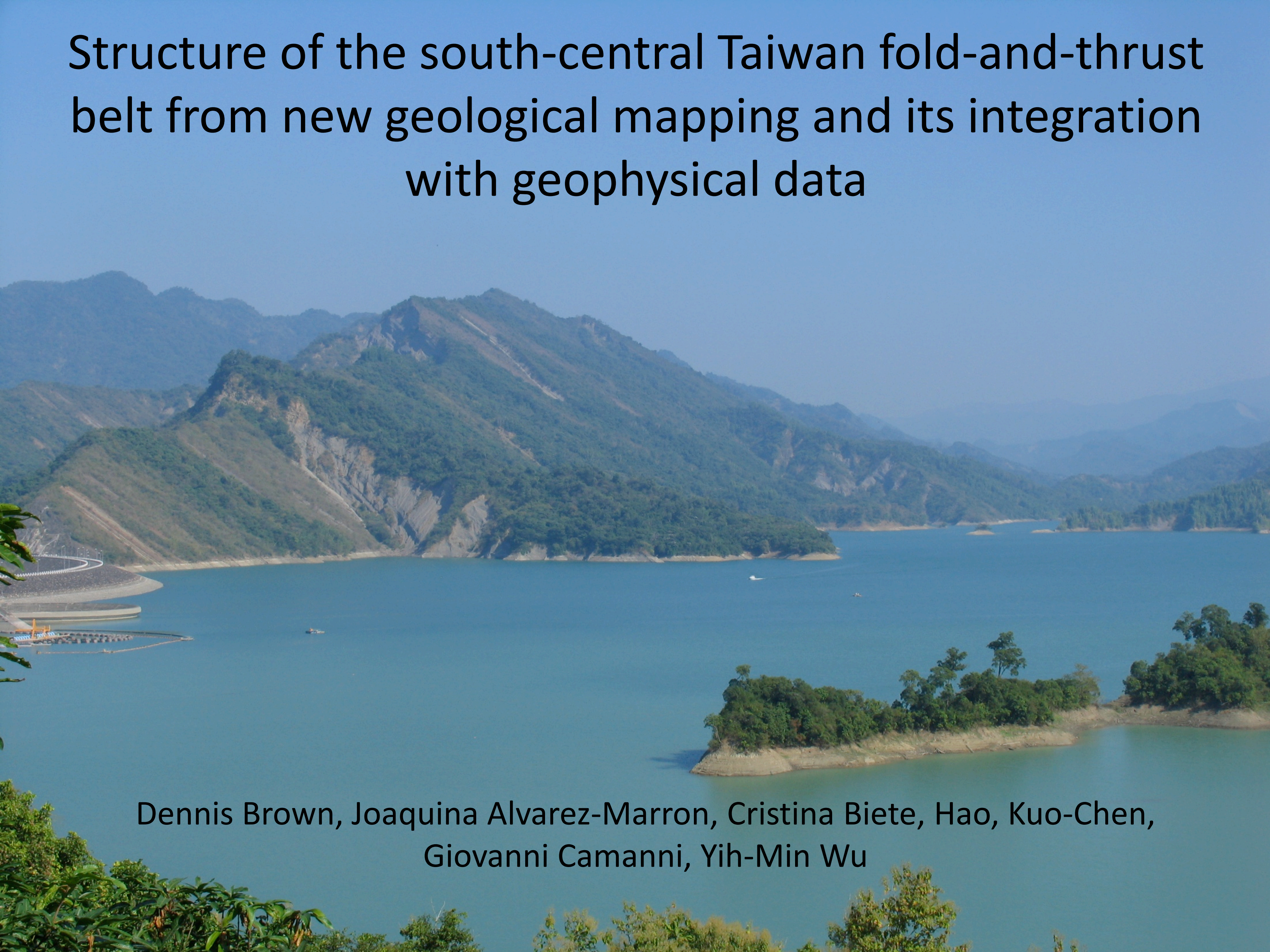
Structure of the south-central Taiwan fold-and-thrust belt from new geological mapping and its integration with geophysical data

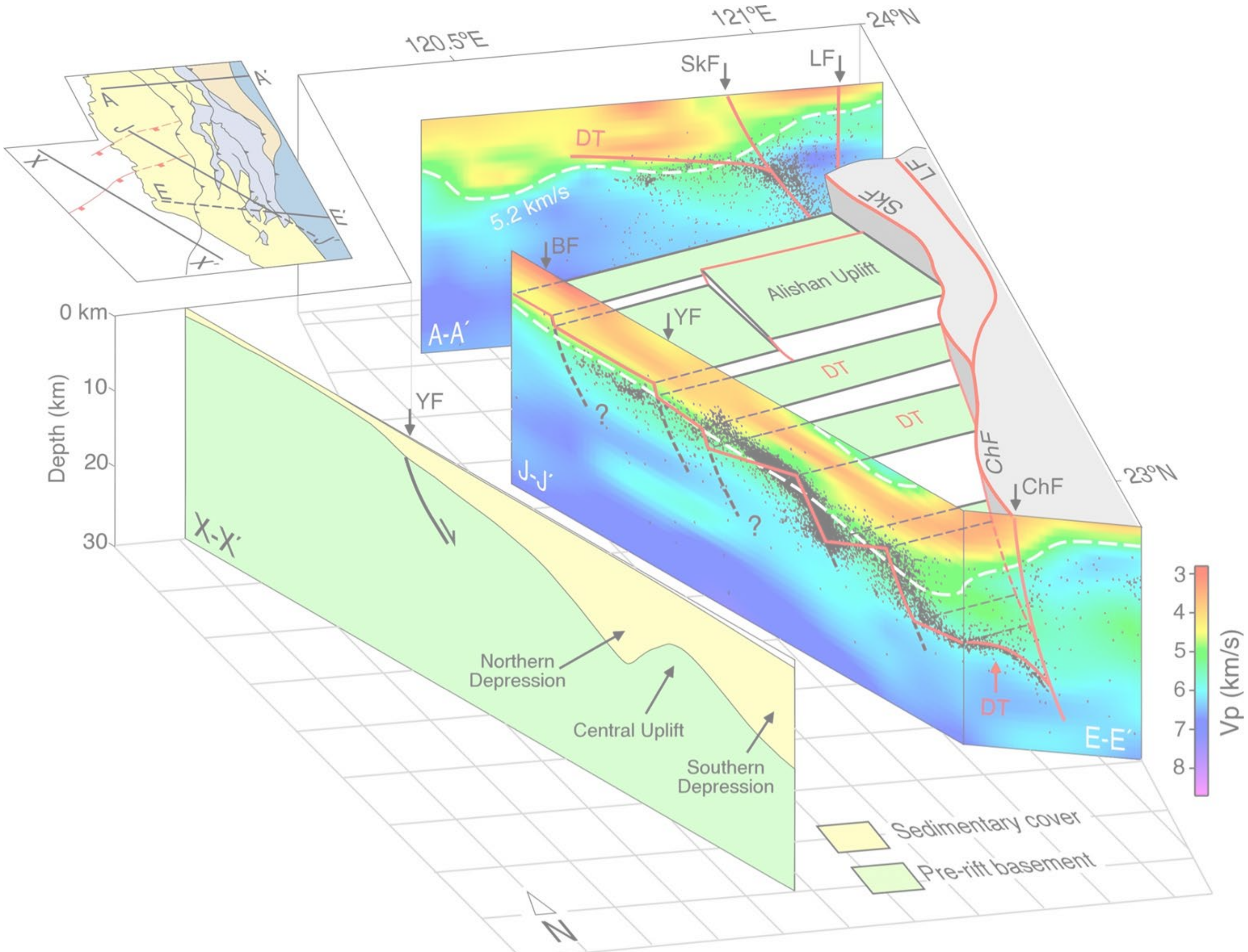


Dennis Brown, Joaquina Alvarez-Marron, Cristina Biete, Hao, Kuo-Chen,
Giovanni Camanni, Yih-Min Wu

Far better an approximate answer to the right question, which is often vague, than the exact answer to the wrong question, which can always be made precise.

John Tukey

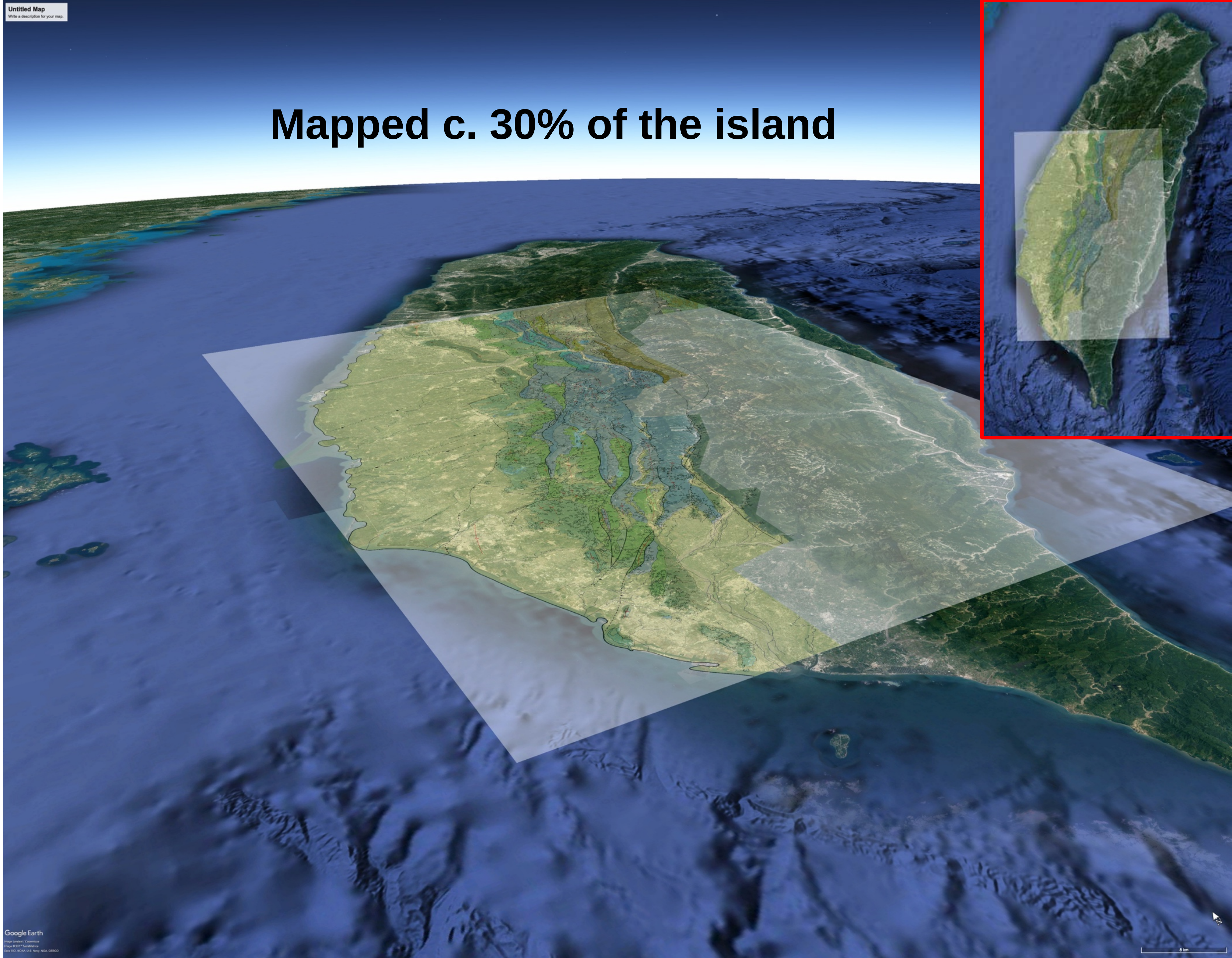
Question: Is the structure, seismicity and topography of the western Taiwan fold-and-thrust belt being affected by the structure and morphology of the margin?



Geological database

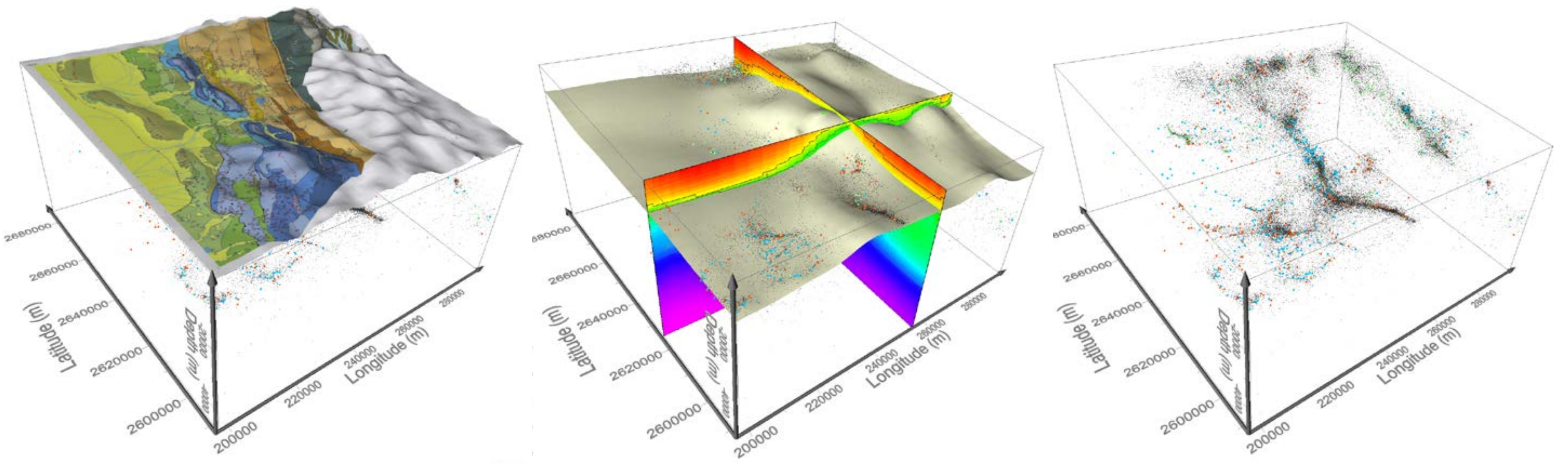
- 11 field campaigns: c. 3 person years of mapping
- Mapping done at 1:50,000 and 1:25,000 scales
- C. 3000 data points
- > 6000 structural data

Mapped c. 30% of the island



Geophysical database: The search for deep structure

- Integrate surface geology with Vp, seismicity, topography



- Vp models of Kuo-Chen et al. (2012) and Wu et al. (2008)
- c. 60,000 Hypocenters (1994 to 2015) relocated using Hypo-DD 3D
- > 2300 focal mechanisms relocated in the same way
- Horizontal stress maps
- Local, high-resolution ambient noise tomography

First, some explanations

We use chronostratigraphy and, for the sake of simplicity in describing the geology, we assign formation names. We know that the facies change from north to south.

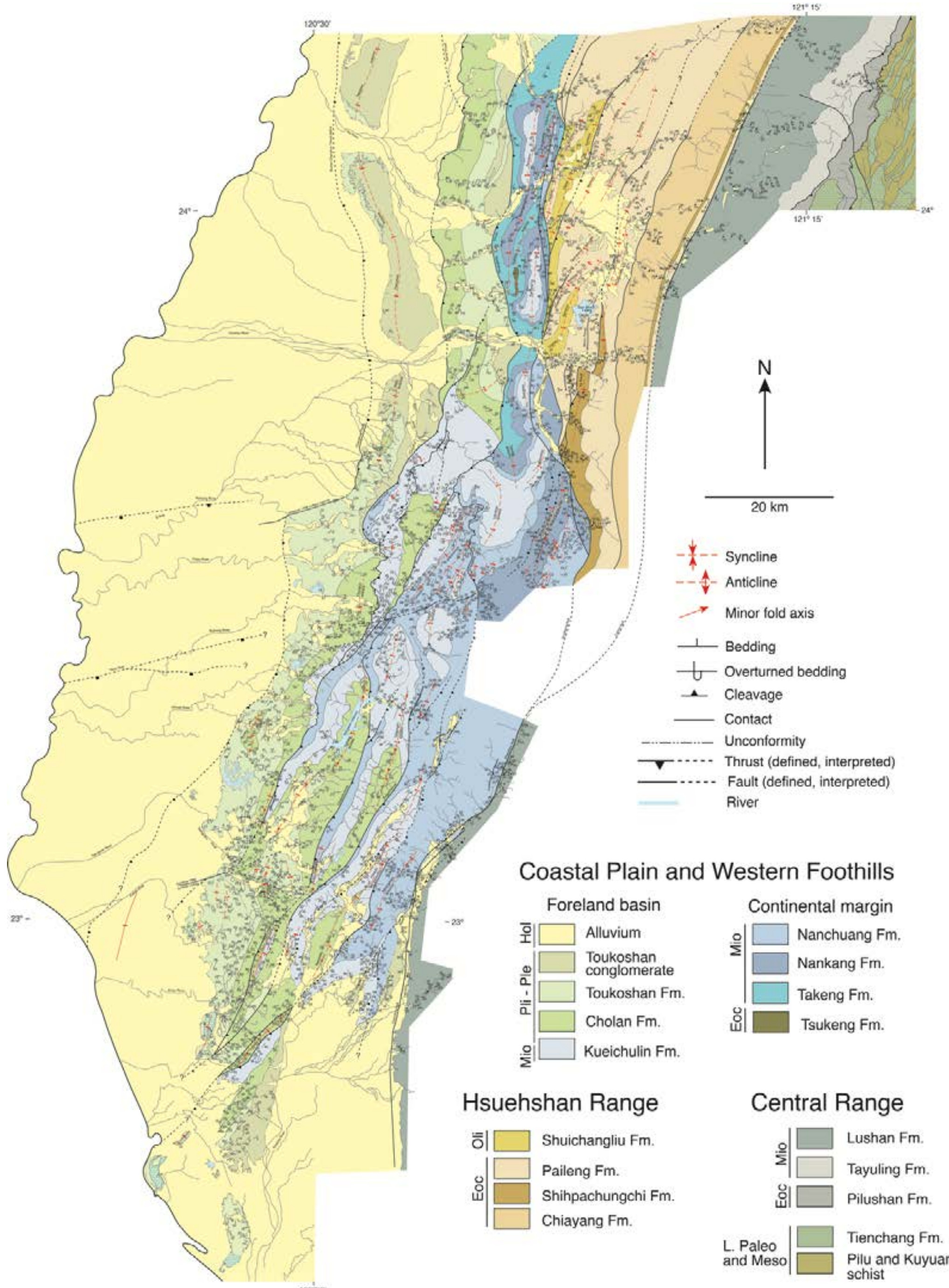
Table 1. Chronostratigraphic correlation chart used in the mapping.

		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.
	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.				

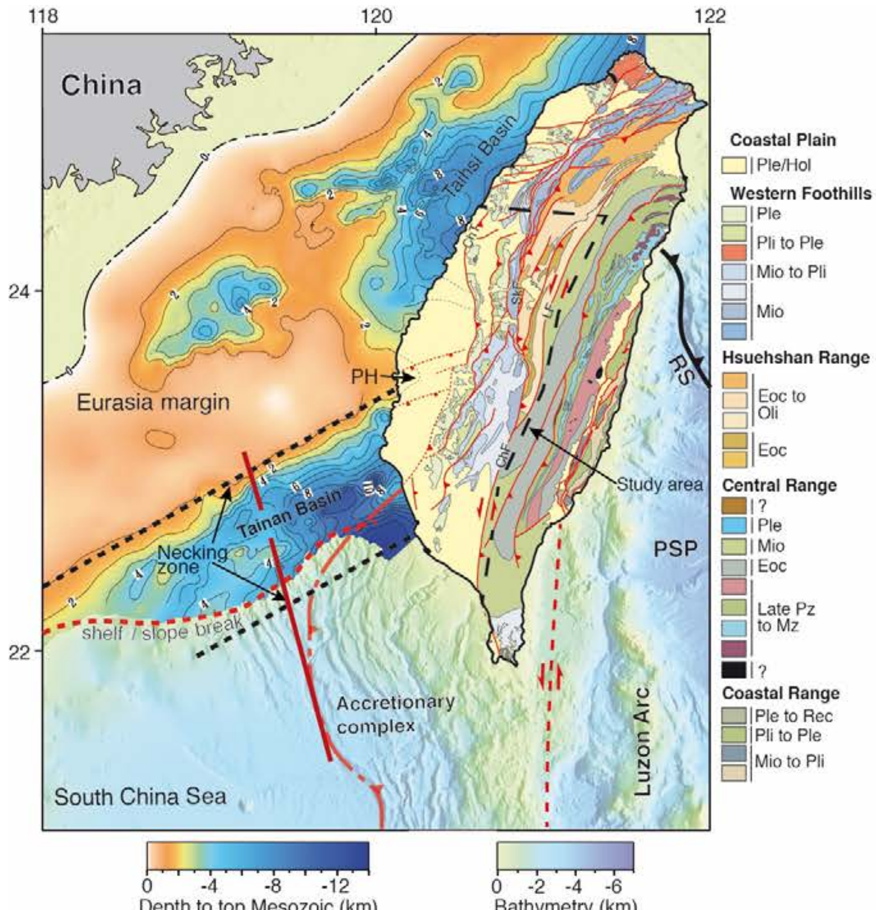
*CC = conglomerate, SS = sandstone, Sh. = shale, Fm. = formation

From Shea et al. (2003), CGS

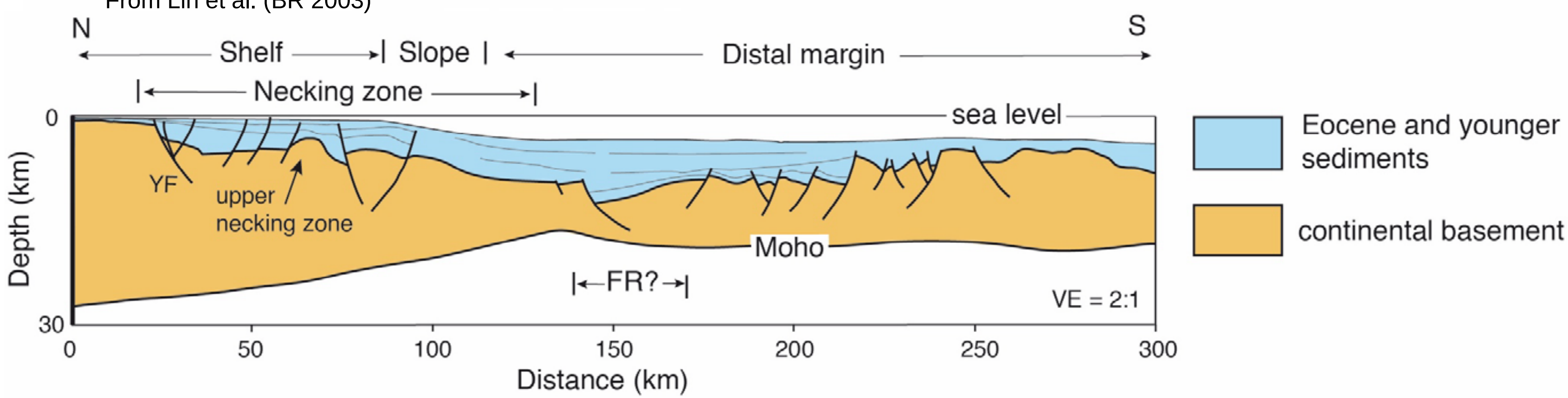
Viewing the geology with a chronostratigraphic scheme allows us to easily visualise and correlate the structure and its relative age from north to south.



Some margin terminology



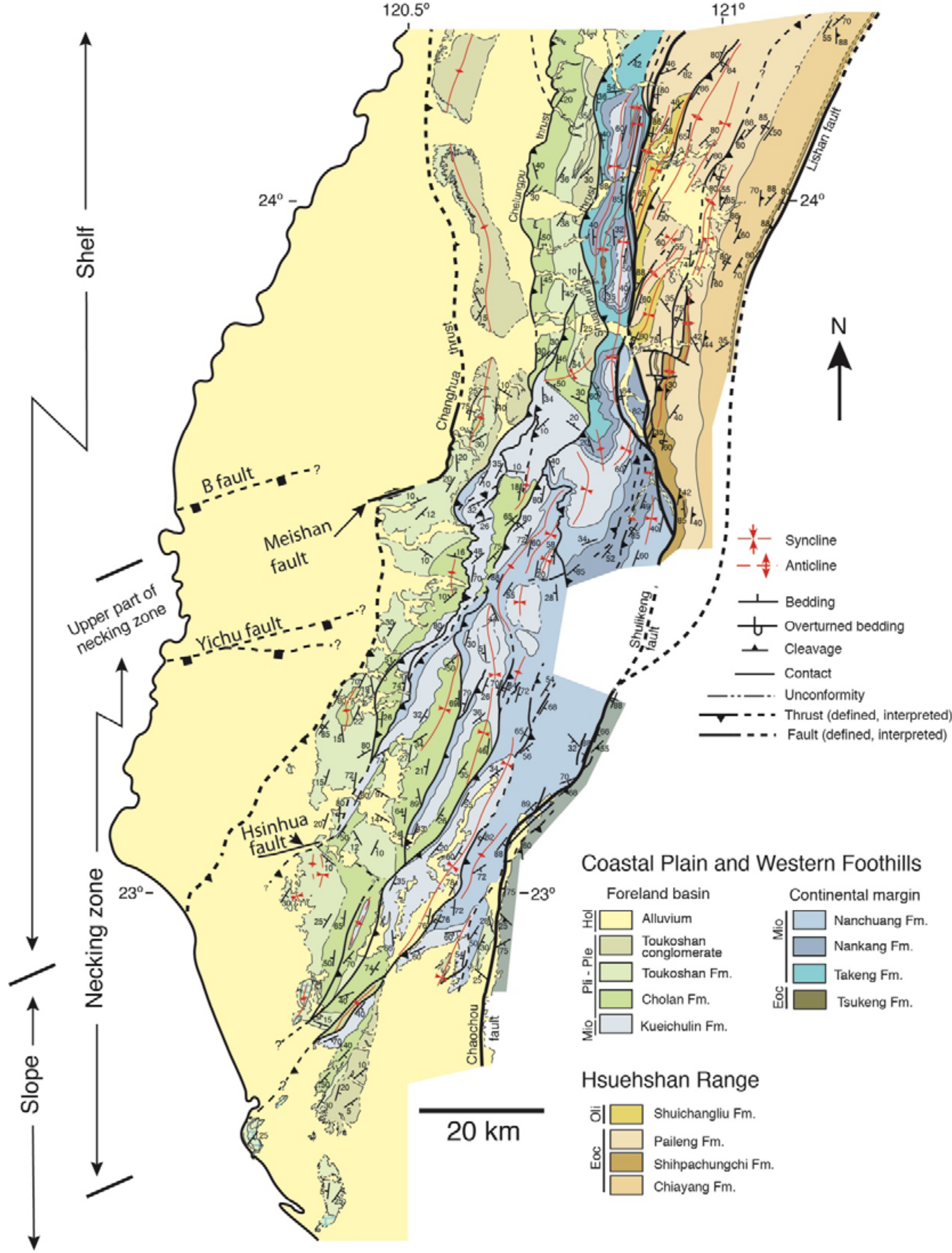
From Lin et al. (BR 2003)



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

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

How does this margin terminology apply to our map area?

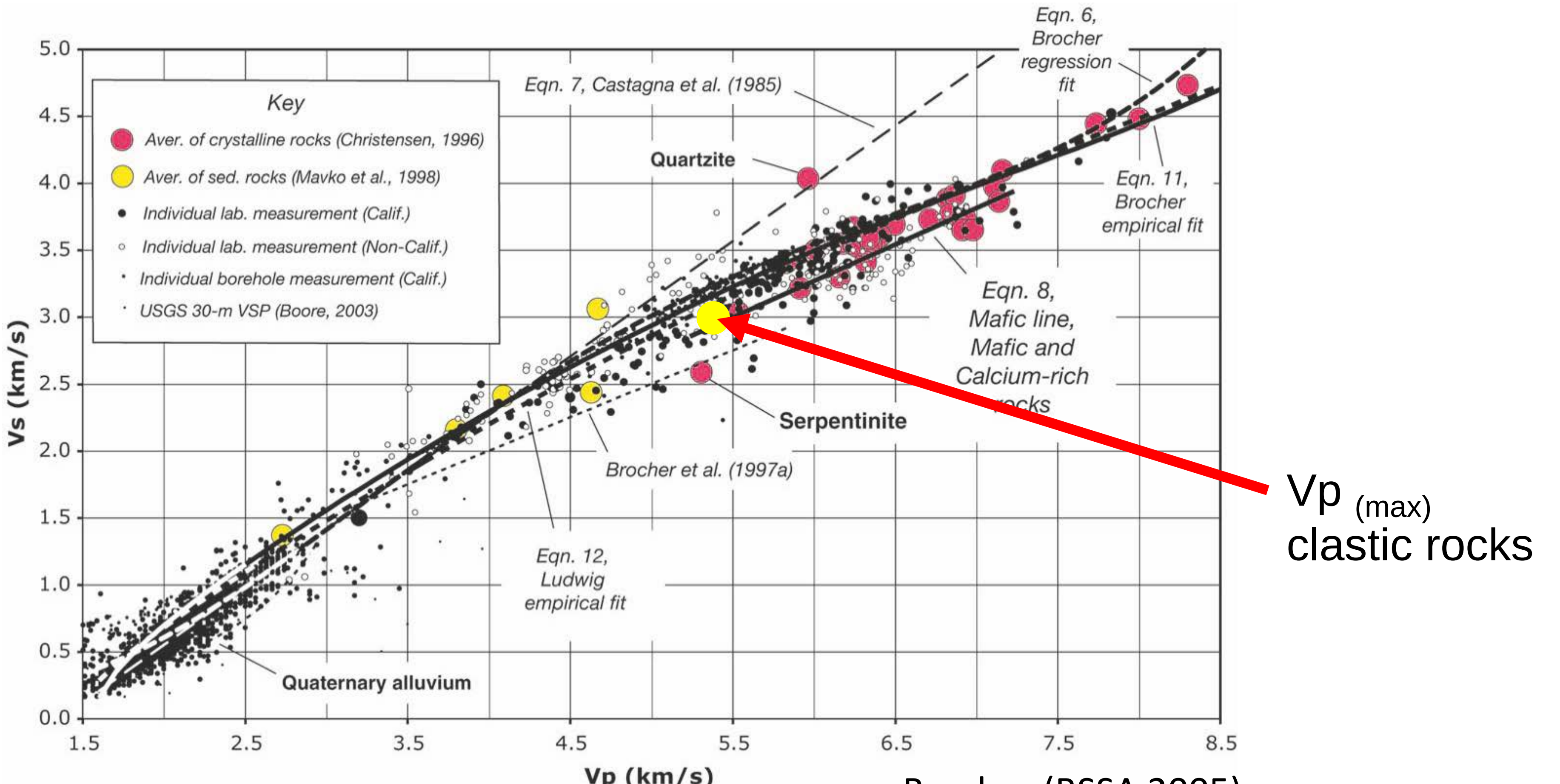


In order to interpret the structure at depth, and the influence that the margin is having on it, we need to define the term "basement", and then we need a way to find it in our data set.

- **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 geophysical proxy has to be in terms of a seismic velocity

- Test various P-wave velocities to get a first approximation.



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.

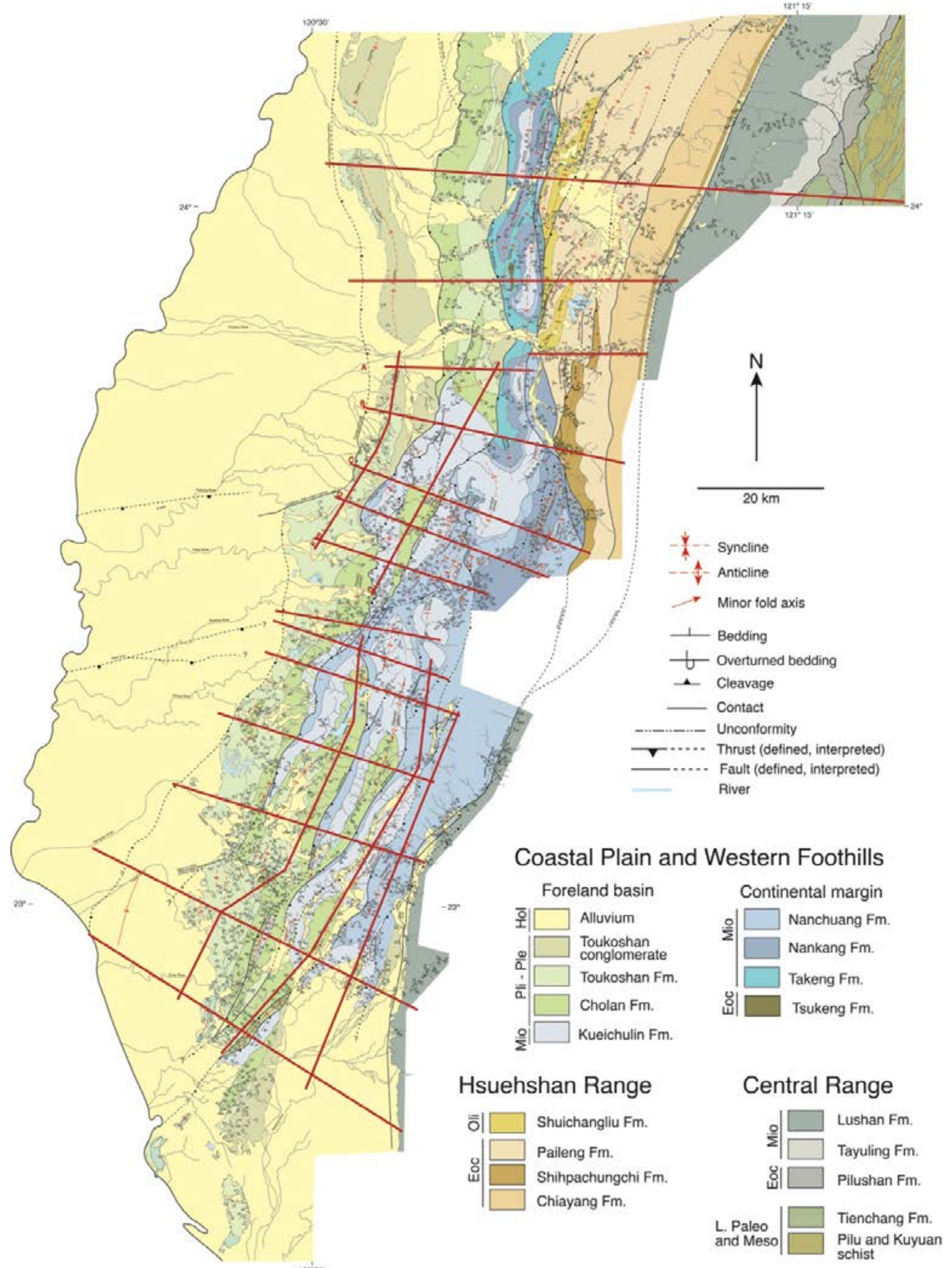
Nothing is perfect! So, what are the possible errors?

- **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

OK, let’s look at some structure!

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

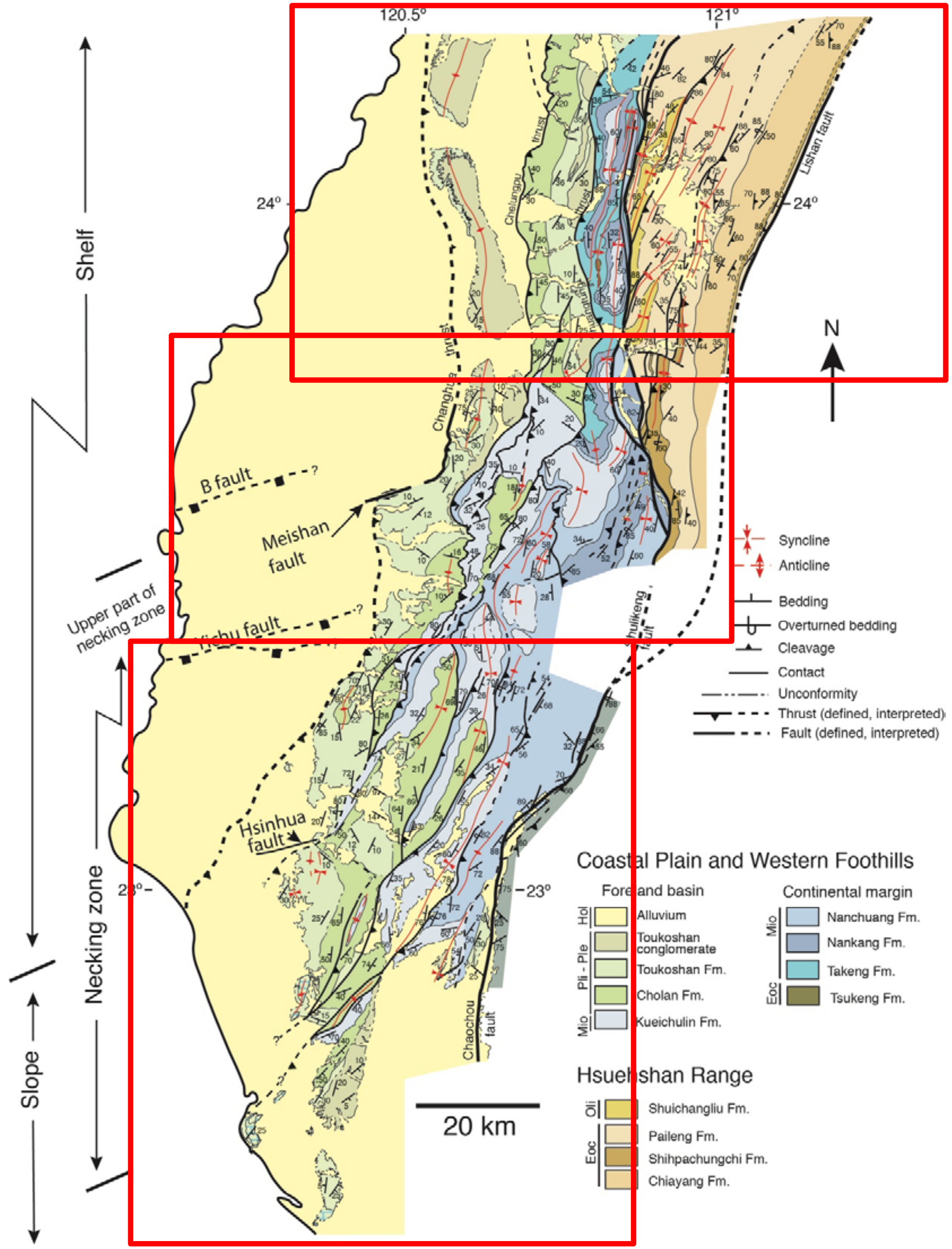
- **Done our own mapping**
- **Constructed 14 balanced and restored cross sections**
- **5 along-strike sections**
- **A map of the basal thrust**
- **Thrust branch line maps**
- **Stratigraphic cut-off maps**



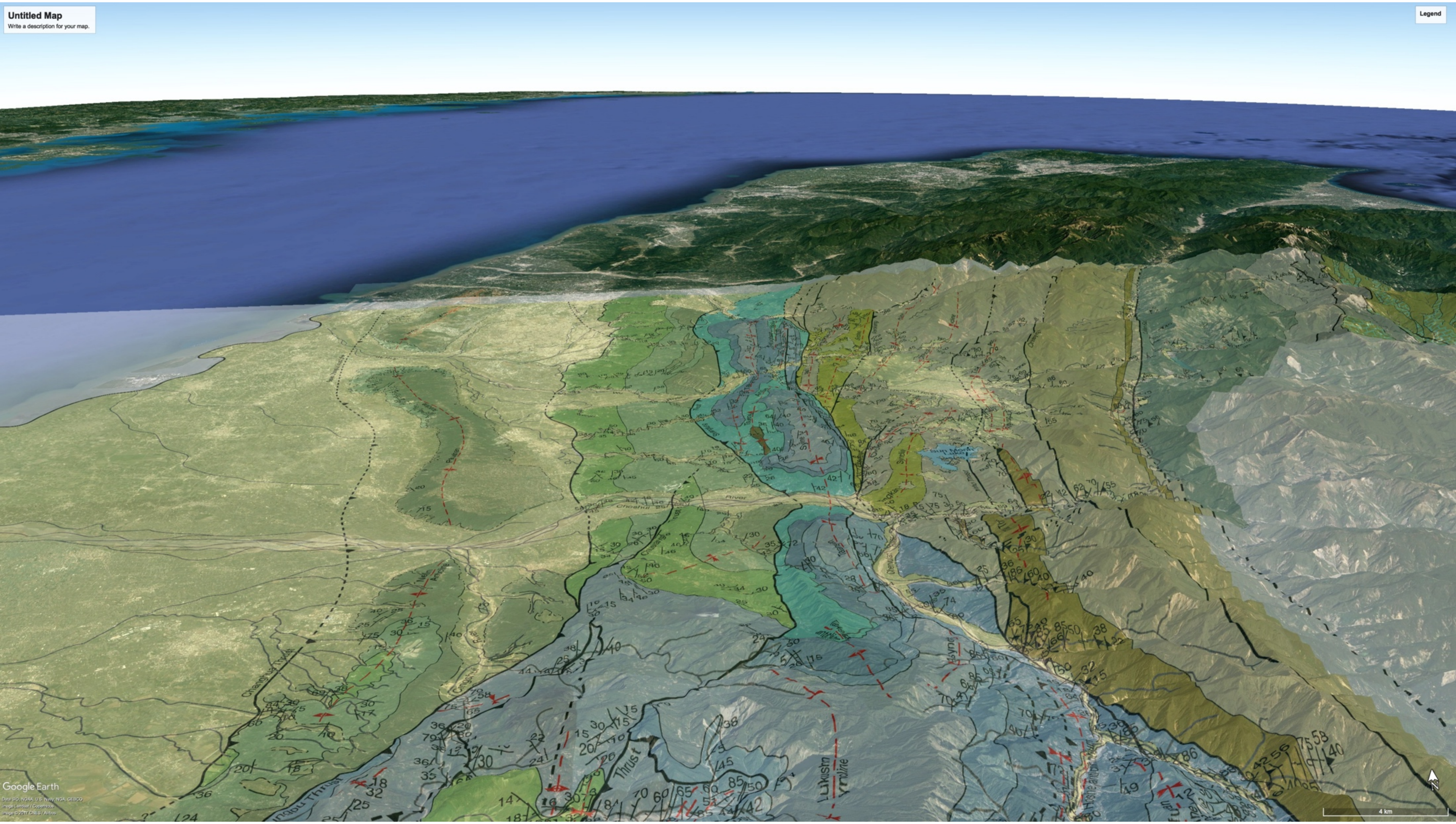
I will describe the structure from north to south in terms of:

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

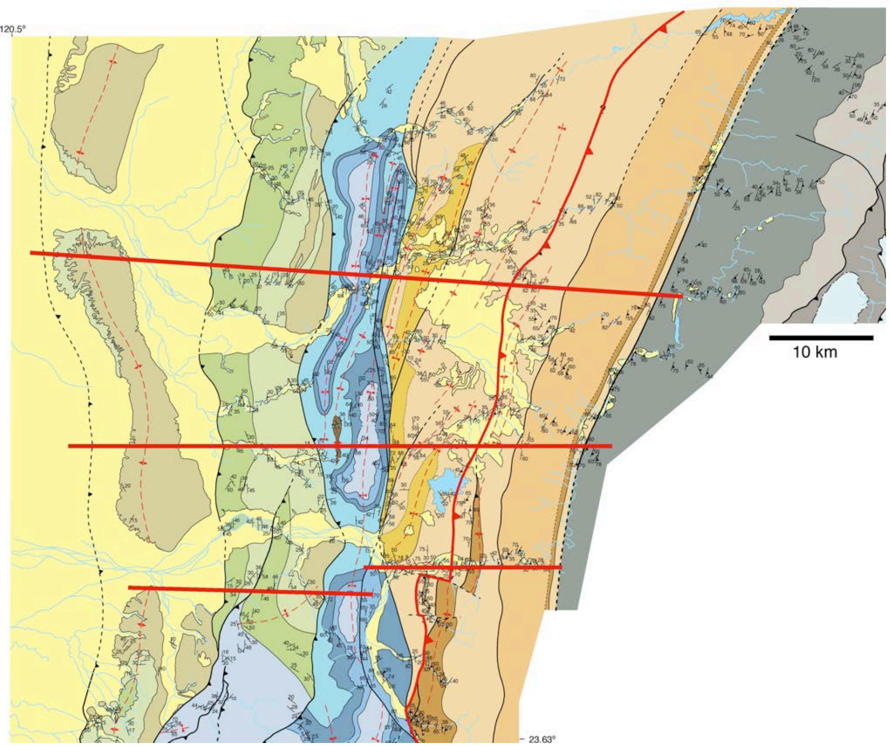
➢ **More about the reason for this approach later**

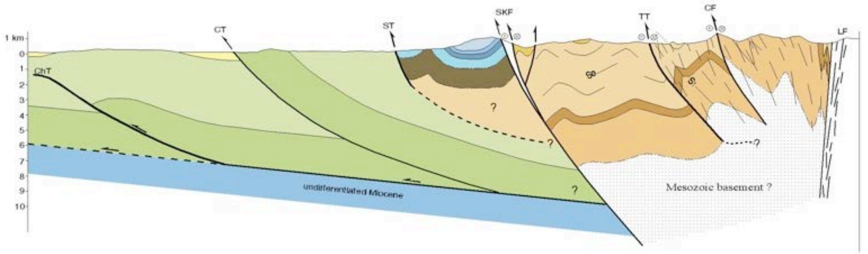


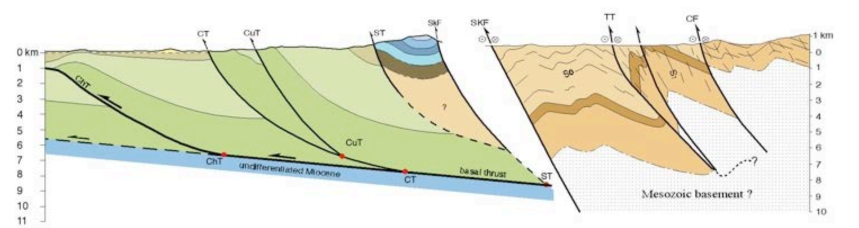
Central Taiwan: the shelf



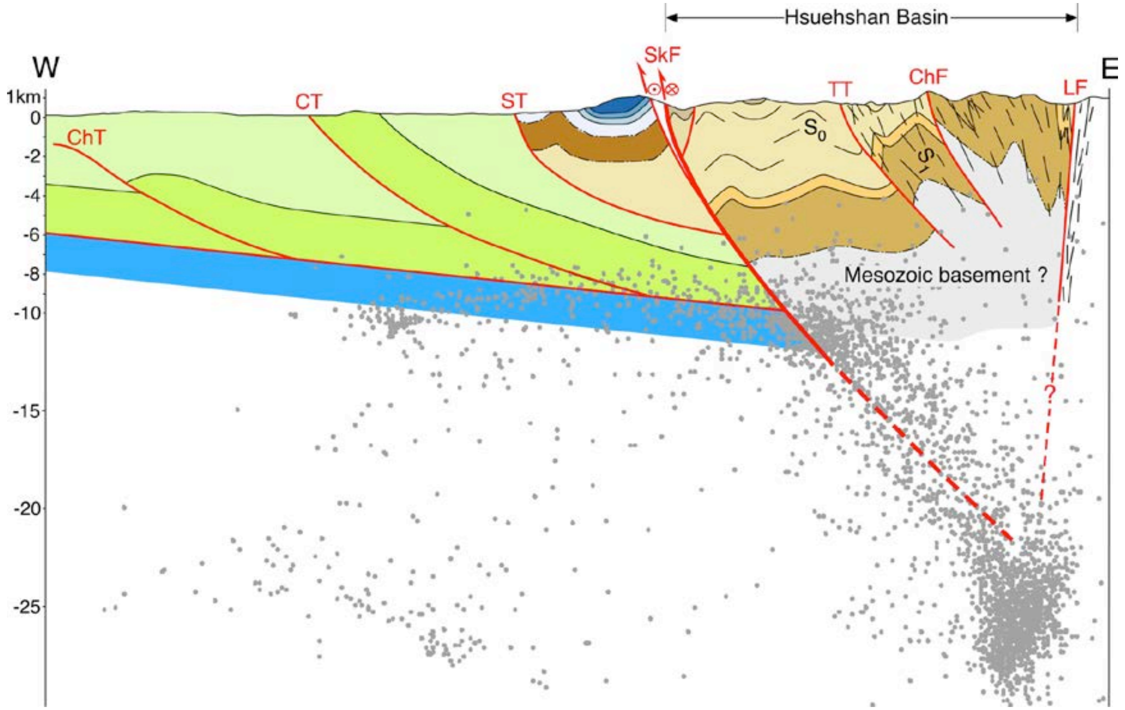
- **Imbricate thrust system in the west beneath syn-orogenic sediments**
- **Shuilikeng fault is a ramp into the middle crust**
- **Inversion of the Hsuehshan Basin (with uplift of basement rocks)**
- **Cleavage front along the Tili thrust**
- **Lishan fault (a major crustal boundary?)**
- **Shortening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



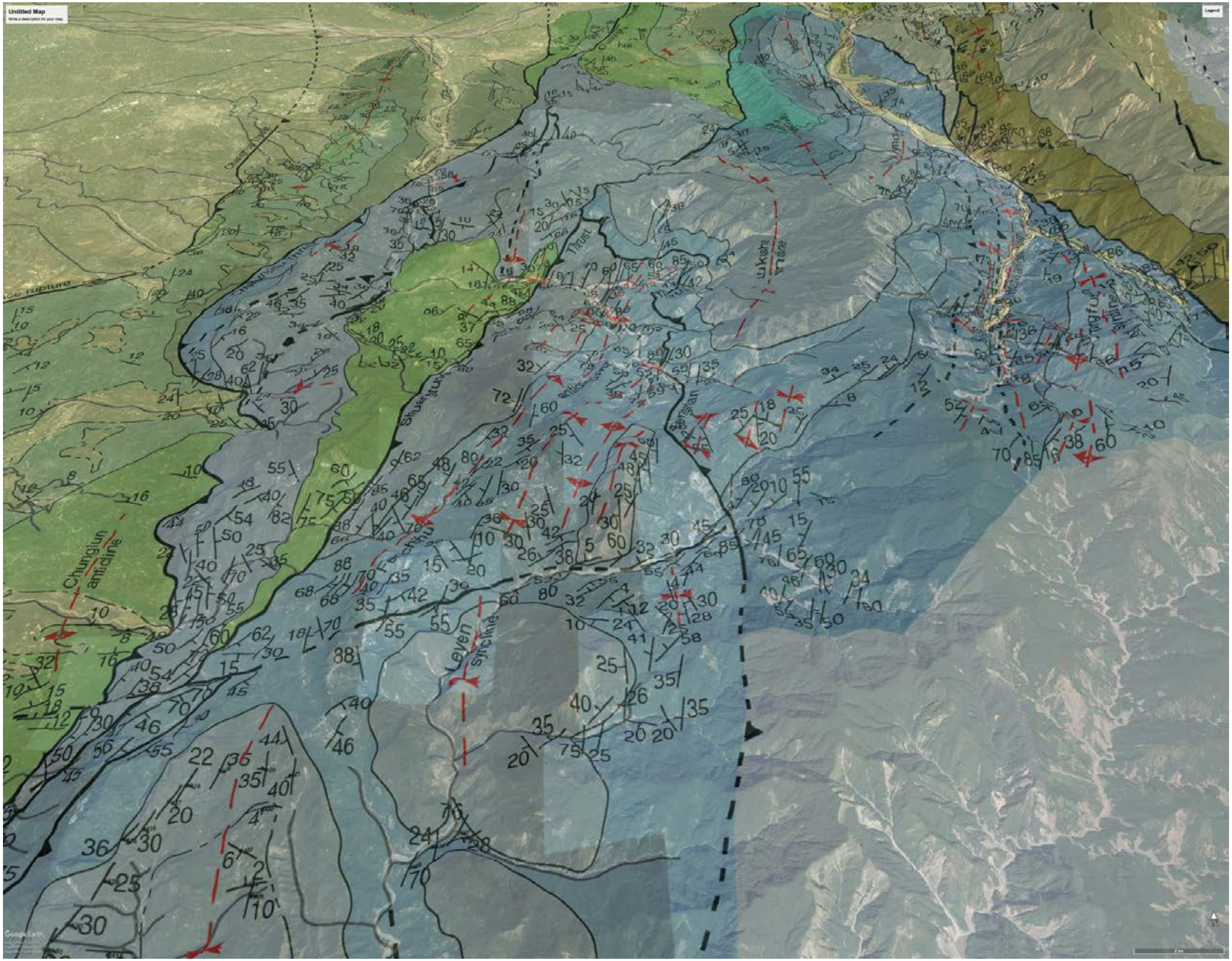




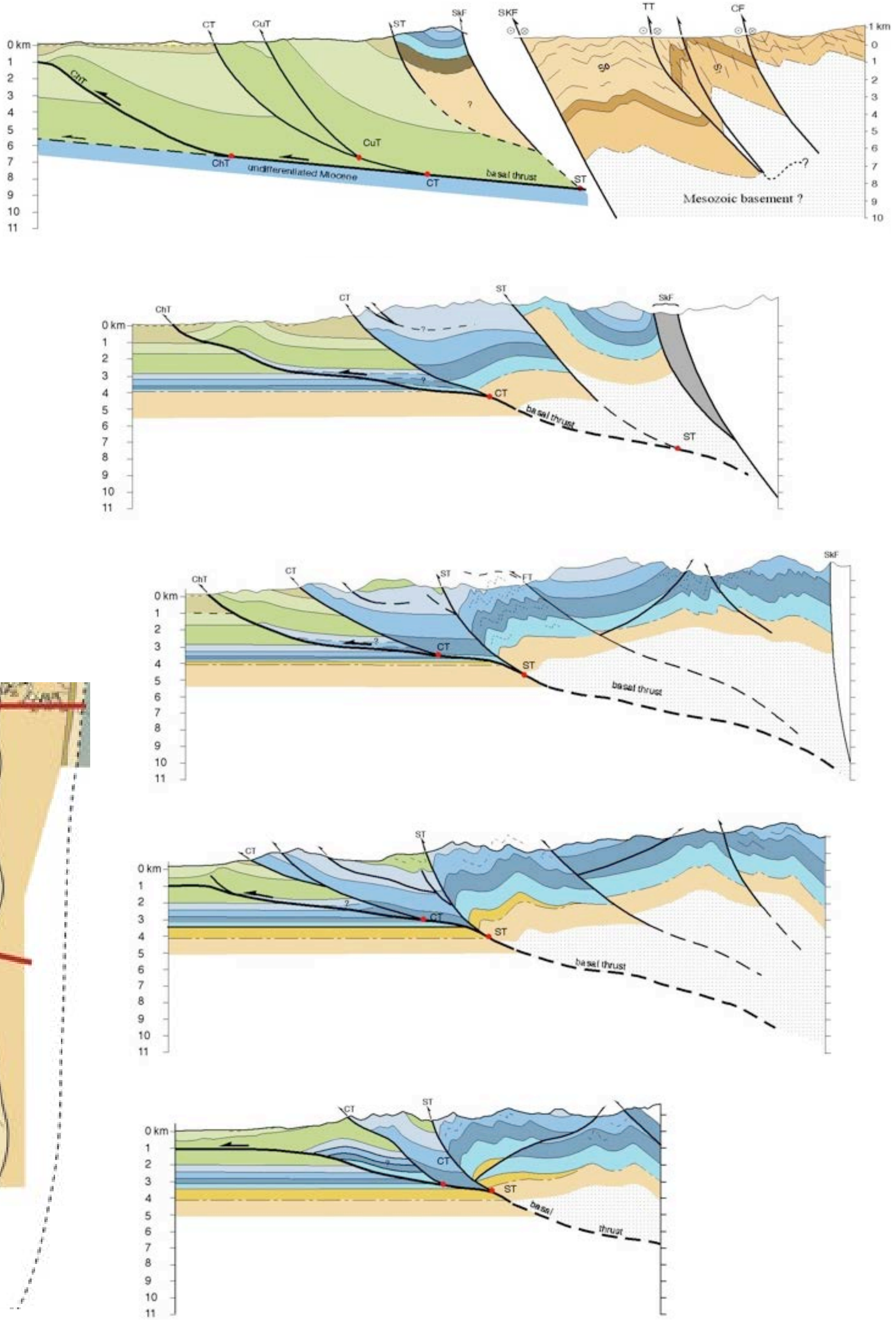
- **Clear evidence for a Shuilikeng ramp into the middle crust**
- **Higher Vp in its hanging wall suggests basement involvement**
- **Kuo-Chen et al. (2015) show that the Lishan fault extends from surface to deep cluster**

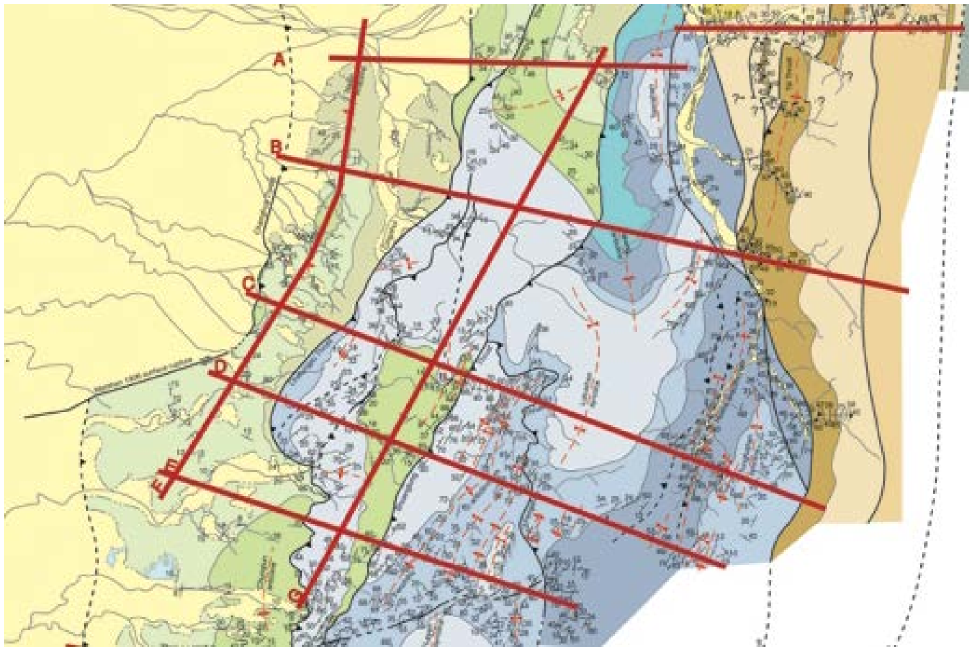


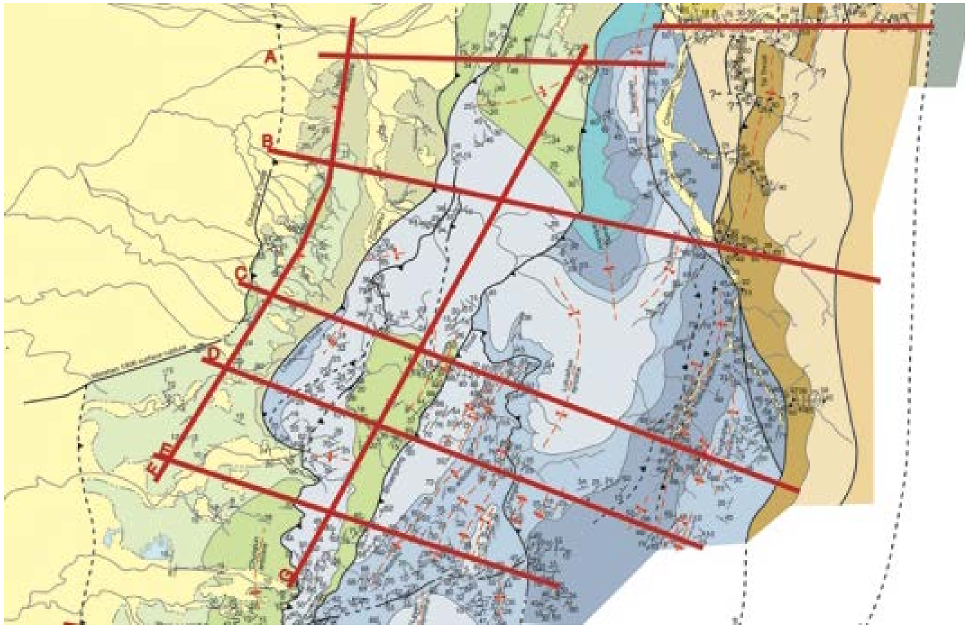
Alishan: The upper necking zone



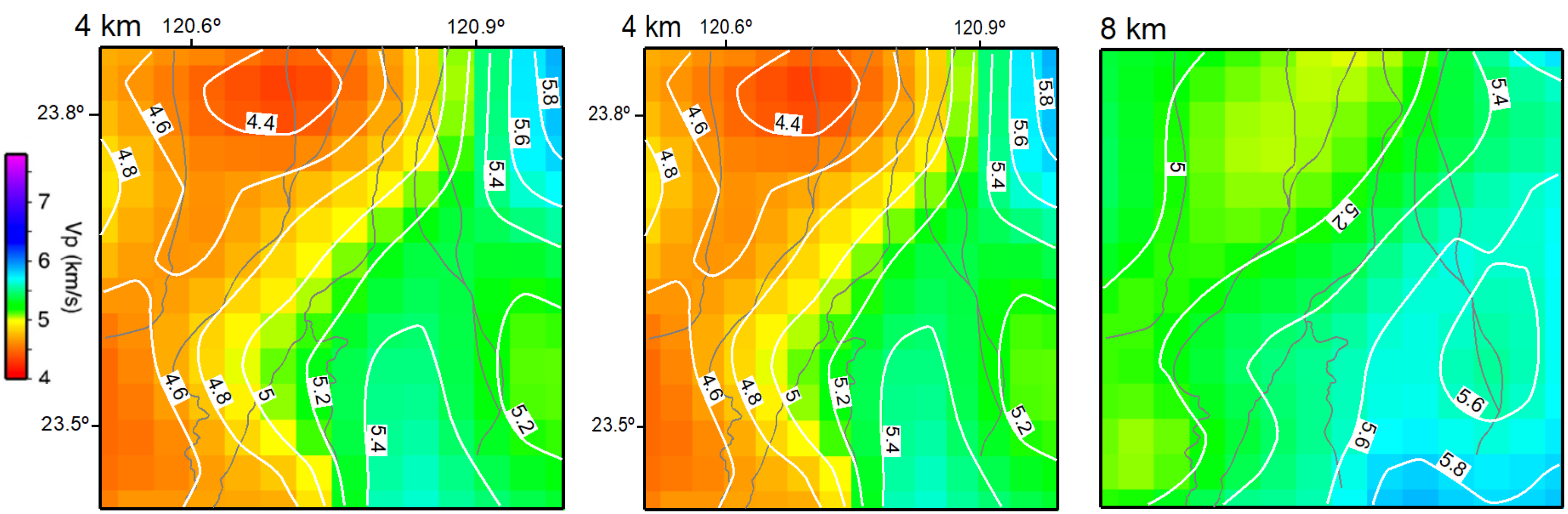
- **Major along-strike change in structure (lateral structure?)**
- **Imbricate thrust system**
- **Steeply dipping basal thrust (basement involvement?)**
- **Shortening is c. 15 km**

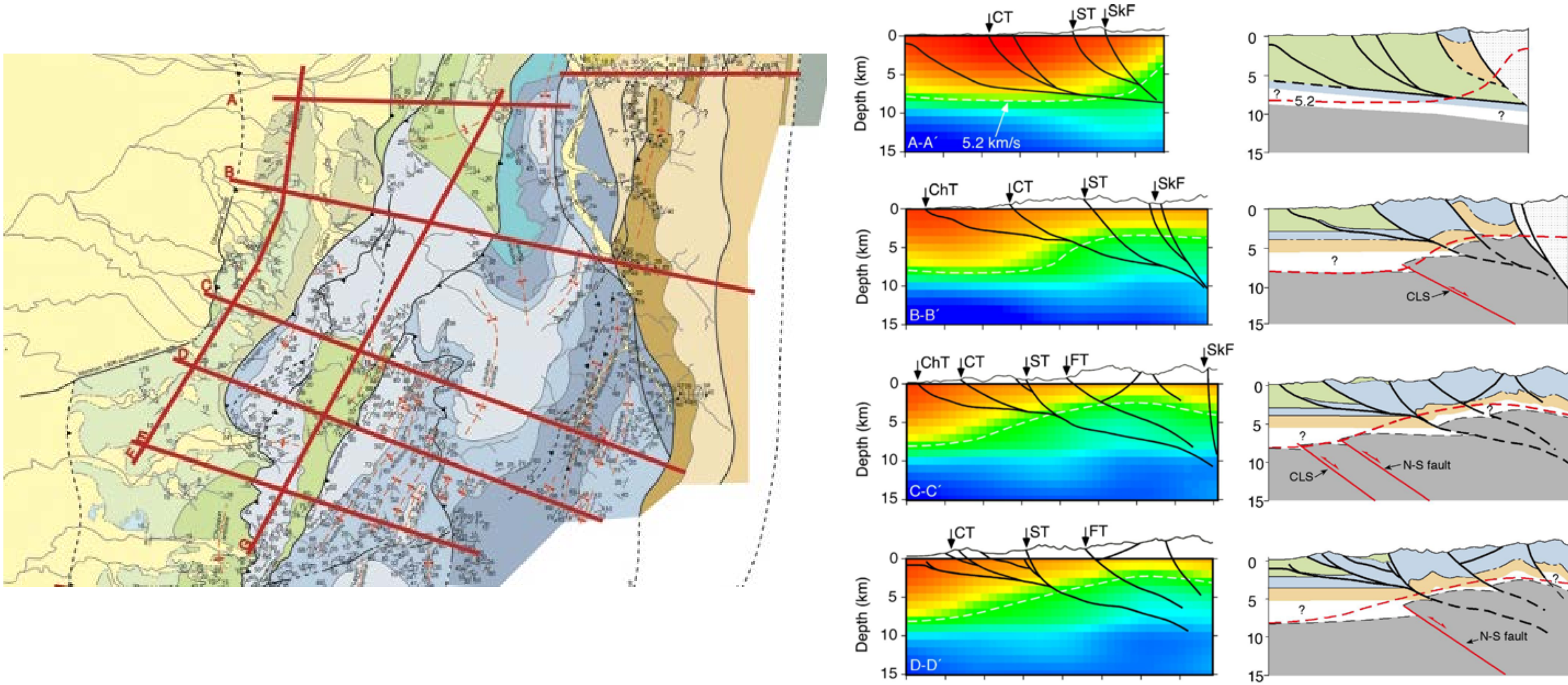




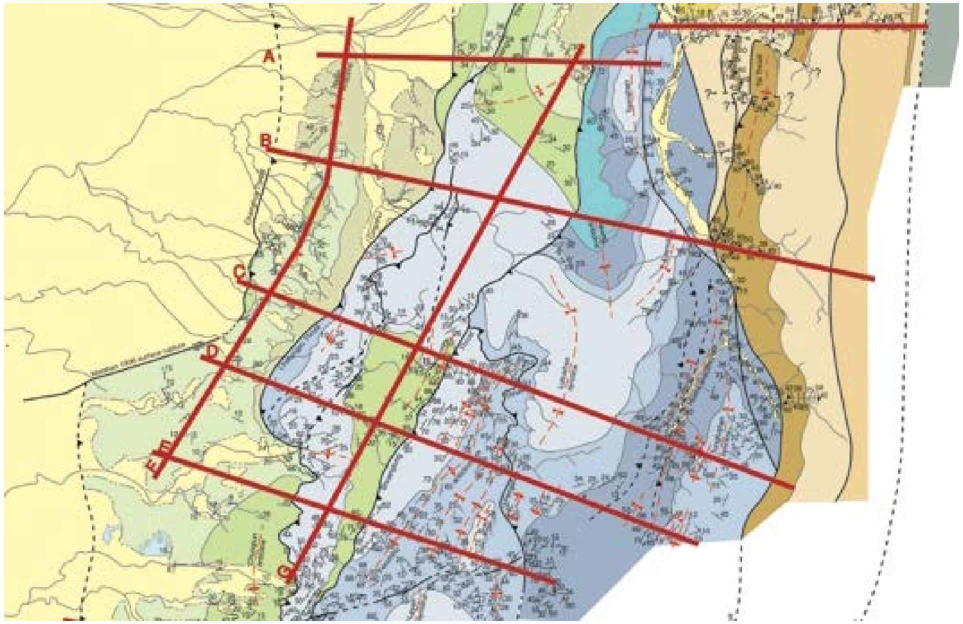


- **Clear correlation between the surface geometry of fault traces and the Vp contours at depth.**
- **Higher Vp rocks are being uplifted toward the SE**
- **5.2 kms^{-1} contour closely follows the Shuangtung thrust**

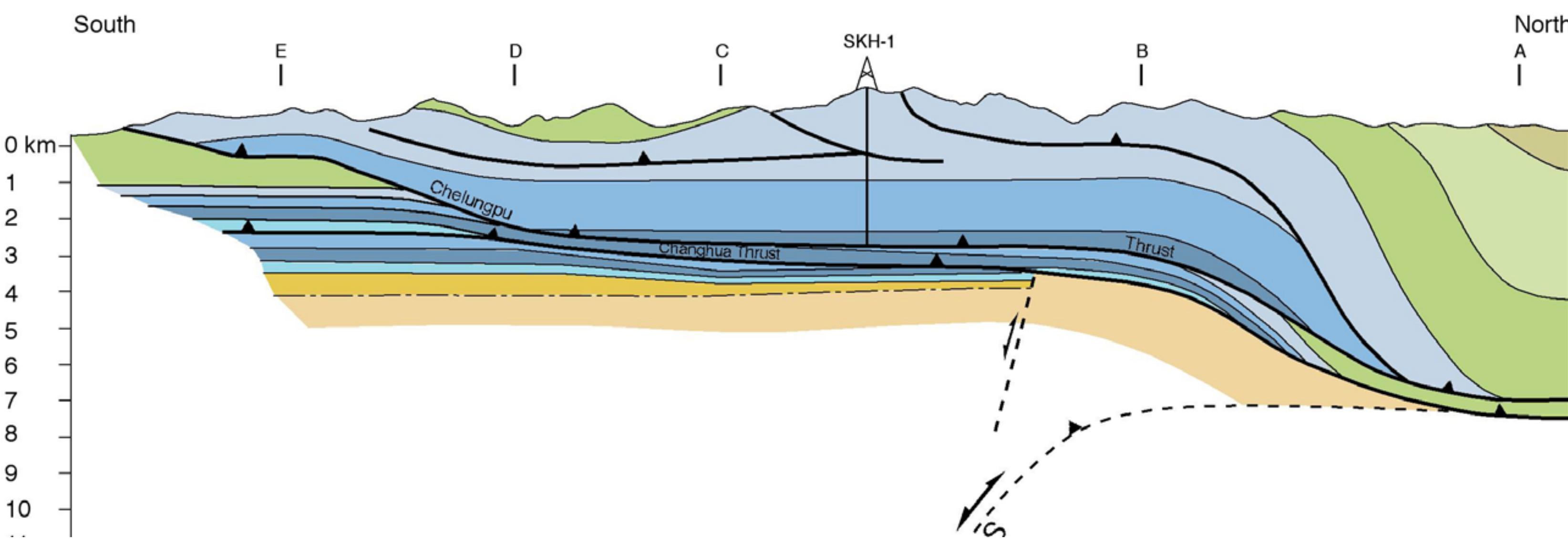


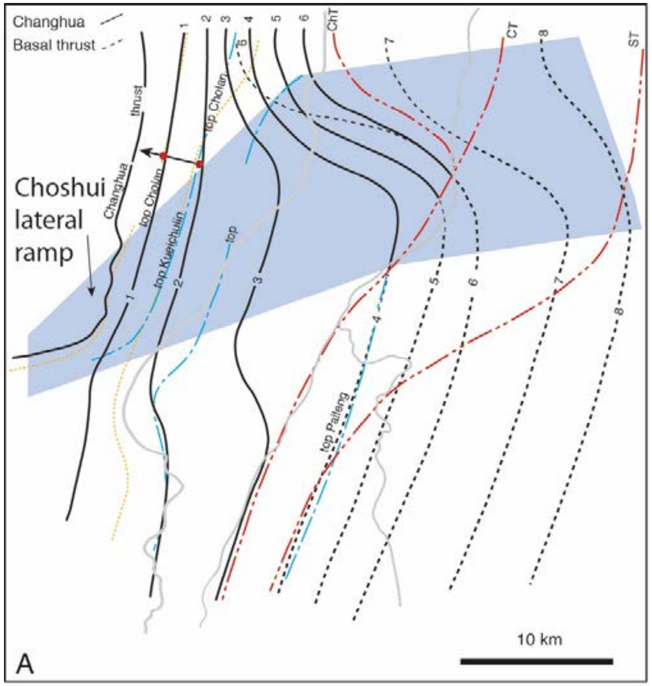


- **We interpret this to indicate that the basal thrust ramps down into the basement along the Shuangtung thrust, uplifting higher Vp basement rocks to the east.**
- **Alishan comprises a basement-cored anticlinorium**



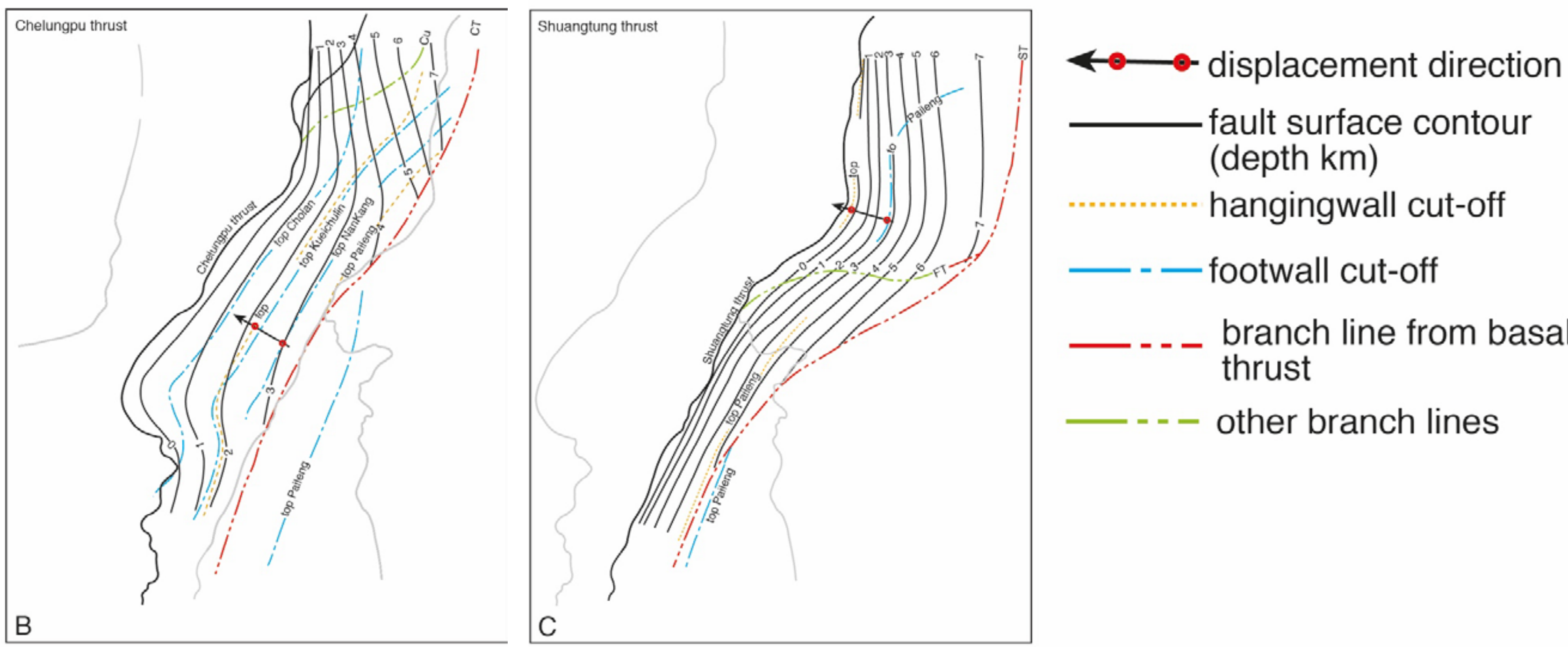
- **There is an important north-south change in structure and stratigraphy across the Choshui River.**
- **Base of the Cholan Fm is uplifted c. 7km from North to South**
- **Suggests the presence of a lateral structure**



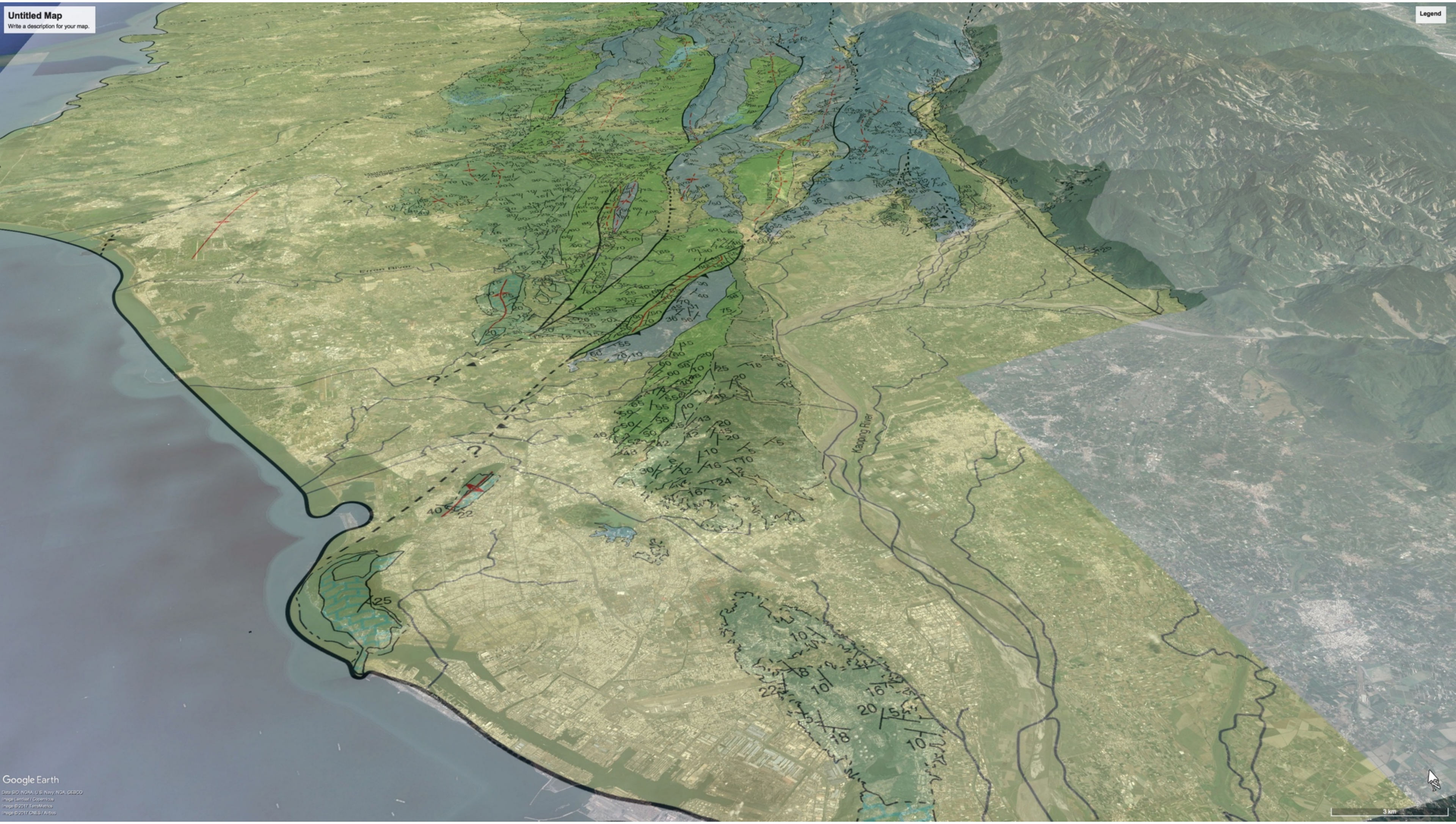


- **Contours of the basal thrust display a sharp bend that indicates a NE-dipping oblique ramp that we call the Choshui lateral ramp**

- **Footwall and hangingwall cut-offs indicate the displacement directions in the Chelungpu and Shuangtung thrust sheets to be NW and W, respectively**

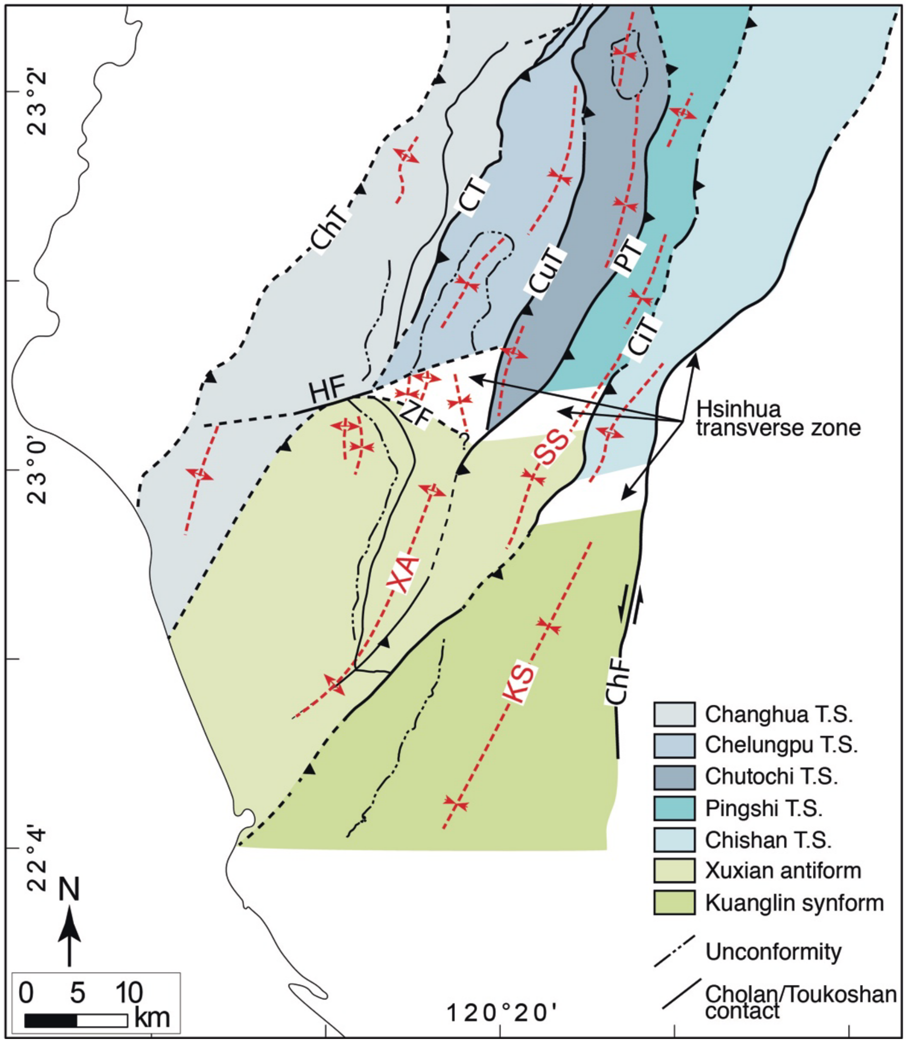


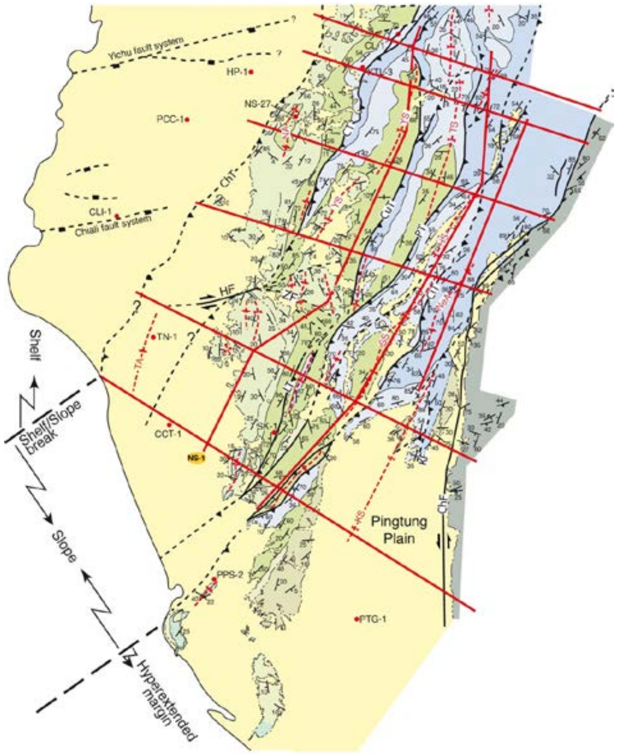
Southwest Taiwan: The necking zone and shelf to slope transition

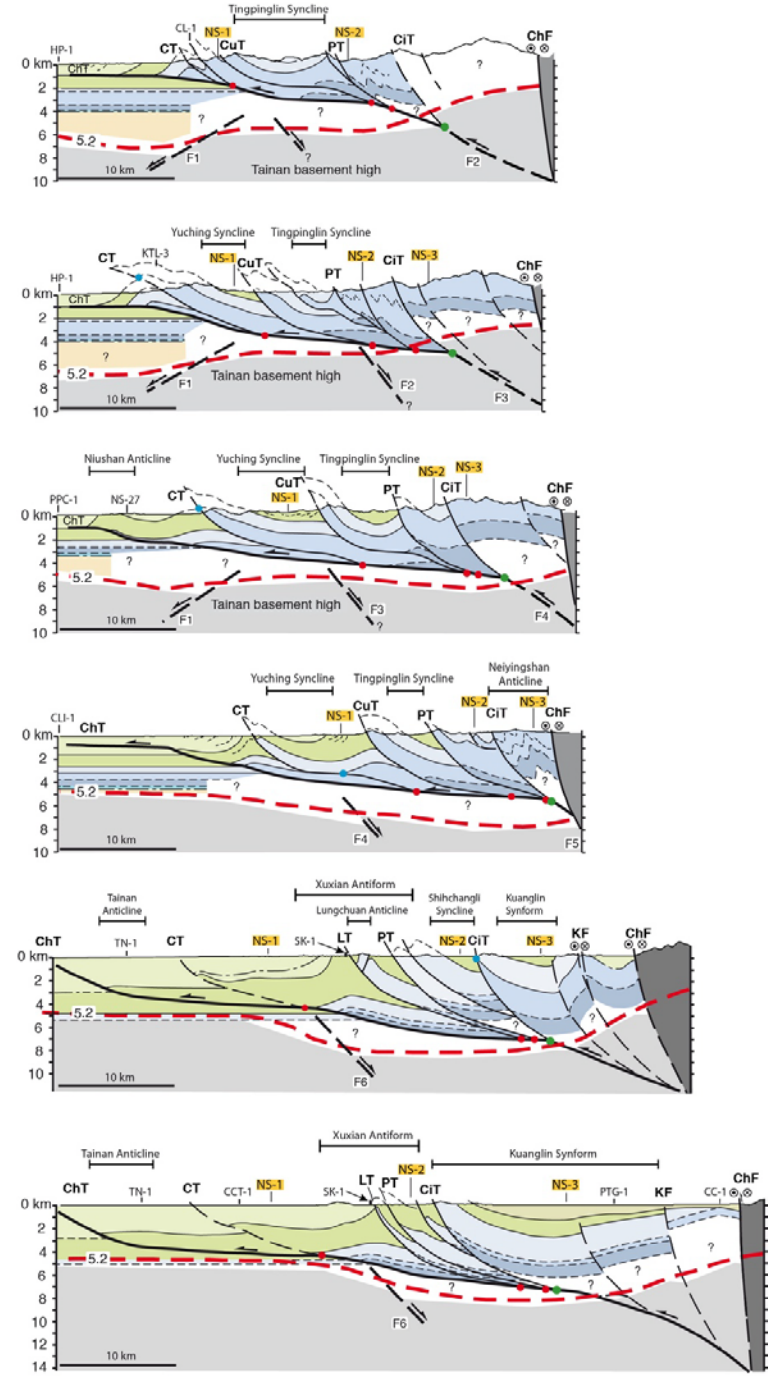


Along-strike changes

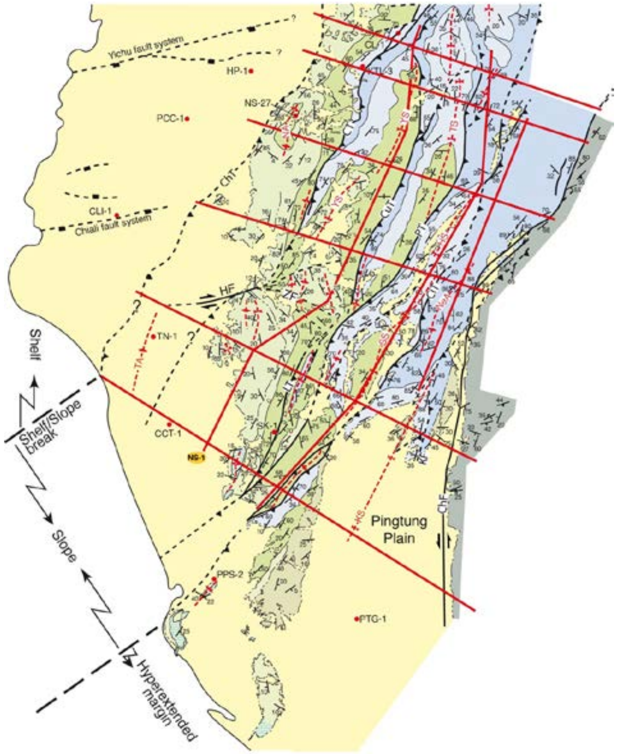
- Changes in structure, stratigraphy and topography from Alishan
- The broad Alishan anticlinorium passes southward into three synclines
- These, in turn, change into an anticline: change in stratigraphy (Gutingkeng Fm)
- The Chishan thrust sheet changes from an anticline in the north to a syncline in the south
- We call this area of change the Hsinhua transverse zone
- Thrust system becomes buried by sy-orogenic thrust-top basins

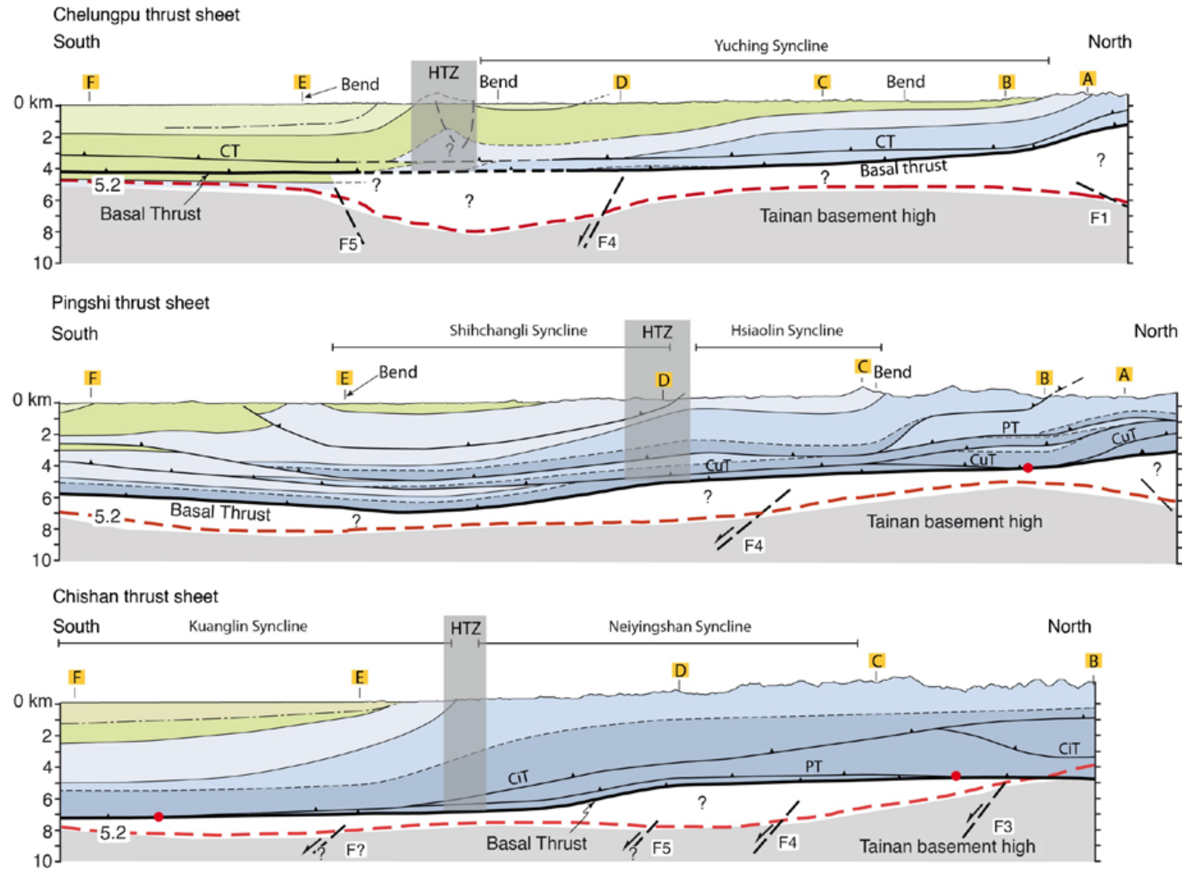




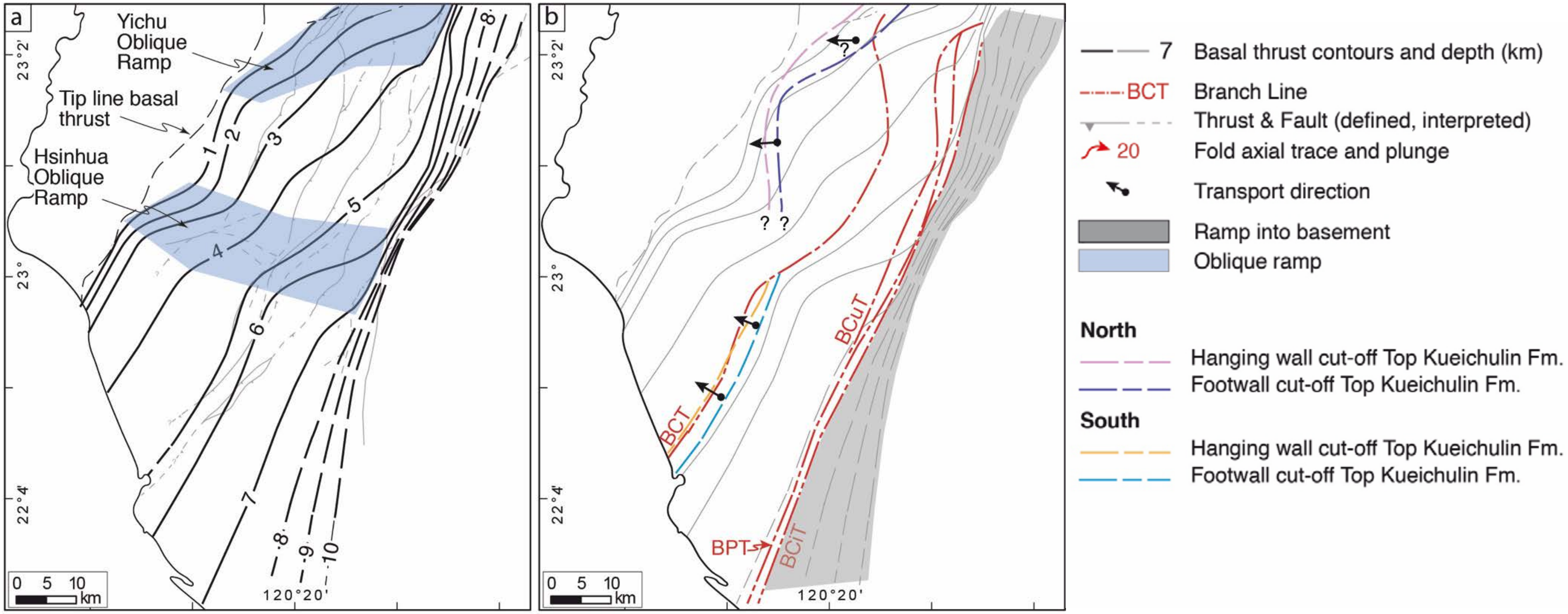


- **Imbricate thrust system**
- **Juxtaposition of synclines with similar erosion level suggest a gently dipping basal thrust**
- **Basal thrust ramps down into the basement along the Chishan thrust: uplift of 5.2 kms^{-1}**
- **Shortening ranges from c. 15 to 20 km**





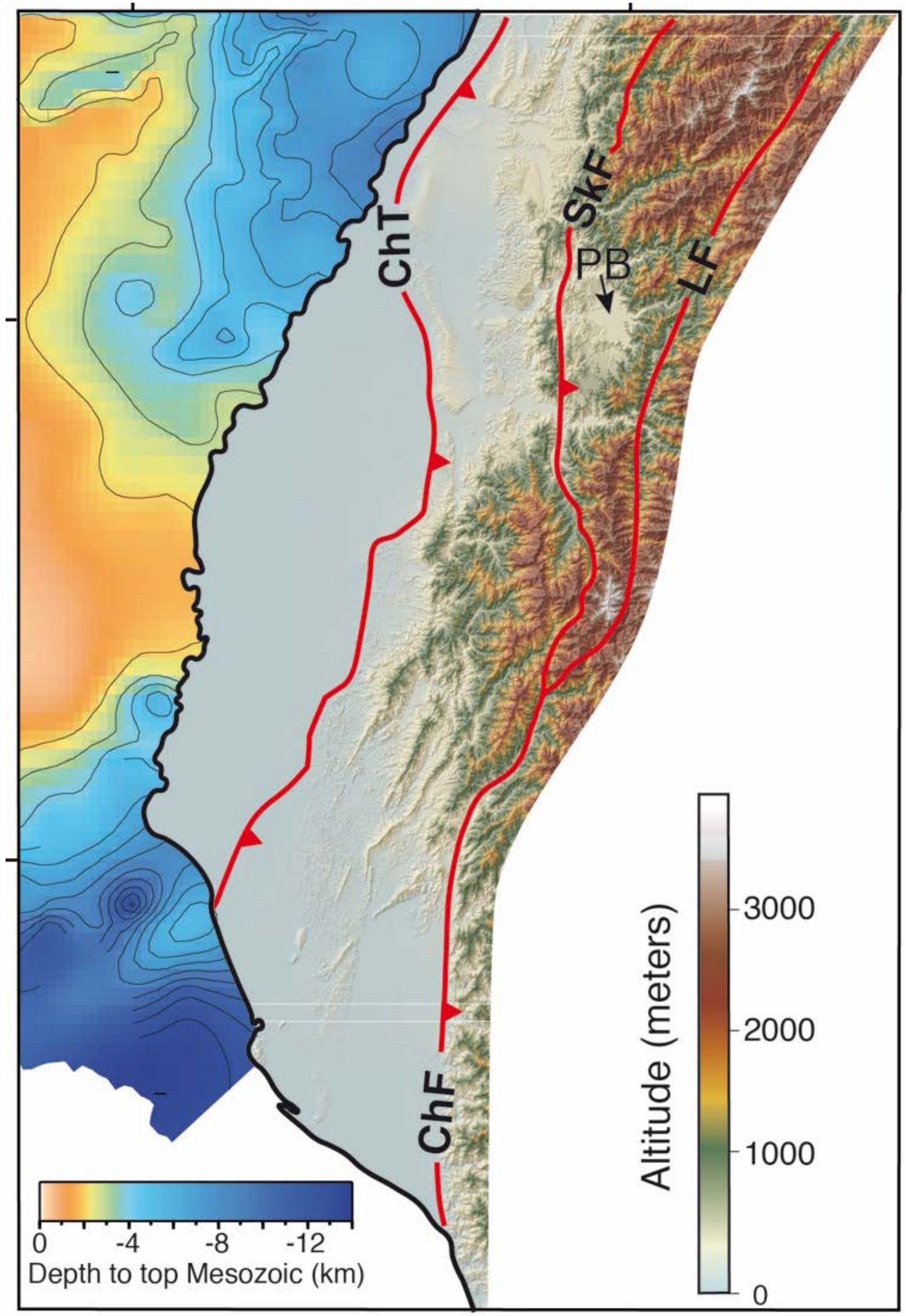
- **Link the cross sections together and provide 3D control**
- **Along-strike sections show deeping of basal thrust toward the south**
- **Thickening of syn-orogenic sediments to the south**
- **Hsinhua transverse zone may be imaged**



- **Basal thrust map shows two major changes in strike: we call these the Yichu and Hsinhua obligue ramps**
- **These can be correlated with the structure at the surface**
- **Hanging wall and footwall cut-offs show that the displacement direction of the Chelungpu thrust is roughly to the west.**

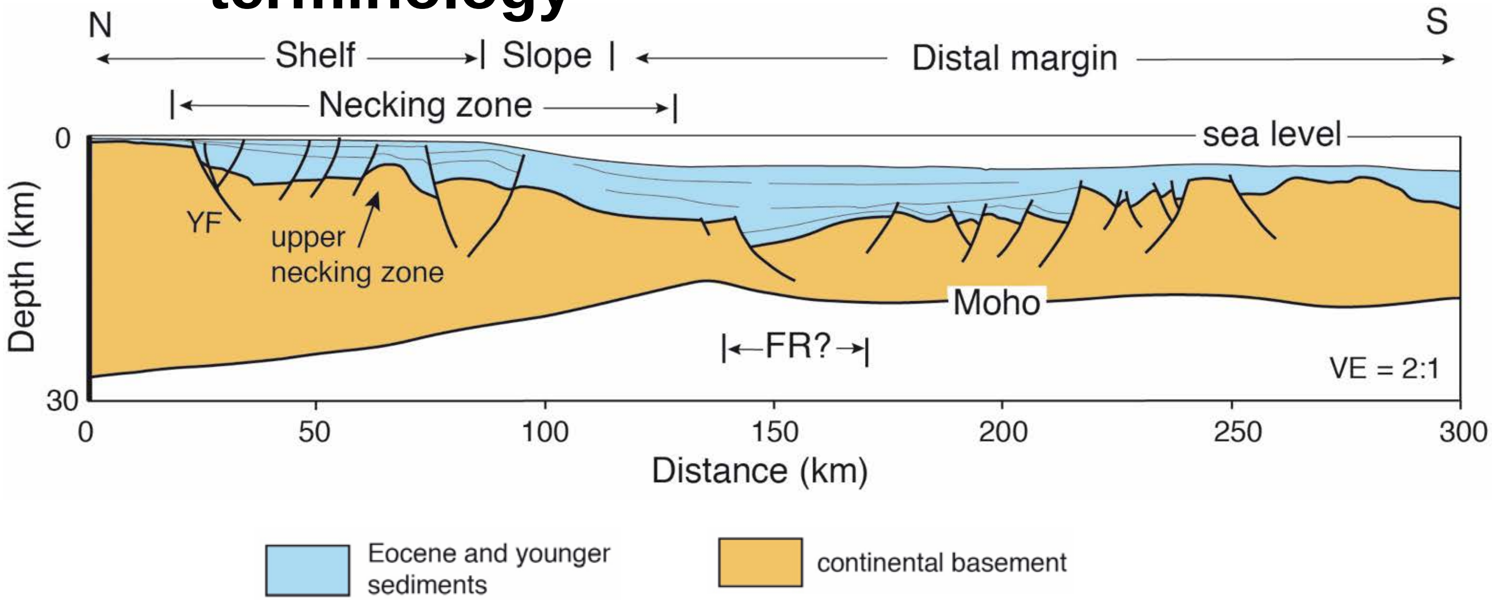
From what we have seen so far I hope that you will agree with me that there are important along-strike changes in various aspects of the geology of the fold-and-thrust belt in western Taiwan.

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




Let’s look more closely

A quick review of margin terminology

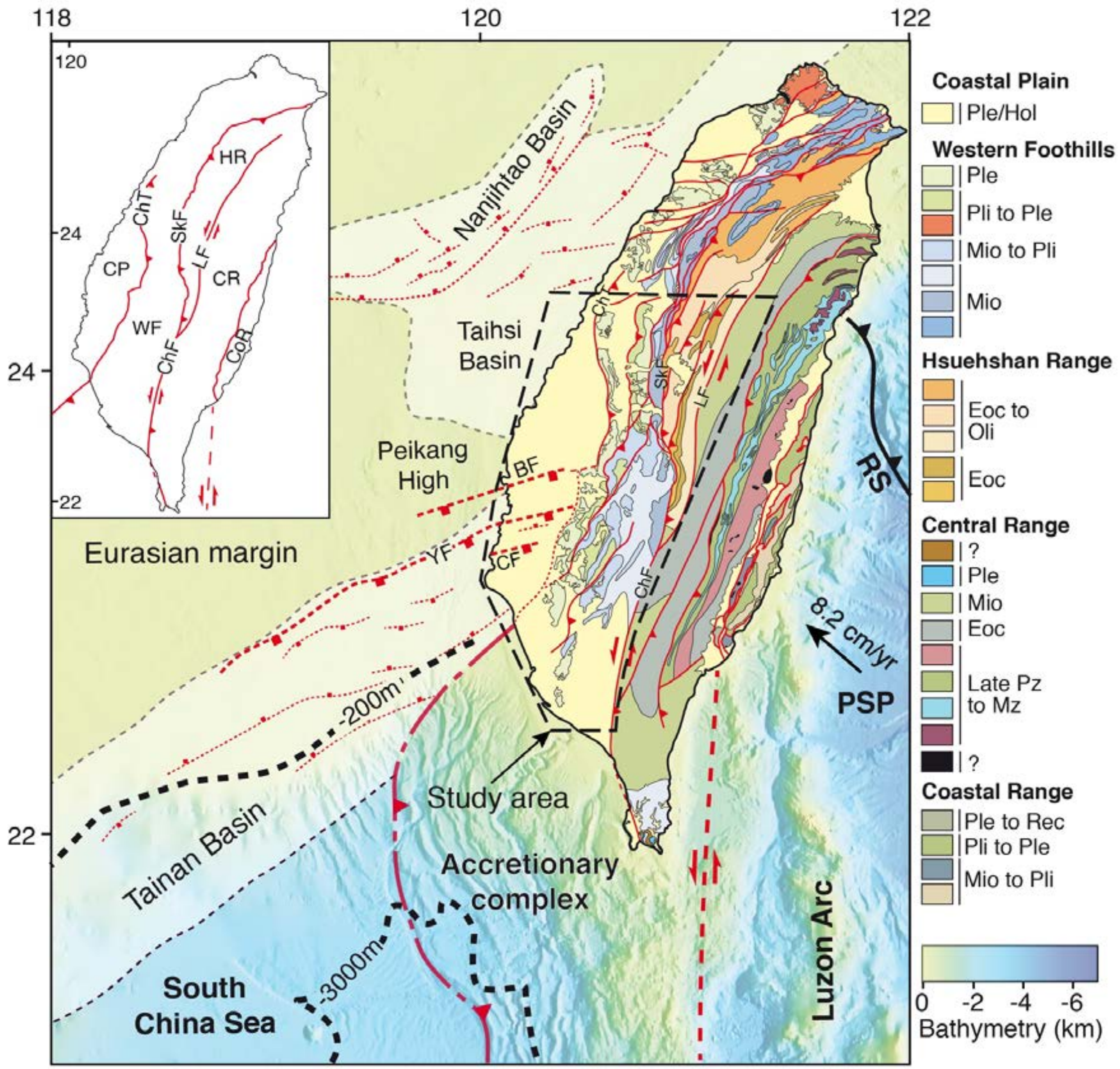


- ➢ **Morphology**
- Shelf
- Slope
- Distal margin

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

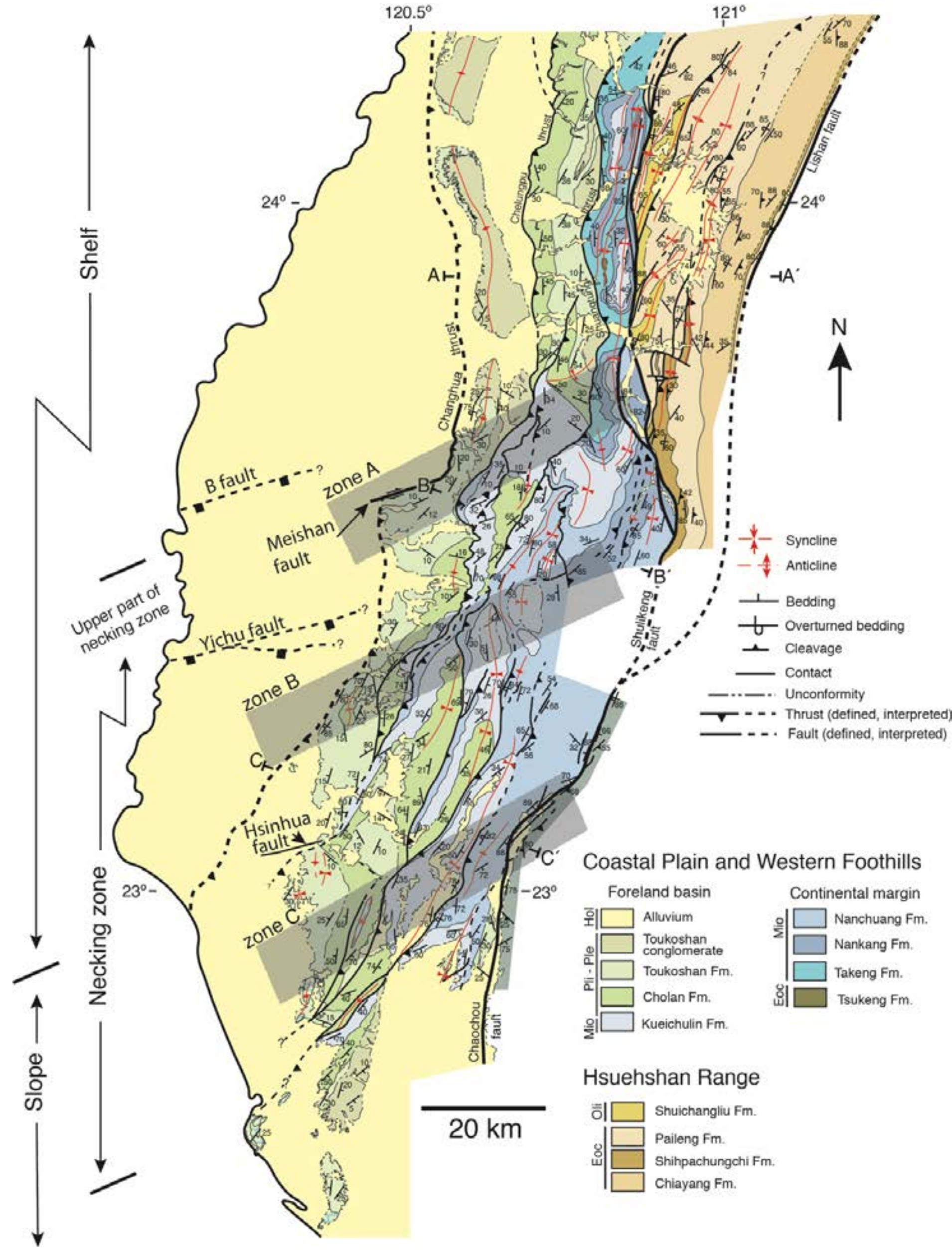
Some first-order observations

- 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

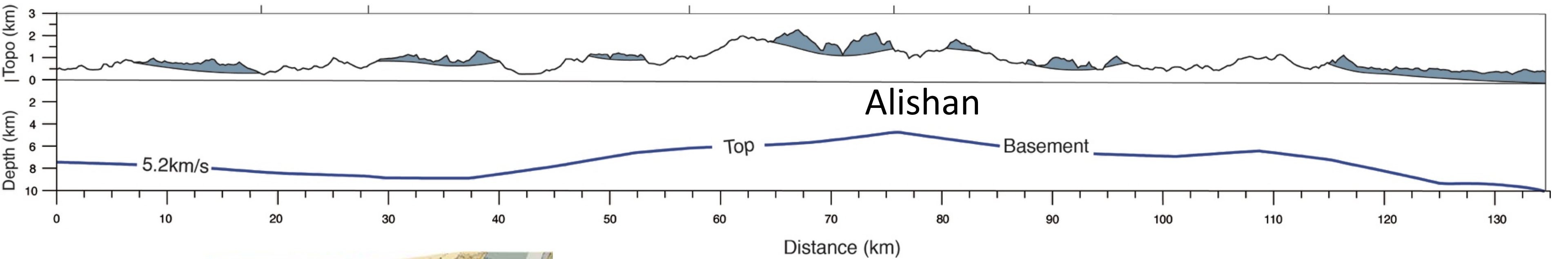


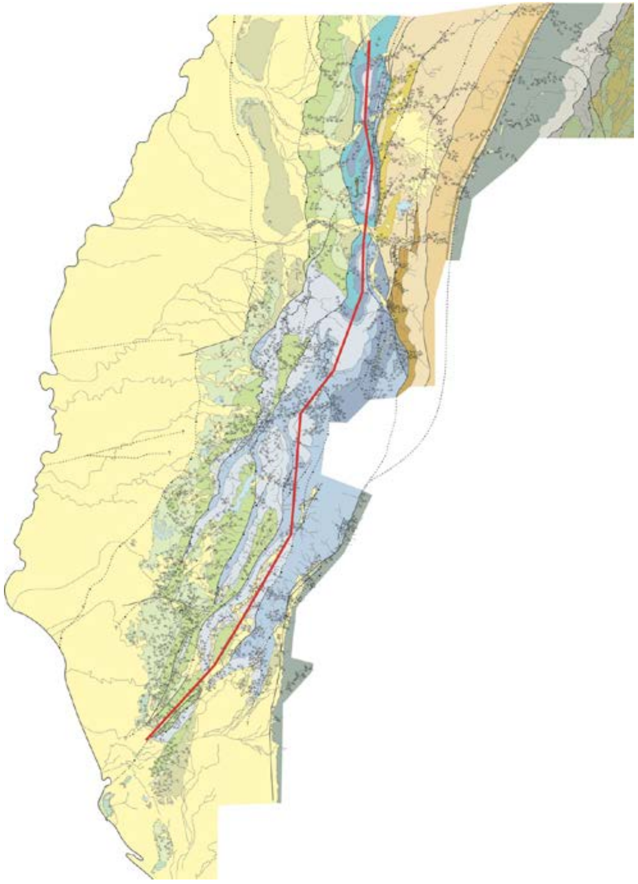
Some second-order observations

- ➢ 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

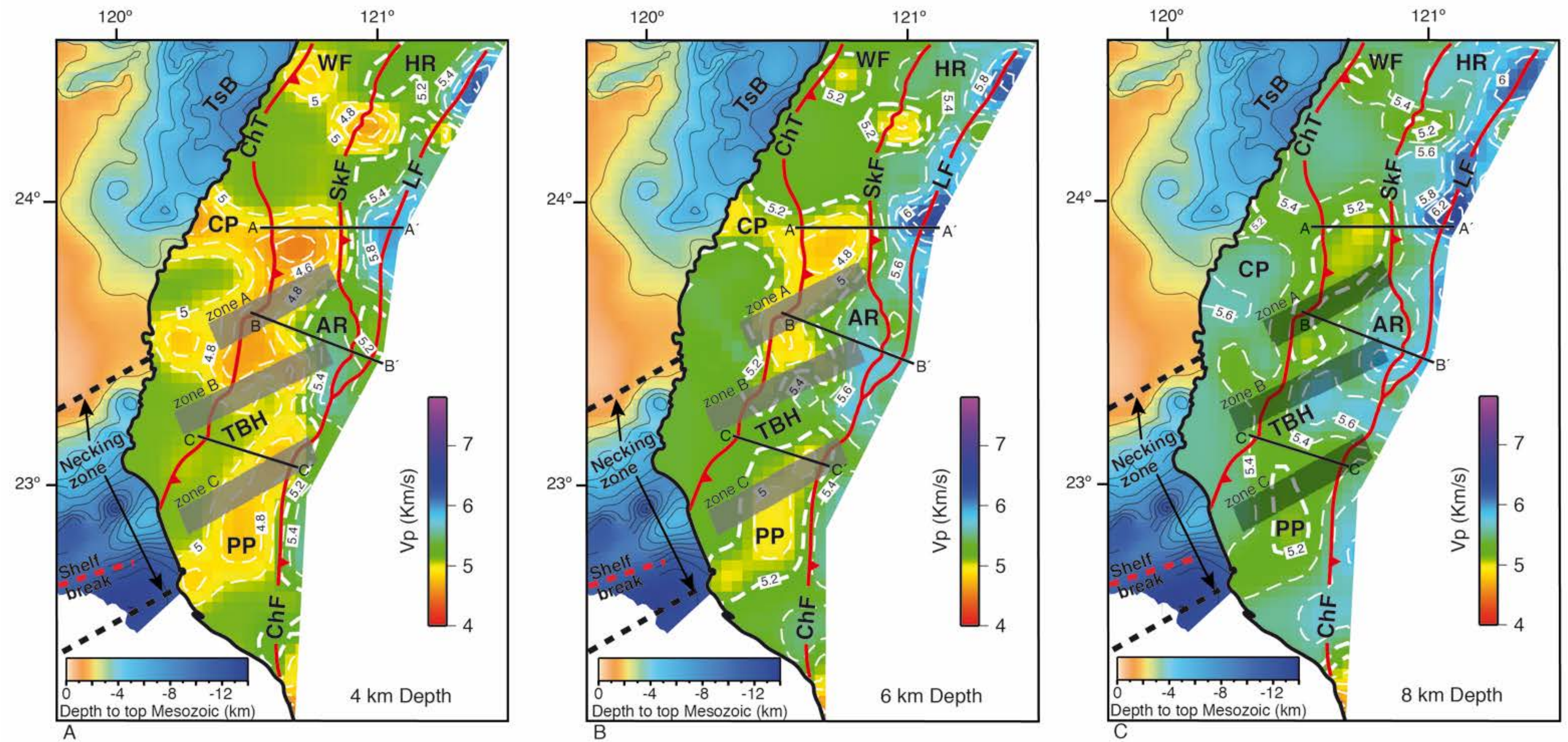


A third-order observation:
Topography and basement involvement in thrusting

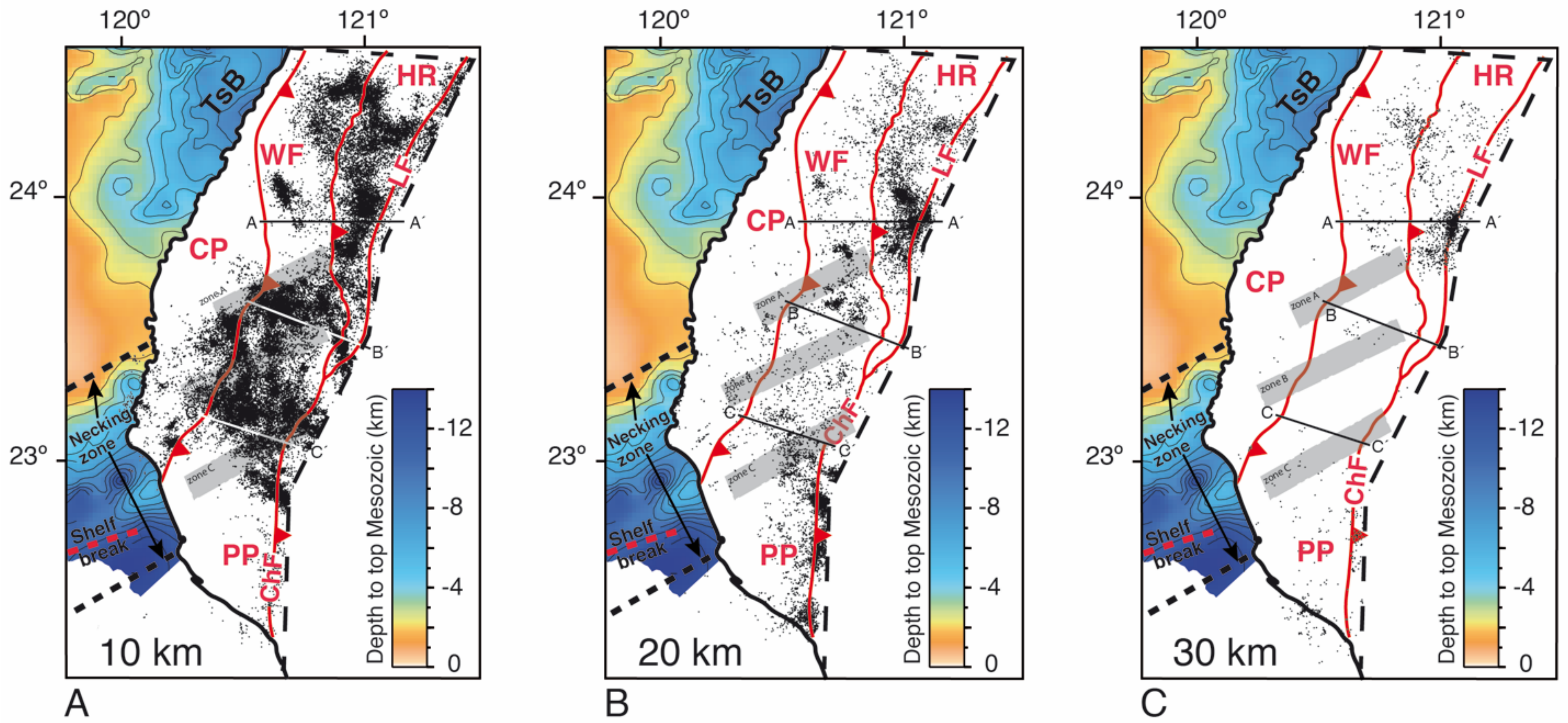




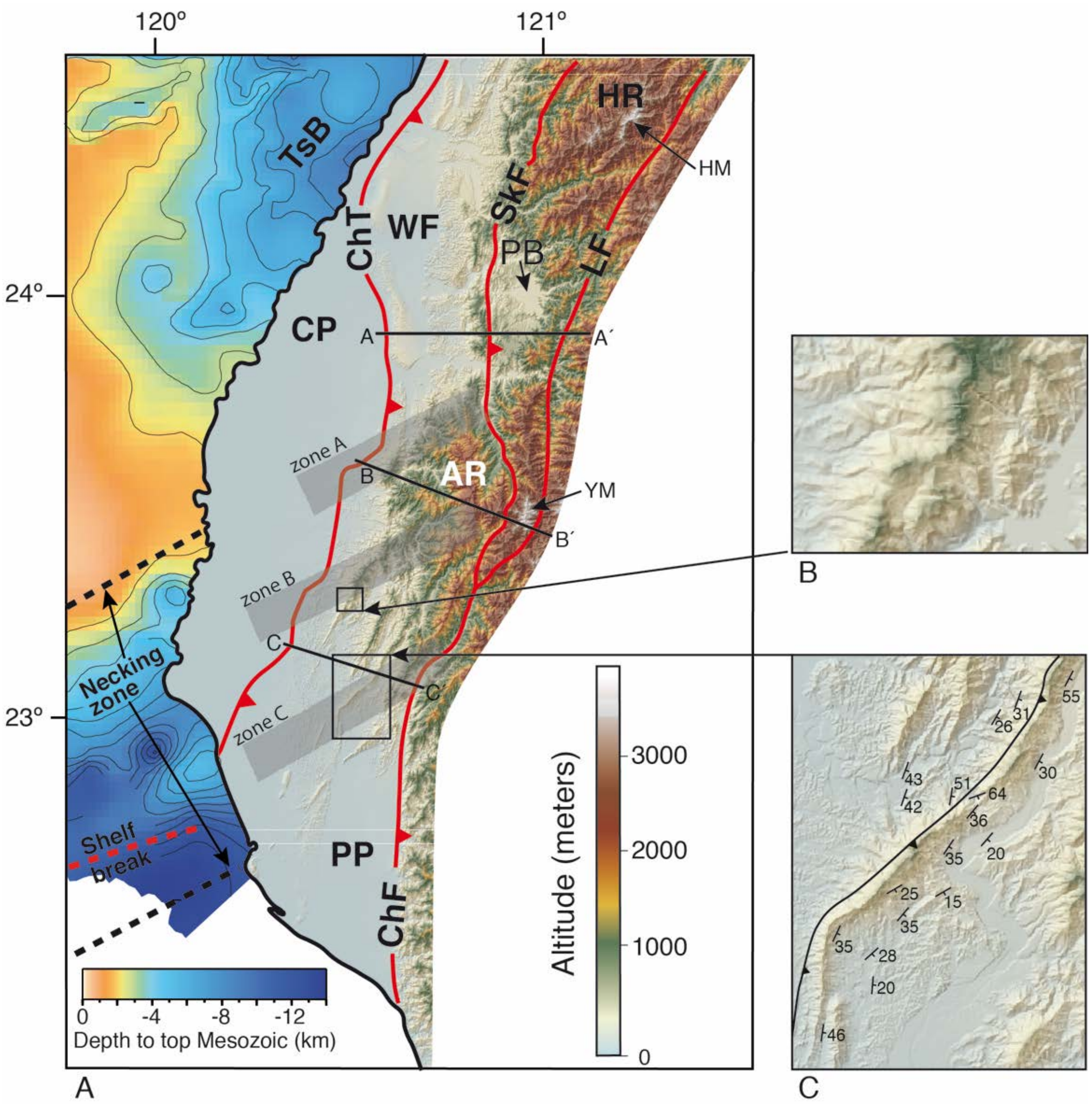
- There is a relationship between topography and basement involvement in the thrusting.
- Here, we plot the mapped base of the Kuechulin Fm on the topography along with the 5.2 km/s proxy for the top of the basement.
- Notice the uplift of basement below the high topography across the upper part of the necking zone (Alishan)?



- 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



- 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

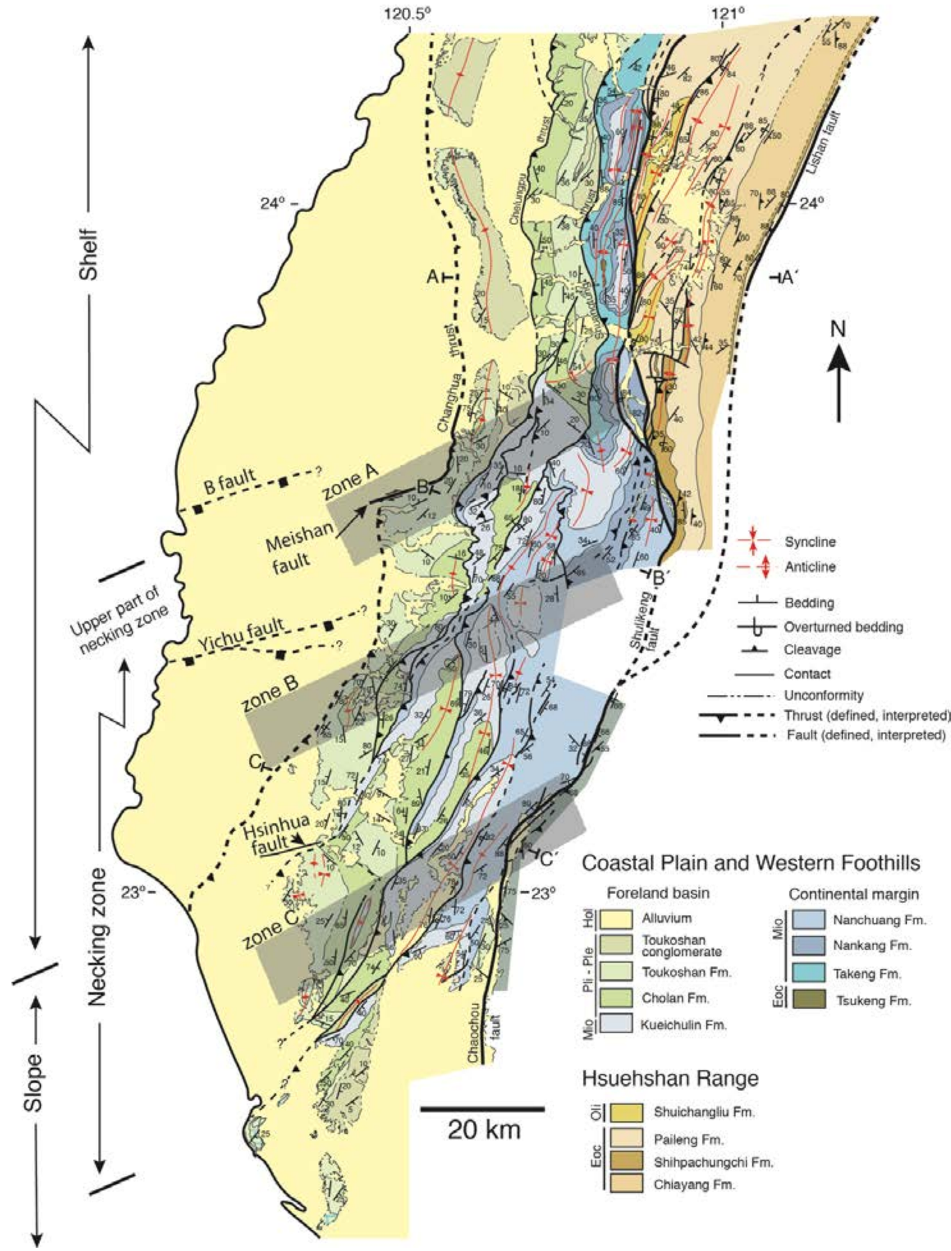


- **Shelf**
  - Hsuehshan Range has highest topography in Taiwan
- **Necking zone**
  - Zone A marks a NE-striking increase in topography toward Alishan. NW flank of the culmination wall.
  - Zones B and C have en-echelon sigmoidal bends in the topography that coinside with along-strike changes in structure.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

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, and topography of the fold-and-thrust belt in this area.

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



But, importantly, what don’t we know?

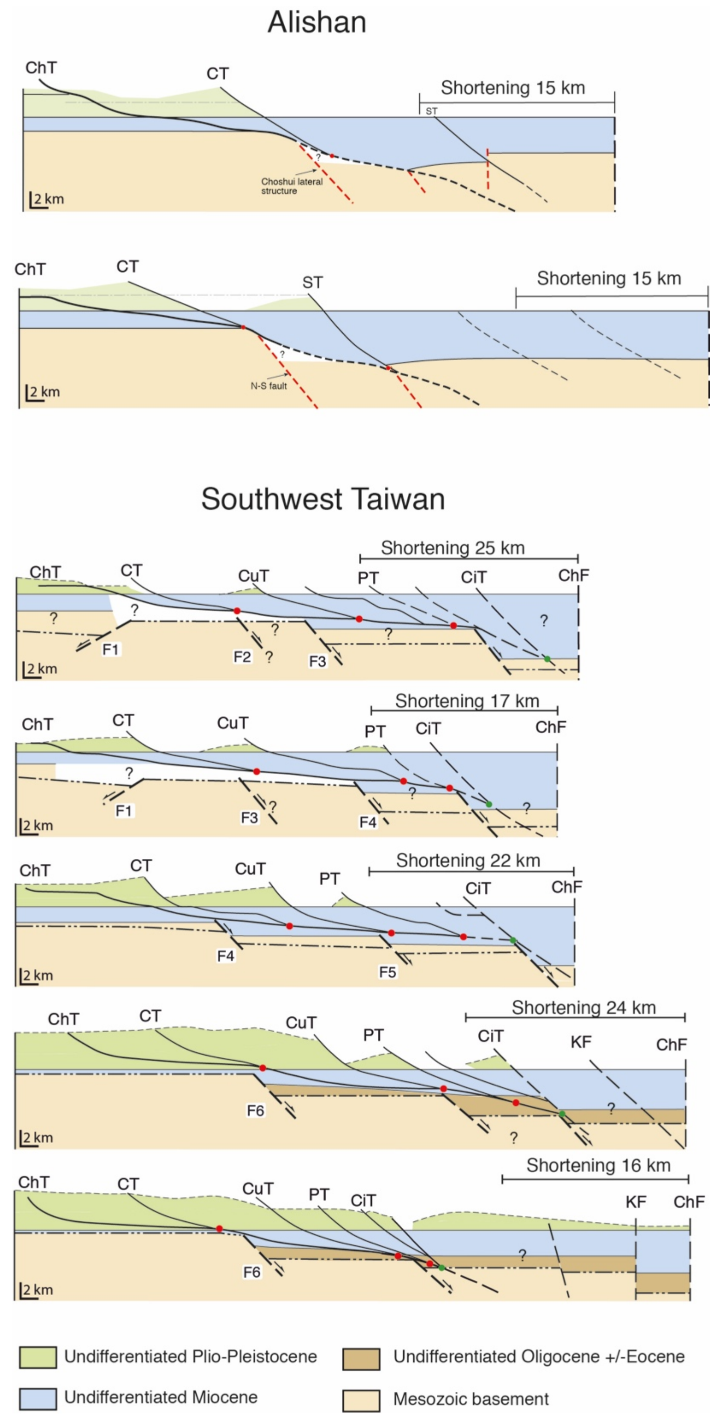
- What is the connection bewteen the Lishan, Shuilikeng and Chaochou faults?
- How is displacement accommodated along this fault system?
- What happens to the basal thrust eastward, beneath the Central Range?
- Is the Central Range the backstop to the fold-and-thrust belt?
- Are we paying enough attention to the basement structure?
- 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: Is our question correct?

Is the structure, seismicity and topography of the western Taiwan fold-and-thrust belt are affected by the structure and morphology of the margin?

- Yes, we think that it is.
- 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 Oligocene +/-Eocene
Undifferentiated Miocene
Mesozoic basement