

Using Neotectonic Deformation at McKinleyville, California, to Test the Validity of Trishear Modelling to Predict Shear Fracture Orientations*

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Abstract

It has been suggested that shear fractures initiate parallel to lines of no finite elongation (LNFE). This idea is attractive, because it opens up the possibility of using simple kinematic models (e.g., trishear) to predict the orientations of shear fractures in subsurface reservoirs. We test the hypothesis that cataclastic deformation bands that cut unconsolidated late Pleistocene sands at McKinleyville, California, developed parallel to LNFE or zero extension directions. Here, the deformation bands form two distinct sets that dip shallowly towards the north-northeast and south-southwest. The acute dihedral angle between the two sets of deformation bands is ca. 47° and is bisected by the sub-horizontal, north-northeast-directed instantaneous and finite shortening directions. Two-dimensional trishear models of fault-propagation folding above the initially buried tip of the McKinleyville Fault predict two sets of LNFE that plunge steeply and shallowly to the south and north, respectively. These predictions are inconsistent with the observed cataclastic-deformation-band orientations and suggest that the deformation bands did not form parallel to these LNFE. Three-dimensional strain modelling using a Mohr construction predicts that the cataclastic deformation bands at McKinleyville could instead have formed parallel to zero extension directions, provided deformation-band localisation was accompanied by a transient-volume increase of ca. 4%. The inference of a small transient-volume increase is consistent with previous experimental and geological observations. The hypothesis that the two sets of cataclastic deformation bands at McKinleyville formed parallel to zero extension directions is, therefore, tenable, but further research is required to quantify transient-volume changes during deformation-band localisation.

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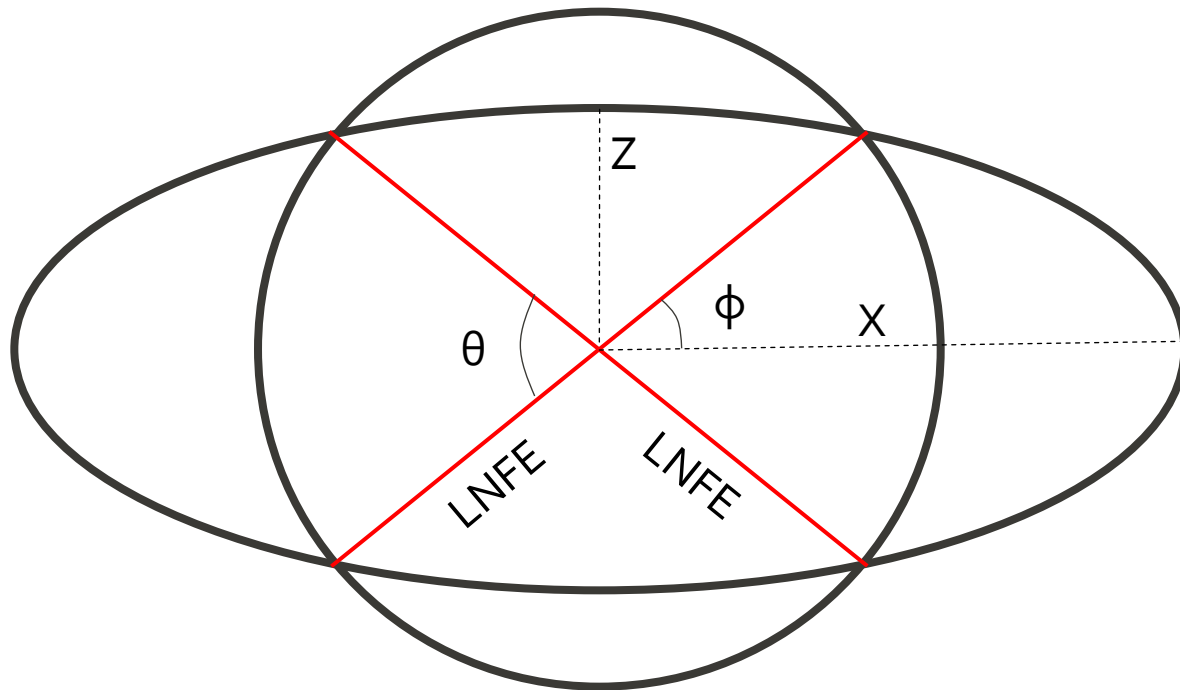
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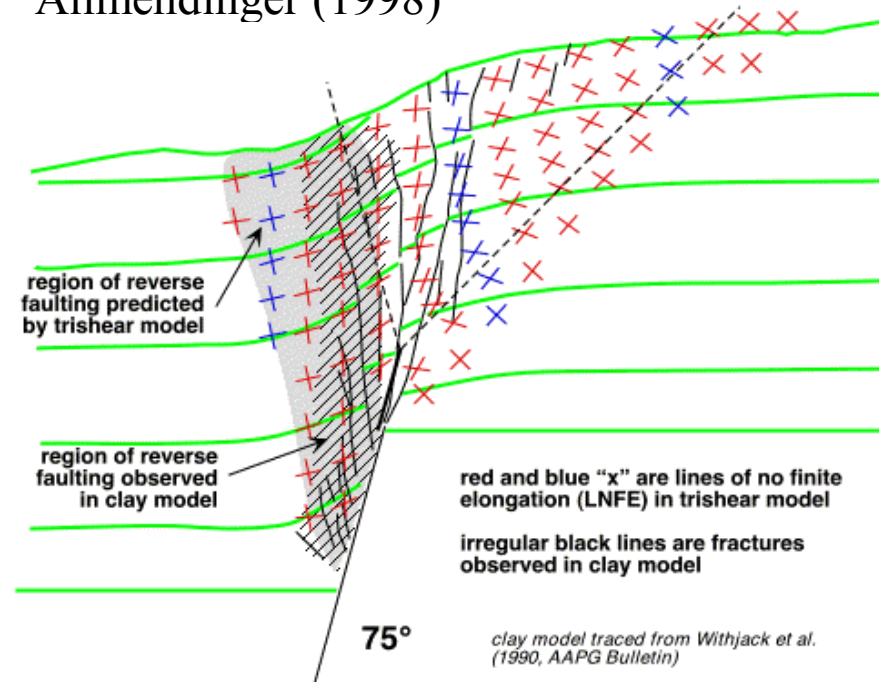
Lines of no finite elongation (LNFE)



- Allmendinger (1998), Cardozo et al. (2005), Jin & Groshong (2006)
- Potentially use kinematic models (e.g., trishear) to predict shear fracture orientations

Comparison with analogue models

Allmendinger (1998)



- Good fit between LNFE and minor faults observed in analogue models of forced folding above a basement normal fault
- Few published comparisons with natural fault systems – why?

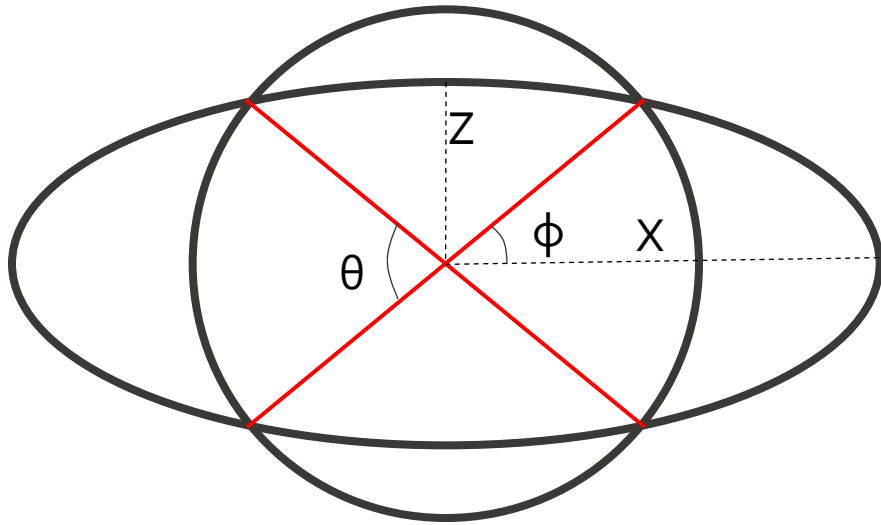
Aim & conclusions

- Use a set of naturally occurring deformation bands at McKinleyville to test the hypothesis that deformation bands form parallel to LNFE
- Deformation bands unlikely to form parallel to LNFE; however, deformation bands may form parallel to *zero extension directions*, assuming a transient volume increase

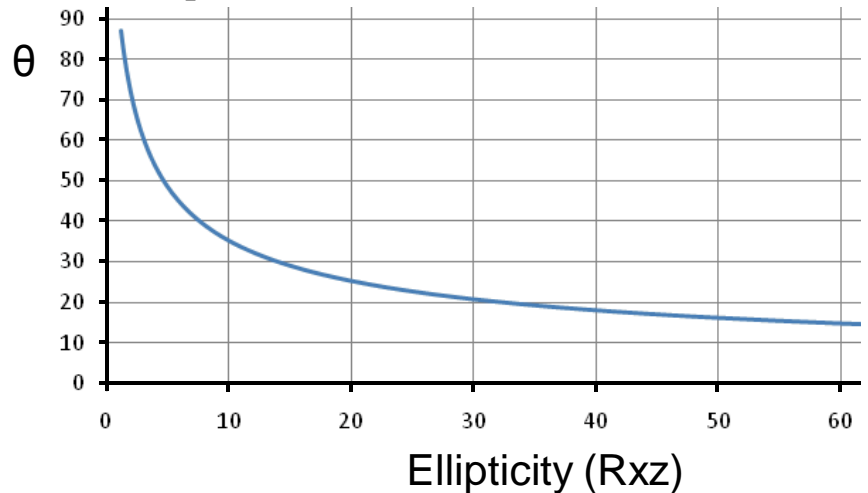
Rationale

- Deformation bands at McKinleyville are low strain, young structures ($< 83\text{ka}$); bands have not been reactivated
- Finite strains are reasonably well documented
- Inferred loading configuration allows comparison with trishear models

Method



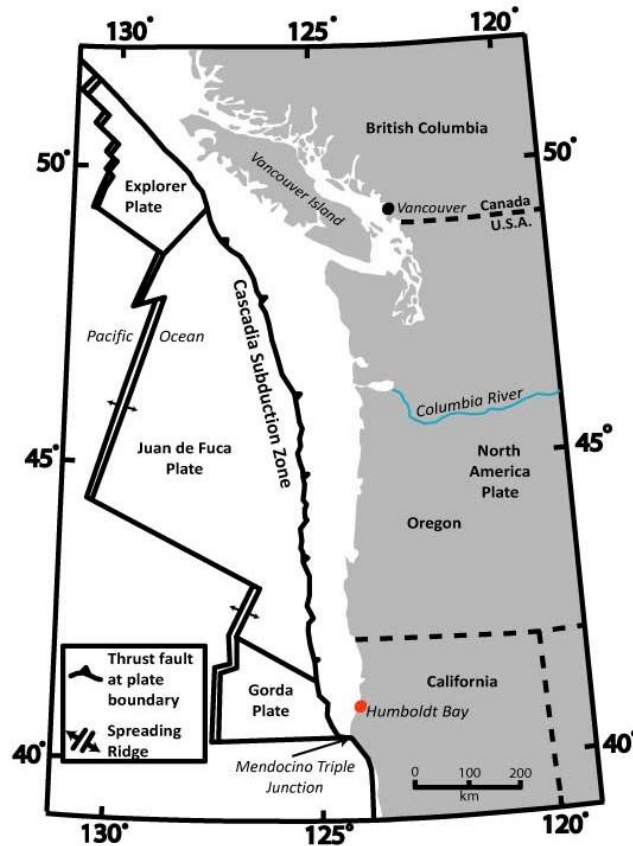
Calculated from Ramsay & Huber (1983)
Eq. D10



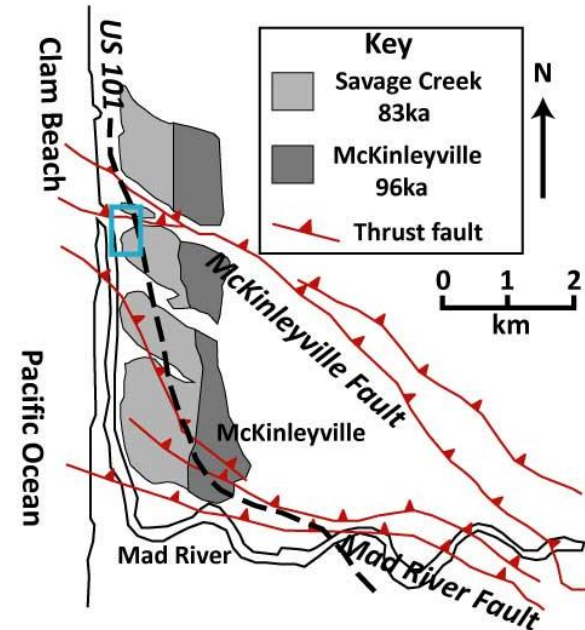
- Assume deformation bands formed parallel to LNFE
- Measure dihedral angle (θ) between conjugate deformation bands
- Make simplifying assumption that bands form during constant volume, plane strain bulk deformation
- Back-calculate ellipticity (R_{xz}) using Ramsay & Huber (1983) Eq. D10; compare with measured ellipticity (Cashman & Cashman 2000) and trishear models

Geological setting

Nelson et al. (2006)

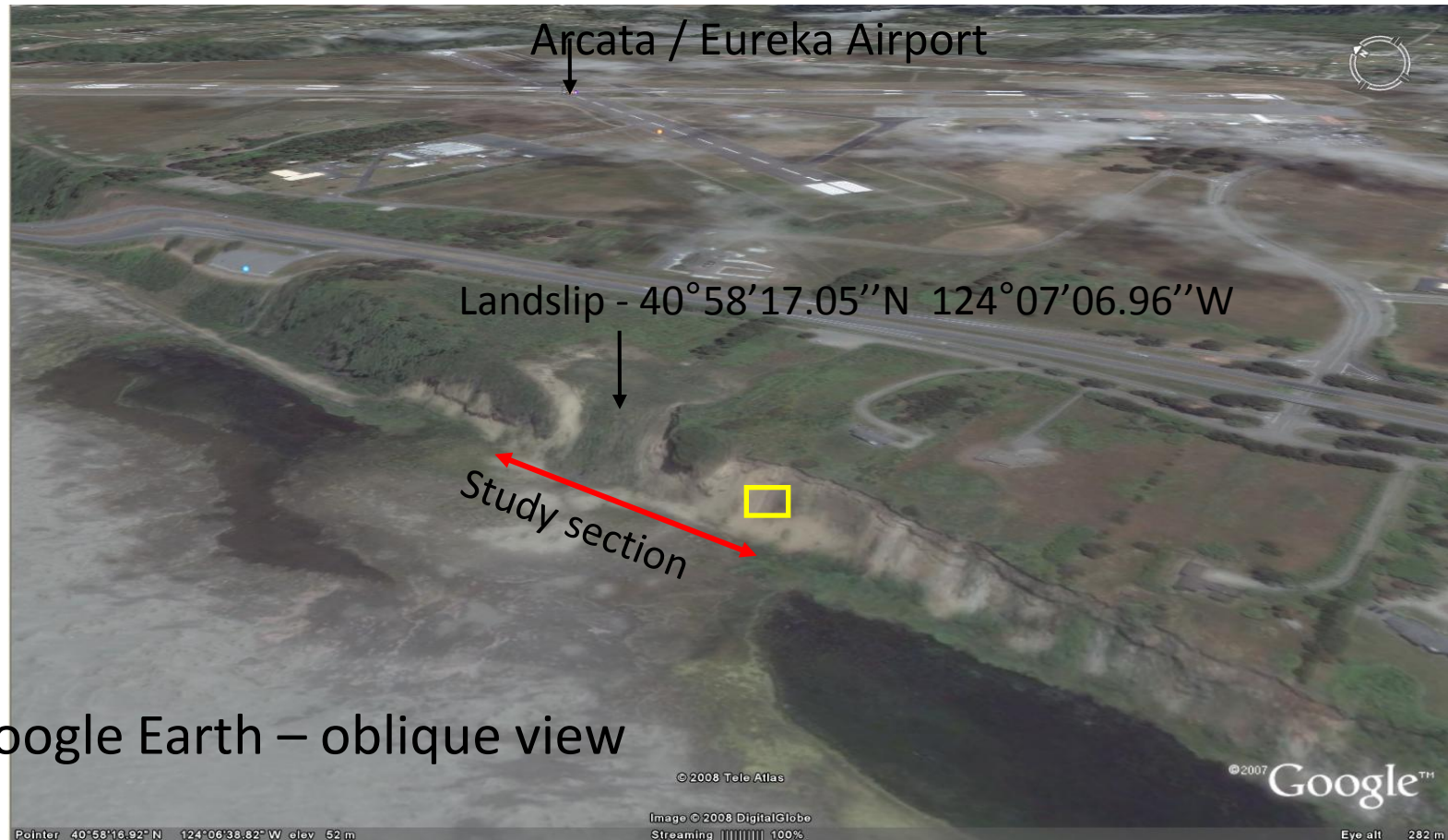


Cashman & Cashman (2000)



Clam Beach study area lies in the footwall of the seismically active, NNE-dipping McKinleyville thrust

Clam Beach study area

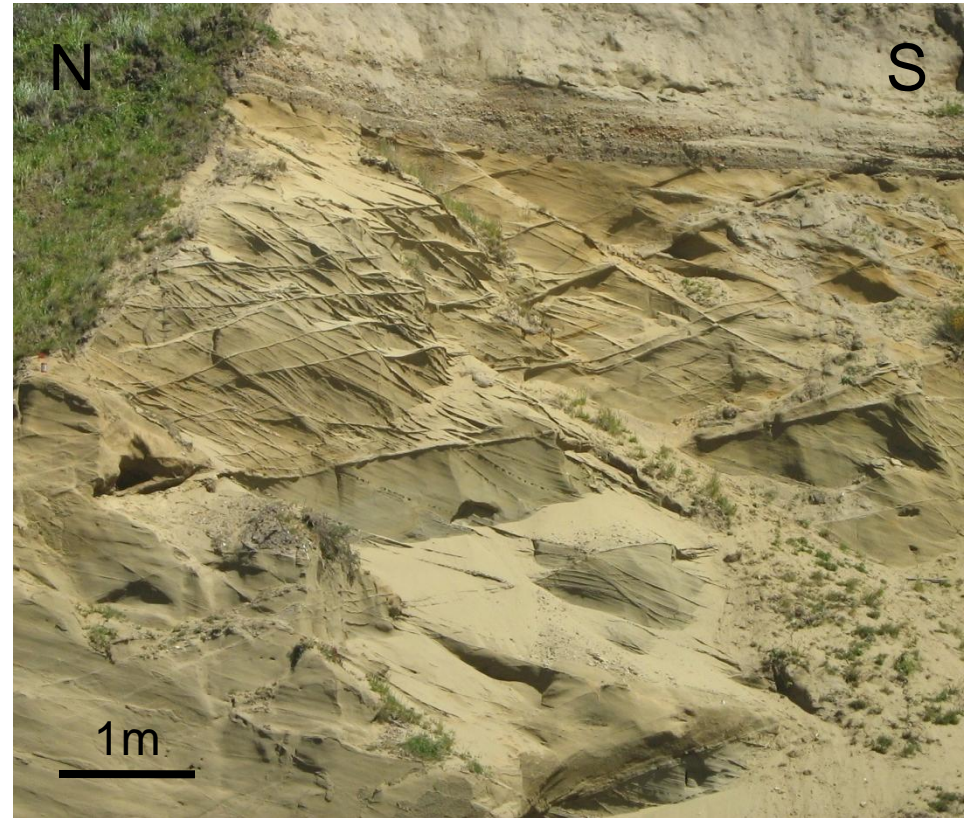


Google Earth – oblique view

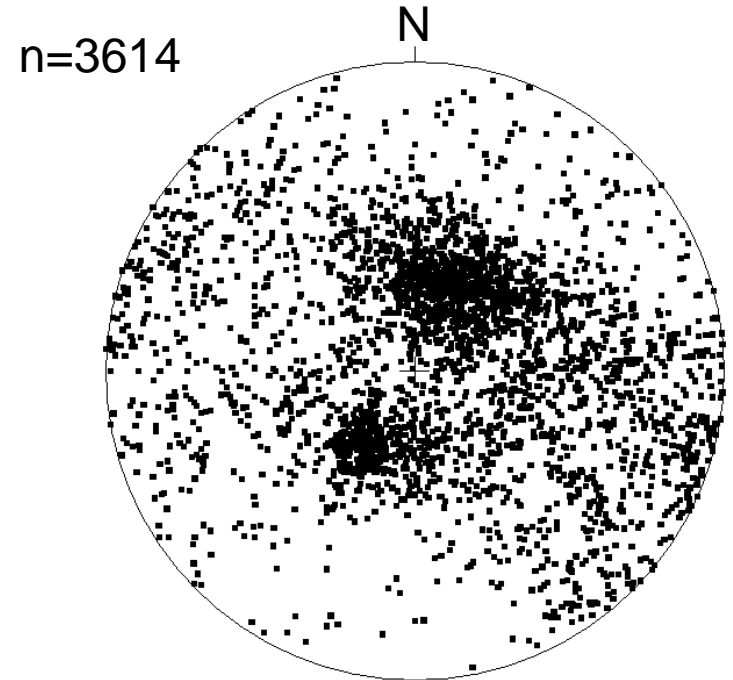
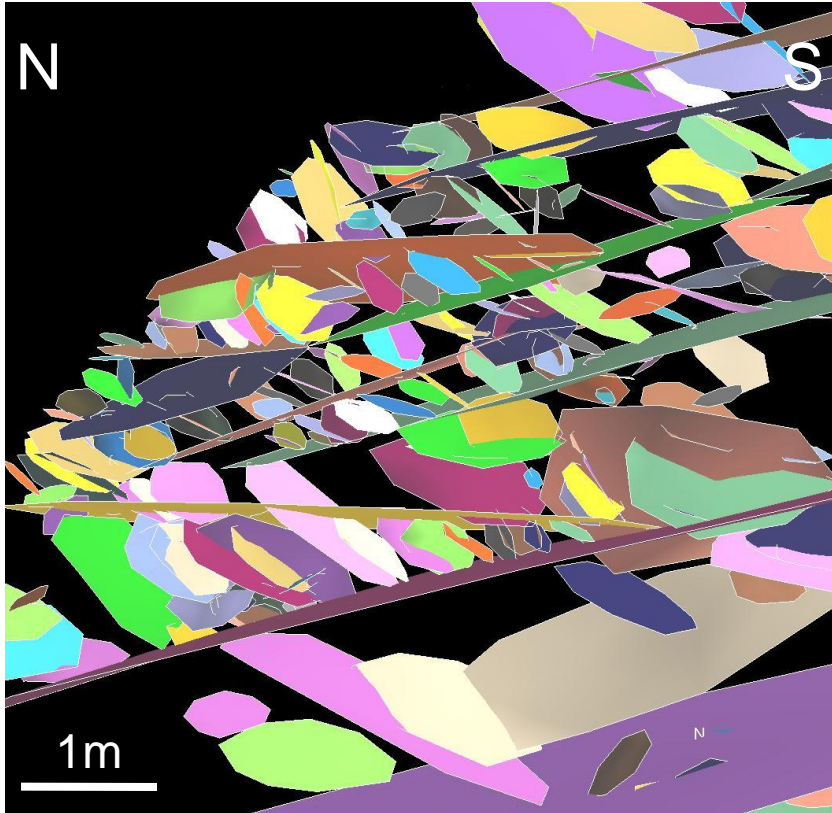
- 150m-long cliff section; 3 distinct exposures

Deformation bands

- Conjugate deformation bands developed in unconsolidated late Pleistocene marine terrace sands
- Maximum burial depth 50m (~1MPa confining pressure)
- Individual bands accommodate <50cm reverse-dip separation (Cashman & Cashman 2000)

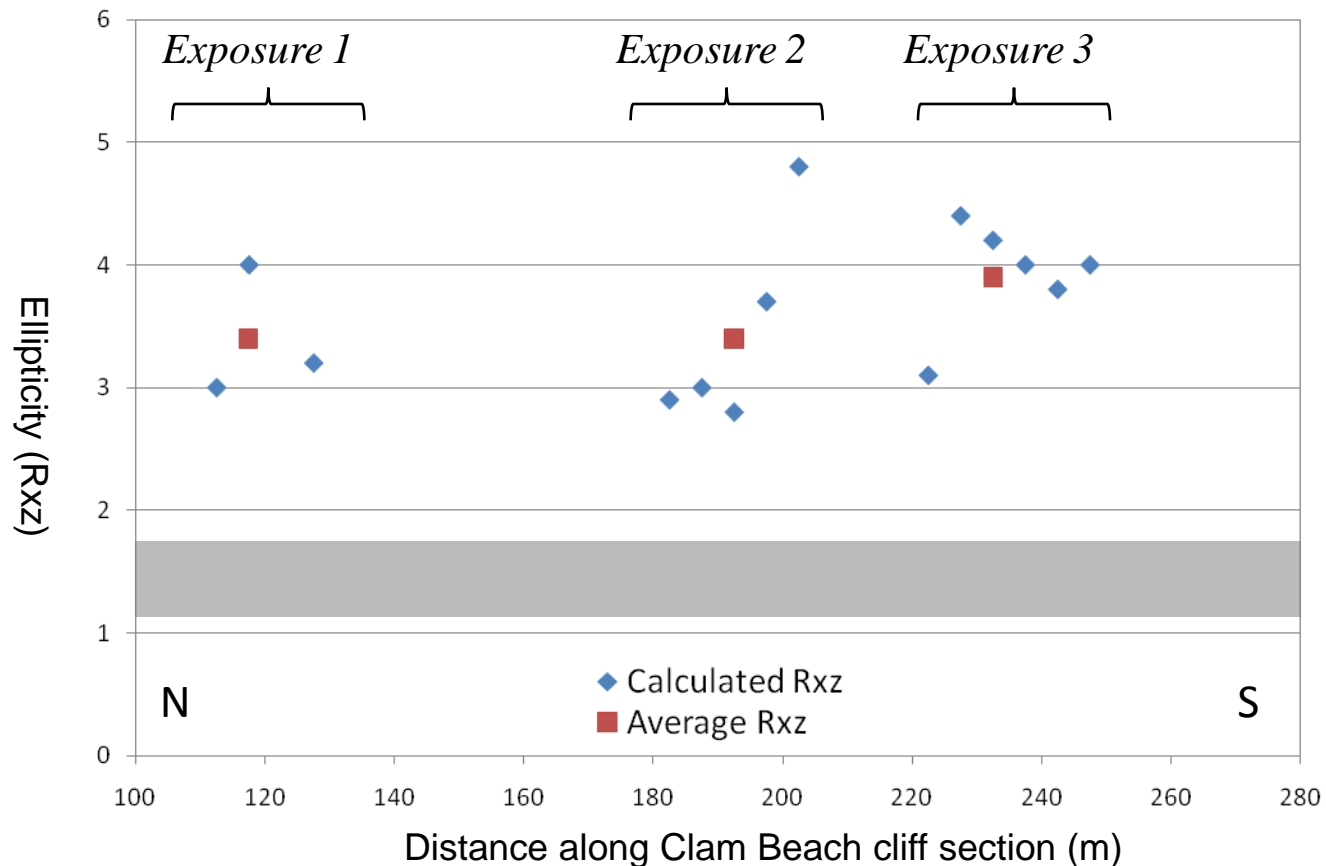


Data analysis



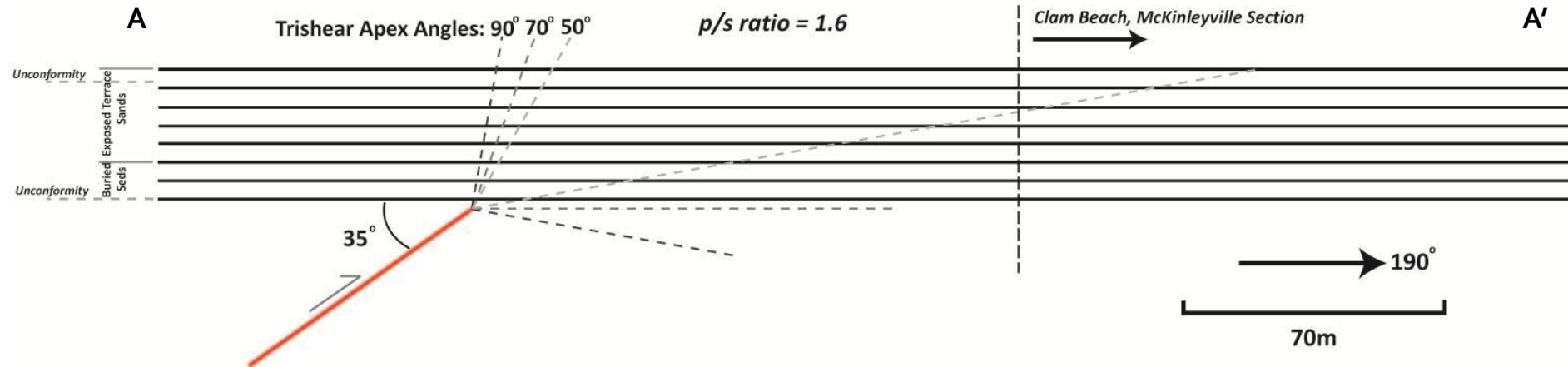
- Lots of scatter but two main sets dip gently to NE & SW
- Bulk dihedral angle $\sim 50^\circ$, corresponding to $Rxz \sim 4$, assuming bands form along LNFE

Results

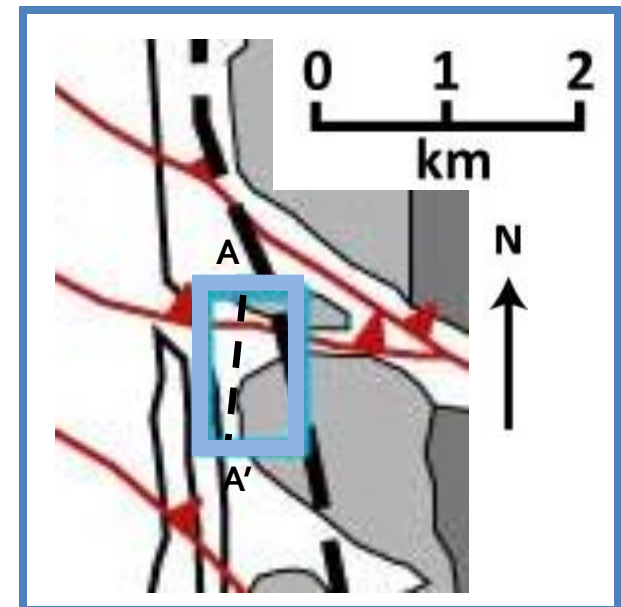


- Measure dihedral angles between bands in sub-areas of each exposed part of the cliff section
- Inferred ellipticities (Rxz) between 3 & 4
- Fry analysis of sand grains in a thin section across a deformation band gives significantly lower Rxz of 1.2-1.7 (Cashman & Cashman, 2000): but single sample & very different measurement techniques

Comparison with trishear models

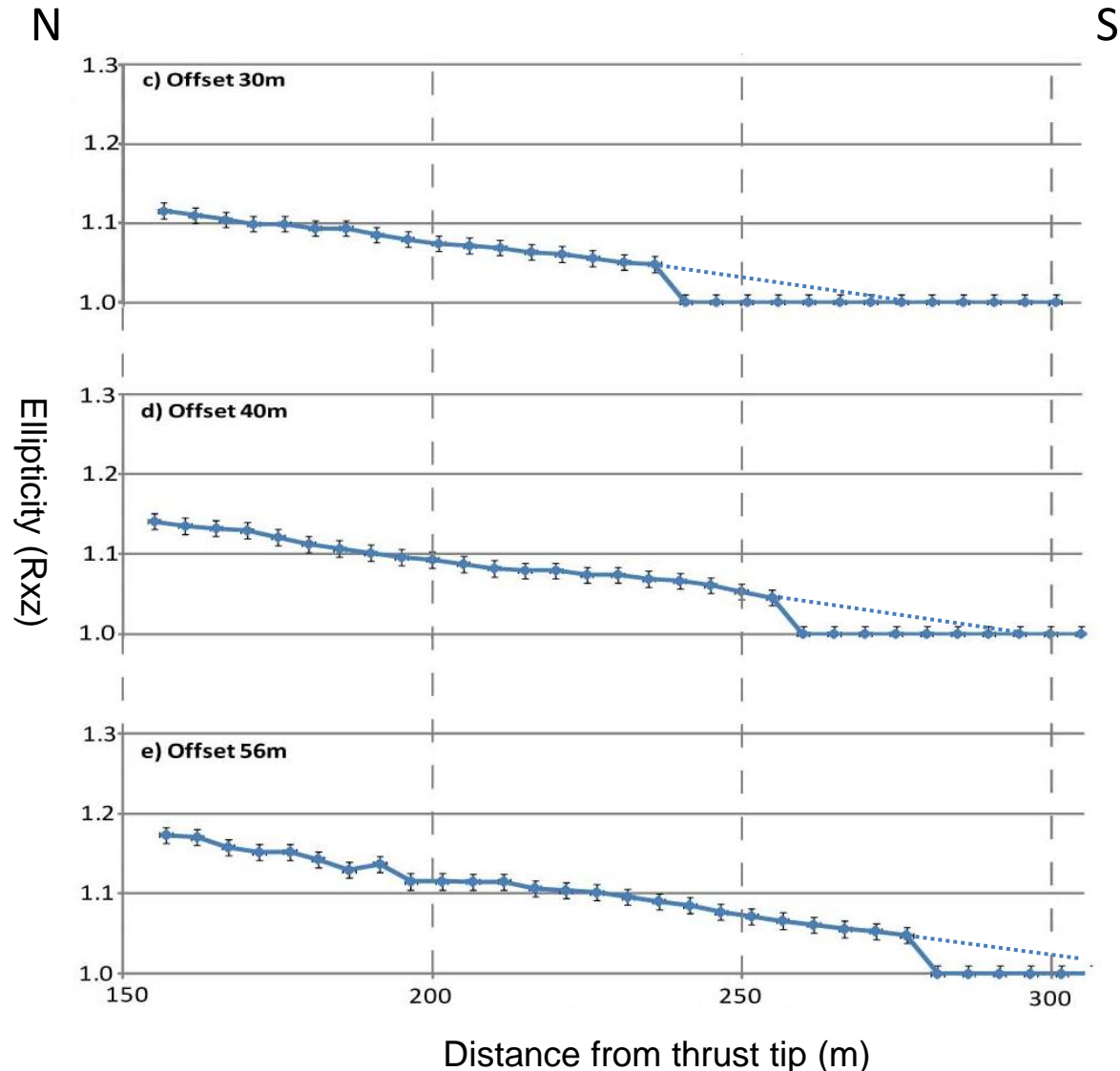


- Trishear apex angles 50, 70 & 90°
- Maximum thrust offset 10, 20, 30, 40 & 56m
- p/s ratio 1.6



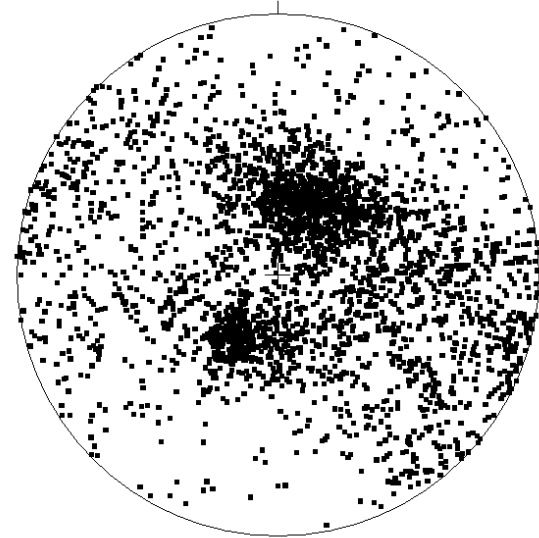
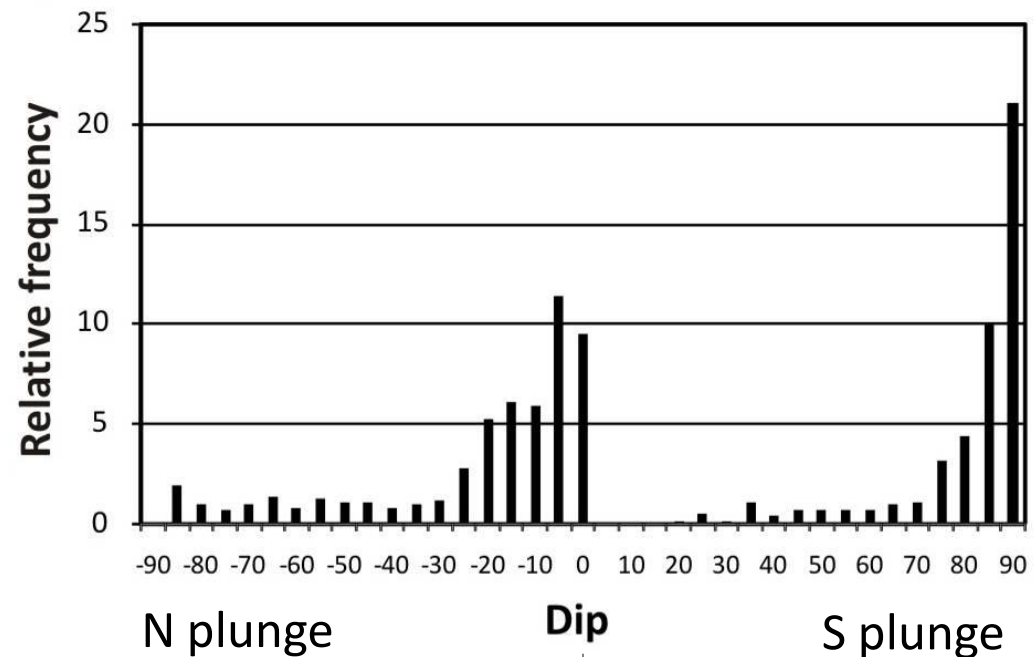
Trishear results - strain

- $R_{xz} < 1.2$ even for large total offset & trishear apex angle of 90°



Trishear results - orientations

- Predicts sub-horizontal N-plunging and sub-vertical S-plunging LNFE
- Strains & orientations are inconsistent with observed deformation band orientations

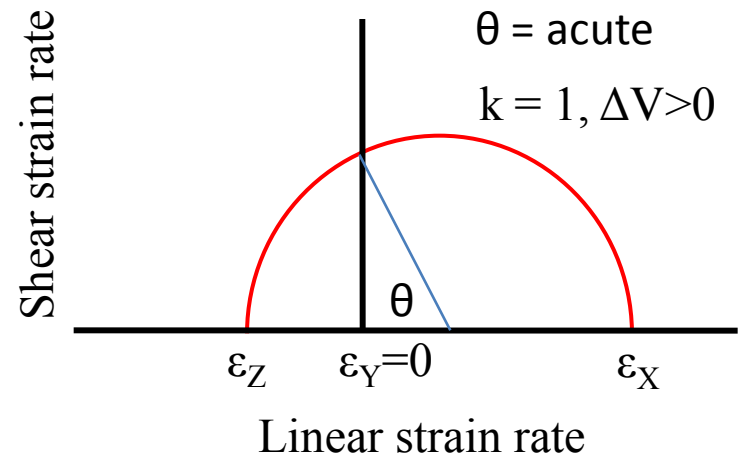
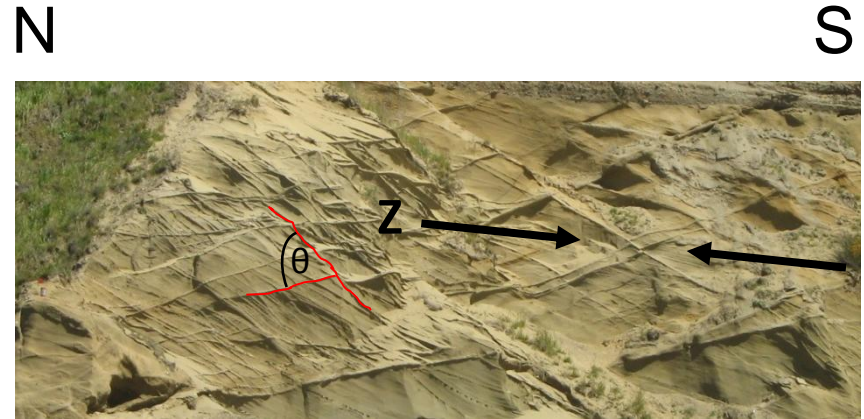


Conclusions #1

- Deformation bands are unlikely to develop parallel to lines of no finite elongation (LNFE), at least at McKinleyville
- Can we use other strain – or strain rate – based methods to predict deformation band orientations?

Zero extension lines

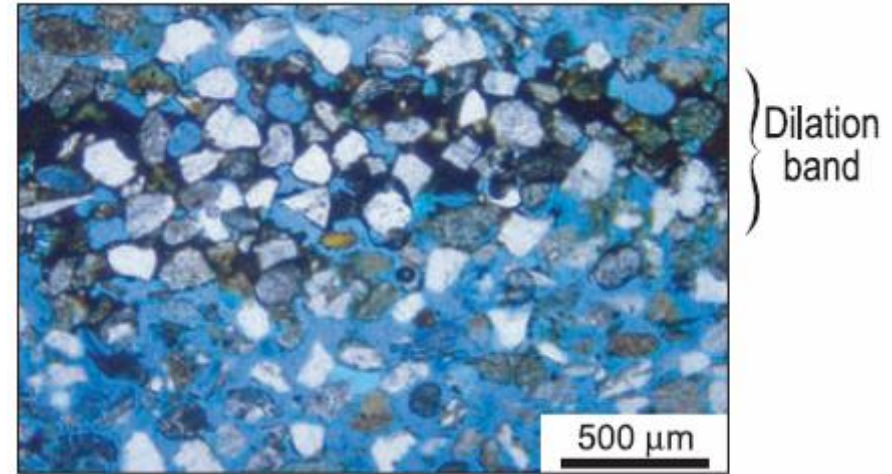
- Axis of maximum shortening rate (Z) should intersect the acute angle (θ) between deformation bands
- Mohr circle for strain rate demonstrates there is an acute angle between pairs of zero extension lines, assuming a transient volume increase



Following Watterson (1999)

Evidence for volume gain

- There is experimental evidence for transient volume increases during deformation band localisation within unconsolidated sand (Desrues & Viggiani, 2004)
- A transient volume gain would be consistent with shallow burial depth (low P_{conf}) at the time of deformation
- Du Bernard et al. (2002) provide direct microstructural evidence for ca. 7% volume gain (porosity increase) along “dilation bands” at McKinleyville



Du Bernard et al. (2002)

Conclusions #2

- Tentatively suggest that the cataclastic deformation bands at McKinleyville may have developed parallel to zero extension lines
- Detailed laboratory deformation experiments are required to characterise the shear and volumetric strain behaviour within samples of previously “undeformed” McKinleyville sand

Acknowledgements

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