Tectonic evolution of an active tectonostratigraphic boundary in accretionary wedge: An example from the Tulungwan-Chaochou Fault system, southern Taiwan

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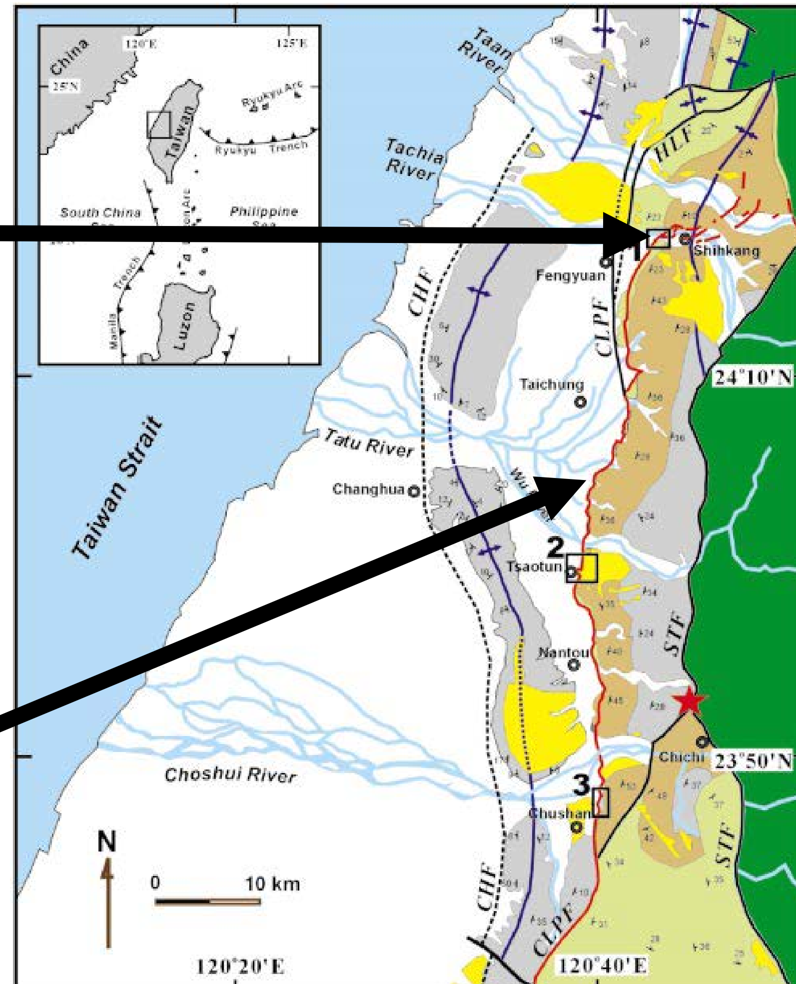
Motivation

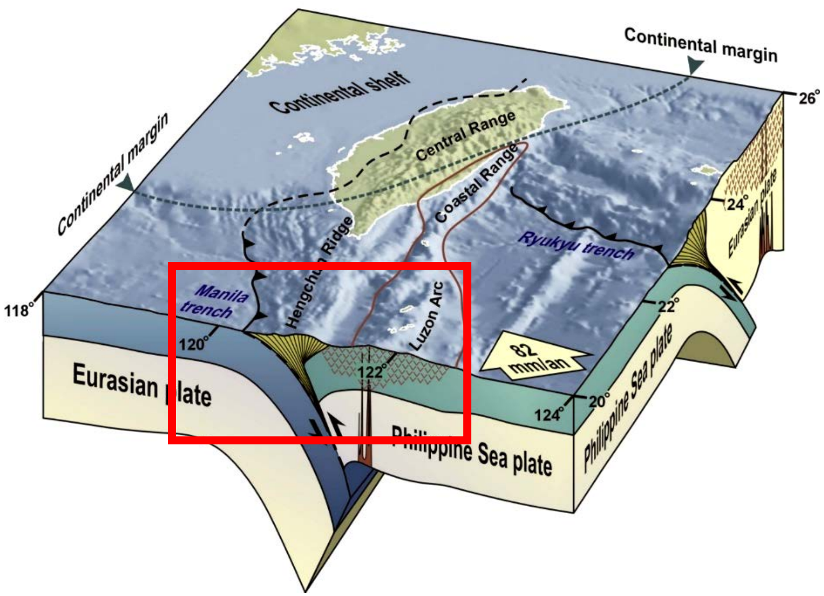
- What is an accretionary wedge?
- How the accretionary wedge deforms?
- Are there any active structures in the inner part of an accretionary wedge?

Taiwan is an active accretionary wedge: 1999 Chi-Chi earthquake

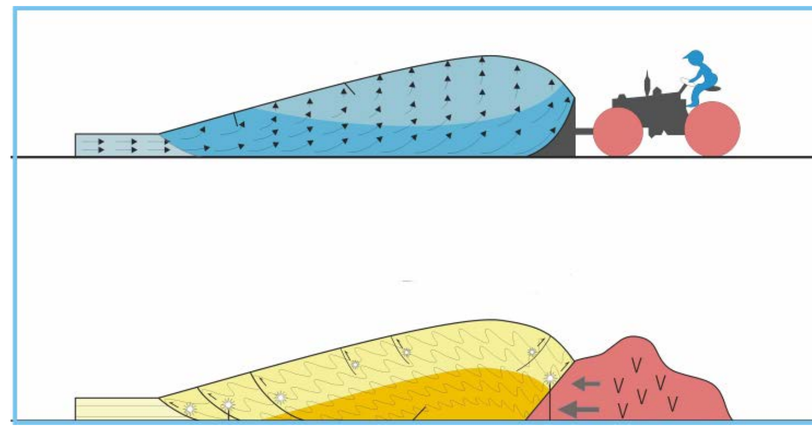


Chen et al., 2002

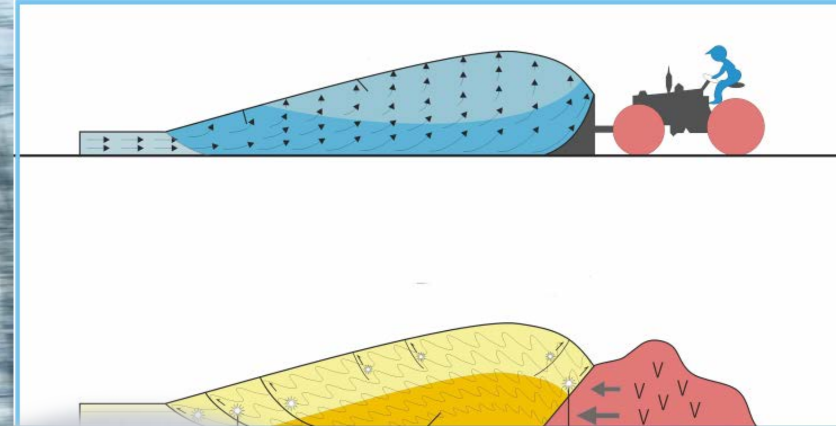
How the Taiwan accretionary wedge formed?

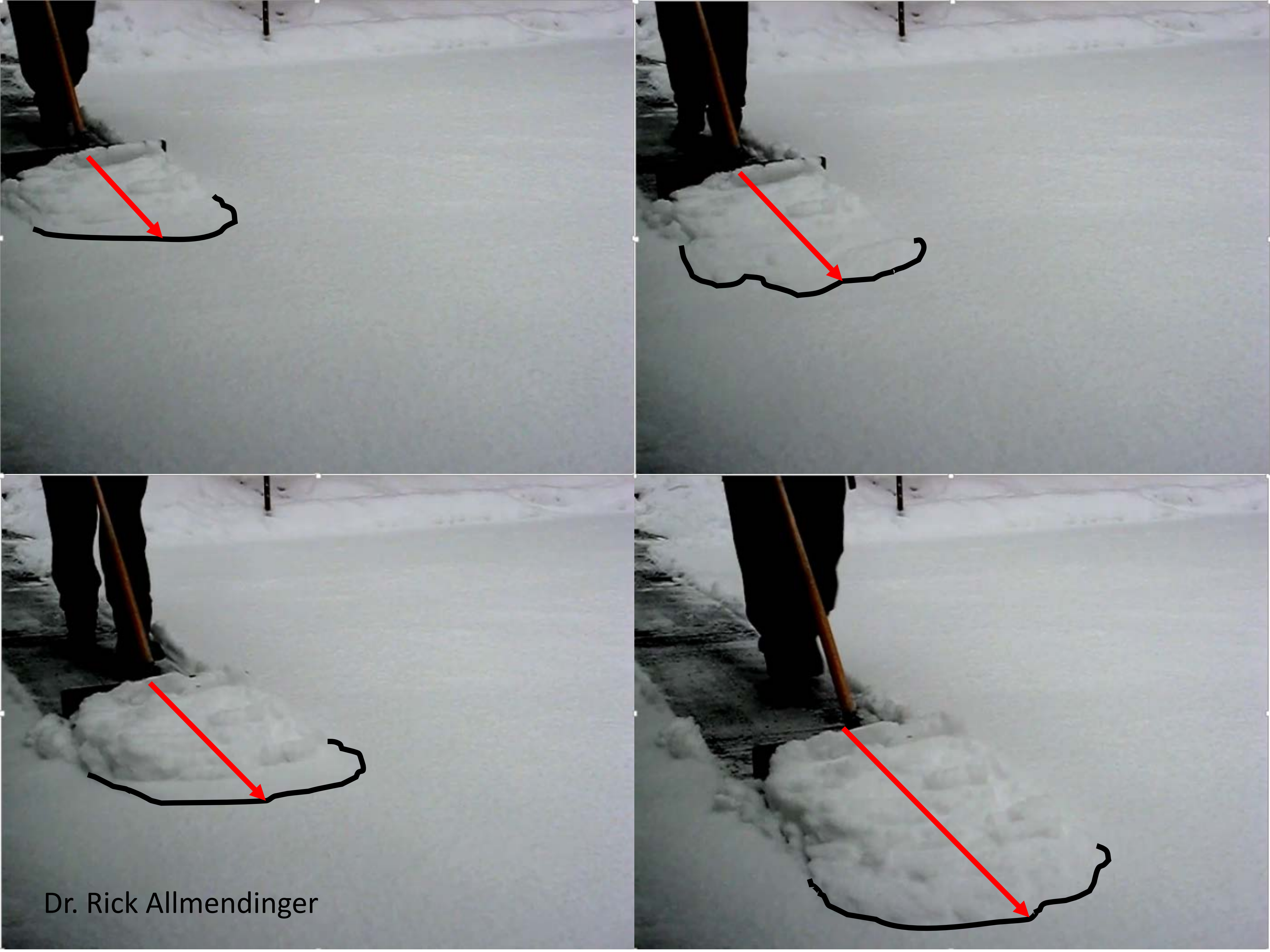


Chung-Pai Chang

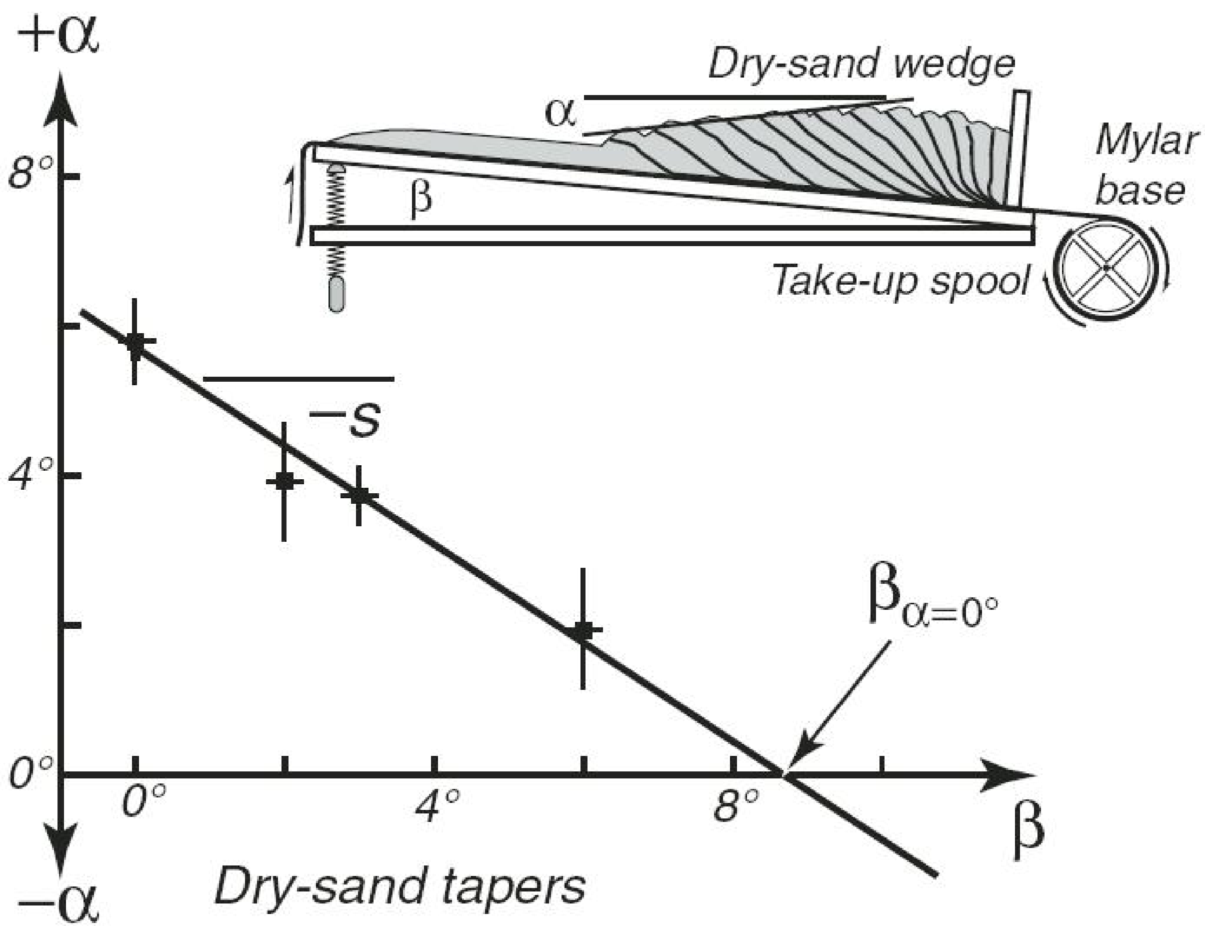


accretionary wedge | volcanic arc


GMC


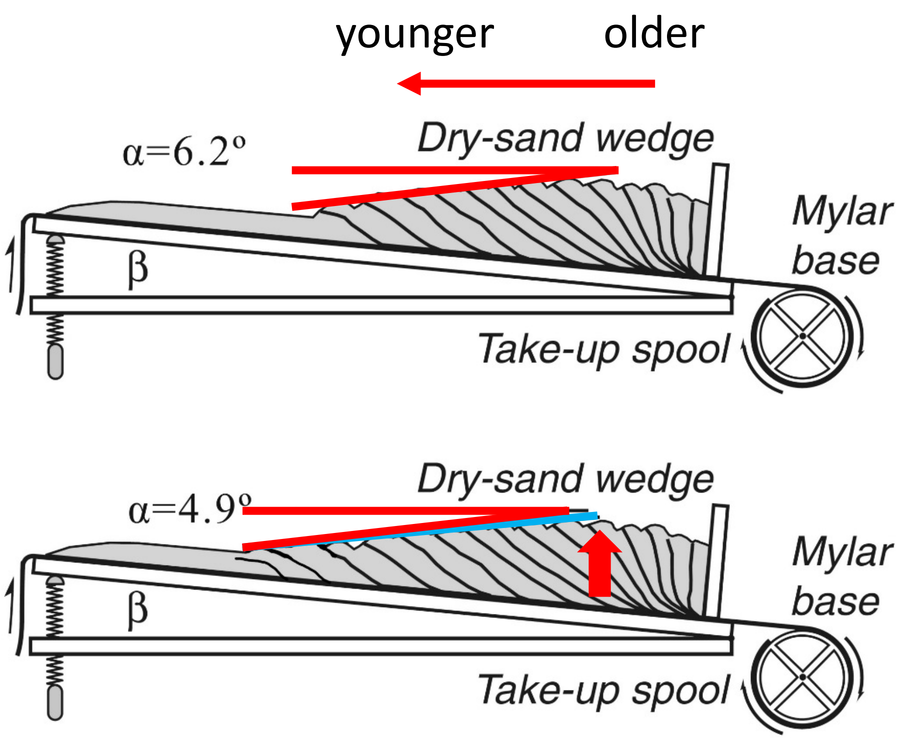


Dr. Rick Allmendinger

What is an accretionary wedge?



Suppe, 2007

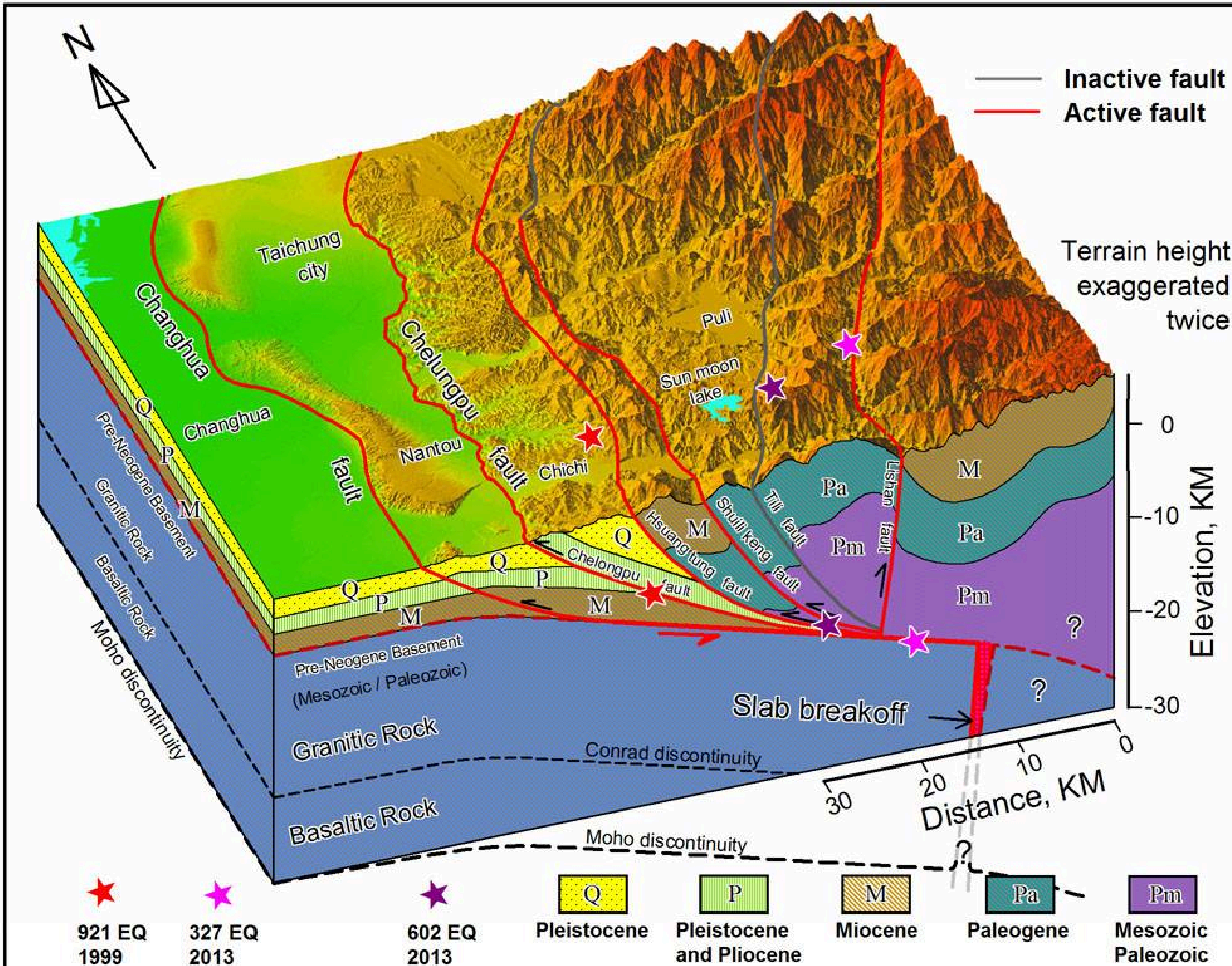
How to maintain the critical taper of an accretionary wedge?



Modified from Suppe, 2007

- Development of thrust faults in the internal part of the mountain belt.
    - The thrusts in the internal part of the mountain belt are often referred to “out-of-sequence thrusts” (OOST).

Active OOST in Central Taiwan

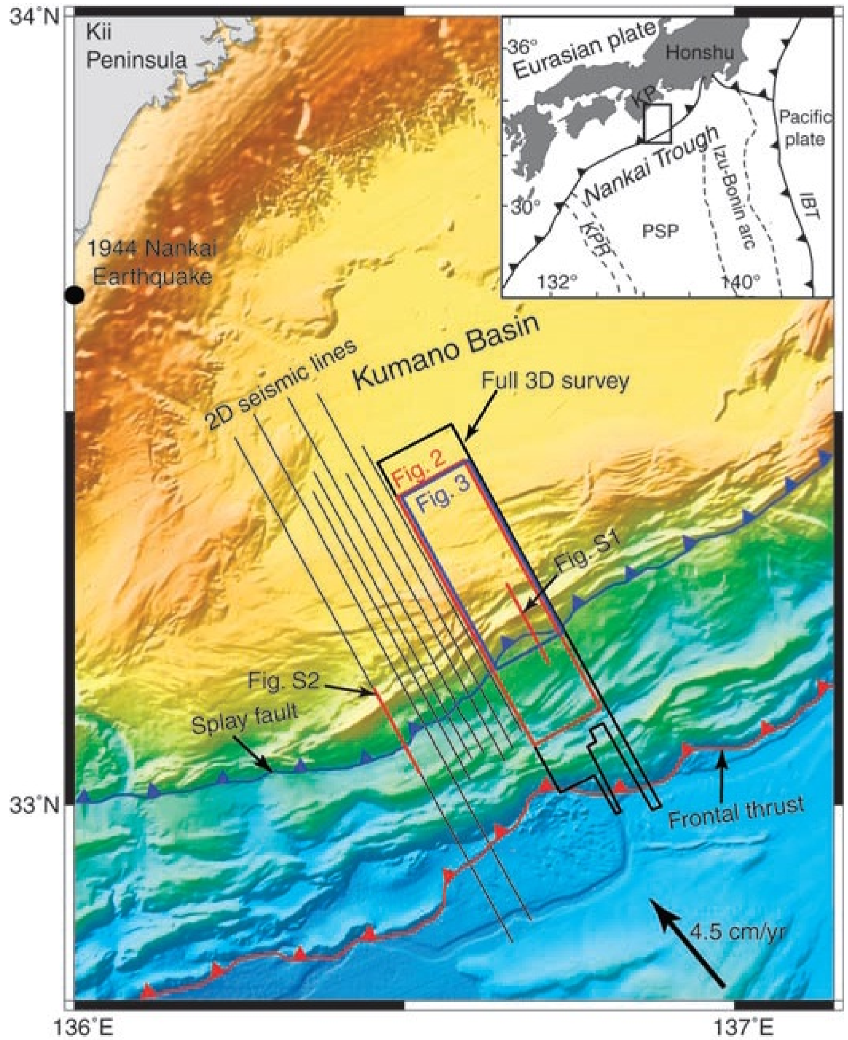


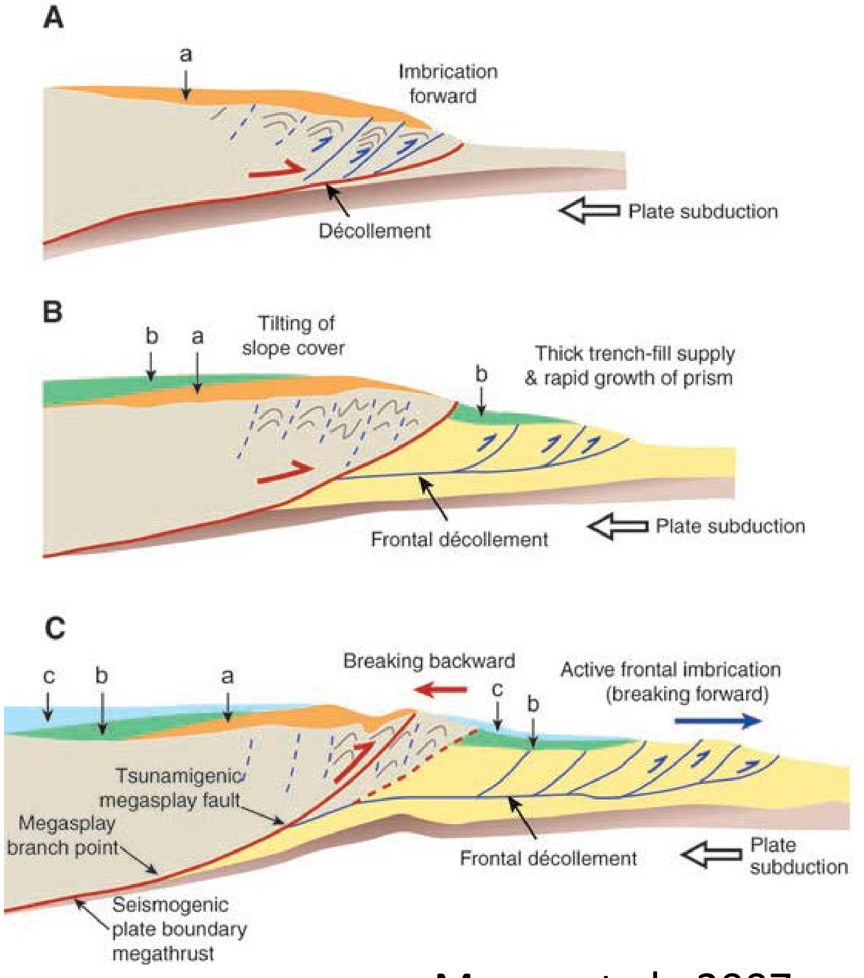
Chyi-Tyi Lee, 2015

What is an OOST?

- OOST branches from the detachment, and can penetrate trough surface, which means large (~10 km) offset between hanging wall and footwall.
- OOST is the boundary and separates two rock types in a wedge (Wang and Hu, 2006):
  - A stronger "inner wedge" on the OOST's hinterland
  - A weaker "outer wedge" on the OOST's foreland side
- Active OOST can make the whole fault plane slip and generate large magnitude earthquake (e.g. Nankai trough area).

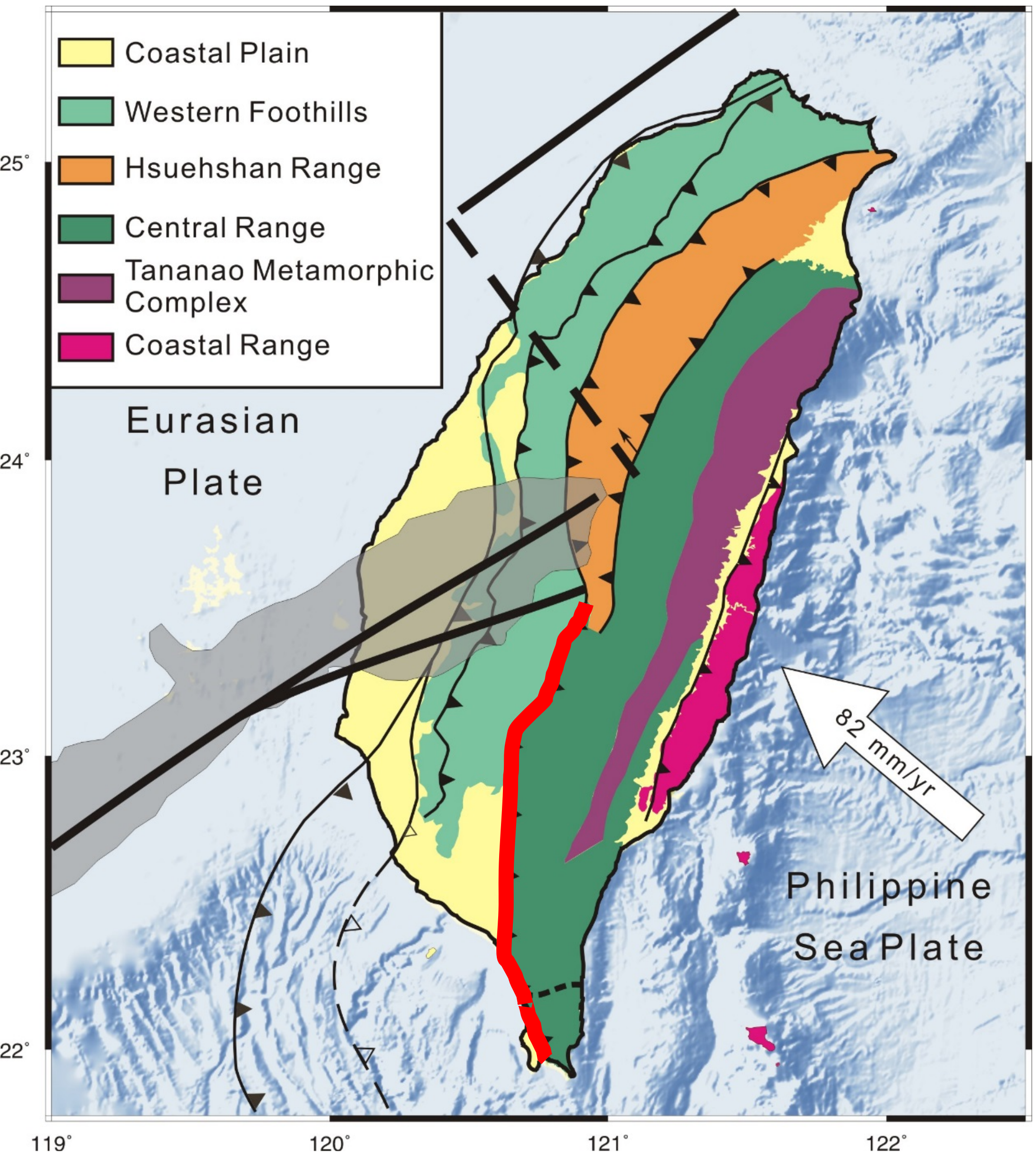
An example of a seismogenic OOST: Nankai Trough megasplay





Moore et al., 2007

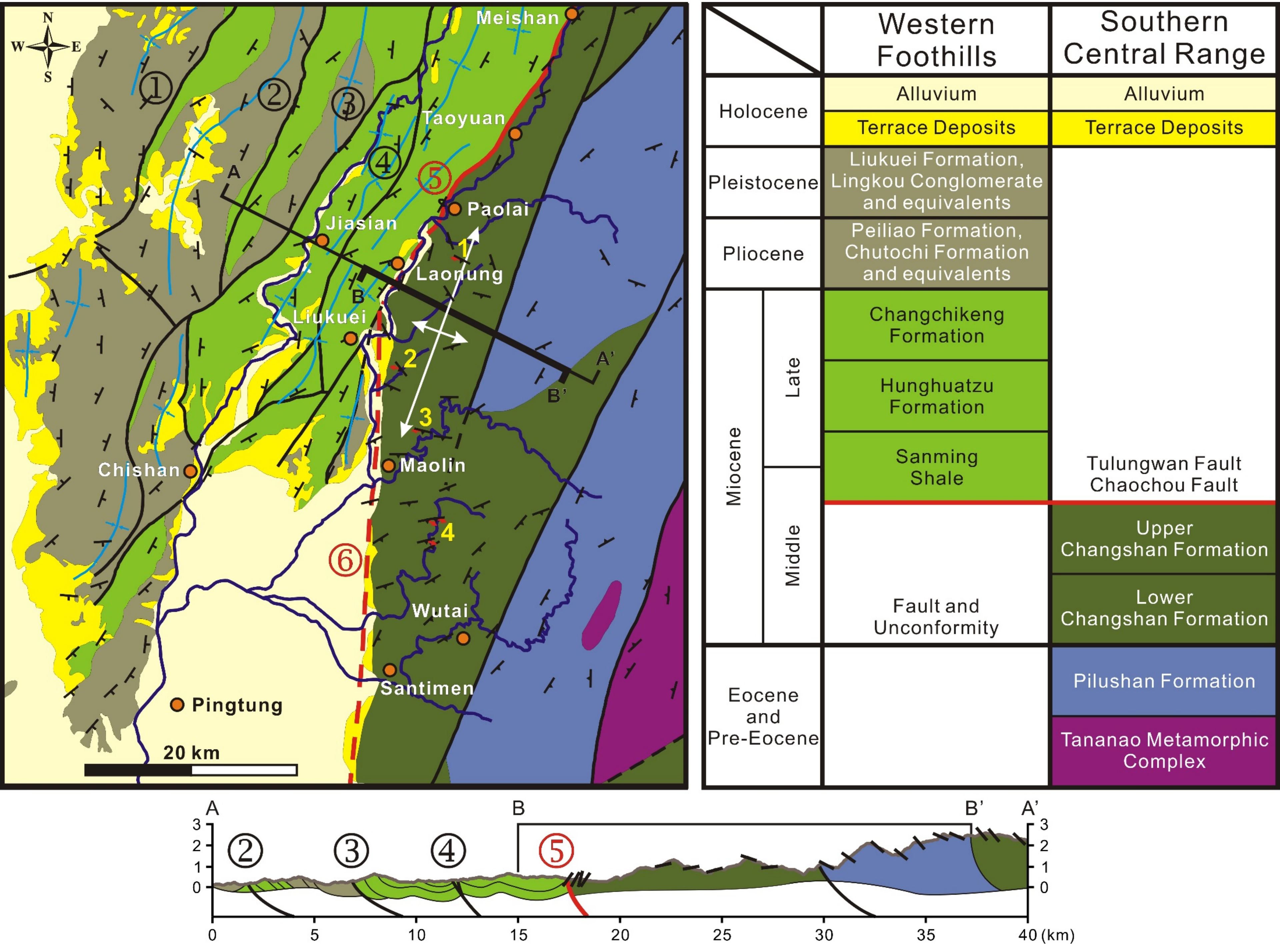
Another possible OOST in Taiwan



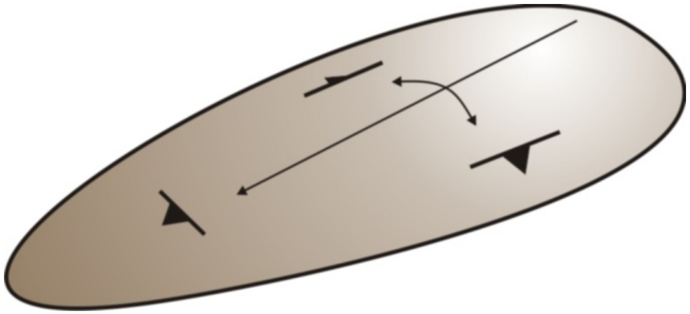
- The boundary between Western Foothills and the southern Central Range is a major structural boundary
- Previous recognized as the Chaochou-Tulungwan Fault system
- Separates unmetamorphosed sedimentary rocks in the footwall from slate in the hanging wall
- Maximum vertical offset could up to 11 km (based on maximum paleo-temperature difference)

Research questions

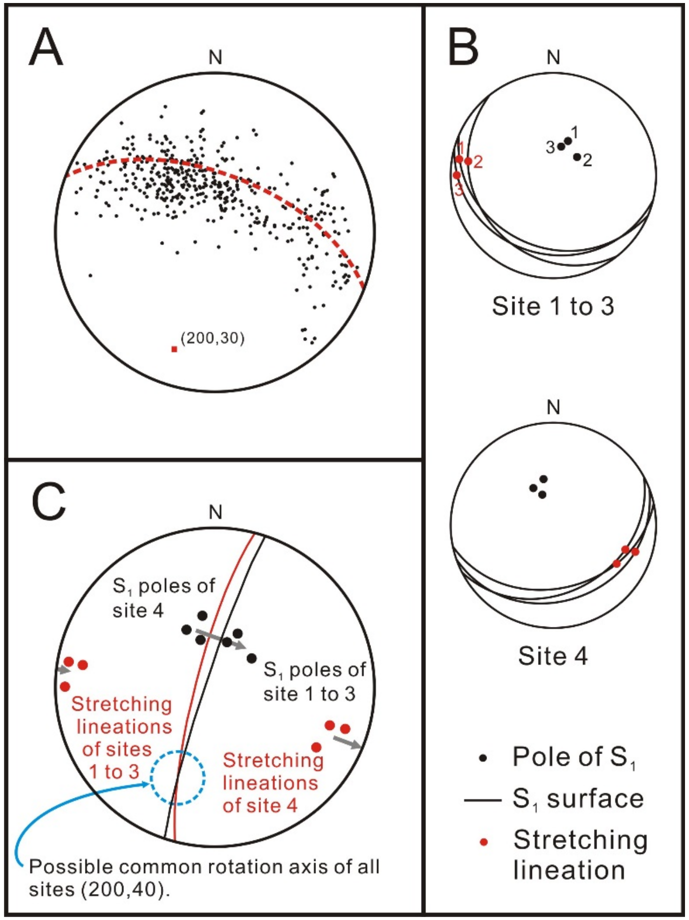
- Are there any structures related to the Chaochou-Tulungwan Fault in southern Taiwan?
- What is the deformation history of the Chaochou-Tulungwan Fault?
- Is the Chaochou-Tulungwan Fault in southern Taiwan active?

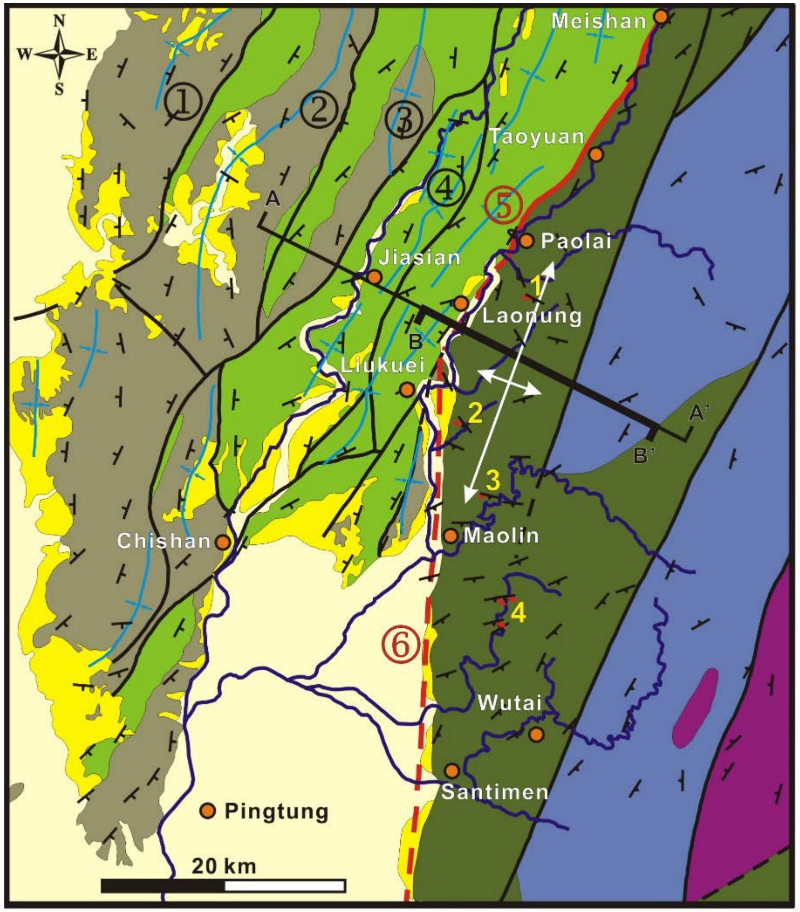

N
S
W
E
①
②
③
④
⑤
⑥
Meishan
Taoyuan
Paolai
Jiasian
Laonung
Liukuei
Maolin
Chishan
Wutai
Santimen
Pingtung
A
A'
B
B'
1
2
3
4
20 km
Western Foothills
Southern Central Range
Holocene
Alluvium
Alluvium
Terrace Deposits
Terrace Deposits
Pleistocene
Liukuei Formation, Lingkou Conglomerate and equivalents
Pliocene
Peiliao Formation, Chutochi Formation and equivalents
Miocene
Late
Changchikeng Formation
Hunghuatzu Formation
Sanming Shale
Tulungwan Fault
Chaochou Fault
Middle
Fault and Unconformity
Upper Changshan Formation
Lower Changshan Formation
Eocene and Pre-Eocene
Pilushan Formation
Tananao Metamorphic Complex
0
5
10
15
20
25
30
35
40 (km)
3
2
1
0

The slate antiform



New discovery: the Laonung antiform



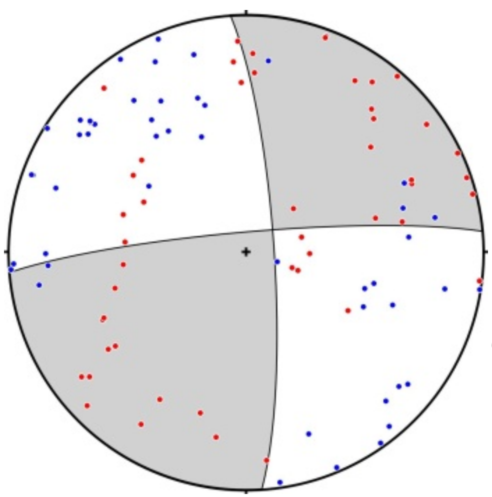


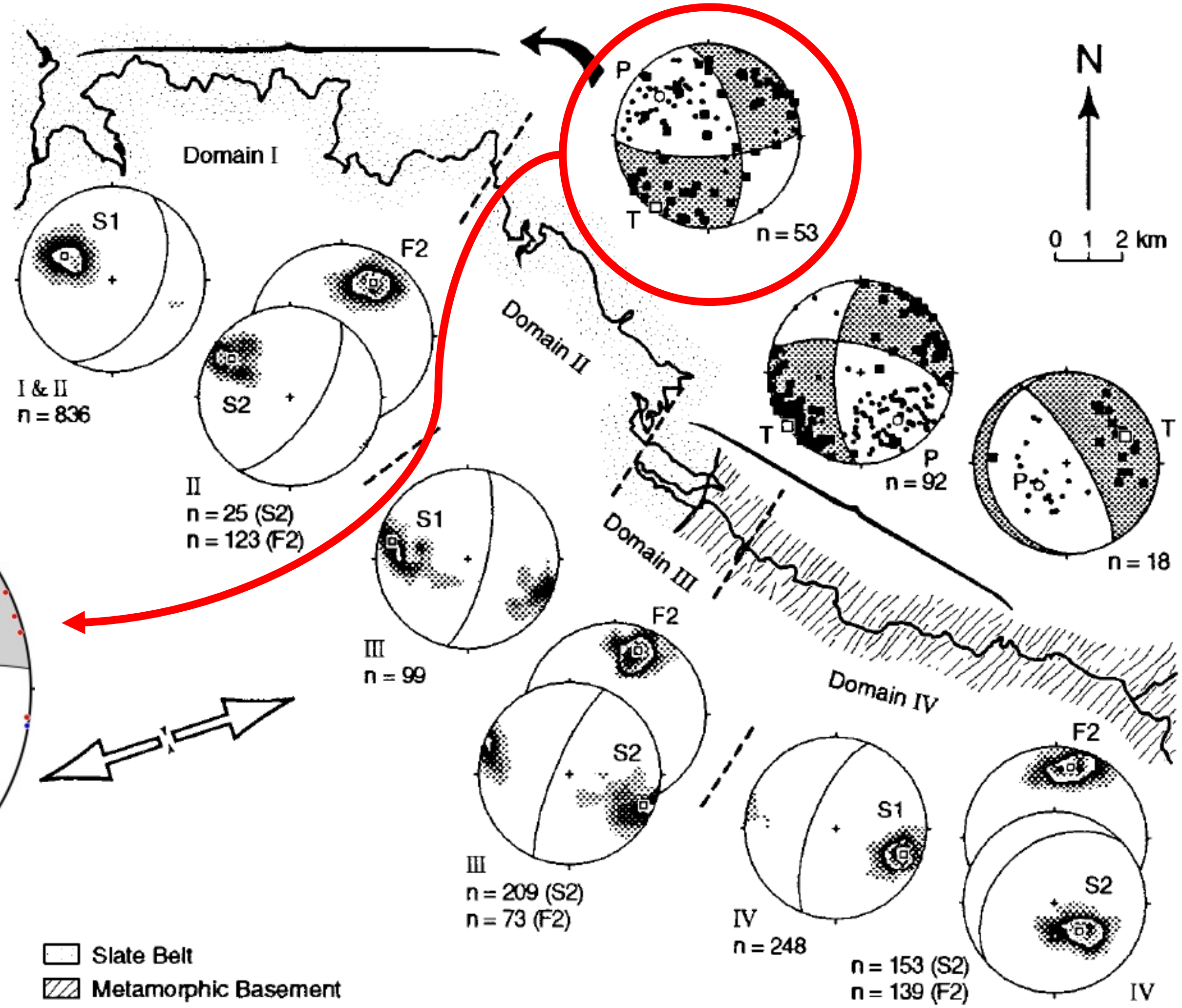
Paleostress inversion of the Tulungwan Fault

Reconstruction of shortening history

Kinematic analysis of field-identified early stage faults

Early stage faults
n = 48, 130-310°

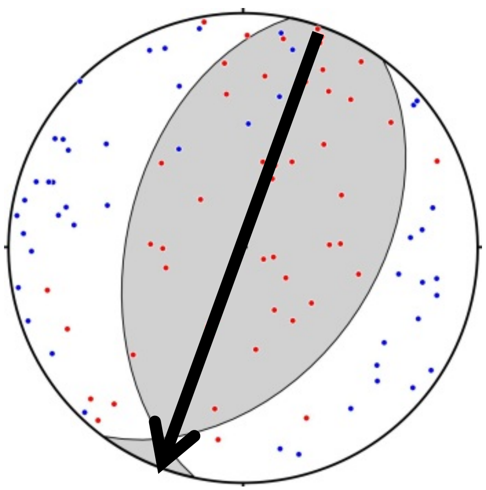


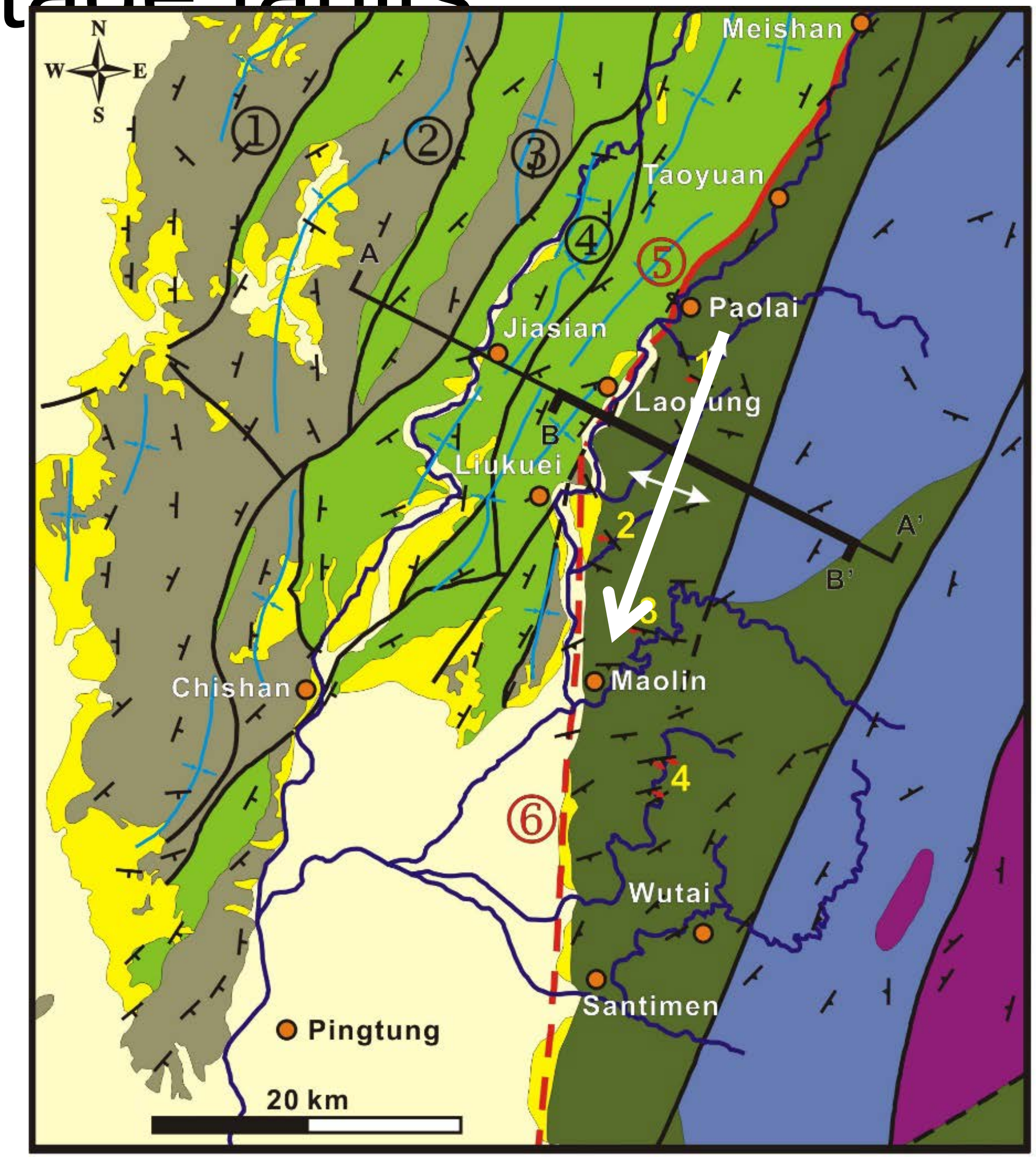


Crespi et al., 1996

Kinematic analysis of field-identified
late stage faults

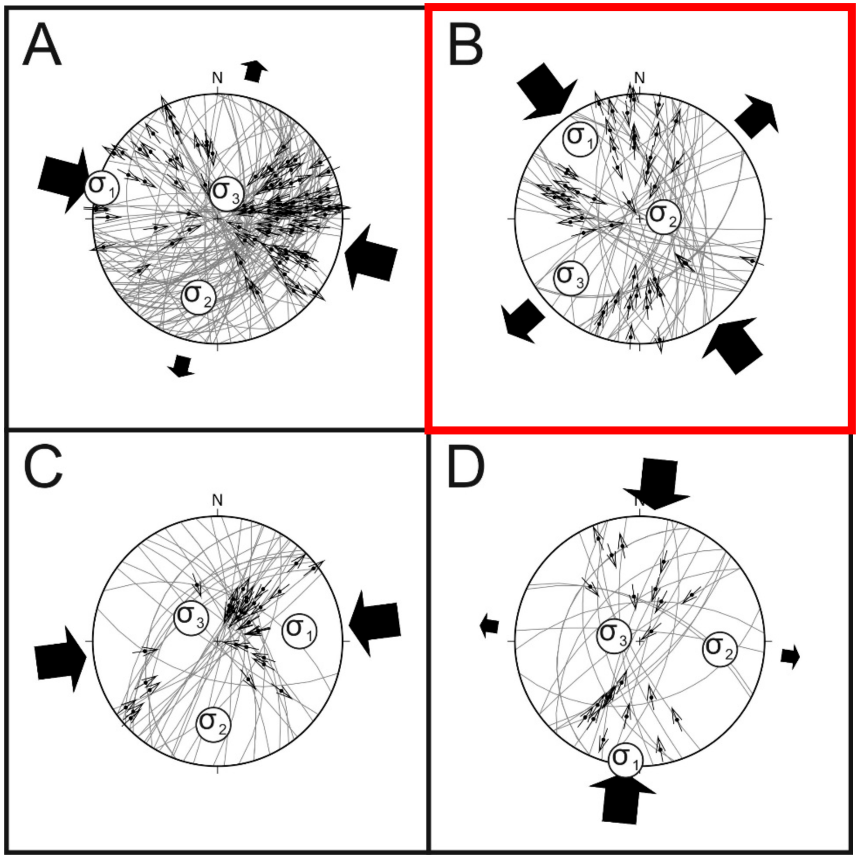
- Late stage faults
- n = 47, 113-293°





Stress inversion of 250 faults without the field-identified relative age control

Stress Inversion		
Phase	Max Orient.	Early / Late
1 (A)	285 / 02	17 / 22
2 (B)	323 / 13	12 / 6
3 (C)	083 / 23	5 / 5
4 (D)	187 / 02	1 / 7



- Three shortening stages
  - Stage 1
    NW-SE
    - Parallel to the plate convergence direction.
  - Stage 2
    WNW-ESE to WSW-ENE
    - Perpendicular to the fold axis of the slate antiform.
  - Stage 3
    NNE-SSE to N-S
    - Parallel to the lateral extrusion and the Jia-Shian earthquake.

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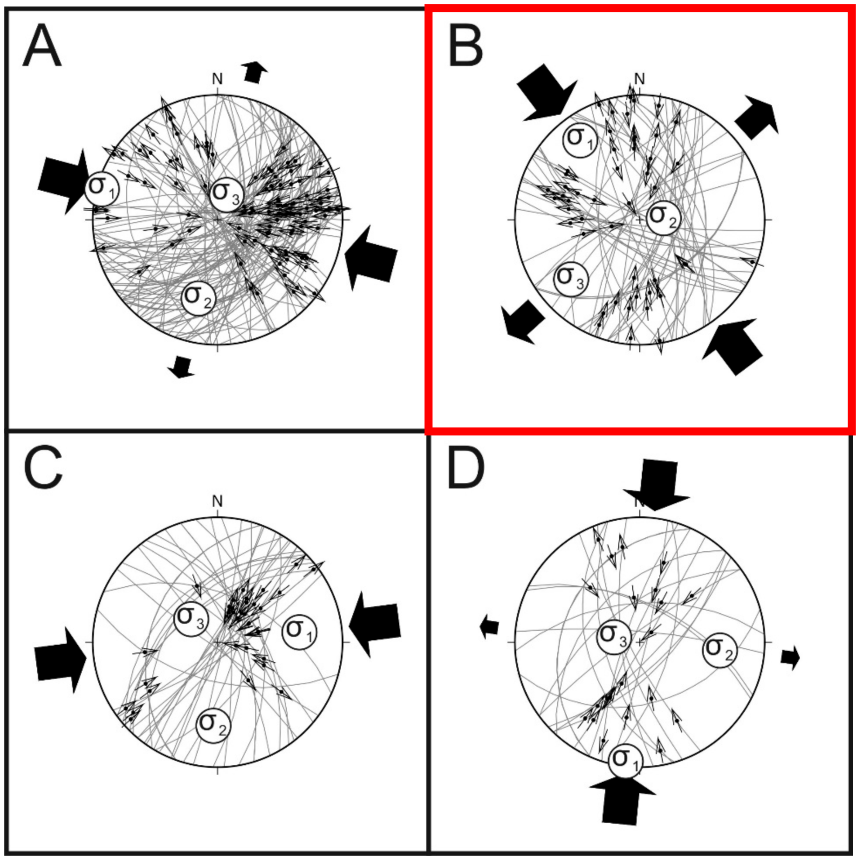
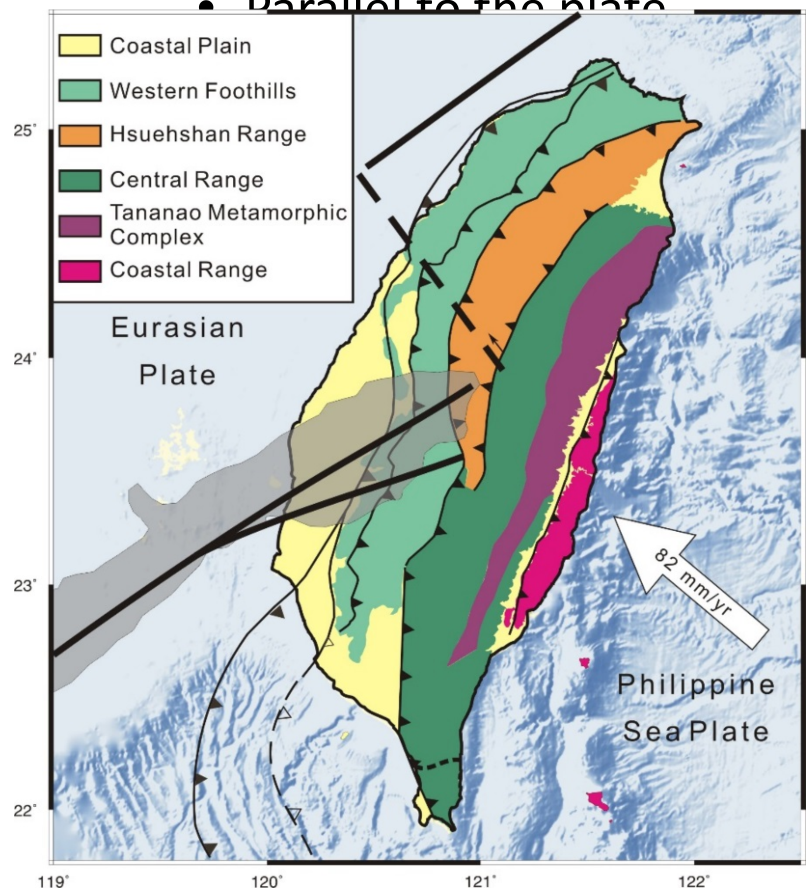


- Three shortening stages
  - Stage 1 NW-SE
    - Parallel to the plate



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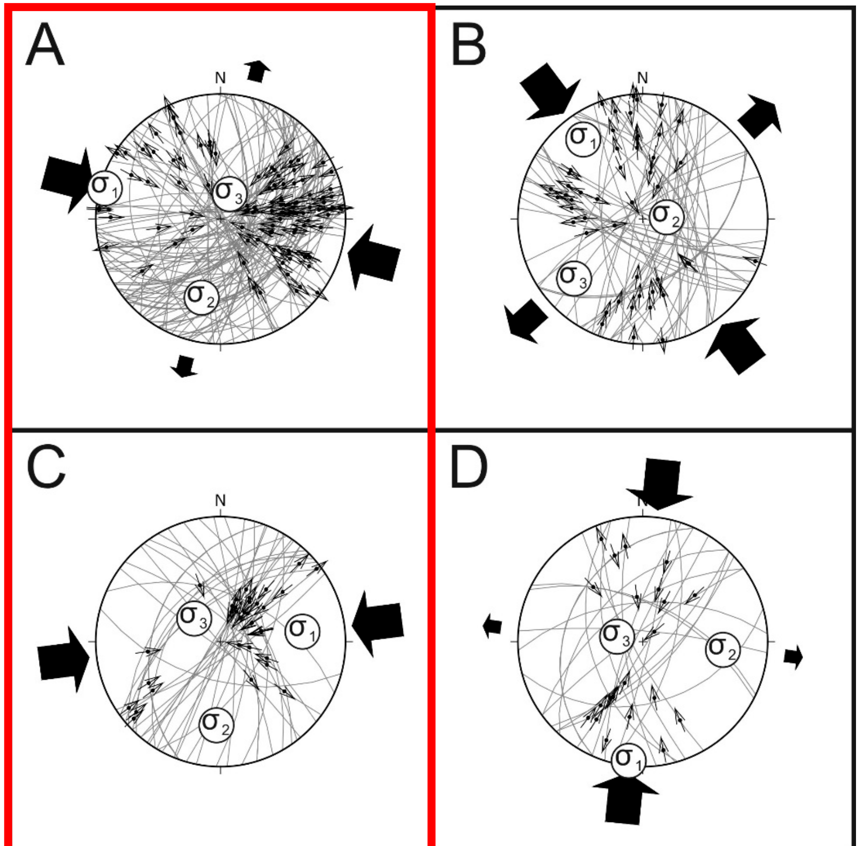

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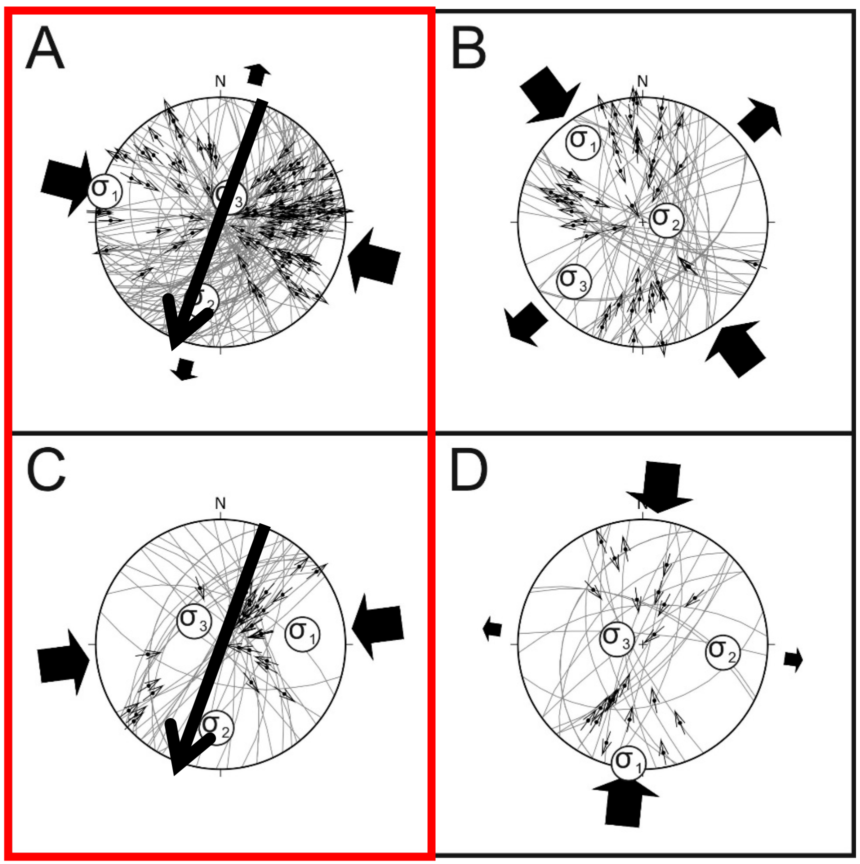

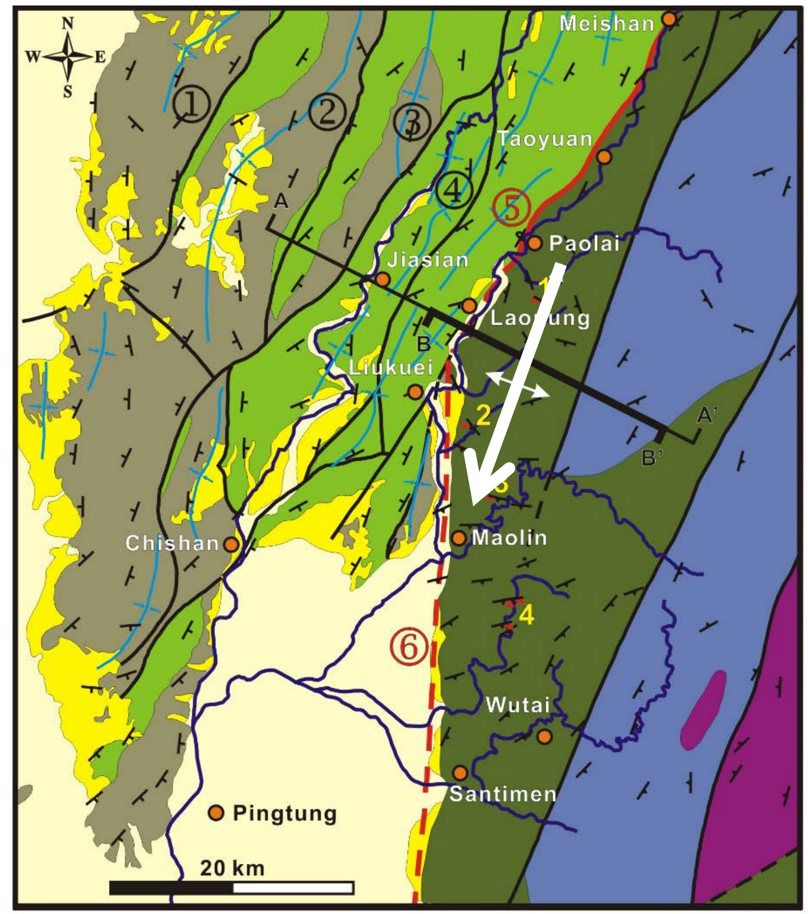

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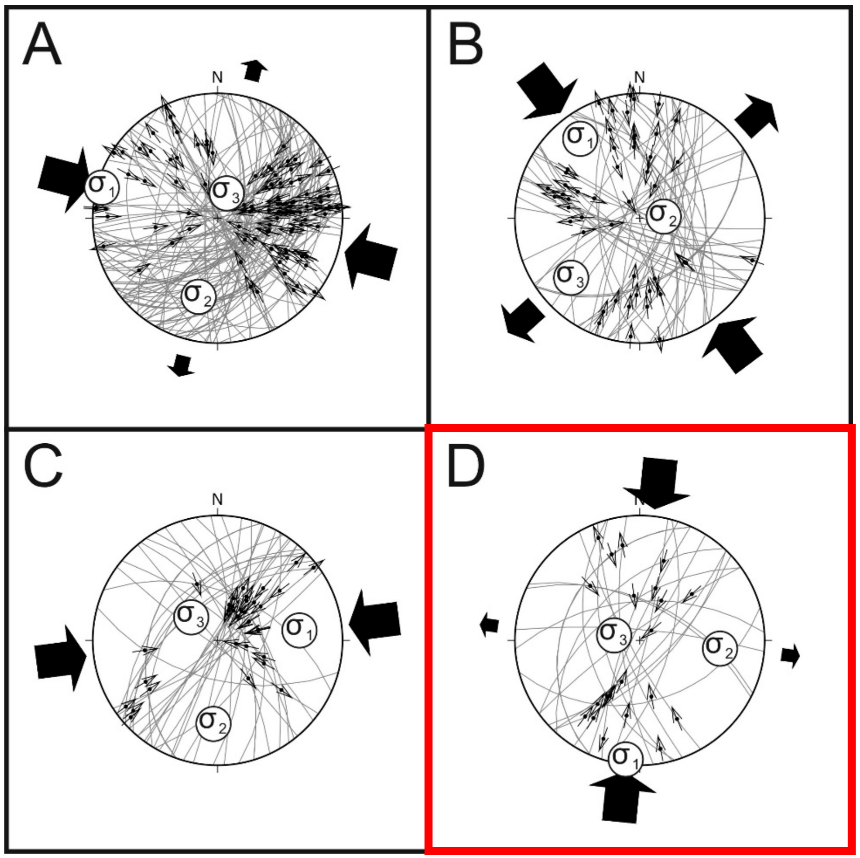

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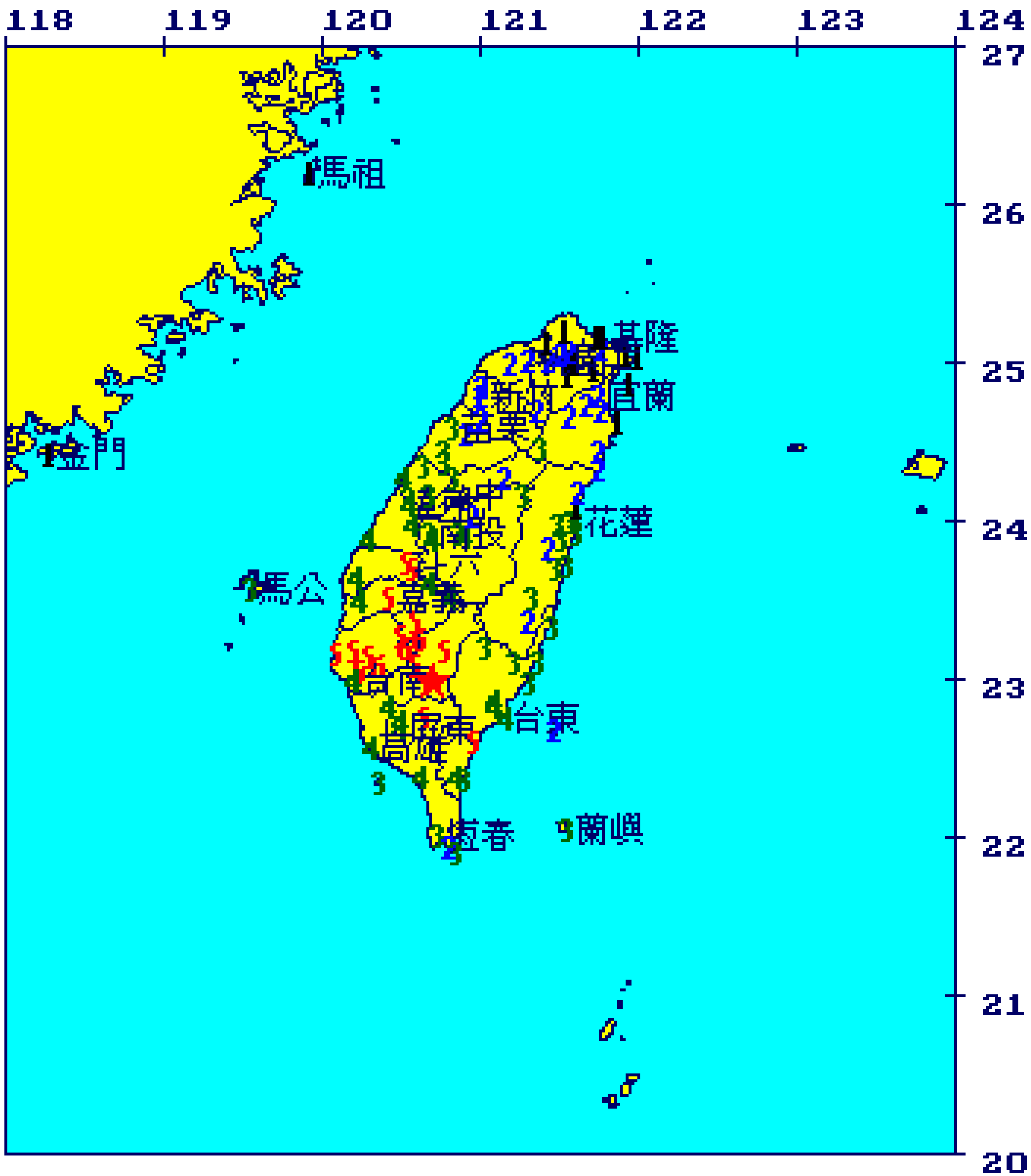


圖說：★表震央位置，阿拉伯數字表示該測站震度

中 央 氣 象 局 地 震 報 告

編號： 第99015號

日期： 99 年 3 月 4 日

時間： 8 時 18 分 52.1 秒

位置： 北緯 22.97 度，東經 120.71 度
即在 高雄甲仙地震站東南方 17.1 公里

地震深度： 22.6 公里

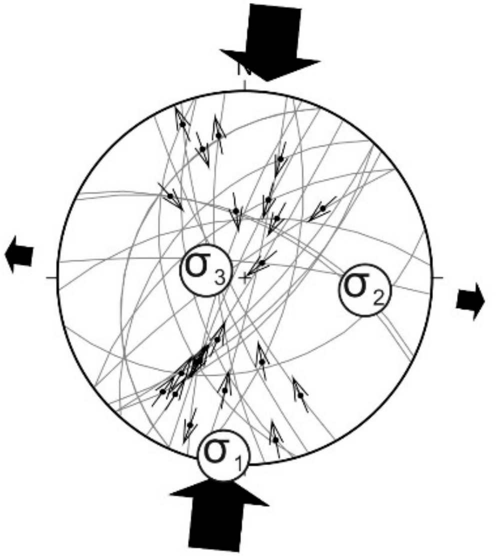
芮氏規模： 6.4

各地最大震度

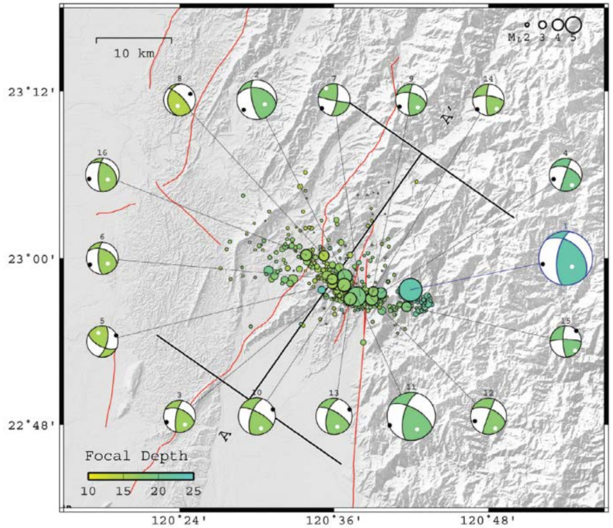
台南楠西	6級	花蓮紅葉	3級
嘉義大埔	6級	南投市	3級
高雄甲仙	5級	台中市	3級
屏東三地門	5級	澎湖馬公	3級
台東太麻里	5級	花蓮市	3級
嘉義市	5級	苗栗鯉魚潭	3級
雲林古坑	5級	宜蘭南山	3級
斗六市	5級	苗栗市	3級
屏東市	4級	桃園三光	2級
台南市	4級	新竹市	2級
台東市	4級	新竹竹北	2級
高雄市	4級	宜蘭市	2級
南投名間	4級	桃園市	2級
彰化大城	4級	台北板橋	2級
彰化市	4級	台北市	2級
台中港	4級	基隆市	1級

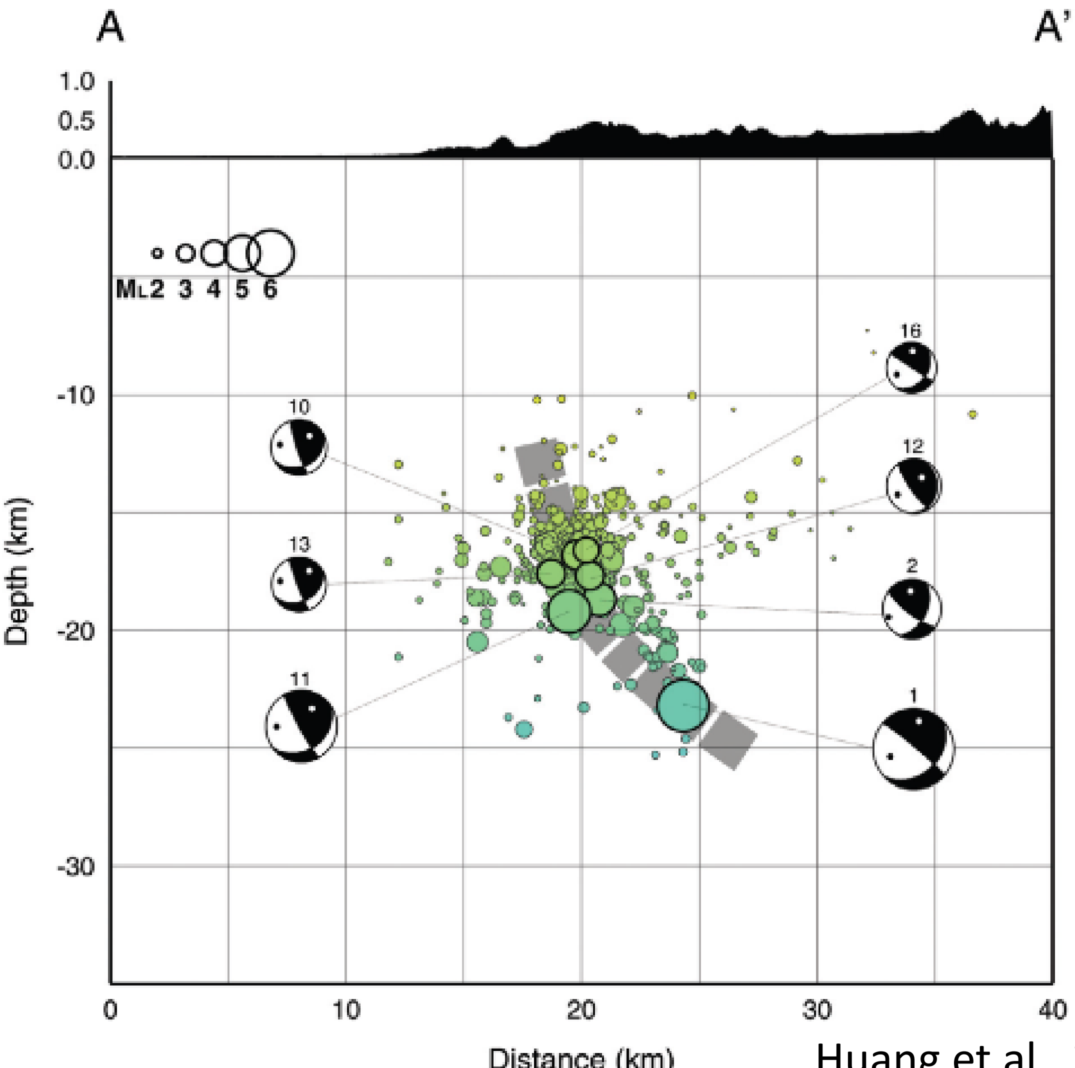
NNE-SSE to N-S, Late stage faults

Parallel to the lateral extrusion and the Jiasian earthquake



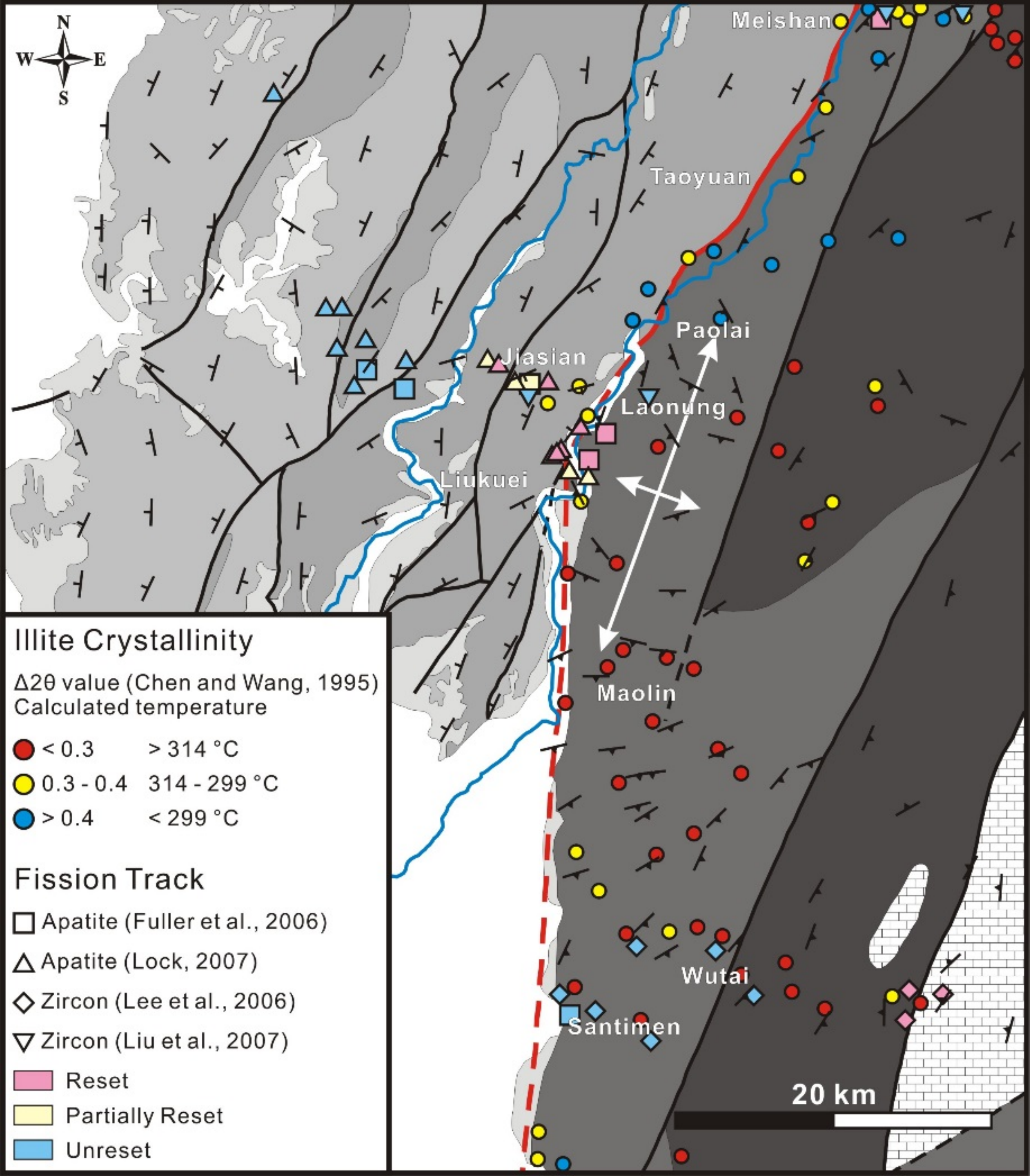
007° - 187°





Huang et al., 2011

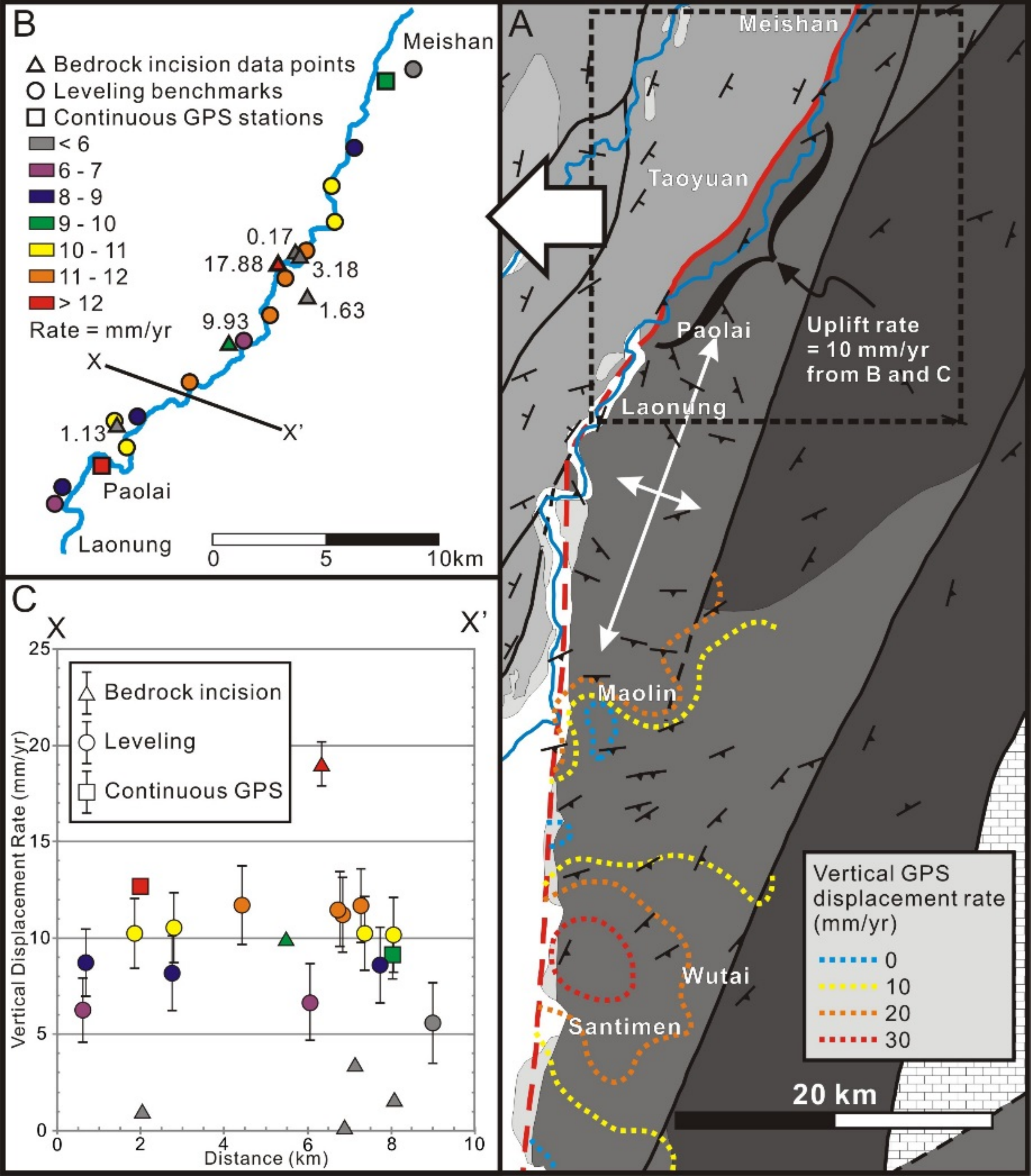
Uplift rates and deformation pattern



Long-term deformation rate

- Apatite Fission Track reset temperature ≈ 100°C
- Geothermal gradient ≈ 30 °C/km, 100°C ≈ 3 km
- AFT reset age: 2.0 – 3.4 Ma (Fuller et al., 2006)
- Uplift rate ≈ 0.7 – 1.1 km/Ma = 0.7 – 1.1 mm/yr

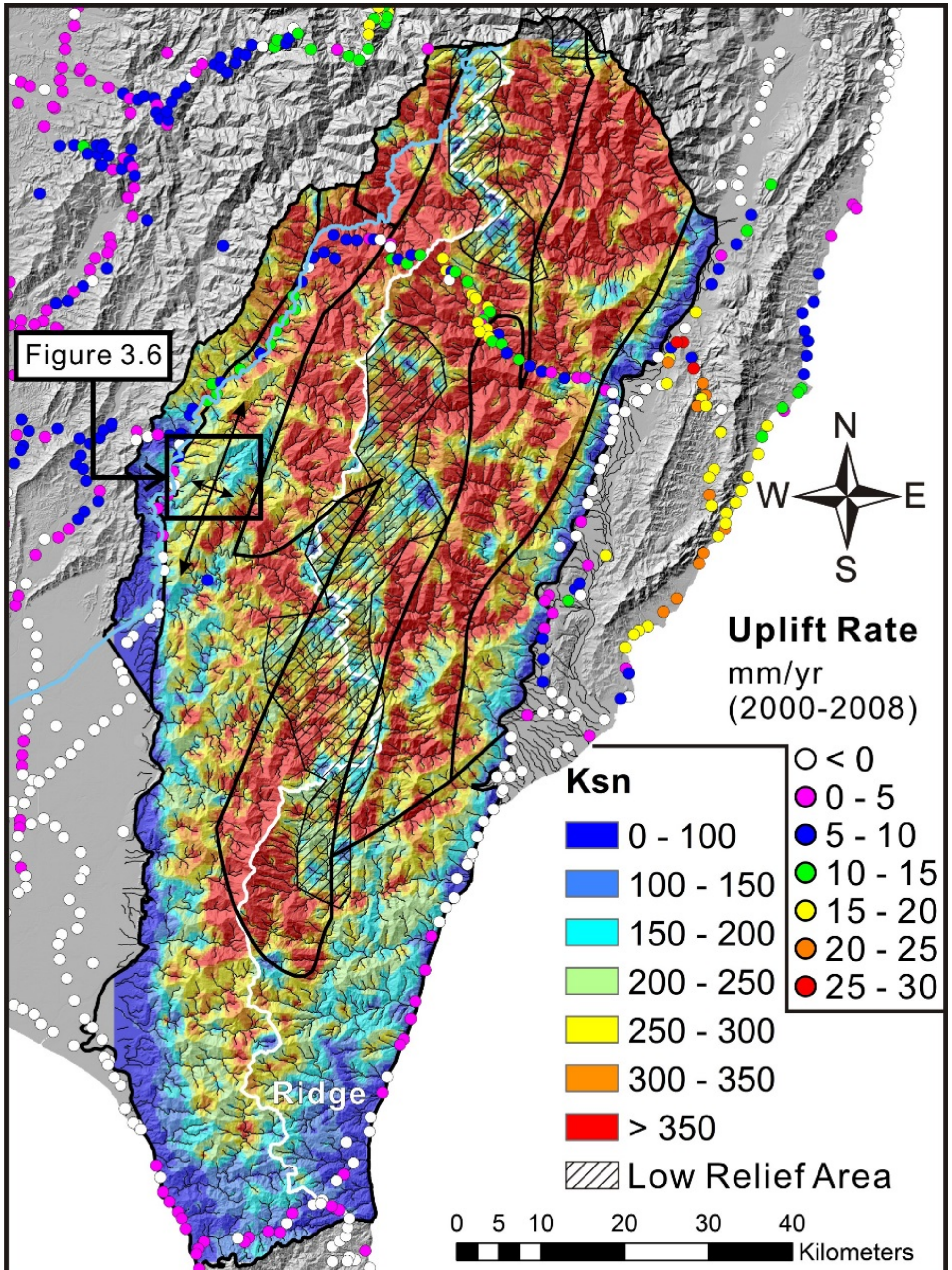
Evidence for active deformation



- Leveling and GPS: 2000 – 2008 (Ching et al., 2011)
- GPS contour: 1995 – 2005 (Ching et al., 2007)

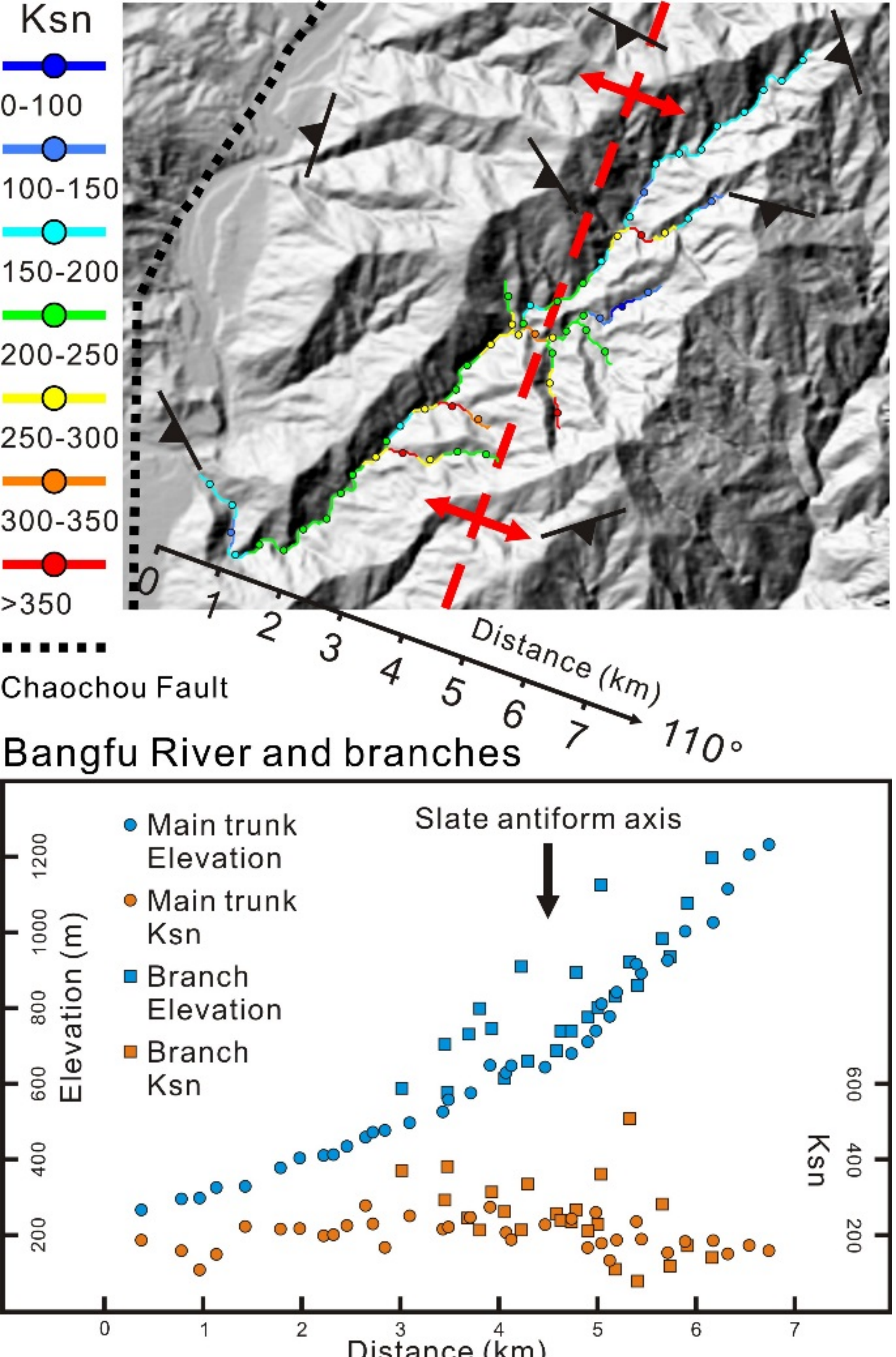
Two geomorphic indices are used in the study

- River steepness index (k_{sn})
  - k_{sn} is normalized steepness: values are normalized to watershed area and river concavities of nearby rivers.
  - k_{sn} values generally relate to uplift rate and rock erodibility, with higher k_{sn} values reflecting stronger rocks or higher uplift rates.
- Drainage basin asymmetry factor (AF)
  - Drainage basin asymmetry records tilting of a drainage basin or bedrock anisotropy within a basin.



k_{sn} of southern Central Range

- High values correlate with Eocene and pre-Tertiary metamorphic rocks in the north and, lower values in the lower grade Miocene slate in the south
- Higher values also correlate with higher uplift rates in the north

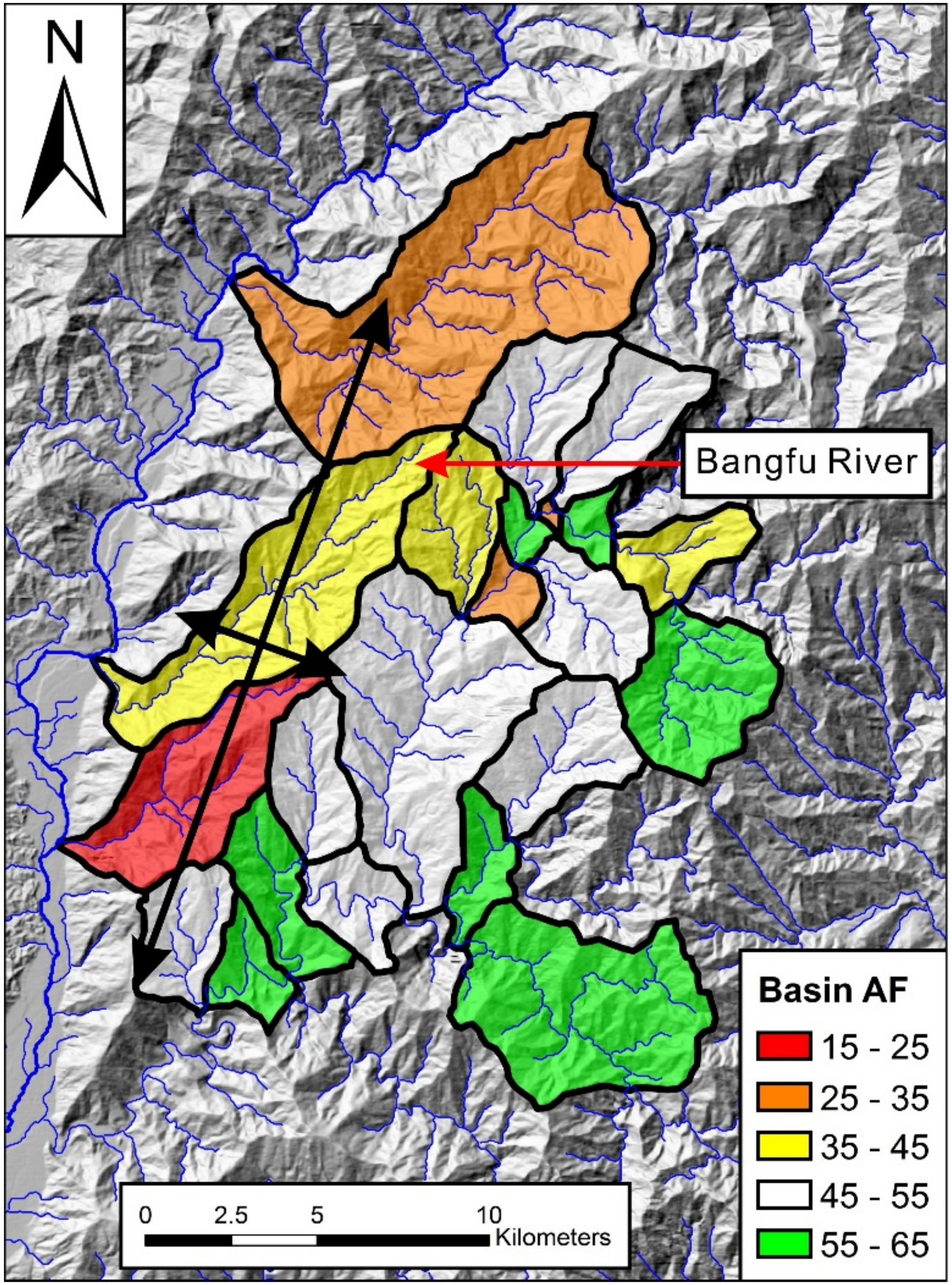


k_{sn} cross the Laonung antiform

- k_{sn} data suggest that the river reaches in the central part of the Bangfu River catchment are steeper (i.e. have higher k_{sn} values) than upstream or downstream
- These steeper reaches may reflect activity of the Laonung antiform

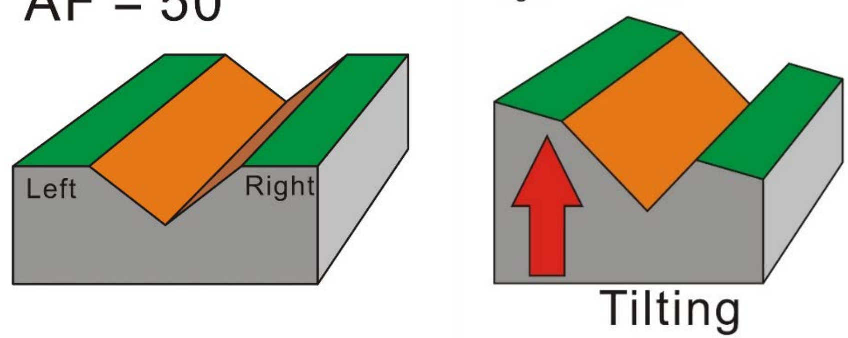
AF cross the Laonung antiform

- AF values in basins along the axis of the Laonung antiform significantly lower than AF values in basins away from the axis
- The low values, when viewed downstream, suggest tilting to



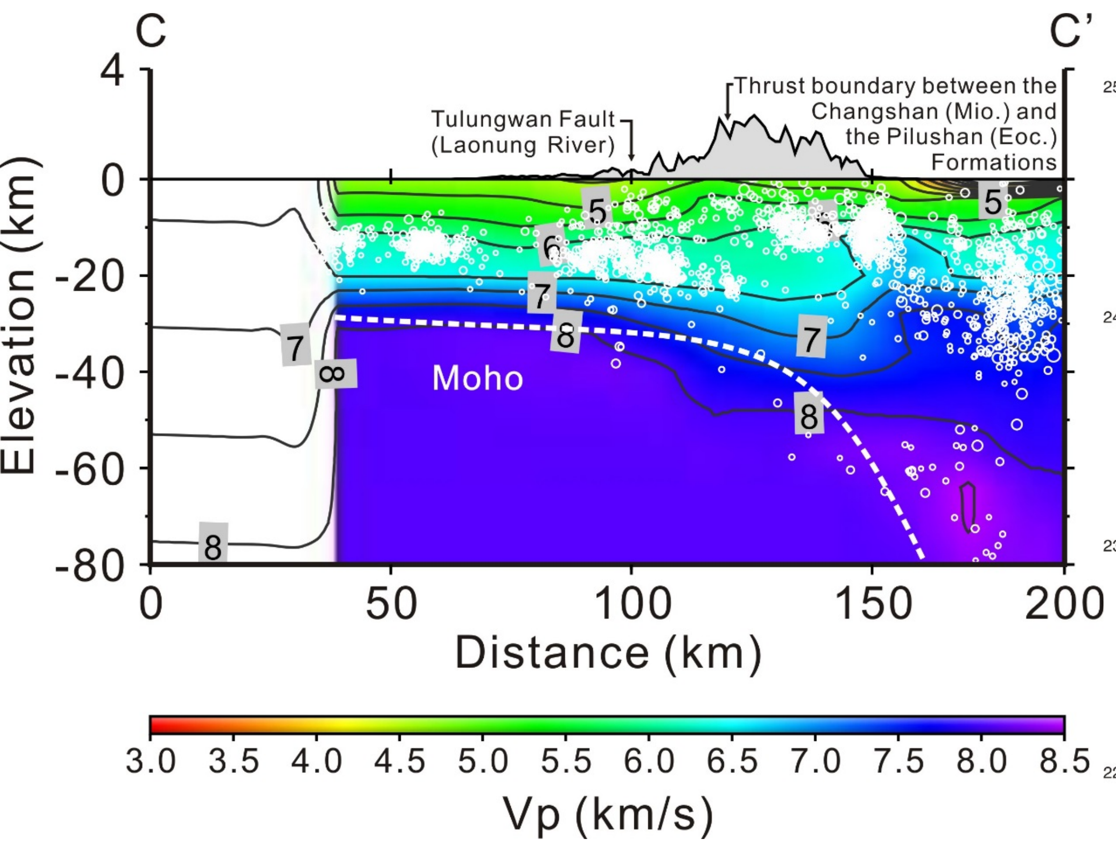
$A_{right} = A_{left}$
$A_{right} / A_{total} = 0.5$
$AF = 50$

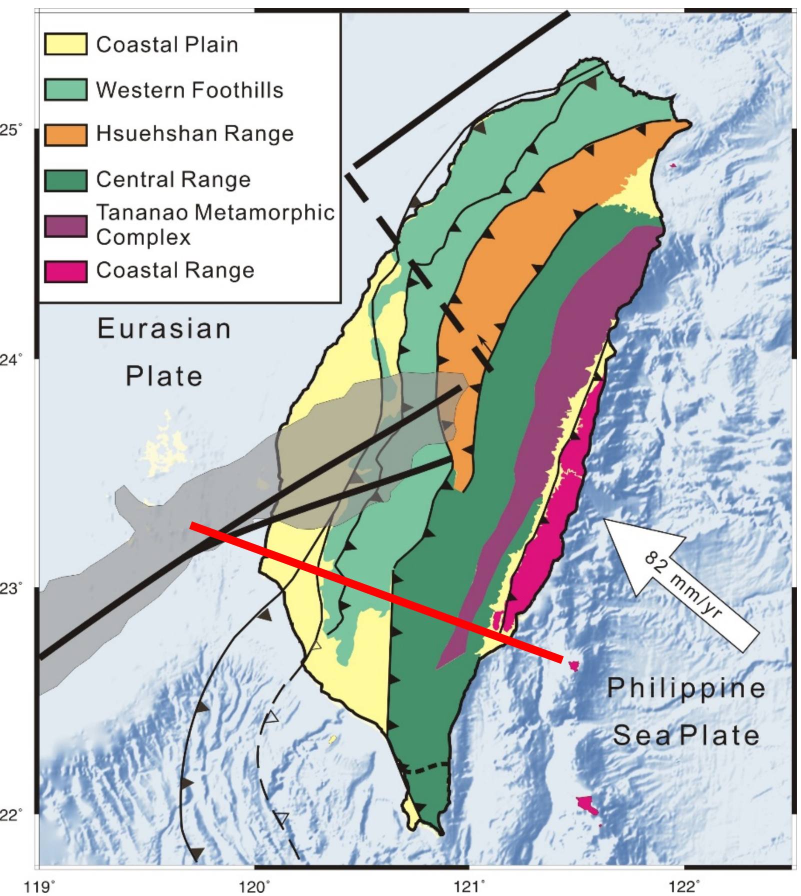
$A_{right} < A_{left}$, $AF < 50$



Tectonic evolution model

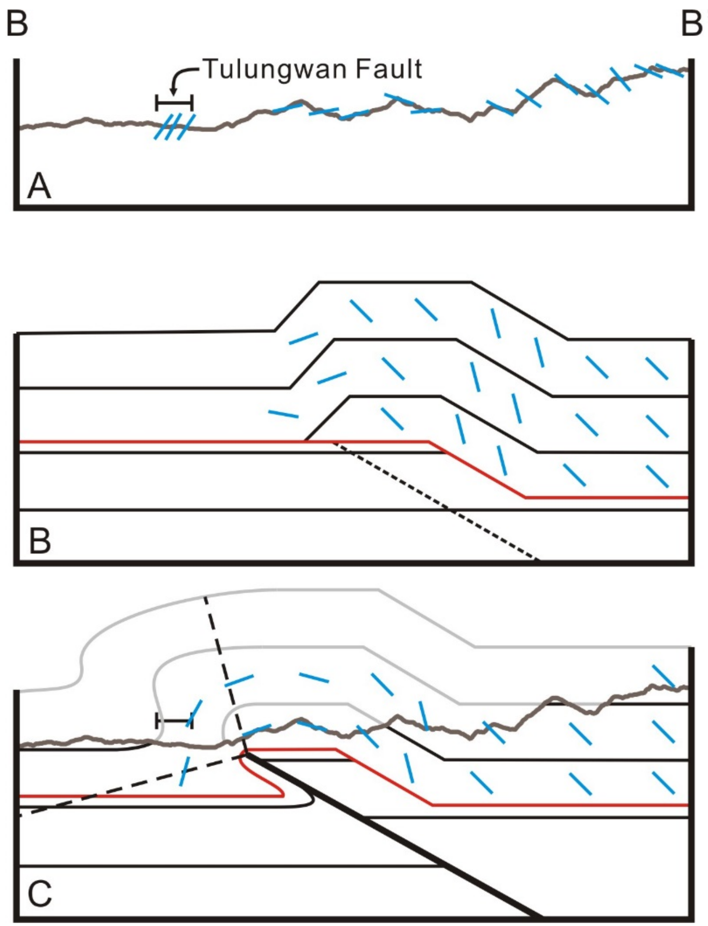
Tomographic profile beneath the antiform

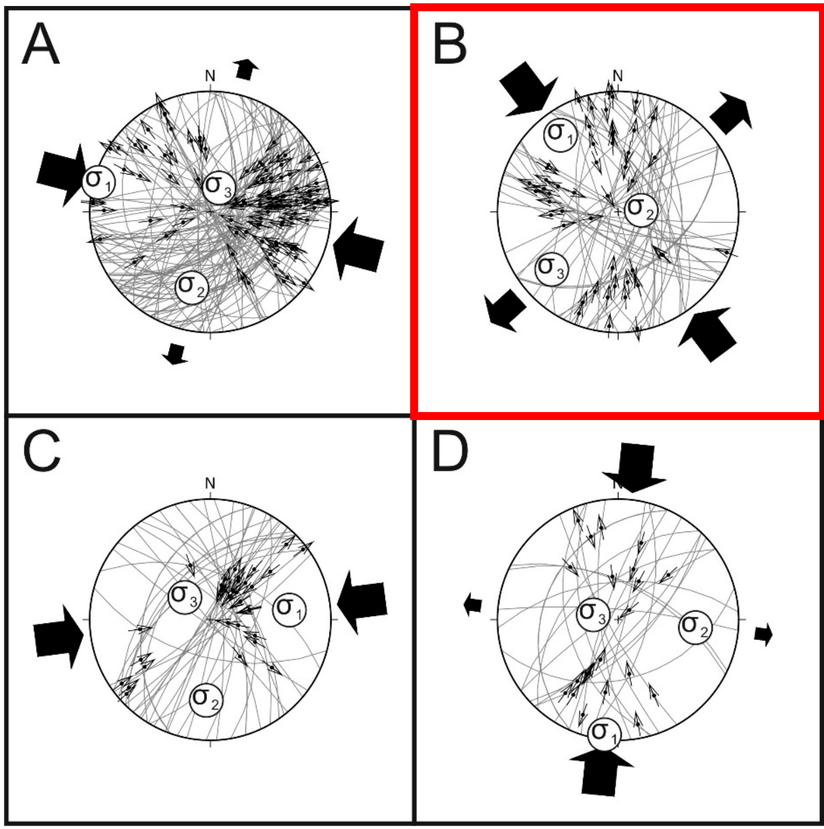




Data from Hao Kuo-Chen

Proposed multiple stage deformation model

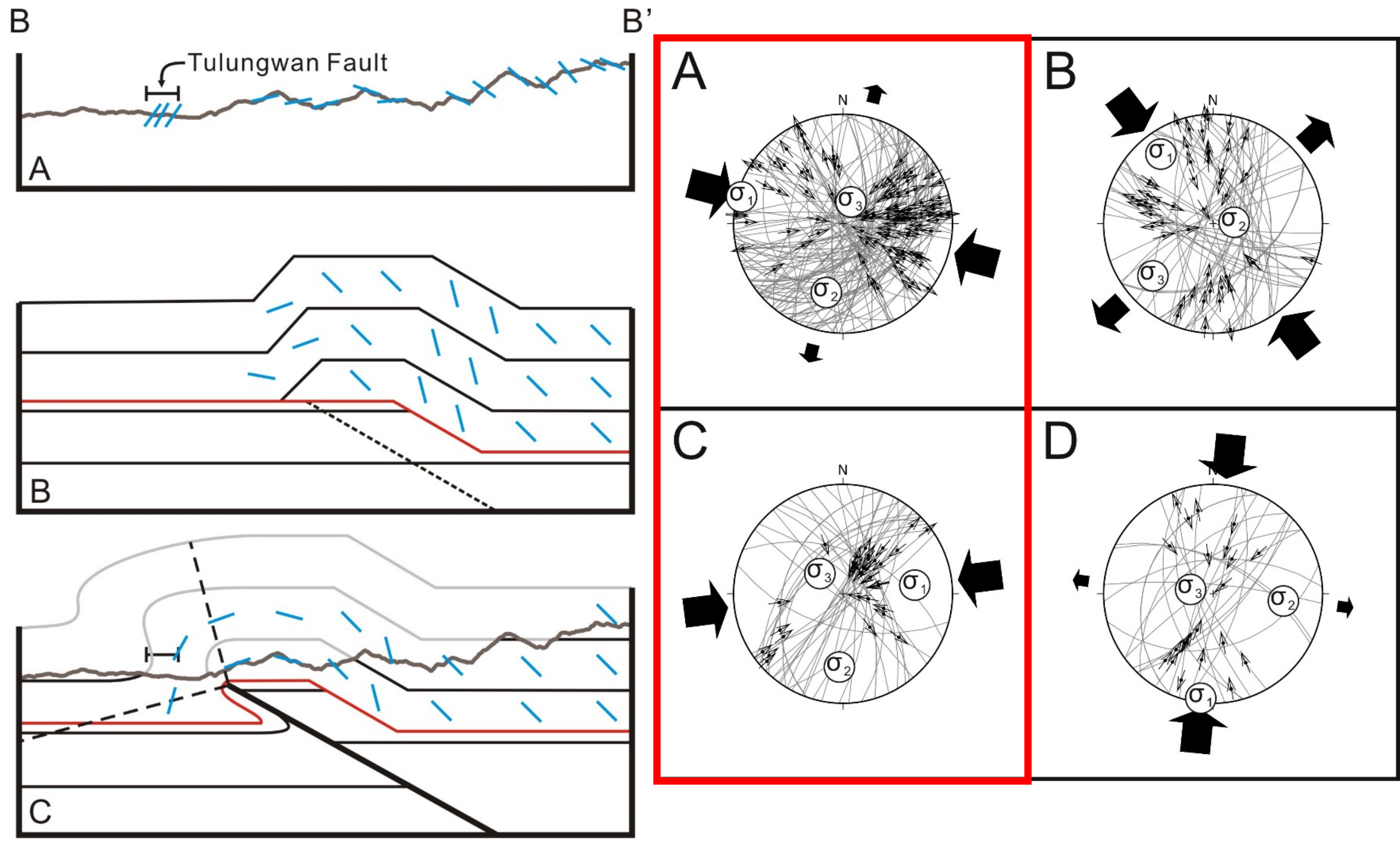




Early stage

Parallel to the plate convergence direction.

Proposed multiple stage deformation model



Late stage

Perpendicular to the fold axis of the Laonung antiform.

Conclusion

- The geometry of deformed cleavage shows a regional-scale antiform
- Paleo-stress analyses of brittle faults in the antiform area indicate a shortening direction that is perpendicular to the fold axis.
- River incision rates and recent leveling data along the Laonung River, consistent with an active structure.
- Leveling data along the Laonung River show relatively high rates of uplift (up to 12 mm/yr), suggesting that the high rates of uplift are more important than rock erodibility in determining k_{sn} value in this area.
- The deformed slates identified an overturned-forelimb of the regional-scale antiform in the Laonung River Valley.
- We propose that the antiform is forming at the tip of a low-angle thrust which splays from a regional scale detachment.

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- National Chung Cheng University: Drs. Yuan-Hsi Lee and Meng-Long Hsieh
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From accretion to collision: Motion and evolution of the Chaochou Fault, southern Taiwan

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Thank you!