# Inferences from the Field - Effects of Geometry on Earthquake Ruptures

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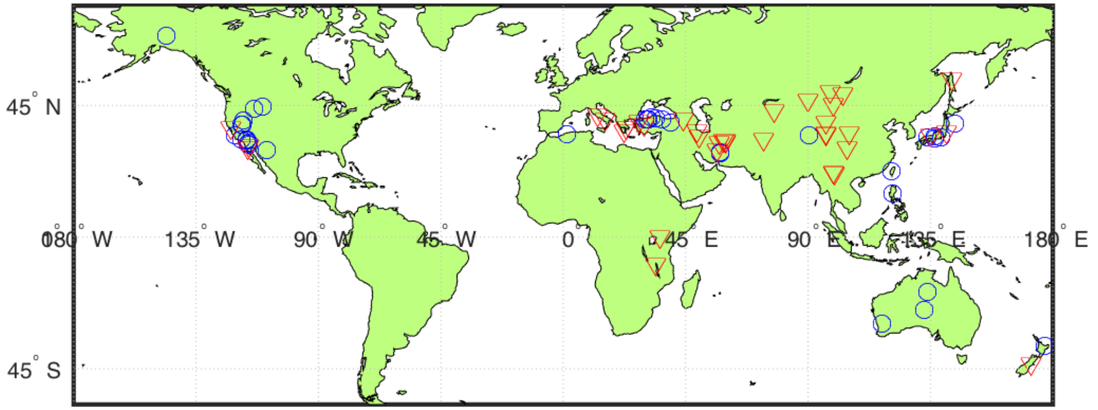
# Surface Rupture Data

- *Steps in surface rupture developed a large data set: 46 strike-slip, 30 dip-slip surface rupturing events.*
- *Bends in surface rupture:  67 rupture maps*
- *Annotated surface rupture maps available at BSSA.*




RESEARCH ARTICLE | MAY 24, 2016

**Steps and Gaps in Ground Ruptures: Empirical Bounds on Rupture Propagation**

Glenn P. Biasi; Steven G. Wesnousky

Bulletin of the Seismological Society of America (2016) 106 (3): 1110-1124.

https://doi.org/10.1785/0120150175

RESEARCH ARTICLE | OCTOBER 10, 2017

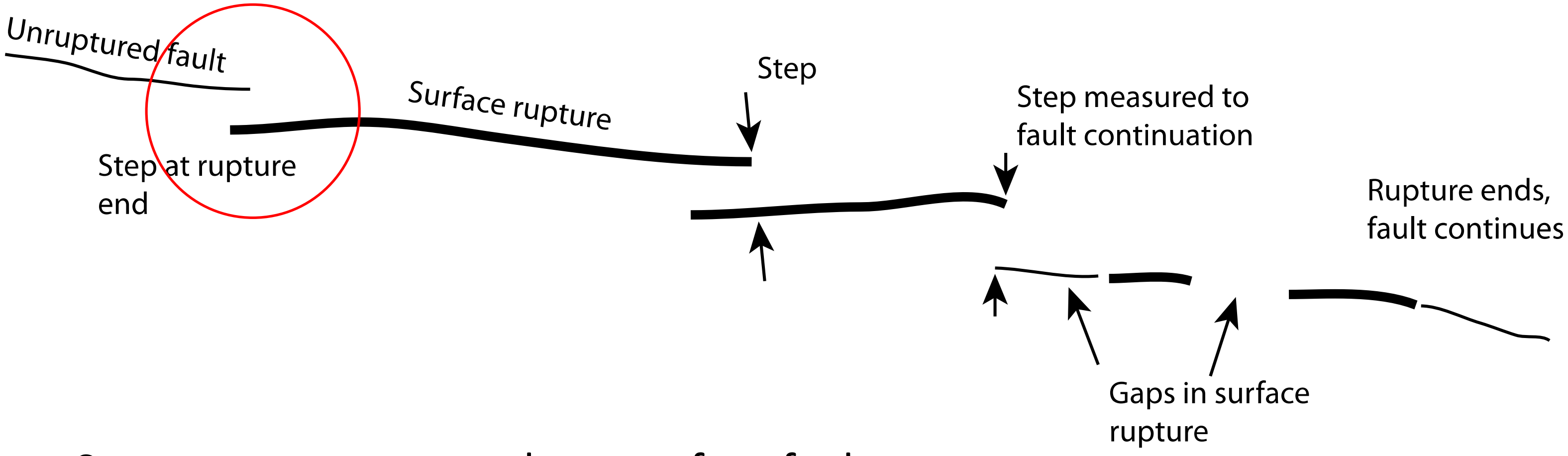
**Bends and Ends of Surface Ruptures**

Glenn P. Biasi; Steven G. Wesnousky

Bulletin of the Seismological Society of America (2017) 107 (6): 2543-2560.

https://doi.org/10.1785/0120160292

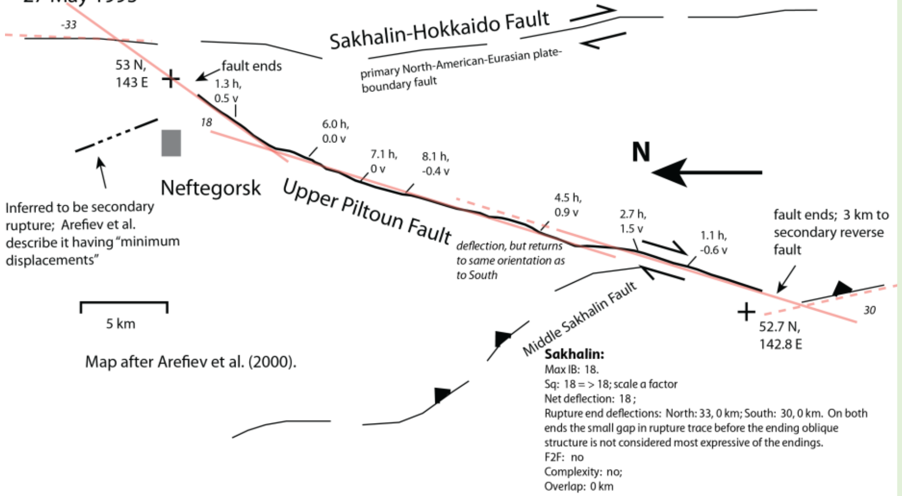
## Step and Gap Measurements




Step measurements only on surface fault sections 5-7 km minimum length.

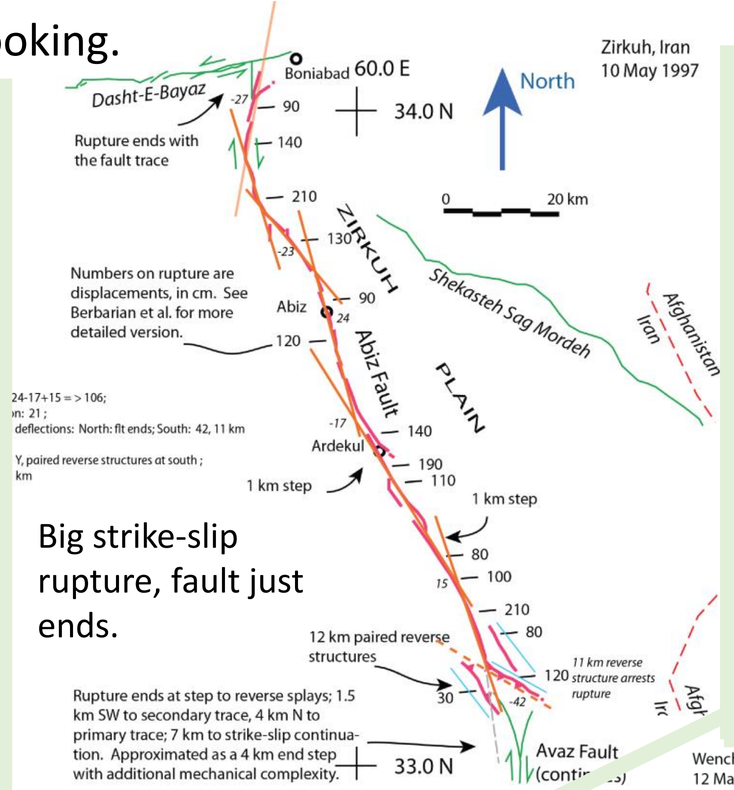
# It is amazing what you can see by looking.

Sakhalin, Eastern Russia
27 May 1995



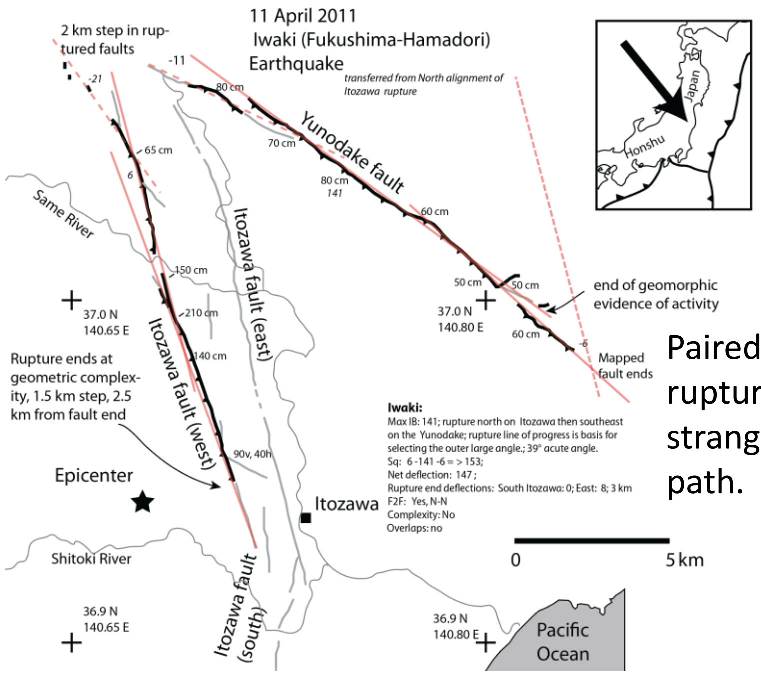

45 km rupture, fault not continuous on either end, 8 m displacement (?!)

Zirkuh, Iran
10 May 1997

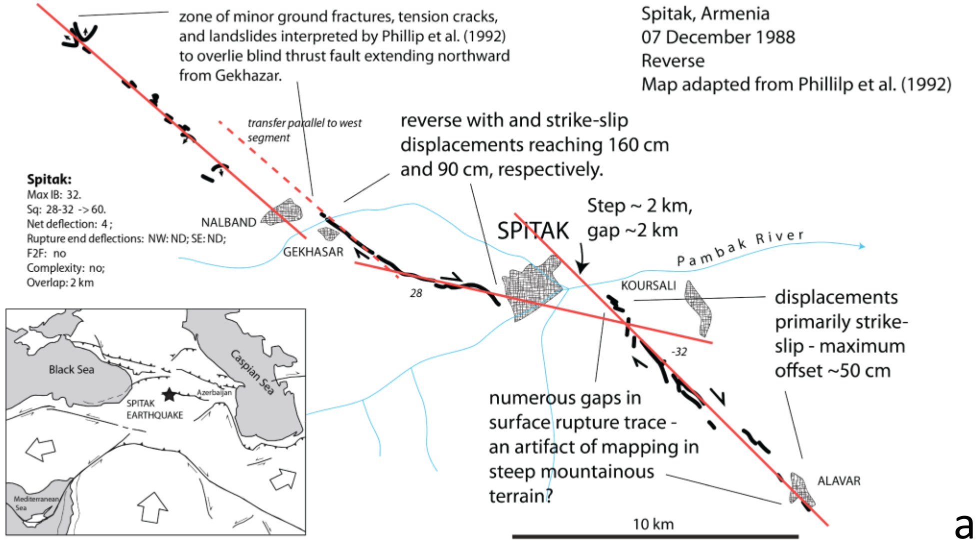



Big strike-slip rupture, fault just ends.

11 April 2011
Iwaki (Fukushima-Hamadori) Earthquake

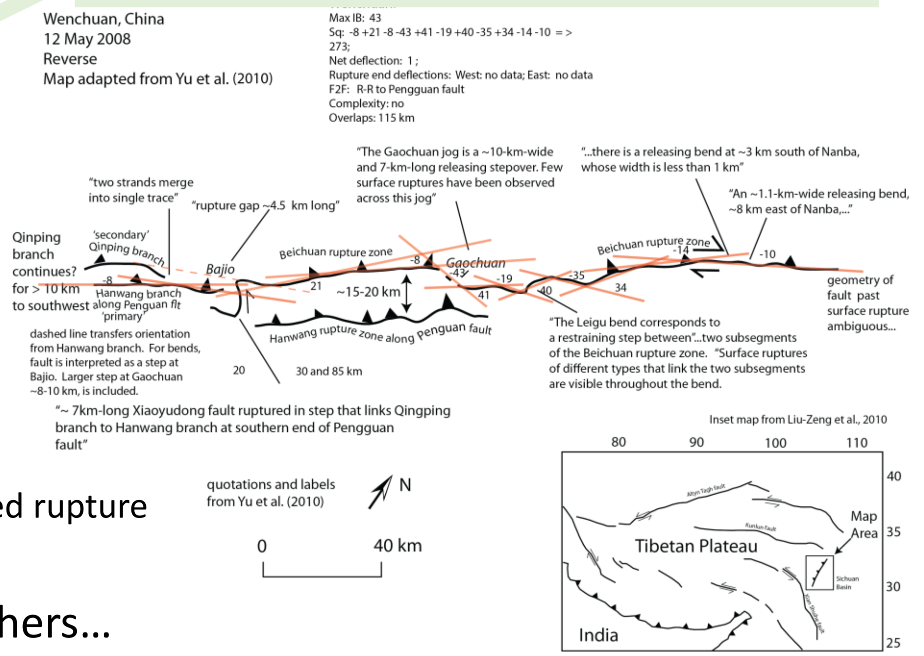



Paired normal ruptures, strange rupture path.




Devastating moderate reverse faulting rupture

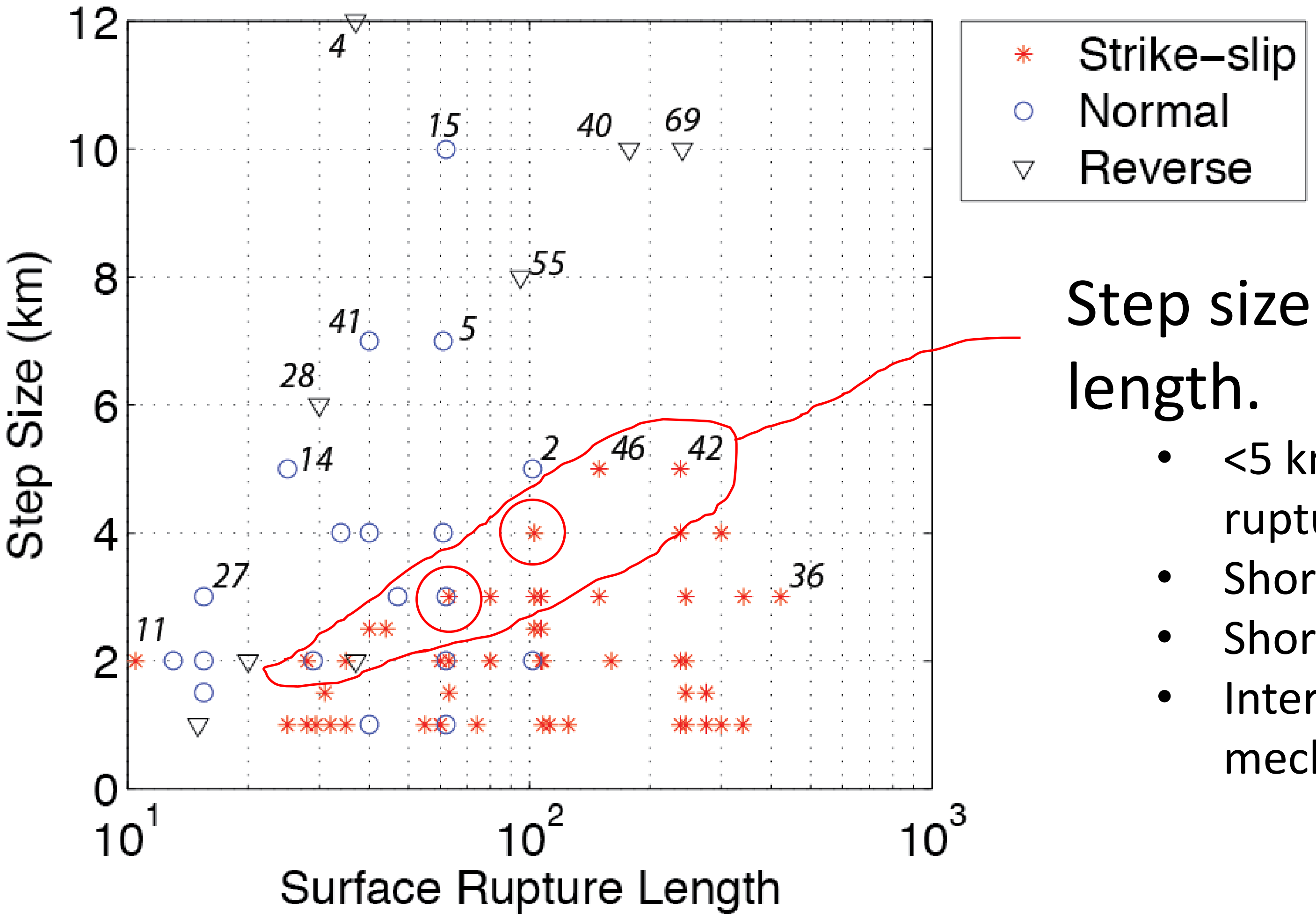
Wenchuan, China
12 May 2008
Reverse
Map adapted from Yu et al. (2010)




Giant paired rupture offsets.

and over 60 others...

# Step sizes passed, strike-slip

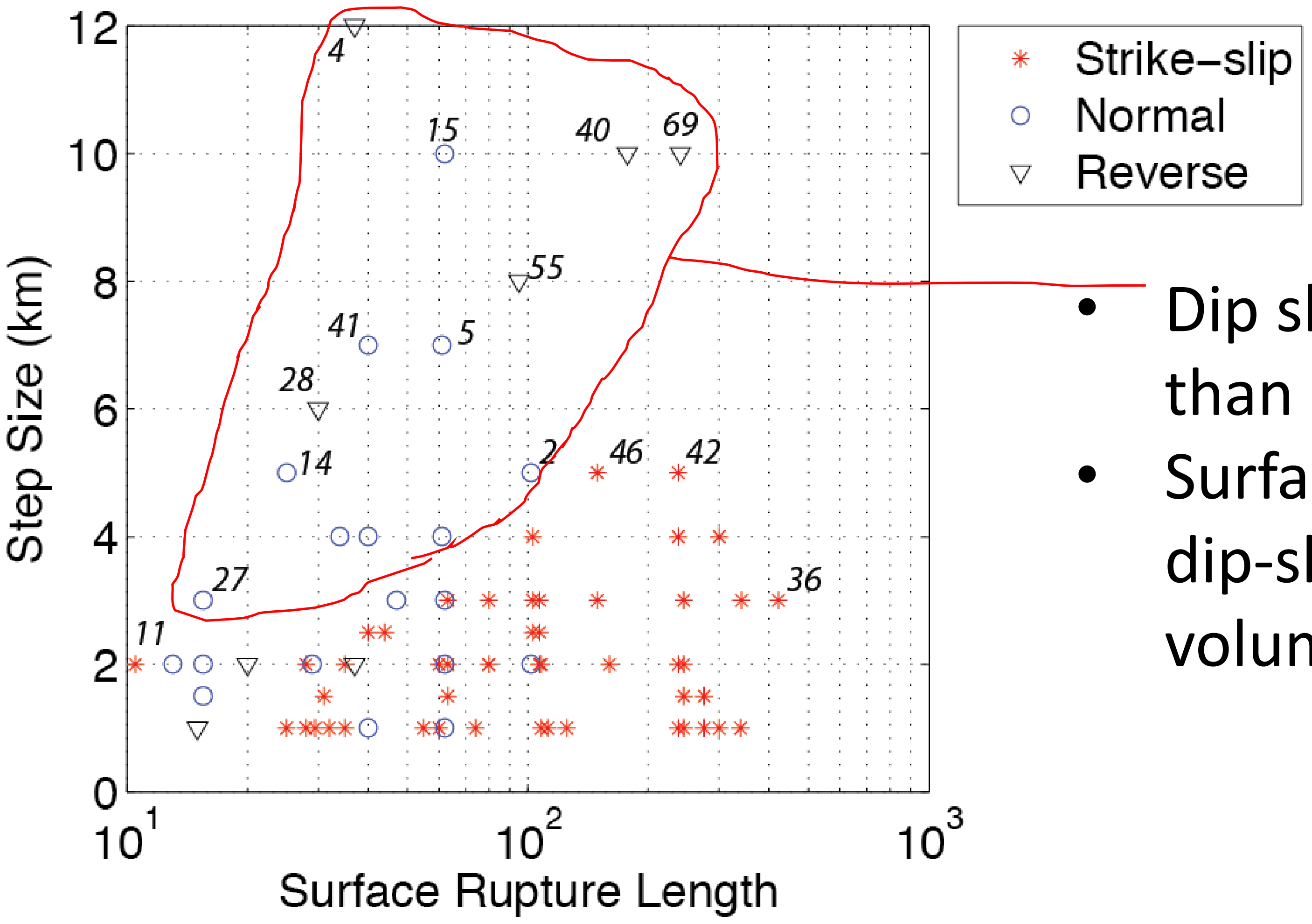



Event numbers from Biasi and Wesnousky, 2016

Step size passed depends on rupture length.

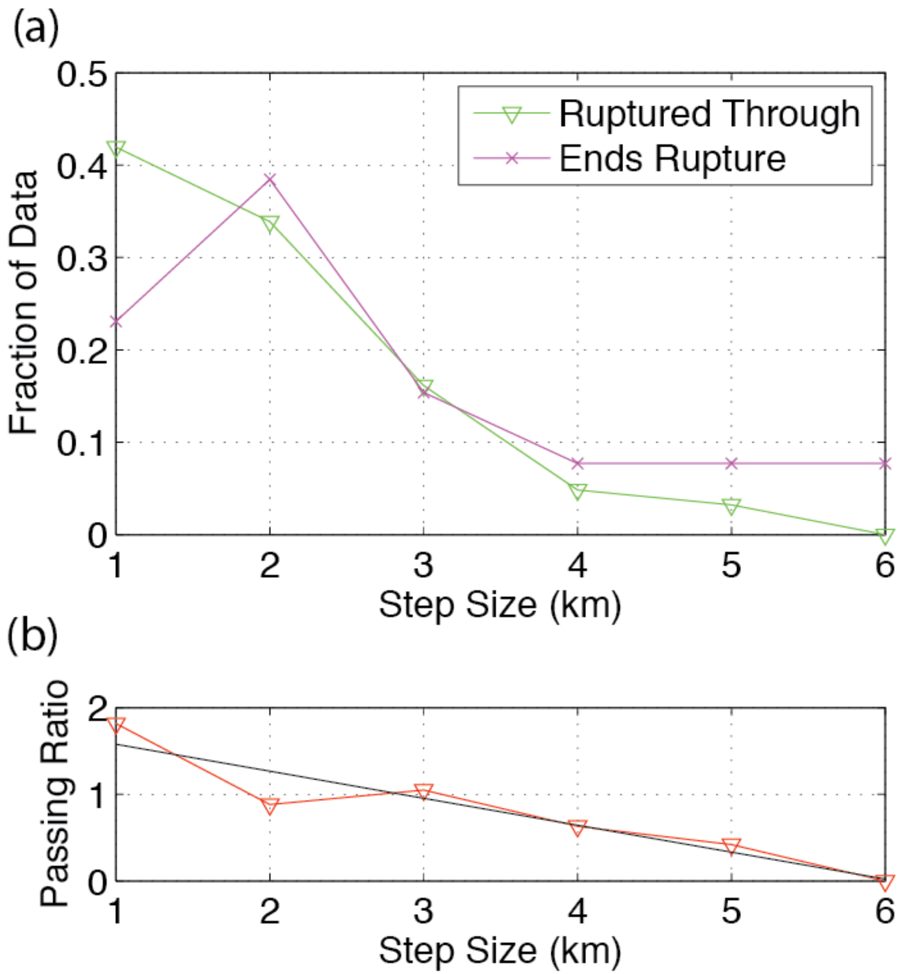
- <5 km rule is too simple; big steps require big ruptures
- Shortest rupture passing 3 km step = 50 km long
- Shortest passing 4 km or more = 102 km long
- Interplay of dynamic/momentum effects vs. mechanical strength of step.

# Step sizes passed vs. rupture mechanism




- Dip slip events pass larger steps than strike slip. Up to 12 km.
- Surface rupture patterns show dip-slip ruptures respond to volumetric stresses

Event numbers from Biasi and Wesnousky, 2016



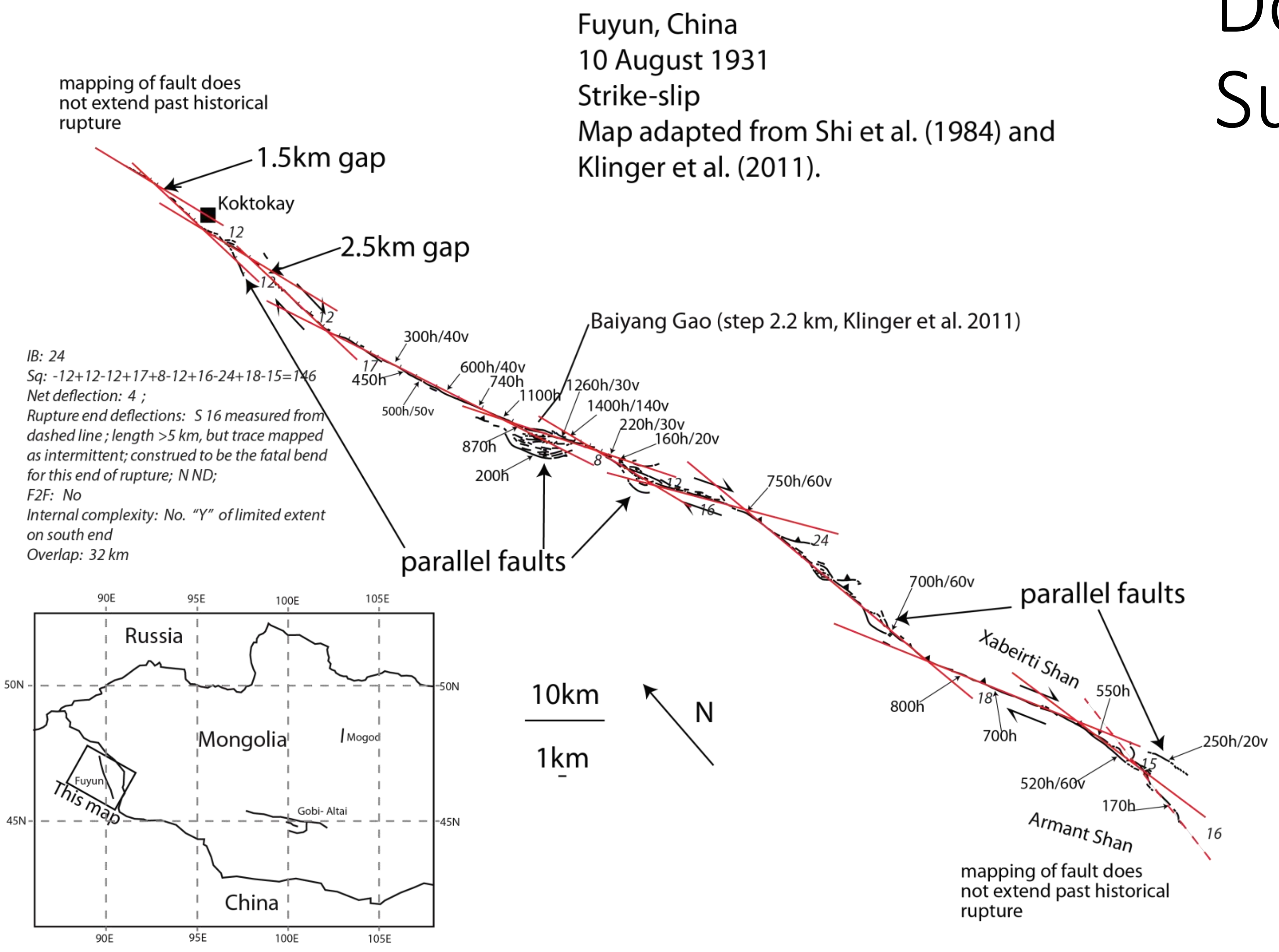

# Passing Ratio

Passing ratio: for a given step size, what fraction of ruptures stop vs. what fraction continue through?

Observations:

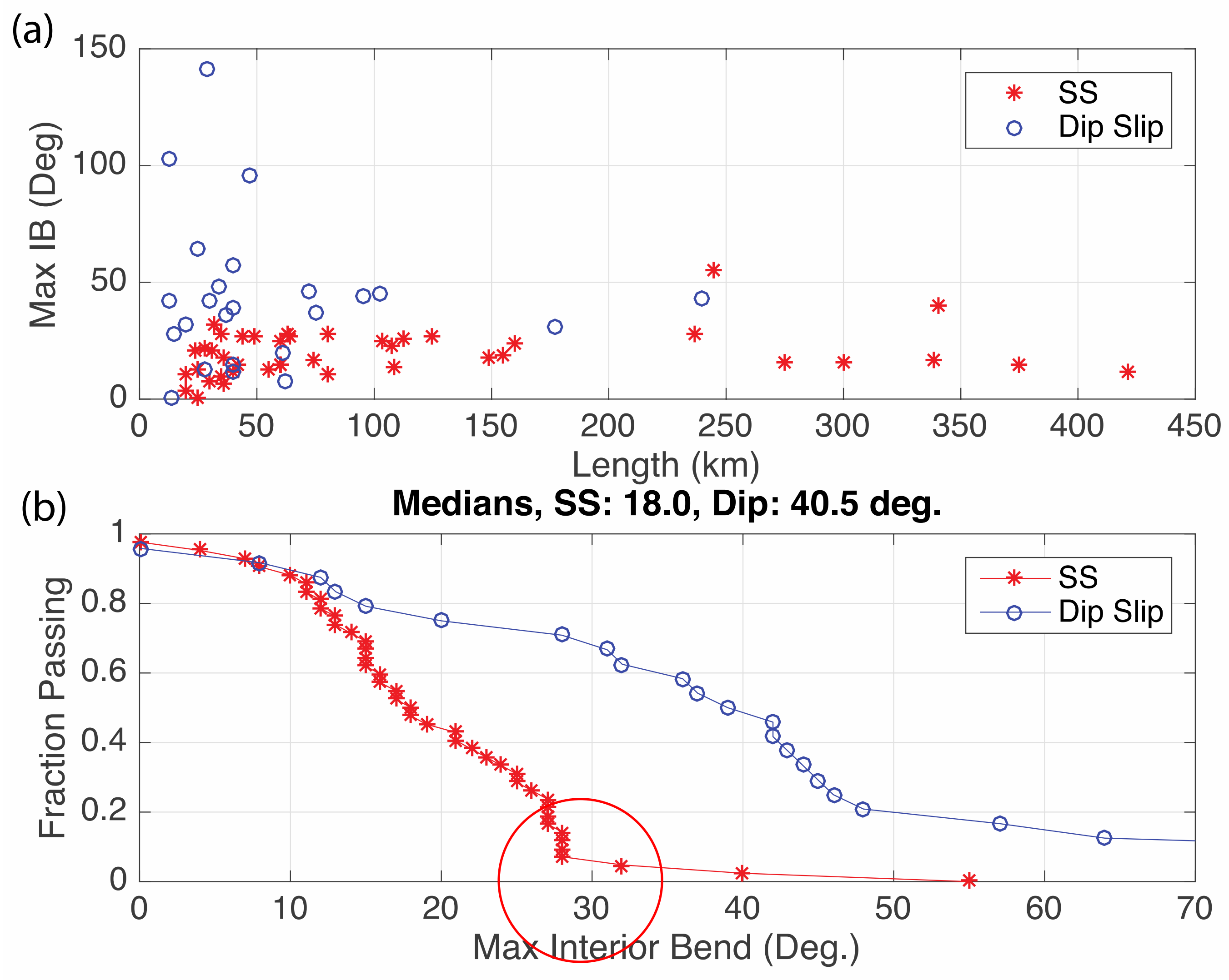
- ruptures rarely stop at small steps: high passing ratio
- ruptures commonly stop at at large steps: low passing ratio
- Modeled as linear: PR=1.89-0.31*W for W=step width (km). Coin-toss at 3 km.
- Ratio should diverge up as step size -> 0.

# Do Bends Arrest Surface Rupture?




- Summarize surface rupture in >=5-7 km linear reaches.
- Measure bends in surface rupture.
- Measure bends at ends where fault continues but rupture did not (these bends stopped rupture).

# Maximum bend angles overcome in rupture

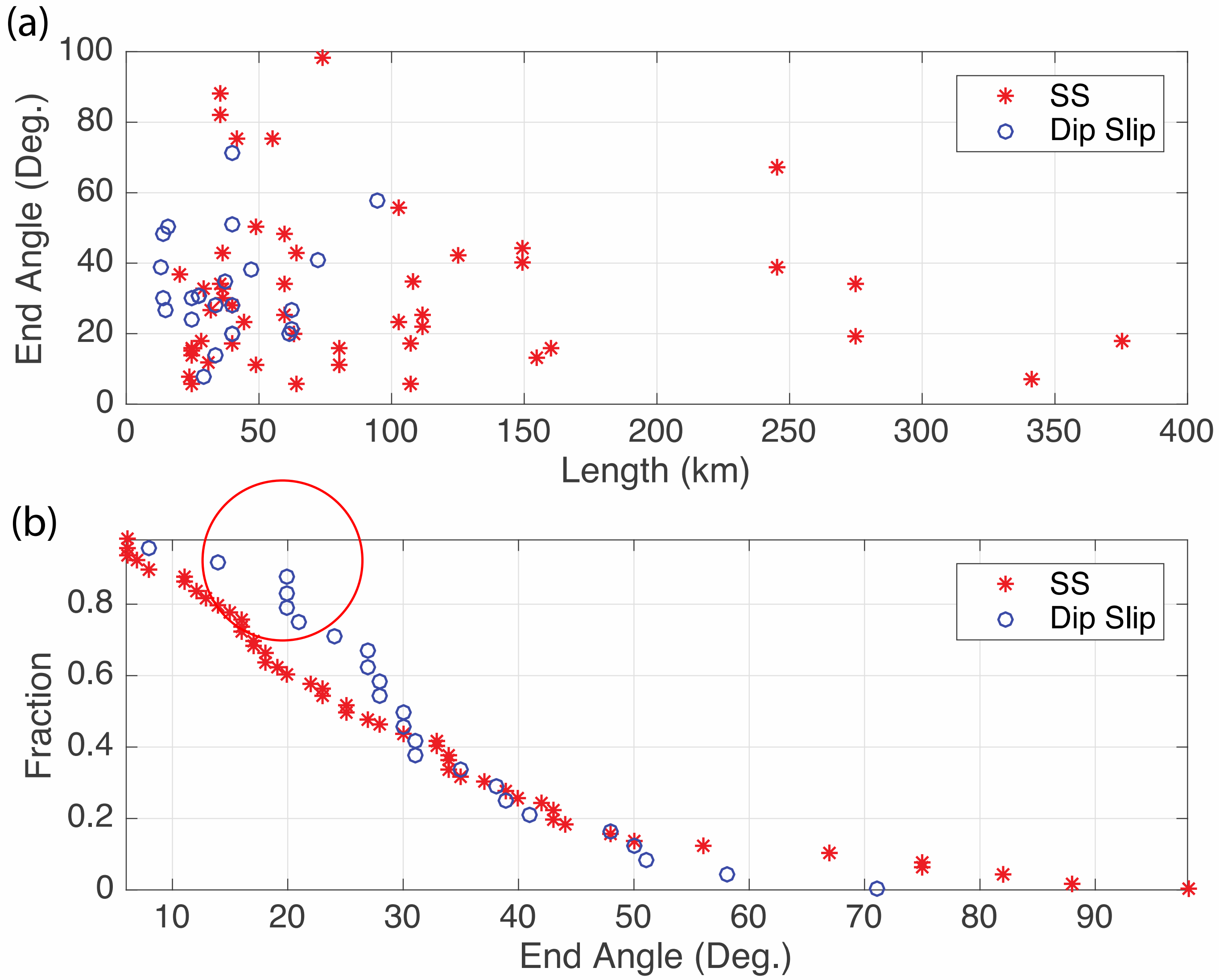



Upper: Maximum bend data for dip slip and strike slip
Lower: Cumulative distribution by rupture mechanism

Strike-slip maximum internal bend ~30 degrees; exceptions have 3-D explanations

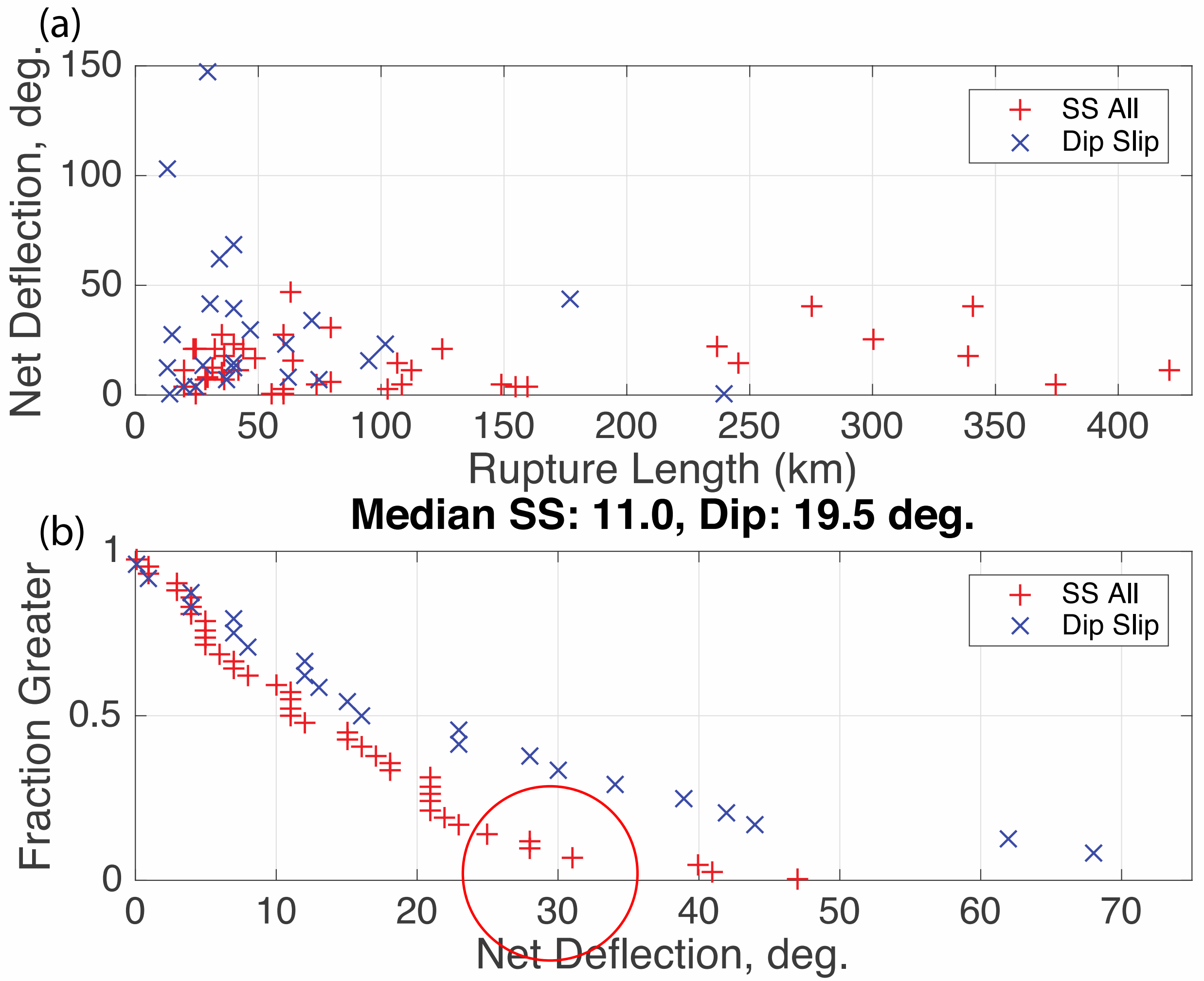
Dip-slip maximum interior bends form distinct population - half are >37 degrees

# Ends of Ruptures




Measure bends of fault at rupture ends.

Dip slip rarely ends at a bend less than 20 degrees (clue to mechanics?)




# Net Deflection: orientation difference between ending sections of the fault

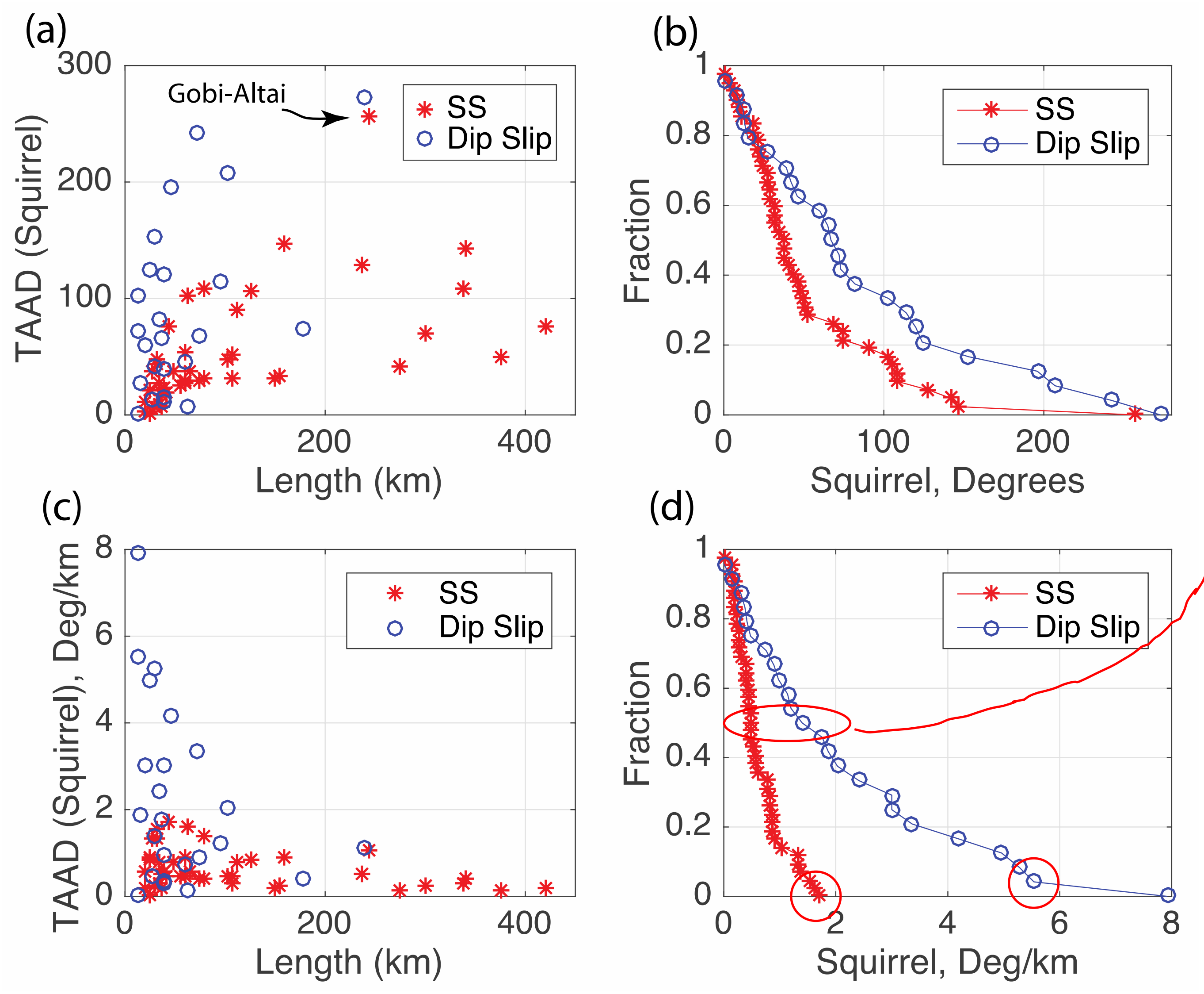
Strike-slip: median difference is 11 degrees, and almost all are less than ~30 degrees.

Exceptions for strike-slip transition to dip slip (2 of 42 cases).

Most strike-slip ruptures consistent with a near-constant regional stress direction.

# Total deflections and average curvature

TAAD: Total absolute angle deviation




Upper Figures: Sum absolute values of trend changes - how much the rupture changes direction.

Lower Figures: Average curvature,

- SS max = median 0.7 deg/km, max: 1.8 deg/km.
- Dip median 1.6 deg/km, max: 5.5 deg/km

Average curvature should scale with energy loss in dynamic rupture.

# passing ratio for bend angles in ruptures

Strike slip:

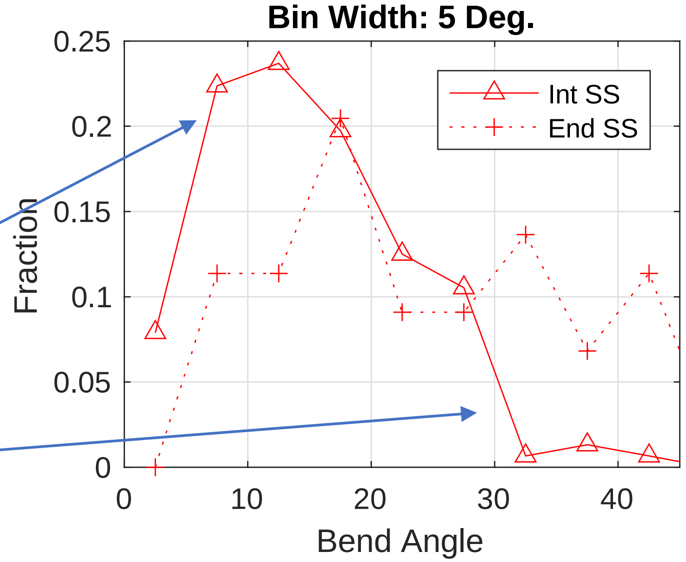
- Small bend angles are crossed more than stop rupture
- Large bends stop ruptures more often than are passed.

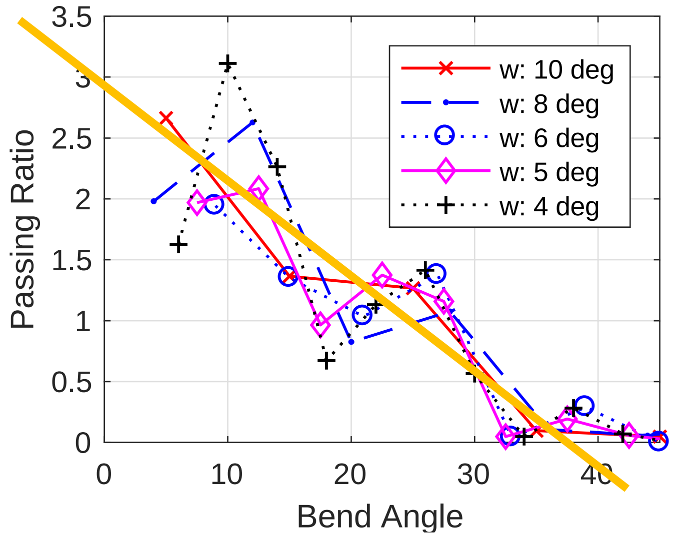
Because of the small data set, average across different bin sizes

Summary:

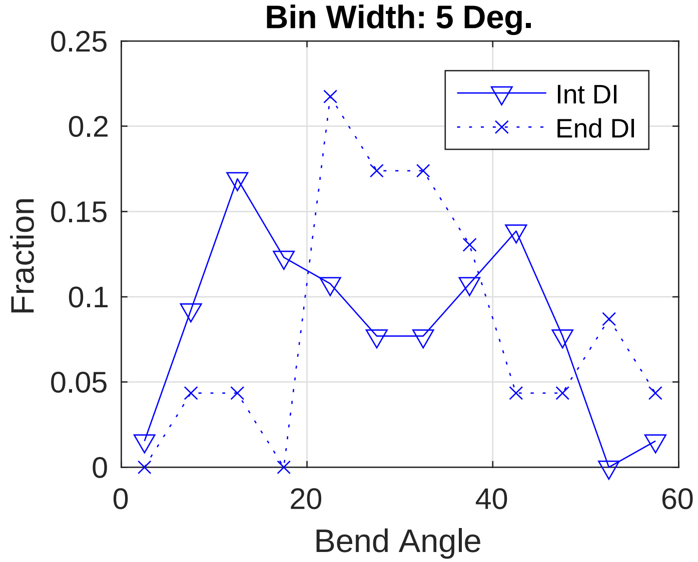
- bends of 11 deg. are passed 2x compared to stopping;
- 31 degrees stop 2x compared to passing.
- Strange pattern for dip slip.

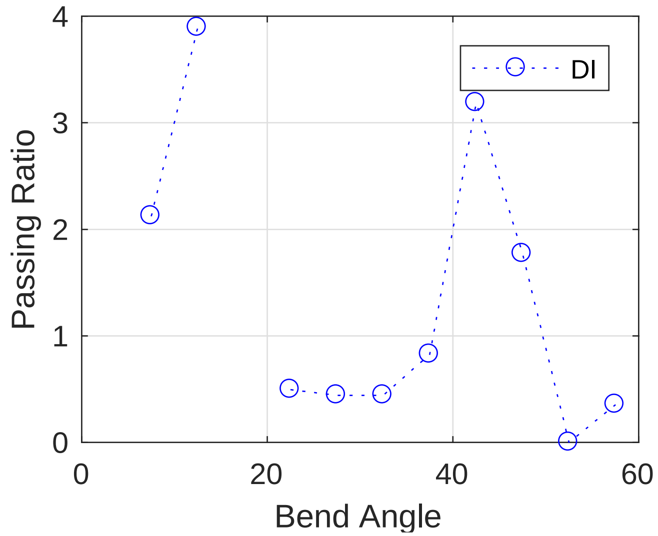
Strike slip



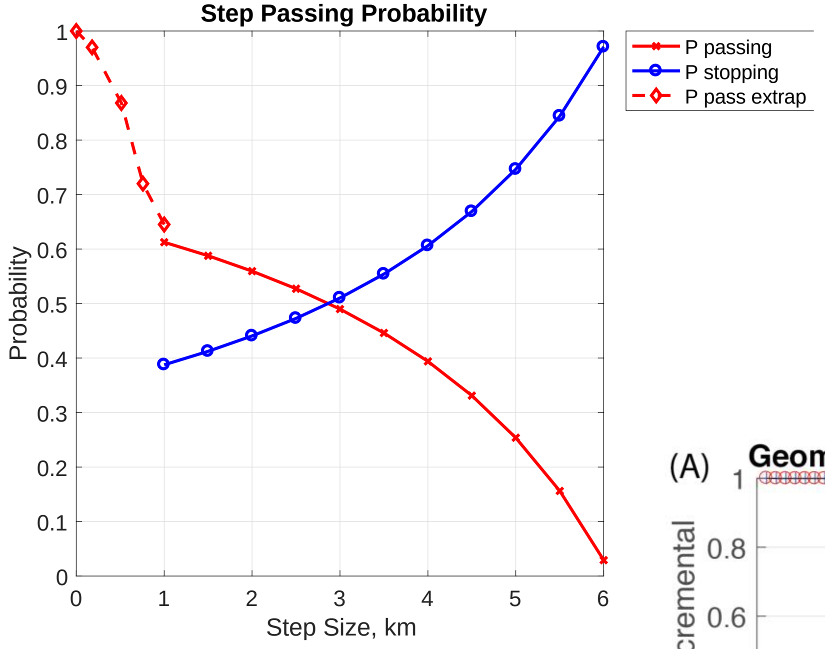



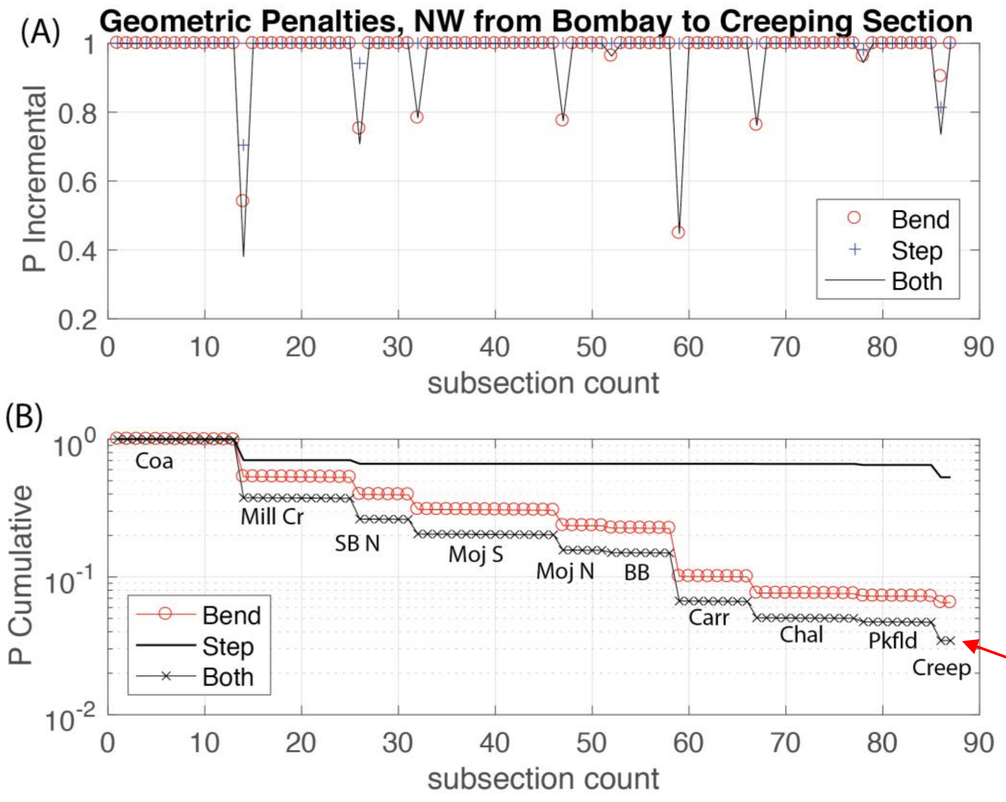

Dip slip

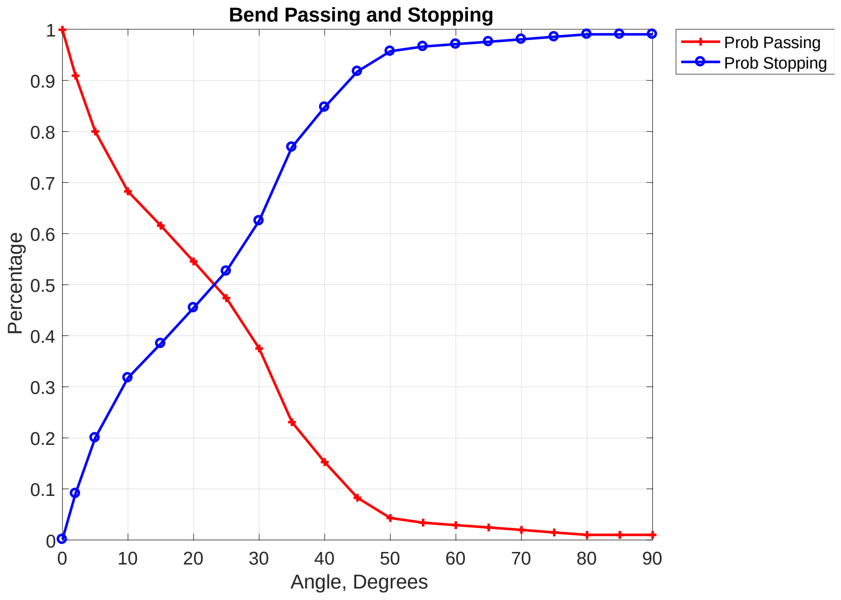


# Probabilities of stopping or passing, strike-slip



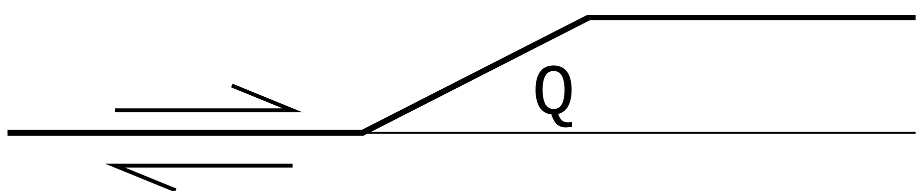




Earthquake early warning application: EEW alert at Bombay Beach, SE San Andreas fault

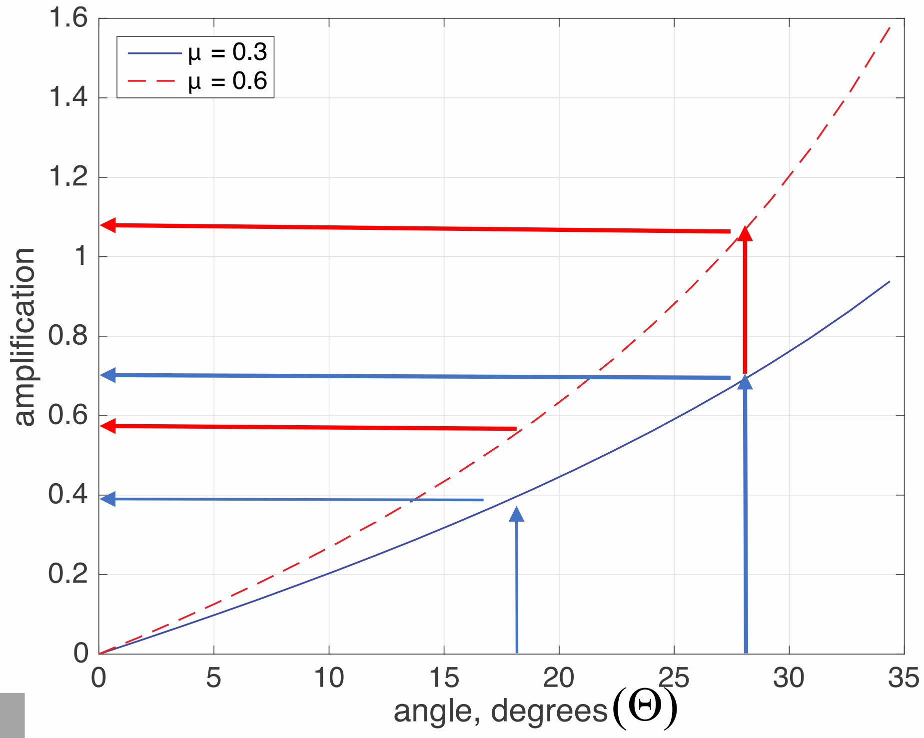
Net probability of length is product of passing each "challenge" NW from Bombay Beach.

# Simple model of a fault bend

Frictional resistance increases with bend angle
(static friction "Amplification")




Jaeger & Cook, 1979



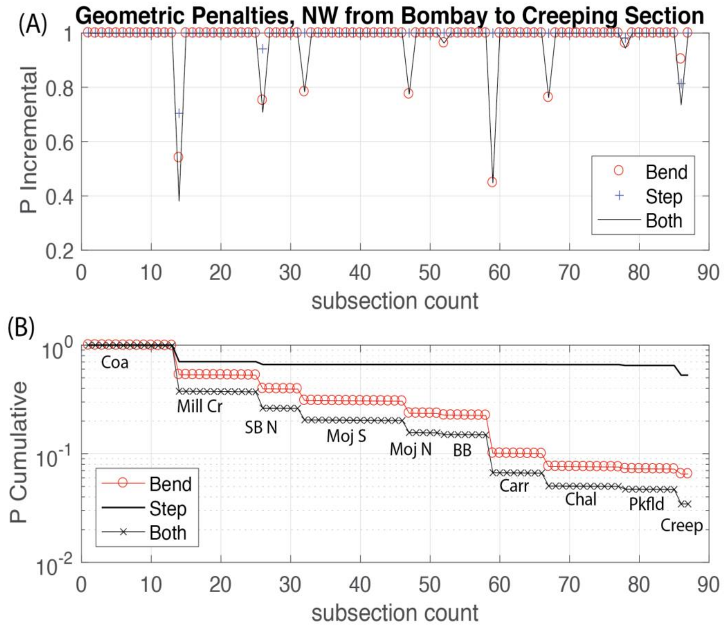

| Angle, degrees | Amplification | |
|---|---|---|
| 18 | .39 to 0.57 | Median largest interior SS bend |
| 28 | .68 to 1.06 | Largest SS interior bends |

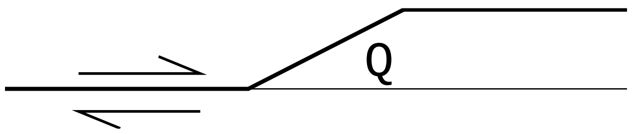
Two friction coefficients:
0.3 – blue
0.6 – red dashed

Empirical data suggest that excess friction at ~28 degrees roughly matches forces of dynamic rupture.

# Conclusions

- Rich set of surface ruptures
  - Strike-slip
    - Maximum step jump depends on rupture length
    - Interior bends and net orientation change rarely exceed 30 degrees
    - Ruptures up to 10's of km can be explained by a constant stress orientation
  - Normal and Reverse
    - Dip-slip faults can rupture together in strange patterns if they share a common stress field.
    - Dip-slip fault step jumps often exceed 5 km.
  - Empirical data suggest excess resistance in bends of ~28 degrees balances dynamic rupture forces.
- Dynamic Modeling
  - Test/validate passing ratio conditions and probabilities.
  - Test rupture length dependence of maximum jump size.
  - Energetics of individual and average orientation changes.



2016 Kaikoura, New Zeland, M 7.8

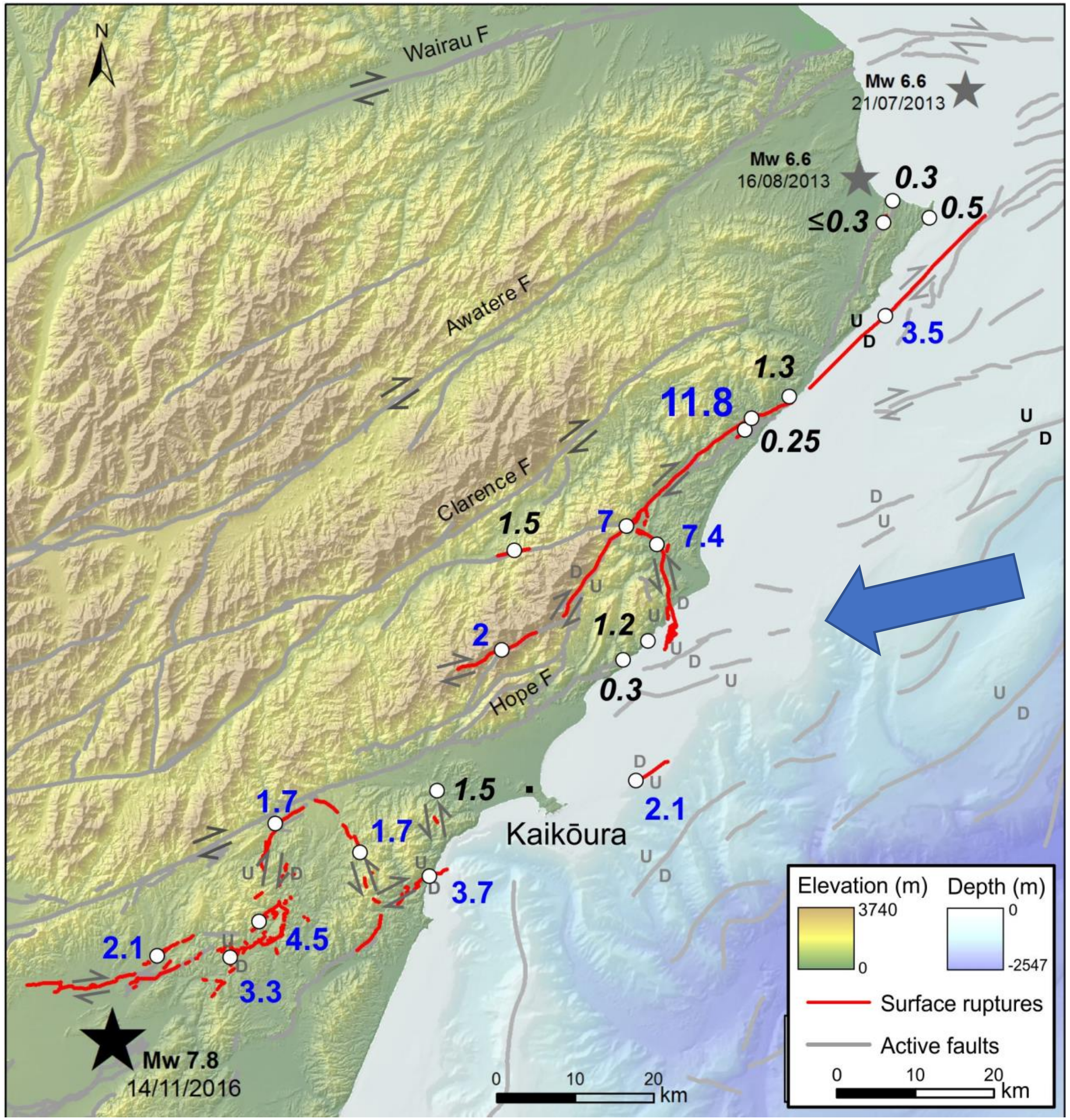
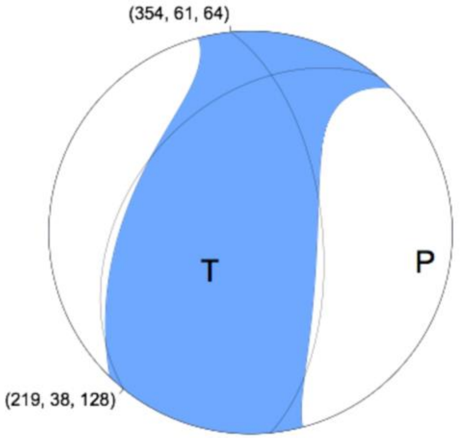



Figure courtesy of Nicola Litchfield

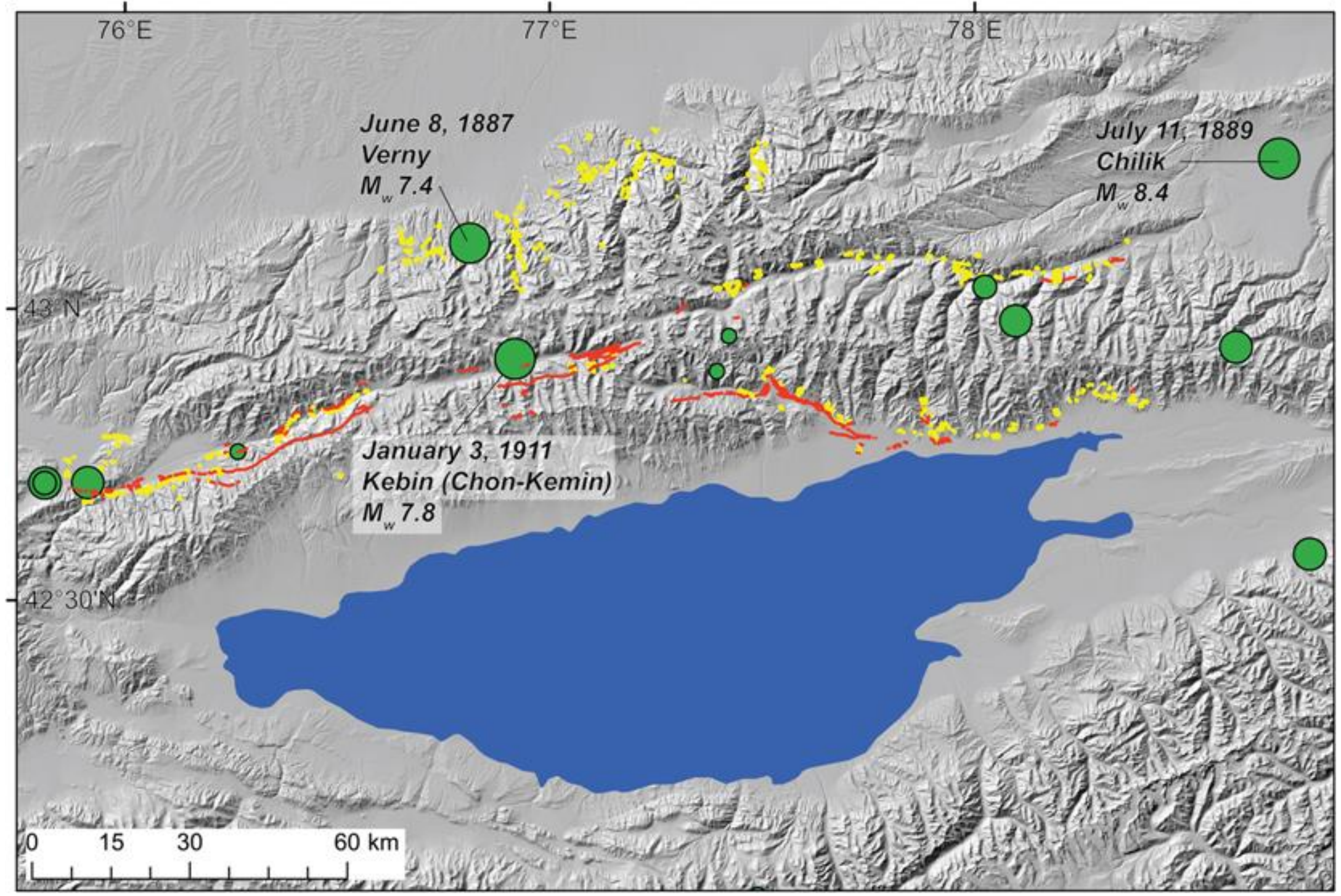
# Kaikoura, New Zealand, 2016

- How to anticipate this in seismic source characterization?
- Hope fault thought to be "ready", but did not break – misaligned with stresses on Kekerengu fault




Oblique moment tensor –> 3D effects.

# 1911 Chon-Kemin, Kyrgyzstan, M7.8



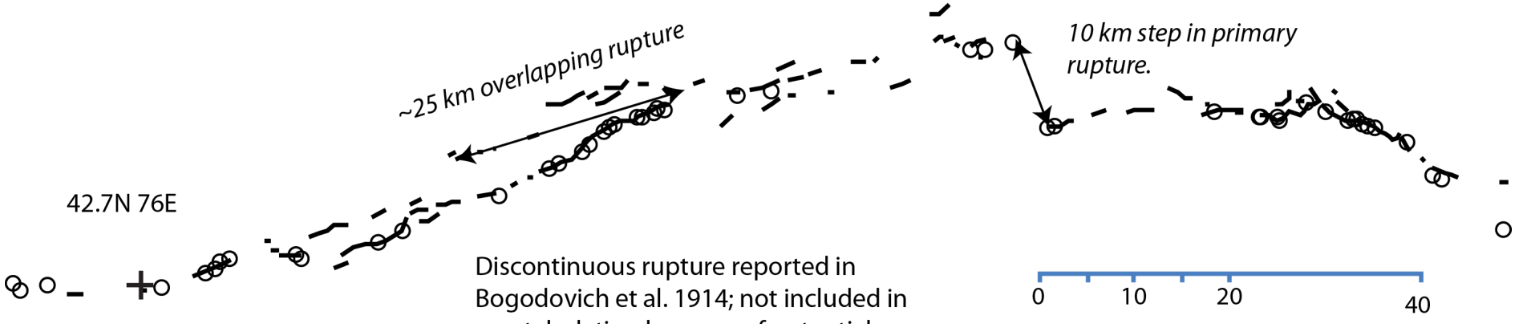

155 to 195 km of co-seismic rupture

25-40 km of overlapping rupture of opposite vergence to main rupture

Reverse rupture steps 10+ km across a mountain range in order to continue.

Circles: locations of slip estimates by Arrowsmith et al on 1911 rupture. View as field confirmation of 1911 rupture map

Arrowsmith et al., 2016



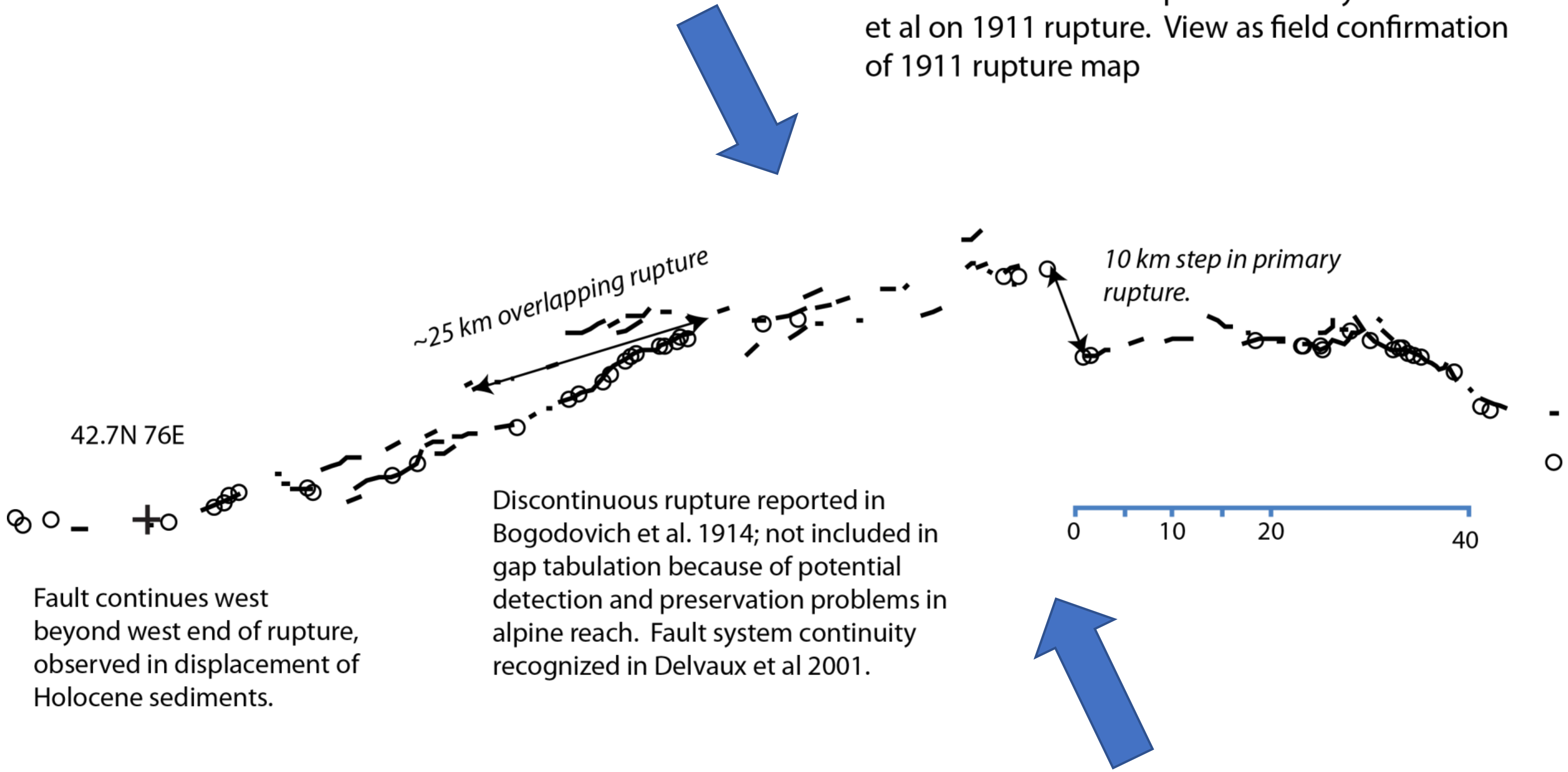

Fault continues west beyond west end of rupture, observed in displacement of Holocene sediments.

Discontinuous rupture reported in Bogodovich et al. 1914; not included in gap tabulation because of potential detection and preservation problems in alpine reach. Fault system continuity recognized in Delvaux et al 2001.

# 1911 Chon-Kemin, Kyrgyzstan

3 January 1911
Chon-Kemin Earthquake
Reverse Mechanism

Circles: locations of slip estimates by Arrowsmith et al on 1911 rupture. View as field confirmation of 1911 rupture map

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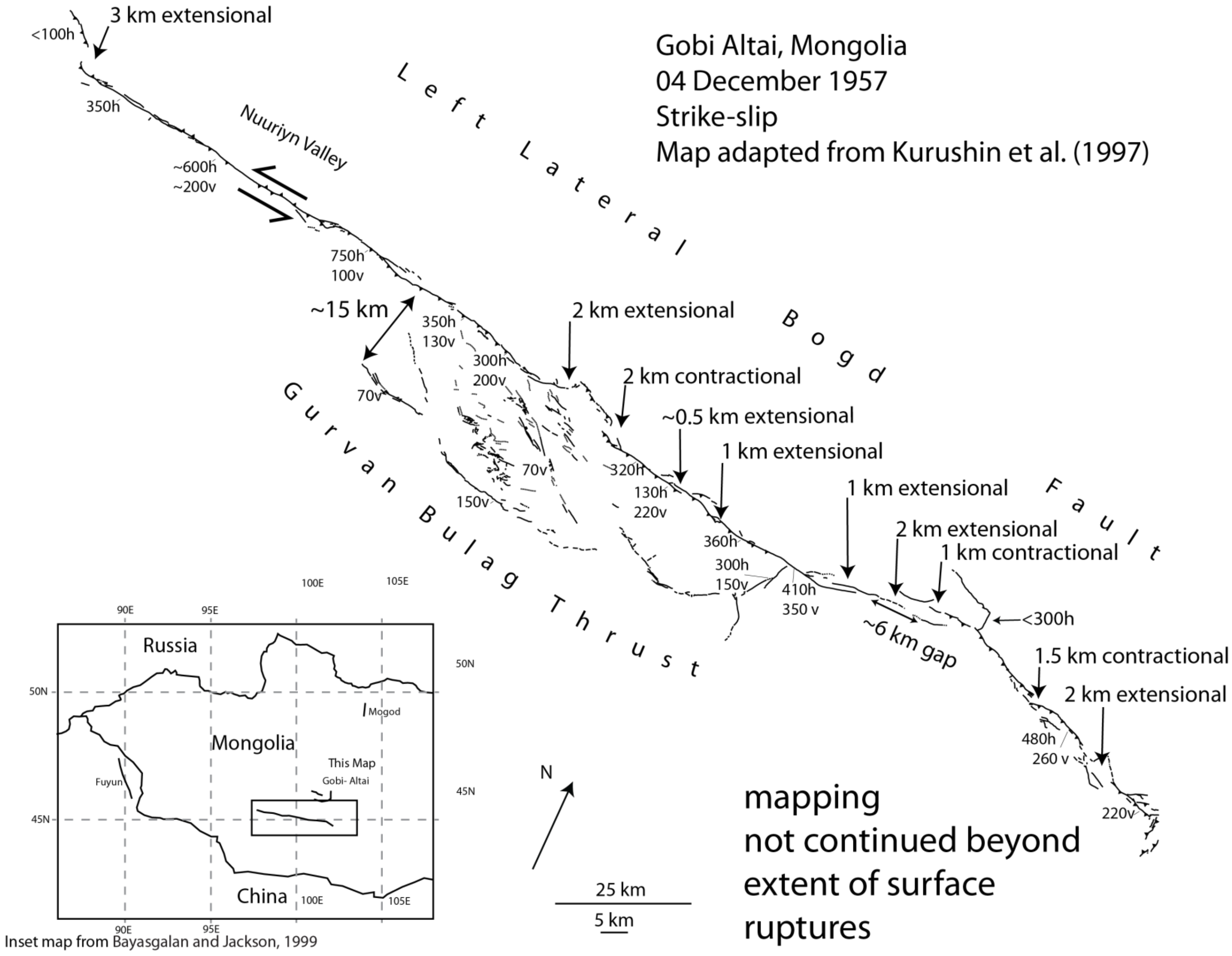
Fault continues west beyond west end of rupture, observed in displacement of Holocene sediments.

Reverse rupture across a mountain range in order to continue.

Vergence and rupture make sense in context of a single regional stress field.

# Complex ruptures



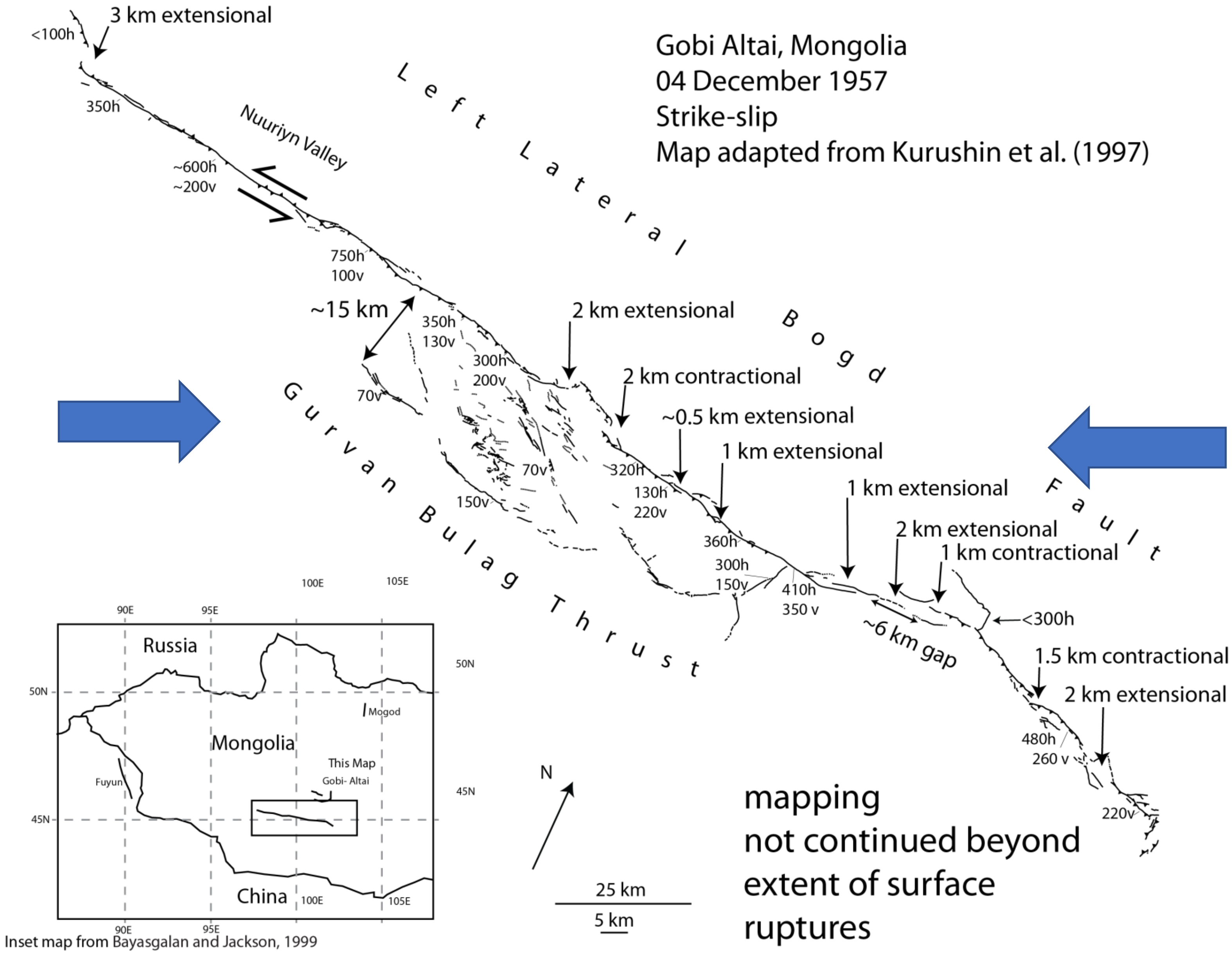

1957 Gobi-Altai, Mongolia rupture

Nominally 235 km long strike slip

100's of km of reverse faulting with multi-meter offsets overlapping with the main trace.

Simple triggering from one fault reach to the next is improbable.

# Complex rupture: 1957 Gobi-Altai




1957 Gobi-Altai, Mongolia rupture

Nominally 235 km long strike slip

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Simple triggering from one fault reach to the next is improbably.

Co-seismic rupture can be understood in the context of a regional stress field