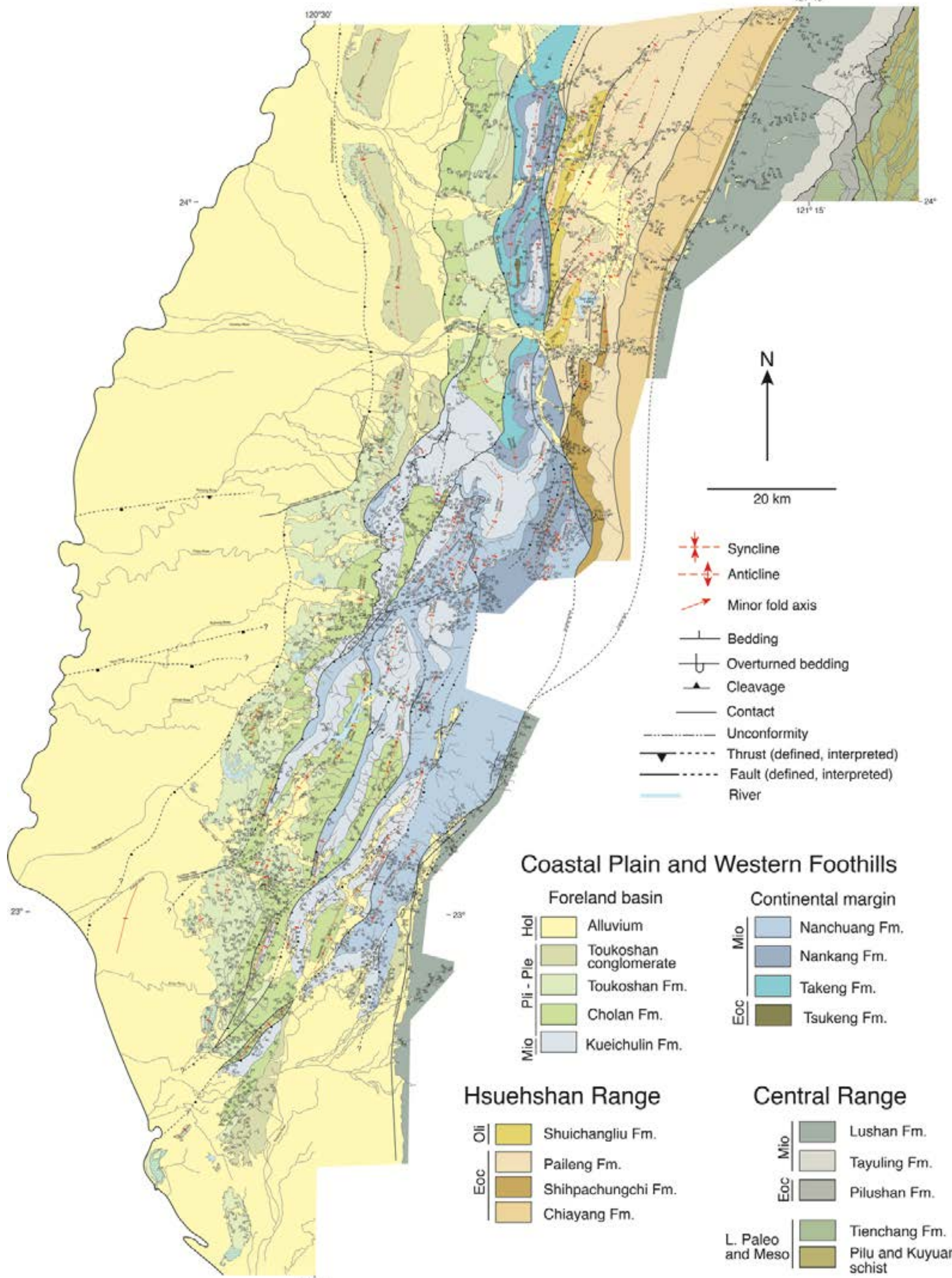
Table 1. Chronostratigraphic correlation chart used in the mapping.

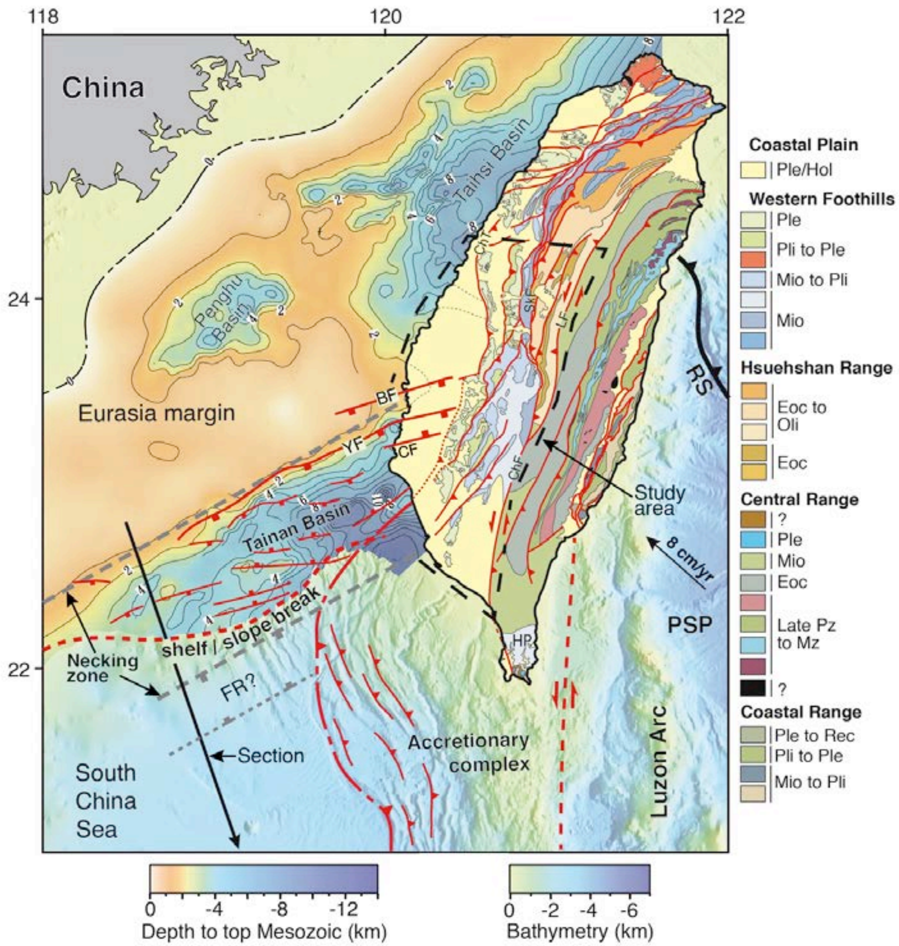
		Shelf		Mesozoic shelf break		Upper slope	
	This map	Nantou / Yunlin		Chiayi / Tainan		Tainan	Kaohsiung
Pli - Ple	Toukoshan CC.* Toukoshan SS.*			Liushuang Fm. Erchungchi Fm. Kanhsialiao Fm.	Yuching Sh.*	Chiting Fm.	Linkou CC. Tashe Fm. (with limestone)
Pli - Ple	Cholan Fm.*			Liuchungchi Fm. Yunshuichi Fm.	Peiliao Sh. Chutouchi Fm.	Gutingkeng Fm. (with limestone)	Nanshihlun SS Kaitzuliao Sh. Wushan Fm.
Mio	Kueichulin Fm.		Tawo SS Shihliufeng Sh. Kuantaoshan SS	Niaotsui Fm. Chunglun Fm.	Maopu Sh. Ailiaochiao Fm. Yenshuikeng Sh. Tangenshan SS.	Wushan Fm.	
Mio	Nanchuang Fm.				Changchihkeng Fm. Hunghuatze Fm. Sanmin Sh.		
Mio	Nankang Fm.	Fulungyuan Fm. Hourdongkeng Fm. Shihmentsun Fm.	Shenkeng SS Changhukeng Sh. Shihmen Fm.				
Mio	Takeng Fm.		Tanliaoti Sh. Shihszeku Fm.				

*CC = conglomerate, SS = sandstone, Sh. = shale, Fm. = formation

From Shea et al. (2003), CGS

Viewing the geology with a chronostratigraphic scheme allows us to easily visualise and correlate the structure and its relative age from north to south.

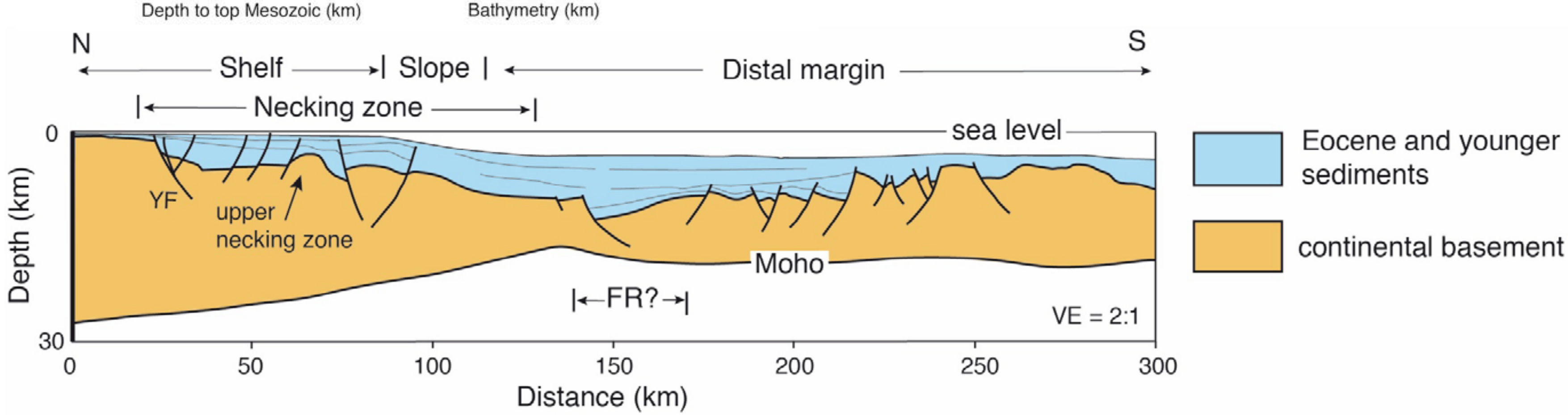




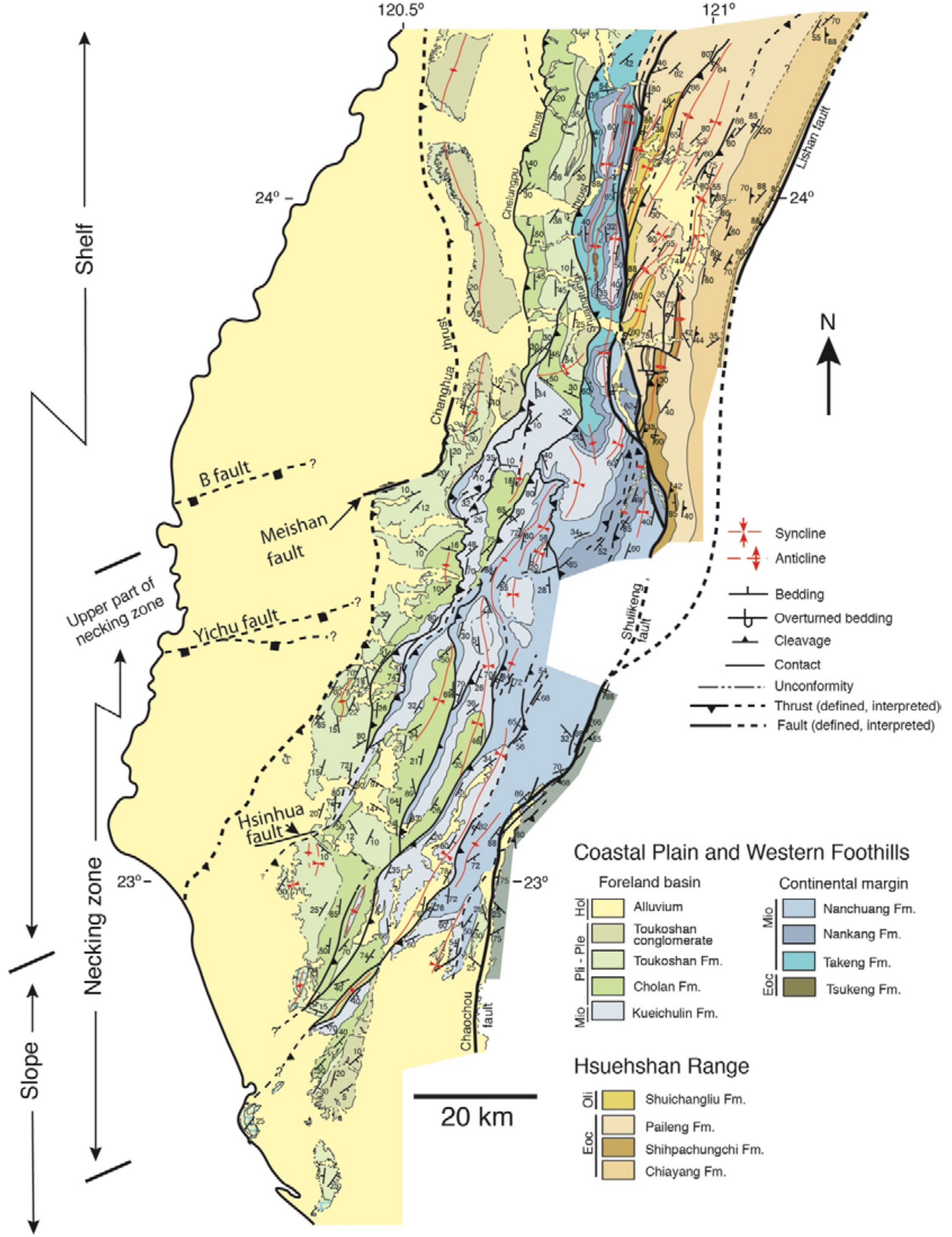
Some margin terminology

- ➢ **Morphology**
- Shelf
- Slope
- Distal margin

- ➢ **Structure**
- Necking zone
- Failed rift
- Hyperextended



How does this margin terminology apply to our map area?

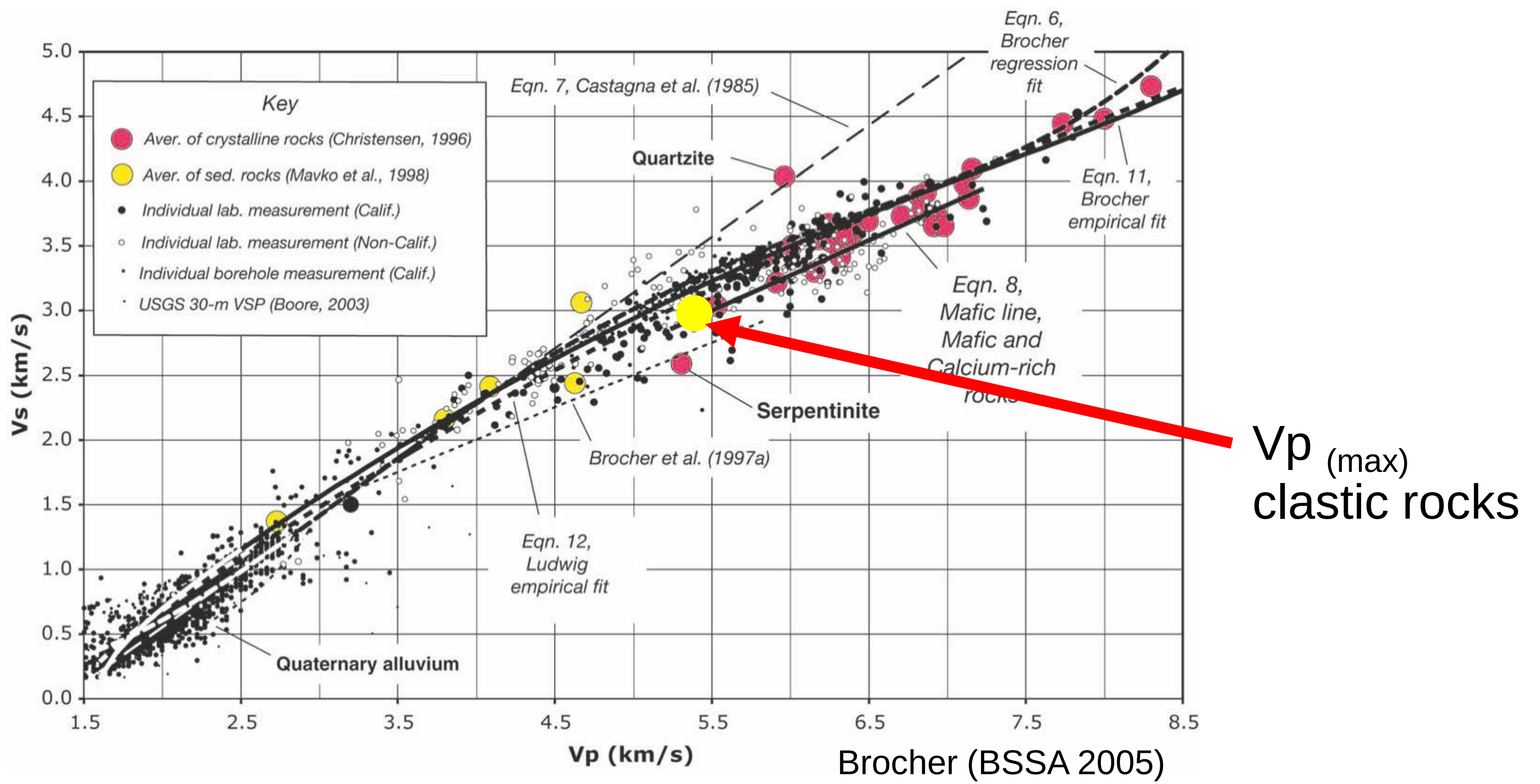


In order to interpret the structure at depth, and the influence that the margin is having on it, we need to define the term “basement”, and then we need a way to find it in our data set.

- **We define the geological basement as any pre-Eocene rifting rocks. In other words, rocks upon which the Eocene and younger continental margin was built.**

- **To find it, we use a geophysical proxy that can be used to describe the interface between the geological basement and the sediments that overlie it.**

Because of our data set, the proxy is in terms of P-wave velocity



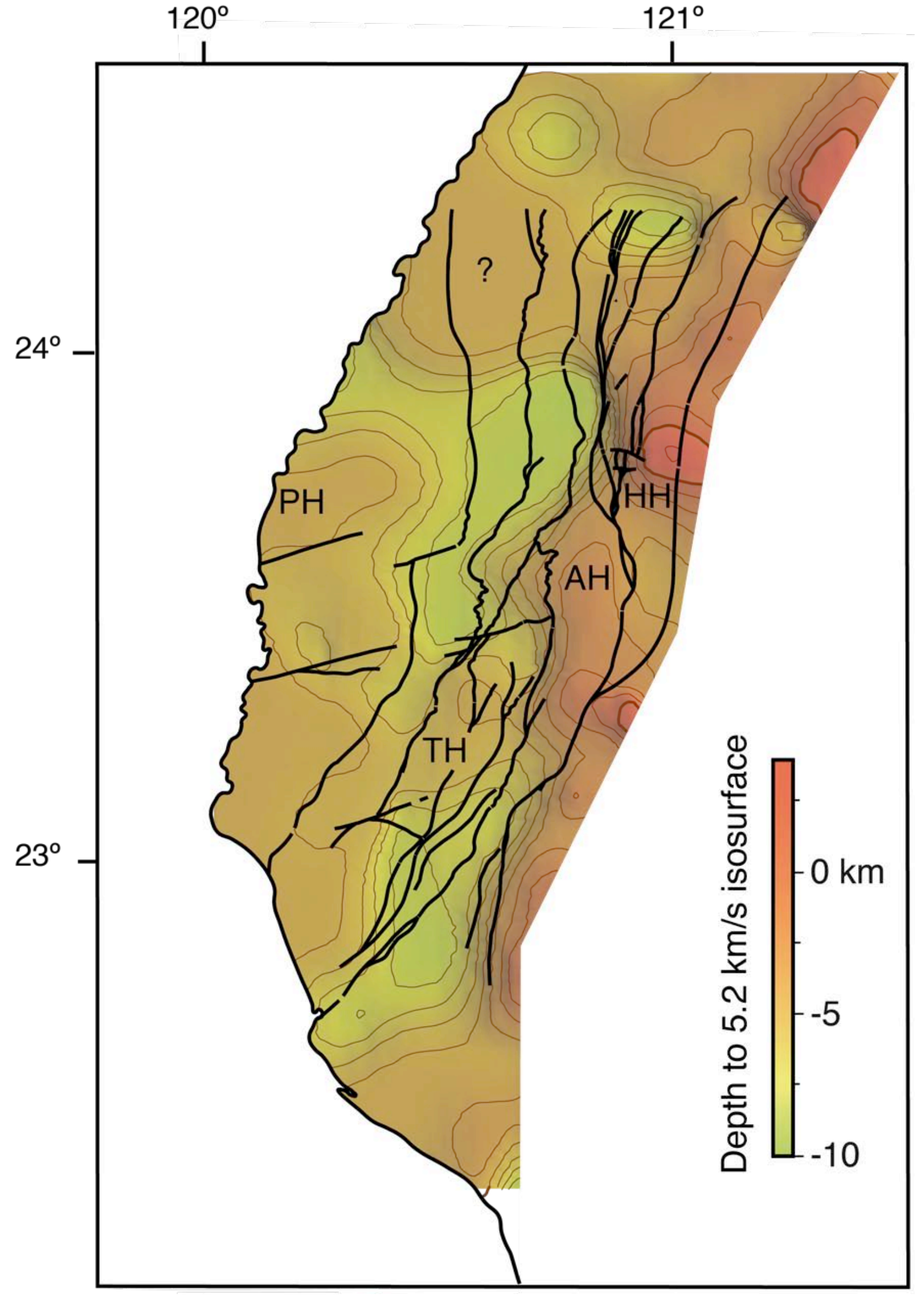
Brocher (BSSA 2005)

We choose a Vp of 5.2 km/s as a **proxy** for the basement-cover interface:

1) c. maximum Vp of laboratory measurements of clastic rocks at P and T

2) > the Vp (< 5 km/s) of the Late Miocene and younger rocks intersected in the Chelungpu Fault Drilling Project borehole A.

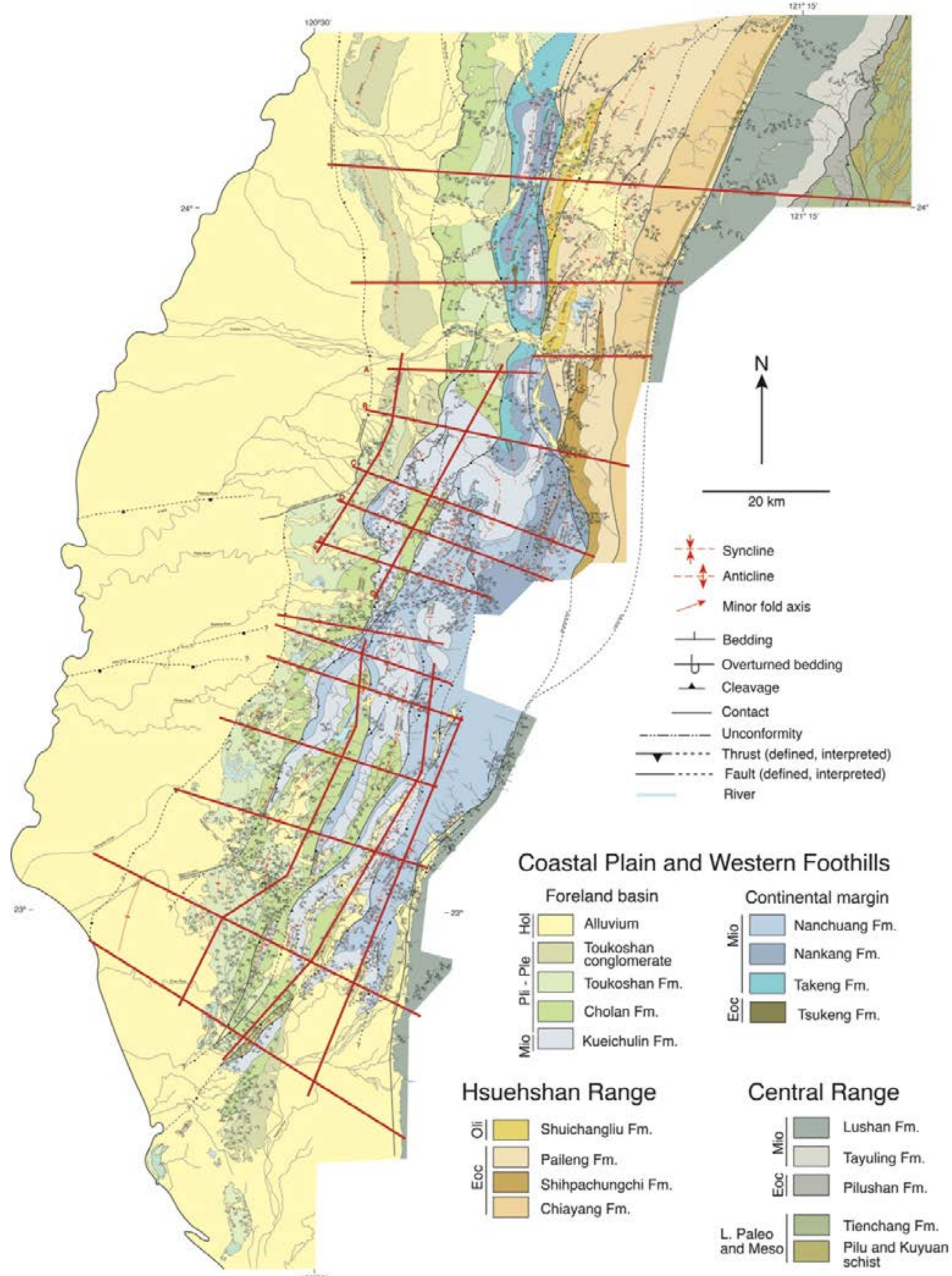
- **Reasonable fit with the estimated stratigraphic thickness**
- **Various highs and lows in the 5.2 km/s isosurface**
- **These coincide with changes in strike of thrusts**
- **And with mapped ENE-striking faults**



OK, let’s look at some structure!

To investigate the structure and its variations from north to south, we have:

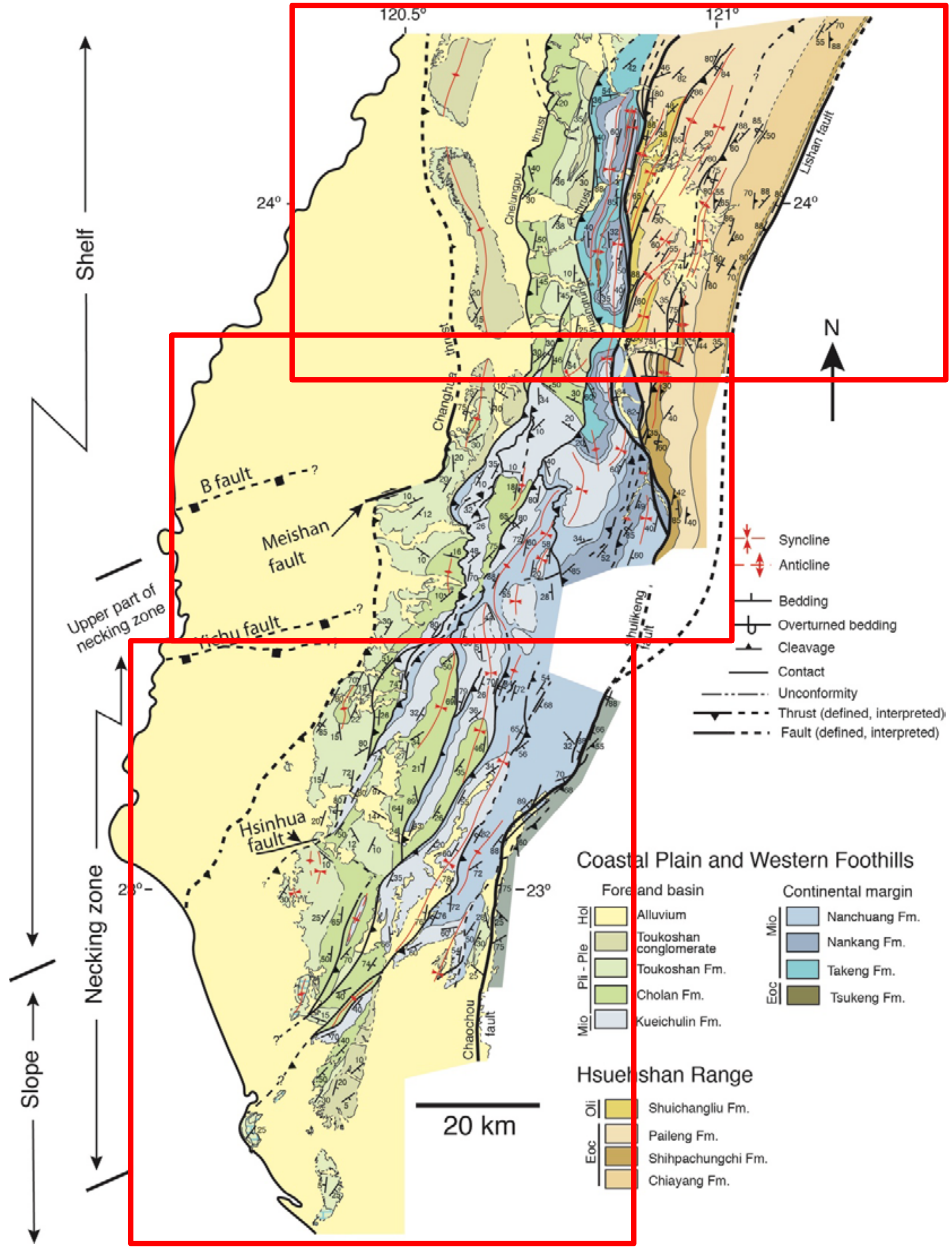
- **Done our own mapping**
- **Constructed 14 cross sections**
- **Where possible, cross sections are balanced and restored**
- **5 along-strike sections**
- **A map of the basal thrust**
- **Thrust branch line maps**
- **Stratigraphic cut-off maps**



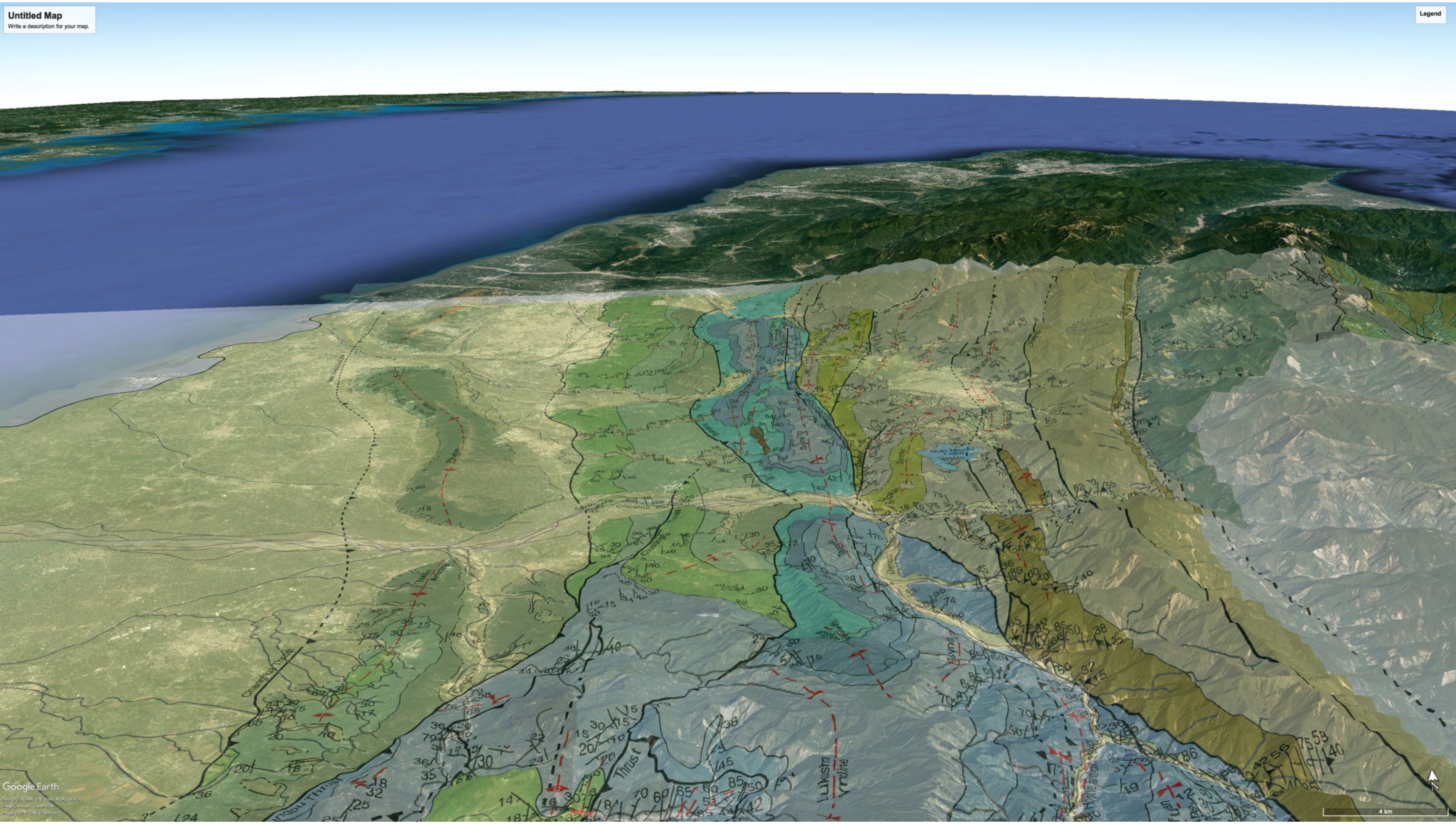
I will describe the structure from north to south in terms of:

- **The continental shelf**
- **The upper necking zone**
- **The necking zone (shelf to slope transition)**

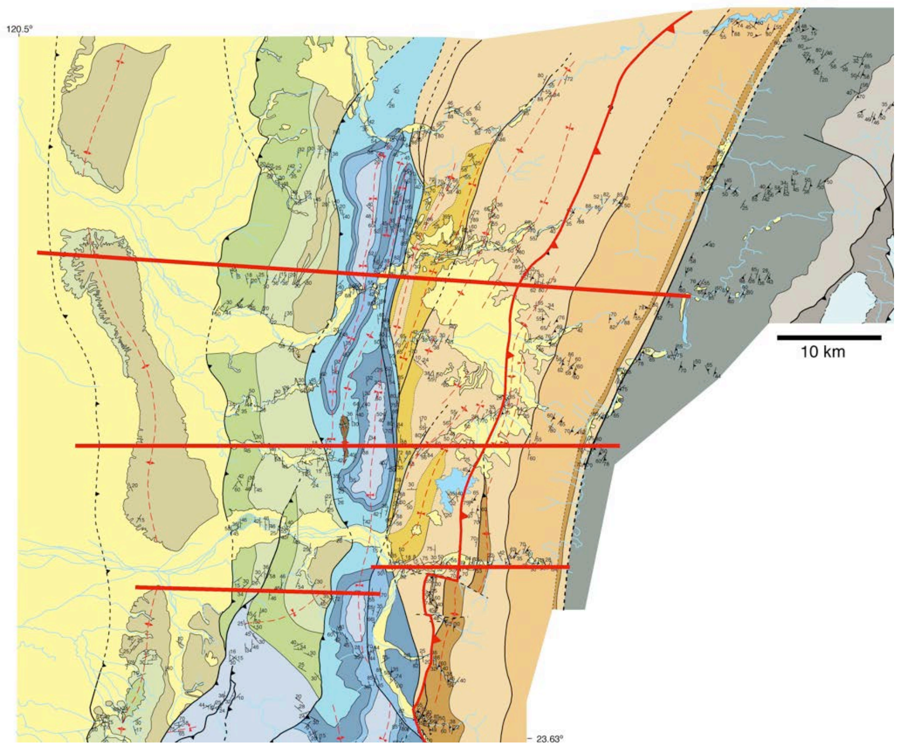
➢ **More about the reason for this approach later**

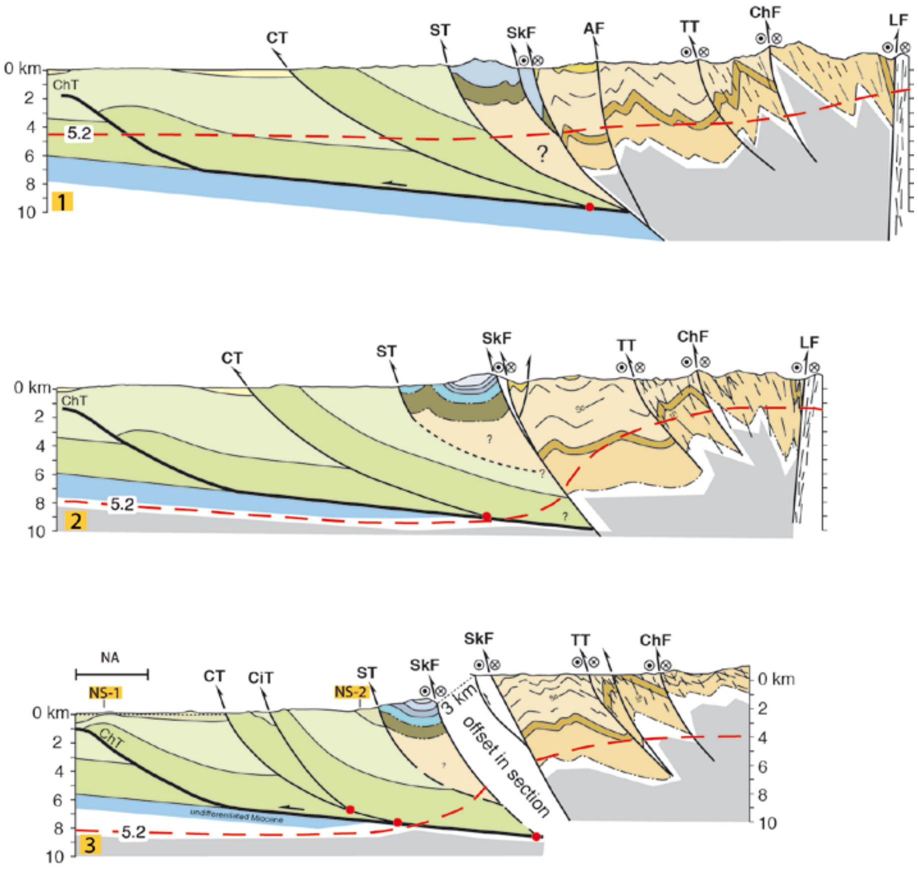


Central Taiwan: The shelf

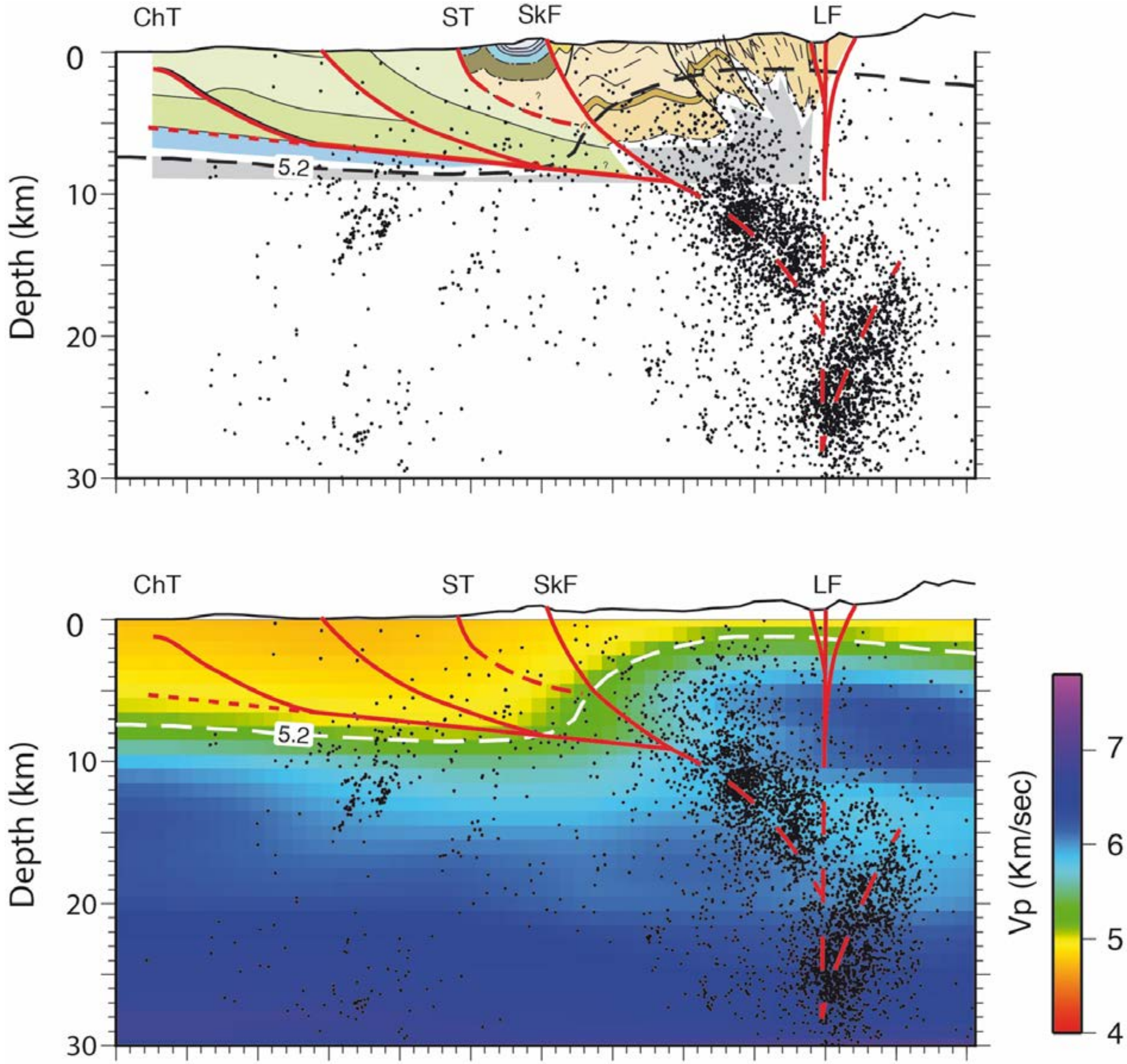


- **Imbricate thrust system in the west beneath syn-orogenic sediments**
- **Shuilikeng fault is a ramp into the middle crust**
- **Inversion of the Hsuehshan Basin (with uplift of basement rocks)**
- **Cleavage front along the Tili thrust**
- **Lishan fault (a major crustal boundary?)**
- **Shortening is difficult to determine for a number of reasons**

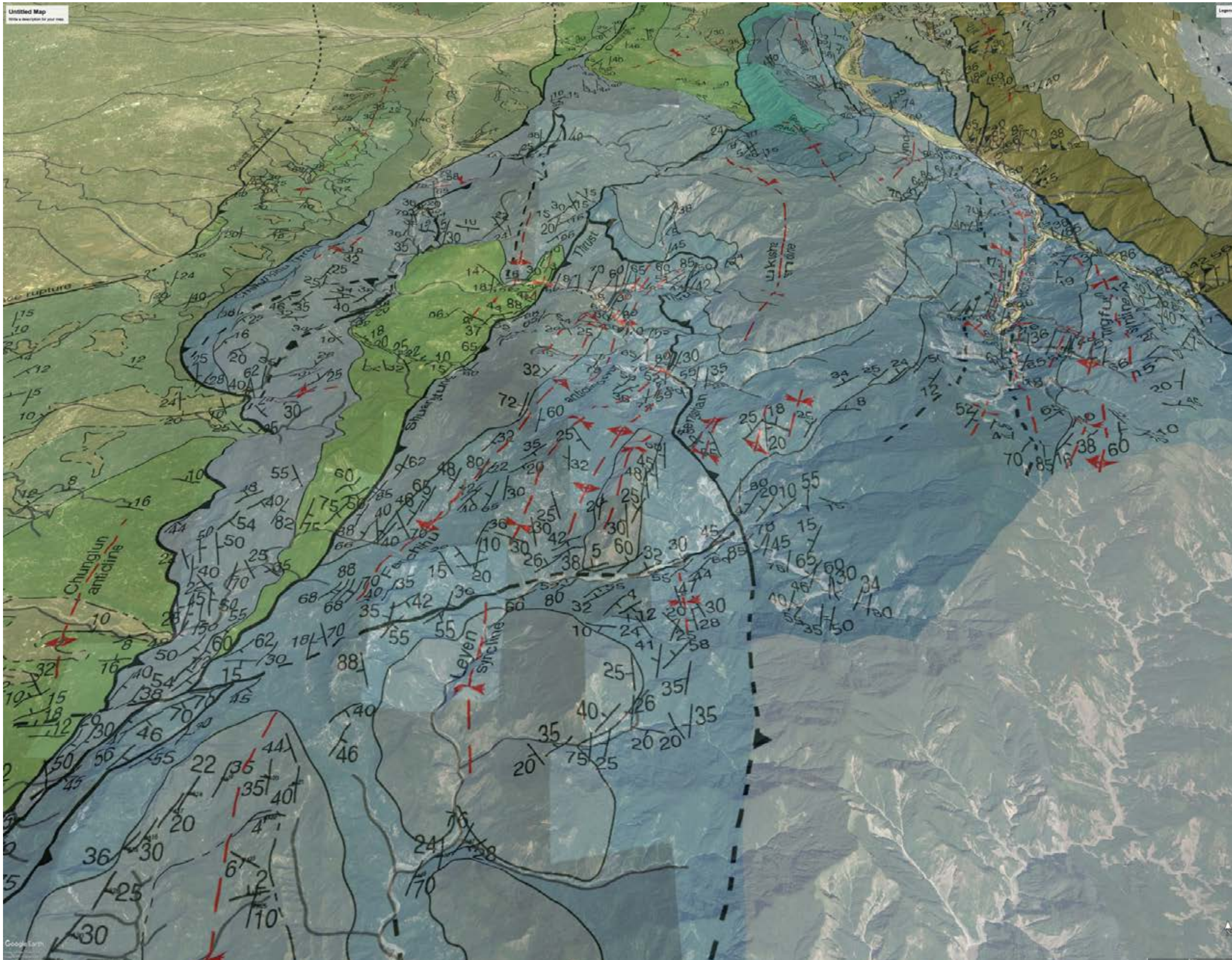




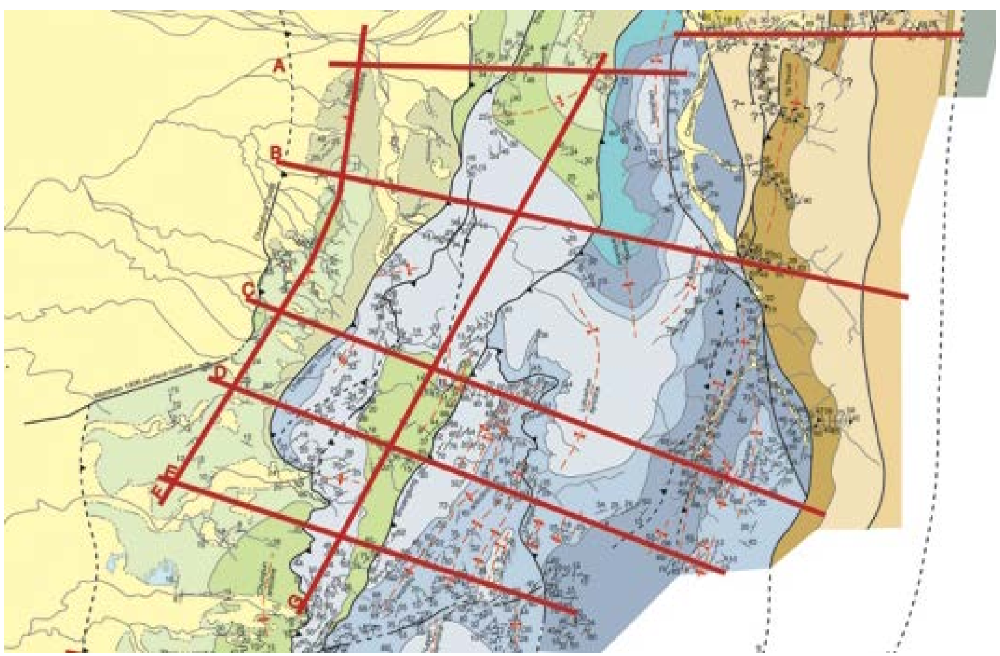
- **Clear evidence for a Shuilikeng ramp into the middle crust**
- **Higher Vp in its hanging wall suggests basement involvement**
- **Kuo-Chen et al. (2015) show that the Lishan fault extends from surface to deep cluster**

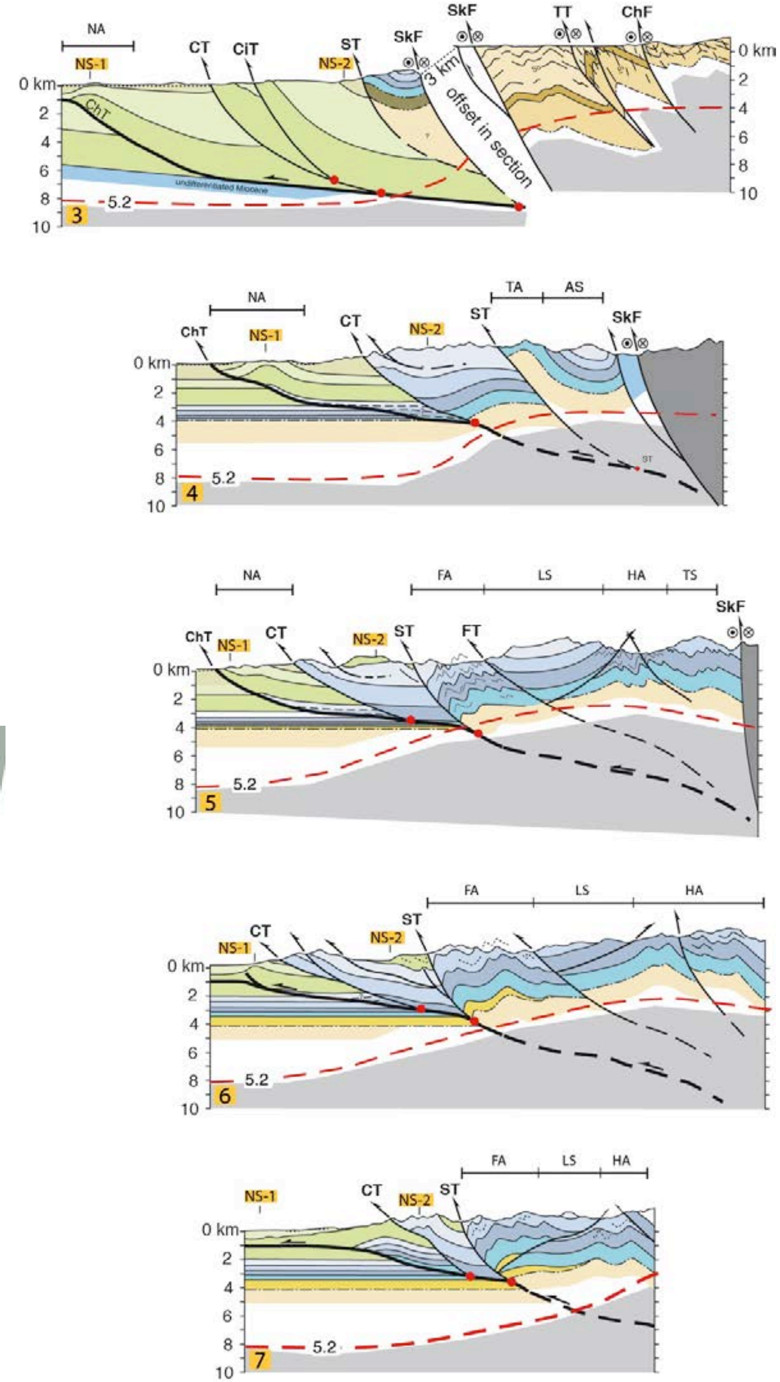


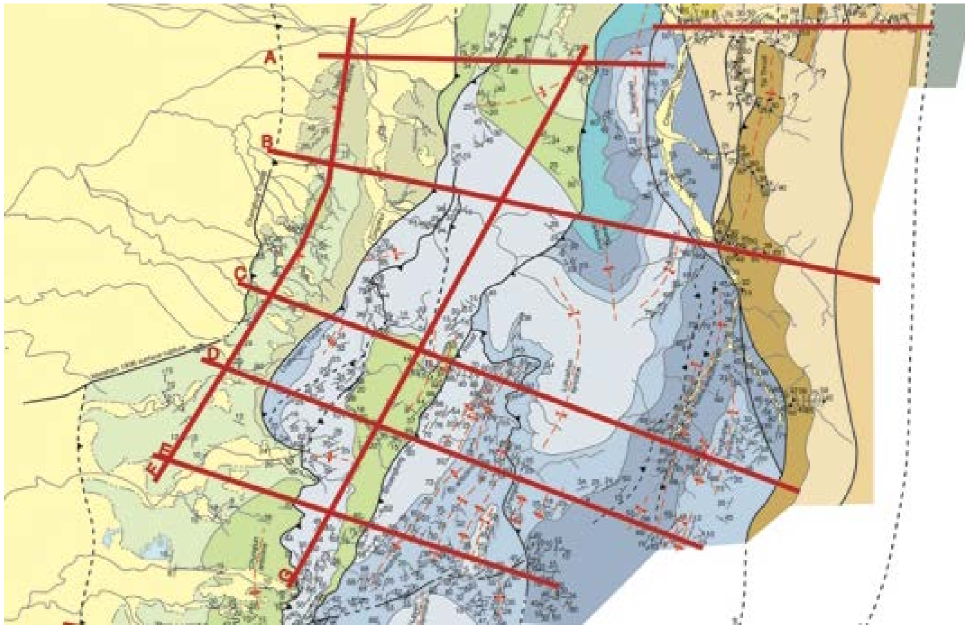
Alishan: The upper necking zone



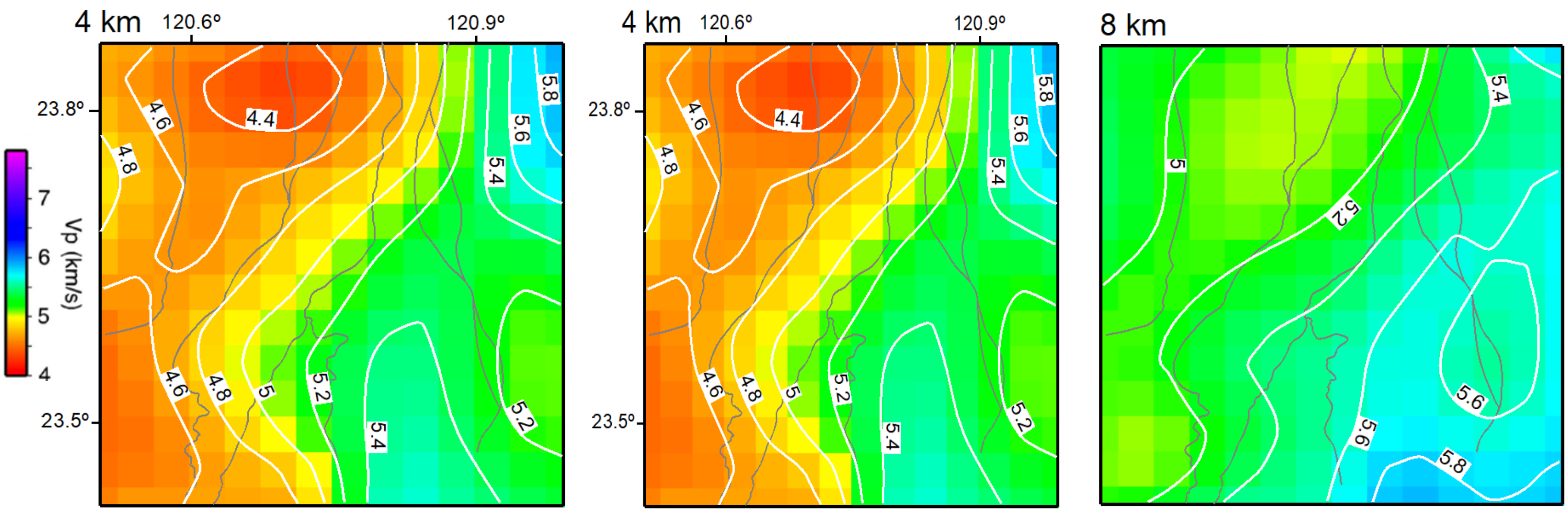
- **Major along-strike change in structure (lateral structure?)**
- **Imbricate thrust system**
- **Steeply dipping basal thrust (basement involvement?)**
- **Shortening is c. 15 km**

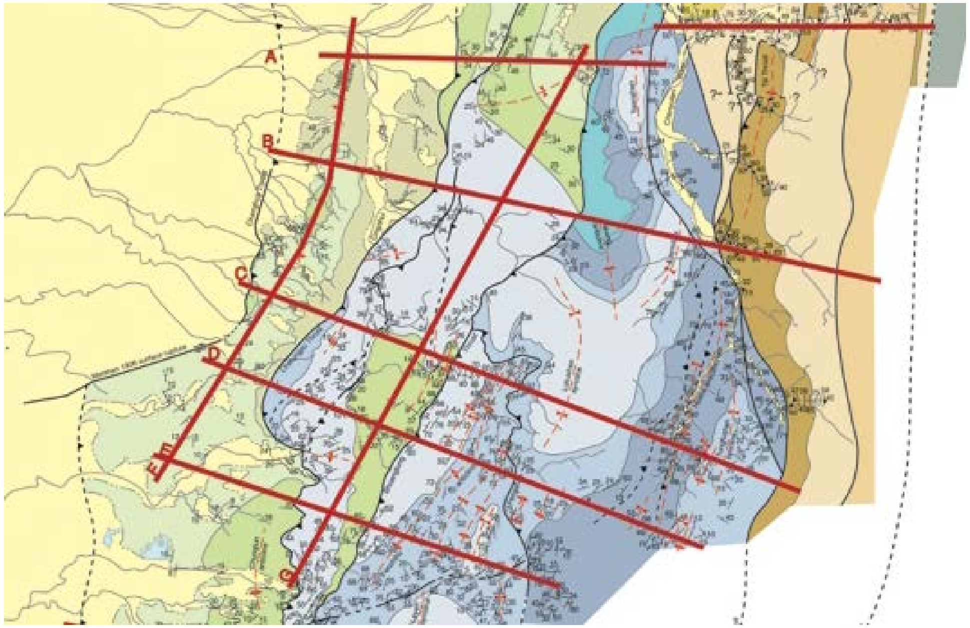


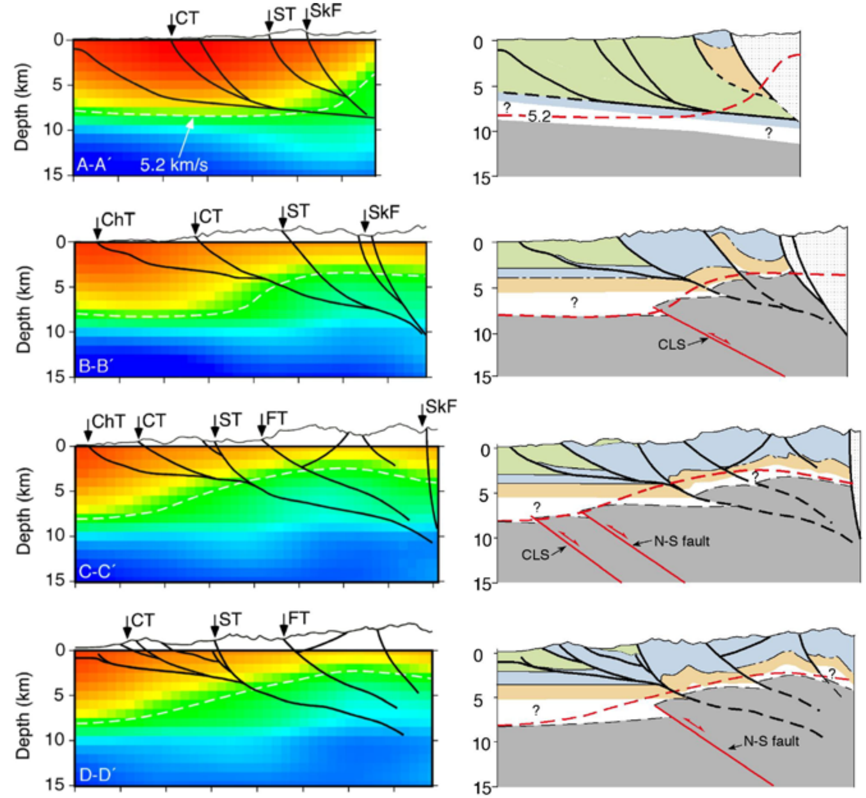




- **Good correlation between the surface geometry of fault traces and the Vp contours at depth.**
- **Higher Vp rocks are being uplifted toward the SE**
- **5.2 kms^{-1} contour closely follows the Shuangtung thrust**

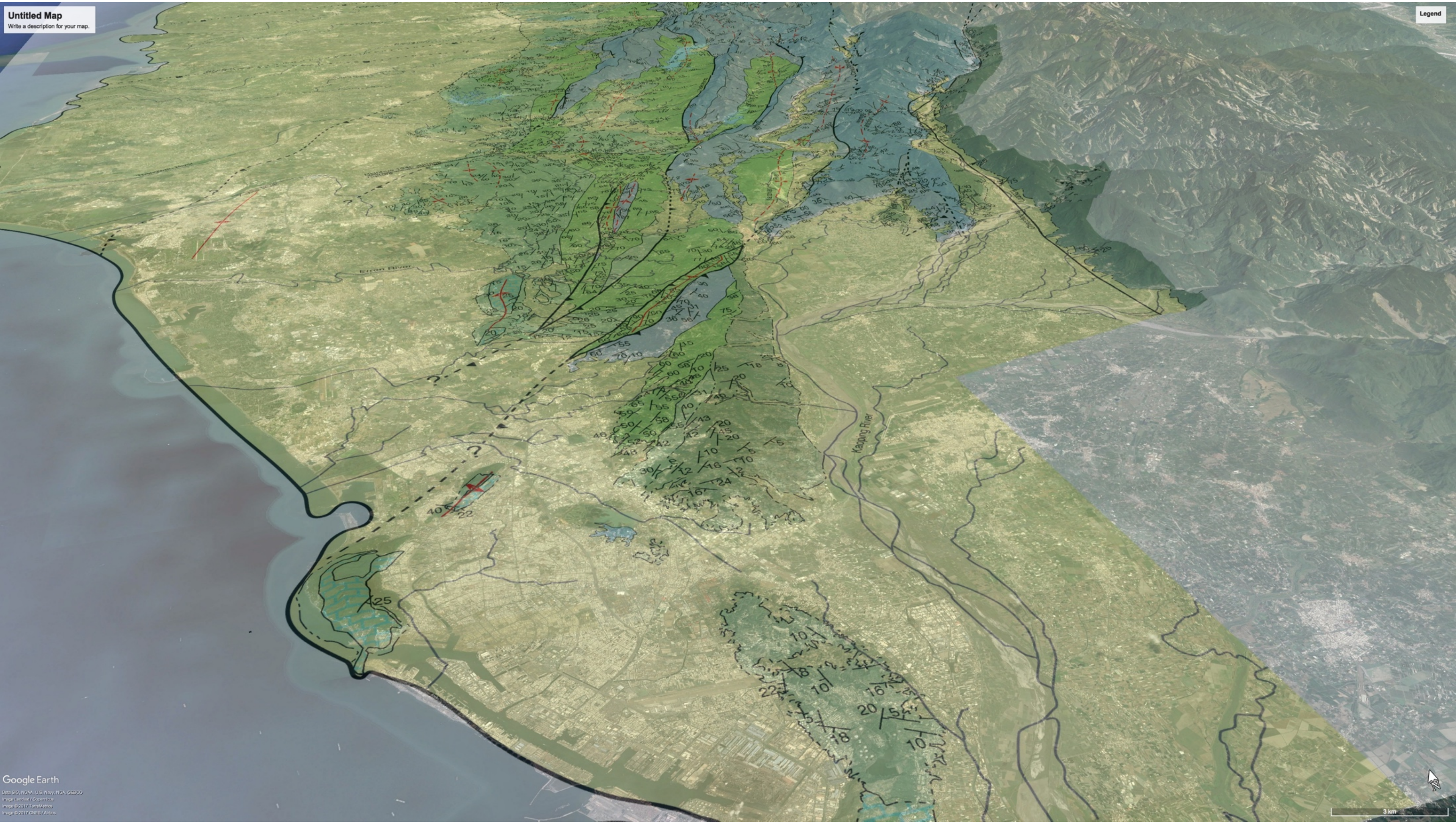


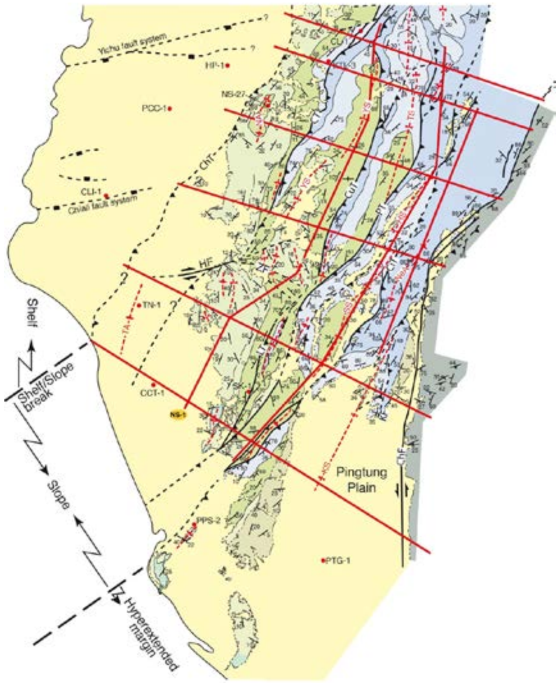


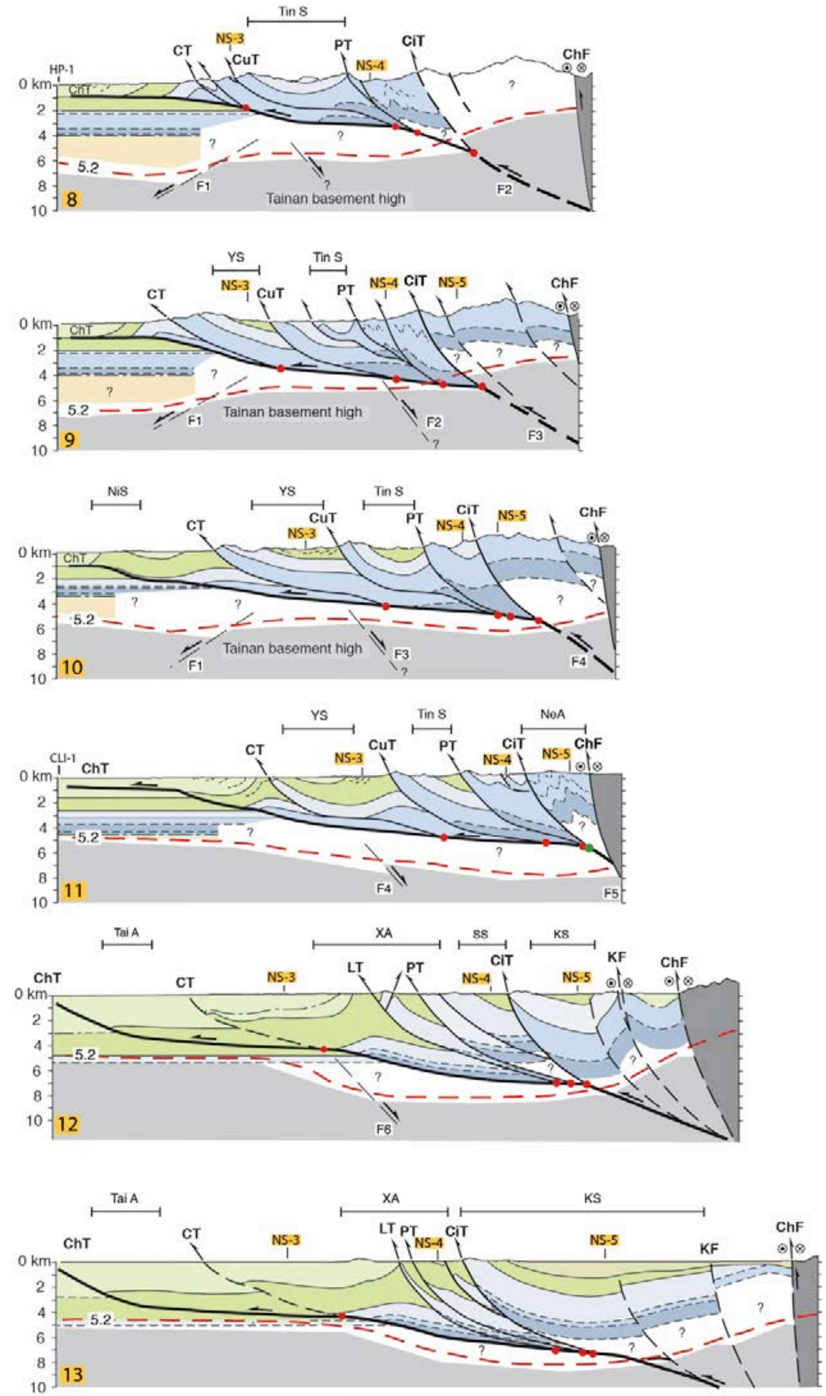


- **We interpret this to indicate that the basal thrust ramps down into the basement along the Shuangtung thrust, uplifting higher Vp basement rocks to the east.**
- **Alishan comprises a basement-cored anticlinorium**

Southwest Taiwan: The necking zone and shelf to slope transition

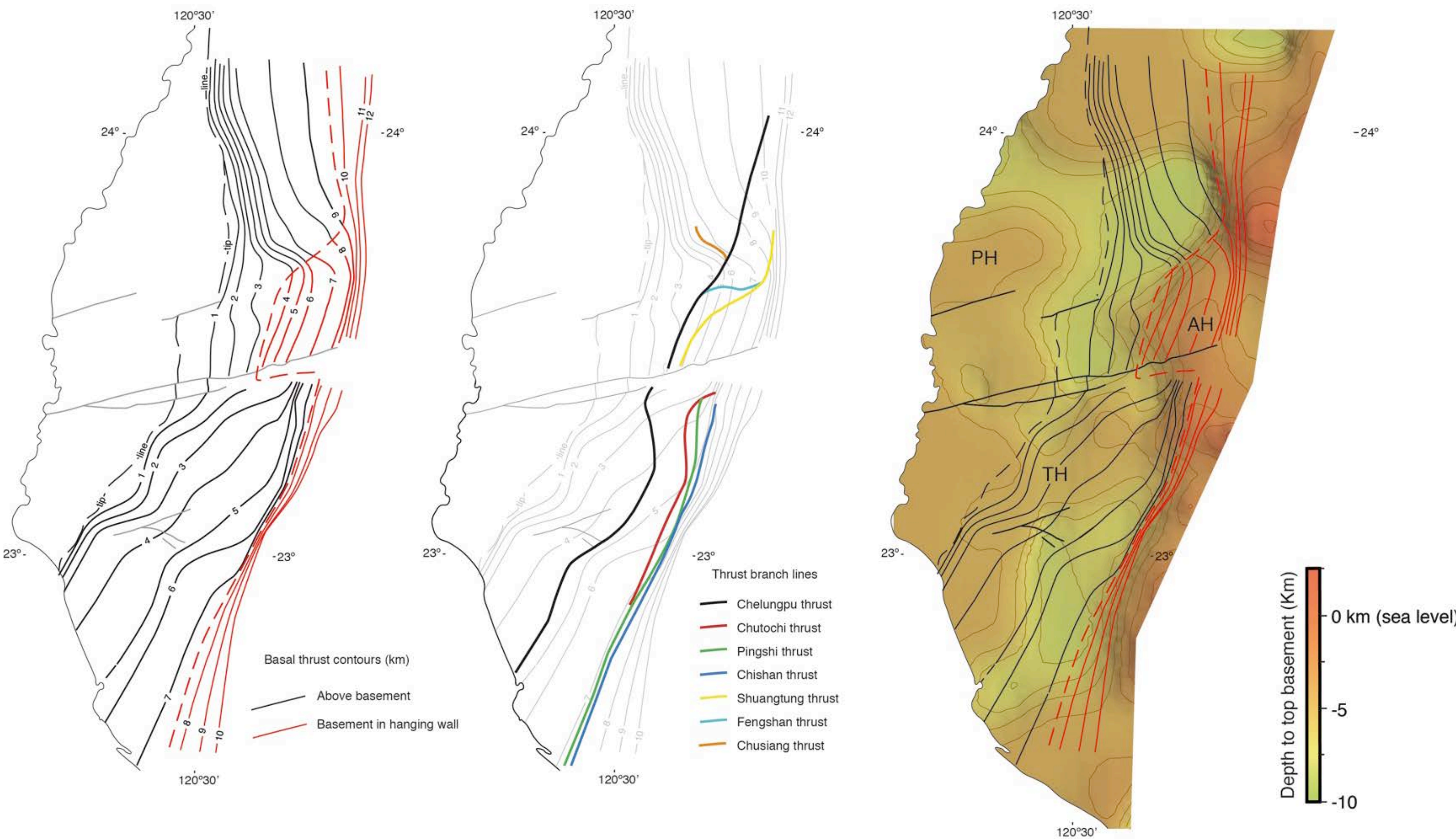






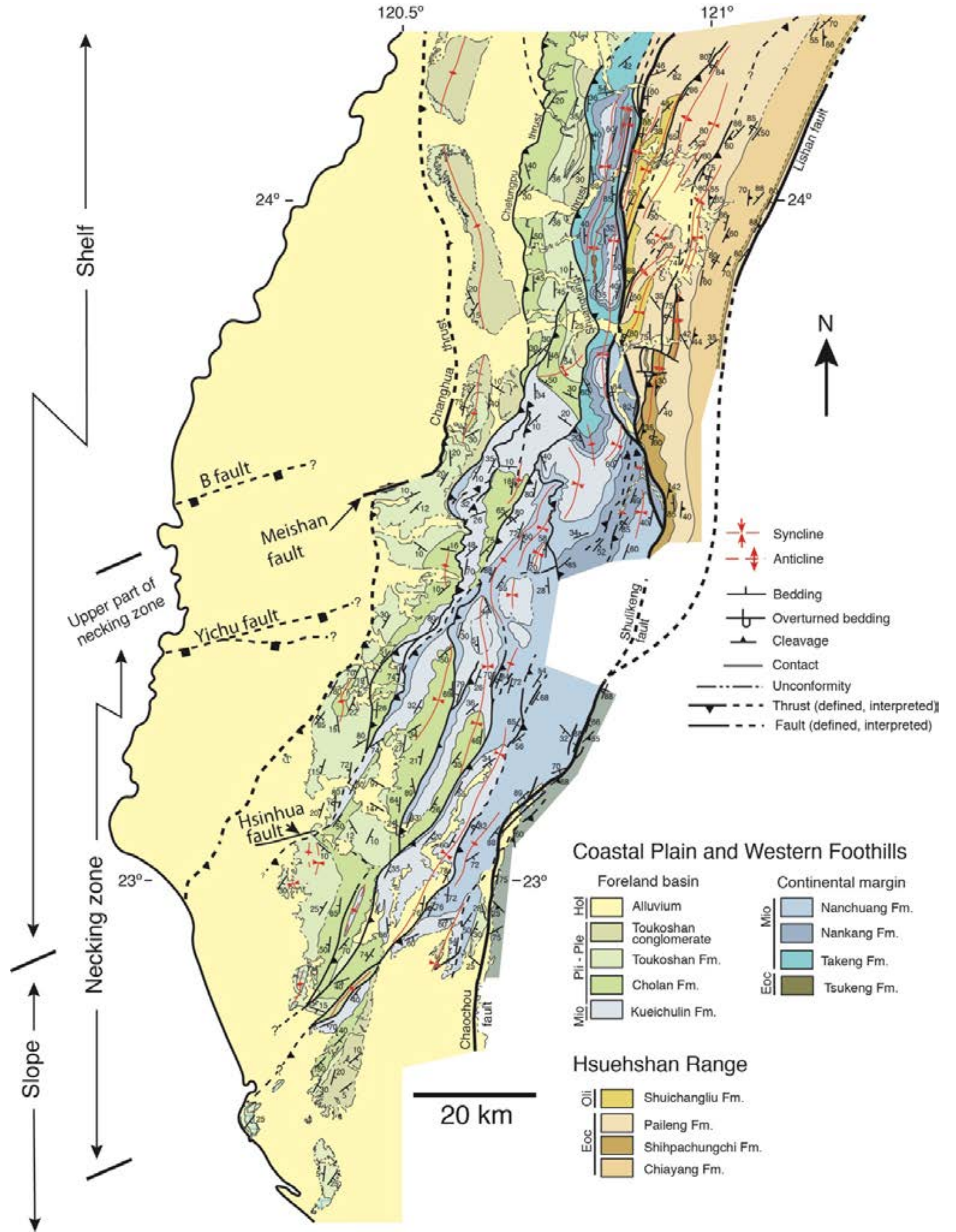
- **Imbricate thrust system**
- **Juxtaposition of synclines with similar erosion levels suggests a gently dipping basal thrust**
- **Southwarrd change from synclines to anticline indicates along-strike change**
- **Basal thrust ramps down into the basement along the Chishan thrust: uplift of 5.2 kms^{-1}**

- **Contours of the basal thrust displays sharp bends that indicate presence of oblique ramps**
- **Complex branch line patterns across oblique ramps**
- **Ramps associated with basement highs and lows**

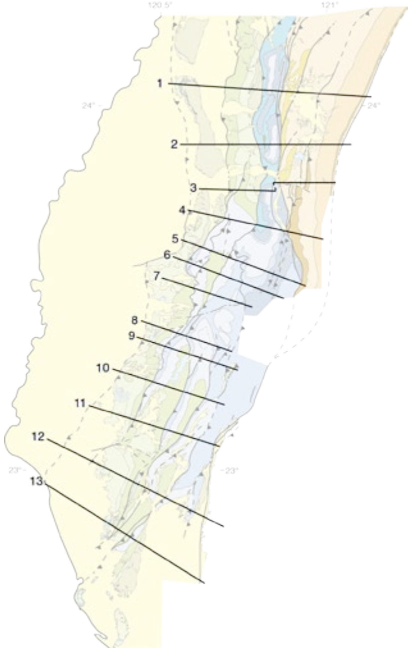


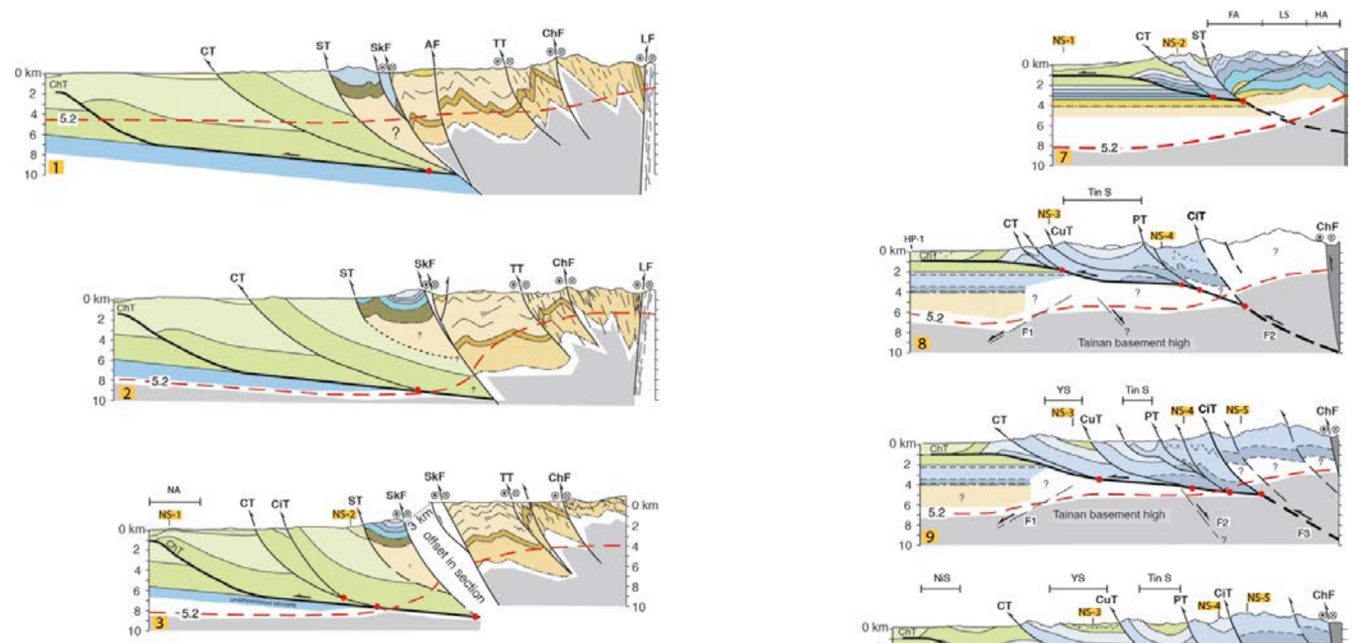
Along-strike changes: Map view

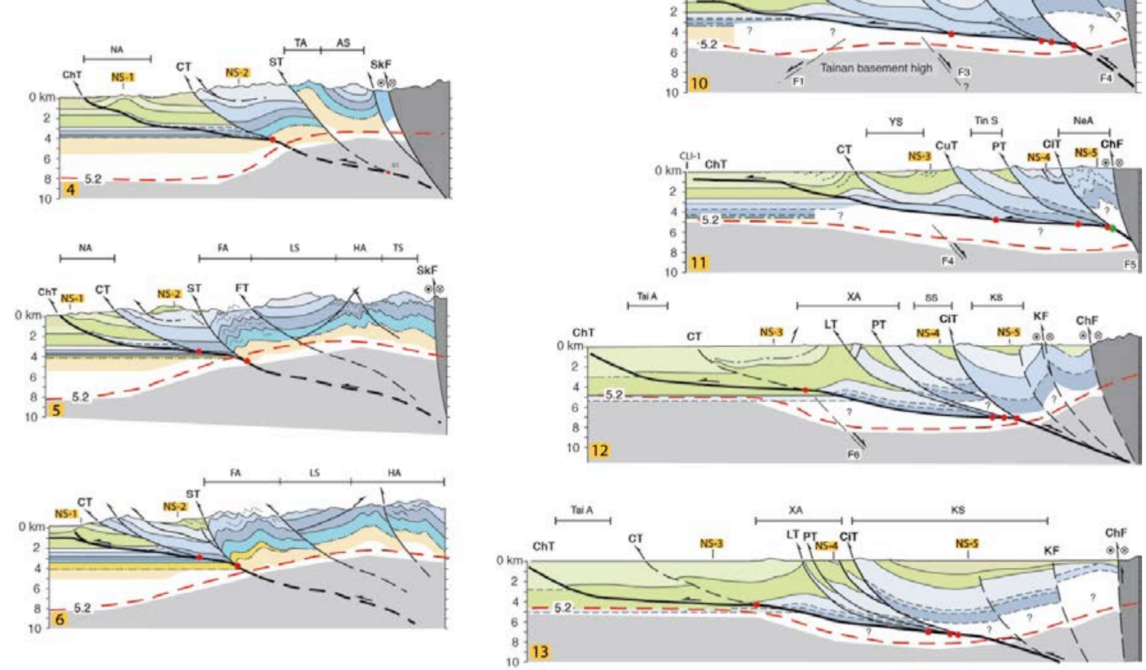
- **North-south change in structure and stratigraphy from the shelf to the necking zone**
- **Inversion of Eocene basin in the Hsuehshan Range**
- **Changes in structure, stratigraphy and topography in the upper necking zone**
- **Alishan anticlinorium passes southward into three synclines on the lower necking zone**
- **These, in turn, change into an anticline: change in stratigraphy**
- **Thrusts take on SW strike near the shelf to slope transition**
- **Thrust system becomes buried by sy-orogenic thrust-top basins**



Along-strike changes: Cross section view



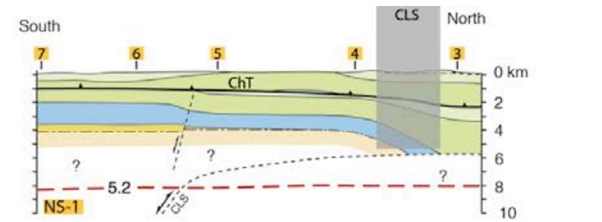


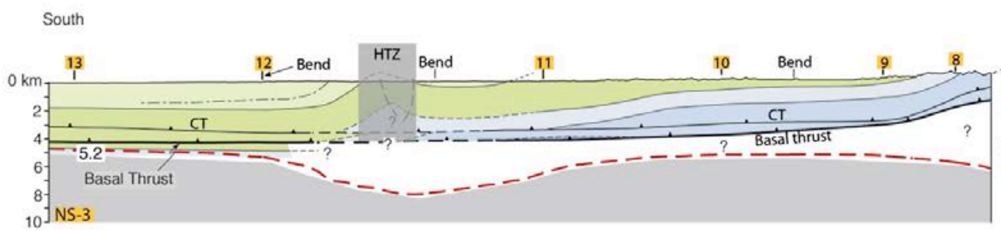


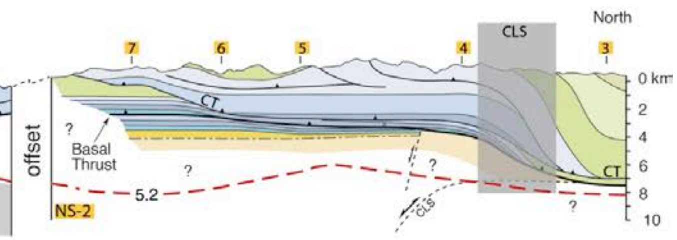
- Inversion of Eocene basin in the Hsuehshan Range
- Change in depth of basal thrust
- Alishan anticlinorium passes southward into three synclines
- Synclines change into an anticline

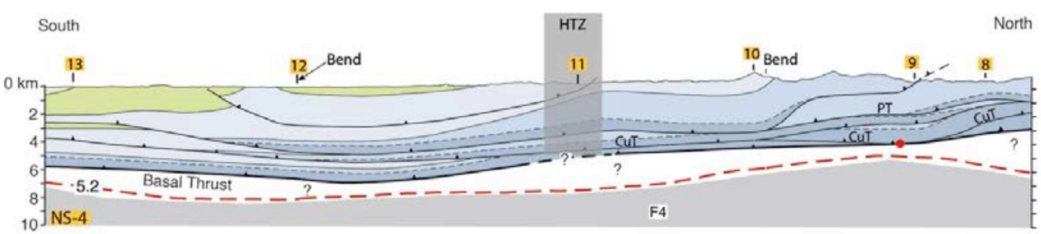
Along-strike changes: Long section view

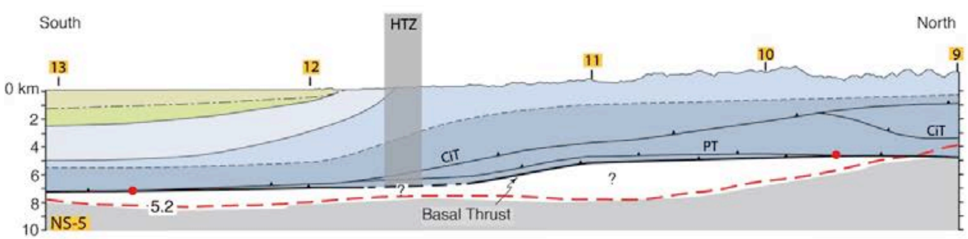
- **C. 3 km shallowing of basal thrust across upper necking zone, before deepening again southward**
- **Thickening of syn-orogenic sediments to the south**
- **Choshui and Hsinhua transverse zones imaged**

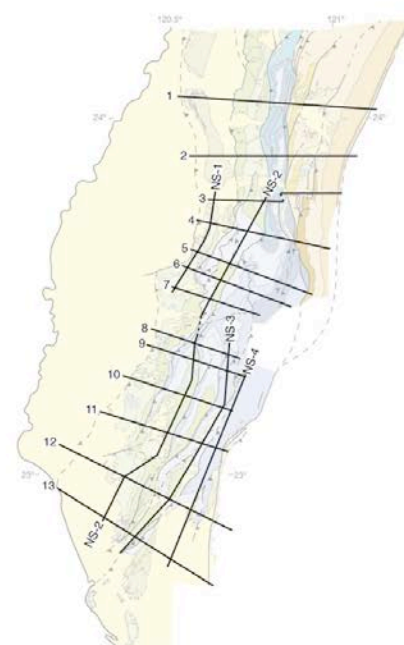


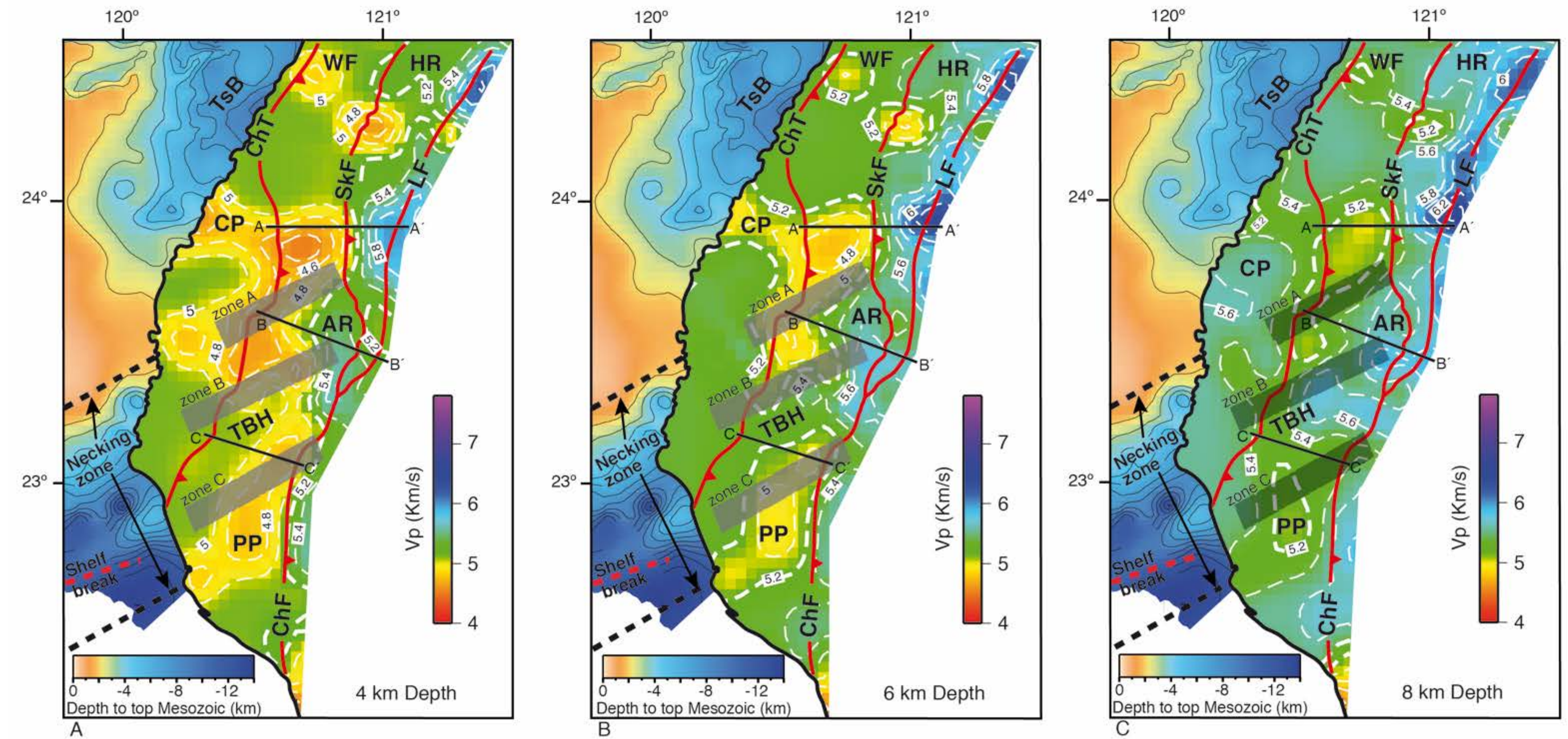




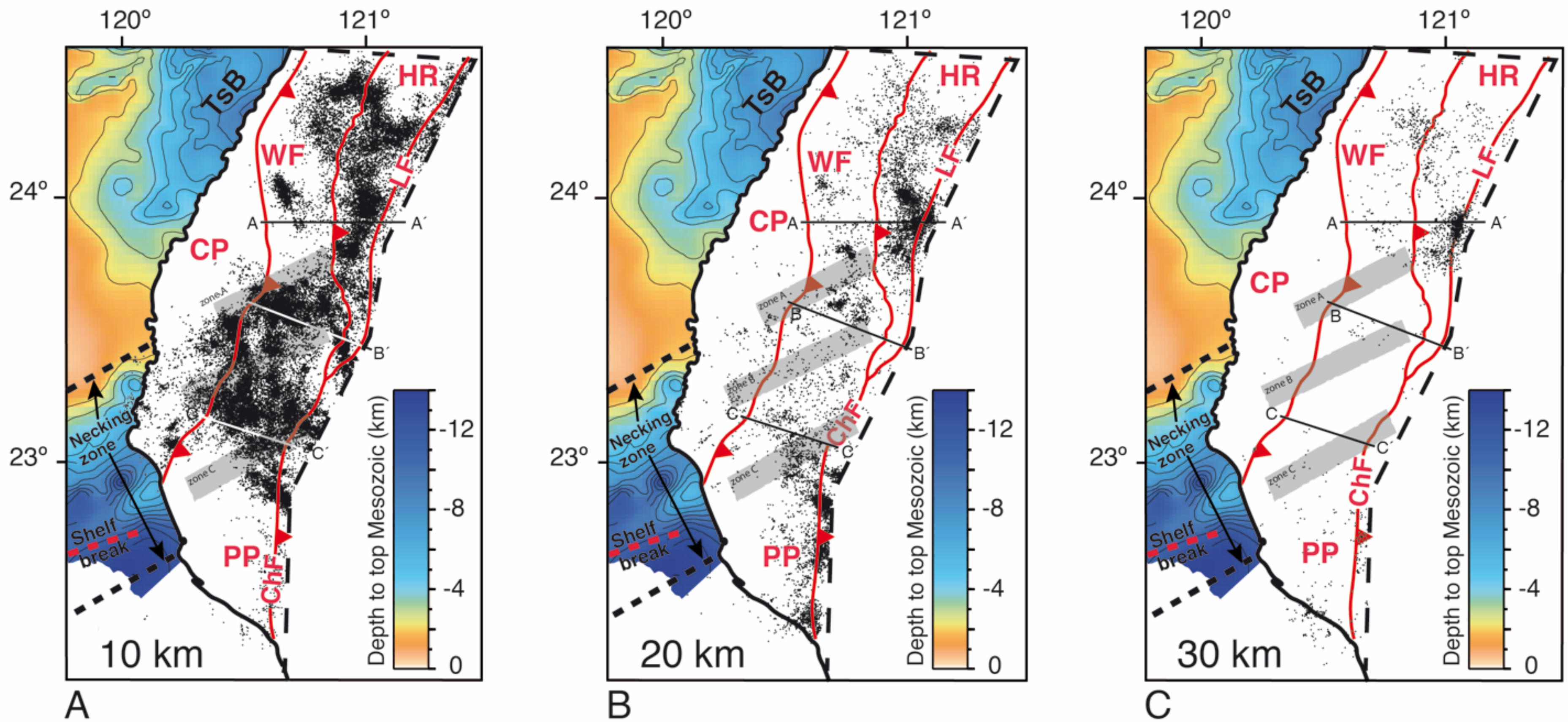








- Hsuehshan Range has a high Vp
- Zone A occurs where there are changes in strike of Vp contours, and N of a Vp high related to Alishan
- Zones B and C flank a NE-striking Vp high that we call the Tainan Basement High (Vp > 5.2 kms^{-1}) – is it a fault-bound horst on the necking zone?
- South of Zone C a NE-striking Vp low correlates with the onset of the hyperextended margin

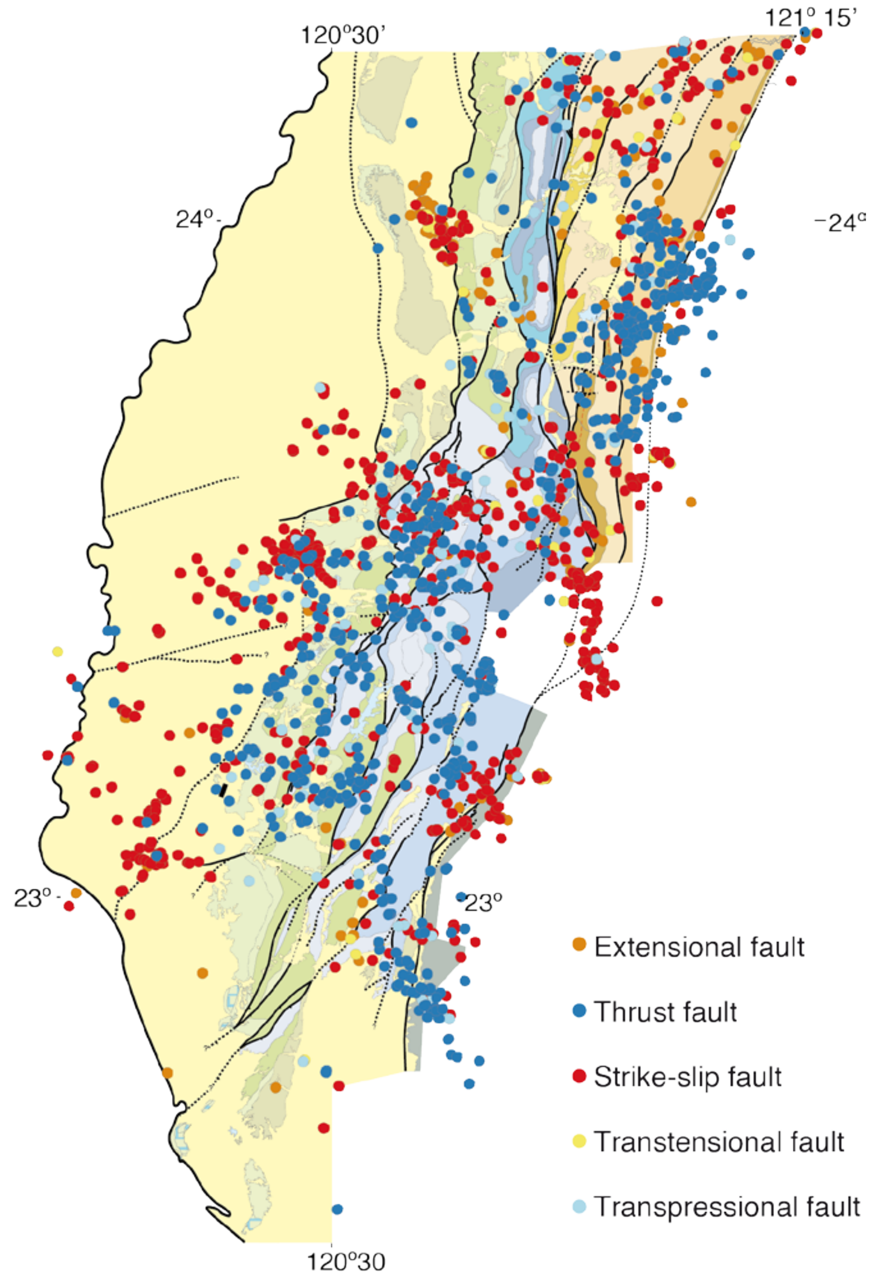


- Hsuehshan Range has high seismicity to > 30 km
- Zone A marks a NE-striking, southward increase in seismicity in the Western Foothills
- Zones B also has a crudely developed NE-striking trend in seismicity
- South of Zone C seismicity is scattered and mostly deep

What about the contemporaneous stress and strain fields?

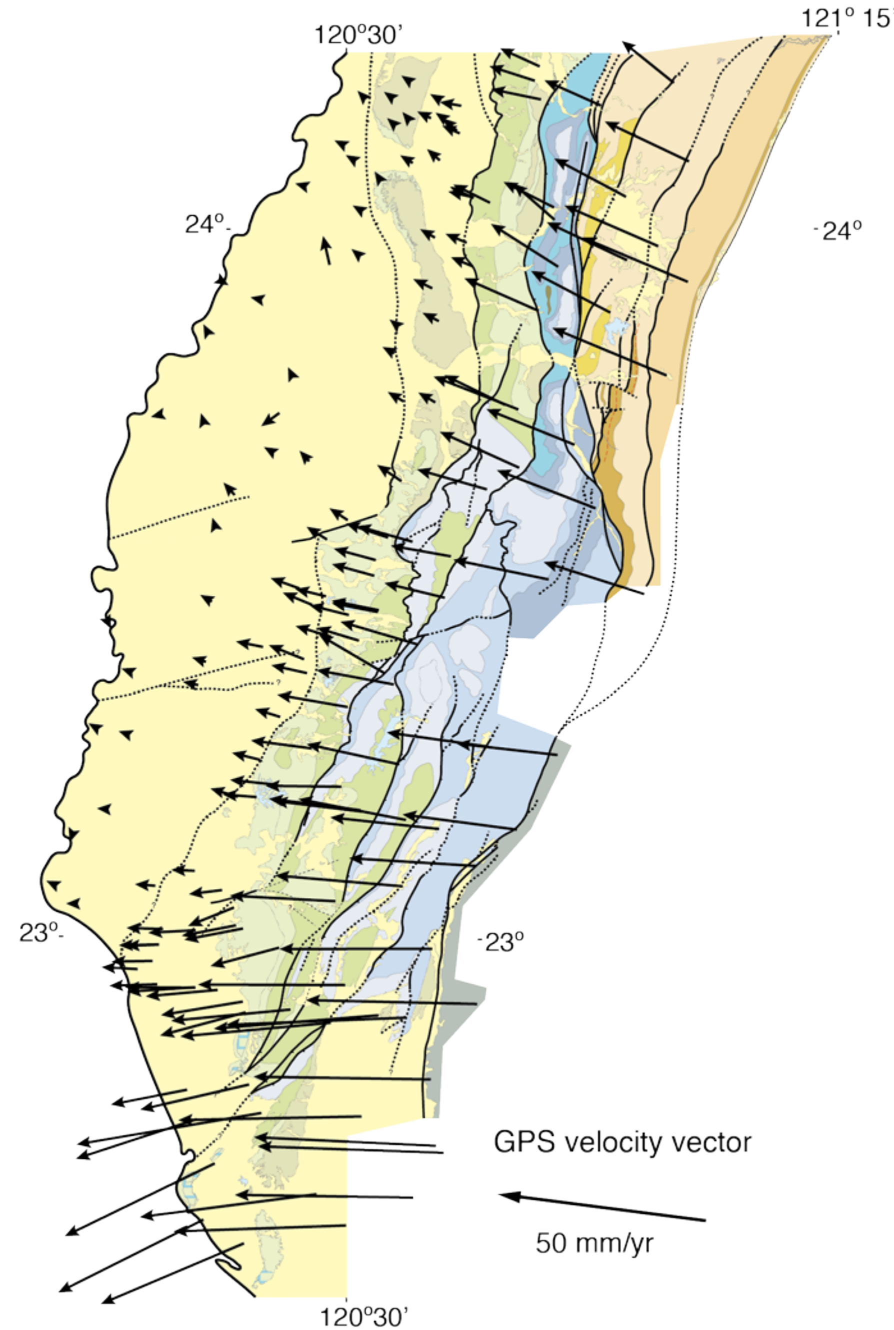
The stress field

- Focal mechanisms from Y.-M. Wu
- Use 2465 events recorded from 1994 to 2015
- Hypothesis driven clustering approach
- Minimum of 20 events in each cluster
- Three depth layers: 0- 7 km, 7 – 15 km, 15 – 40 km
- Determine the maximum compressive horizontal stress direction (S_H)
- Stress inversion methodology of Lund and Slunga (1999)

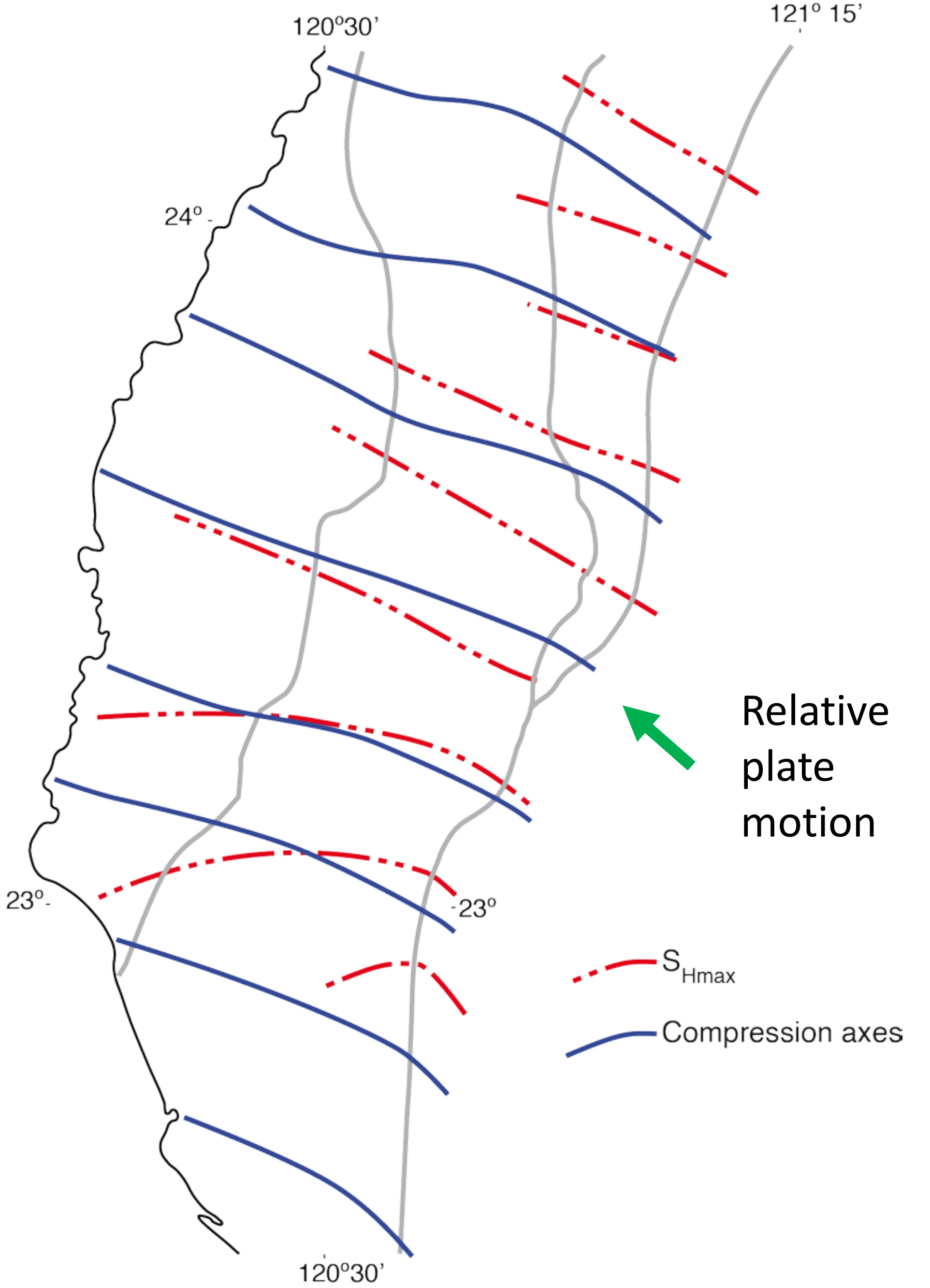


GPS data to determine the surface displacement and strain field

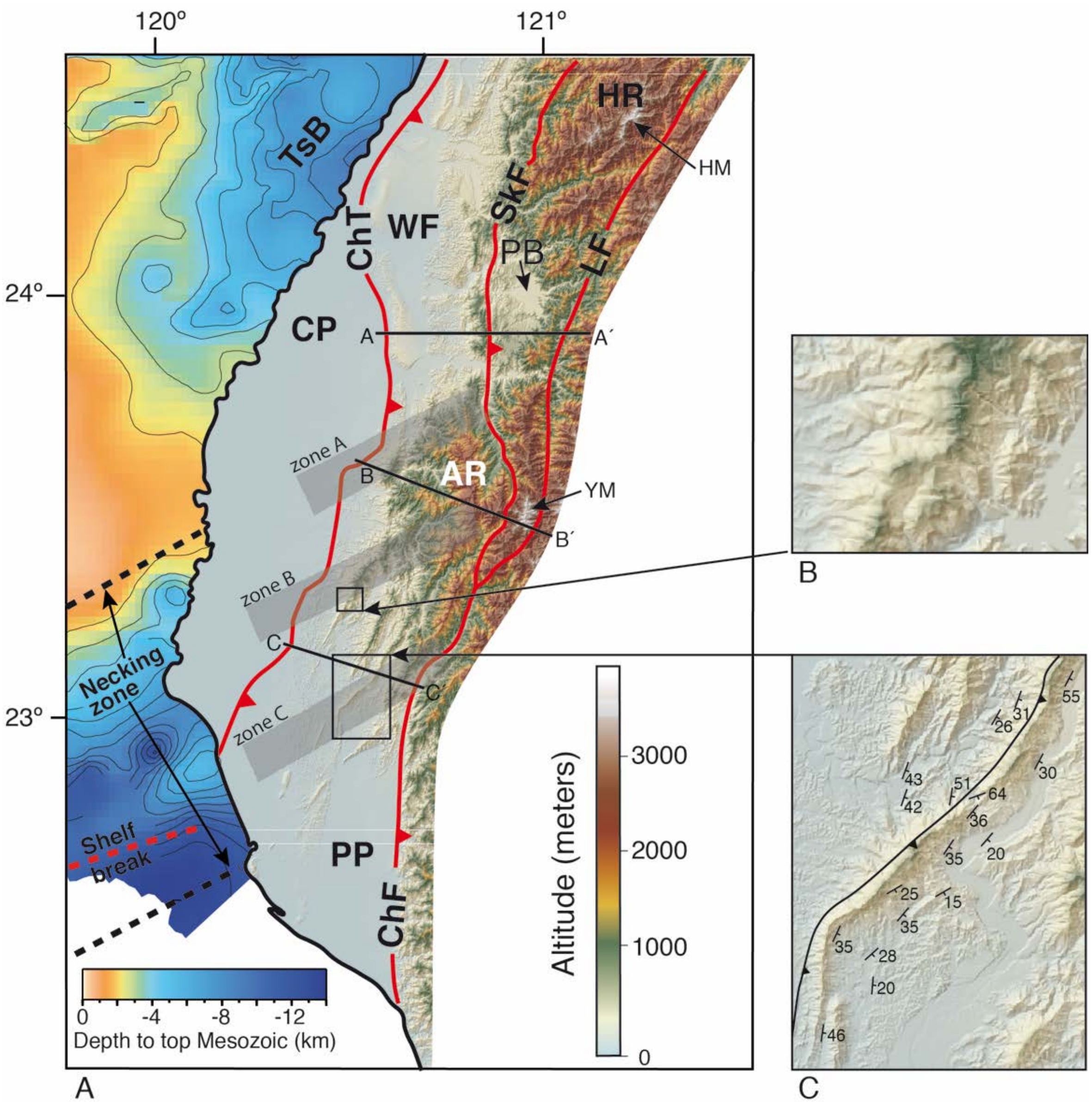
- Data from from 2005 to 2009
- Processed after Yu et al (1997)
- Strain rates calculated using SXPX software
- 5 km by 5 km grid, grid-nearest neighbour method, 10 nearest stations within radius of 35 km
- Determine the horizontal maximum compressive strain axes (ε_H)



- In the north and in the Central Range both S_H and ε_H are roughly parallel to the relative plate motion
- Southward, there if a sharp change in the direction of S_H across the Chaochou fault
- Across the necking zone (Zone A) the direction of S_H rotates from NW to SW
- ε_H shows only minor rotation southward



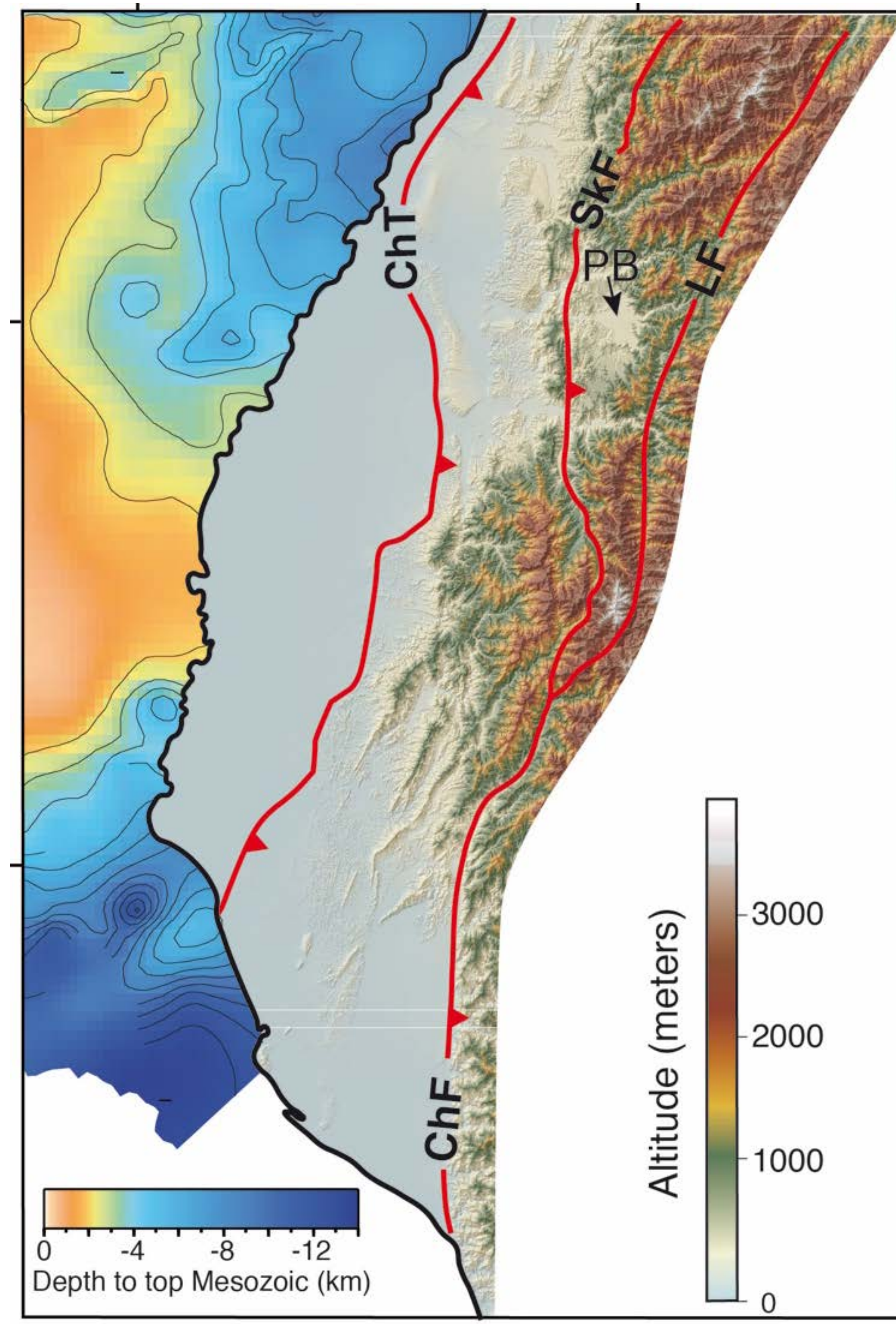
What about topography?



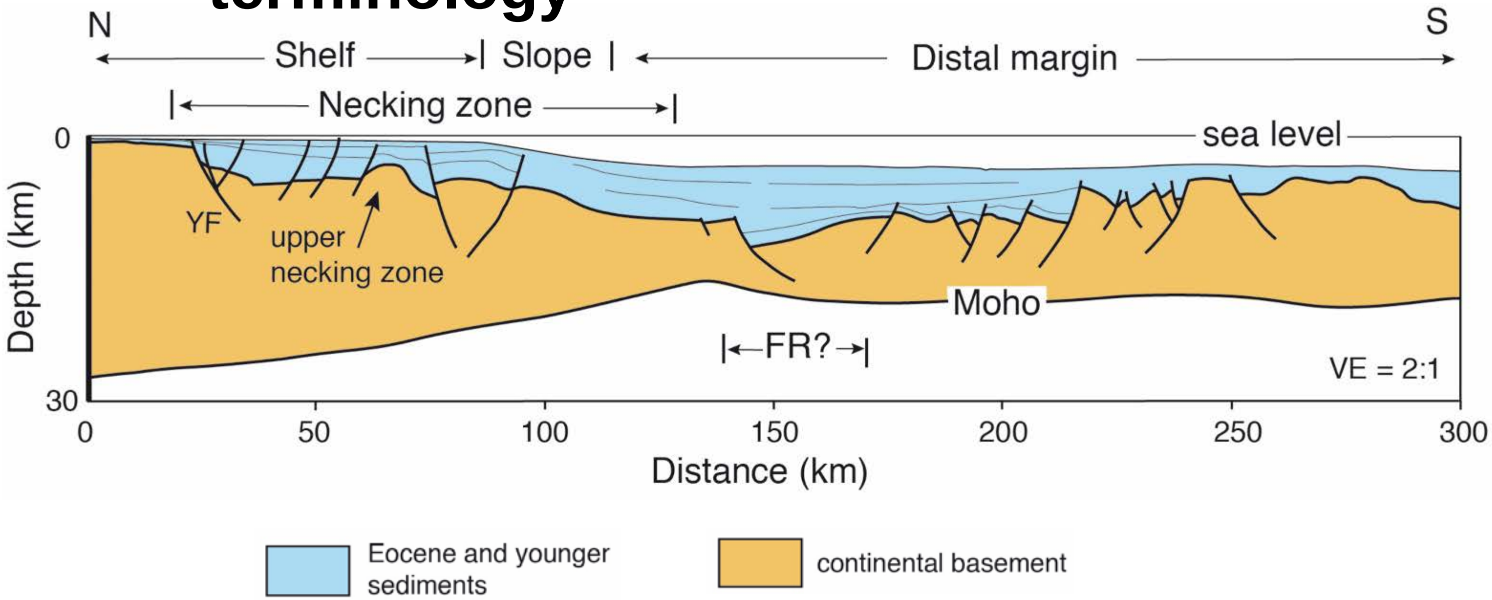
- ➢ **Shelf**
- Hsuehshan Range has highest topography in Taiwan
- ➢ **Necking zone**
- Zone A marks a NE-striking increase in topography toward Alishan. NW flank of the culmination wall.
- Zones B and C have en-echelon sigmoidal bends in the topography that coinside with along-strike changes in structure.
- ➢ **Necking zone**
- Low relief

From what we have seen so far I hope that you will agree with me that there are important along-strike changes in various aspects of the geology of the fold-and-thrust belt in western Taiwan.

But are these caused by, or influenced by, the structure and morphology of the margin?



A quick review of margin terminology

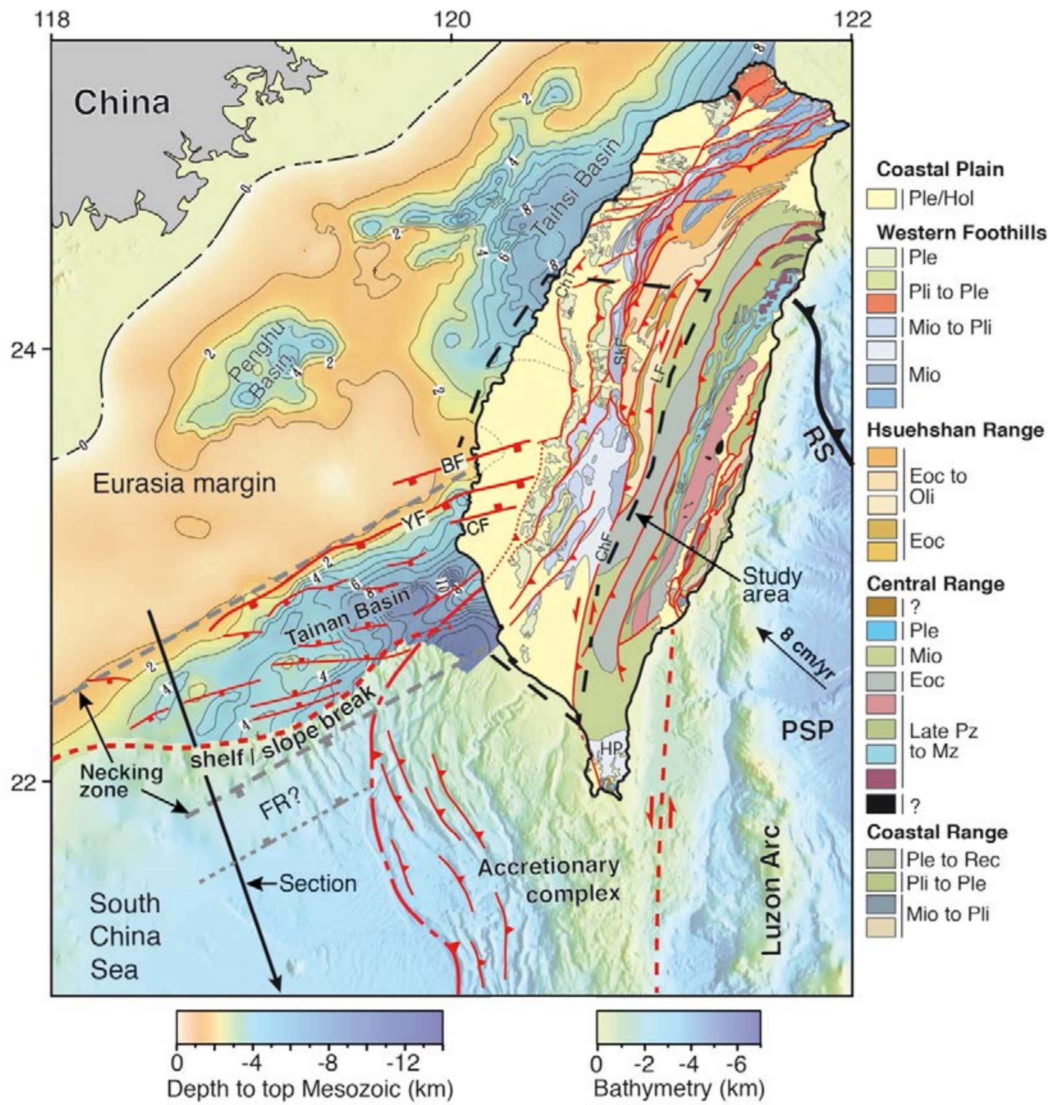


- ➢ **Morphology**
- Shelf
- Slope
- Distal margin

- ➢ **Structure**
- Necking zone
- Failed rift
- Hyperextended

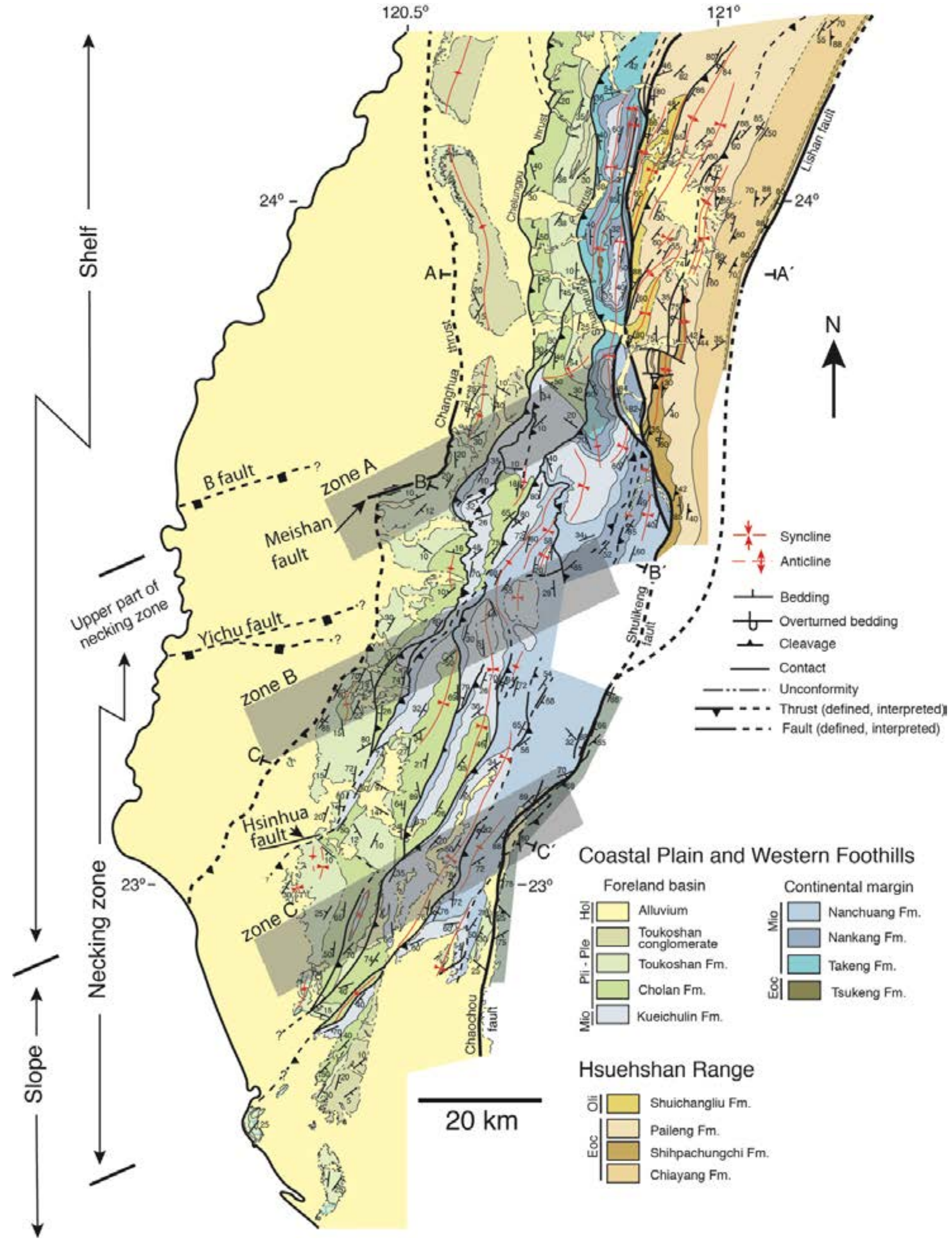
Some first-order observations

- Two fault systems: Eocene (mostly shelf) and Miocene (mostly necking zone)
- Faults mapped offshore can be traced into the Coastal Plain
- The on-land projection of the upper necking zone is along the north flank of Alishan
- The on-land projection of the shelf-slope break is where the thrust belt takes on a SW strike
- On the slope area thrust-top basins cover the thrust belt



Some second-order observations

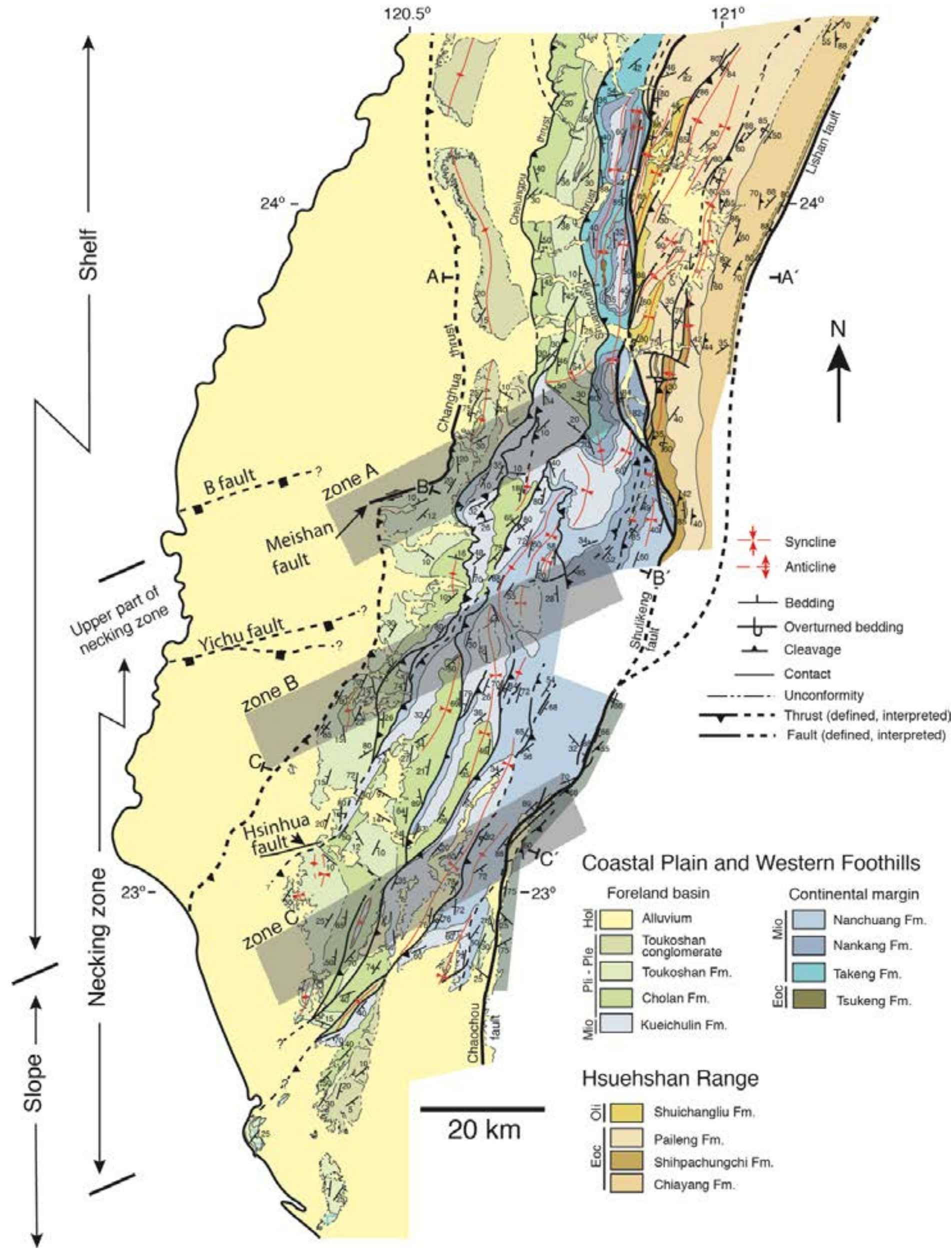
- On the shelf, inverting Eocene-age basin forming Hsuehshan Range
- Sigmoidal bending of thrusts and topography mark three distinct zones of along-strike change
    - Zone A correlates with the onset of the necking zone
    - Zone B occurs on the necking zone, along the outer part of the shelf
    - Zone C occurs near the shelf-slope transition



Summing up

Faults and basins mapped on the necking zone of the margin can be traced into the fold-and-thrust belt where they are being reactivated, supporting our hypothesis that a number of these are causing important along-strike changes in structural architecture, seismicity, stress and strain fields, and the topography of the fold-and-thrust belt in this area.

There are differences in structure, seismicity, topography depending on whether it is the shelf or necking zone areas of the margin that are involved in the deformation.



Nothing is perfect! So, what are the possible errors?

➢ The geological map

- using a chronostratigraphic correlation that links different rock units and facies together on the basis of age alone
- correlating thrusts and stratigraphic contacts along strike through difficult terrain with sparse outcrop

➢ The cross sections

- assume plane strain, a horizontal top for the Kueichulin, or the depth to the basal thrust calculations
- no original borehole data: descriptions or locations taken from publications and may contain errors.

➢ Geophysical data

- Vp of 5.2 km/s as a proxy for the top of the basement
- Resolution of Vp model (20 km by 20 km by 10 thick)
- Resolution of hypocenter locations
- Focal mechanism determination (1st motion)
- Clustering methodology

But, importantly, what don't we know?

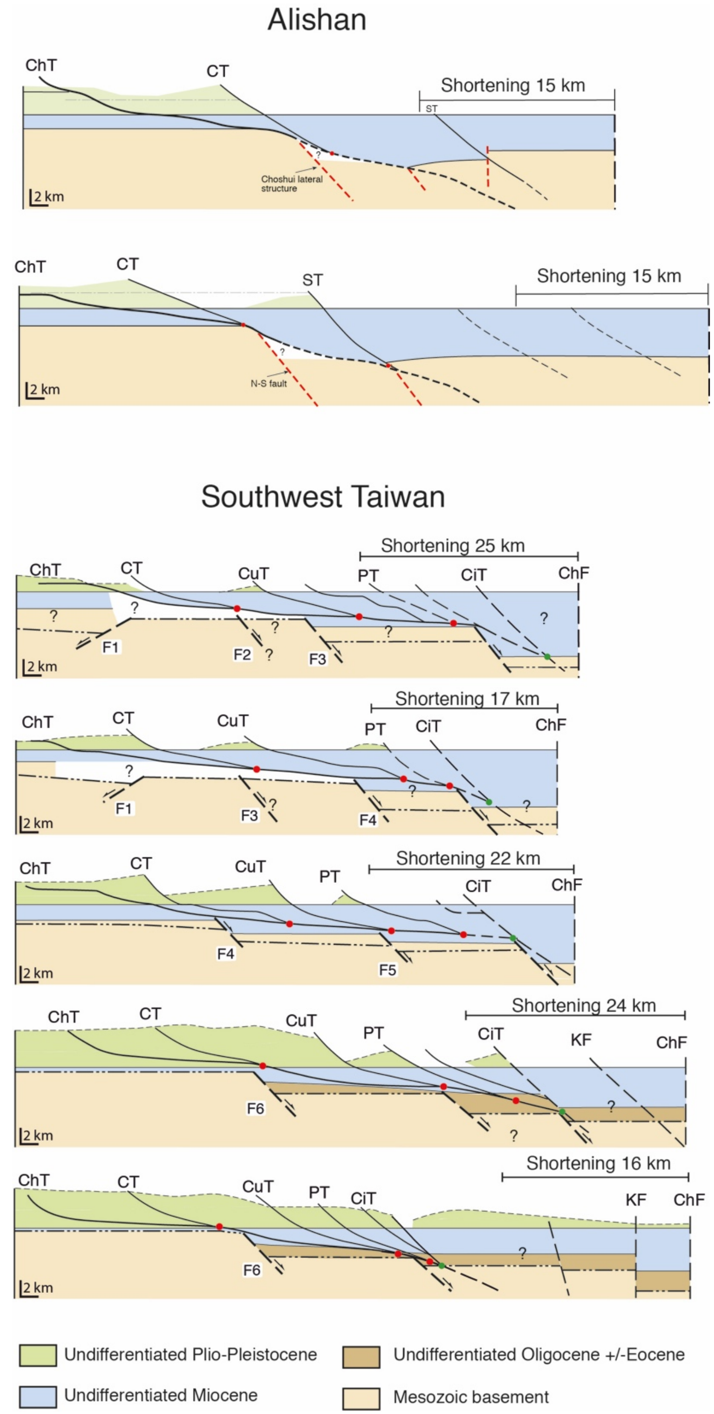
- What is the connection between the Lishan, Shuilikeng and Chaochou faults?
- How is displacement accommodated along this fault system?
- What happens to the basal thrust eastward, beneath the Central Range?
- Is the Central Range the backstop to the fold-and-thrust belt?
- Do we know the basement structure very well?
- How are the margins faults linked with those of the fold-and-thrust belt?
- Why is so much seismicity concentrated below the basal trust?

To conclude: Are we asking the right question?

Is the structure, seismicity, stress and strain fields, and topography of the south-central Taiwan fold-and-thrust belt affected by the structure and morphology of the margin?

- Yes, we think so.
- We can also add a corollary to this: there are differences in all of these elements depending on whether or not the deformation is taking place on the margins shelf or on its necking zone

Thank you for your attention


Alishan
ChT
CT
Shortening 15 km
ST
Choshui lateral structure
2 km
ChT
CT
ST
Shortening 15 km
N-S fault
2 km
Southwest Taiwan
Shortening 25 km
ChT
CT
CuT
PT
CiT
ChF
F1
F2
F3
2 km
Shortening 17 km
ChT
CT
CuT
PT
CiT
ChF
F1
F3
F4
2 km
Shortening 22 km
ChT
CT
CuT
PT
CiT
ChF
F4
F5
2 km
Shortening 24 km
ChT
CT
CuT
PT
CiT
KF
ChF
F6
2 km
Shortening 16 km
ChT
CT
CuT
PT
CiT
KF
ChF
F6
2 km
Undifferentiated Plio-Pleistocene
Undifferentiated Miocene
Undifferentiated Oligocene +/-Eocene
Mesozoic basement