Shear Strength of Rock Joints

Steve Hencher

Hencher Associates Limited

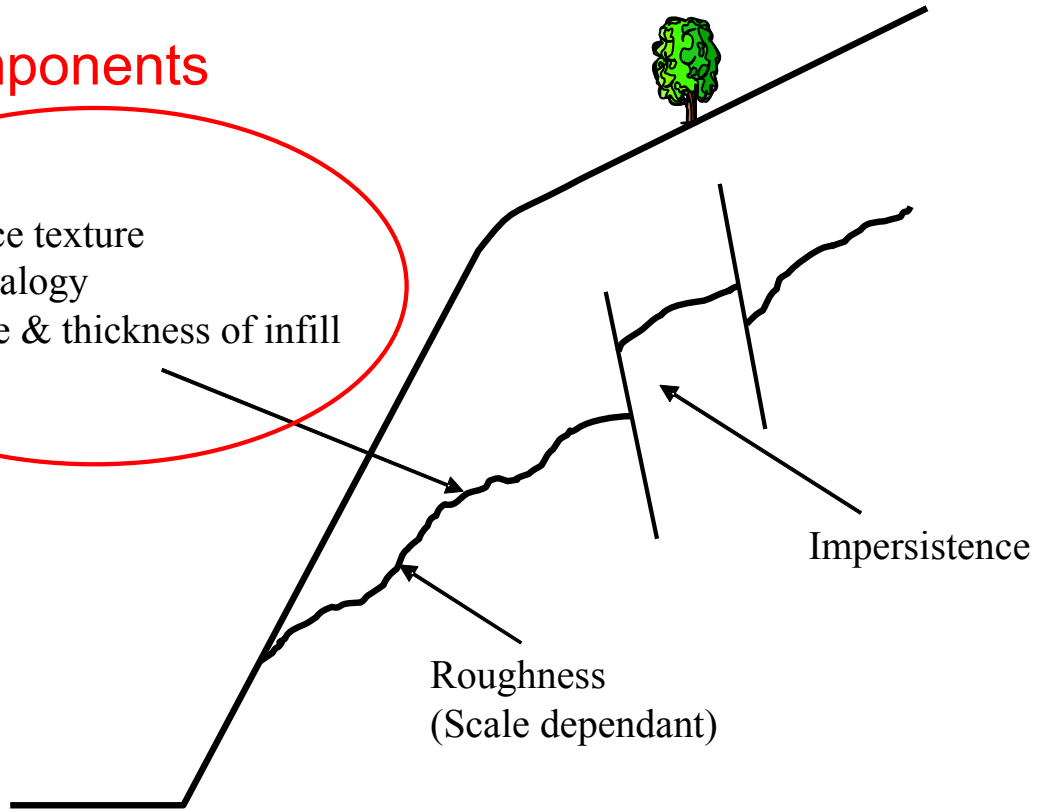
Fundamentals of Shear Strength

Steve Hencher

Factors Controlling Shear Strength of Rock Joints

Frictional components

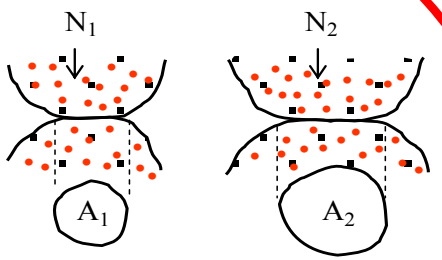
- Surface texture
- Mineralogy
- Nature & thickness of infill



+ Water effects (effective stress)

1. ADHESION (lower bound friction)

increasing normal load →



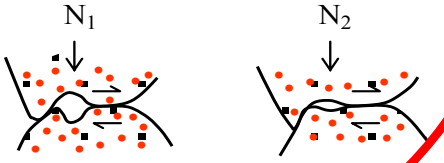
– **Bonding over true area of contact (A1, A2)**

- proportional to normal load
- does not cause dilation (by definition)
- same for different textural surfaces and roughness

Frictional components

2. INTERLOCKING AND PLOUGHING
(additional friction)

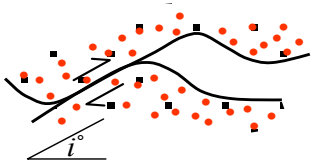
increasing normal load →



– **Surface texture component**

- proportional to normal load
- does not cause dilation (by definition only!!)
- generally decreases with displacement due to damage and the production of debris
- increases with rougher surface texture

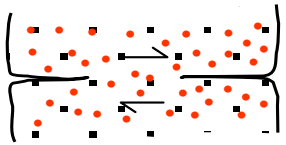
3. OVERRIDING



– **Work done due to dilation or compression**

- uphill sliding leads to an increase in measured strength and vice versa
- purely geometrical effect
- decreases with increasing normal load and decreasing wall rock strength

4. COHESION



– **Shearing of rock bridges and locked asperities**

- not proportional to normal load
- independent of dilation
- lost after peak strength

Steve Hencher

What is Basic Friction?

- How defined? Lower bound strength?

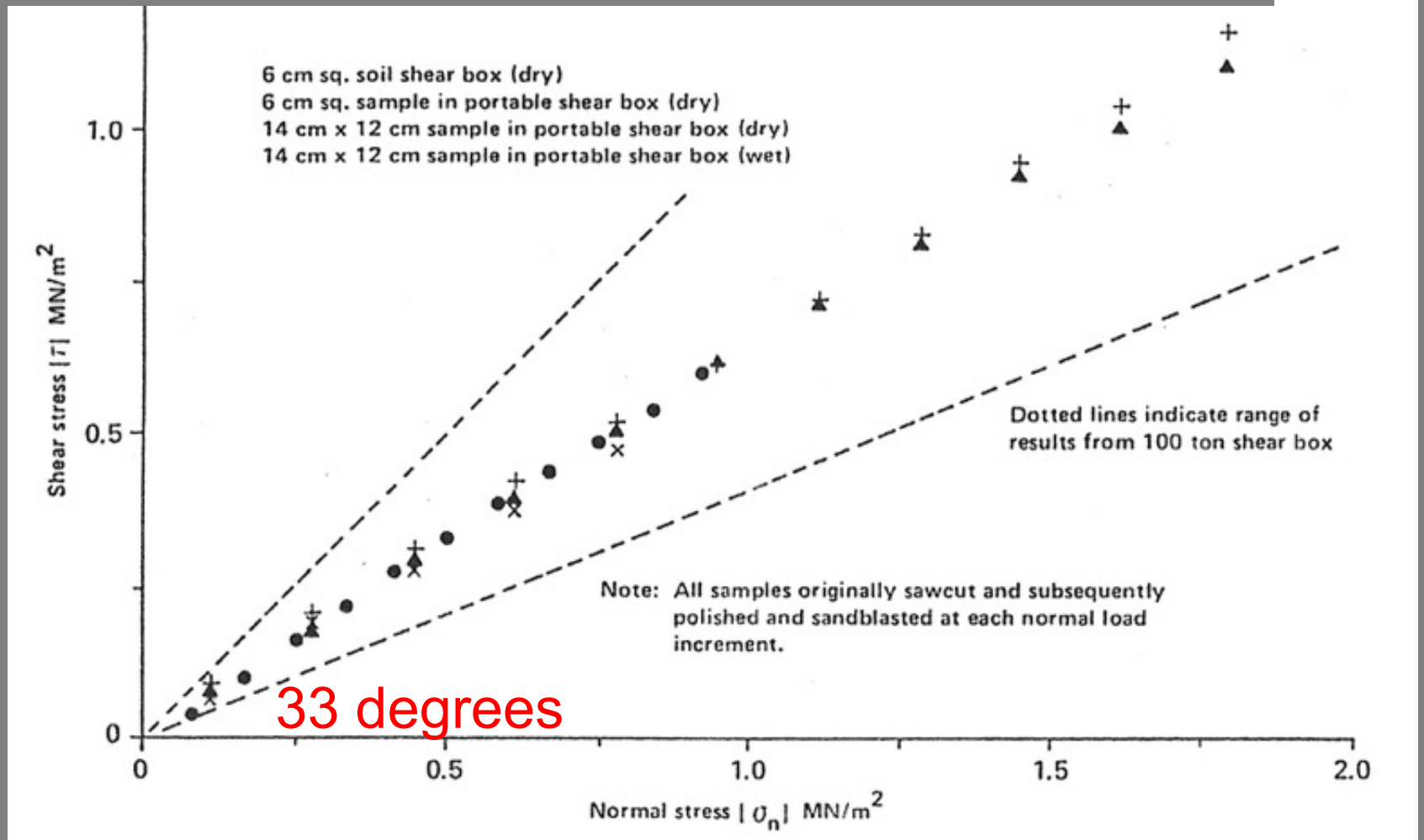
Non-dilational might be a better definition

- Is it a constant, determinable from a tilt test?

No

Steve Hencher

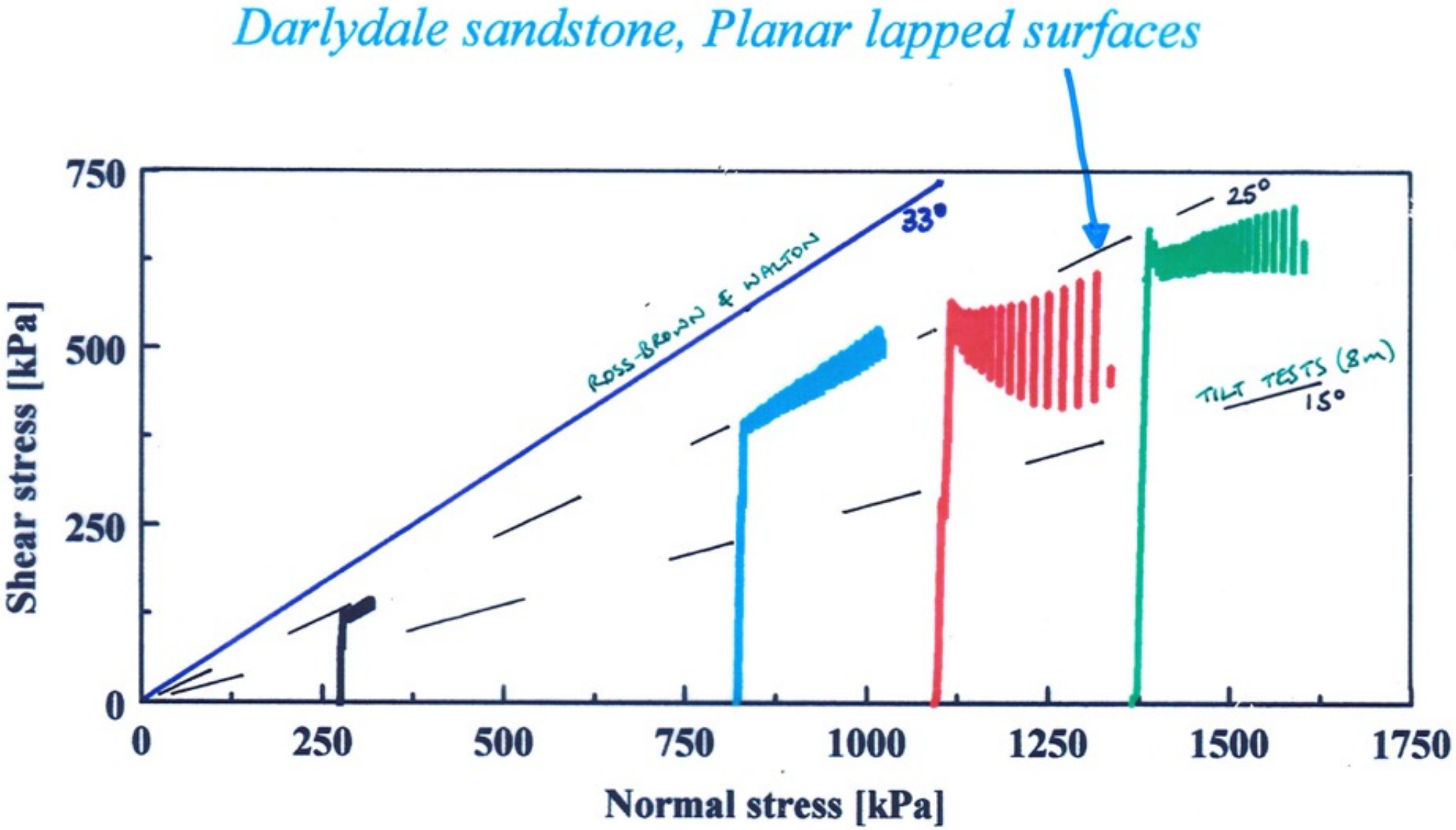
Sawcut surfaces– certainly frictional - but is it a "basic" frictional strength??



Ross Brown & Walton (1976)

Steve Hencher

We can measure lower strengths than saw cut by reducing the surface texture

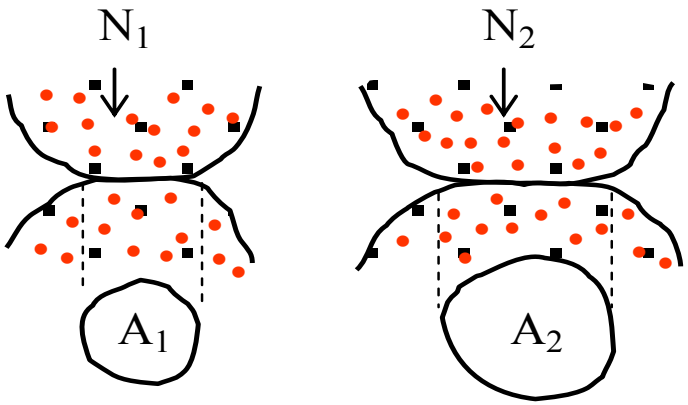


Frictional components

i.e. the increase in shear strength is directly proportional to increased normal stress (Amonton's laws)

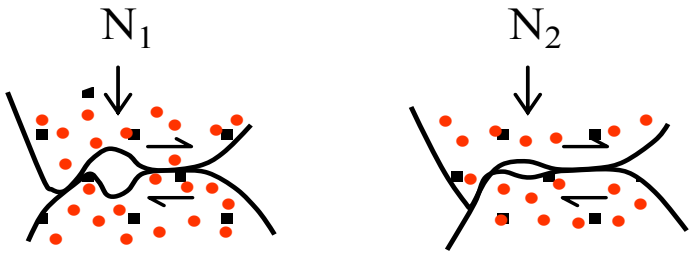
1. ADHESION (lower bound friction)

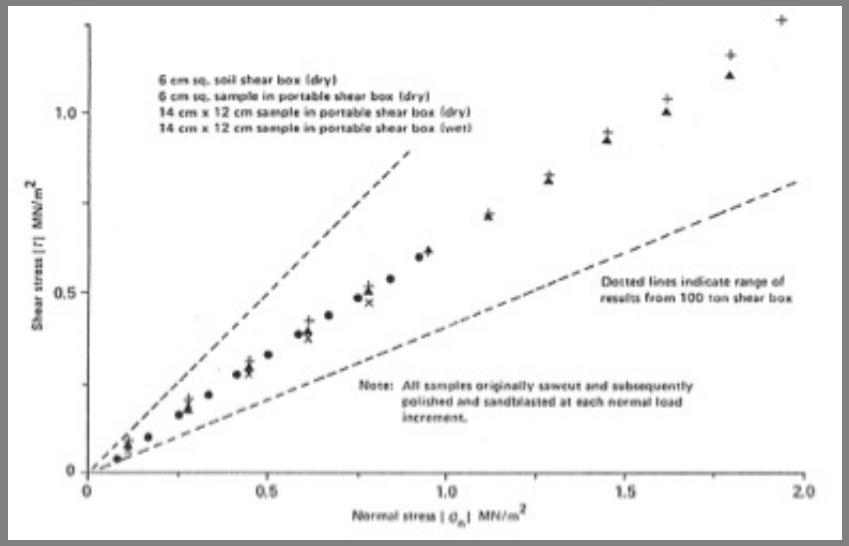
increasing normal load →



2. INTERLOCKING AND PLOUGHING (additional friction)

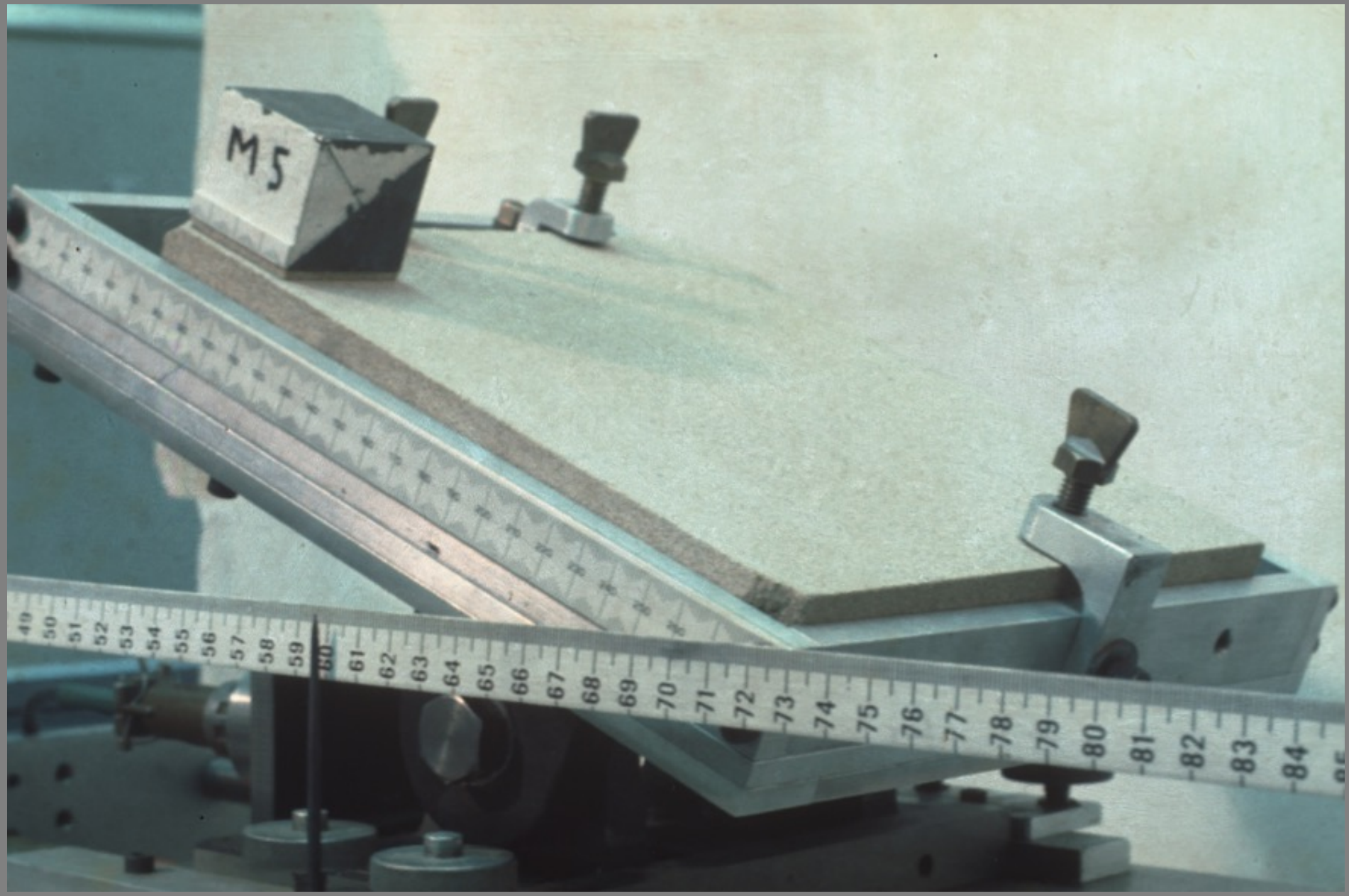
increasing normal load →





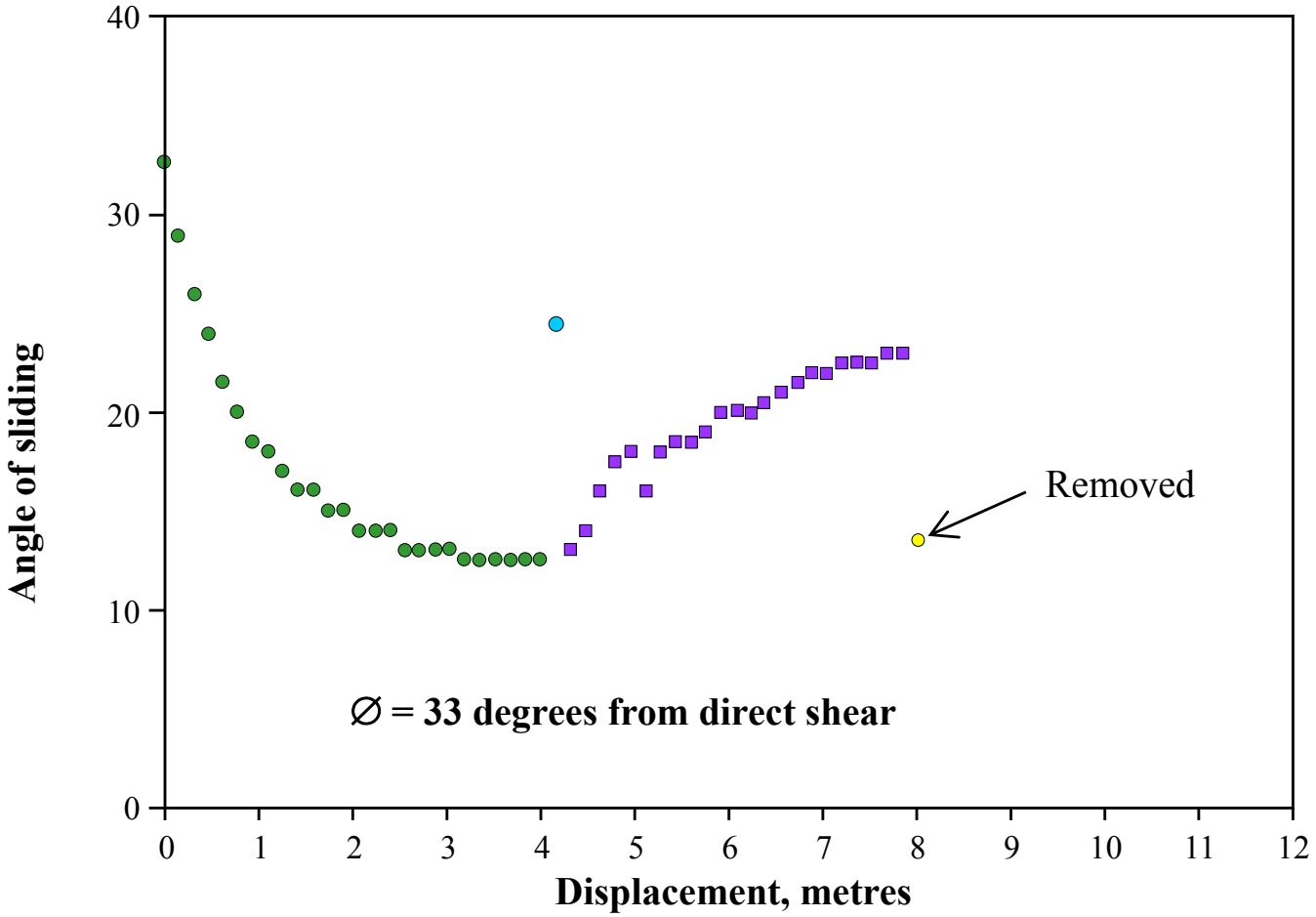
This component can be reduced by polishing

Steve Hencher



Steve Hencher

Darleydale Sandstone
Tilts test; Saw Cut Surfaces

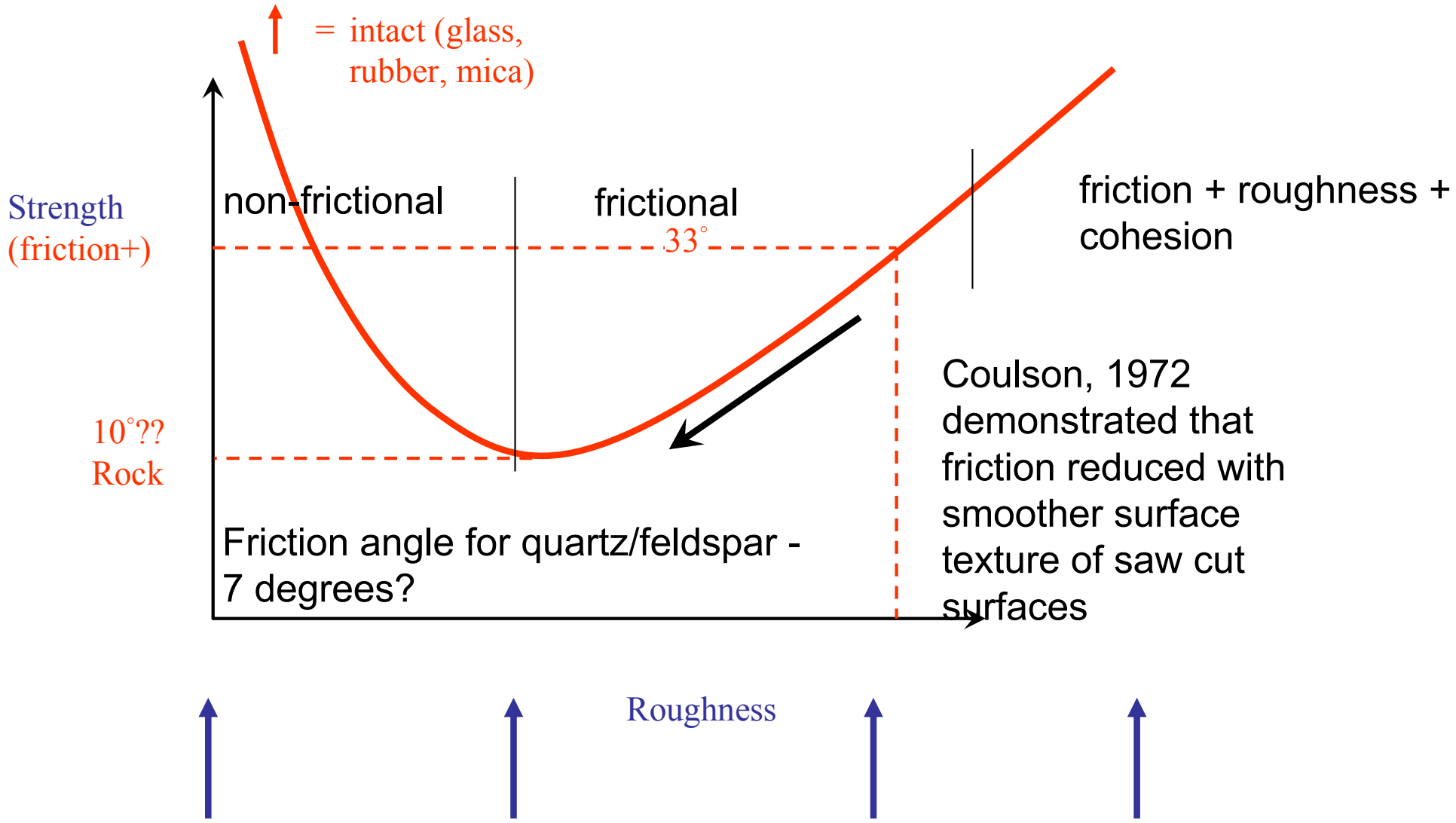


Test 2

- flour removed
- worn block placed elsewhere
- flour accumulated
- flour removed

Steve Hencher

Discontinuity Strength



Steve Hencher

Contribution due to Roughness (vaguely equivalent to JRC / JCS of Barton Bandis model) NOT textural friction

- Causes interlocking and dilation resulting in additional strength
- Sample-dependent
- Direction-variable

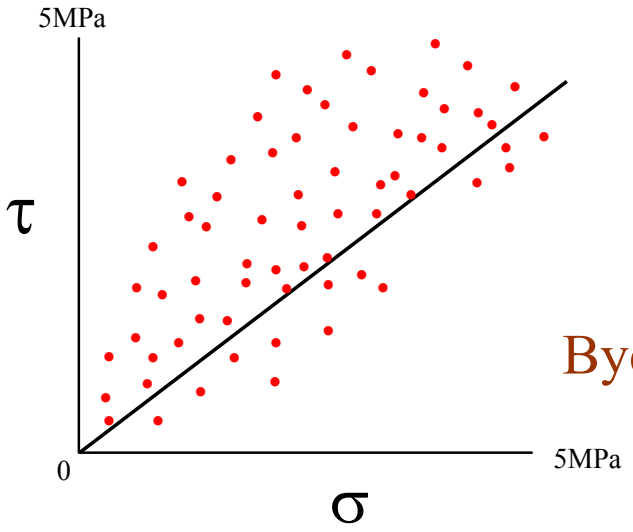
Steve Hencher

Planar joint through volcanic rocks

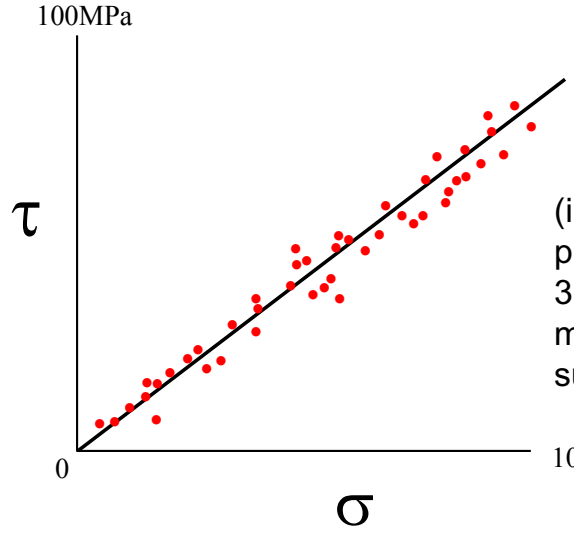
Steve Hencher

Rough joint through volcanic rocks

Steve Hencher



Byerlee



$\tau = 0.85\,\sigma$

(i.e. non-dilational, 'basic' phi of about 40 degrees, not 30 degrees that might be measured for a saw-cut surface)

Much scatter at relatively low normal stresses due to roughness variation

At relatively high normal stresses contribution of roughness is lost

Steve Hencher

Shear Strength of a Single Joint Sample

- At typical engineering stresses (say < 1 MPa, 40metres of rock)

Steve Hencher

Are small scale direct shear tests on rock relevant?

- “Results are unlikely to have significant relevance to the shear strengths of discontinuities *in situ.*”

  Attewell, Comprehensive Rock Engineering, 1993

- “Specimen size for acceptable shear tests quite large; accordingly, most joint samples from drillholes are unsuitable for shear tests.”

  Goodman, Rankine Lecture, 1995

- “Variation in of 12.5 degrees for saw cut surfaces excessive. For naturally rough samples variability likely to be much greater.”

  Nicholson, 1st NARMS, 1994

Steve Hencher

I would argue that the opposite is true

- Direct shear tests are essential to determine the "basic" shear strength
- You need to recognise that each sample has a different roughness and must take that out as a variable
- What you then measure is a "*non-dilational*" friction (constant volume in critical state terms) that relates to
  - » Surface texture
  - » Mineralogy

Steve Hencher

iron oxide coated joint

Steve Hencher

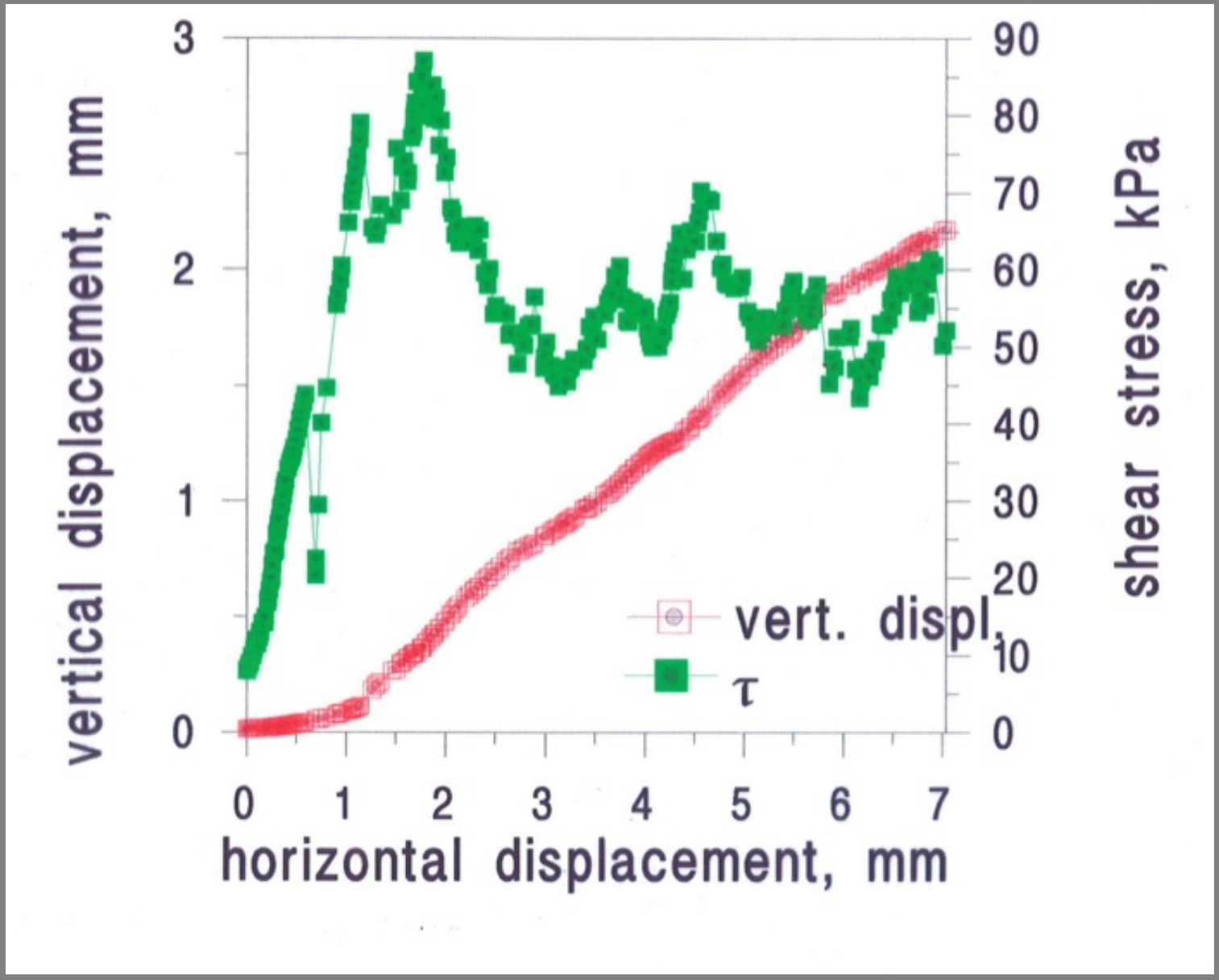
manganese dioxide coated joint

Steve Hencher

chlorite coated joint

Steve Hencher

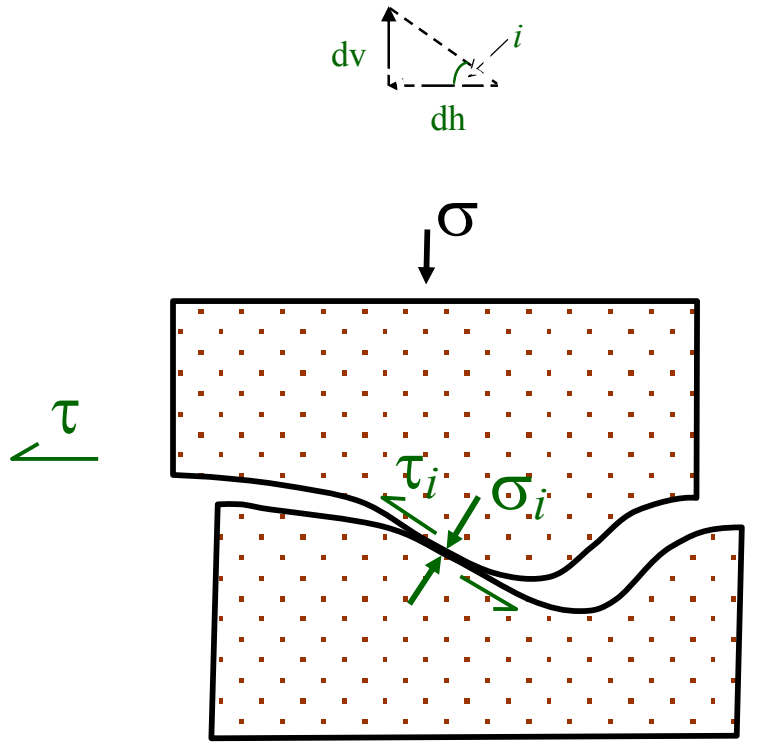
Example of direct shear test on rough, interlocking limestone joint



Steve Hencher

How to correct? Over what displacement interval?

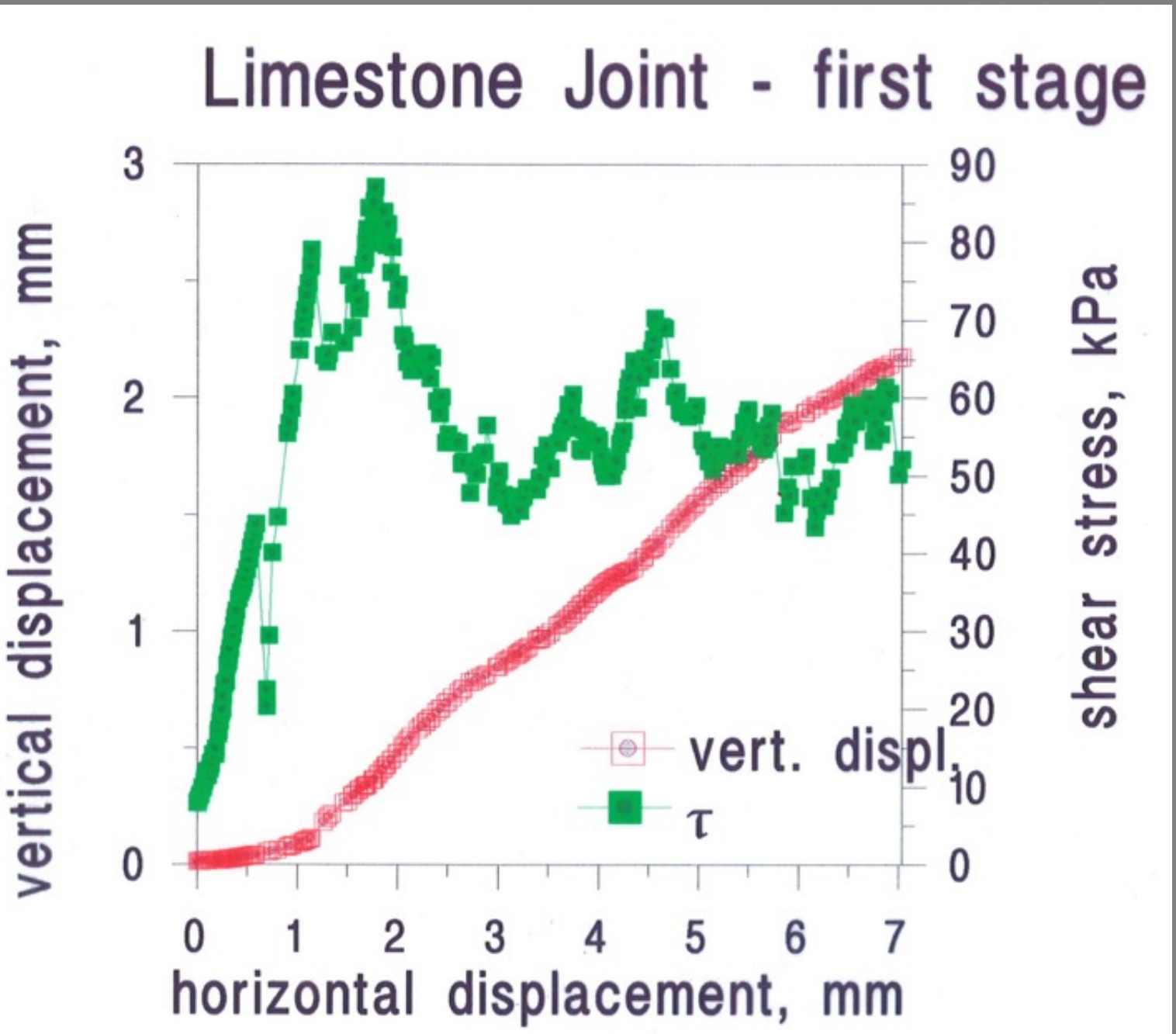
Corrections for dilation



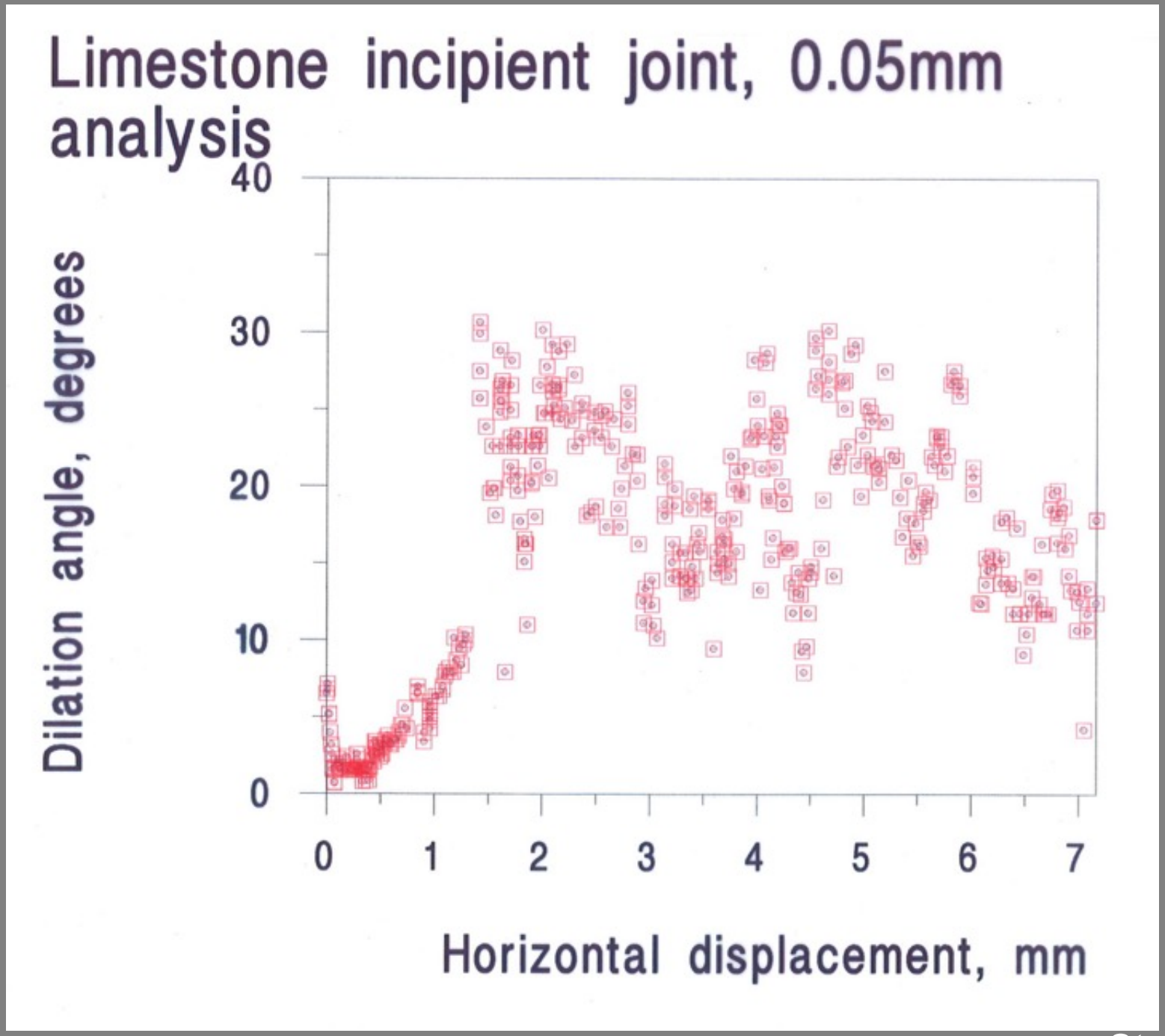
$$\tau_i = (\tau \cos i - \sigma \sin i) \cos i$$

$$\sigma_i = (\sigma \cos i + \tau \sin i) \cos i$$

Steve Hencher

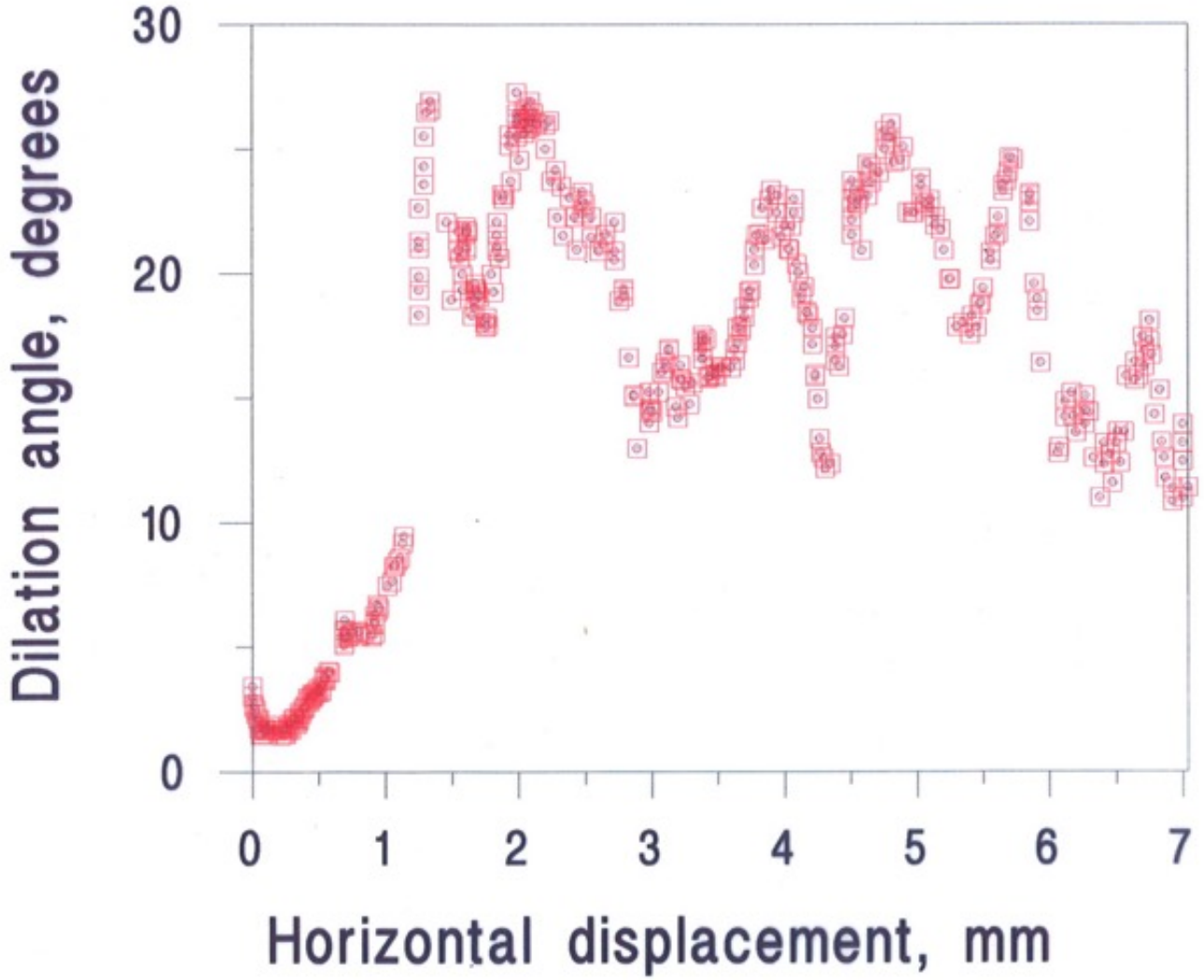


Steve Hencher



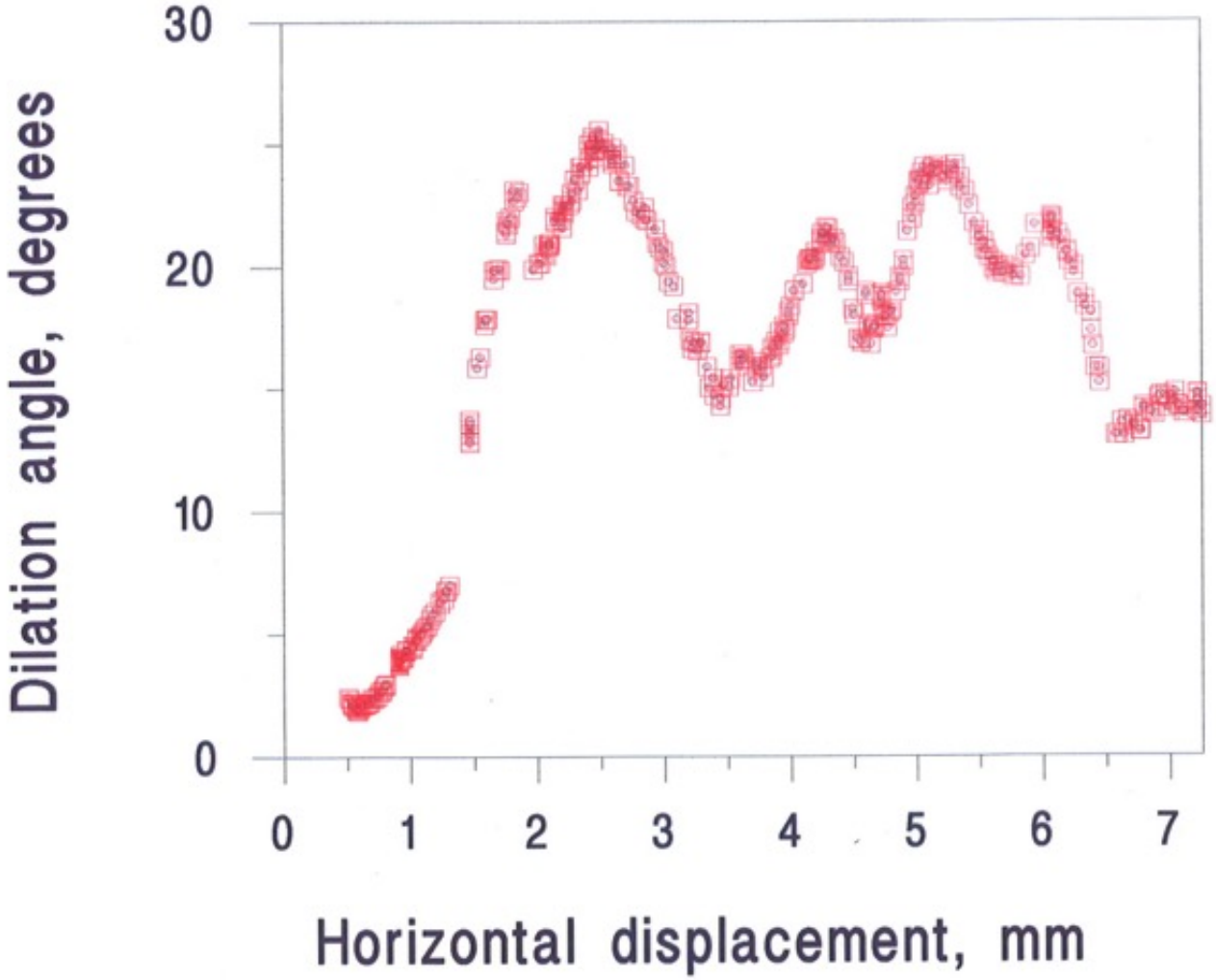
Steve Hencher

Limestone incipient joint, 0.2mm analysis

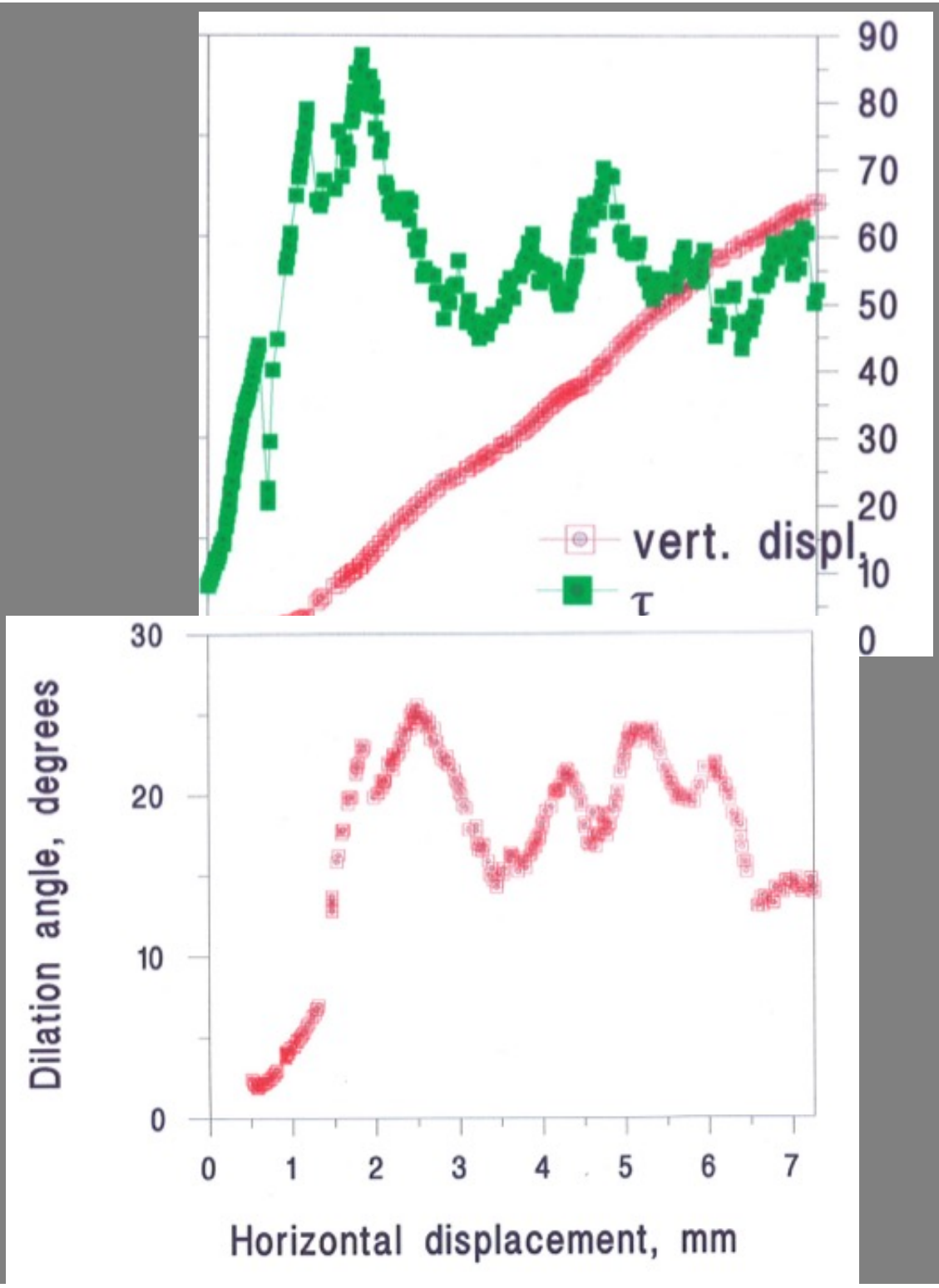


Steve Hencher

Limestone incipient joint, 0.5mm analysis

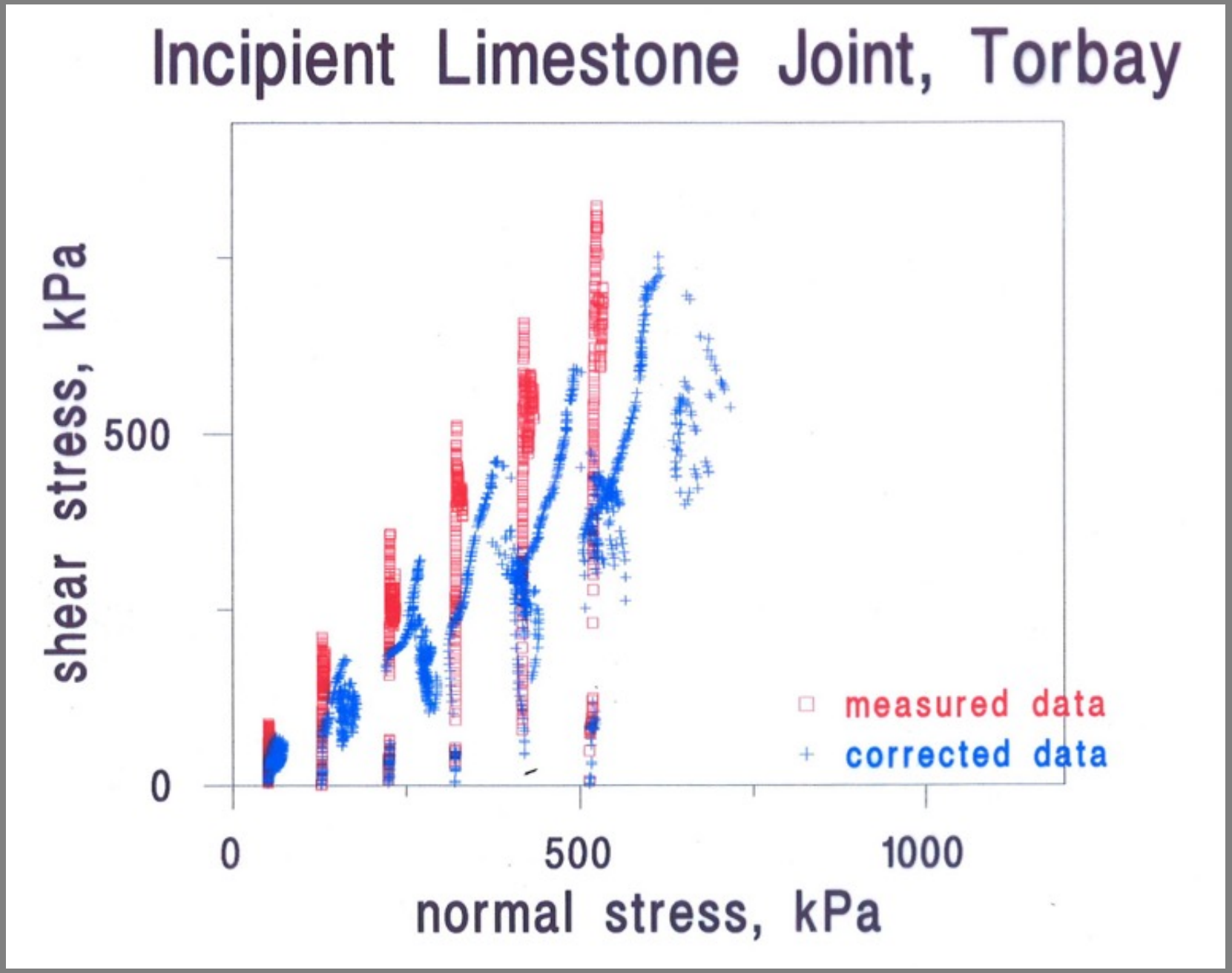


Steve Hencher



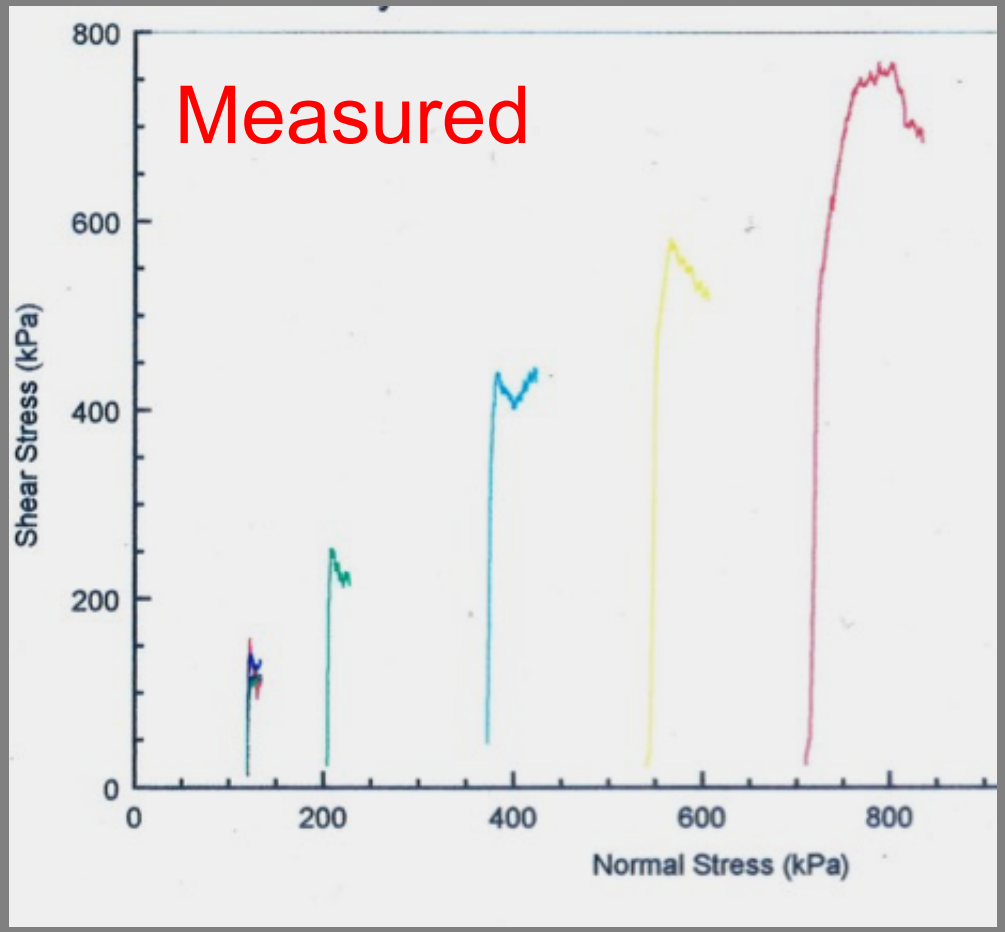
Note: Very close correlation between dilation angle and measured shear strength

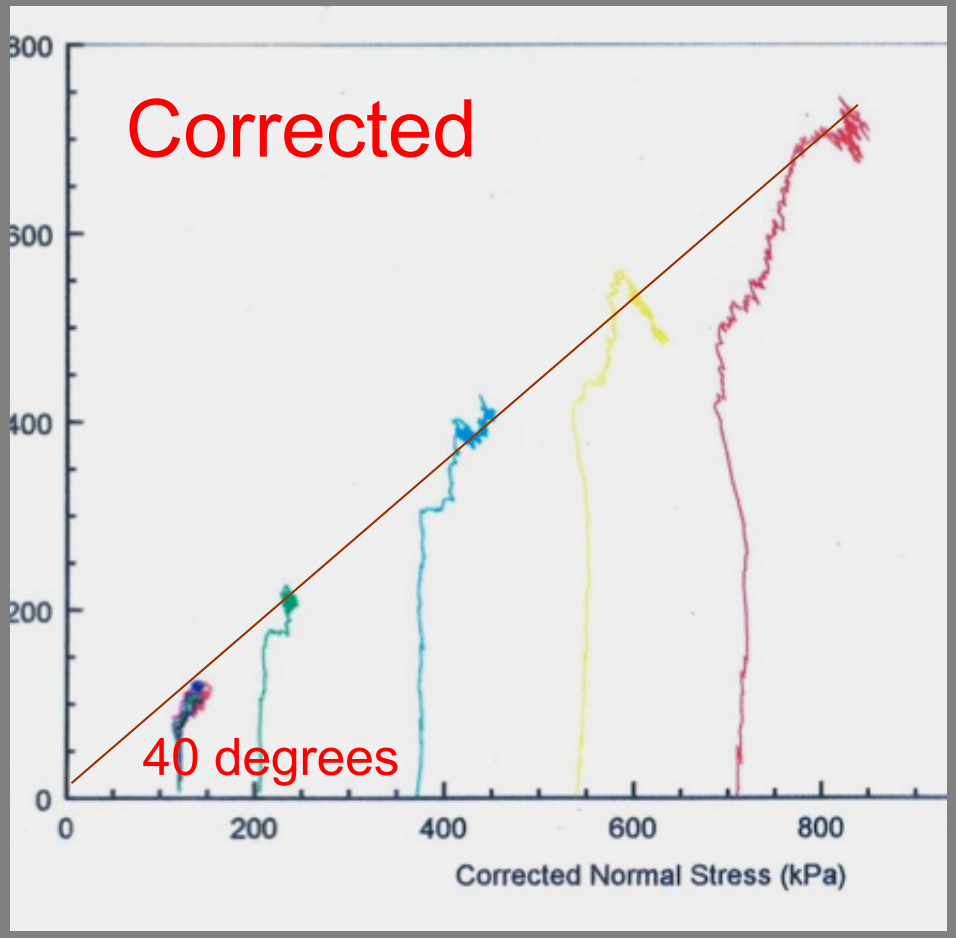
Steve Hencher



Steve Hencher

Tensile fracture – Darleydale Sandstone

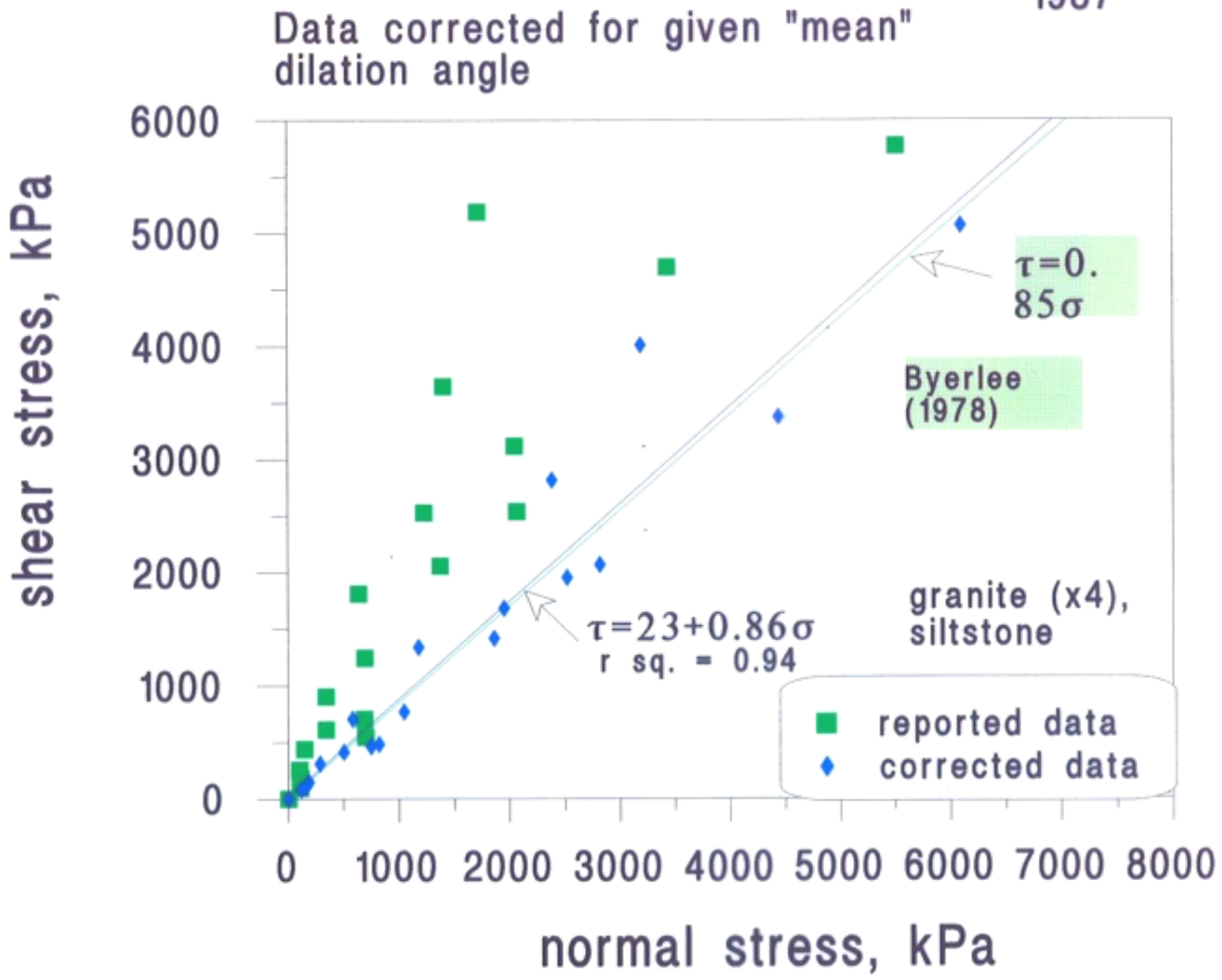




Steve Hencher

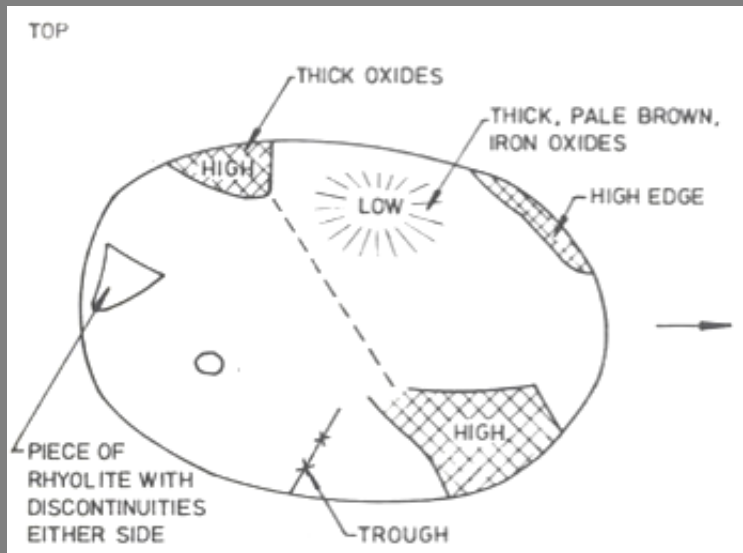
Reported data - various sources

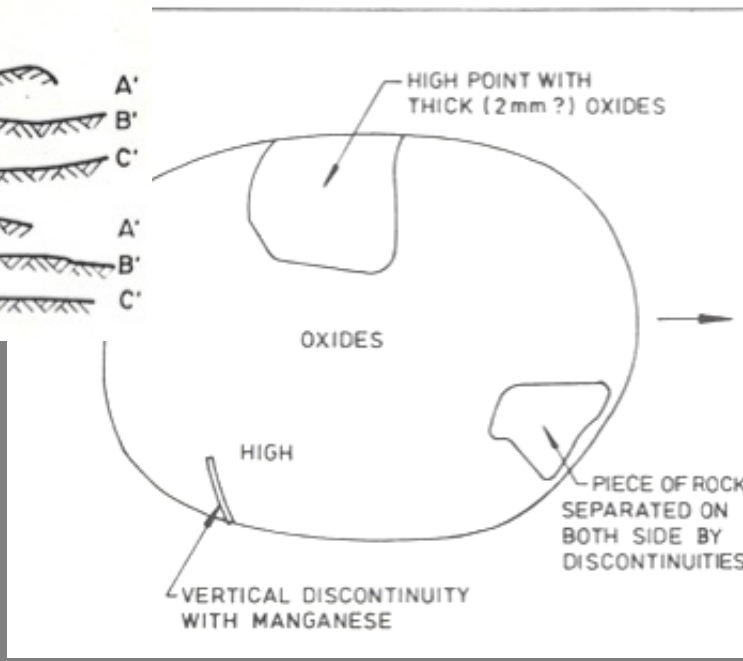
Listed by Barton & Bakhtar, 1987

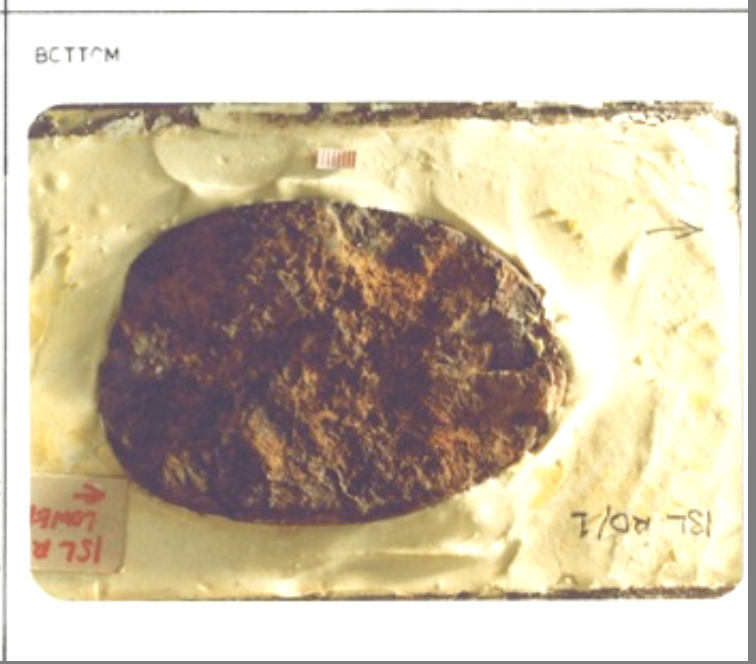


Steve Hencher

Island Road: Rough matching joint

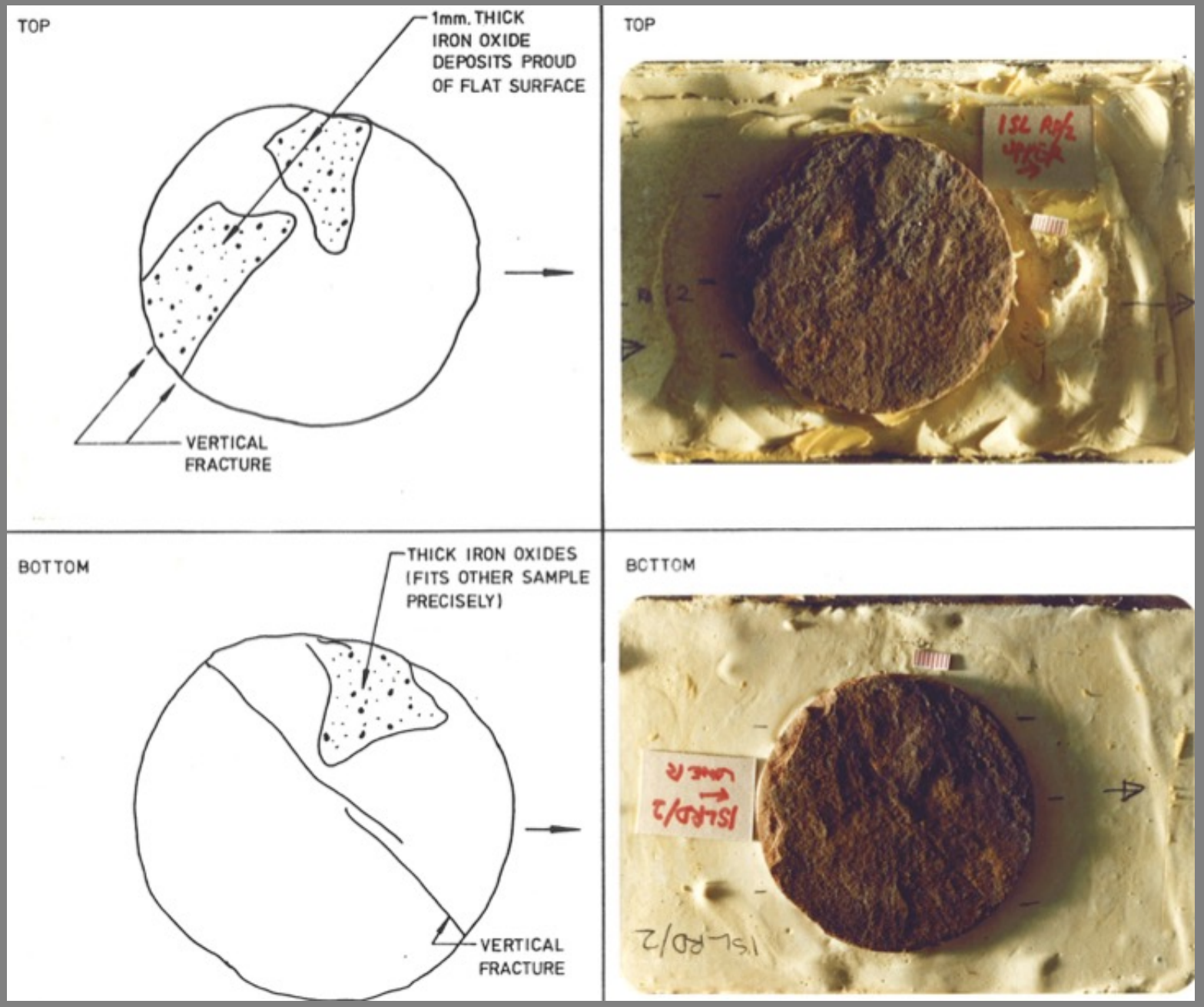




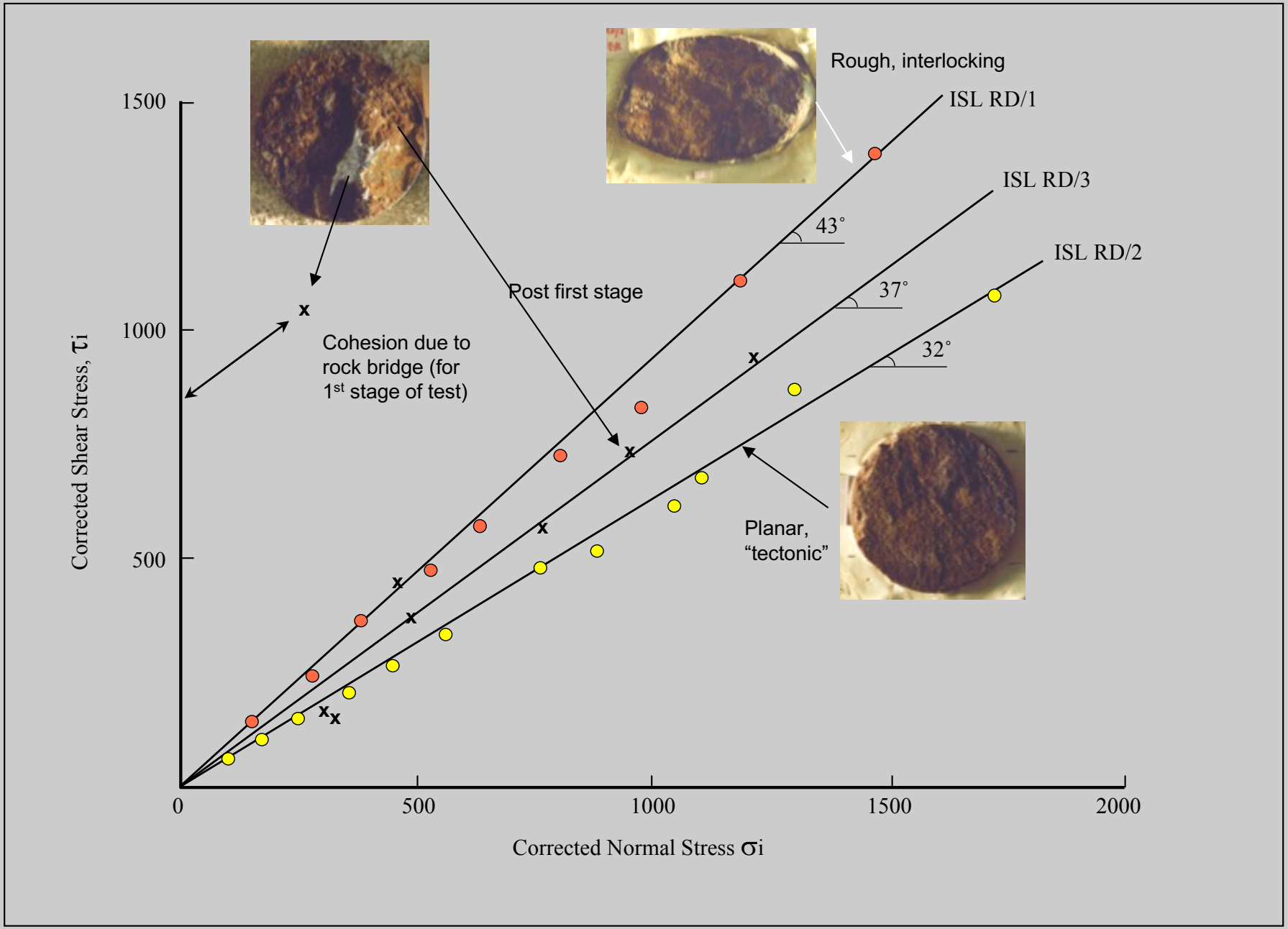


Steve Hencher

Island Road: Planar, “tectonic” joint



Steve Hencher

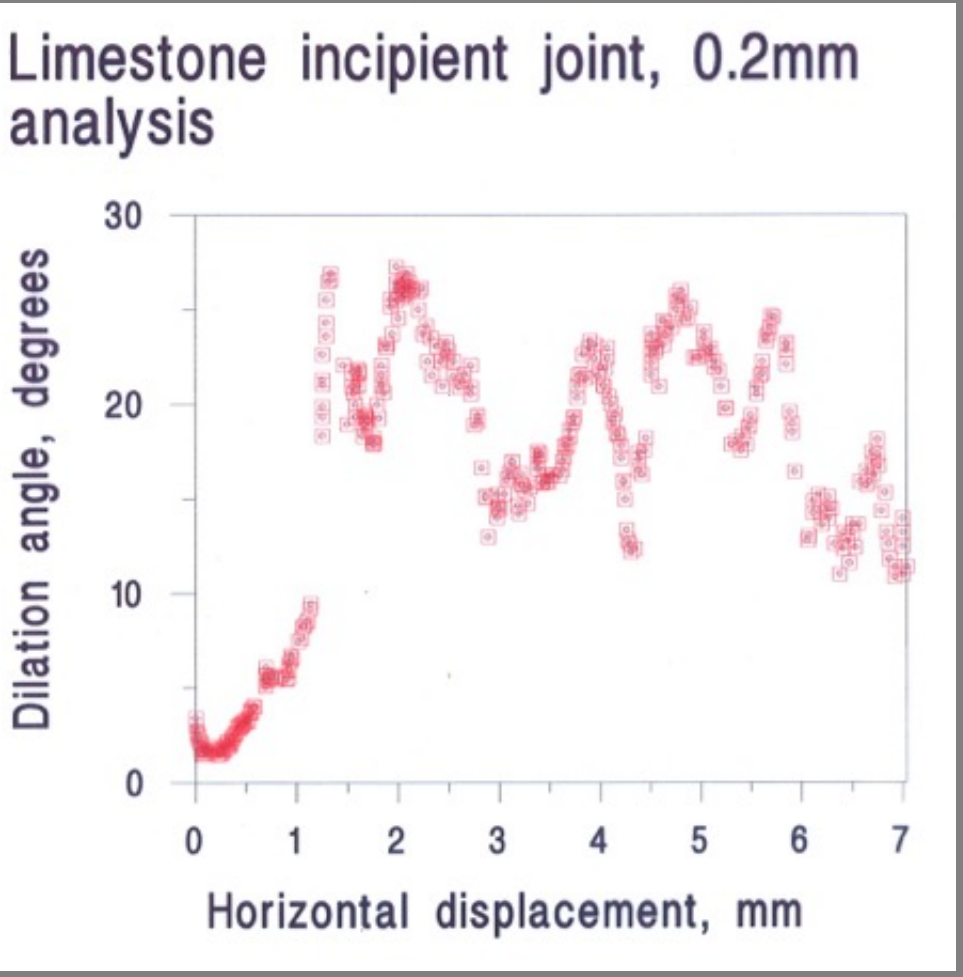


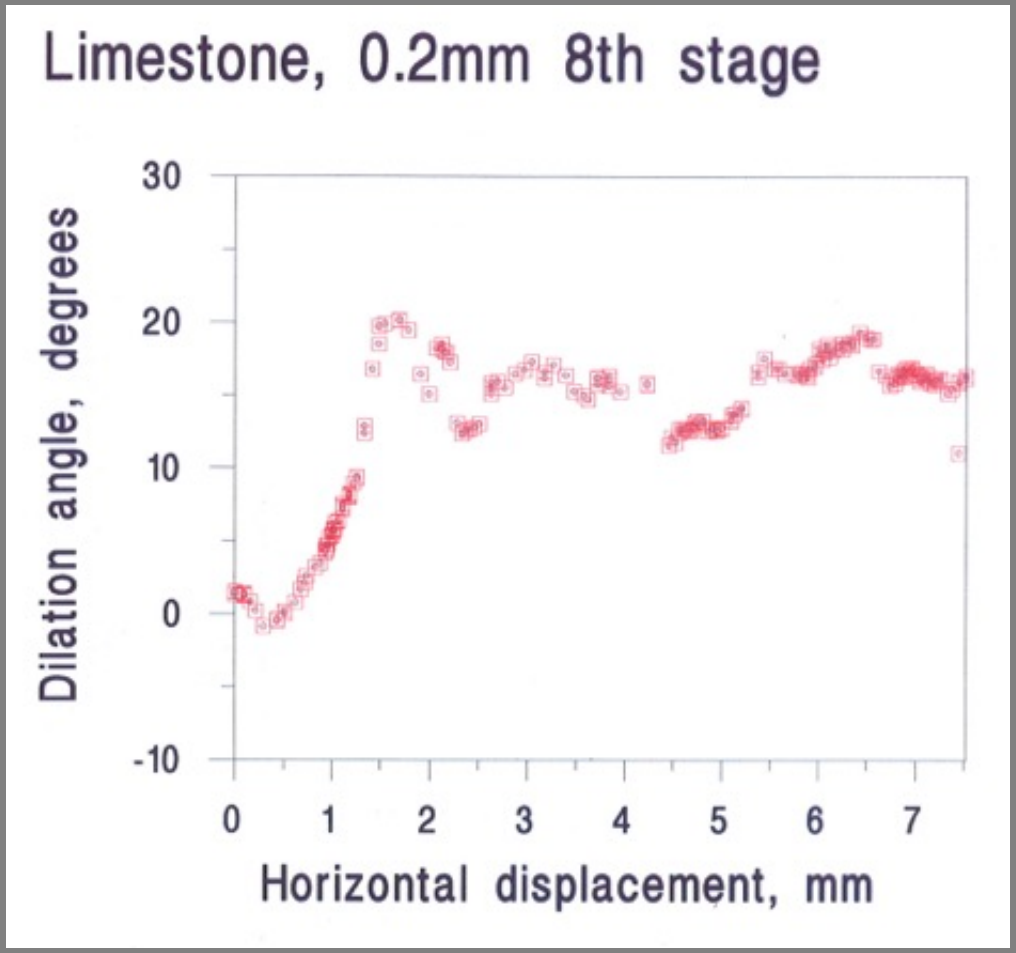
Steve Hencher

Loss of roughness with displacement

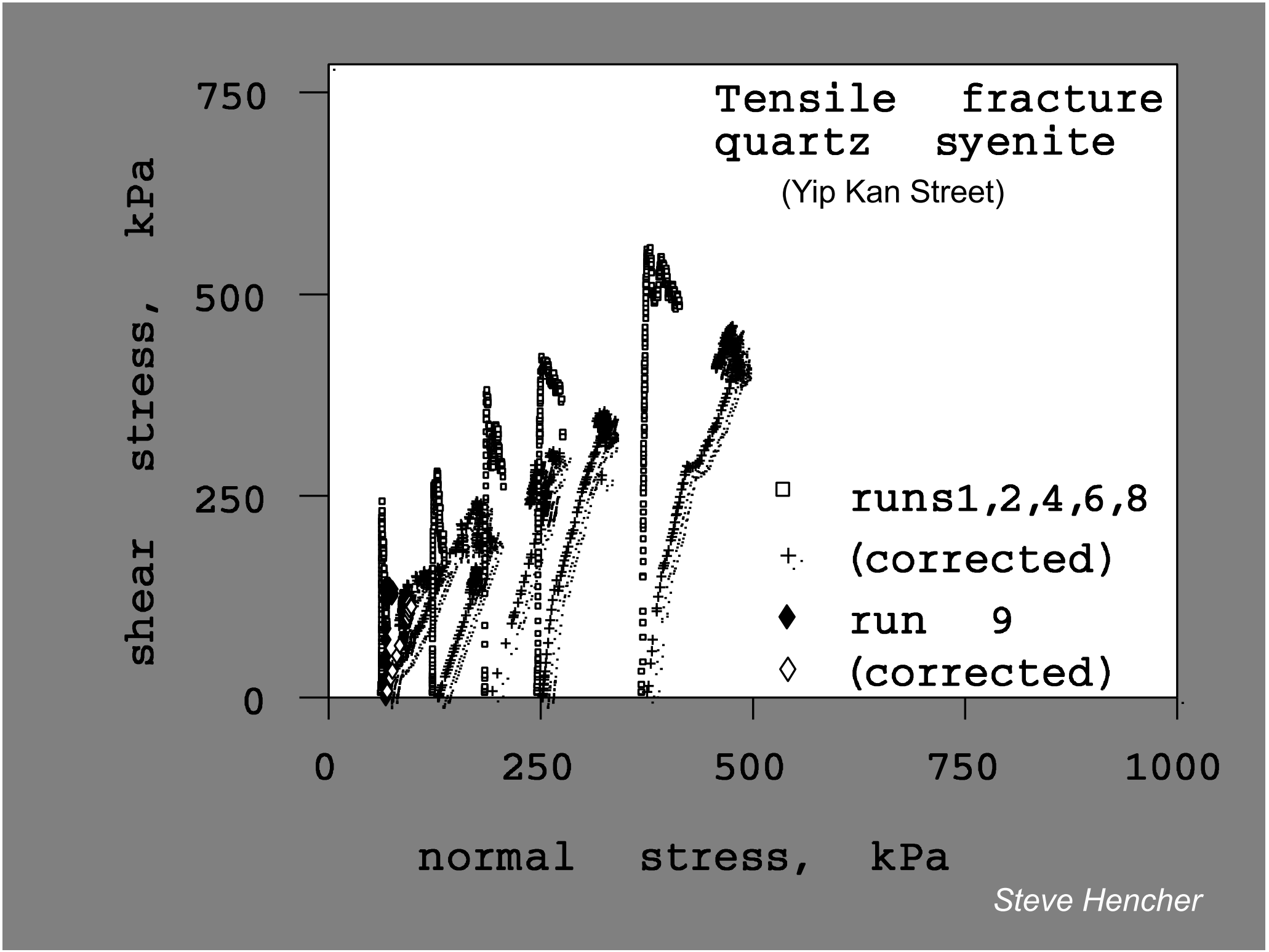
Steve Hencher

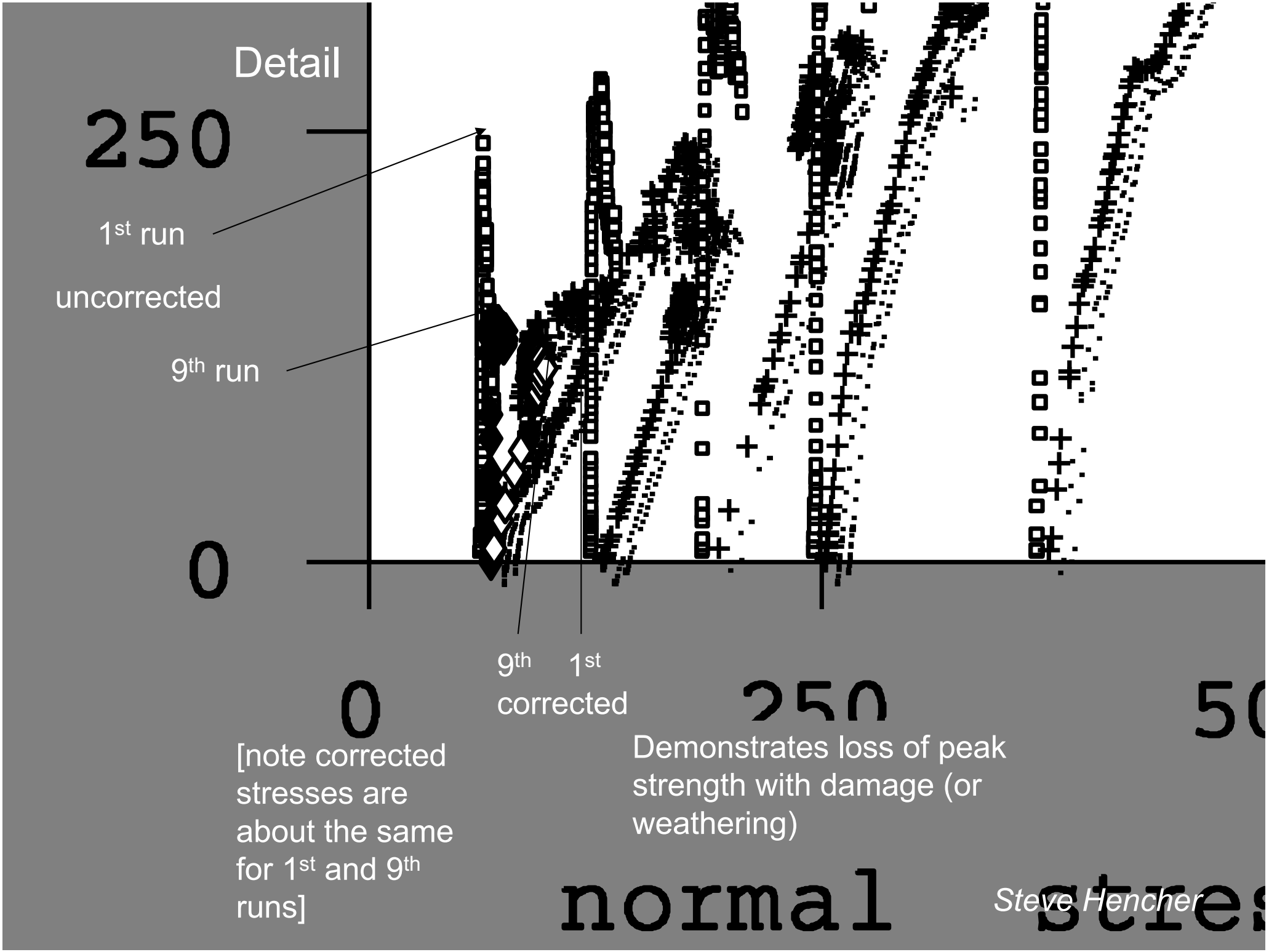
Same limestone joint, repeated testing





Steve Hencher


Tensile fracture
quartz syenite
(Yip Kan Street)
shear stress, kPa
750
500
250
0
0
250
500
750
1000
normal stress, kPa
runs1,2,4,6,8
(corrected)
run 9
(corrected)
Steve Hencher

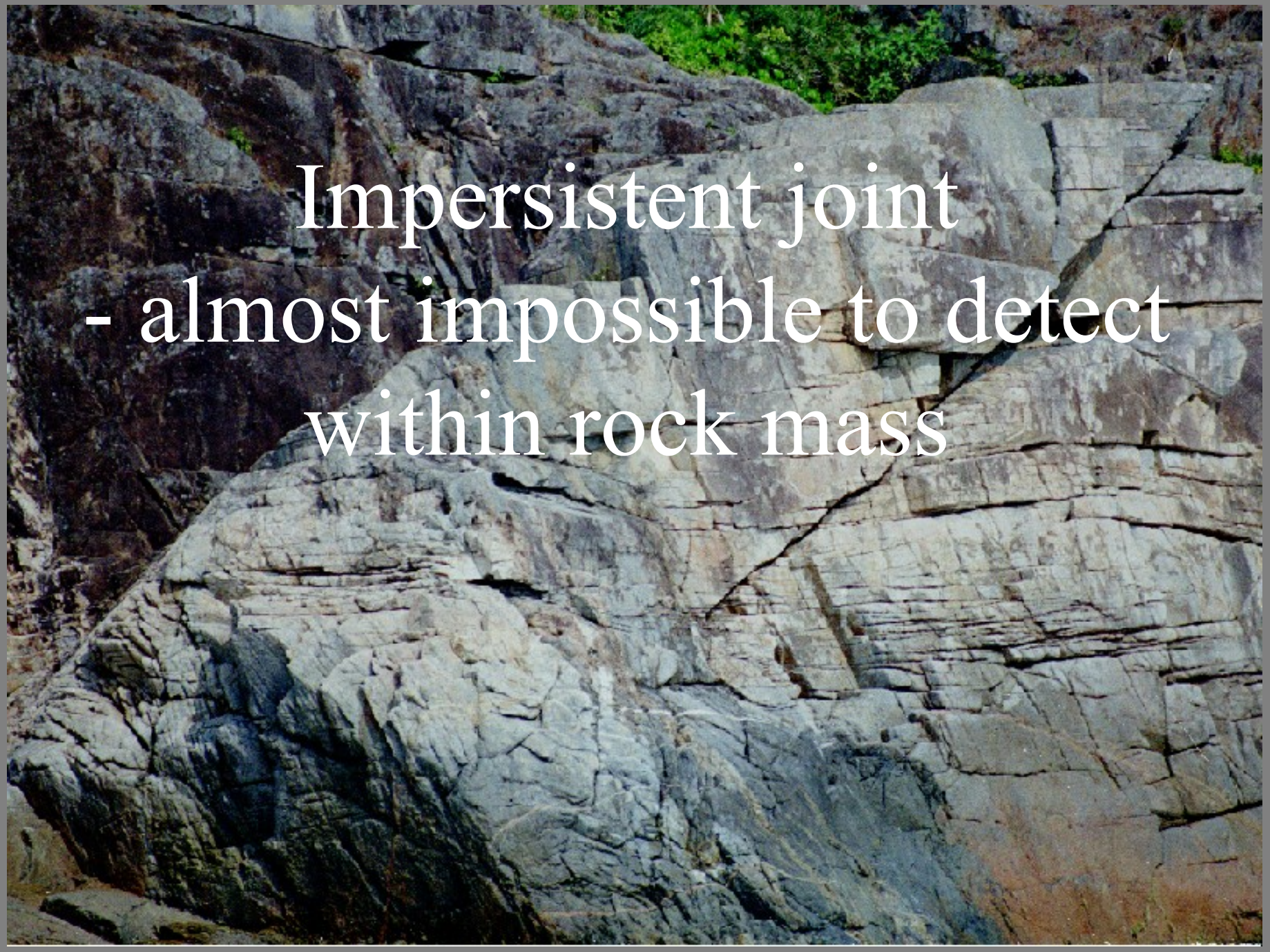

Detail
250
1st run
uncorrected
9th run
0
9th
1st
corrected
0
250
50
[note corrected stresses are about the same for 1st and 9th runs]
Demonstrates loss of peak strength with damage (or weathering)
normal
Steve Hencher

Third Component of Shear Strength after Friction and Dilation is Cohesion

- Cohesion is non-frictional (independent of normal stress) and due to impersistence (rock bridges)
- magnitude depends on the cross sectional area of intact rock to be sheared

Steve Hencher

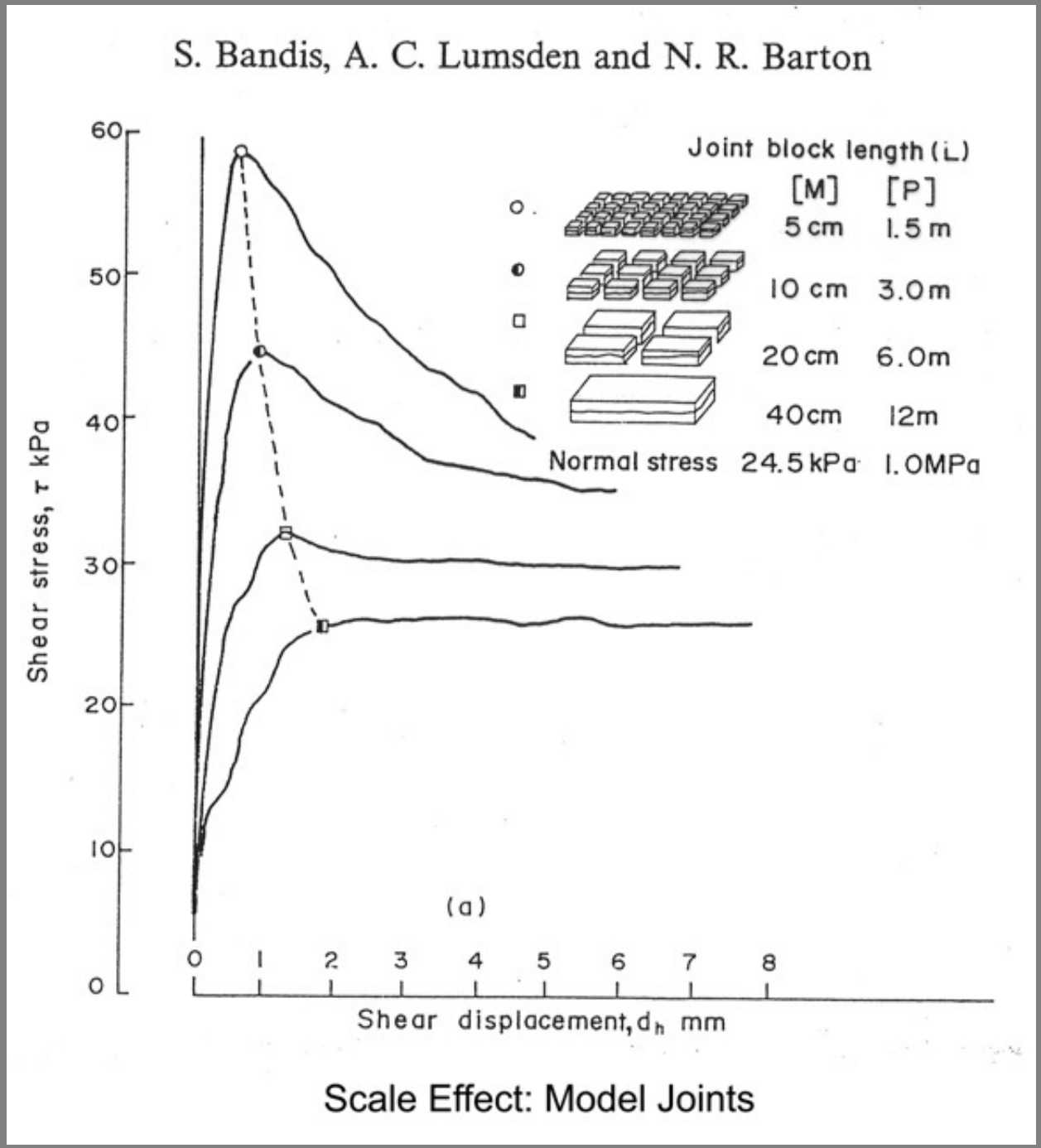
Steve Hencher



Steve Hencher

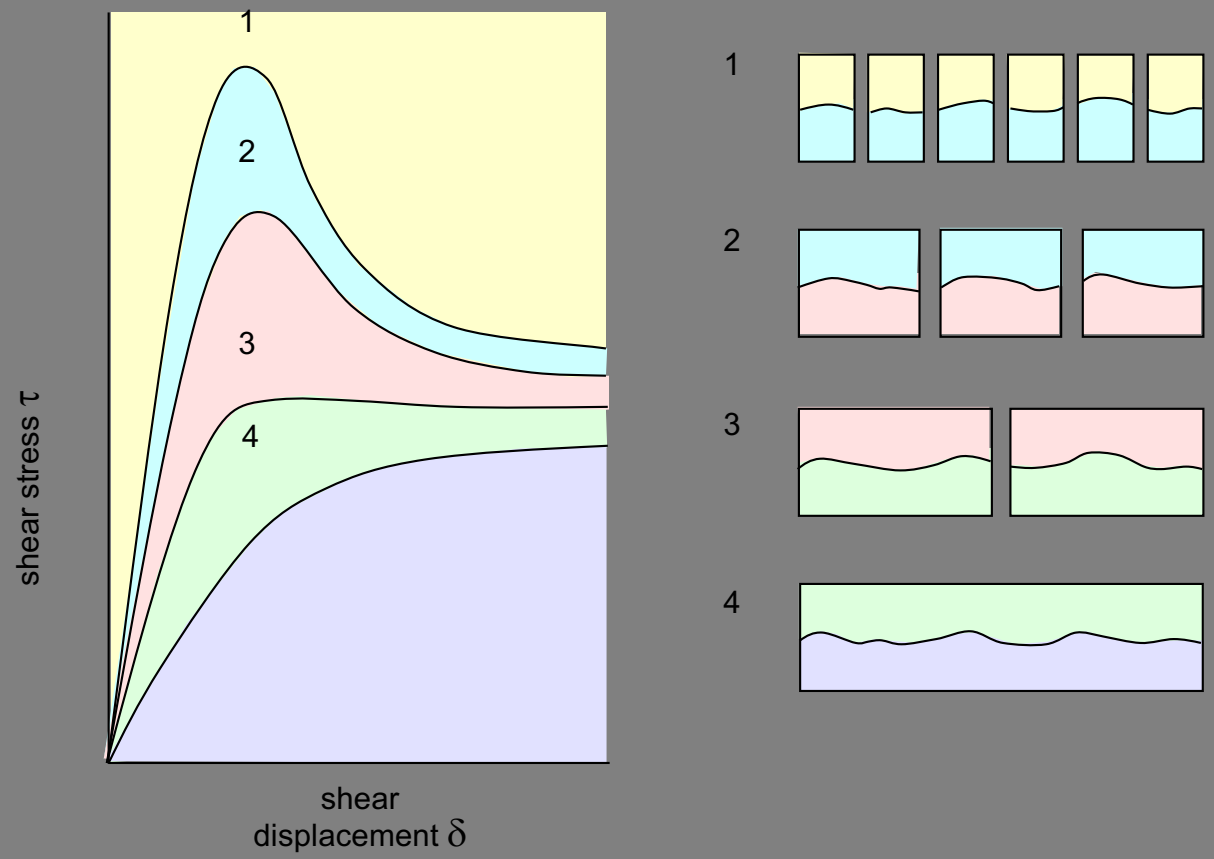
Scale Effects

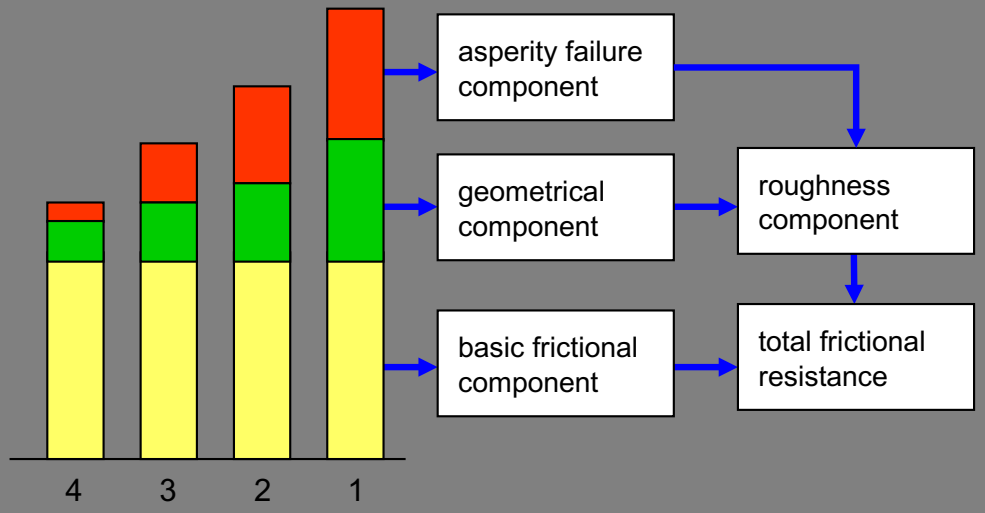
-Does strength change with the size of joint being sheared (contrary to Amonton's laws for friction alone)



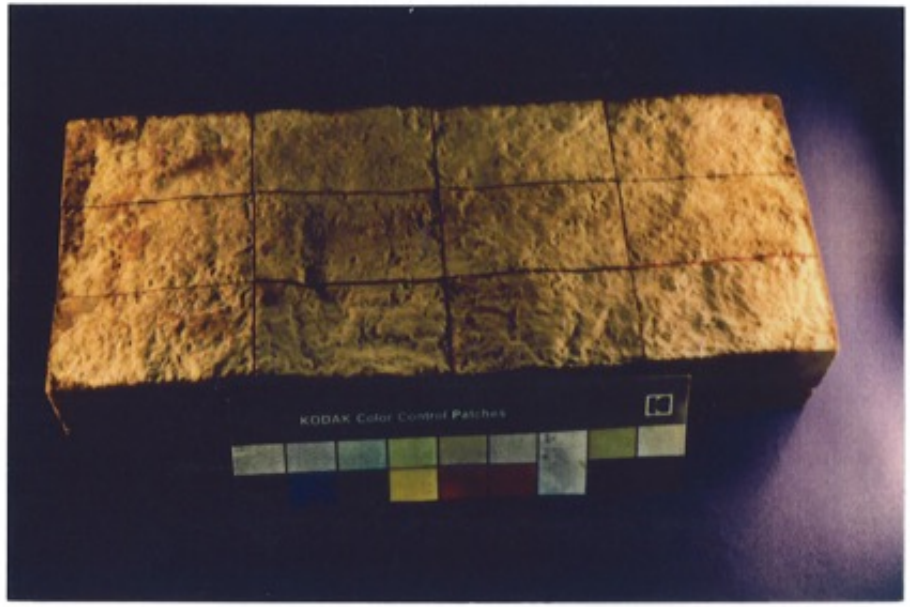
Scale Effect: Model Joints

Steve Hencher





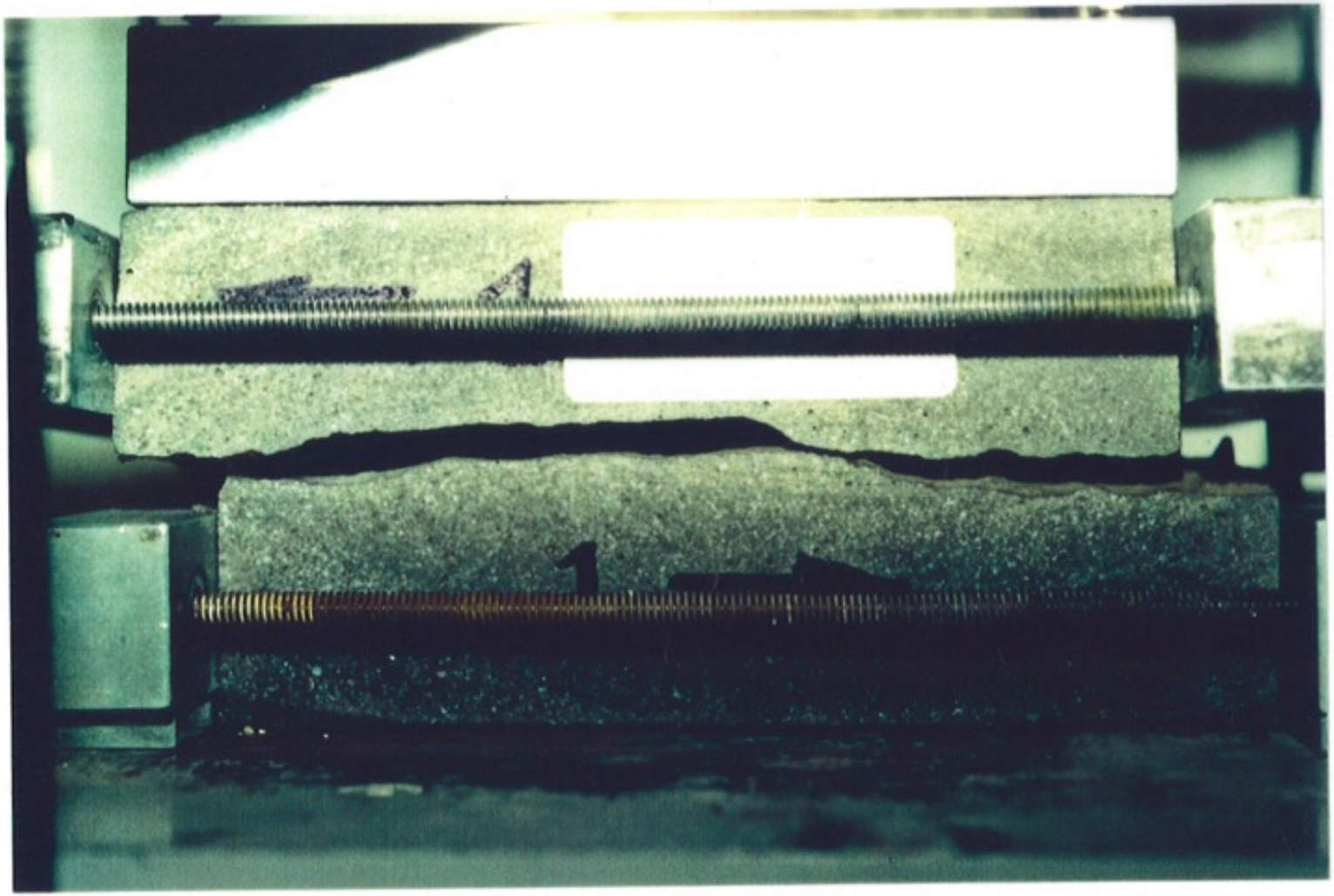
Steve Hencher



LOWER HALF

NUMBERING OF SMALL SAMPLES
(Papaliangas '93)

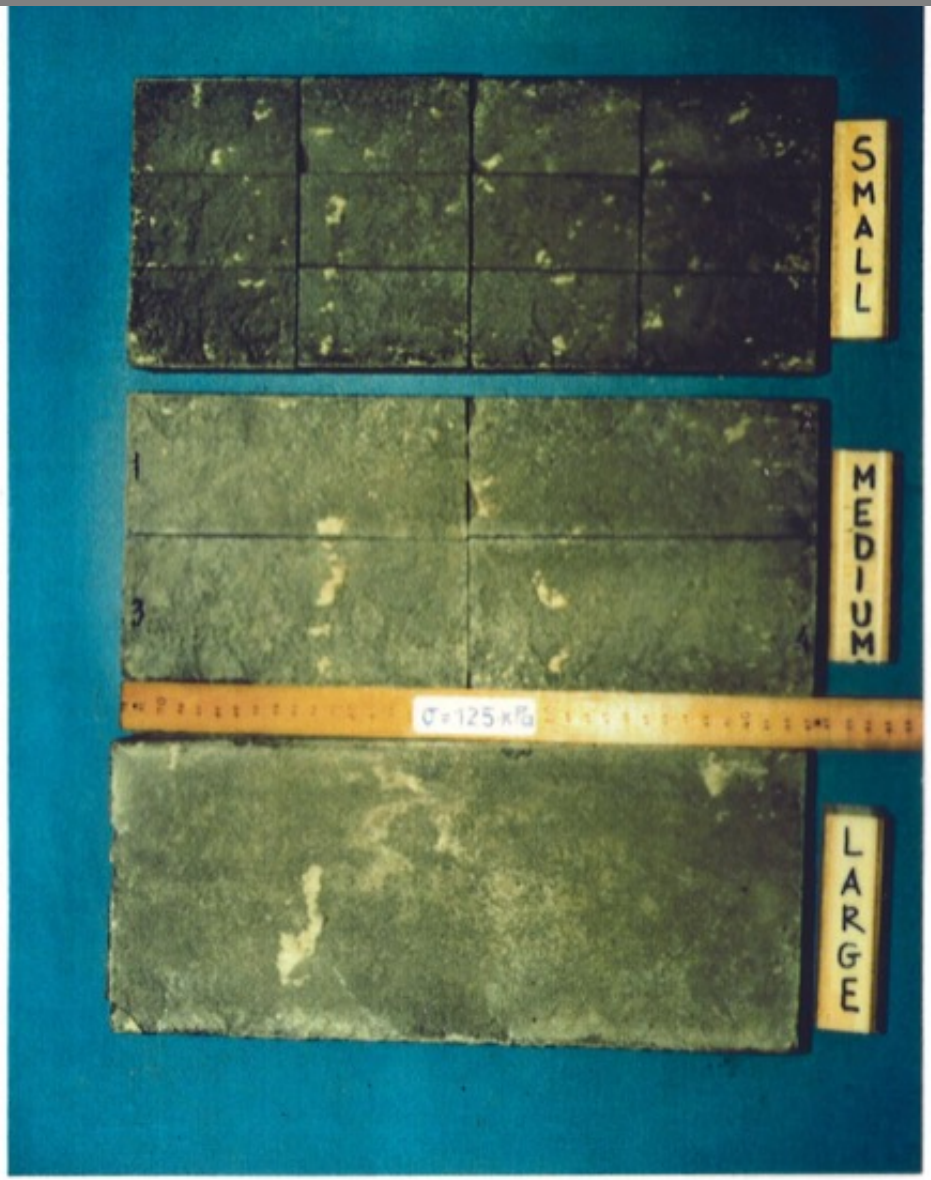
Steve Hencher



DILATION OF QUARTER BLOCK #1

(Papaliangas '93)

Steve Hencher

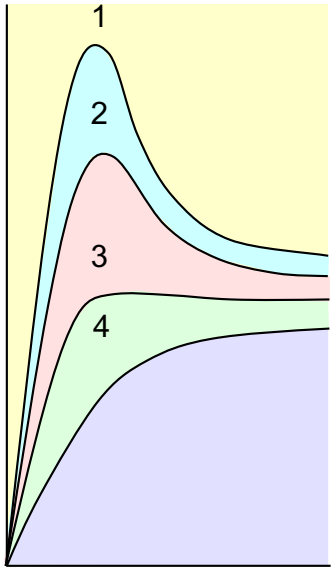


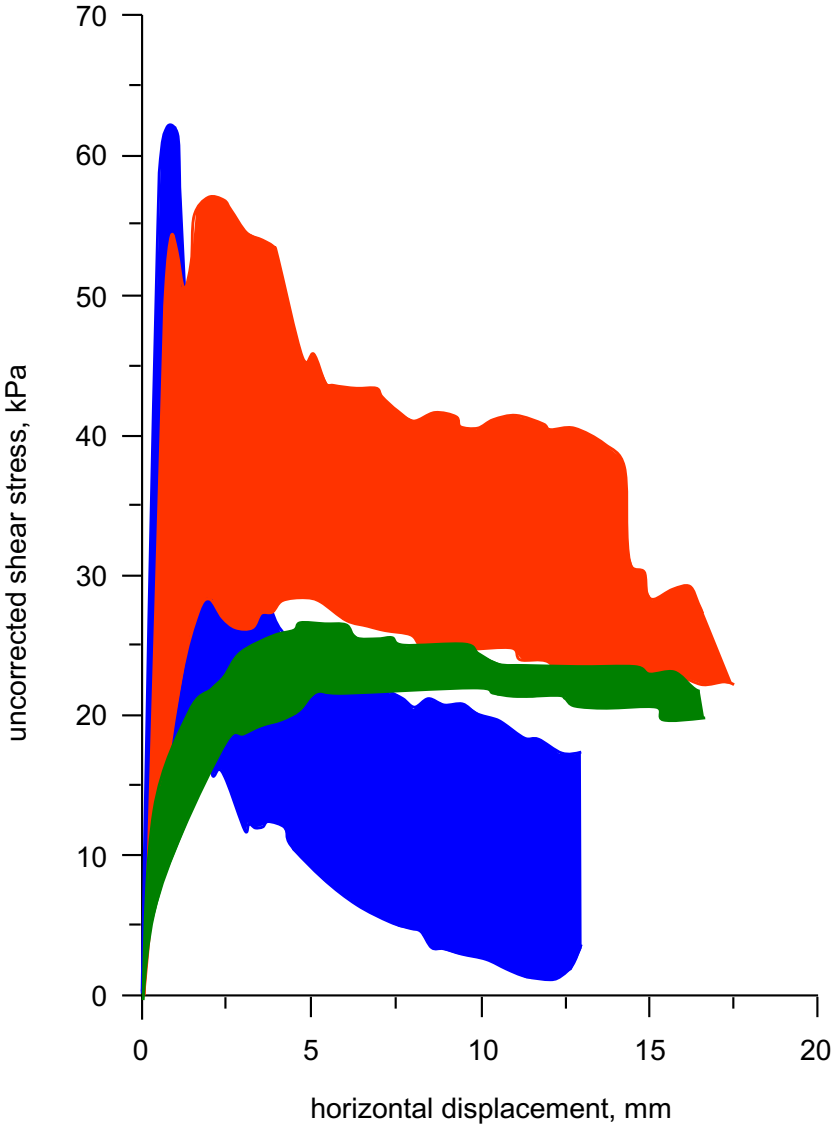
DAMAGE TO MODELS AT DIFFERENT SCALES

(Papaliangas '93)

Steve Hencher

Peak shear strength of blocks at different scales

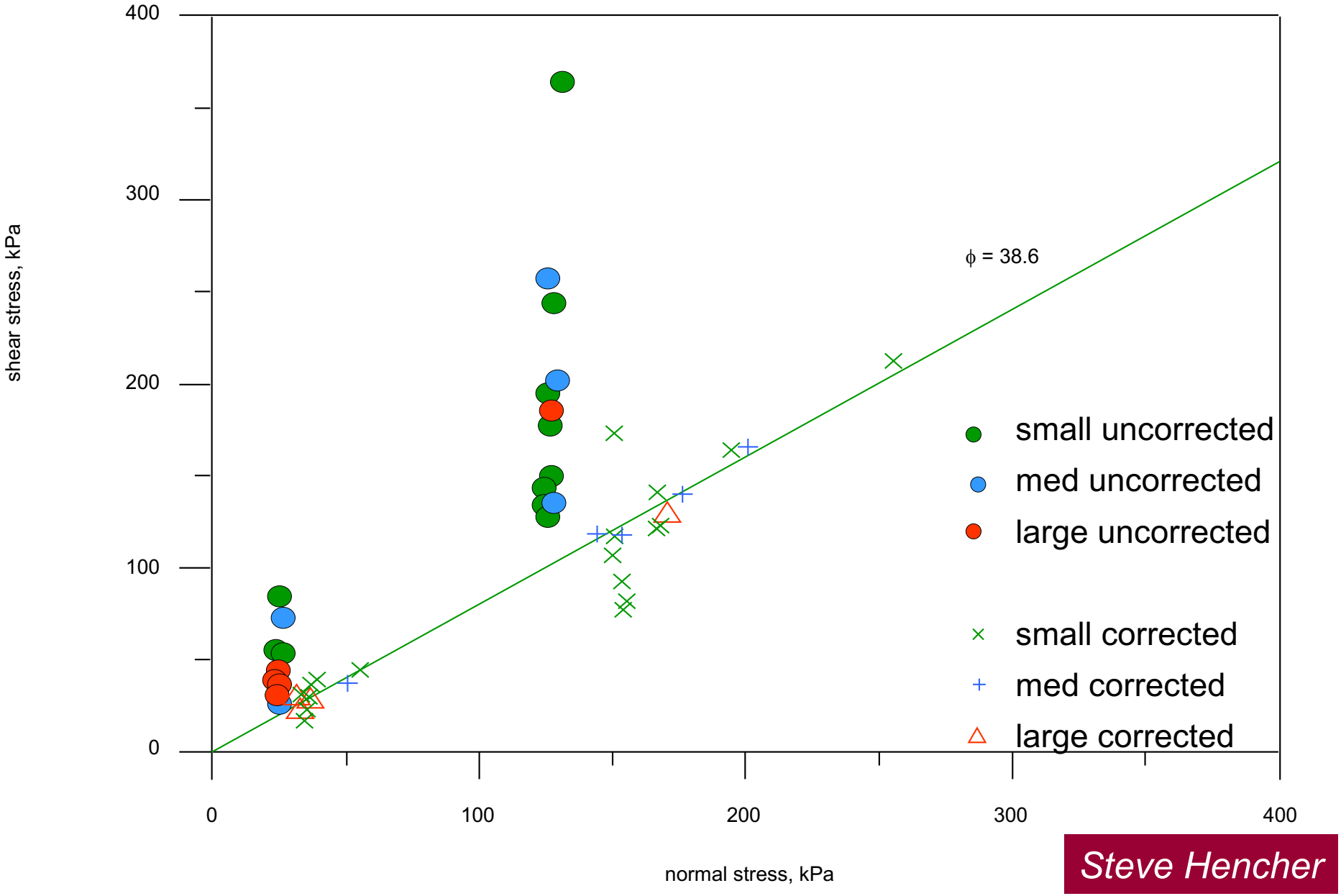




length	width
88 mm	50mm
176 mm	75mm
354mm	150mm

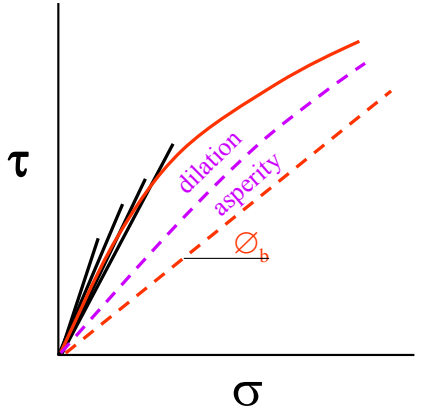
Steve Hencher

Scale effects Corrections for dilation

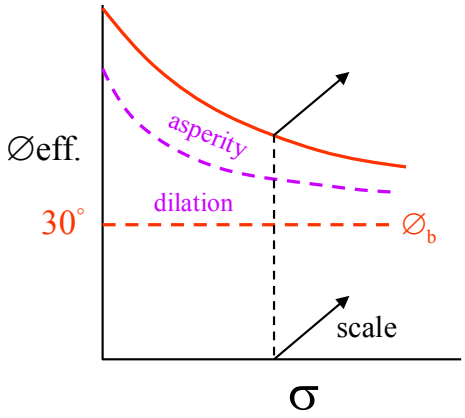


Steve Hencher

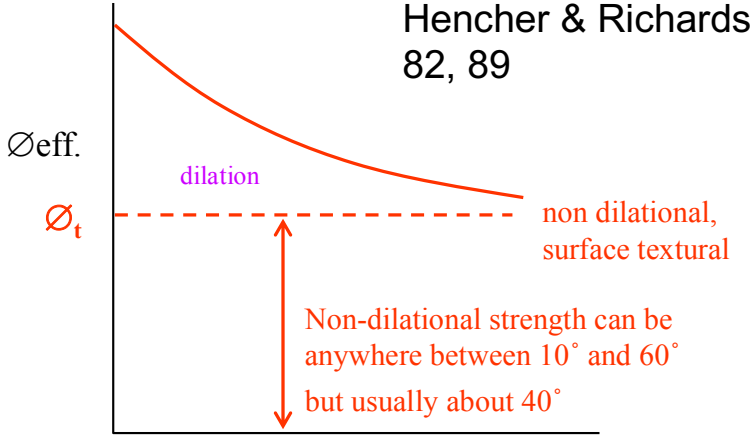
Alternative Expressions of Shear Strength



Barton – Bandis model



asperity+ dilation + saw cut friction



Hencher & Richards 82, 89

non dilational, surface textural

Non-dilational strength can be anywhere between 10˚ and 60˚ but usually about 40˚

dilation + textural

CONCLUSIONS re SCALE EFFECTS

There may or may not be scale effects depending upon geometry

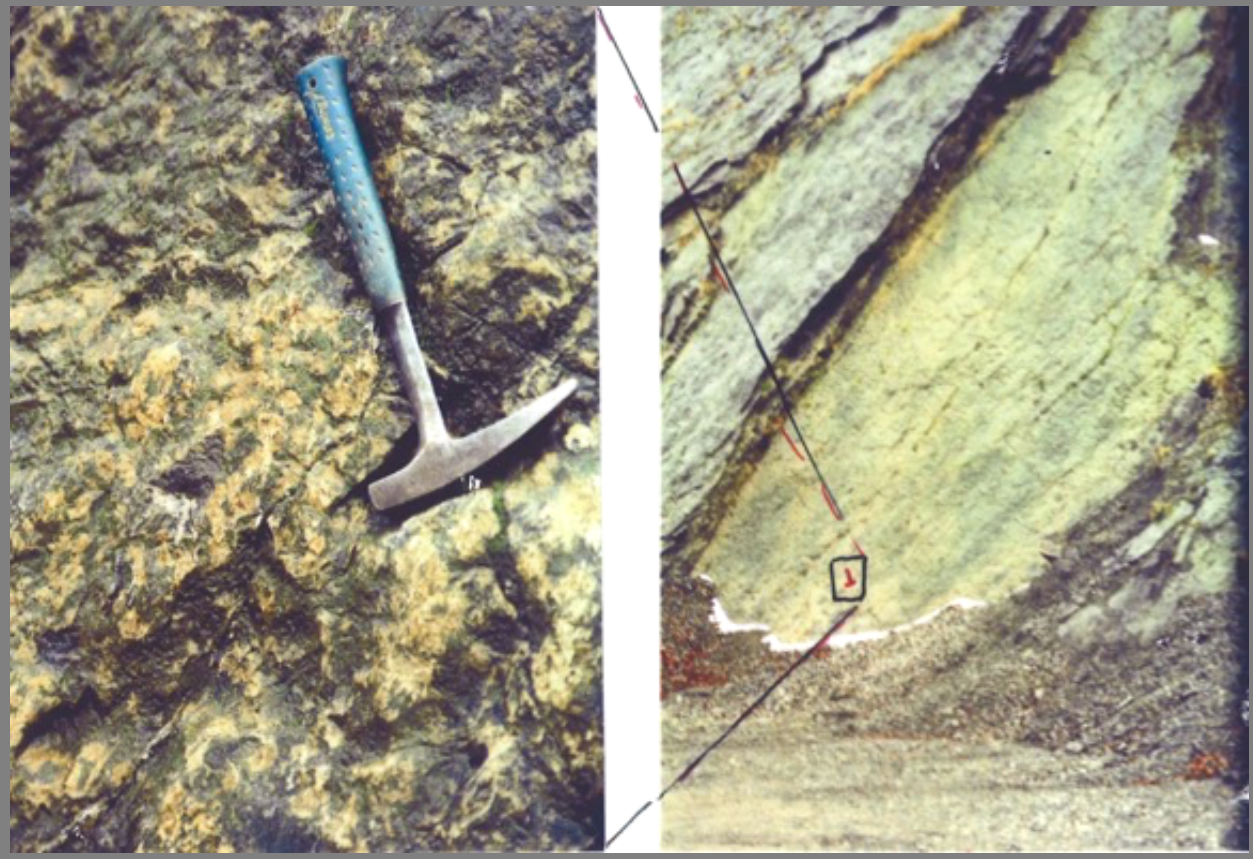
According to Barton / Bandis model, correction for dilation should be to a curved envelope (the JCS factor)

My experience is that correction for dilation is to a straight line (given constant mineralogy / texture)

Scale effect is simply dilational (the freedom to rotate which changes with base length)

Steve Hencher

Predicting Dilation at Field Scale



Rough at small scale but at large scale?

What counts is the dilation angle that the centre of gravity of the sliding block has to go through to pass peak strength. In this case I would make NO allowance for dilation for large slab failure.

Steve Hencher

Rock Slope Failures: Shear Strength in Reality

Steve Hencher

Yip Kan Street, Aberdeen

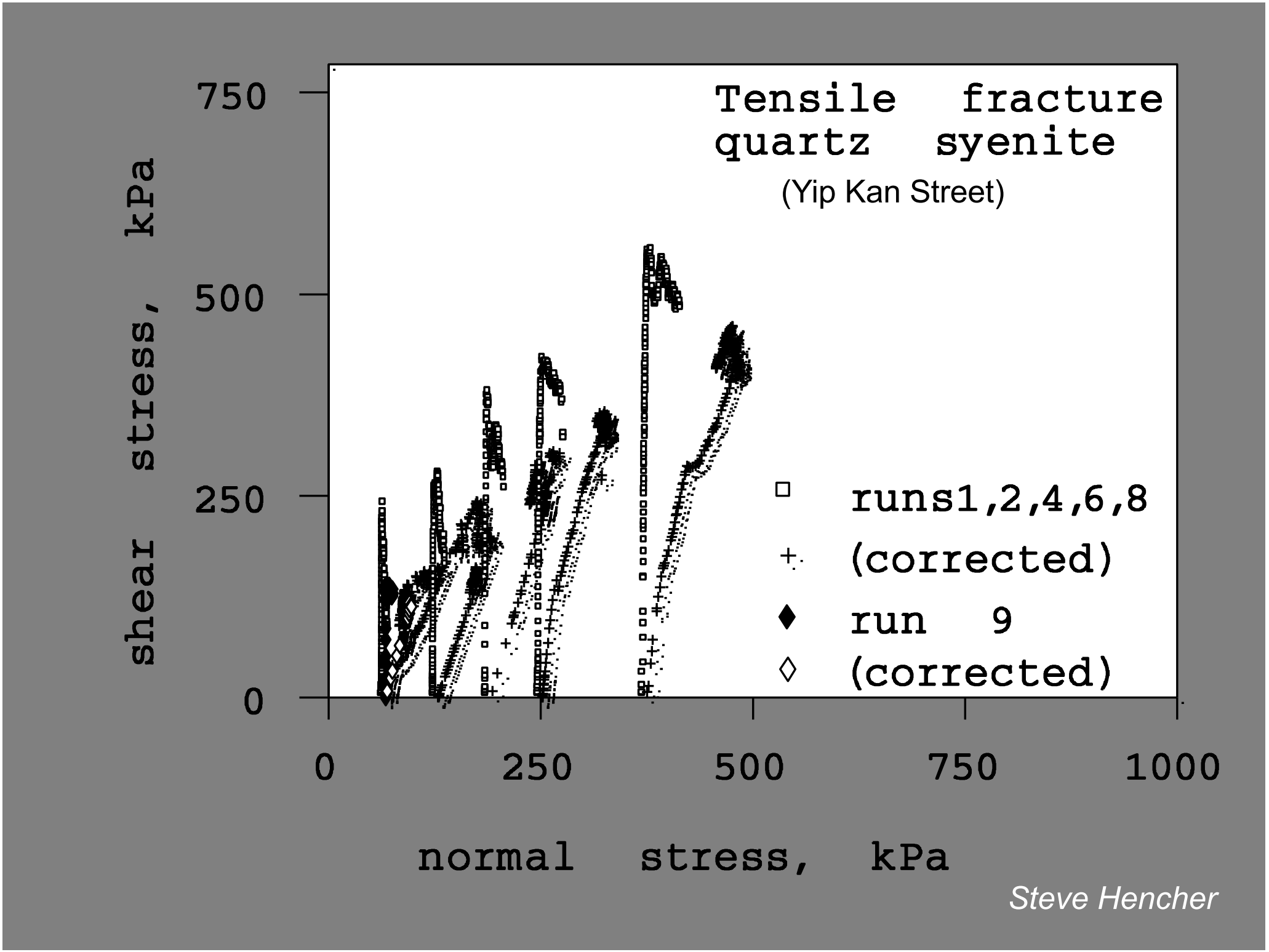
Steve Hencher

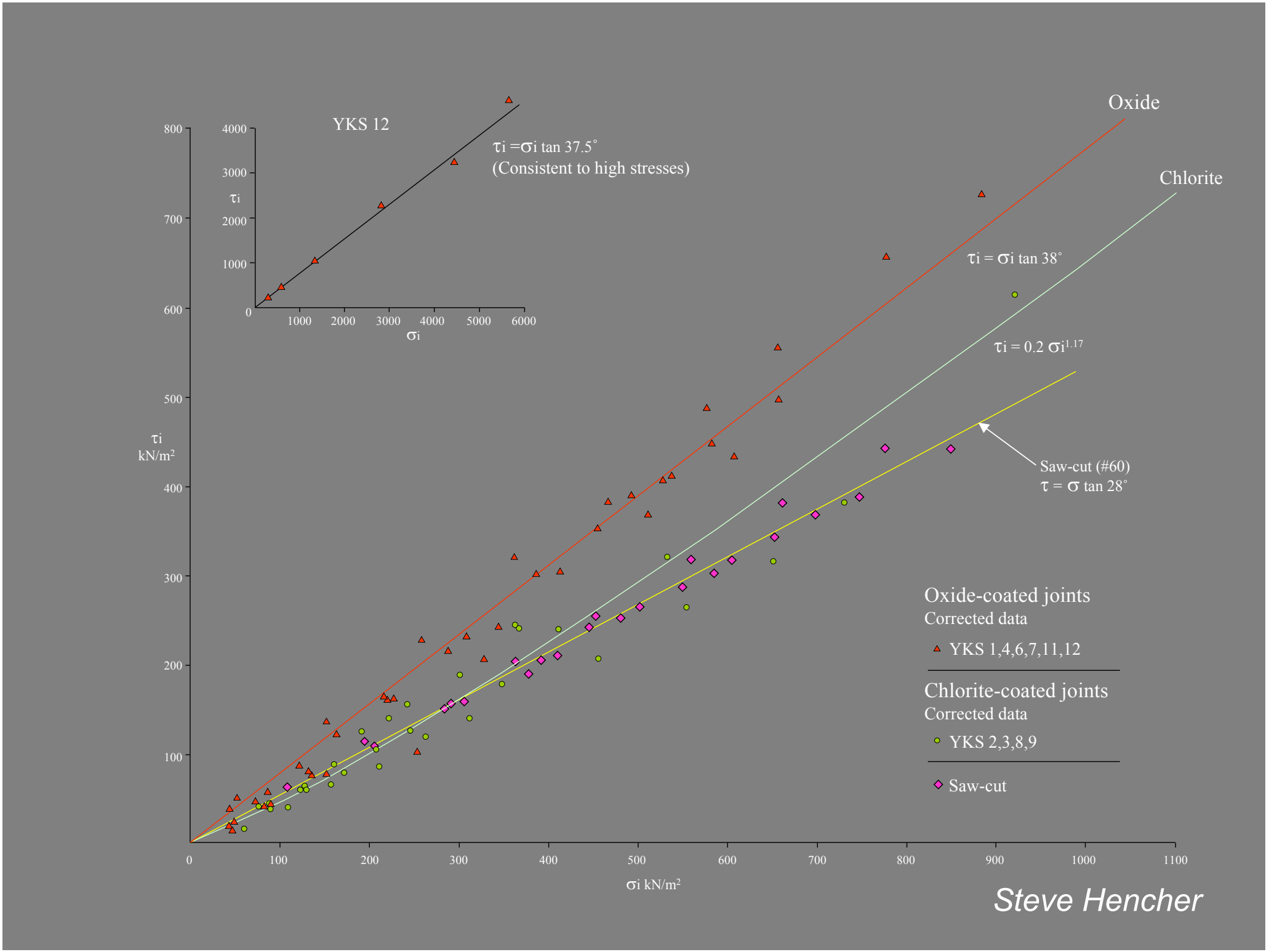
Steve Hencher

Steve Hencher

Friction angle 10 degrees lower than saw cut!

Steve Hencher


Tensile fracture
quartz syenite
(Yip Kan Street)
runs1,2,4,6,8
(corrected)
run 9
(corrected)
shear stress, kPa
normal stress, kPa
0
250
500
750
1000
Steve Hencher

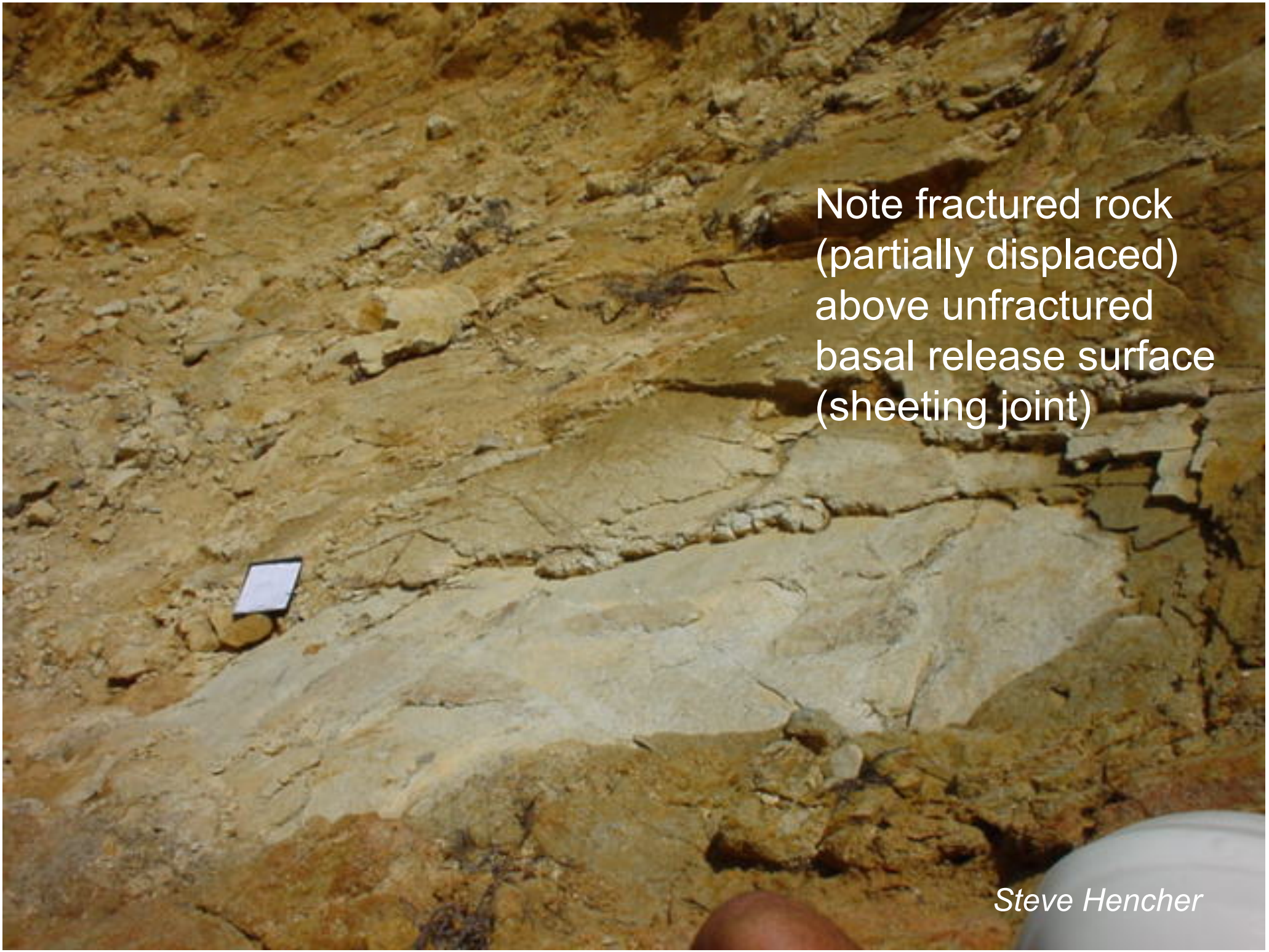

YKS 12
τi =σi tan 37.5°
(Consistent to high stresses)
τi
σi
Oxide
Chlorite
τi = σi tan 38°
τi = 0.2 σi^1.17
Saw-cut (#60)
τ = σ tan 28°
τi kN/m²
σi kN/m²
Oxide-coated joints
Corrected data
YKS 1,4,6,7,11,12
Chlorite-coated joints
Corrected data
YKS 2,3,8,9
Saw-cut
Steve Hencher

Leung King Estate

Steve Hencher

Steve Hencher

Steve Hencher


Note fractured rock (partially displaced) above unfractured basal release surface (sheeting joint)
Steve Hencher

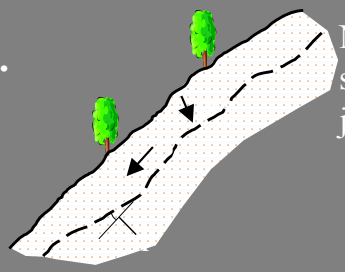
Steve Hencher

Steve Hencher

Steve Hencher

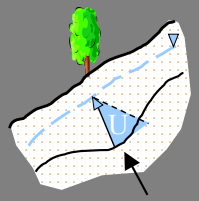
DETERIORATION OF SLOPE WITH INTERMITTENT MOVEMENTS ON SHEETING JOINT

1.



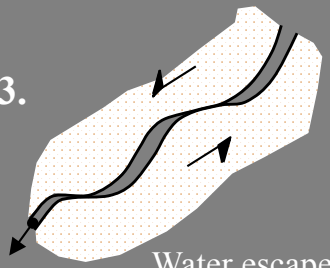
- Rough, tensile fracture develops parallel to hillside
- Shear resistance = $\sigma_3 \tan(\phi + i)$ [$\phi \approx 38^\circ$ typically]

2.



- Water pressure develops in fracture
- Shear resistance reduces to $(\sigma_3 - U) \tan(\phi + i)$
- Movement initiated

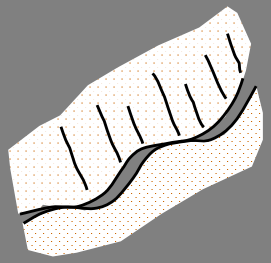
3.



Water escapes, pressure $\rightarrow 0$

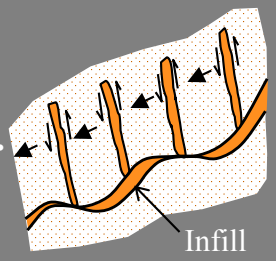
- Movement opens joint
- Permeability increases
- Water pressure drops
- Movement ceases

4.



- Tensile fractures develop in overlying displaced mass

5.



- Some continued creep movement (intermittent)
- Vertical tension cracks and sheet joint apertures become infilled with clay
- Local vertical shearing on joints
- Note that rock (albeit weathered and weakened) still controls friction until waviness fully overcome

Steve Hencher

Steve Hencher

Steve Hencher

Steve Hencher

Steve Hencher

Aznalcollar Open Pit Mine, Spain

Steve Hencher

Steve Hencher

Steve Hencher

Steve Hencher

Steve Hencher

Steve Hencher

Steve Hencher

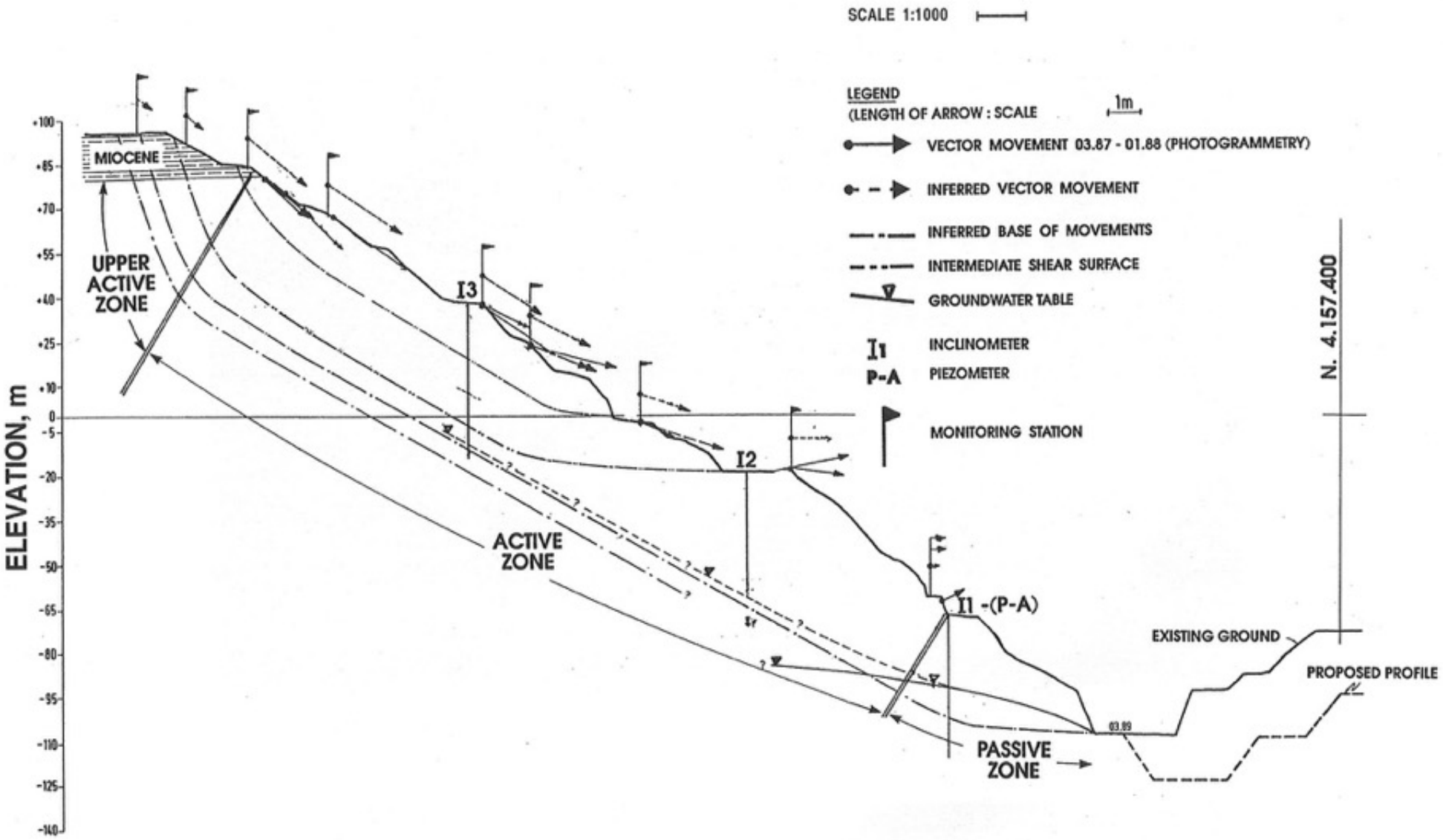


Fig. 9 Schematic cross-section of footwall slope at Aznalcóllar showing inferred stability conditions

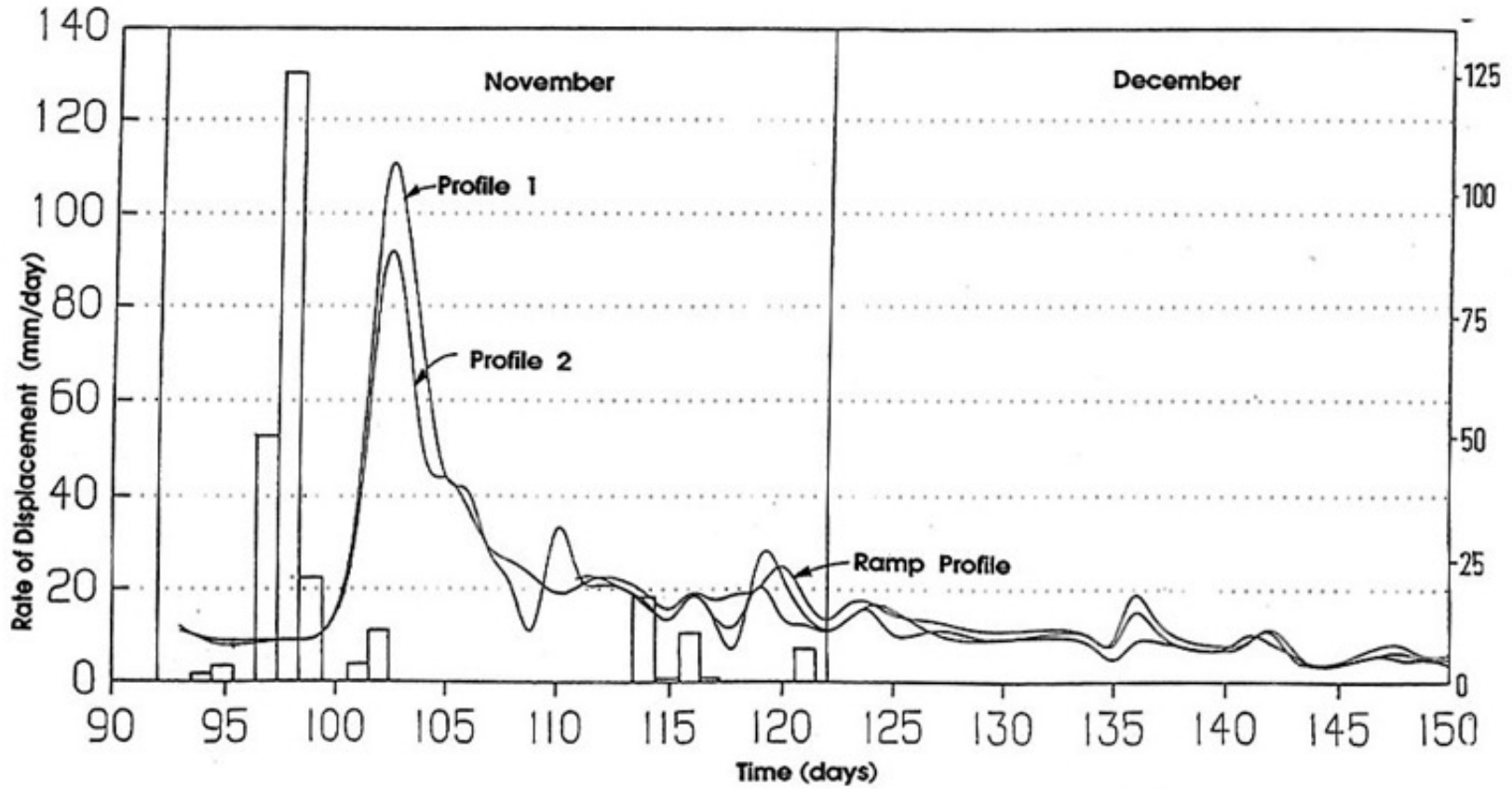
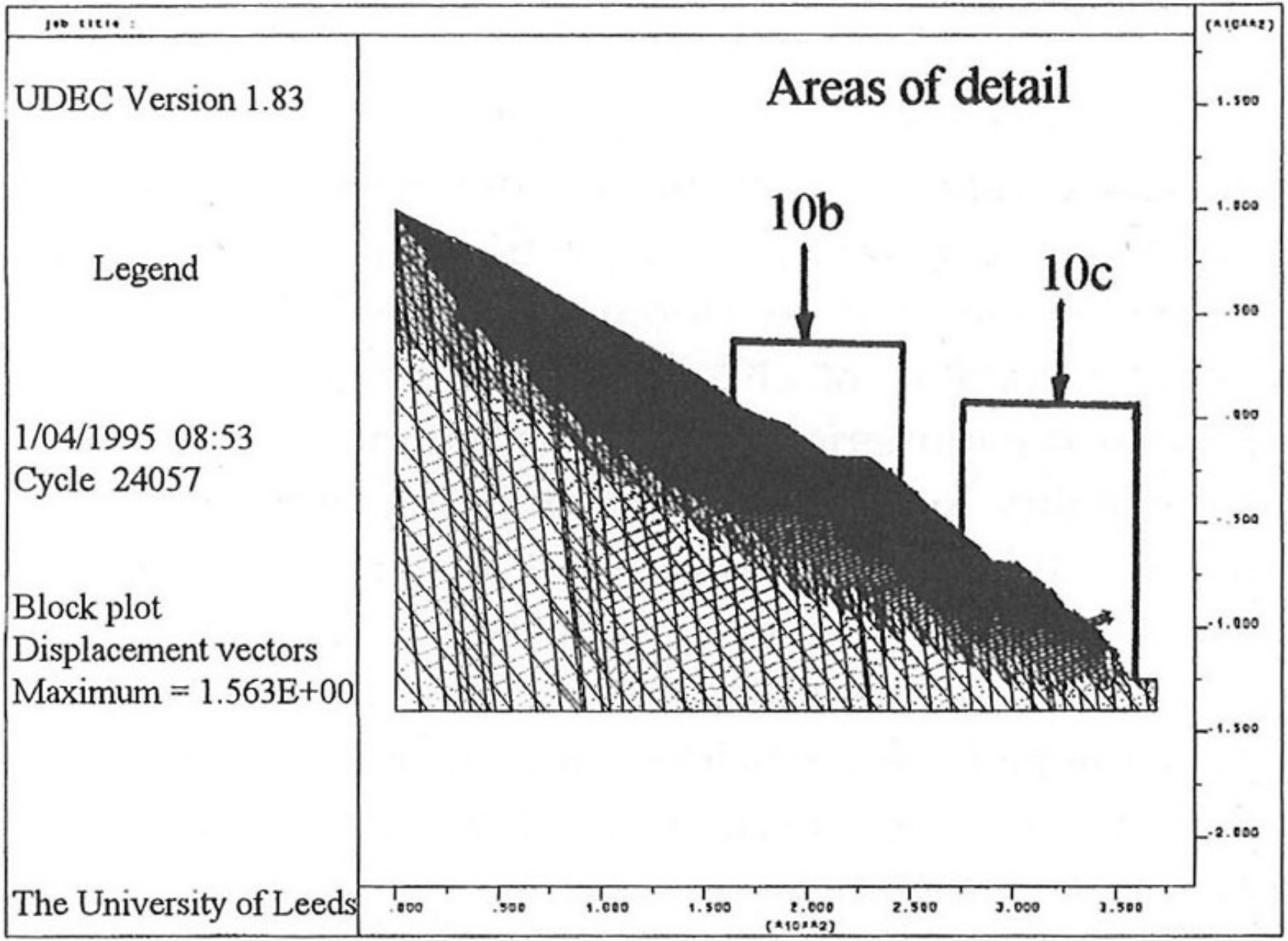
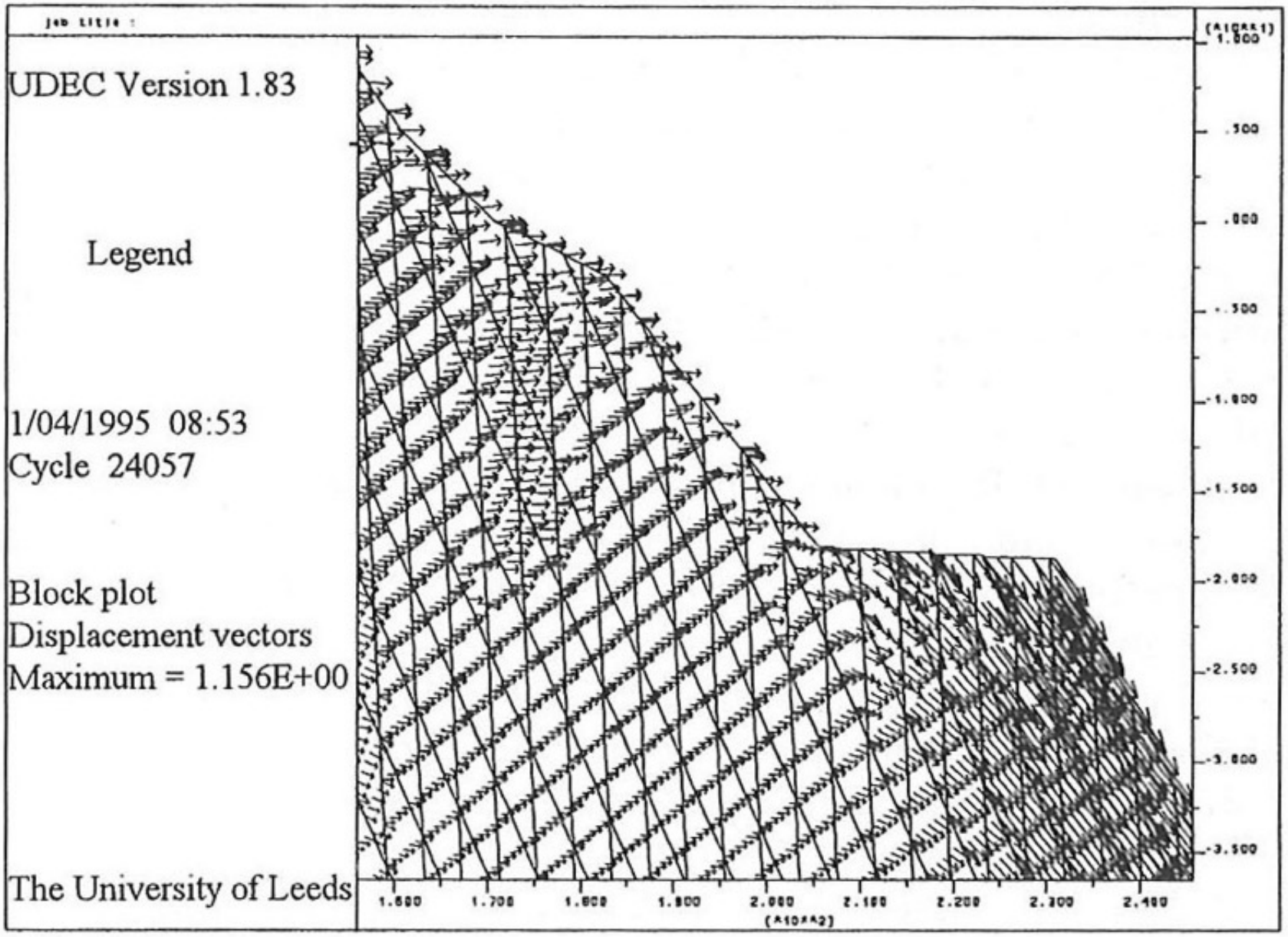


Fig. 8 Acceleration of displacement in footwall slope at Aznalcóllar following intense rainfall (indicated by bars) during November, 1988. Maximum daily diplacements given for monitoring points on three separate profiles (1, 2 and ramp)

Steve Hencher



Steve Hencher



Steve Hencher

A Quarry, Somewhere in England

Steve Hencher

Steve Hencher

Steve Hencher

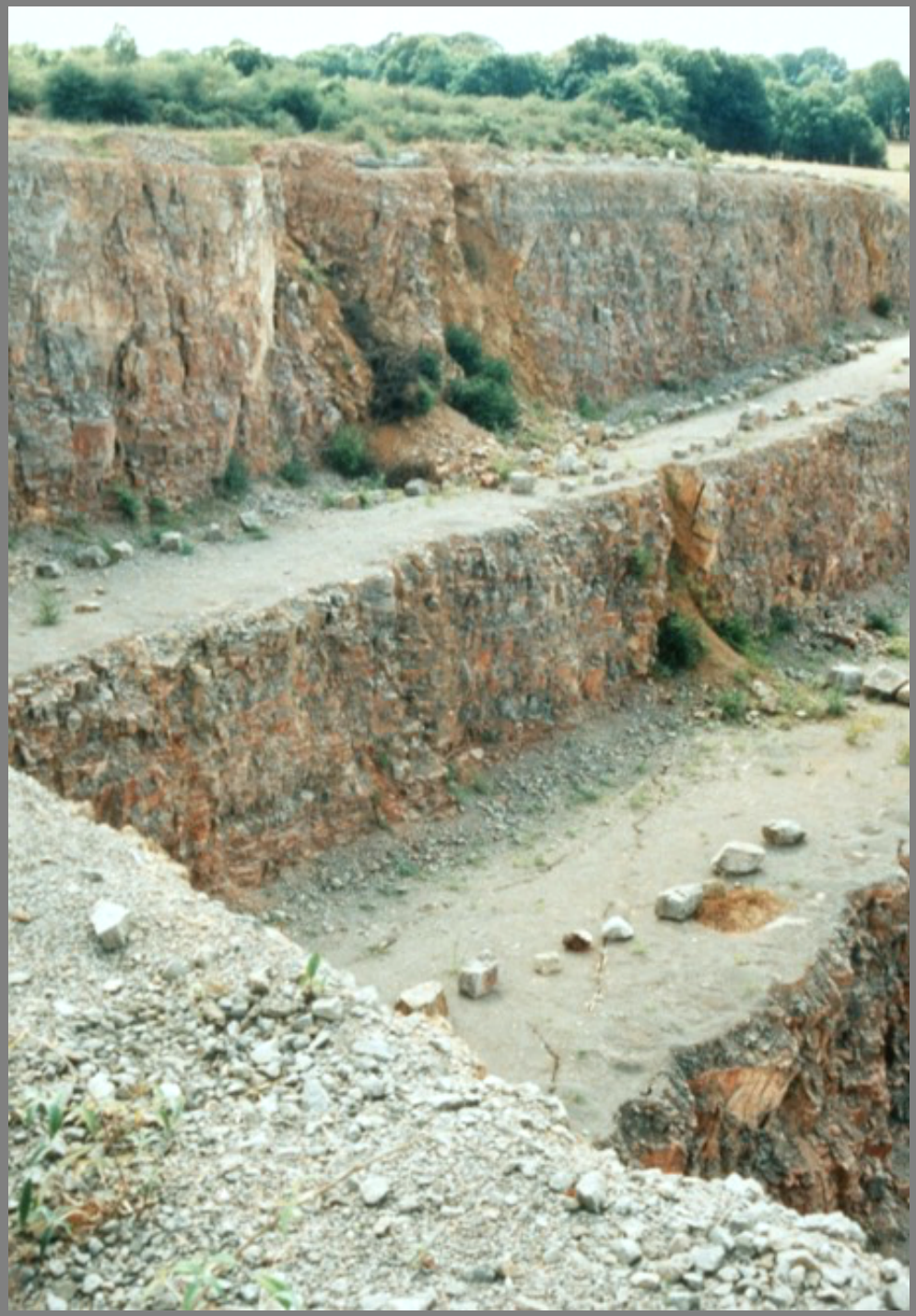
Steve Hencher

Steve Hencher

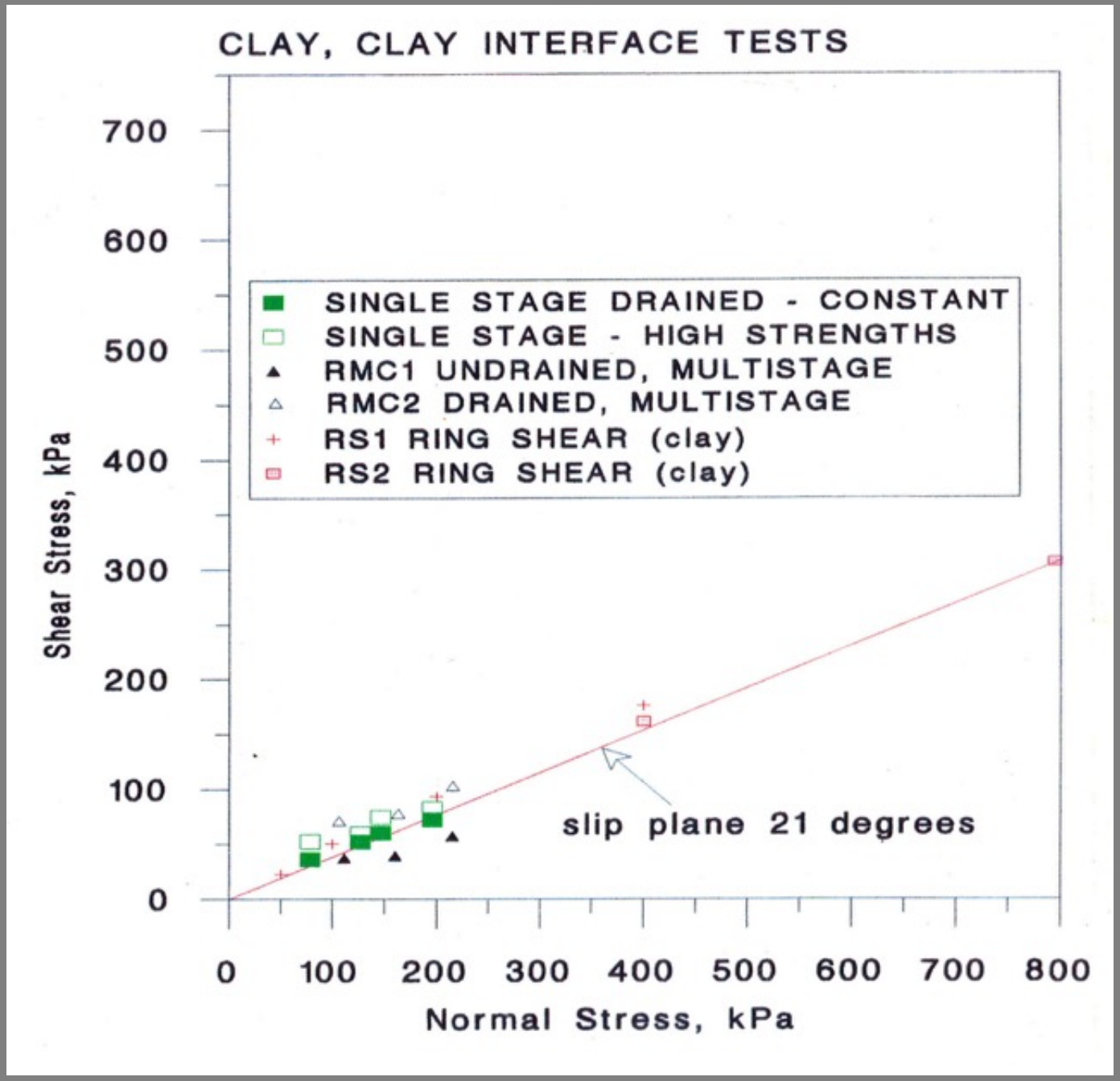
Steve Hencher

Steve Hencher

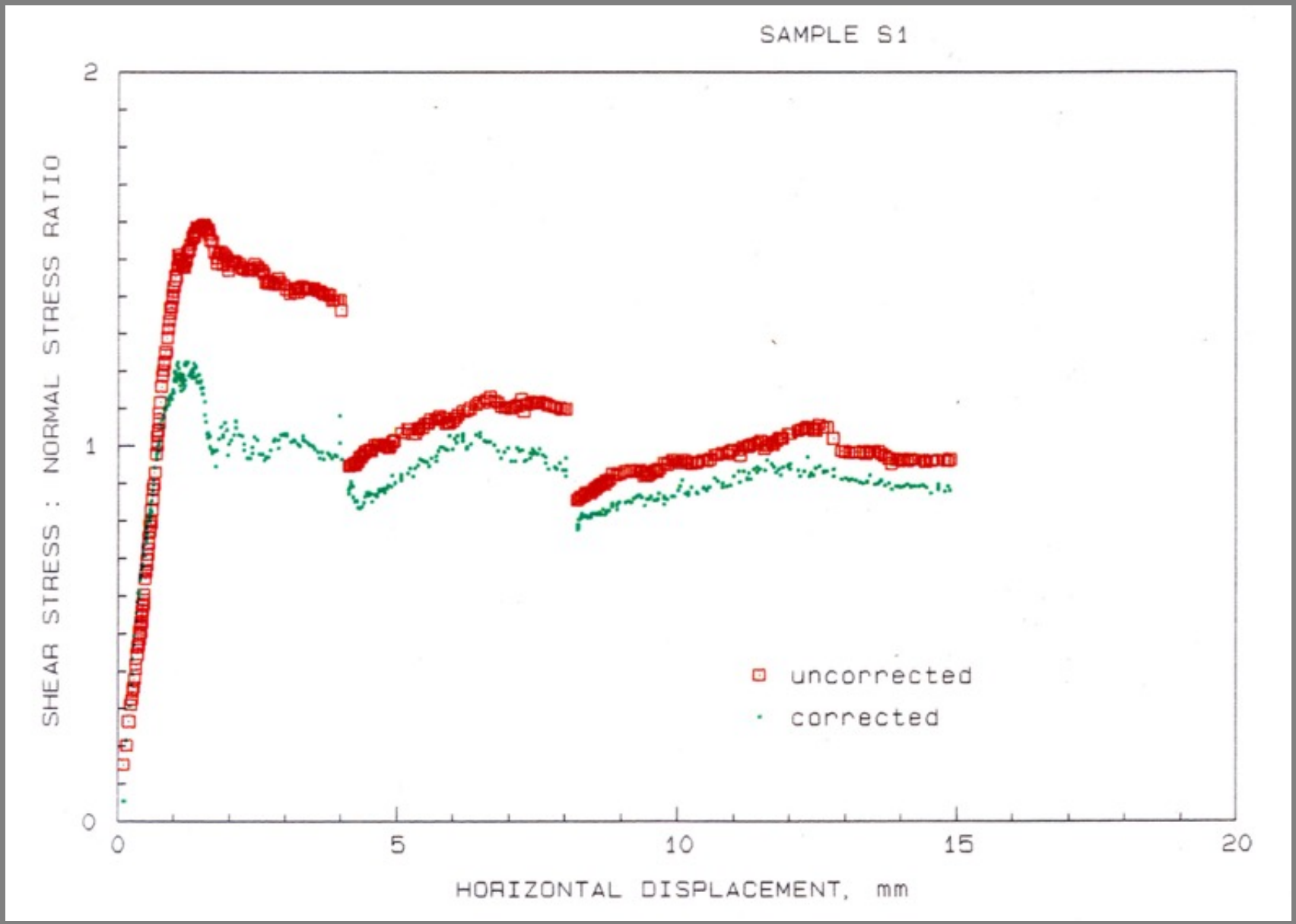
Steve Hencher



Steve Hencher

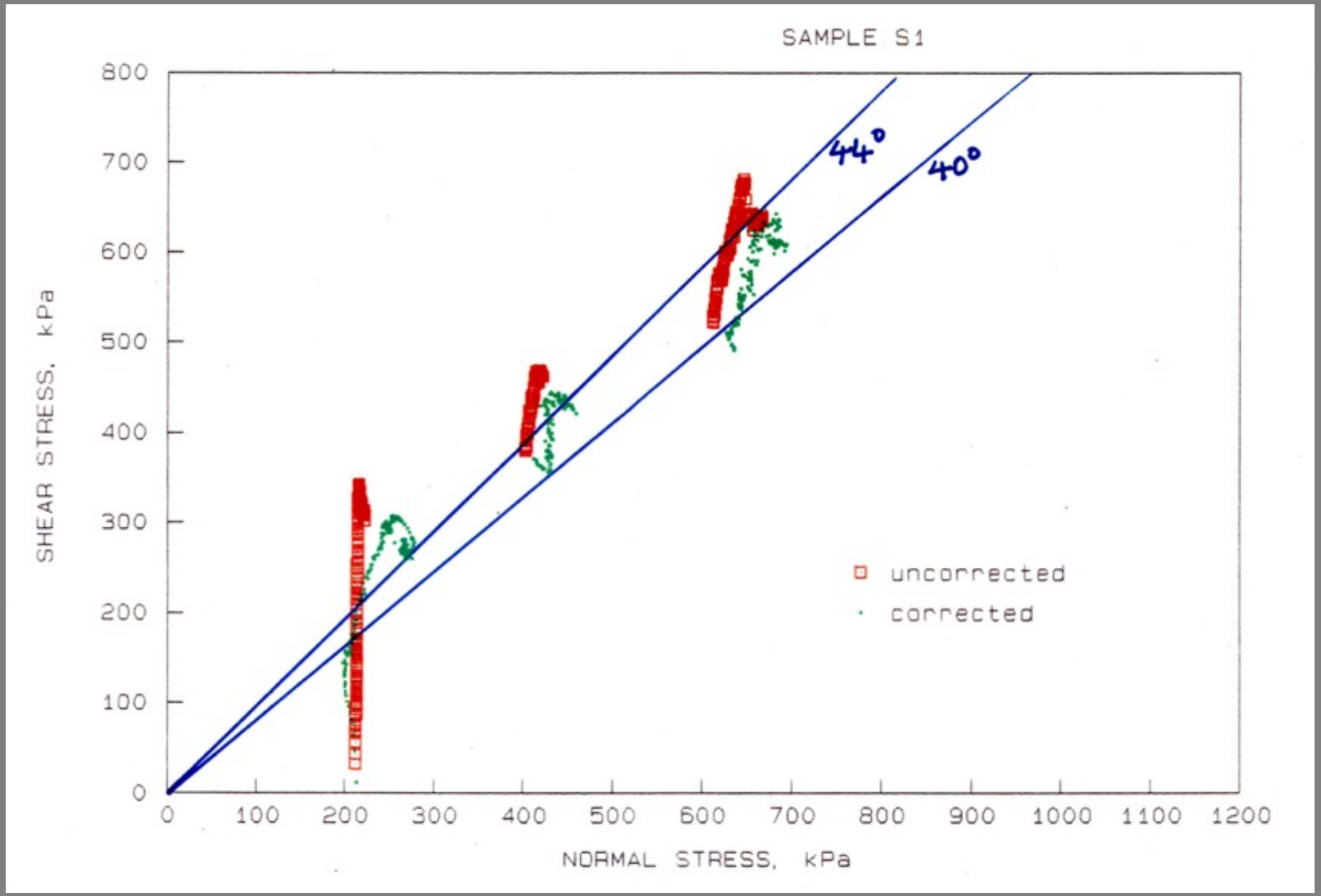


Steve Hencher



Rock contact

Steve Hencher



Steve Hencher

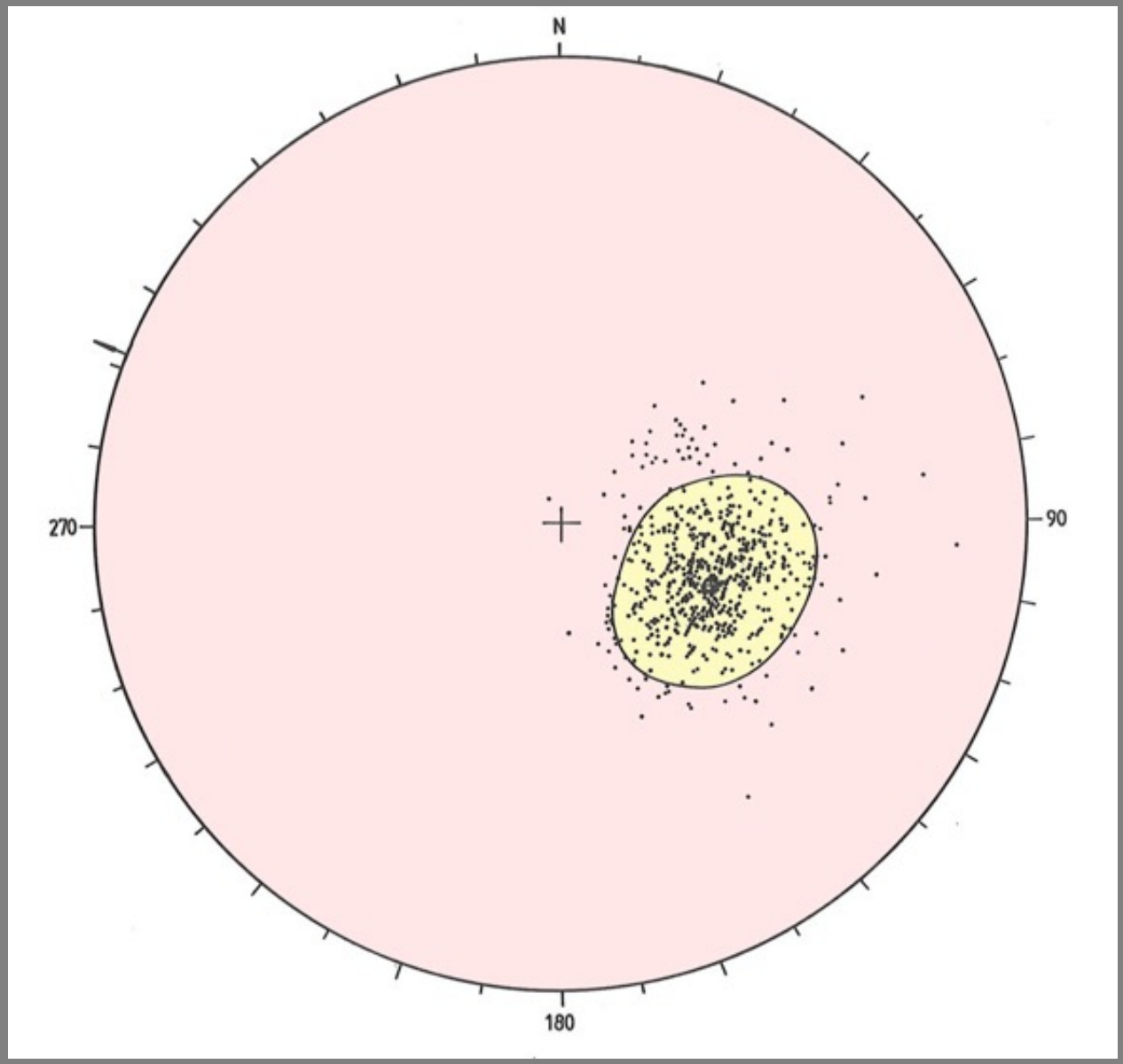
South Bay Close

Steve Hencher

South Bay Close, Repulse Bay, 1982

Steve Hencher

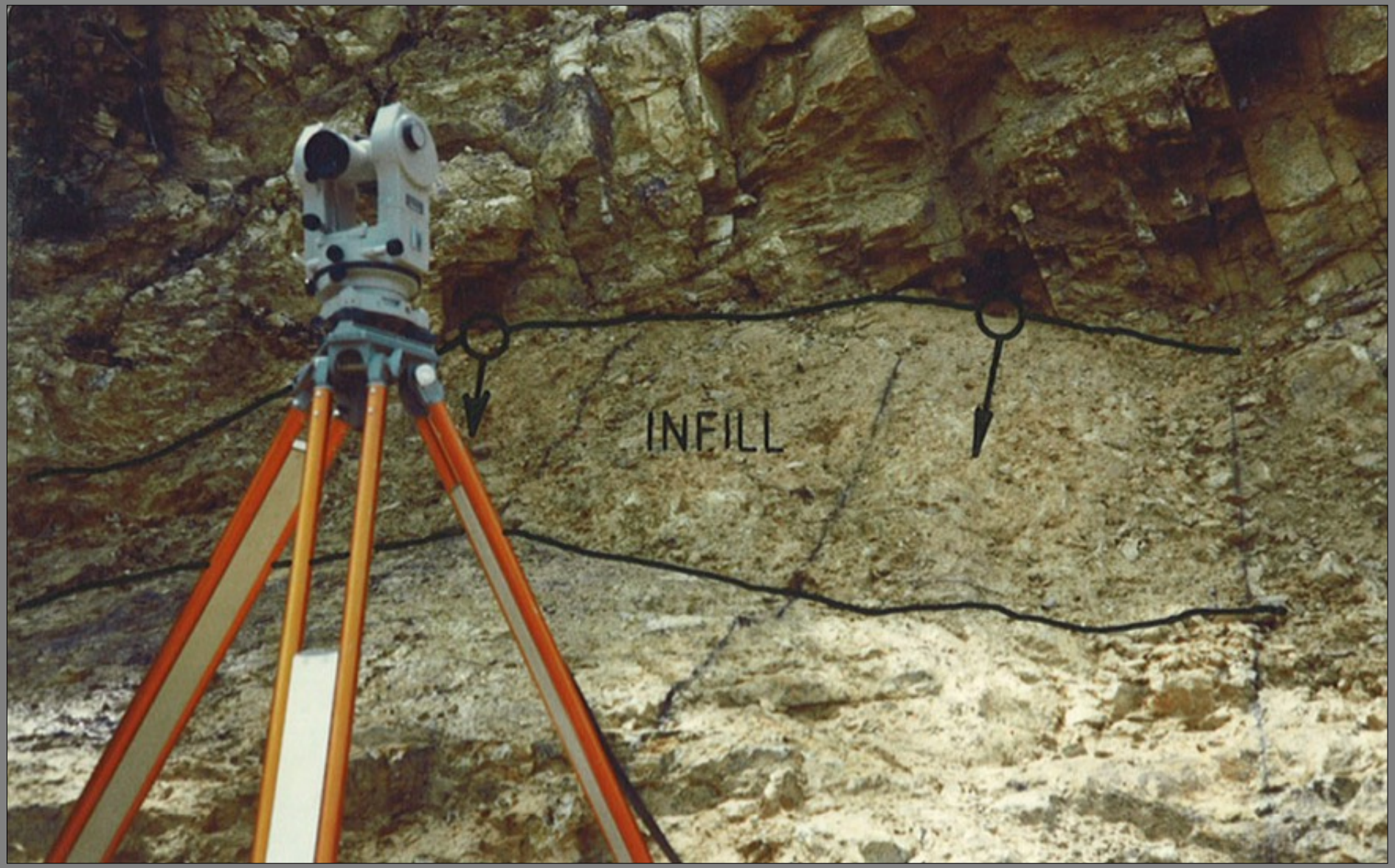
Steve Hencher



Average DIP 29/292
i = 16°
(sketch contour only)

Equal area hand plotted Stereoplot for 420mm plate – South Bay close failure

Steve Hencher



Close-up of failure surface showing infilled zone within highly jointed rock. Note ‘pipes’ from which water flowed for several days following the failure marked by circle & arrow

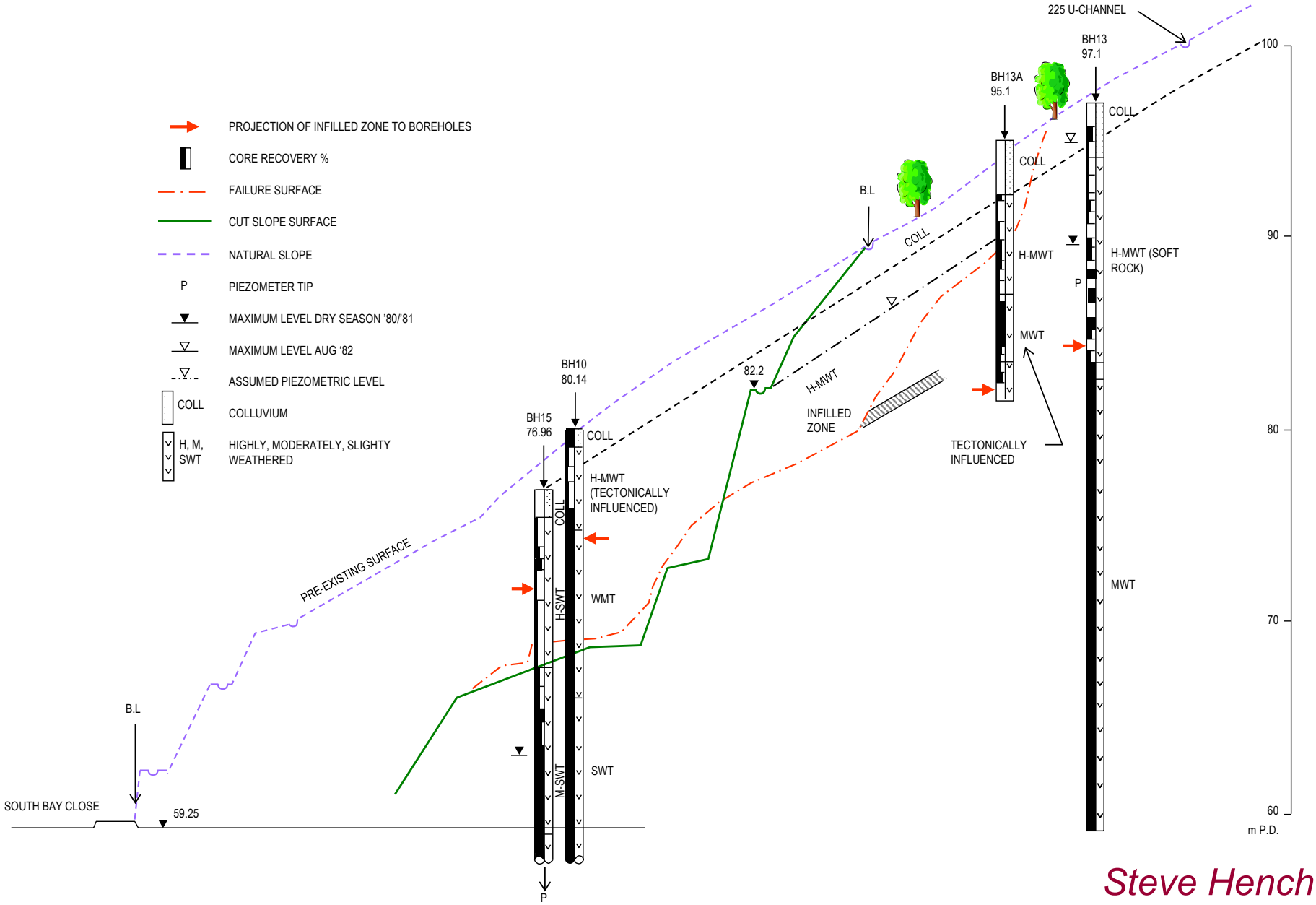
Steve Hencher

Steve Hencher

Local area of volcanic rock fragments in clay matrix (probably fault breccia)

Steve Hencher

South Bay Close, 1982



Steve Hencher

Steve Hencher

Conclusions – Determination of Shear Strength

- Characterise joints – mineralogy, geometry
- Take samples of each joint set and measure non-dilational shear strength for effectively planar natural joints (can often estimate from knowledge of similar joints)
- Measure roughness distribution using base plates (Fecker & Rengers) or some other method
- Determine dilation value by considering the steepest typical wave that can be relied upon not to be sheared through (given the potential rotational freedom of the sliding block – scale effect)
- Add that to the basic friction angle
- True cohesion will exist if there are rock bridges. If joints look to be persistent, ignore cohesion
- Consider using a design approach assuming no dilation, using low F of S
- Remember that effective stress rules!

Steve Hencher