Overview of two MATLAB-based methods for semi-automatic measurement of lateral and vertical fault offsets in topographic data

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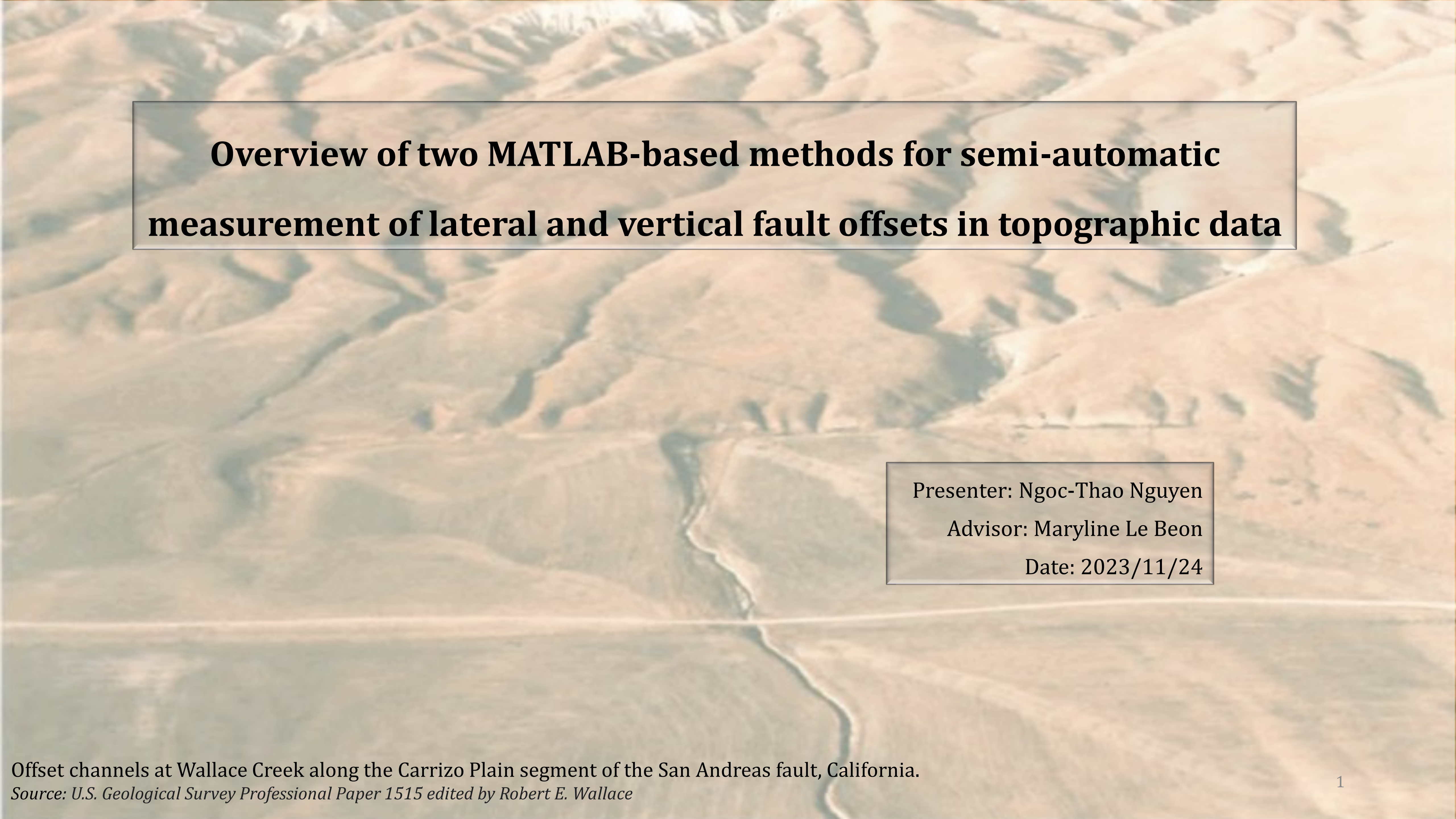


Offset channels at Wallace Creek along the Carrizo Plain segment of the San Andreas fault, California.
Source: U.S. Geological Survey Professional Paper 1515 edited by Robert E. Wallace

Introduction

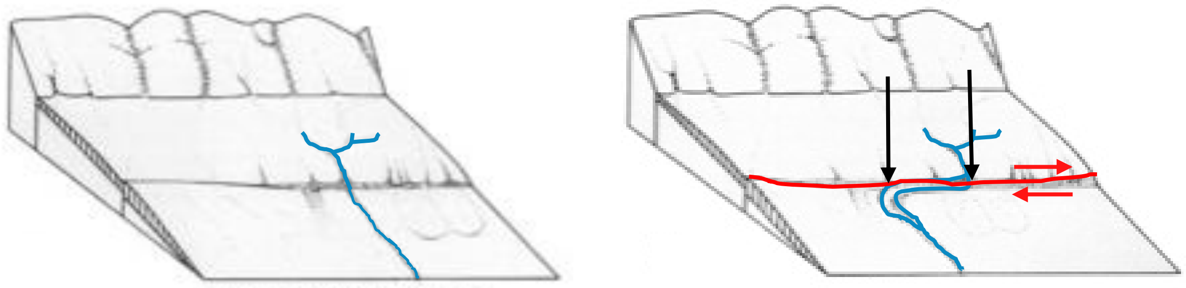
Fault movements → Earthquake Creep → Tectonic deformation

Disrupt and displace Geologic and *Geomorphic units*

- Knowing how much slip a fault has accumulated during one earthquake or over the long term is important in a better understanding of fault kinematics and mechanics *(Armijo et al., 1989; Gaudemer et al., 1989, 1995; etc)*, the relation between earthquakes and cumulative slips *(Tapponnier et al., 2001; Zielke, Klinger, & Arrowsmith, 2015; etc)*, and also the earthquake magnitude and stress distribution *(Klinger et al., 2011; Lasserre et al., 1999; Zielke et al., 2012; etc)*

- *How to quantify fault activity?*

Geomorphic markers

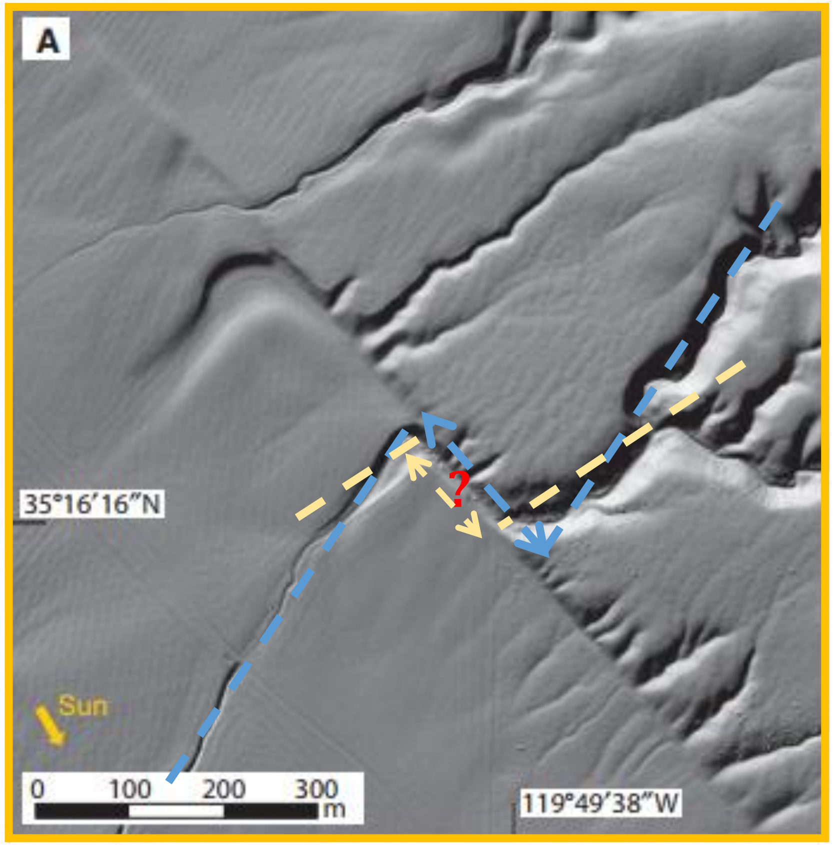


t_0 t_1

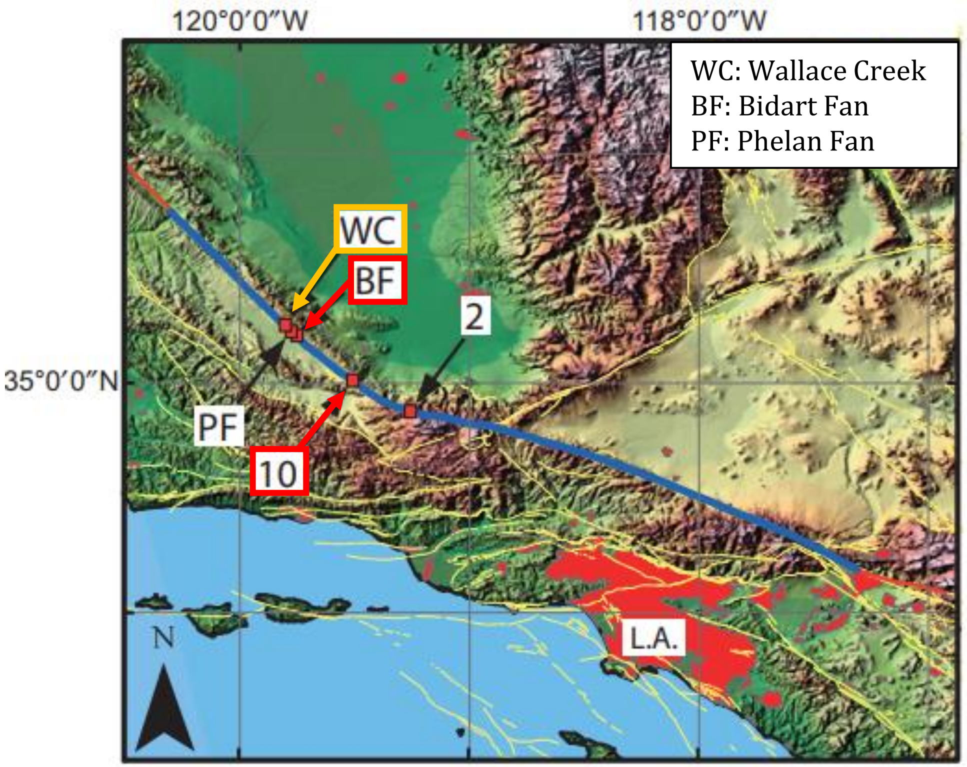
Modified from Sieh and Jahns (1984)

Motivation

✓ A fault-offset marker is **identified visually** by the expert in satellite, aerial images, or on the field (manual measurements)



Digital elevation model for Wallace Creek (WC)



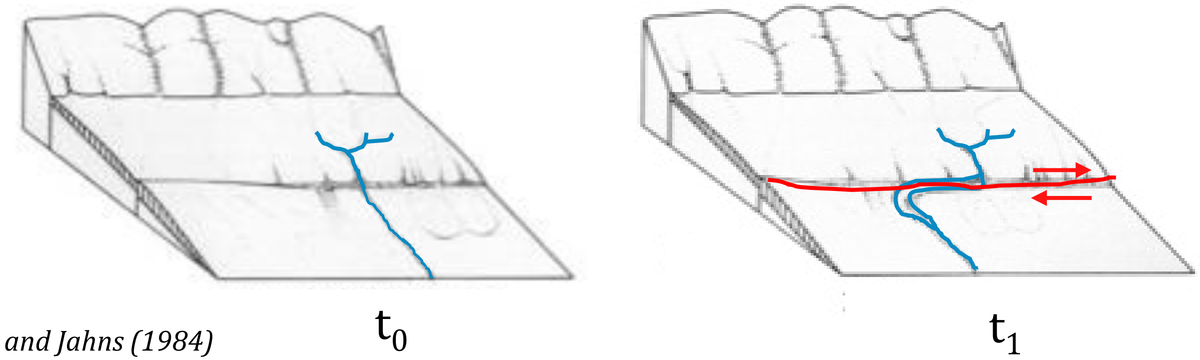
The San Andreas Fault (SAF) rupture trace for the M7.8 Fort Tejon earthquake in 1857

- *Offset measures and their uncertainties might be disputed*
- *With the large rupture length fault, the measurement is time-consuming*

Developing automated methods for remotely measuring fault slip in topography data

Methods

	LaDiCaoz (Lateral Displacement Calculator) (Zielke & Arrowsmith, 2012; updated version, LaDiCaoz_v2, released by Haddon et al., 2016)	**3D_Fault_Offsets** (Stewart et al., 2018)
Target	Linear geomorphic features (e.g., fluvial channels, terrace risers)	
Correlation	Two along-fault profiles crossing an offset marker on either side of the fault trace (2D)	Nine identified geometric characteristics across each offset marker section on either side of a fault (3D)
Offset Calculation	Horizontal offset Vertical offset *(updated version, LaDiCaoz_v2)*	Horizontal offset and vertical offset
Uncertainties	Estimating from the range of back slip reconstructions	Computed from the various sources of error *(DEM resolution, each point position within a regression, piercing points position onto the fault plane, fault positions, strike and dip)*

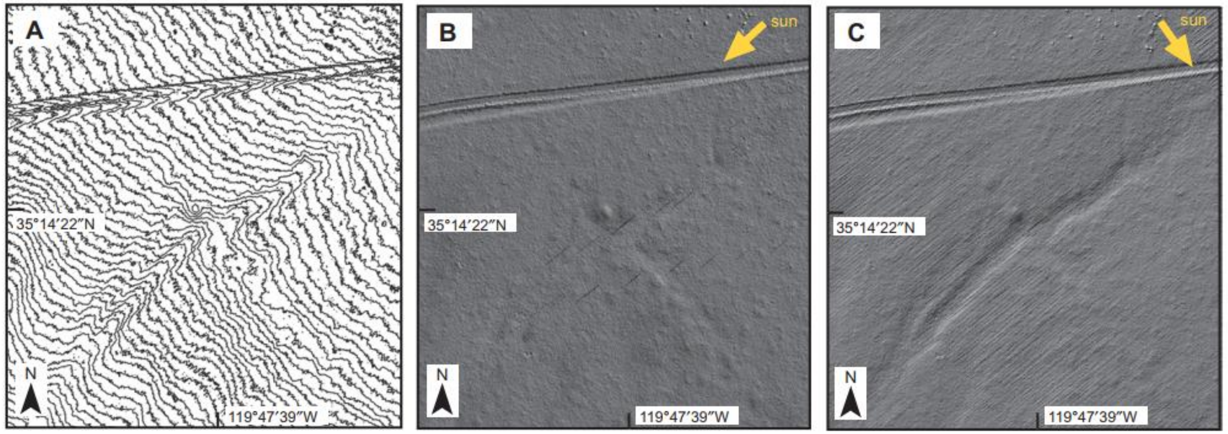


Modified from Sieh and Jahns (1984)

LaDiCaoz *(Lateral Displacement Calculator)*

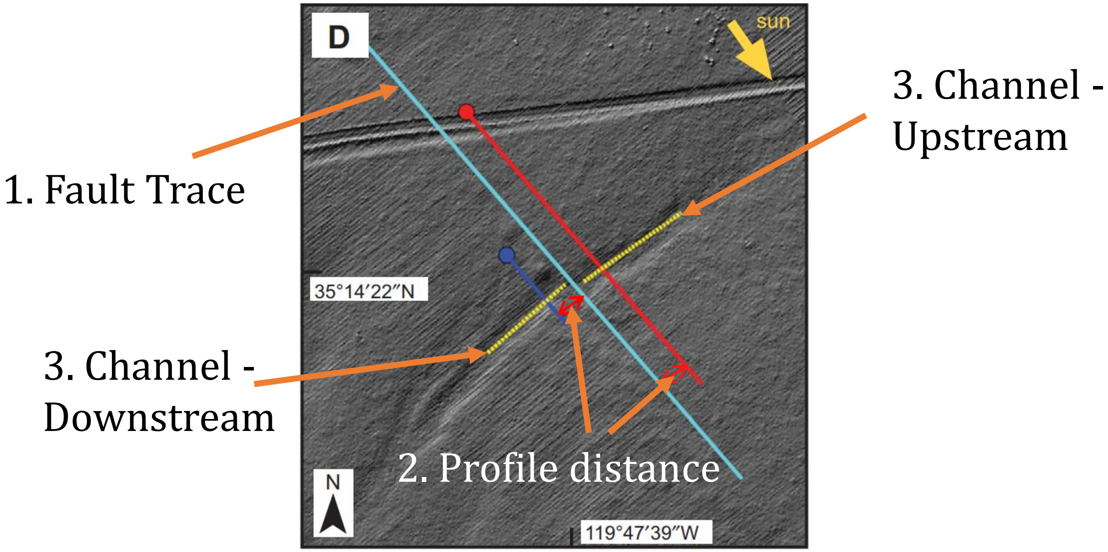
(Zielke & Arrowsmith, 2012; updated version, LaDiCaoz_v2, released by Haddon et al., 2016)

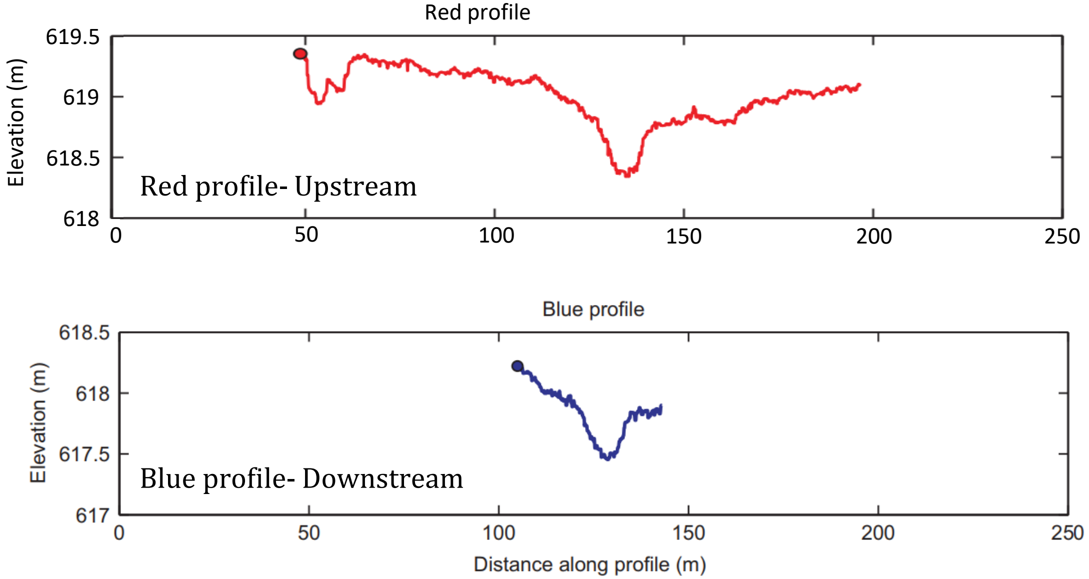
Input data



Base maps of a channel in the Carrizo Plain (A. Slope map, B, C. Hillshade map)

Fault and Channel Trace Mapping



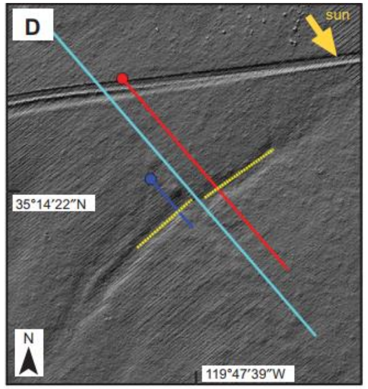


1. Define fault line- **Manually**
2. Define profile distance
3. Define channel trend- **Manually**

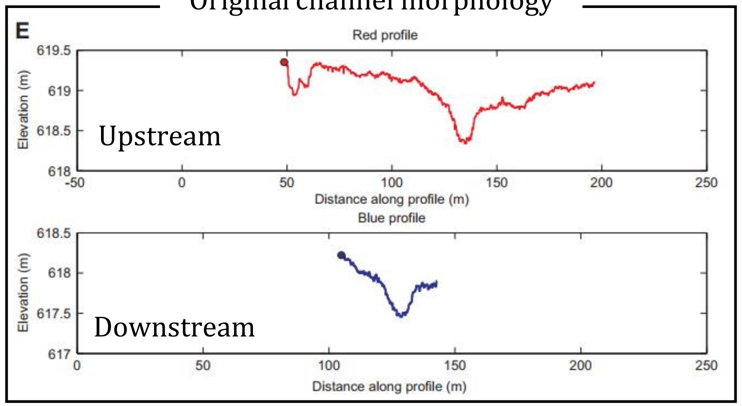
LaDiCaoz *(Lateral Displacement Calculator)*

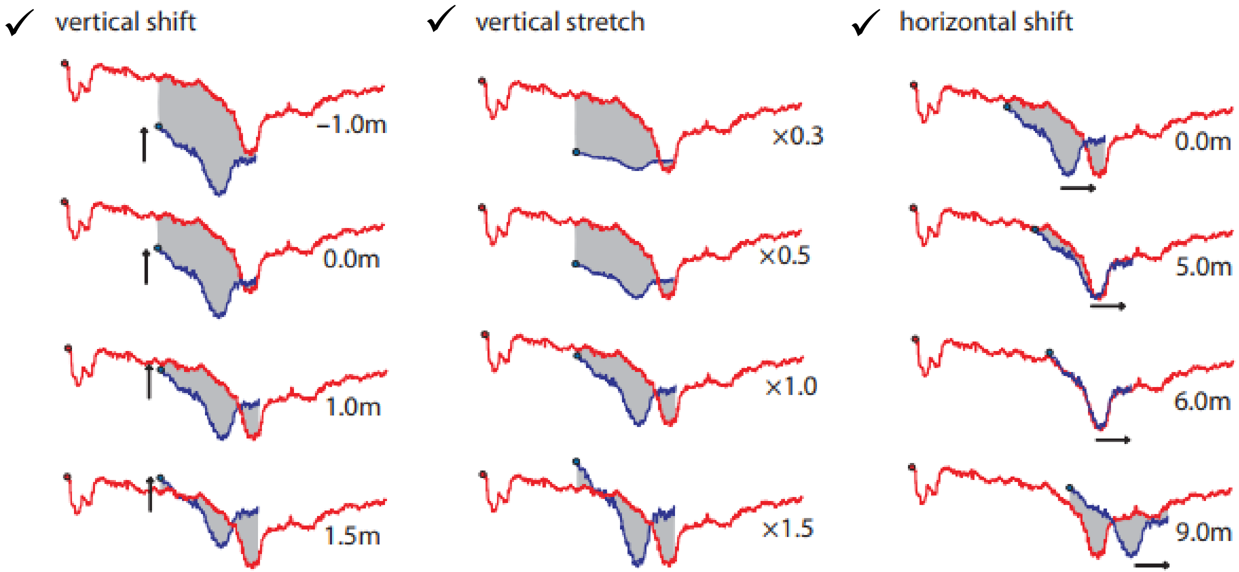
(Zielke & Arrowsmith, 2012; updated version, LaDiCaoz_v2, released by Haddon et al., 2016)

Automated offset calculation

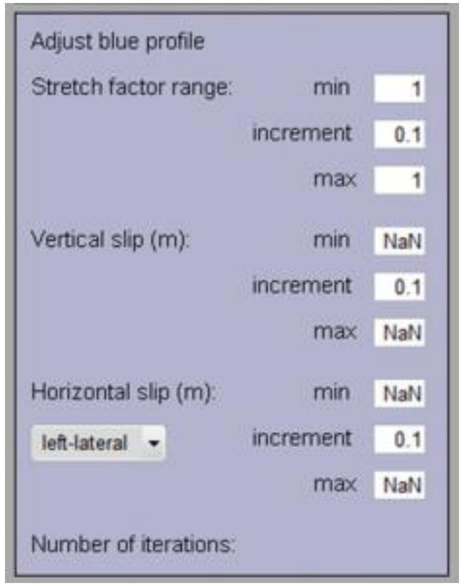


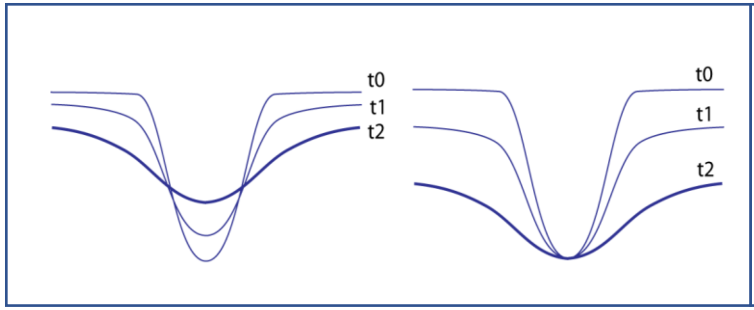
Original channel morphology



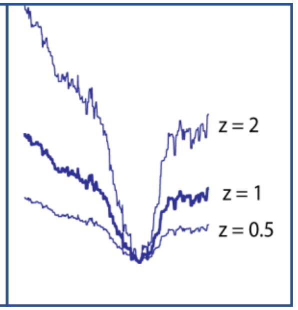


The summed absolute elevation difference $\sum[\Delta(\text{elevation})]$





Simple channel profile



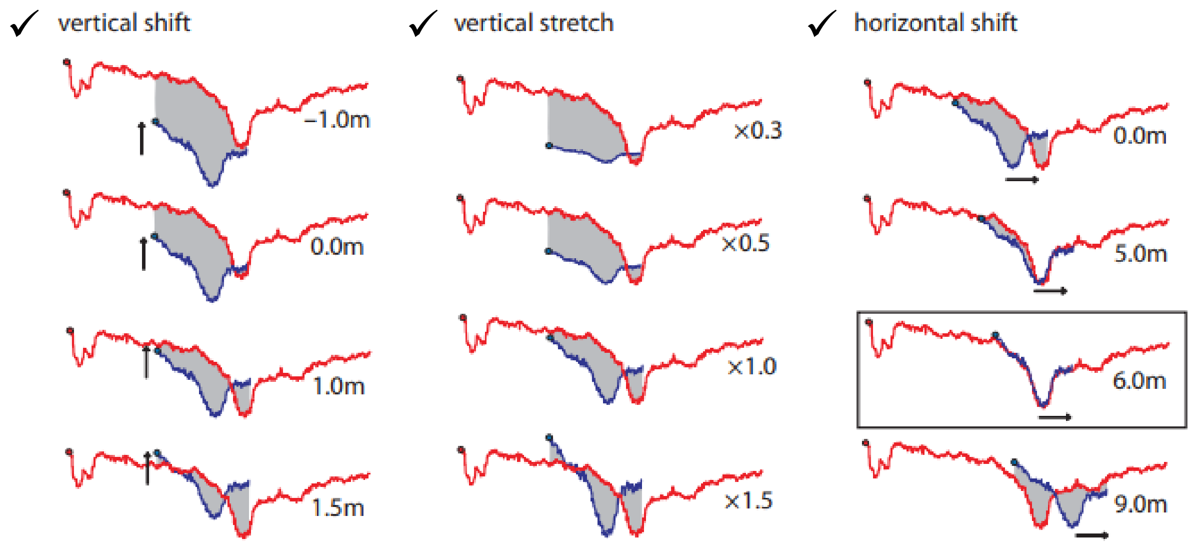
An actual profile

✓ The **optimal horizontal offset** is defined by **the parameter combination** for which **the summed elevation difference** between the profiles (*grey area*) has its **minimum**

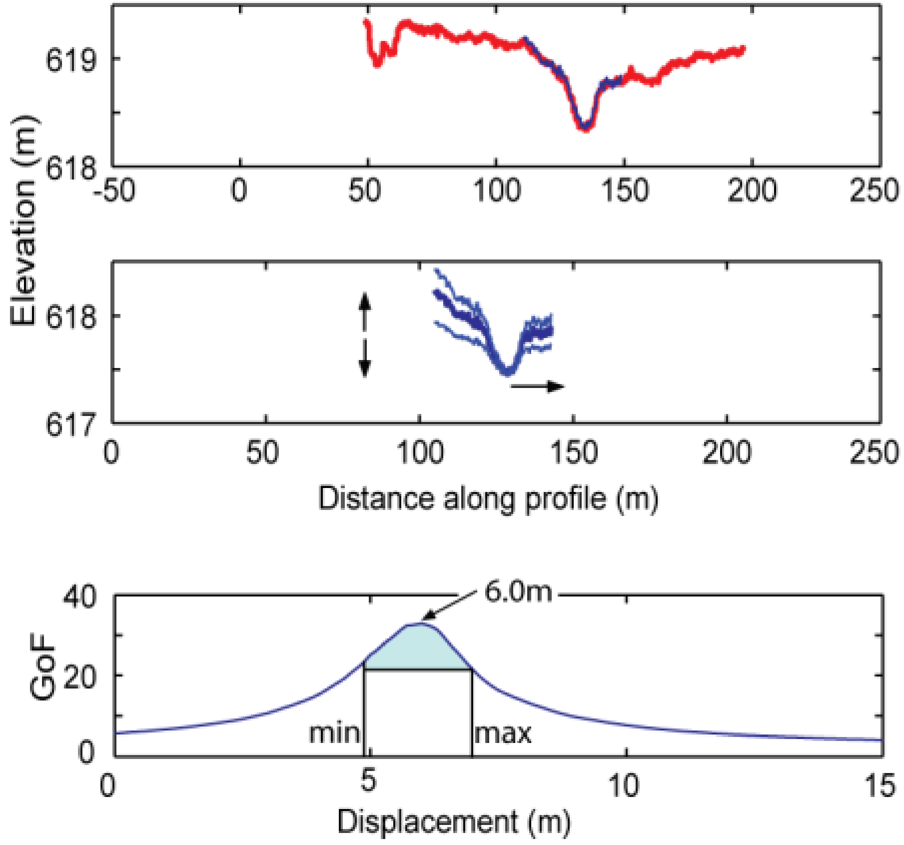
LaDiCaoz *(Lateral Displacement Calculator)*

(Zielke & Arrowsmith, 2012; updated version, LaDiCaoz_v2, released by Haddon et al., 2016)

Automated offset calculation



The summed absolute elevation difference $\sum[\Delta(\text{elevation})]$

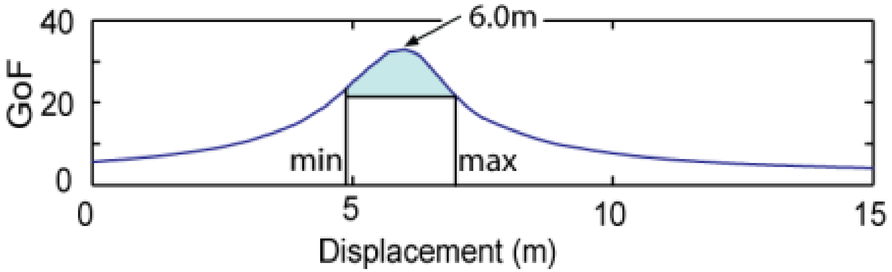


$$Goodness\ of\ Fit\ (GoF) = \frac{1}{\sum[\Delta(\text{elevation})]}$$

LaDiCaoz *(Lateral Displacement Calculator)*

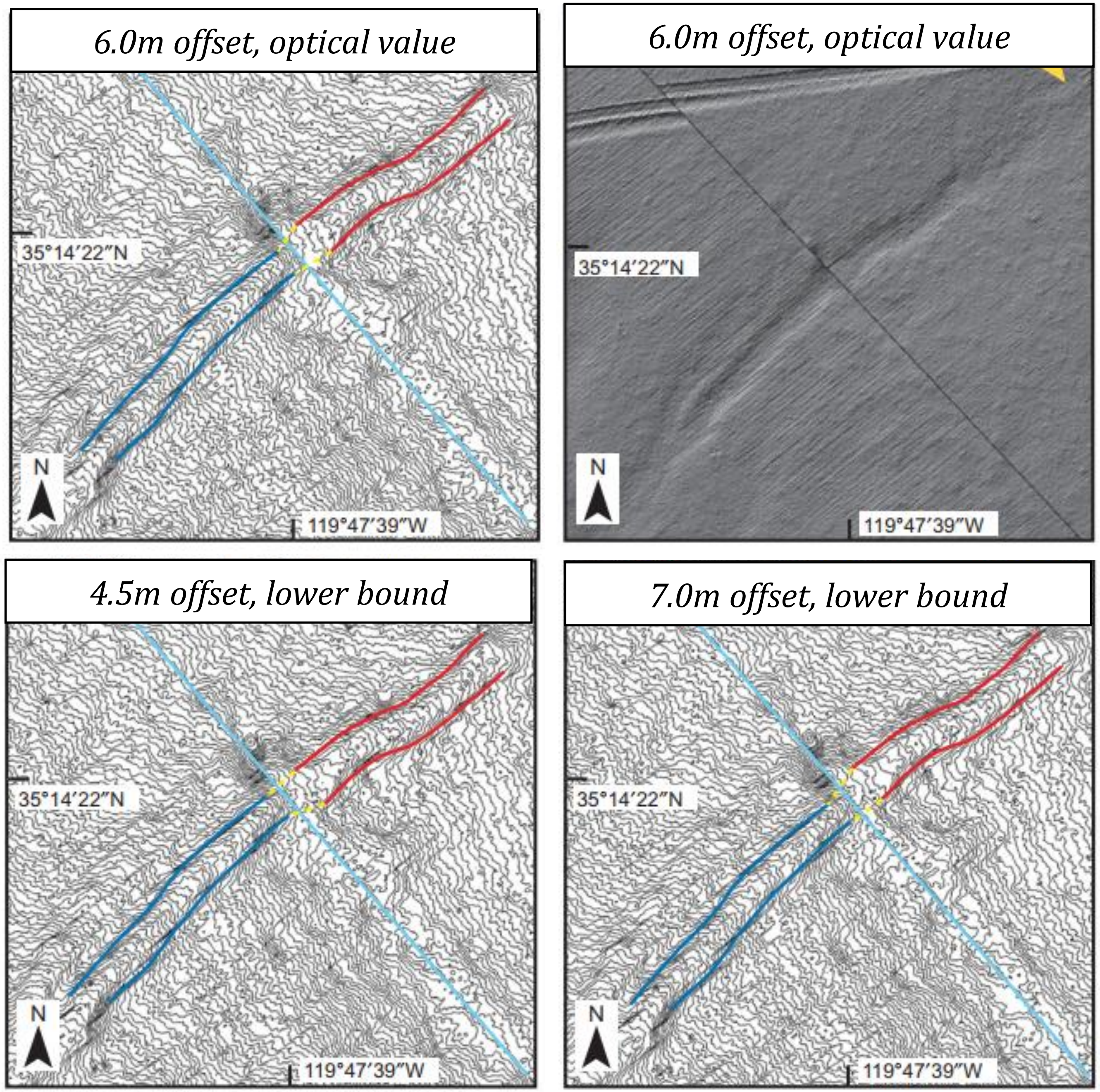
(Zielke & Arrowsmith, 2012; updated version, LaDiCaoz_v2, released by Haddon et al., 2016)

Back Slip of Hillshade and Contour Plots



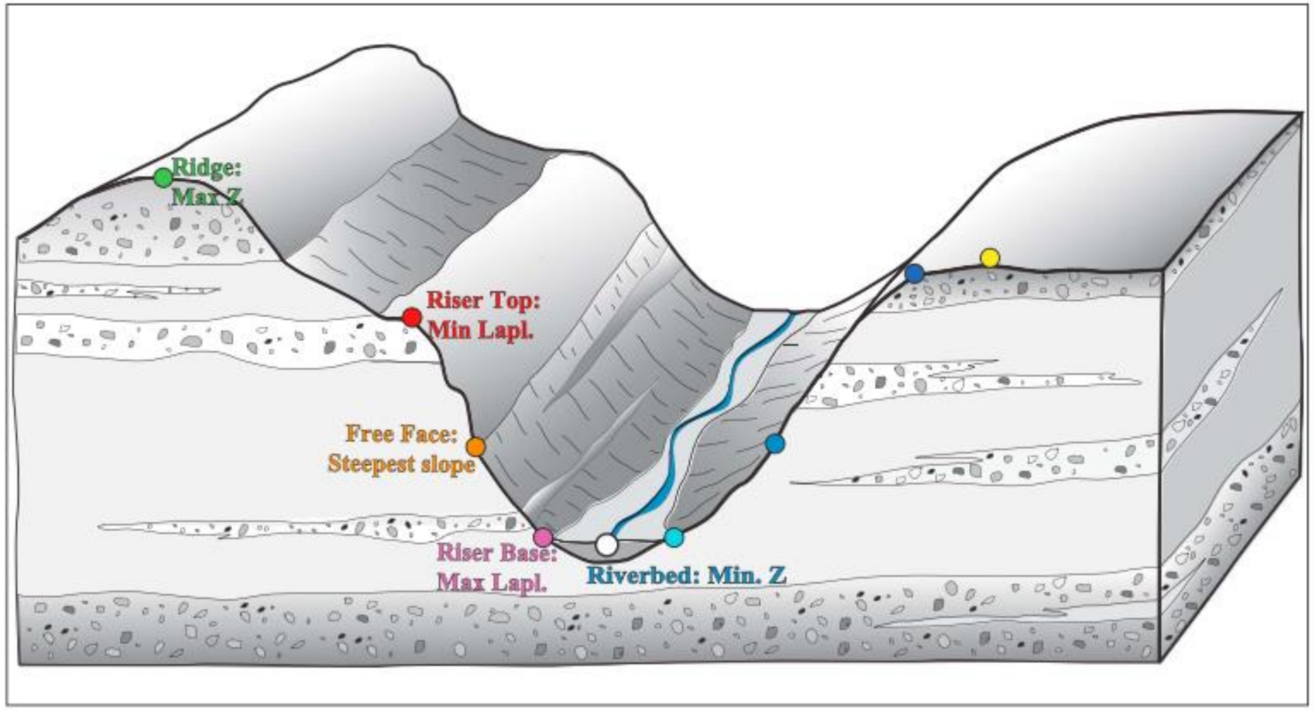
- ✓ The **maximum and minimum** displacement values are done by **"trial and error"**
- ✓ After defining the optimal value of the displacement, the software **back-slipped** a certain **displacement value** (near the optimal value).
- ✓ When the **trend lines on both sides** of the gully (riser edges) are **aligned** respectively, the **maximum** and **minimum** values are **determined**.

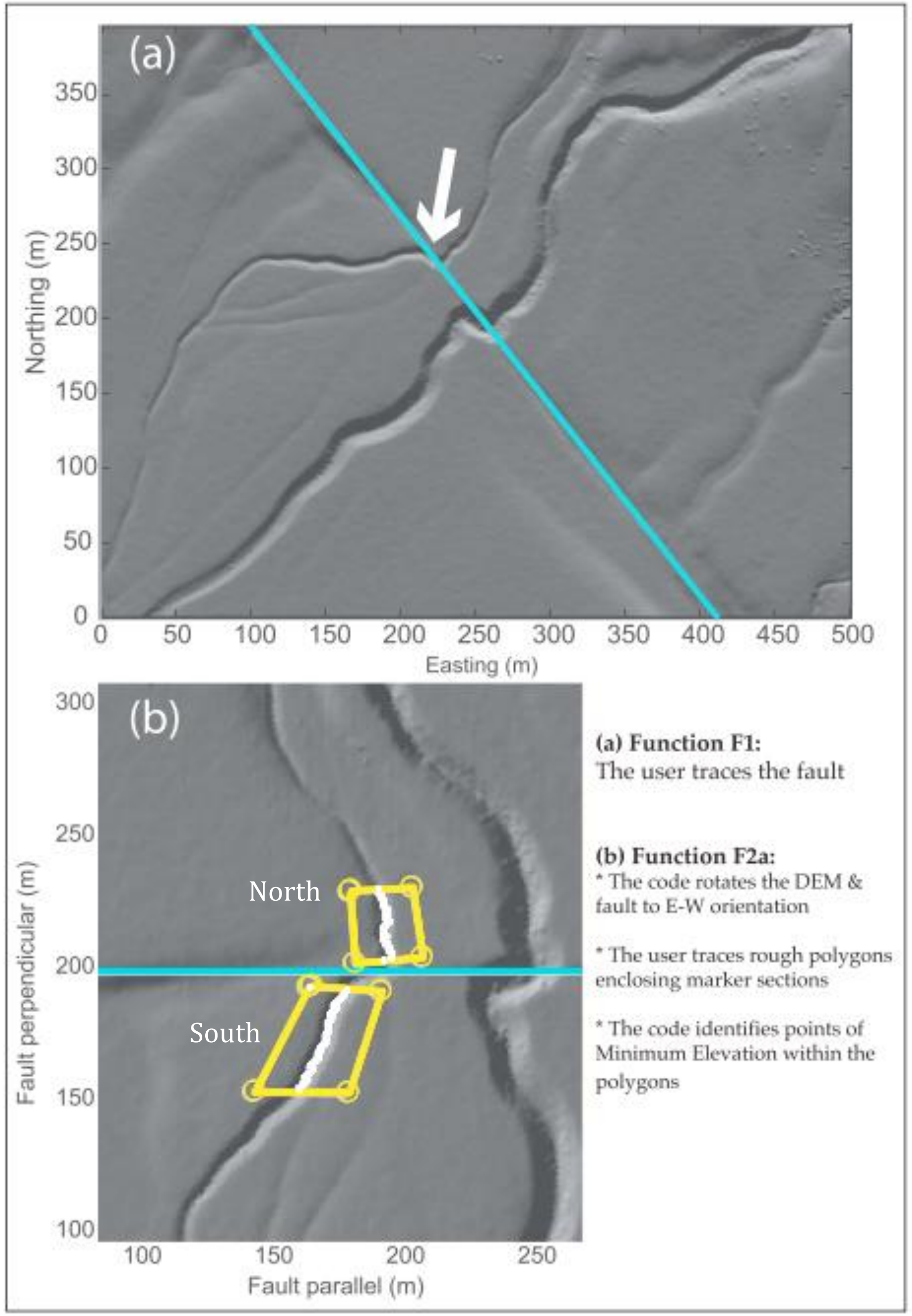
⌧A common **cause** for **mismatches** in **the back-slipped topography** while the cross-sectional profiles show a very good match- is **an incorrect representation** of **fault** and/or **channel segment trend** and/or **position.**



3D_Fault_Offsets

(Stewart et al., 2018)





1. Define fault line – **Manually**
2. Tracing rough polygons enclosing marker sections- **Manually**

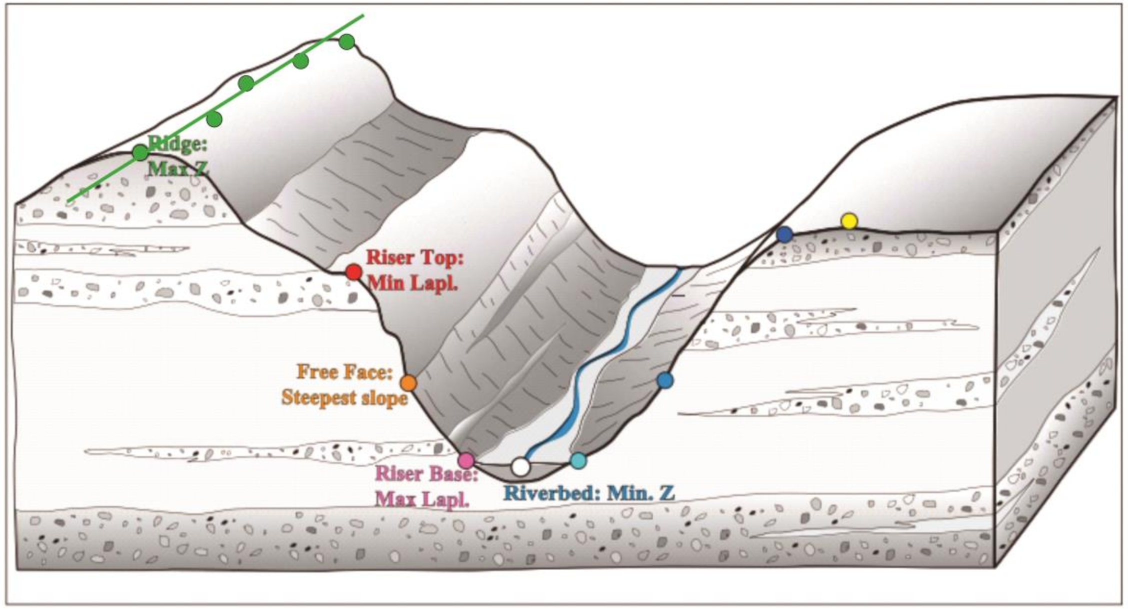
3D_Fault_Offsets

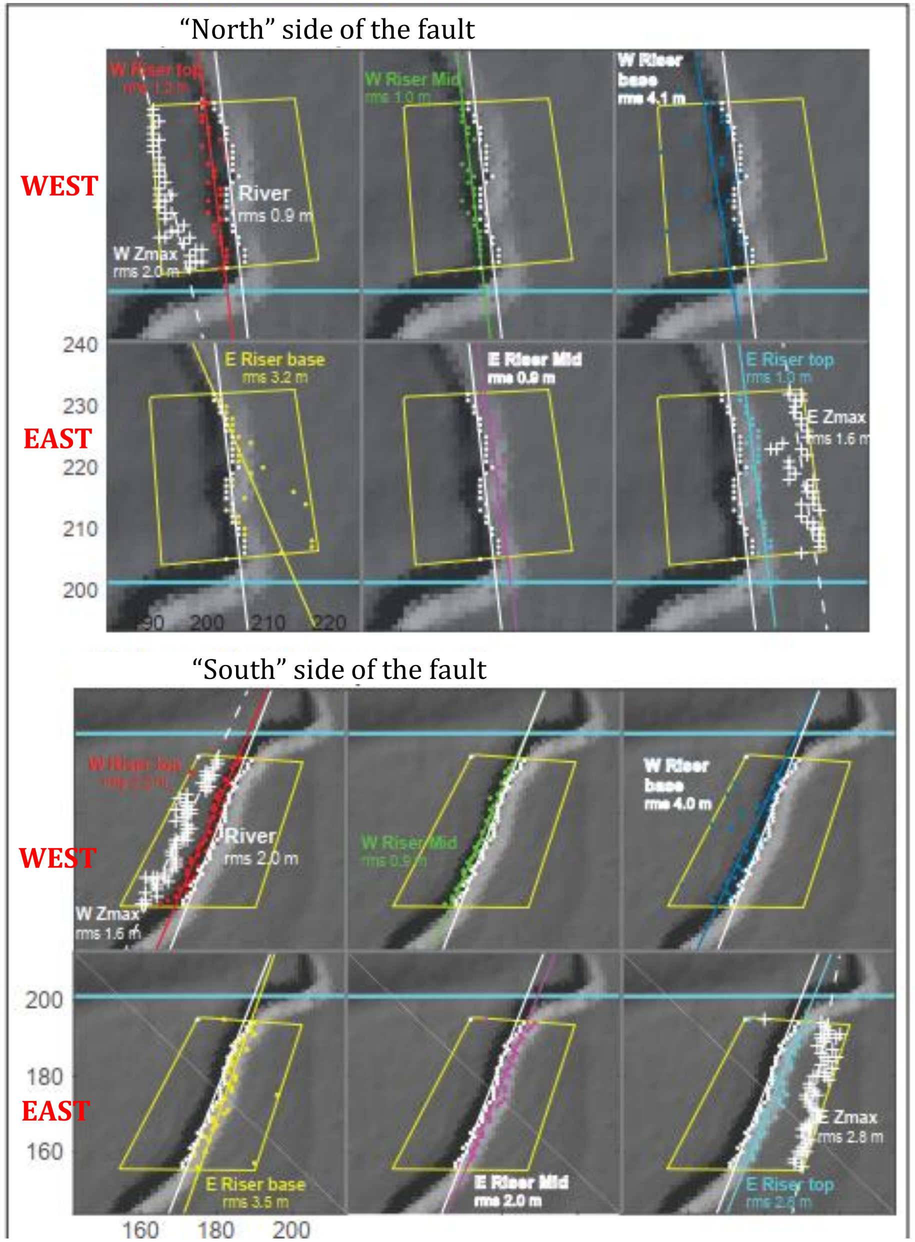
(Stewart et al., 2018)

Specific geometric points characterizing the marker morphology

Riverbed: The zone of lowest elevation **(Min Z)**
Ridge: Points of maximum elevation **(Max Z)**
Riser Top: A zone of **slope break** with a **maximum downward concavity**
(Min Laplacian of the topography)
Free Face: Steepest slope
(Maximum gradient of the topography)
Riser Base: A zone of **slope break** and **maximum upward concavity**
(Max Laplacian of the topography)

✓ Using **the least-square method**, this function computes a **3D best-fitting straight line** through each of the 9-point clouds on either side of the fault



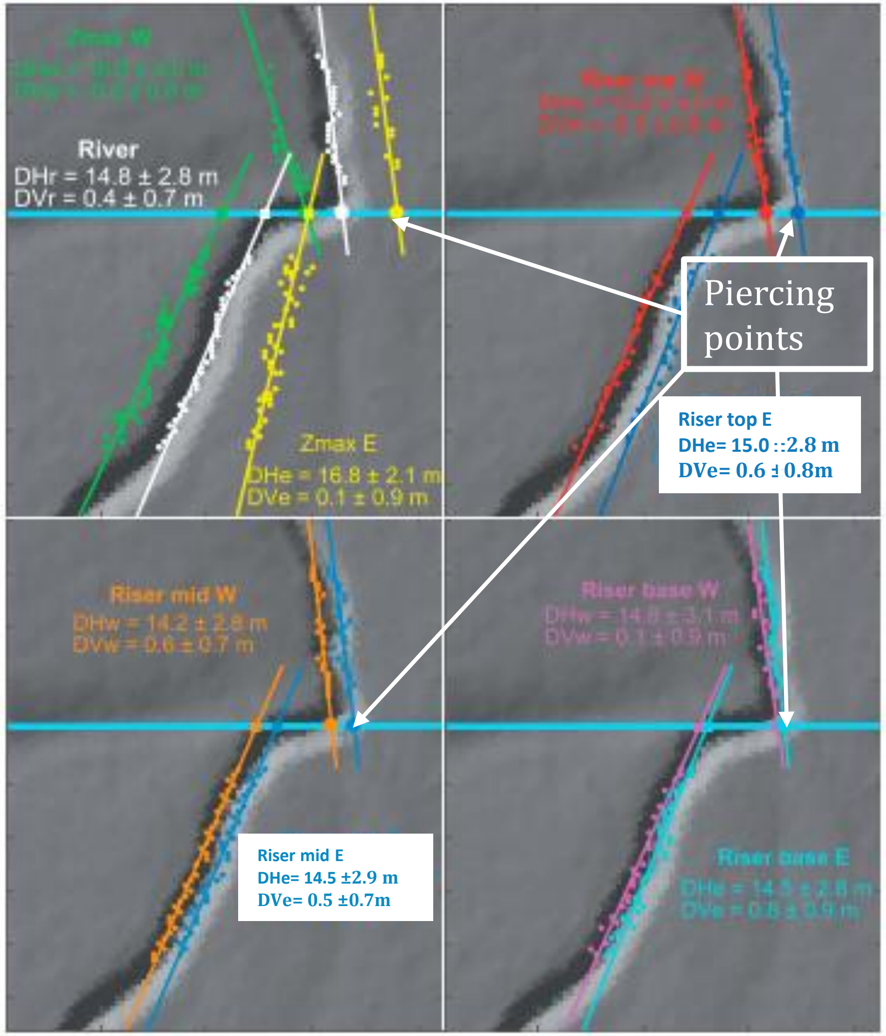


✓ 2 groups of 9 pairs of 18 linear geomorphic markers in total

3D_Fault_Offsets

(Stewart et al., 2018)

Calculating <u>the lateral and vertical offsets</u>, along with the <u>total uncertainties</u> on these offsets



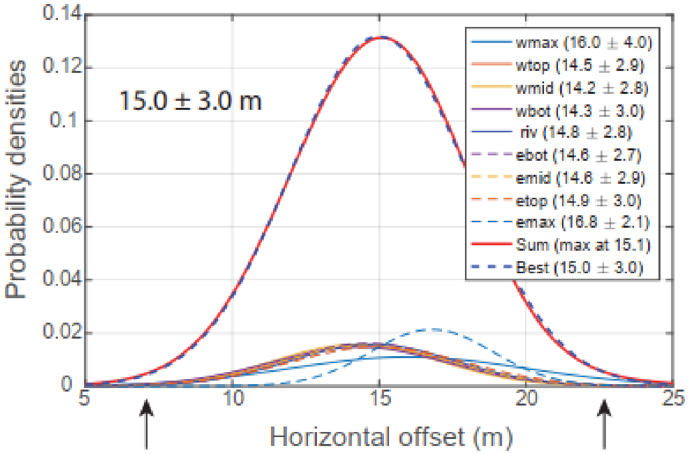
Calculating the lateral and vertical offsets

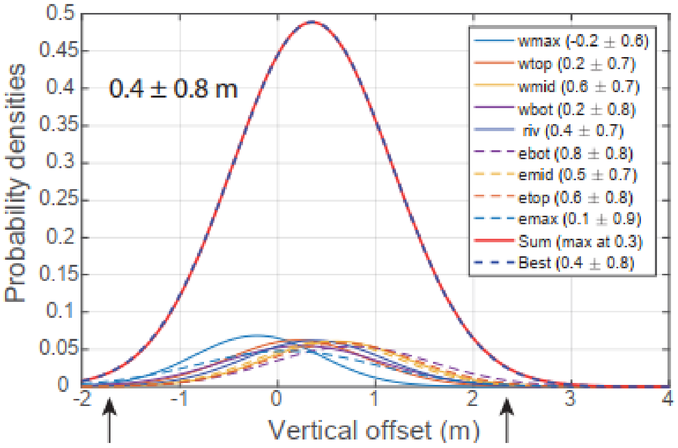
$$\text{Horizontal offset} = x_N - x_S \ (m)$$

$$\text{Vertical offset} = z_N - z_S \ (m)$$

The total uncertainties on these offsets (Using the Monte Carlo approach)

Various sources of error (*DEM resolution, each point position within a regression, piercing points position onto the fault plane, fault positions, strike and dip*)

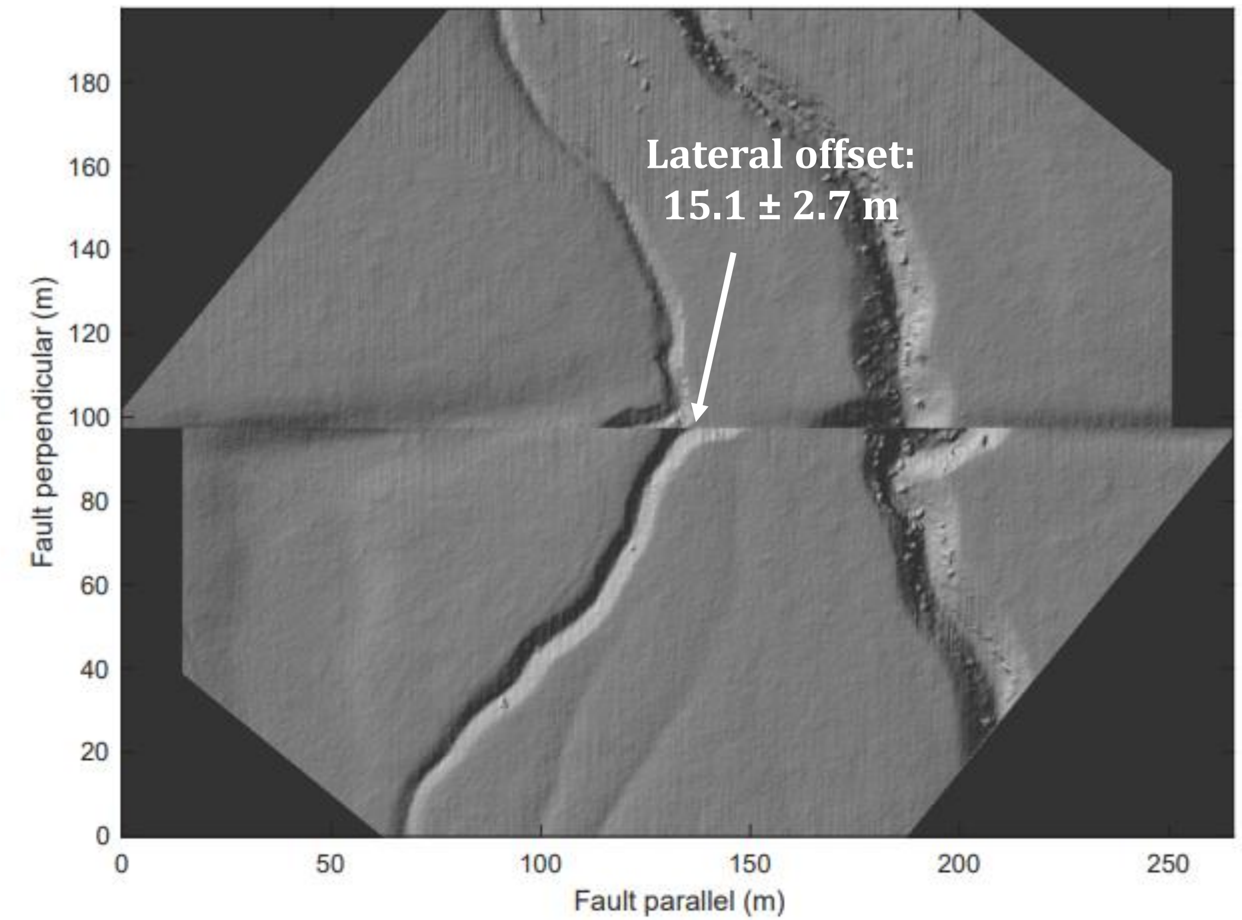


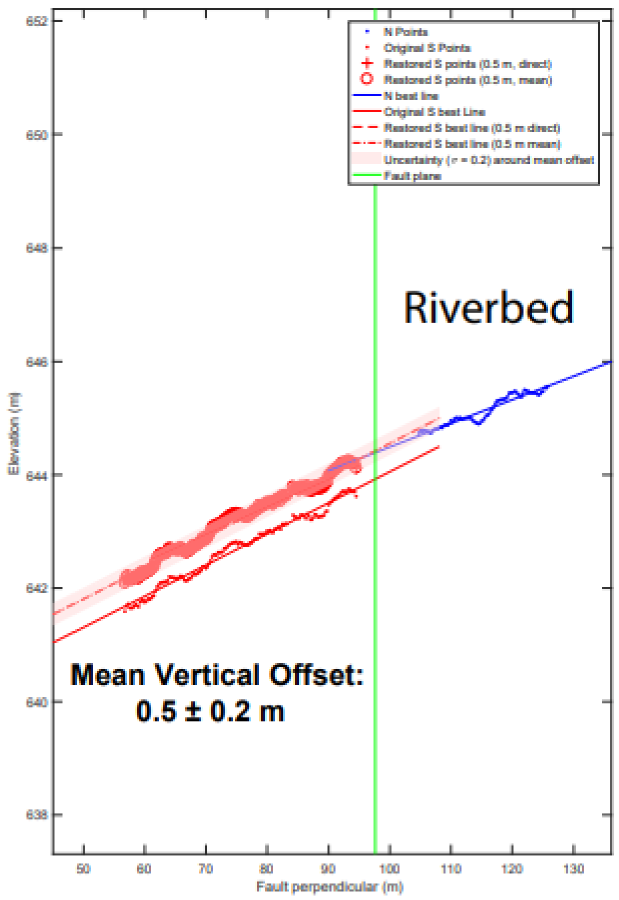


3D_Fault_Offsets

(Stewart et al., 2018)

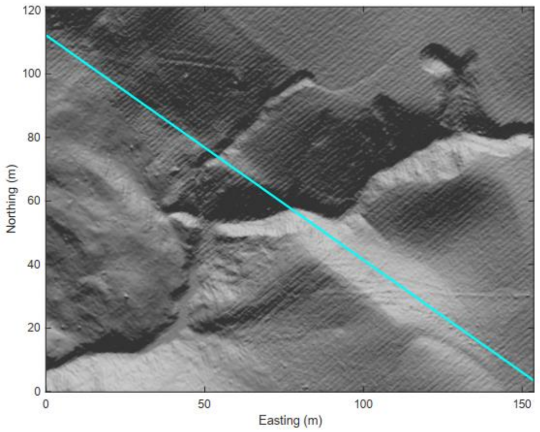
Functions 7a and 7b: Reconstruction of the DEM map view representation horizontally and vertically

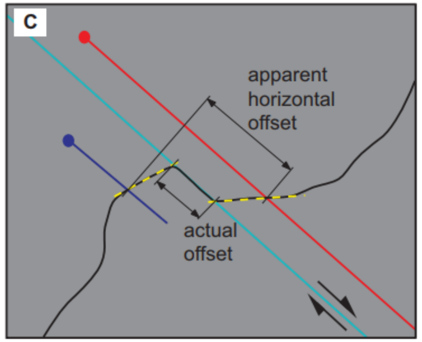


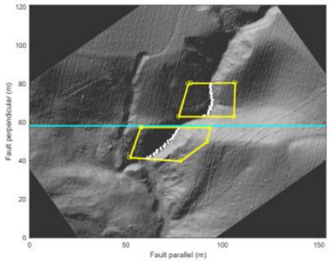


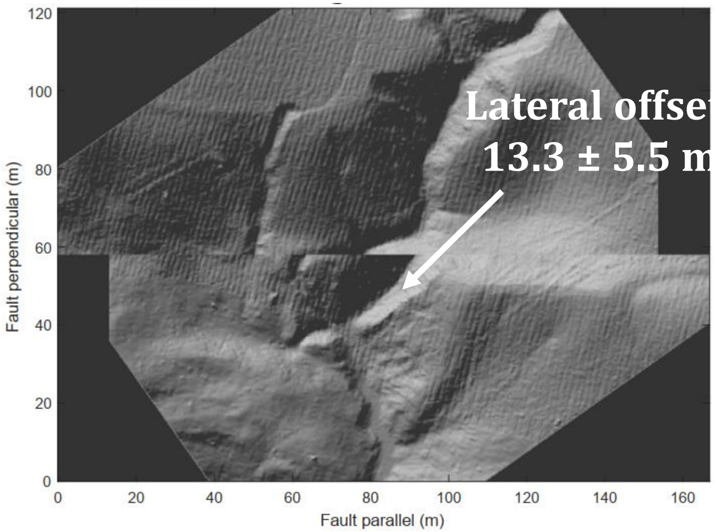
Discussion

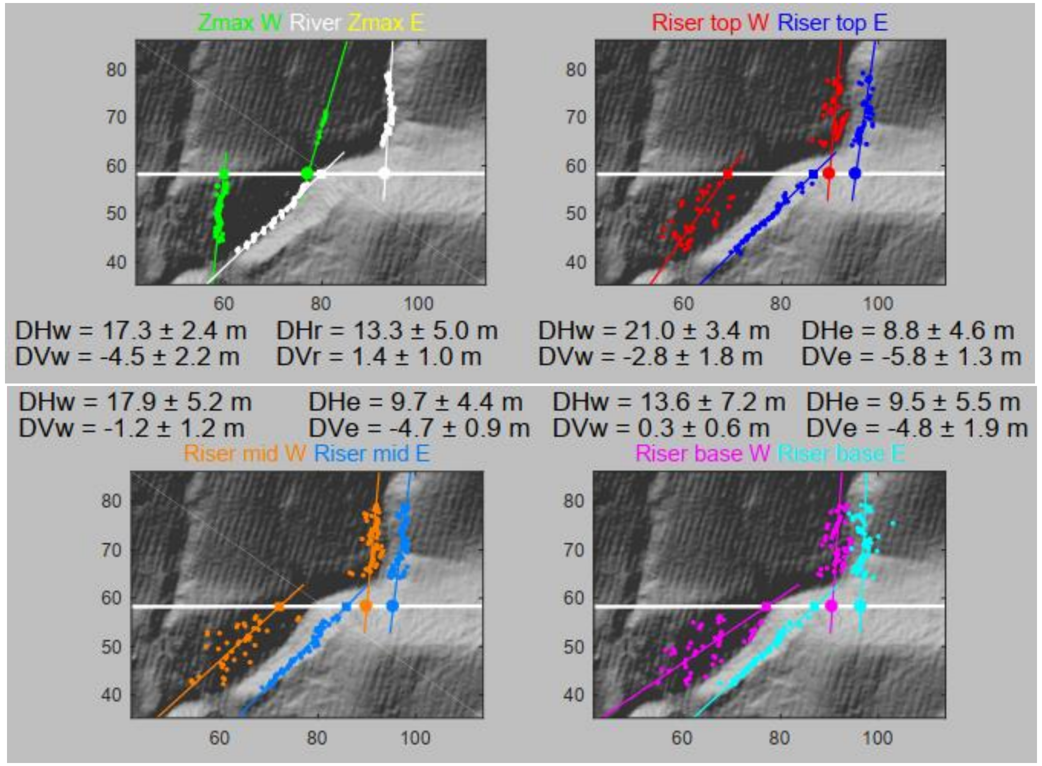
- **LaDiCaoz** includes a number of **user interactions** and primarily analyzes horizontal **offset markers in 2-D**.
- Meanwhile, **3D-Fault_Offsets** requires only **a small amount of user interaction**, therefore, it limits most of the possible bias that are commonly associated with fault offset measurements.
- Especially with the moderate-low to low channel rating (channel at oblique angle to fault trace, degraded, curvature when crossing the fault,…) *(e.g., Sieh, 1978; Lienkaemper, 2001),* the 3D-Fault-Offsets method presents the result with better-assigned uncertainty.
- Measurement of vertical displacement has been included in **3D-Fault_Offsets**. Although the uncertainty remains equivalent to or greater than the offset, it still allows us to study the preservation of vertical offsets across the complete set of markers.











Conclusions

- Both methods suggested a better idea of measuring fault offset with more precision.
- **LaDiCaoz** semi-automized method has proven to be relevant and efficient in many studies that have used it *(Haddon et al., 2016; Ren et al., 2016; Salisbury et al., 2012; Zielke et al., 2010, 2012)*. It allows measuring hundreds of offsets along a fault, about 10 times more than ever before.
- **3D-Fault_Offsets** succeeds in mathematically identifying and representing nine of the most prominent geometric characteristics.
- The authors of those two approaches all emphasize that in order to make meaningful measurements, it is important to have a basic understanding of tectonic geomorphology.

THANK YOU FOR LISTENING

References

- Haddon, E. K., Amos, C. B., Zielke, O., Jayko, A. S., & Bürgmann, R., 2016. Surface slip during large Owens Valley earthquakes. *Geochemistry, Geophysics, Geosystems*, 17, 2239–2269.
- N. Stewart, Y. Gaudemer, I. Manighetti , L. Serreau, A. Vincendeau, S. Dominguez , L. Mattéo, and J. Malavieille., 2018. "3D_Fault_Offsets," a Matlab Code to Automatically Measure Lateral and Vertical Fault Offsets in Topographic Data: Application to San Andreas, Owen Valley, and Hope Faults. *Journal of Geophysical Research: Solid Earth*, 123, 815-835.
- O. Zielke and J.R. Arrowsmith., 2012. LaDiCaoz and LiDARimager- MATLAB GUIs for LiDAR data handling and lateral displacement measurement. *Geosphere*, 8(1), 206–221.