A new technique to measure 3D slip-vectors from high-resolution topography applied to photogrammetry of historic ruptures

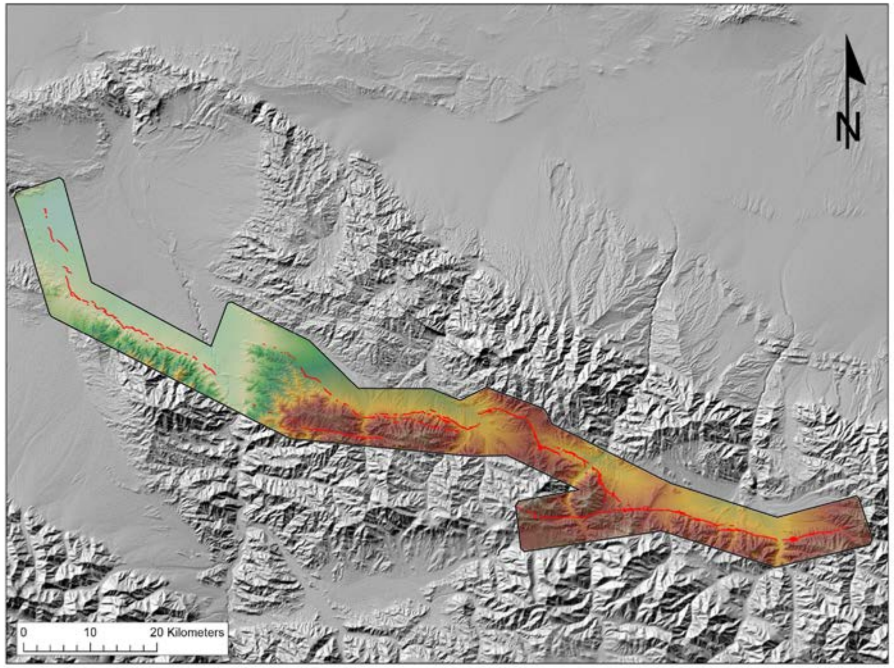
Austin Elliott, David Mackenzie, Barry Parsons, Eleanor Ainscoe

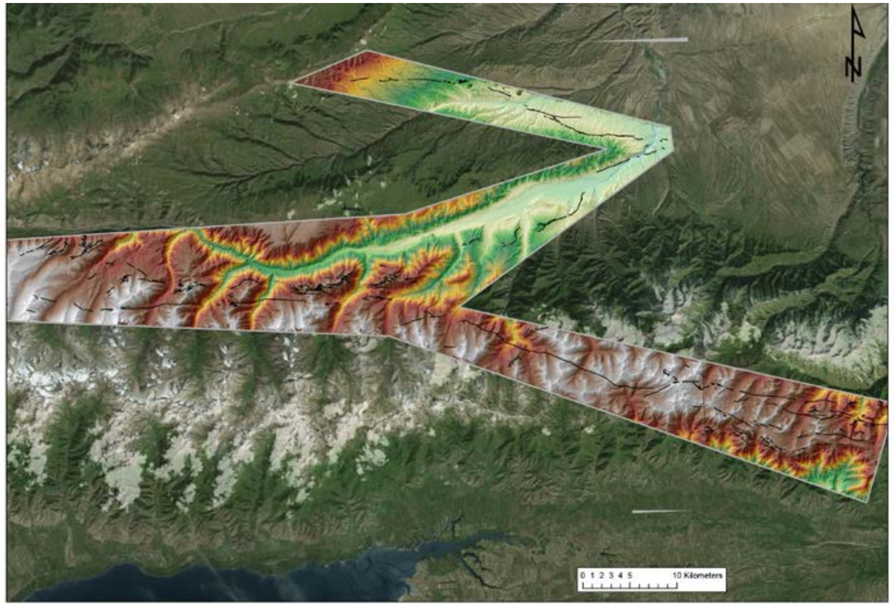
COMET
UNIVERSITY OF OXFORD
CENTRE FOR OBSERVATION & MODELLING OF EARTHQUAKES, VOLCANOES & TECTONICS
LiCS LOOKING INSIDE THE CONTINENTS FROM SPACE
NERC SCIENCE OF THE ENVIRONMENT

Past quakes, hi-res topo, & 3D slip vectors

Talk Outline

- Motivation
  - Information preserved but limited on past rupture scarps
  - Modern availability of 2.5D topo fields
- Specific ruptures we're studying
- Uncertainties in conventional profile measuring methods
- New approach to exploit planar rather than linear features
- Application of method to recent & past ruptures



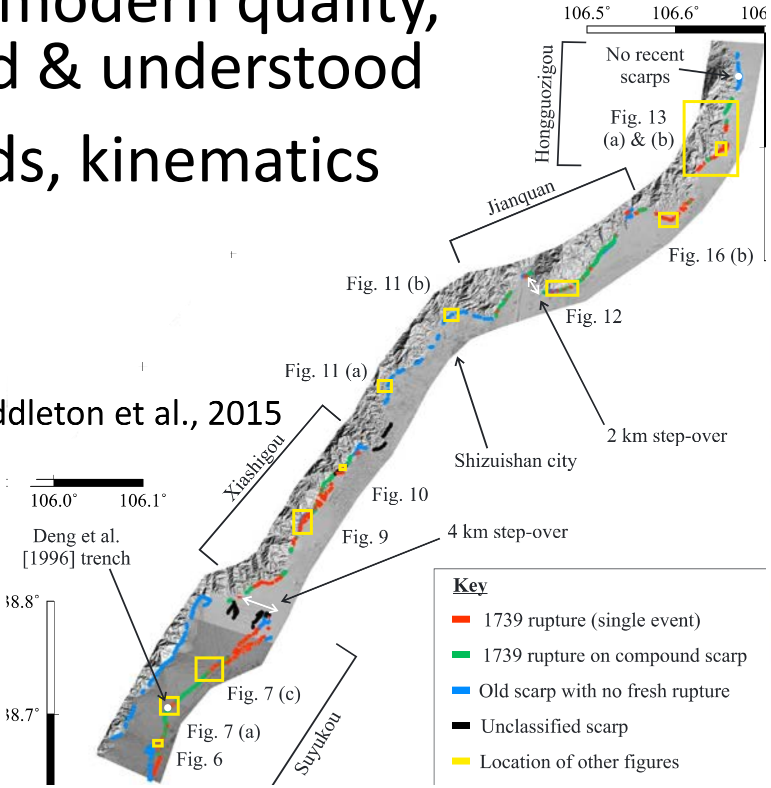


Past earthquakes in high-resolution topography

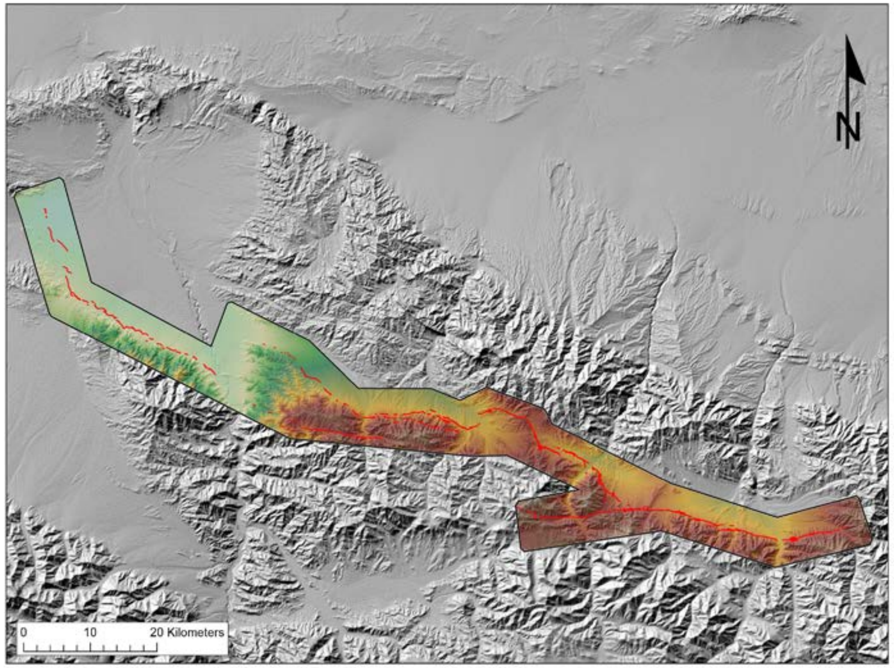
- Historic & pre-instrumental earthquakes imaged
  - Preserved in landscape
  - Recorded in modern high-res imagery & topography

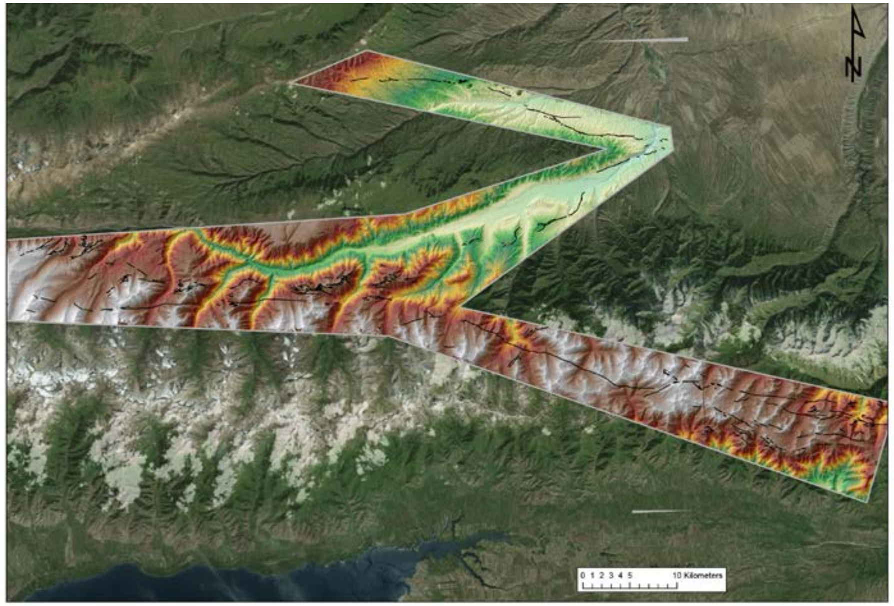
- Without primary surveys of modern quality, fault slip poorly documented & understood
- Without instrumental records, kinematics may be unknown

- Need way to reconstruct landscape other than individual linear markers
- Applicable also to contemporary studies

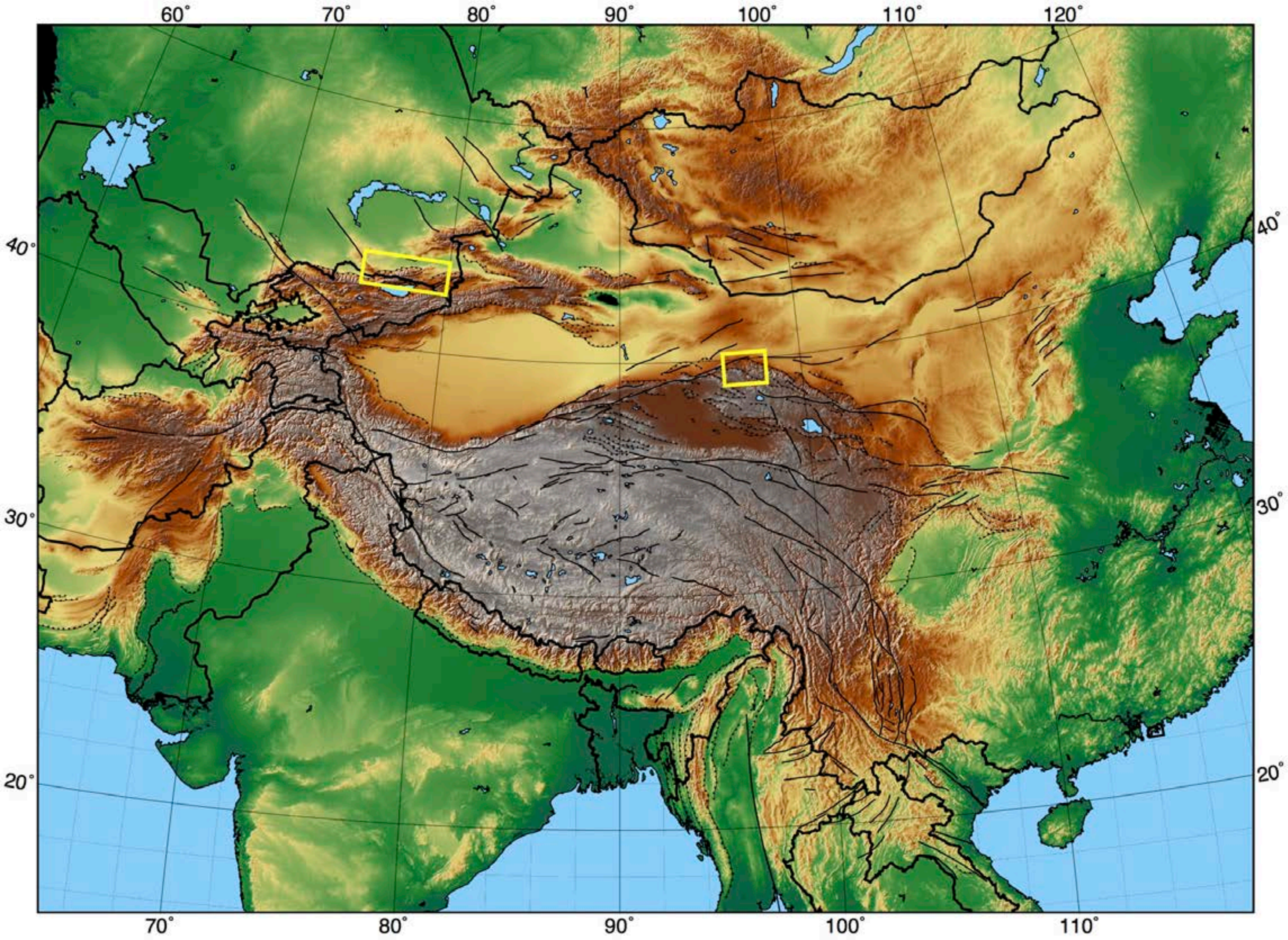


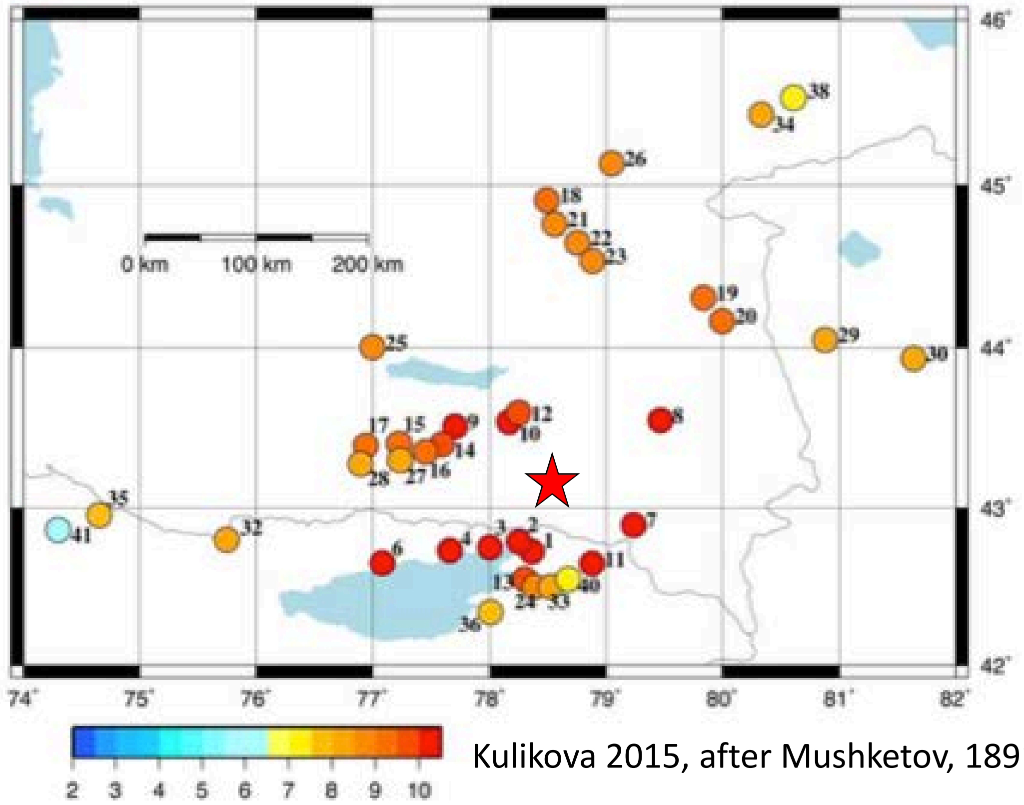
Middleton et al., 2015



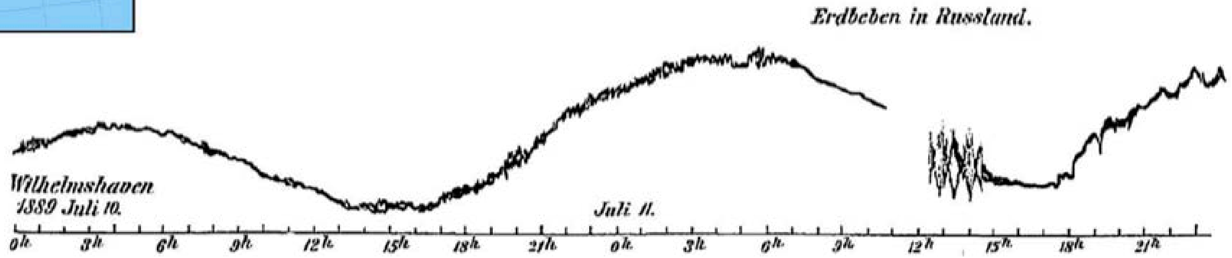


Motivation: enigmatic 1889 Chilik earthquake





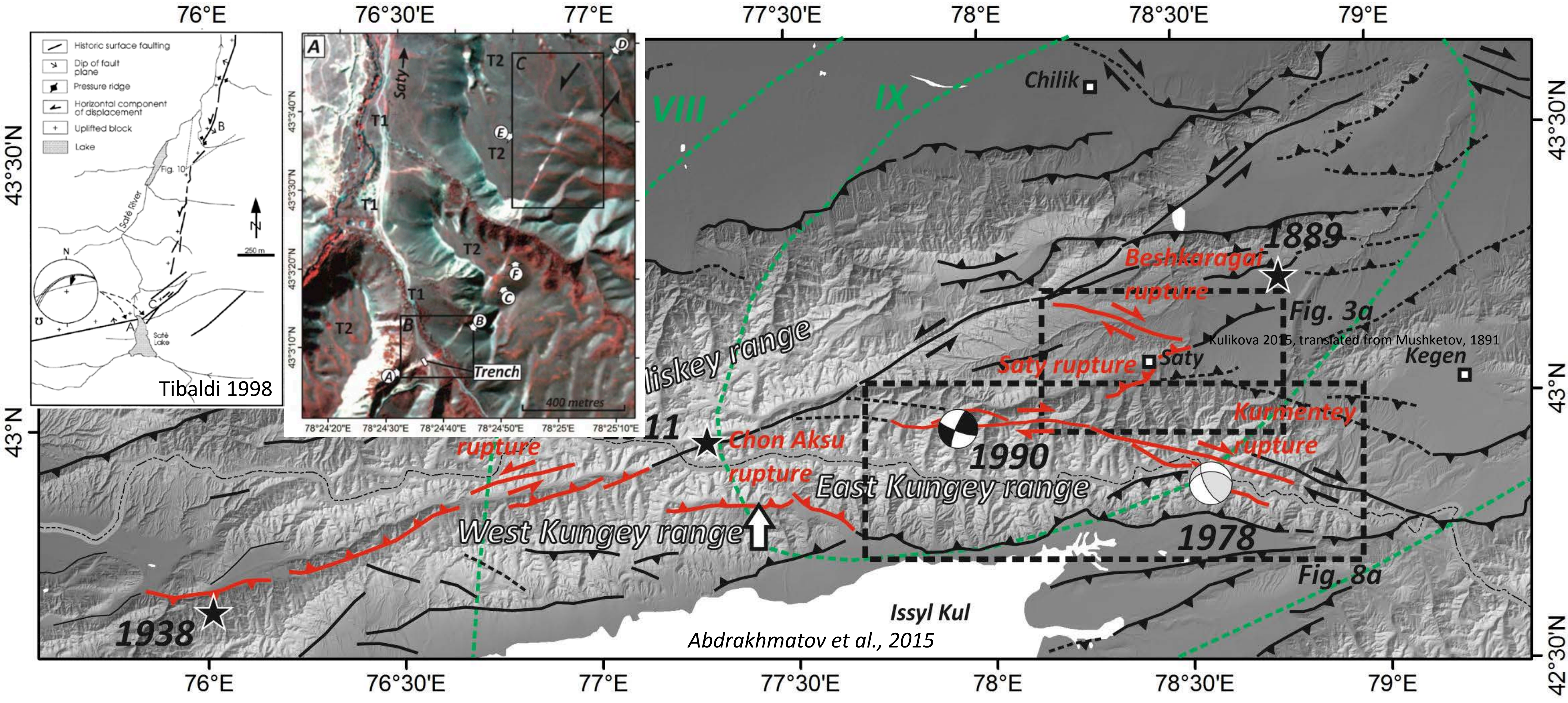
Kulikova 2015, after Mushketov, 1891



- Macroseismic magnitude: **8.3**
- Forensic seismology: M **8.0-8.3**

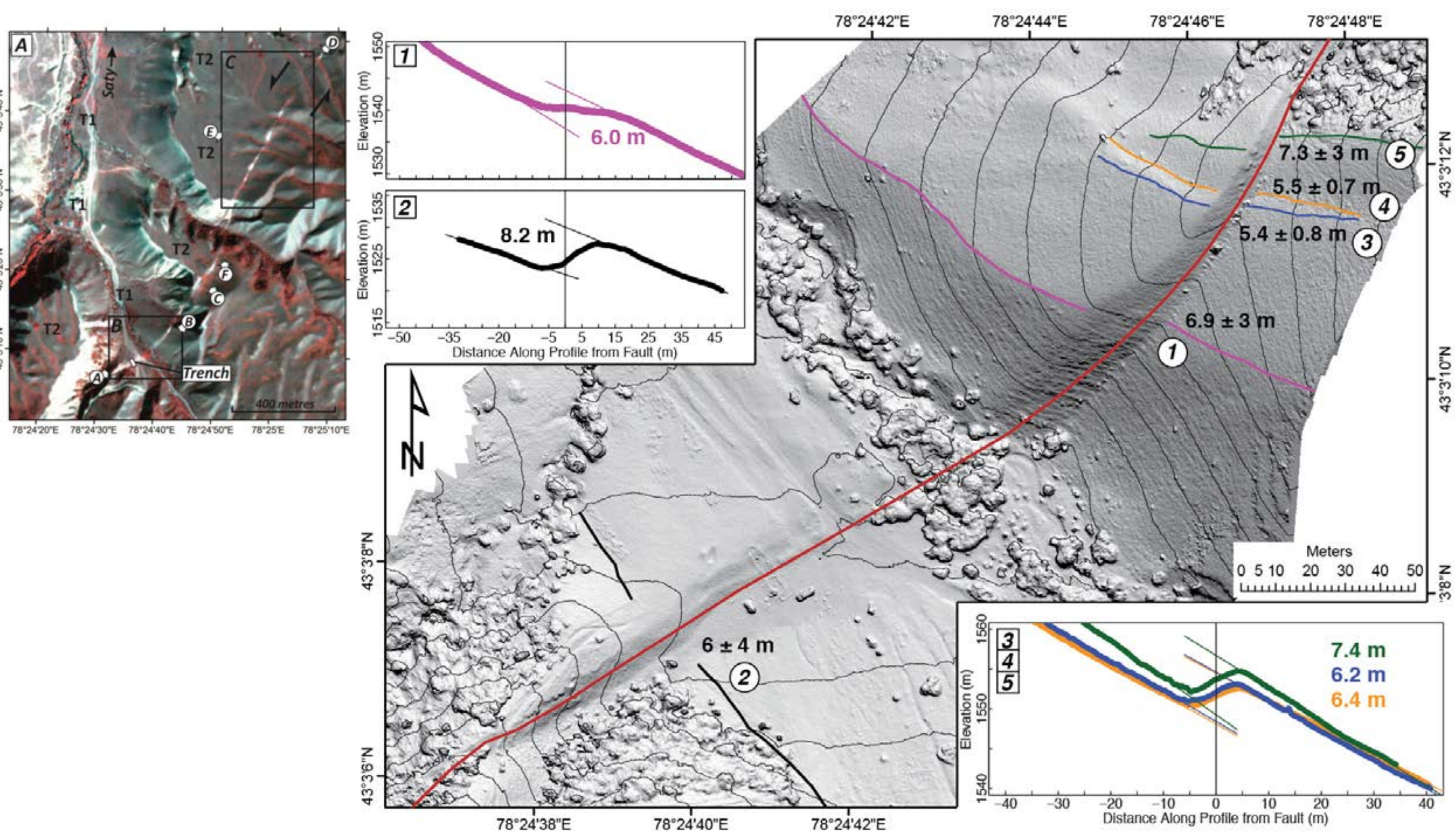
Motivation: enigmatic 1889 Chilik earthquake

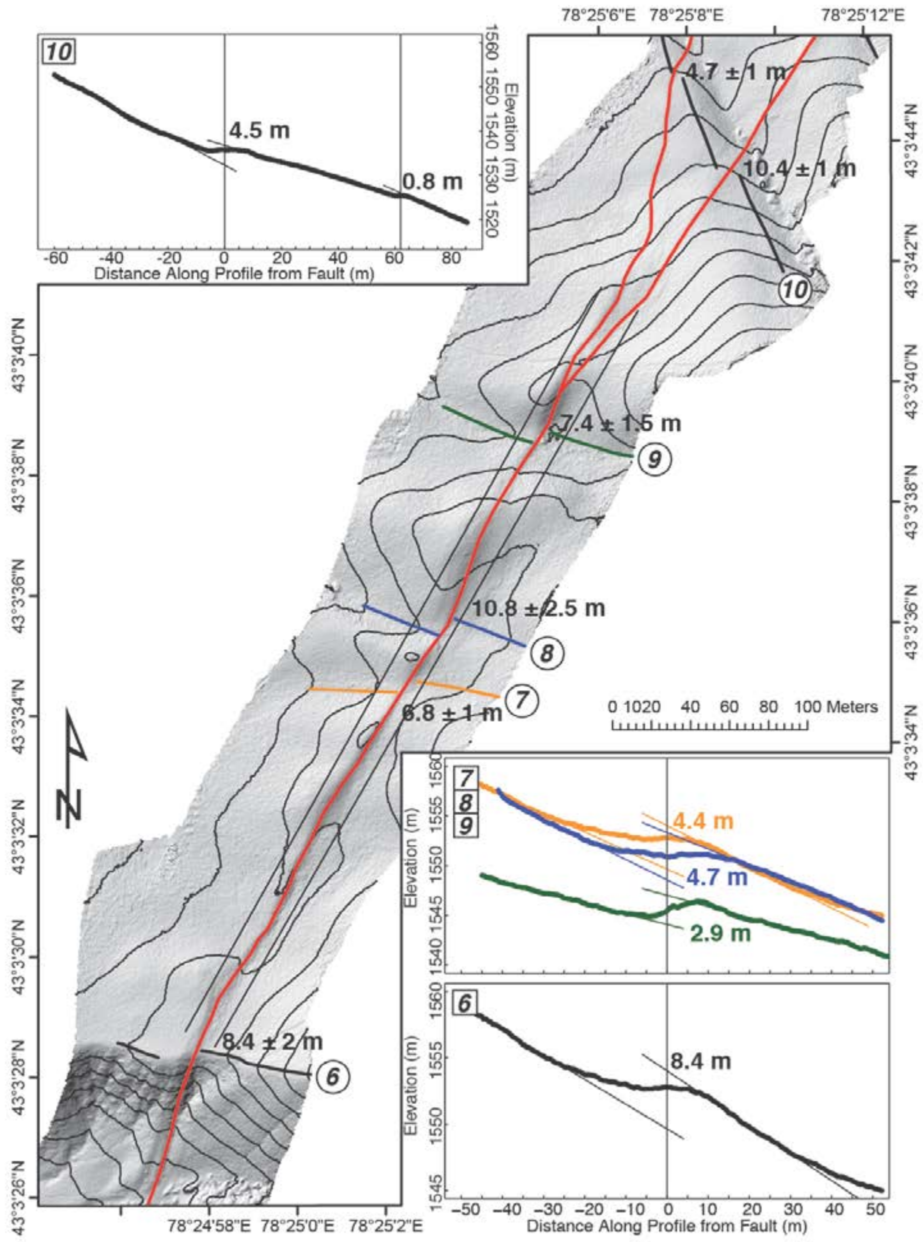
Complex combination of faults: 30 + 20 (+ 80?) km conjugate segments



Abdrakhmatov et al., 2015

Offsets in 1889 from linear markers

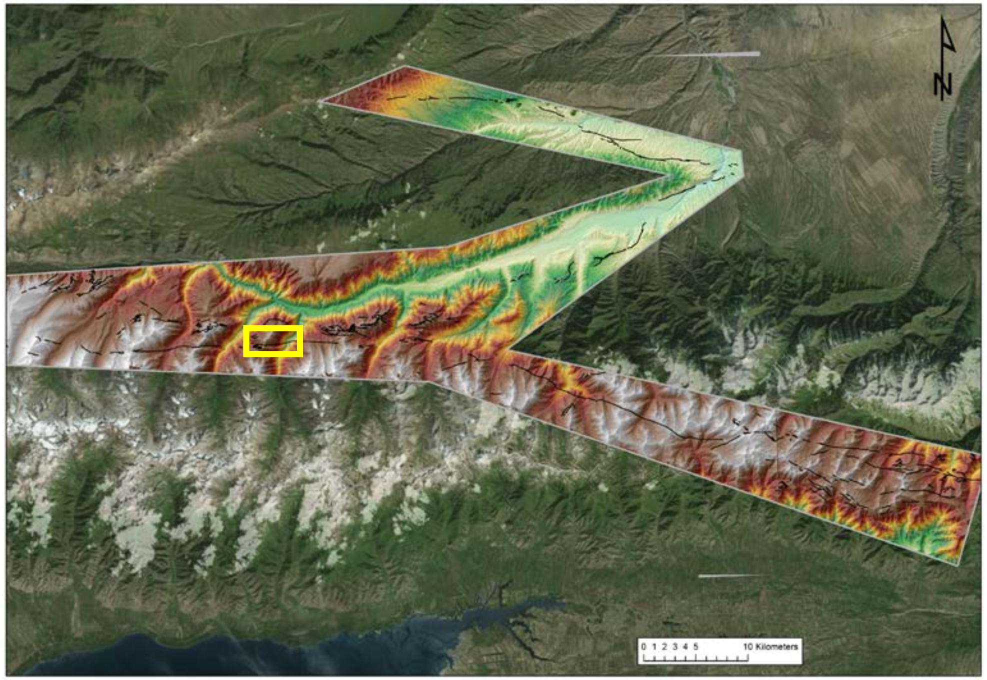




Abdrakhmatov et al., 2015

- Clearly defined linear features allow precise reconstruction
- Features defined by intersecting surfaces
- Fault dip ambiguity (unknown fault normal component) contaminates horizontal signal

Offset ridges at Salimbay – slip sense of fault?

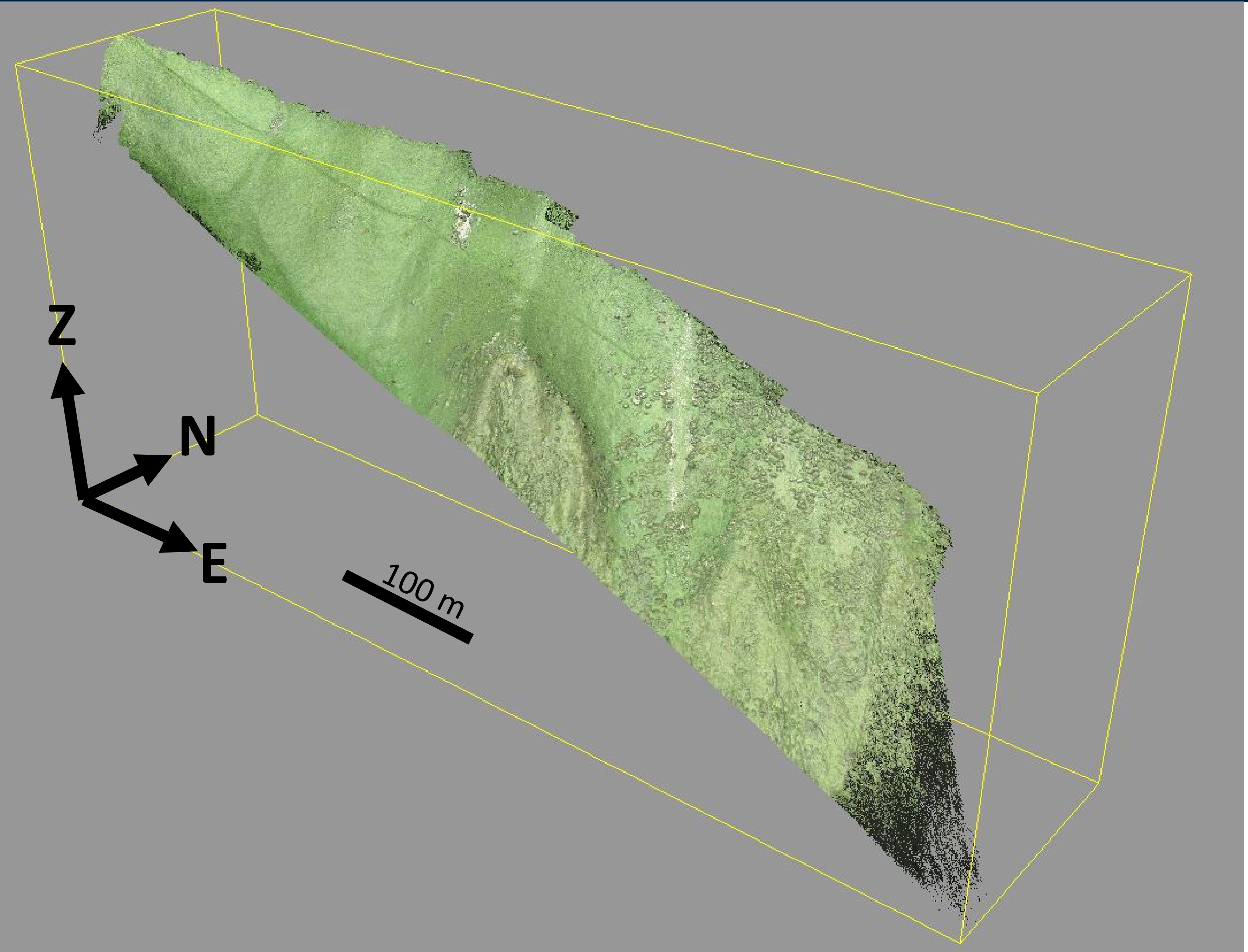


- Right-oblique & left-oblique flts
- Scarps along throughgoing structure, away from mountainfront
- No other small-scale evidence of faulting than MRF

What is the sense of slip on this fault?

SPOT-6/7 DEM

Offset ridges at Salimbay – drone survey

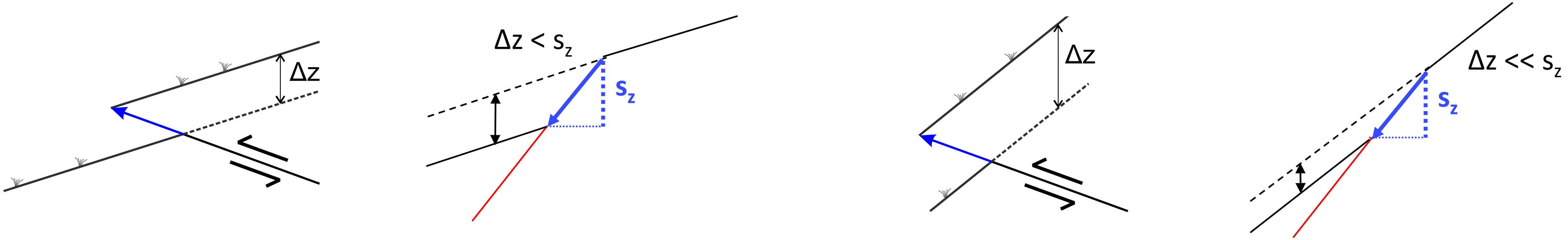


- Highly oblique hillside
  - steep slope in X and Y dir
- Uphill-facing scarp
- Apparent steep N dip
- Fault-normal motion apparently quite different from northeastern reaches of fault system

The problems with profiles

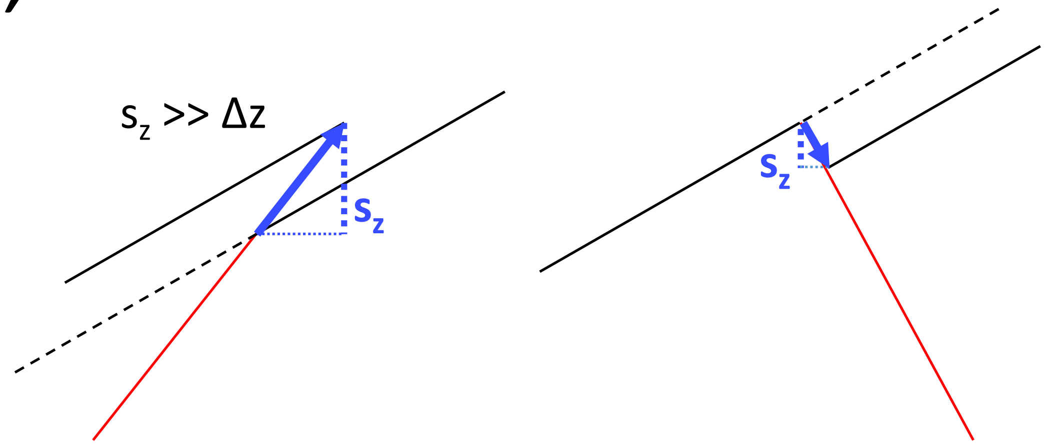
Surface slope has strong control on measured vs. actual throw

- For a given fault dip, increasing slope increases error of height change



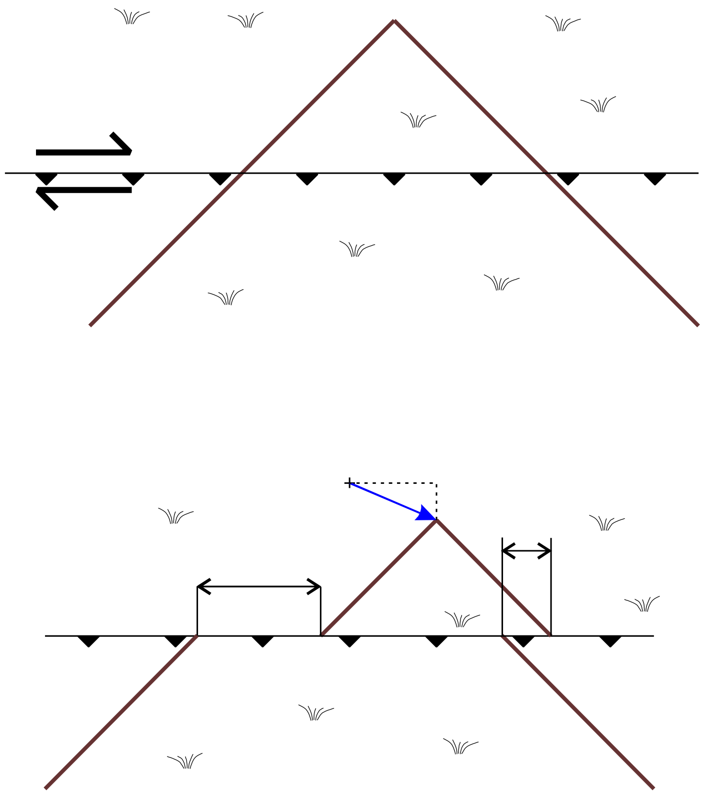
Conversely,

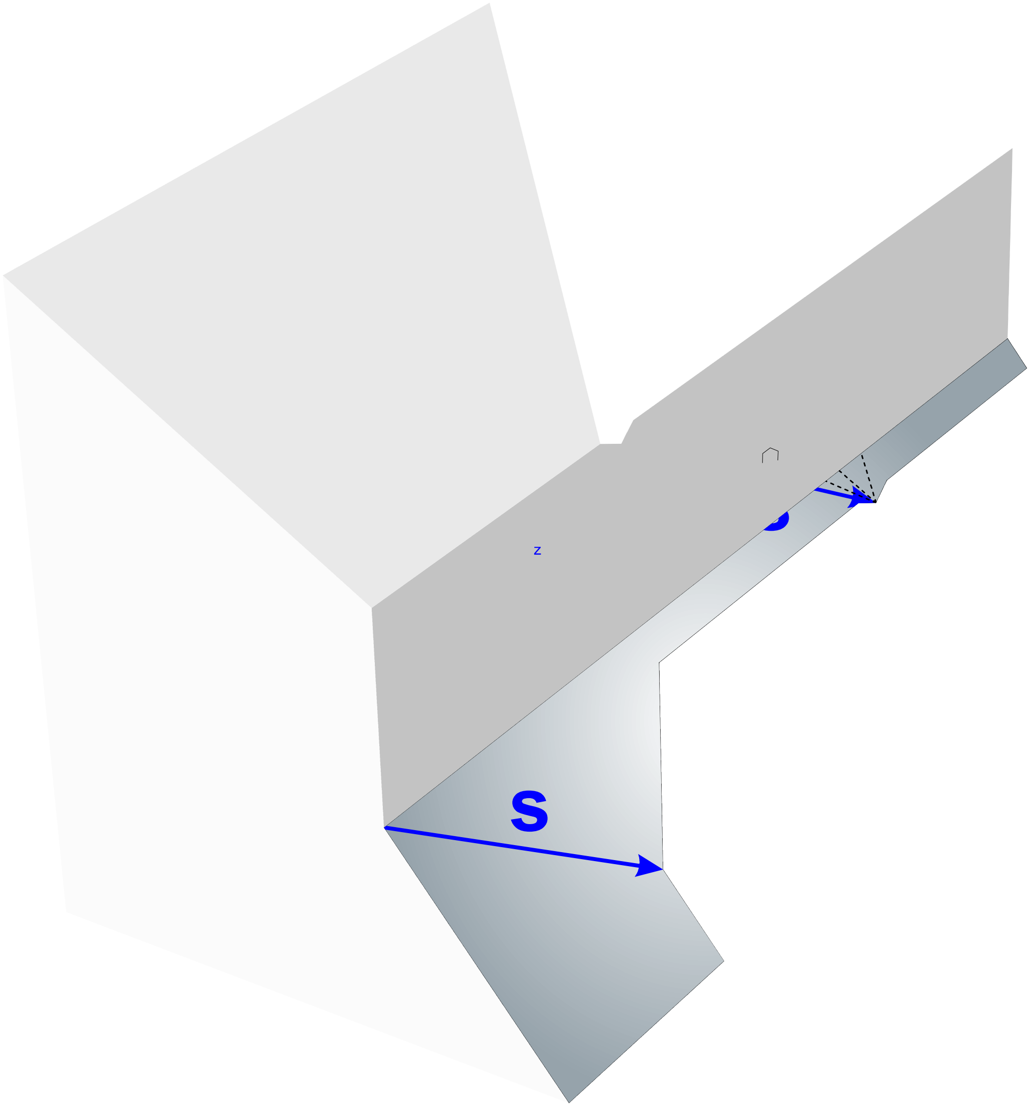
- For a given [mod. – high] surface slope, changing fault dip has a strong impact on error btwn measured and actual offset



The problems with profiles

Lateral-slip problem too





The problems with profiles

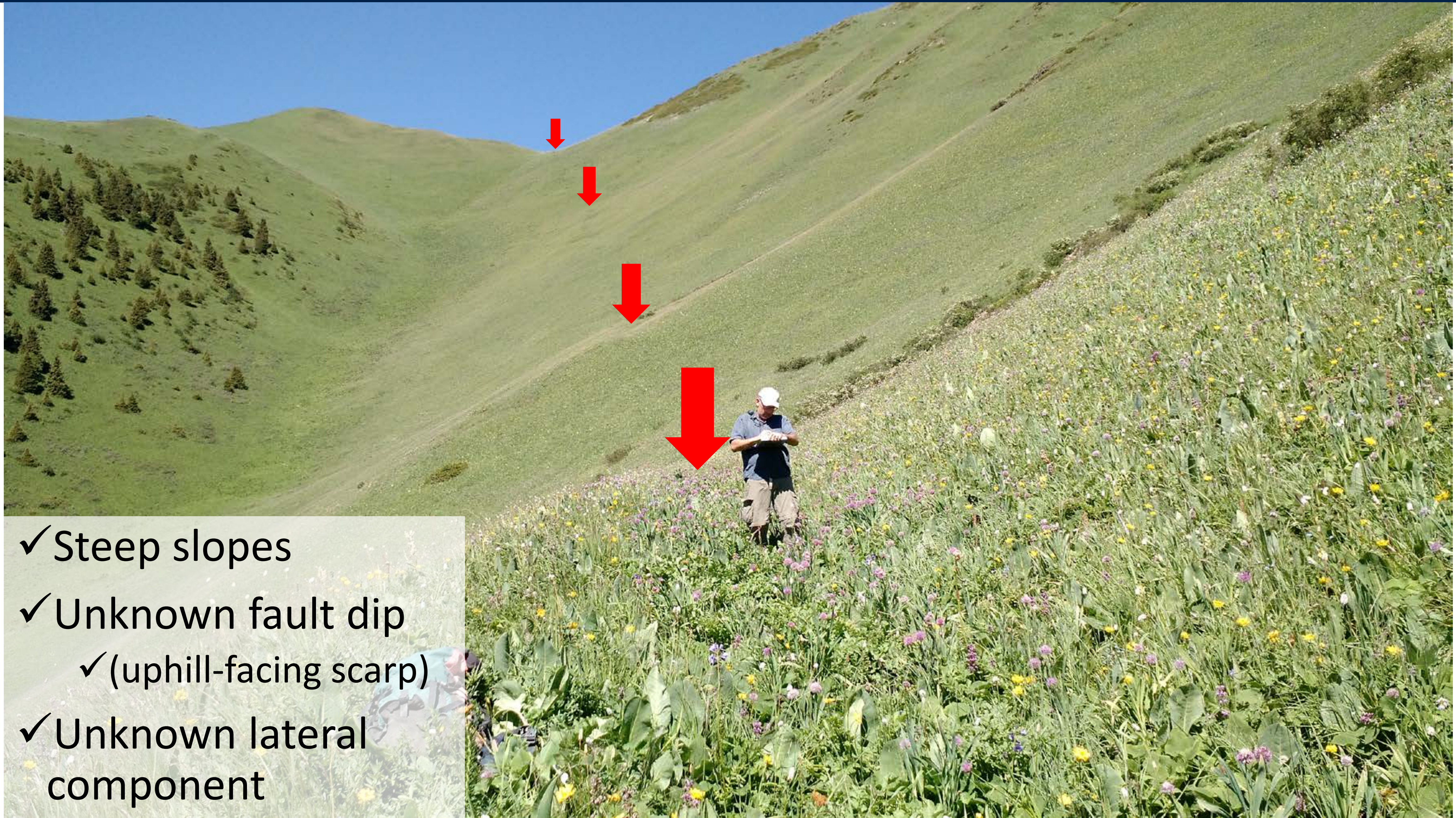
Because of these overwhelmingly confounding factors, profile sites are chosen to satisfy **3 assumptions:**

1. pure dip-slip
2. surface slope is low
3. fault dip is known &/or moderately high to vertical

- Don’t take into account lateral slip
- Often “chosen,”
  - Not necessarily perpendicular to fault
  - Nor representative of landform
- Require knowledge of fault dip

The problem with profiles

The problem with profiles



- ✓Steep slopes
- ✓Unknown fault dip
  - ✓(uphill-facing scarp)
- ✓Unknown lateral component

How slope-fault angle distorts measured offset

Analytical uncertainty calculation

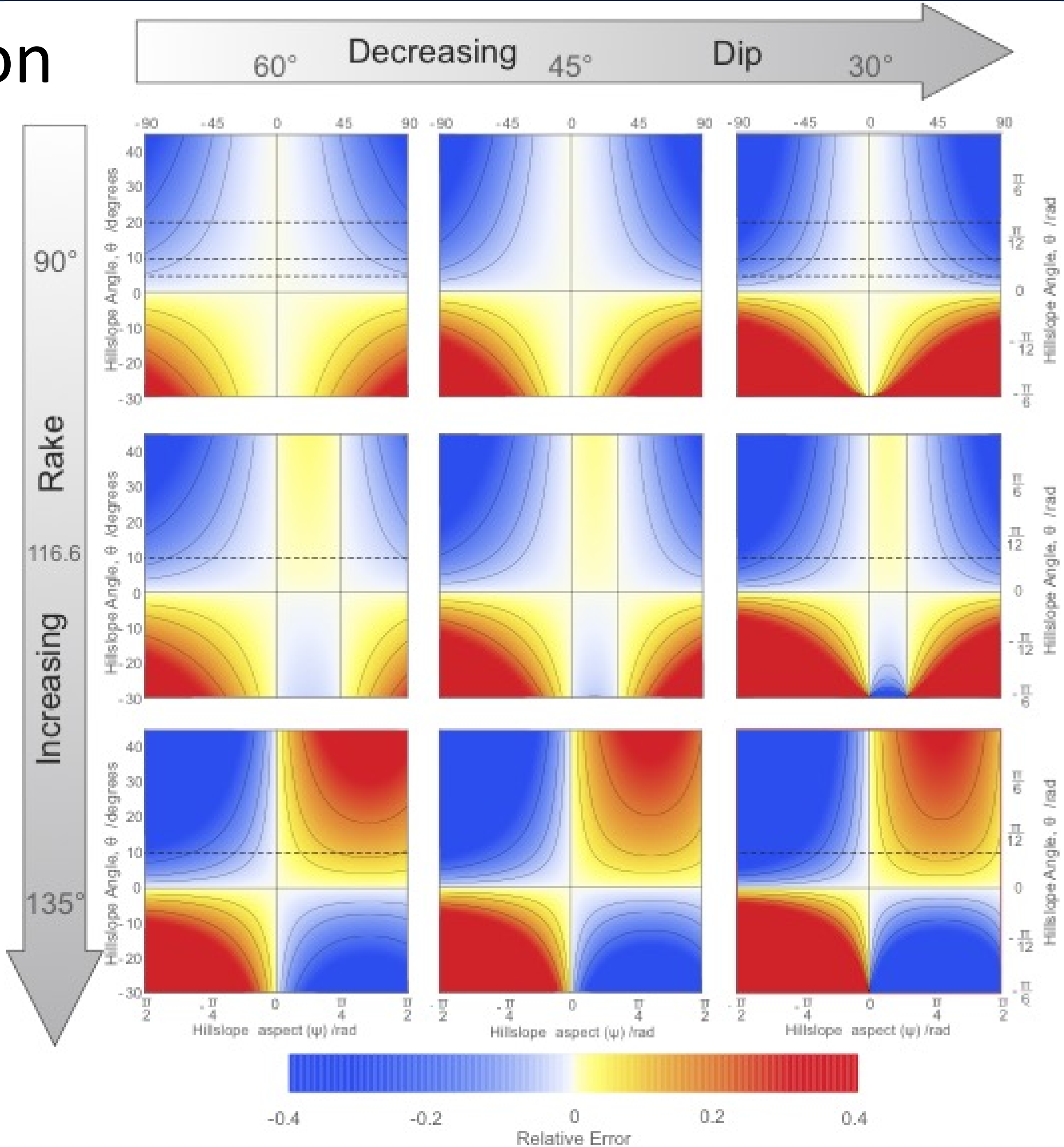
Relative error

(measured throw / actual throw)

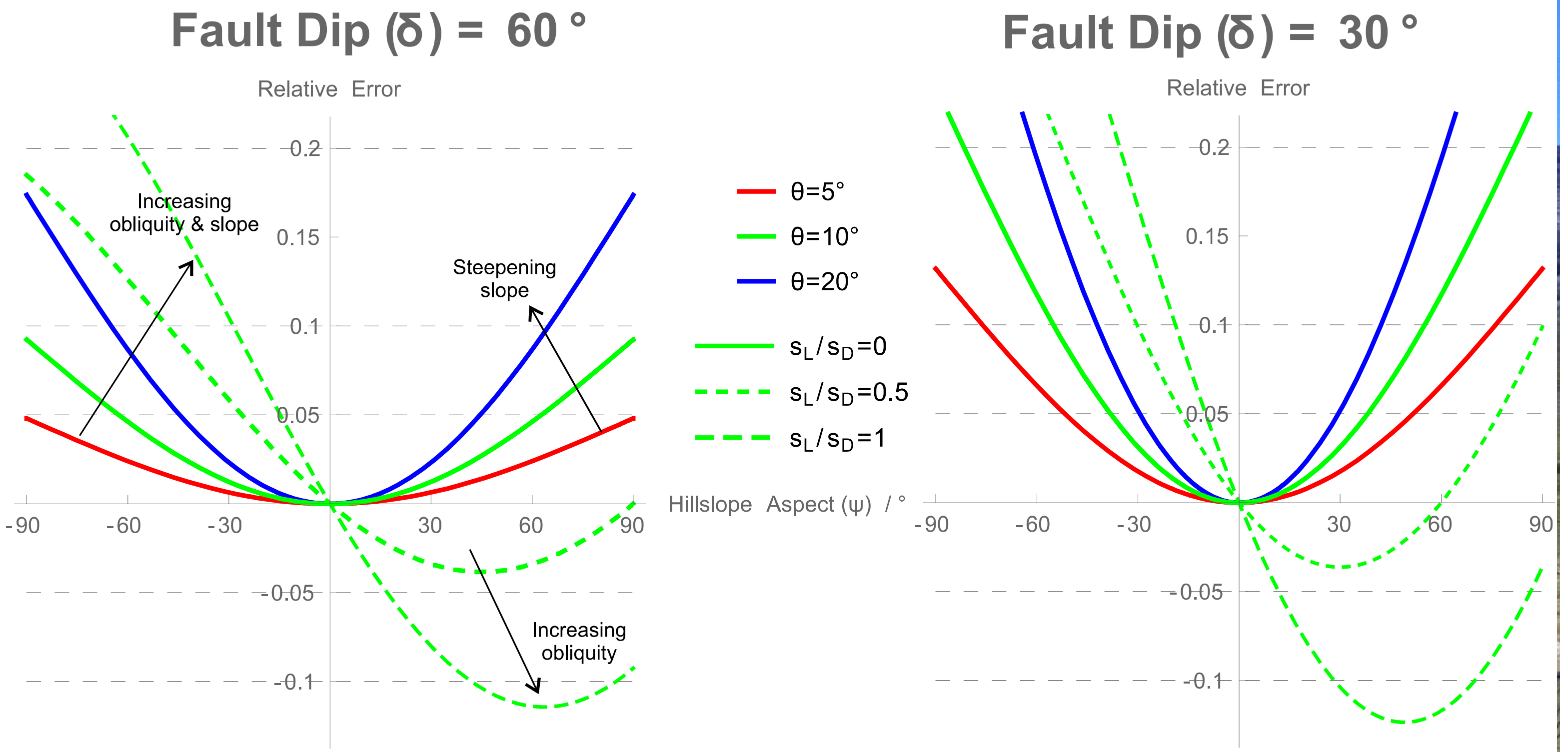
…plotted varying by hillslope orientation (angle & aspect)

…for different cases of fault dip

…and different lateral-to-dip-slip ratios



How surface slope increases offset uncertainty

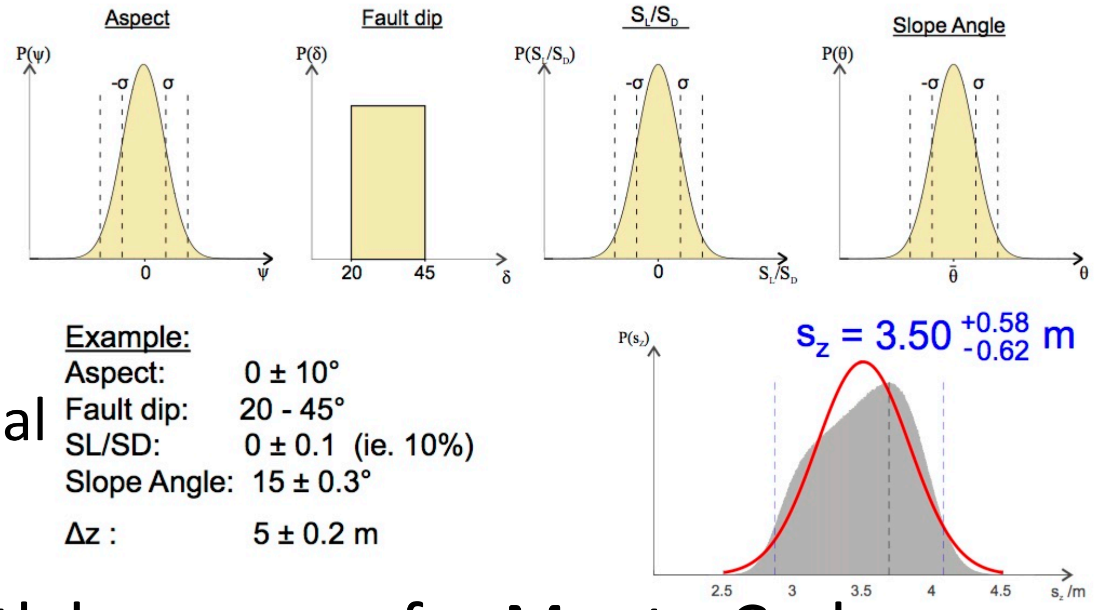


- increasing slope obliquity increases apparent offset
- increasing topographic slope angle increases apparent offset
- decreasing fault dip increases apparent offset
- increasing slip obliquity increases uncertainty + or -

Recommendation

When measuring throw from profiles,

- Profiles in suspect sites should be accompanied by uncertainty analysis that incorporates artifacts of fault-slope-slip geometry



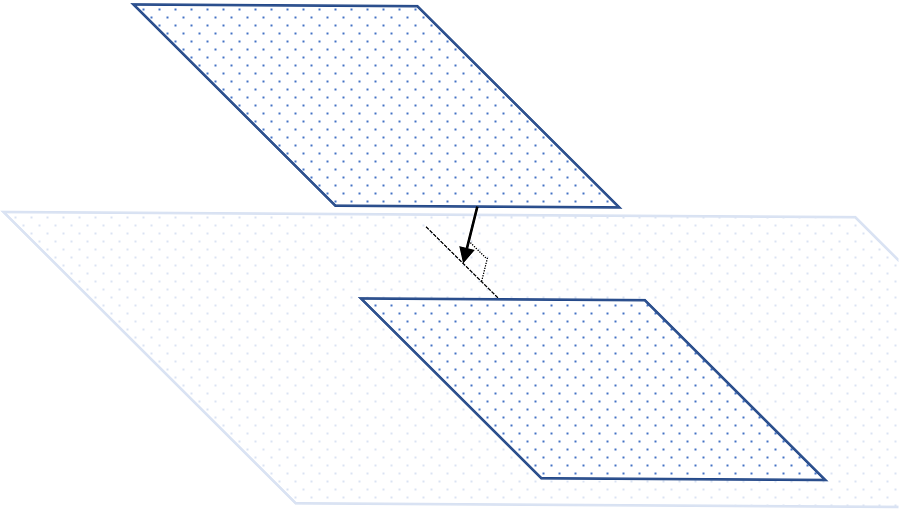
- Particularly for:
  - surface slopes >10°
  - obliquity > 10-20% lateral slip
  - especially when slope aspect is not flt-normal

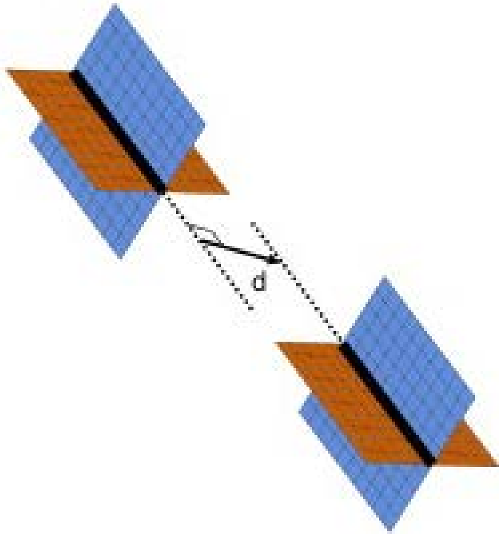
- Mackenzie and Elliott (in review) has Matlab program for Monte-Carlo uncertainty analysis of these variables

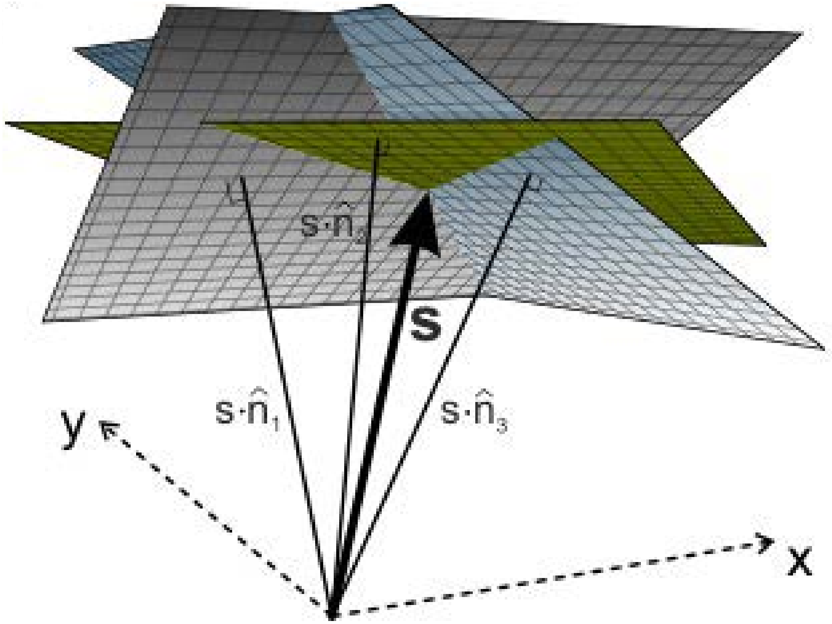
Changing apparent offset can resolve real 3D offset

Changing apparent offset can resolve real 3D offset

- Single offset surface (1 correlative pair) → plane-orthogonal offset
  - (clear intersections with fault constrains slip to 3rd plane) commonly not available!
- Additional intersecting surface (2 corr. pairs) → line-orthogonal offset
- Third pair of correlative offset surfaces → 3D slip vector







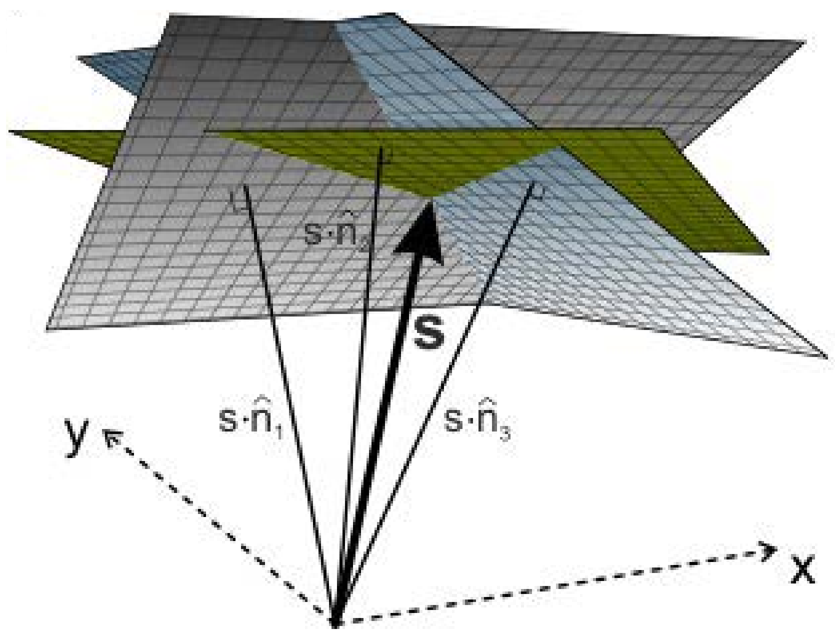
Solving multiple offset planes for shared slip vector

Measurable displacement of a plane is slip vector resolved onto plane-normal direction

$$\mathbf{s} \cdot \hat{\mathbf{n}} = d$$

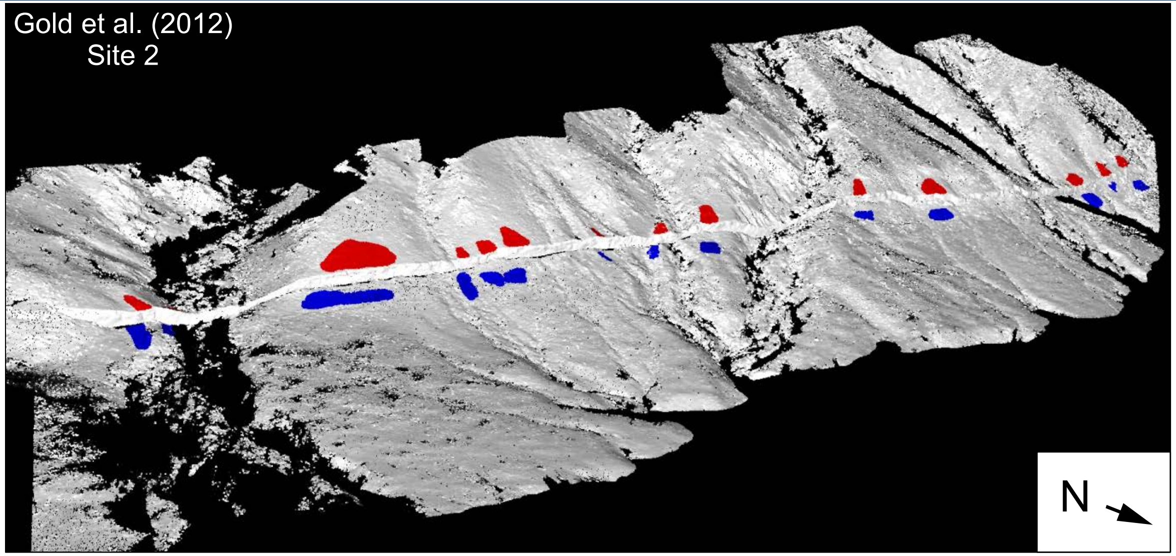
With 3+ plane-orthogonal separations measured, 3 component slip vector can be resolved

$$\hat{\mathrm{N}} = \begin{pmatrix} n_{x,1} & n_{y,1} & n_{z,1} \\ n_{x,2} & n_{y,2} & n_{z,2} \\ \vdots & \vdots & \vdots \\ n_{x,m} & n_{y,m} & n_{z,m} \end{pmatrix}, \quad s = \begin{pmatrix} s_x \\ s_y \\ s_z \end{pmatrix}, \quad d = \begin{pmatrix} d_1 \\ d_2 \\ \vdots \\ d_m \end{pmatrix}$$



David Mackenzie’s Matlab program solves for a slip vector shared by 3 or more pairs of offset planes

Test case on El Mayor Cucapah TLS



old et al. (2012)
Site 2

Plot of:

- Analytically predicted plane-separations
- Plane separations predicted by average slip vector (solution)
- Plotted plane separations measured

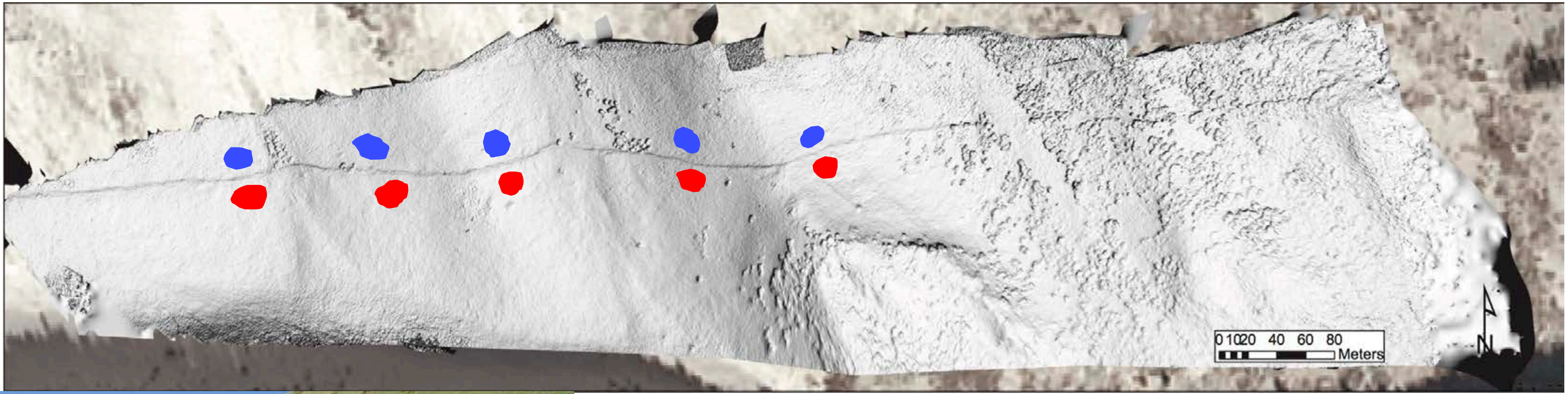
Vertical: 1.2 m
Lateral: 2.1 m

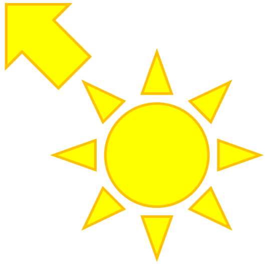
…in agreement with Gold et al. 2013
Individual features have < lateral, >fault-normal, differences arising where Gold's estimates omit extensional component!

Results at Salimbay Canyon

5 correlative surface pairs

1.0±0.2 1.2±0.2 0.5±0.1 2.2±0.2 0.3±0.1





<u>Offsets of upthrown side</u>

Fault-parallel:	-3.9 ± 2.5
Vertical (throw):	2.8 ± 2.7

More **right-lateral** than vertical!

Takeaway Messages

- Problems with profiles lead to restrictive filtering of offset markers
- 2.5-D high-res topographic fields offer new suite of markers
- We recommend accompanying vertical offsets from profiles with full uncertainty analysis of geometric configuration at site
- We have developed a tool that calculates a slip vector based on multiple (3+) correlative-offset-surface pairs.
- We recommend trying to measure offset piercing lines using 2 planes that define them (e.g. V-shaped stream channel walls, or riser & tread)
- Together tool & uncertainty allow > inclusion of measurements