Coupling geodynamics and surface processes

Phaedra Upton[1]
Peter O Koons[2], Sam Roy[2], Nick Richmond[2]

[1]GNS Science, Lower Hutt, New Zealand; [2]University of Maine, Orono, ME

Coupling geodynamics and surface processes

- **Largely focusing on collisional settings**
  - High erosion, uplift rates
  - Mostly supply limited
  - Rock available to surface
- **Modelling processes and materials**
- **Conceptual framework**

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Photo: Danilo Hegg, Southern Alps Photography

Dynamic Landscapes

- **We want to examine the intersection of:**
  - Geodynamics: forces associated with deep Earth processes
  - Geomorphology: shaping of the Earth's surface

…in dynamic environments with complex and competing interactions:

Lloyd Homer, GNS

Kali Gandaki River, Nepal. Christoff Andermann

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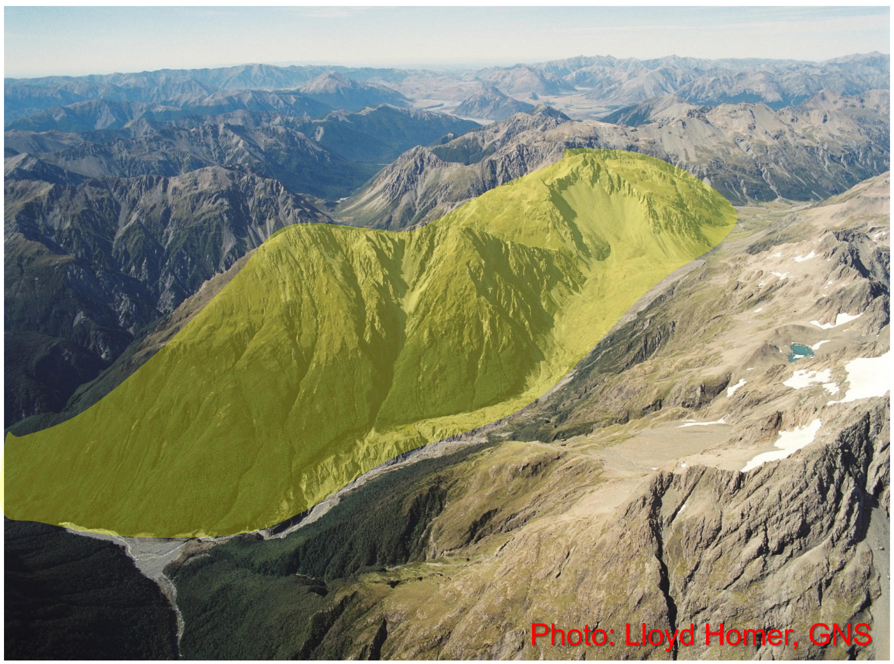

Constructive and destructive forces acting on geological materials with varying strength profiles:

- **Topographic (slope and load)**
- Fluvial (river-generated)
- Glacial
- Tectonic
- Seismic
- …. and more

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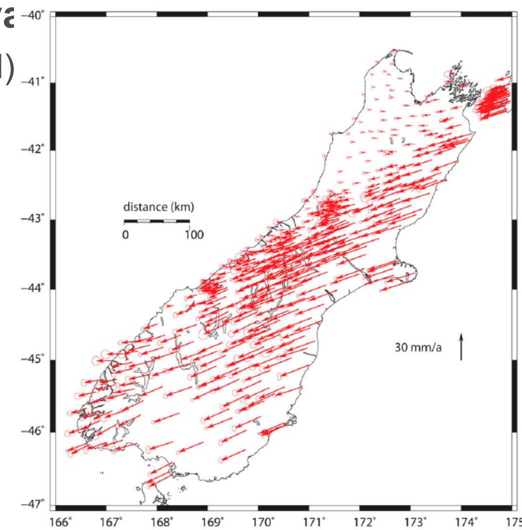

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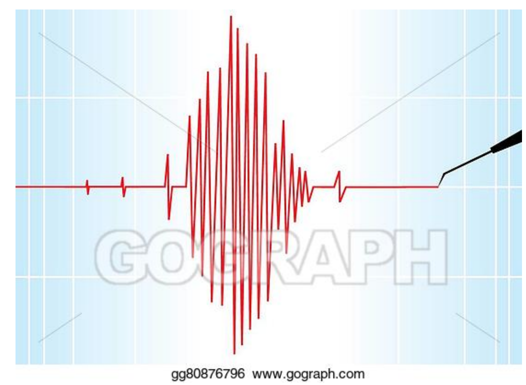
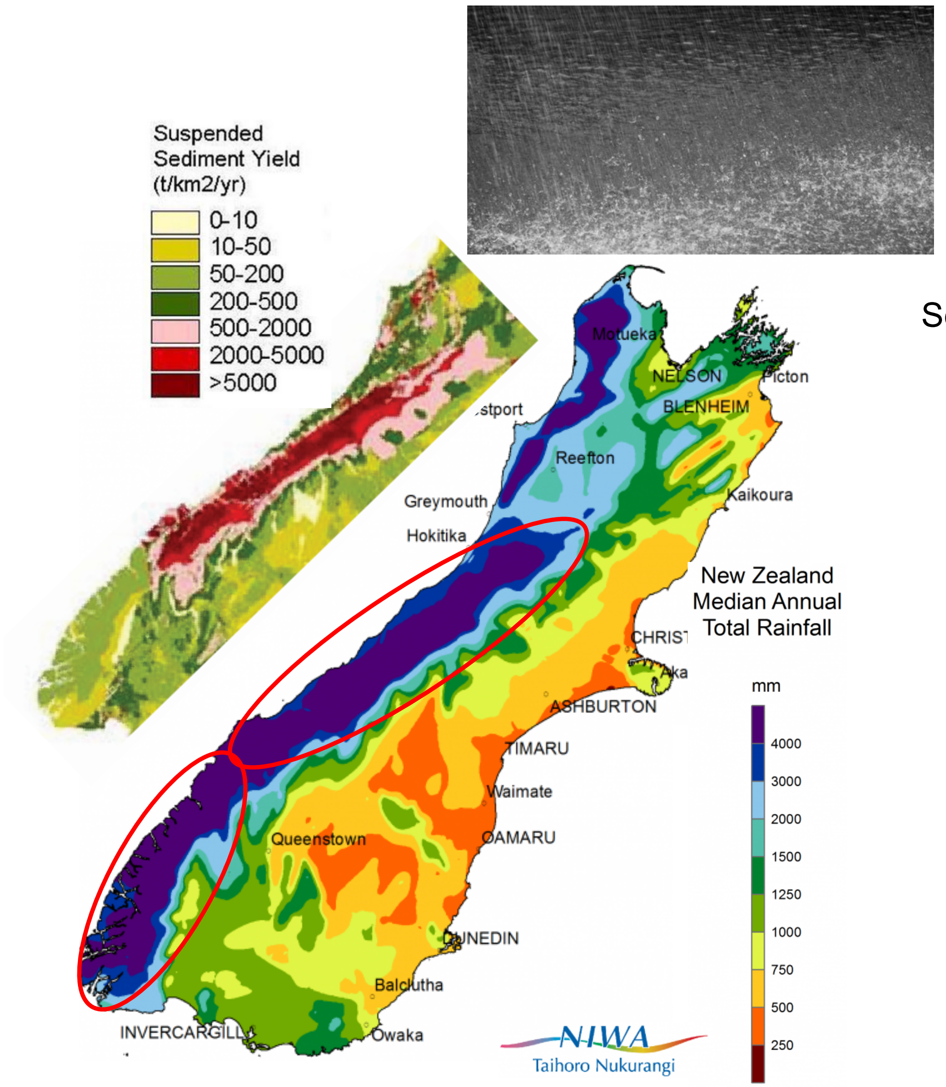




Southern Alps

Moderate - steep slopes

Rain 5-10 m/yr

Schist and greywacke

>2000 t/km^2/yr

Fiordland

Near vertical slopes

Rain ~12 m/yr

Granite

<200 t/km^2/yr

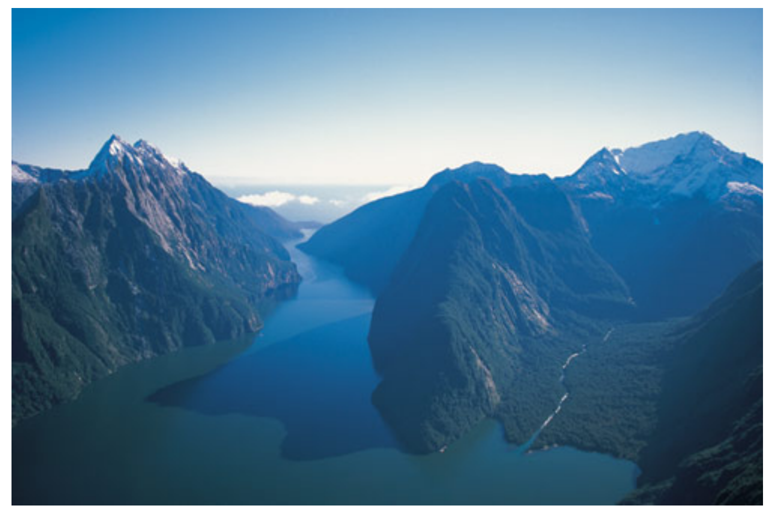
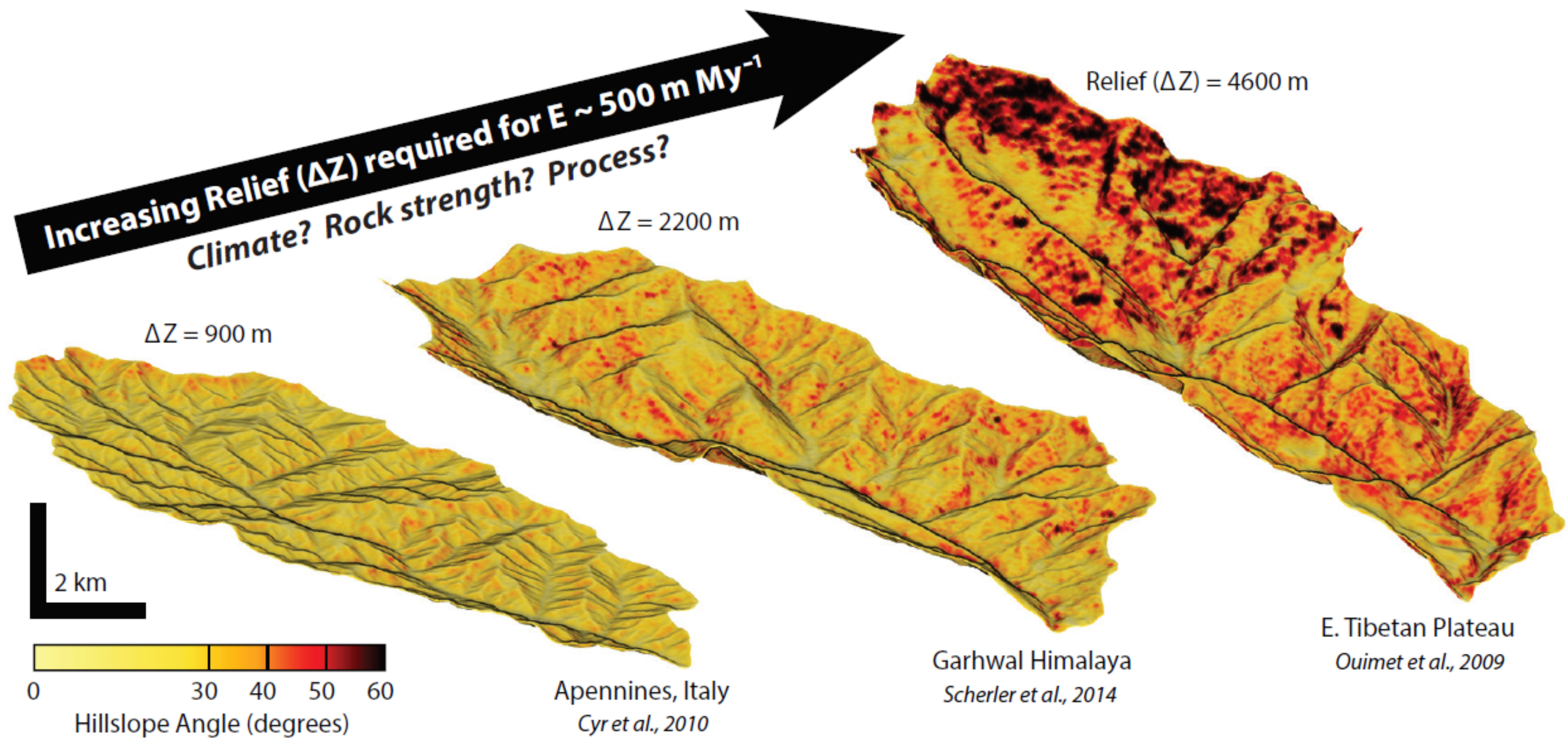
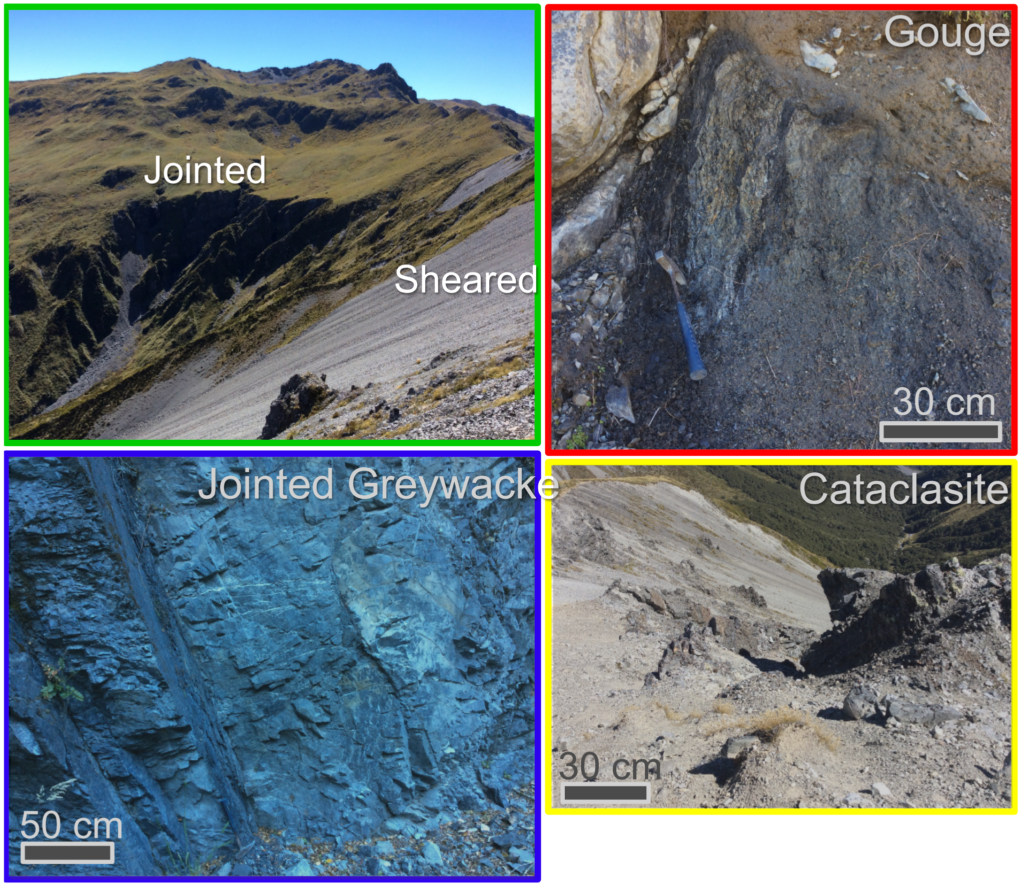
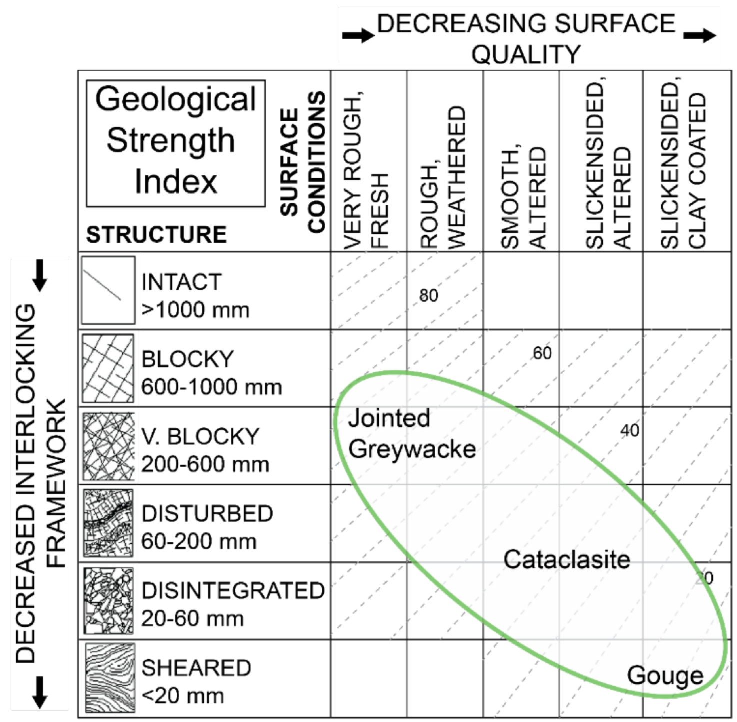


Figure 4.4 Three watersheds exhibit similar erosion rates despite a fivefold variation in topographic relief, likely a result of differences of rock material properties.



Cohesion → erodibility, fracture spacing → grainsize





Hoek & Brown (1980) Criterion

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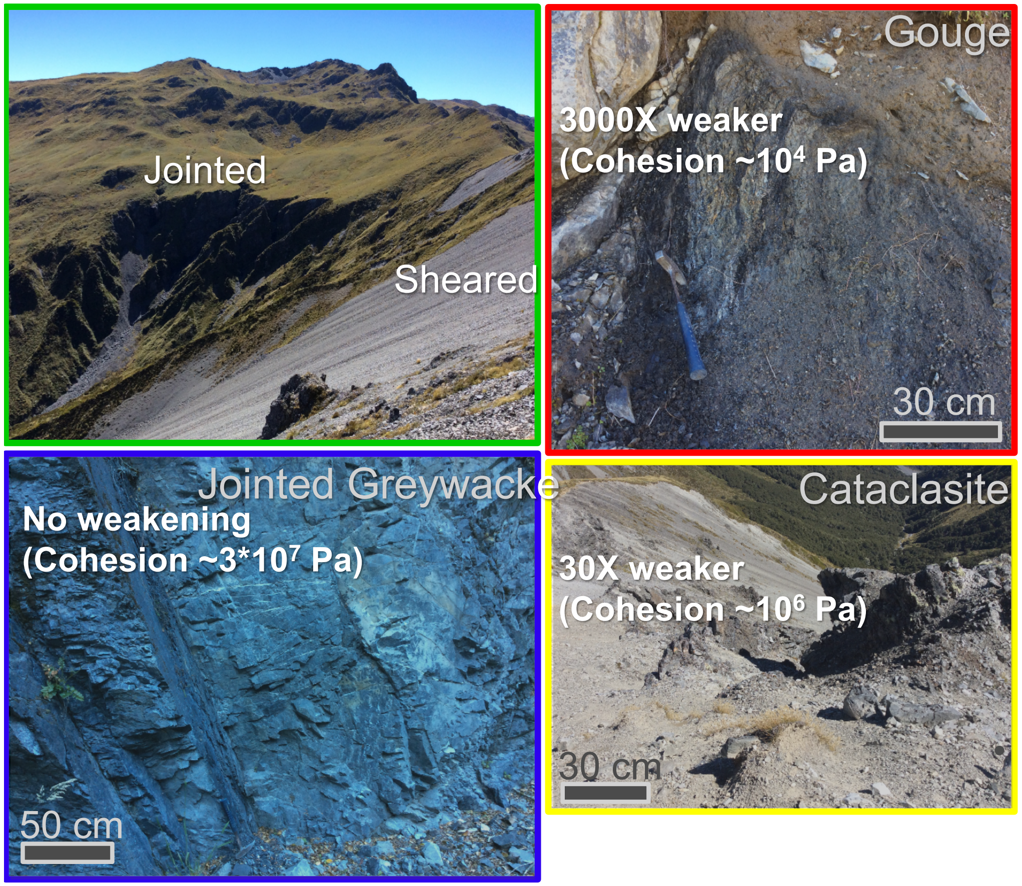

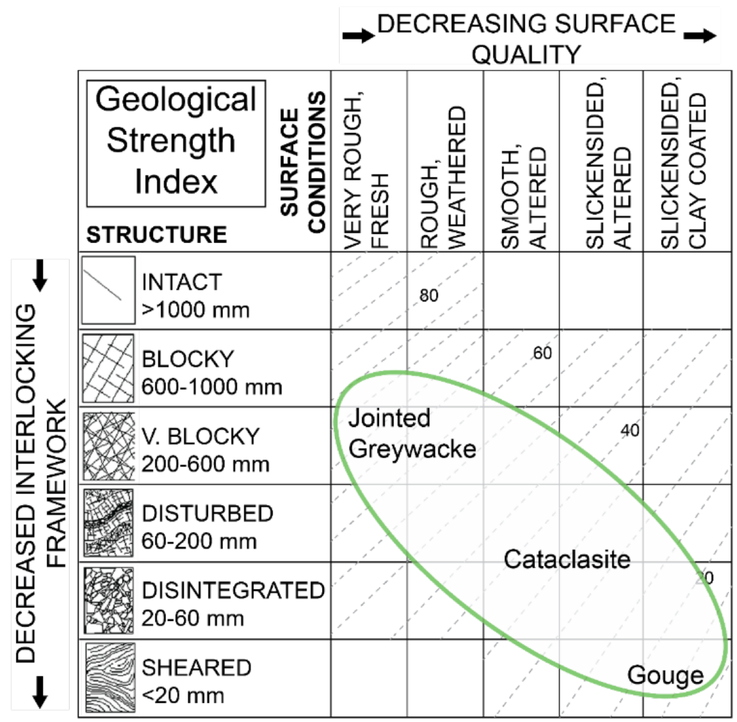

Detachment capacity: f(shear stress, erodibility)

- Erodibility α cohesion^{-1}

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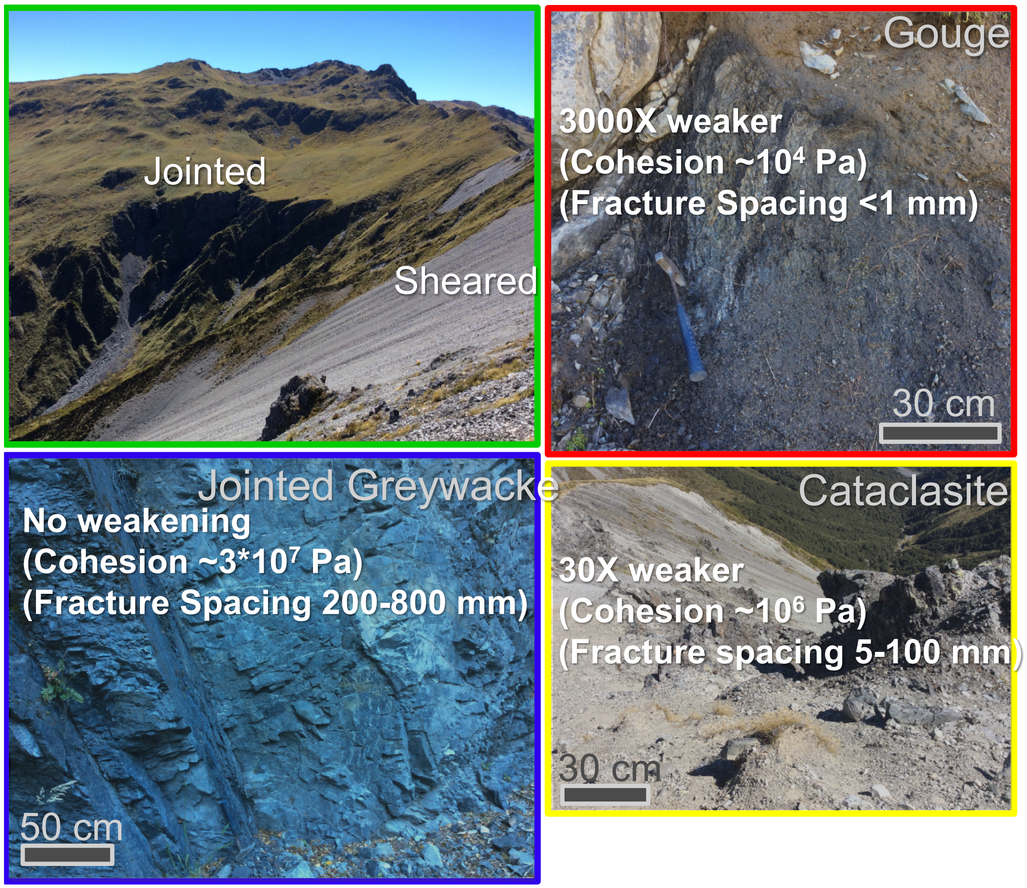
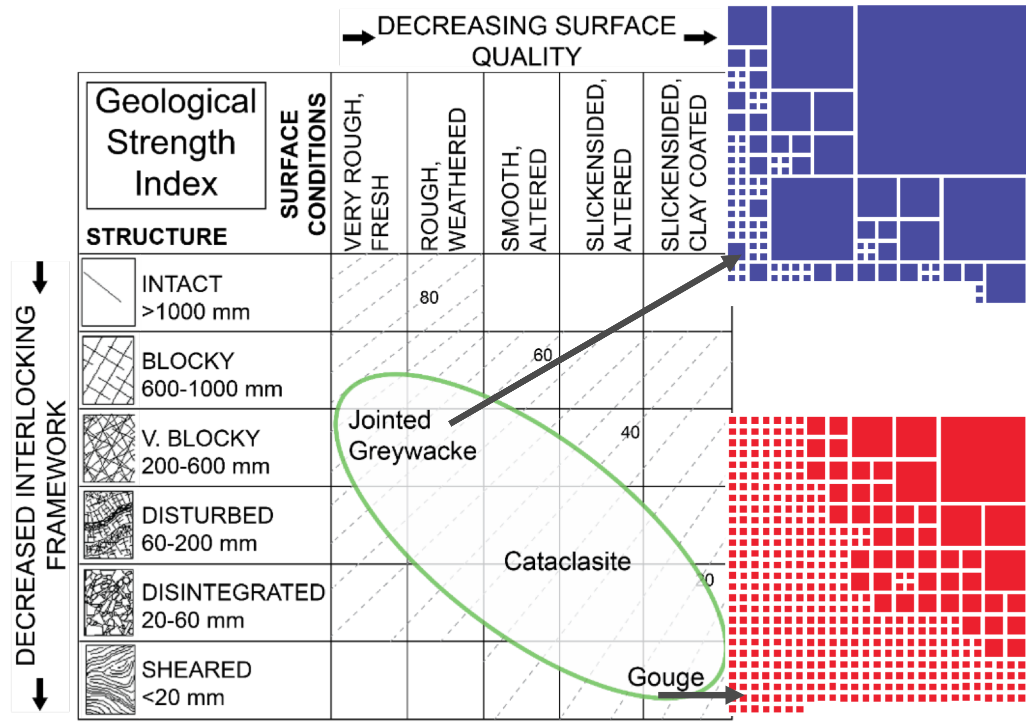
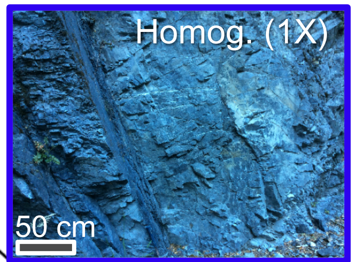
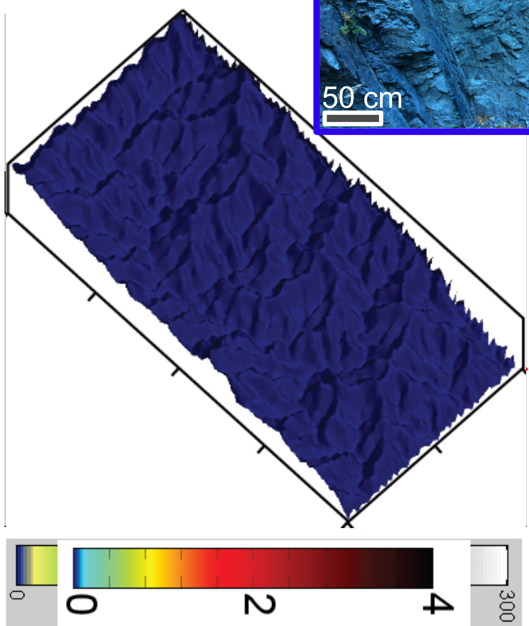




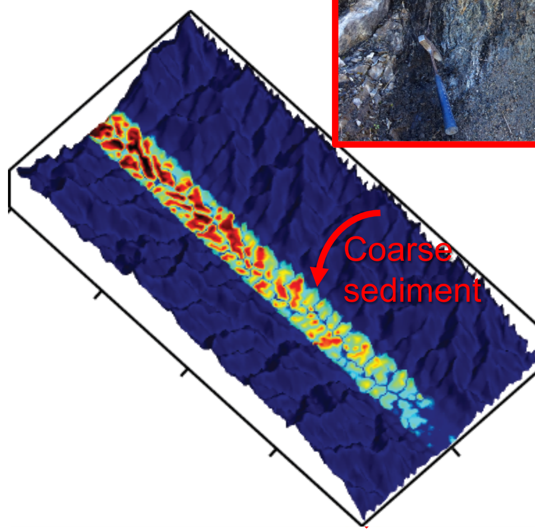
- Detachment capacity: f(shear stress, erodibility)
  - Erodibility α cohesion^{-1}
- Transport capacity: f(shear stress, grain size mix)
  - Grain size α fracture spacing

Erosion with heterogeneous erodibility, grainsize



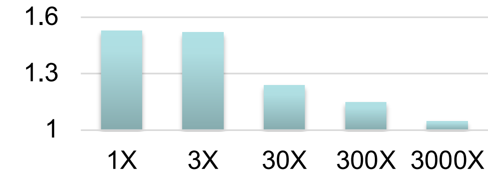


Sediment residence time (ky)

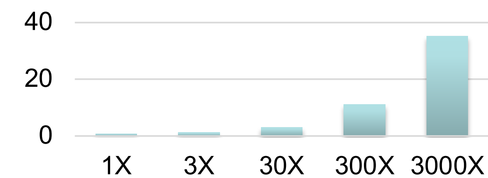


Sediment storage in damage zone

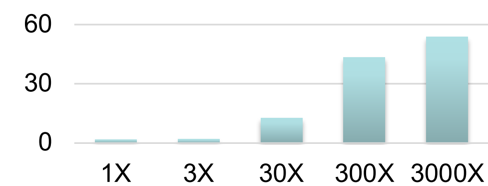
Sinuosity



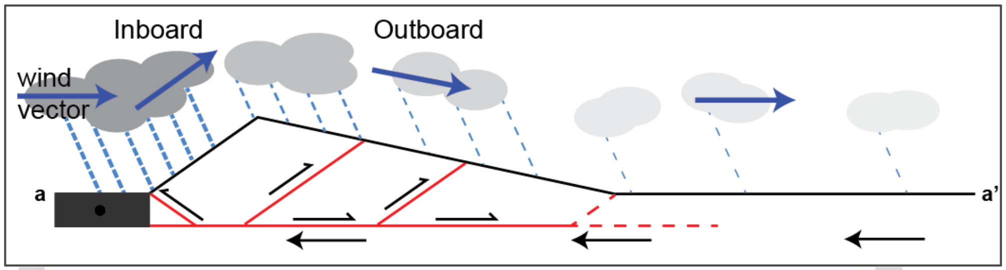
Normalized knickpoint migration rate

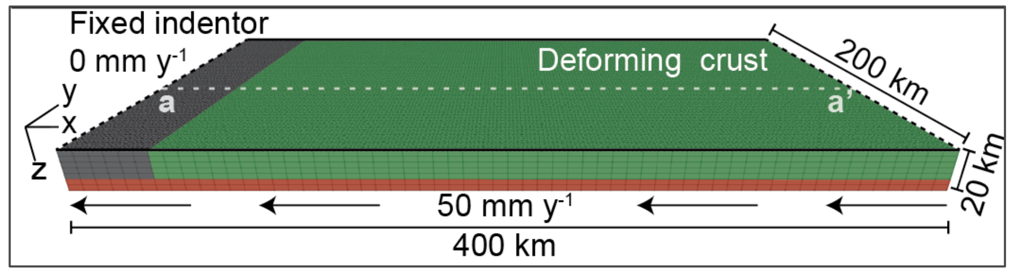


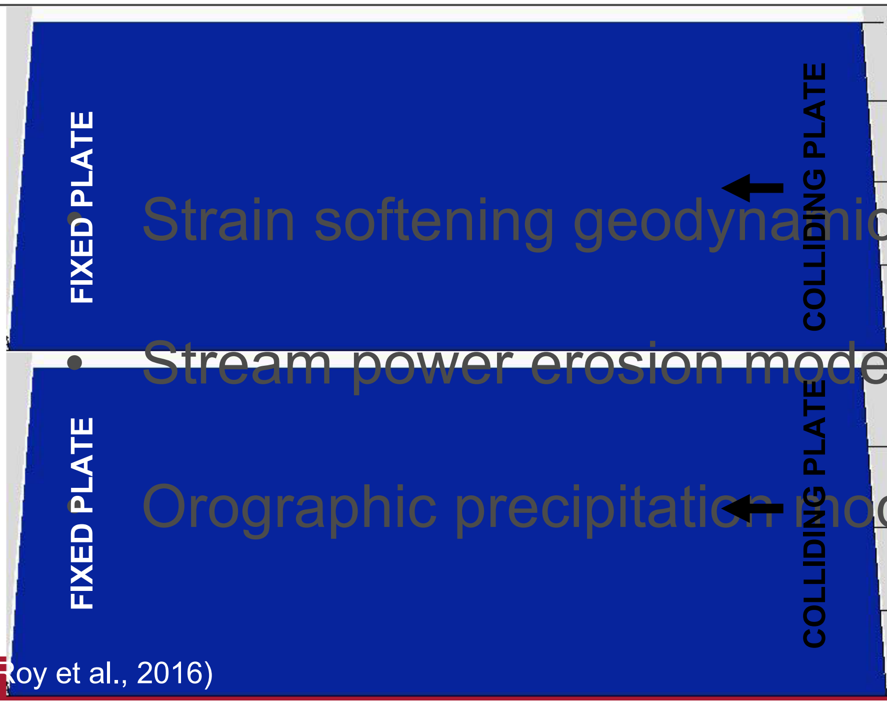
Mean % time bedrock is armored



CHILD ± variable erodibility coupled to Geodynamic model



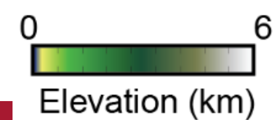




Homogeneous erodibility, no link to weakening zones

- Strain softening geodynamic model of plate collision (Cundall & Board, 1988)
- Stream power erosion model (Tucker et al., 2001)
- Orographic precipitation model (Smith, 1979)

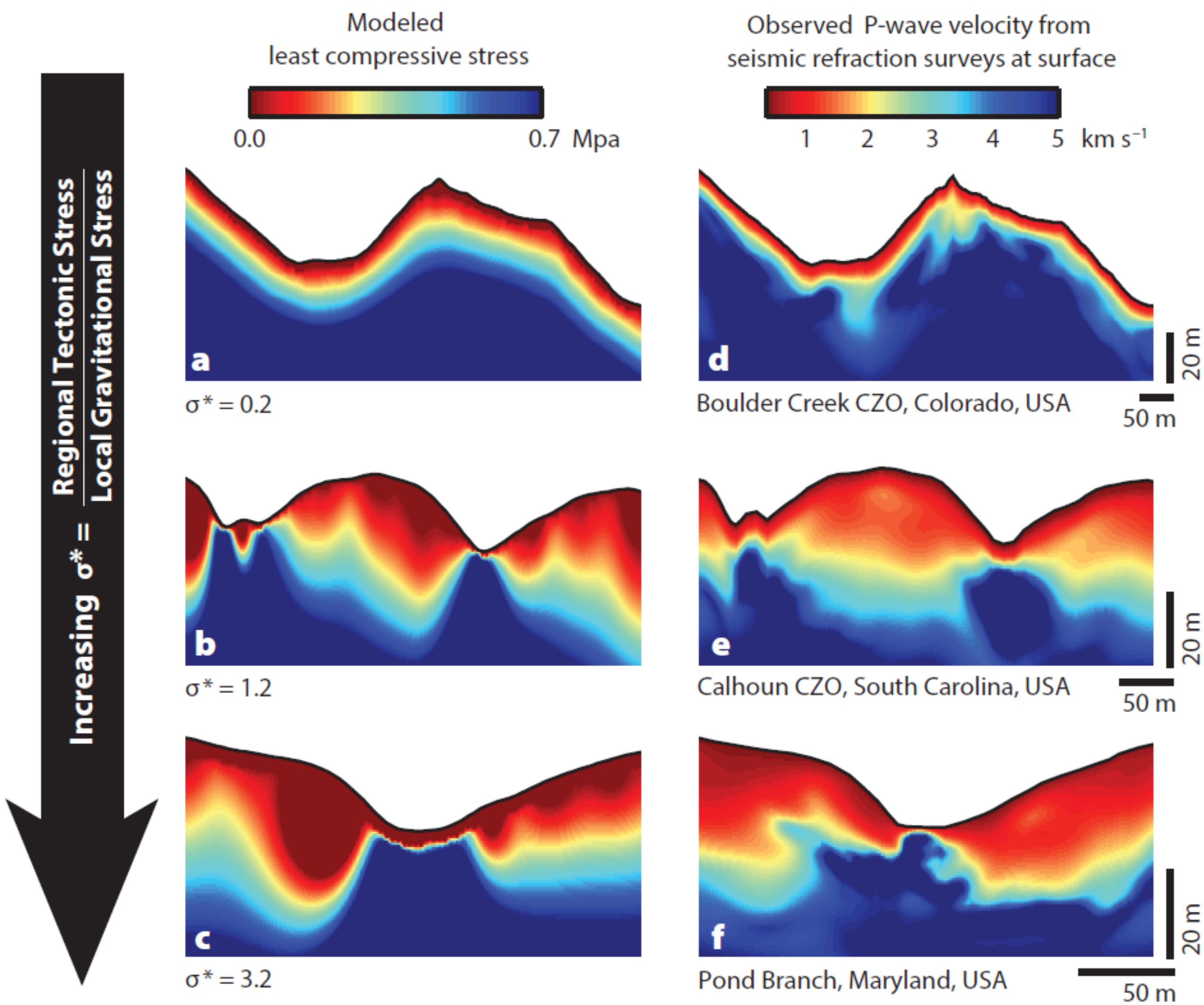
Variable erodibility, link to weakening zones with erodibility a function of the cohesion



(Roy et al., 2016)

Topography and relief

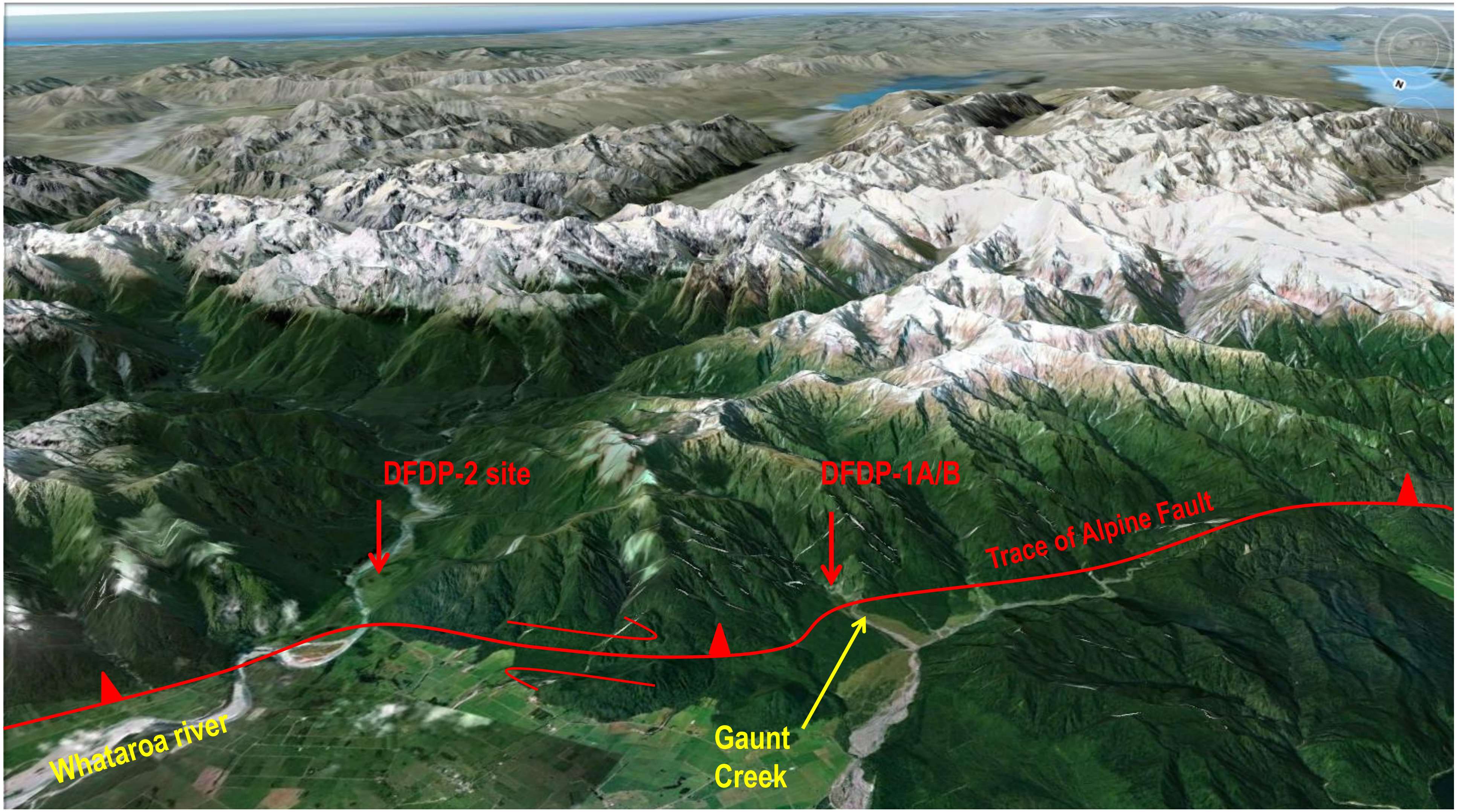
GNS Science

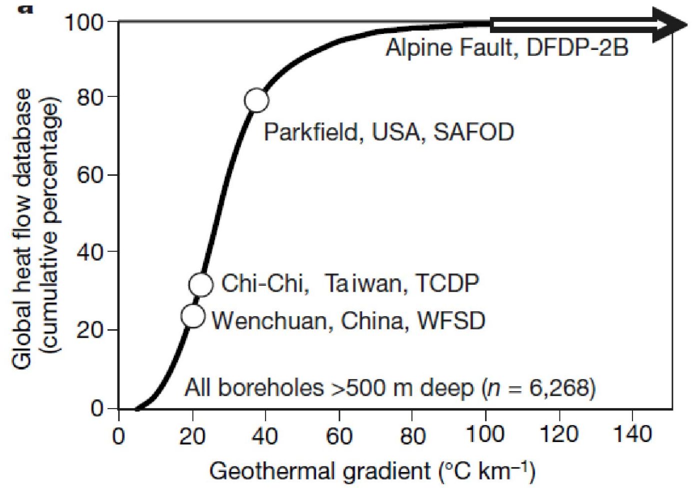


St Clair et al. compare calculated stresses with rock damage measured by seismic reflection survey

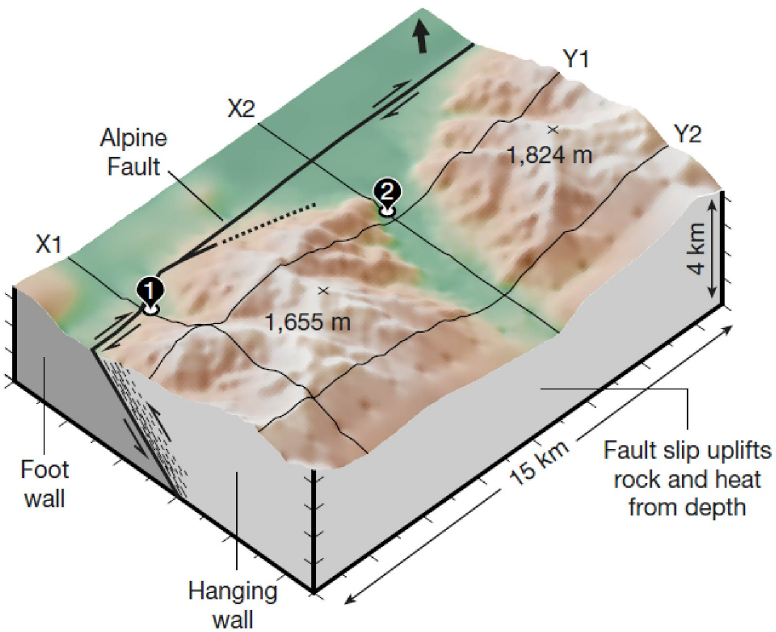
Tectonic stresses interact with the topography to influence

- Bedrock disaggregation
- Groundwater flow
- Chemical weathering
- Depth of critical zone

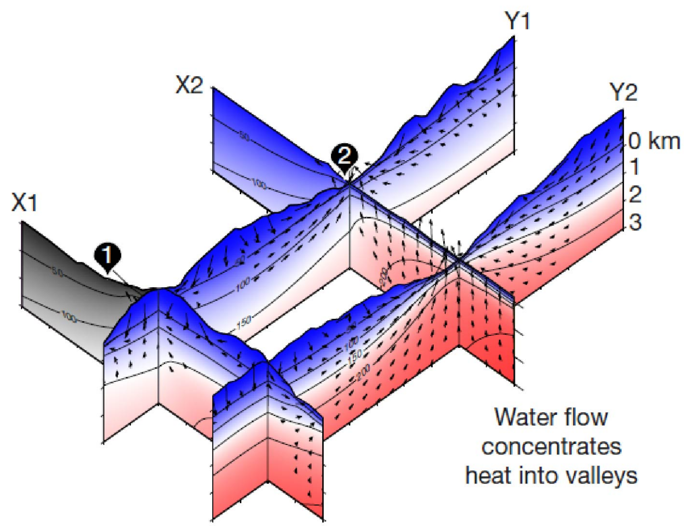

DFDP-2 site
DFDP-1A/B
Trace of Alpine Fault
Whataroa river
Gaunt
Creek



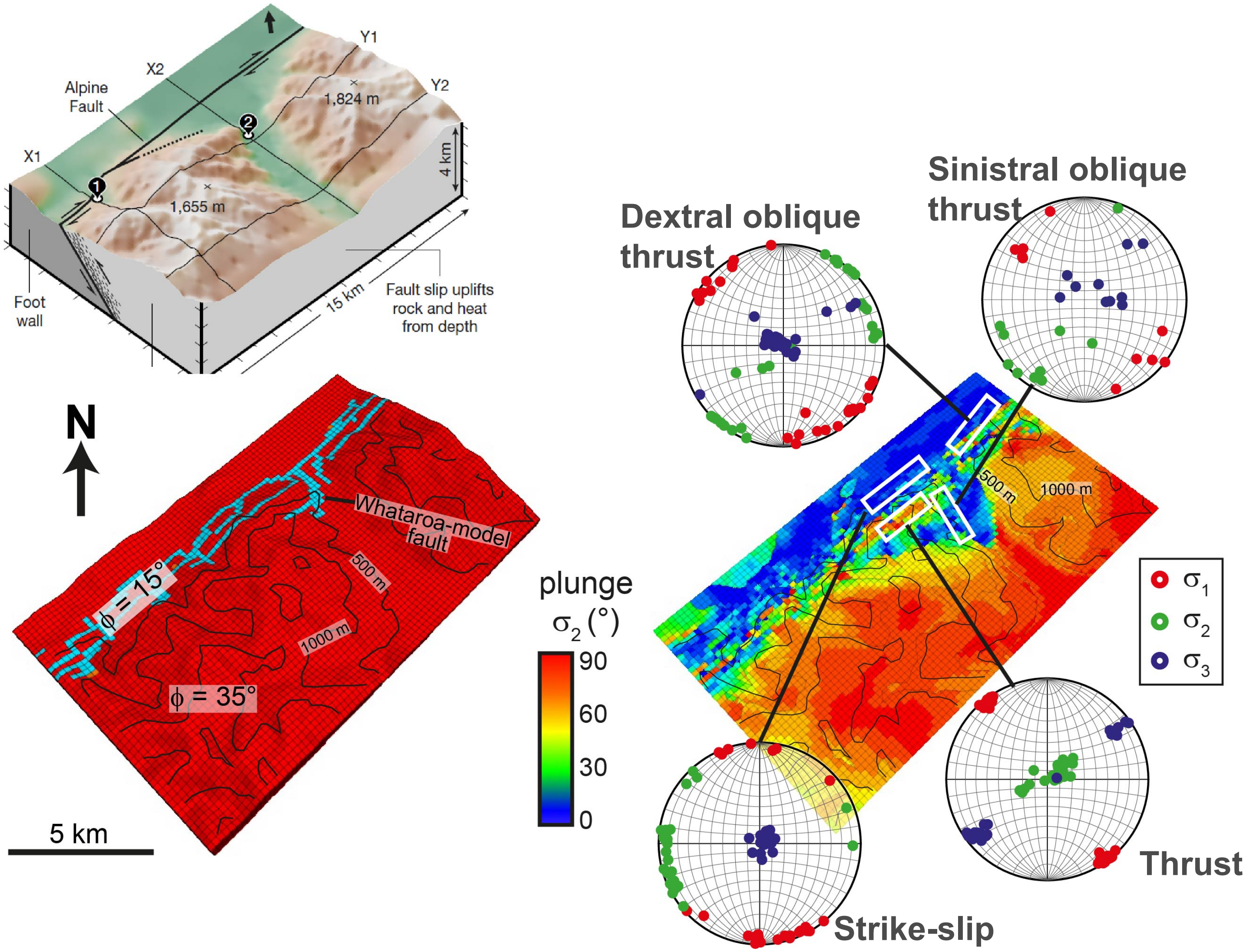
a
100
80
60
40
20
0
Global heat flow database (cumulative percentage)
Alpine Fault, DFDP-2B
Parkfield, USA, SAFOD
Chi-Chi, Taiwan, TCDP
Wenchuan, China, WFSD
All boreholes >500 m deep (n = 6,268)
0
20
40
60
80
100
120
140
Geothermal gradient (°C km^{-1})



Y1
X2
Alpine Fault
Y2
1,824 m
2
4 km
X1
1
1,655 m
Foot wall
15 km
Fault slip uplifts rock and heat from depth
Hanging wall



Y1
X2
Y2
0 km
1
2
3
X1
2
1
Water flow concentrates heat into valleys

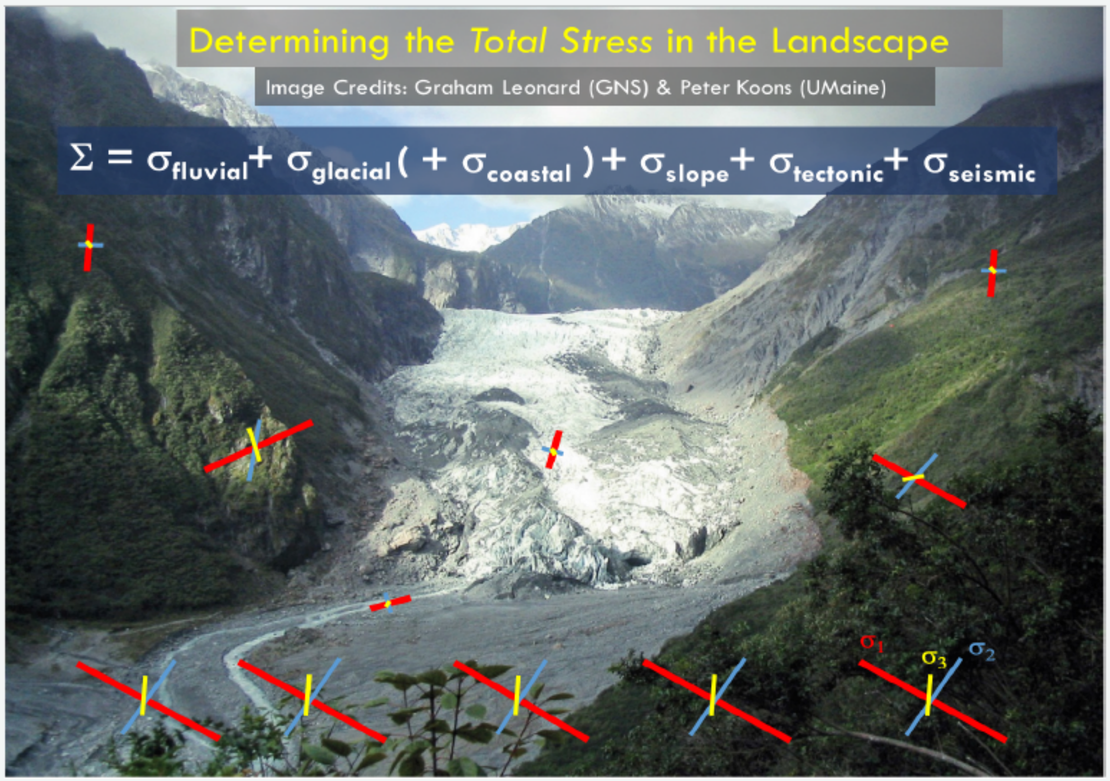


Topography and relief can rotate the stress tensor

- Influences type of faulting – thrust vs strike-slip vs normal
- Influences where deformation takes place
- Deformation weakens the rock, influences where erosion may occur

Failure Earth Response Model (FERM)

FERM uses a Mohr-Coulomb approach to failure of Earth materials wherein failure occurs if the local differential stress (τ) exceeds the local strength (C) of the Earth material.



Will failure occur at a given point in the domain?

Compute Local Material Strength (C)

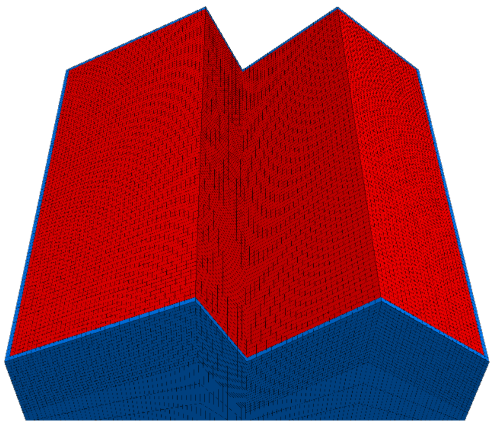
Compute Sum of Differential Stresses (τ)

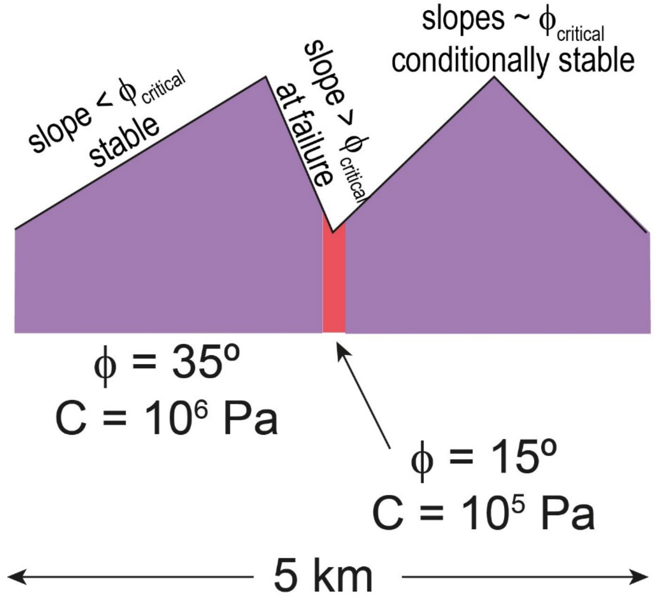
Does τ equal C?

C:τ >1 $\longrightarrow$ No Failure

C:τ $\leq$1 $\longrightarrow$ Failure

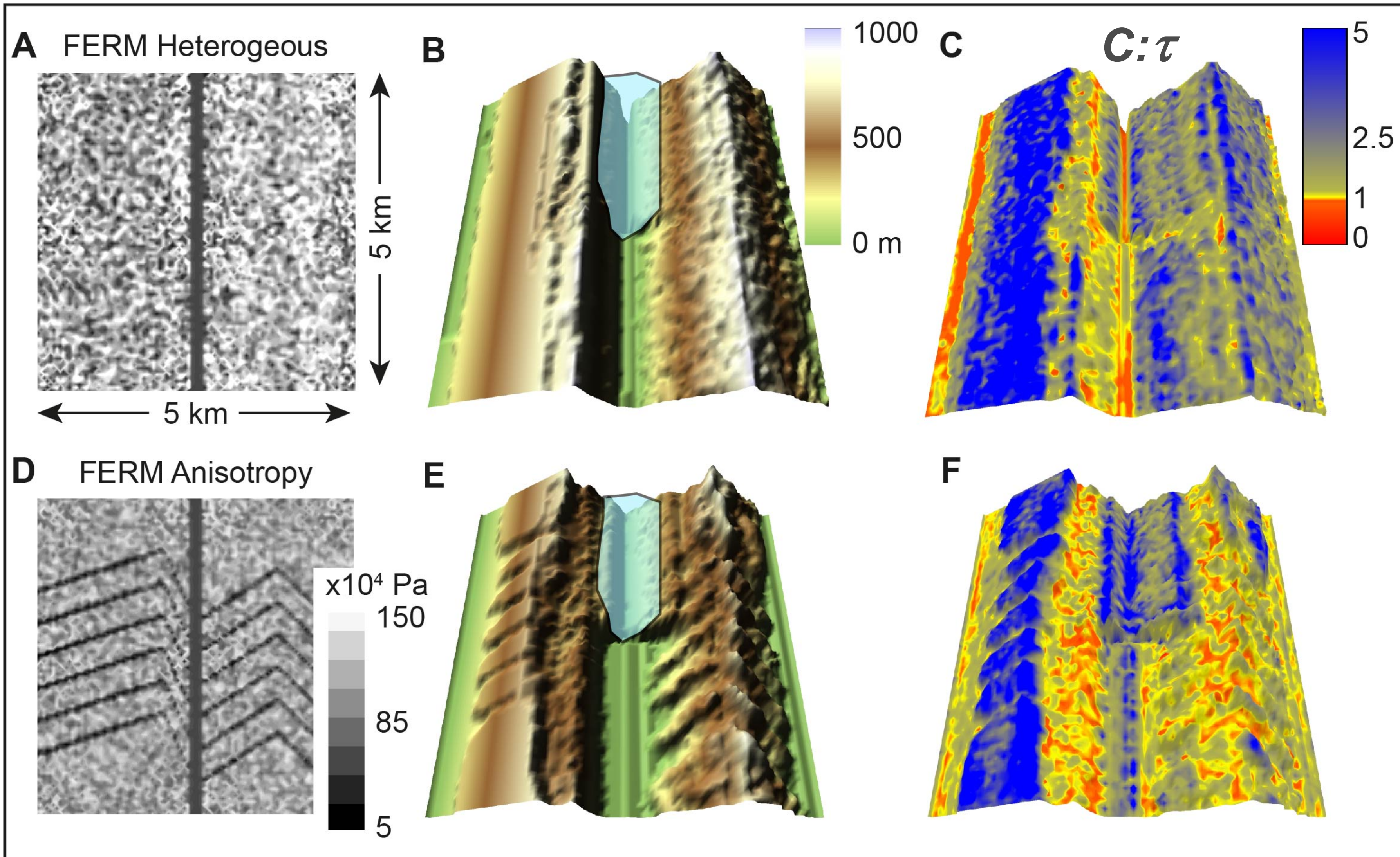
Failure Earth Response Model (FERM)





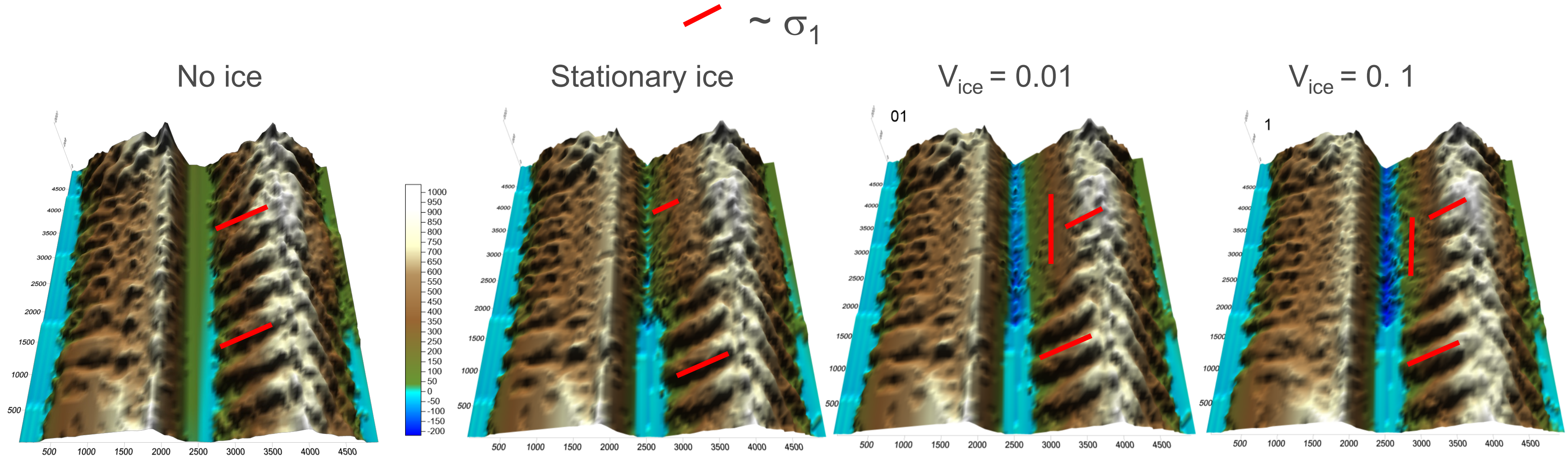
For each point:

1. Sum all stresses: <u>Geomorphic</u> (slope and inertial), <u>Tectonic</u> (Static and potentially Dynamic) into a single Total Stress tensor
2. Describe Earth failure using effective stress formulation (potential to include local fluid pressure)
3. We can distinguish shear and tensile failure states
4. Solve in 3D using FLAC^{3D} in these examples. *(no transport yet)*



A
FERM Heterogeous
5 km
5 km
B
1000
500
0 m
C
C:τ
5
2.5
1
0
D
FERM Anisotropy
x10⁴ Pa
150
85
5
E
F

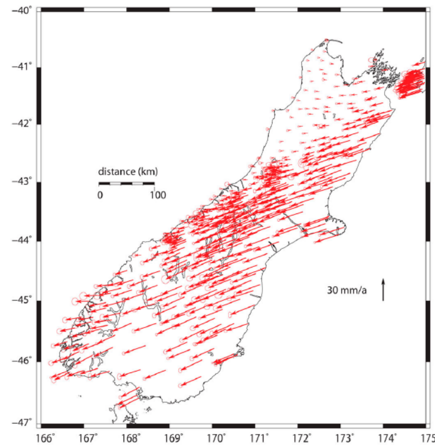
Example: Rock erosion and stress orientation as function of ice velocity

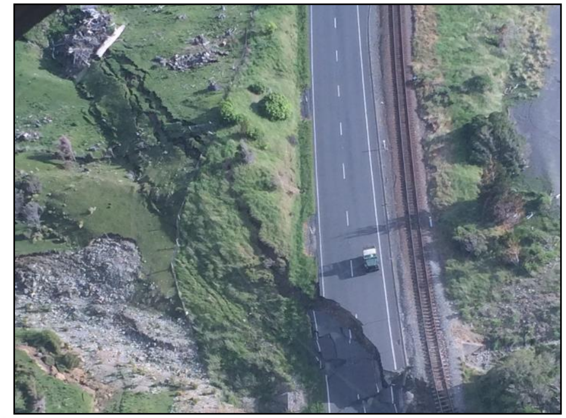


- In absence of ice, σ_1 ~ parallel to slope
- Ice load with no velocity; ***C:τ*** >1 beneath ice; Non-ice erodes more quickly
- Increasing velocity; Weak zones fail and are eroded; Asperities increasingly dominate
- Transition between slope and ice are sites where rapid failure occurs

Challenges/Opportunities

- **Timeframes**
  - Long term tectonics: $10^3 – 10^6$ yr
  - Dynamic (seismicity): sec – min
  - Landscape processes: sec – 10^3 yr
  - Weather/Climate: days – 10^4 yr
- **Imposing realistic surface processes onto FERM**
  - Estimating stresses generated by stream hydrodynamics
  - Including other components such as tools





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Hydraulic Forces with Smoothed Particle Hydrodynamics (SPH)
A tool to derive the fluvial contribution to the total stress state of dynamic landscapes

$$\mathbf{F} = m \sum \frac{d\mathbf{v}_a}{dt}$$

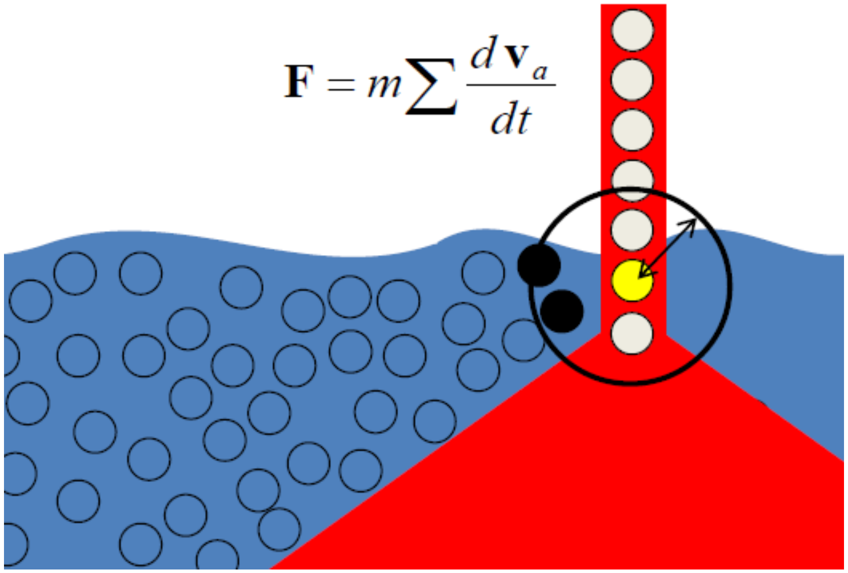
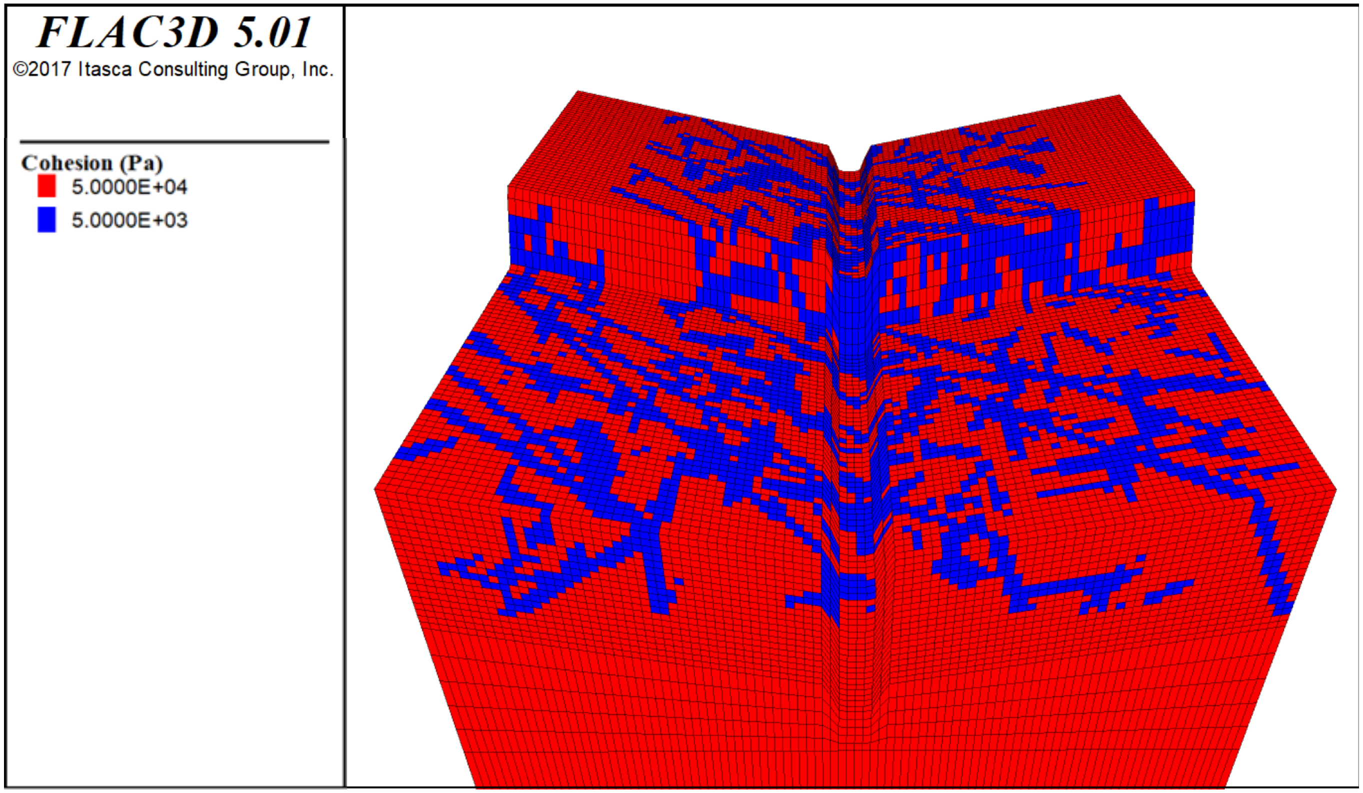
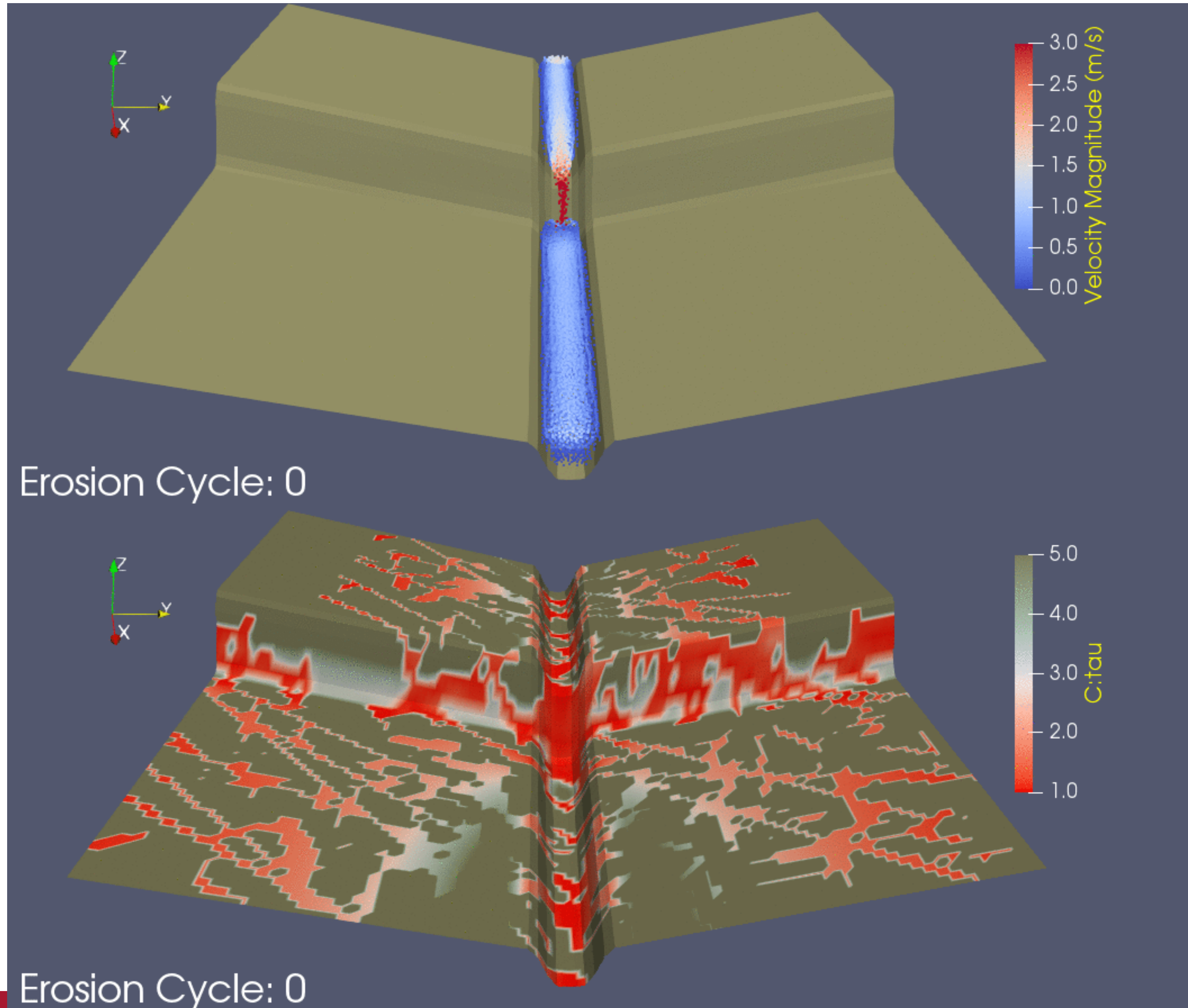


Image Credit: Crespo et al., 2015

FEA Solution

- FERM is presently implemented in FLAC^{3D} (Fast Lagrangian Analysis of Continua in 3 Dimensions), a commercial FEA solver traditionally used for geotechnical investigations
- Strength heterogeneities can be defined by fracture networks which interconnect weak zones




Z
Y
X
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Velocity Magnitude (m/s)
Erosion Cycle: 0
Z
Y
X
5.0
4.0
3.0
2.0
1.0
C:tau
Erosion Cycle: 0

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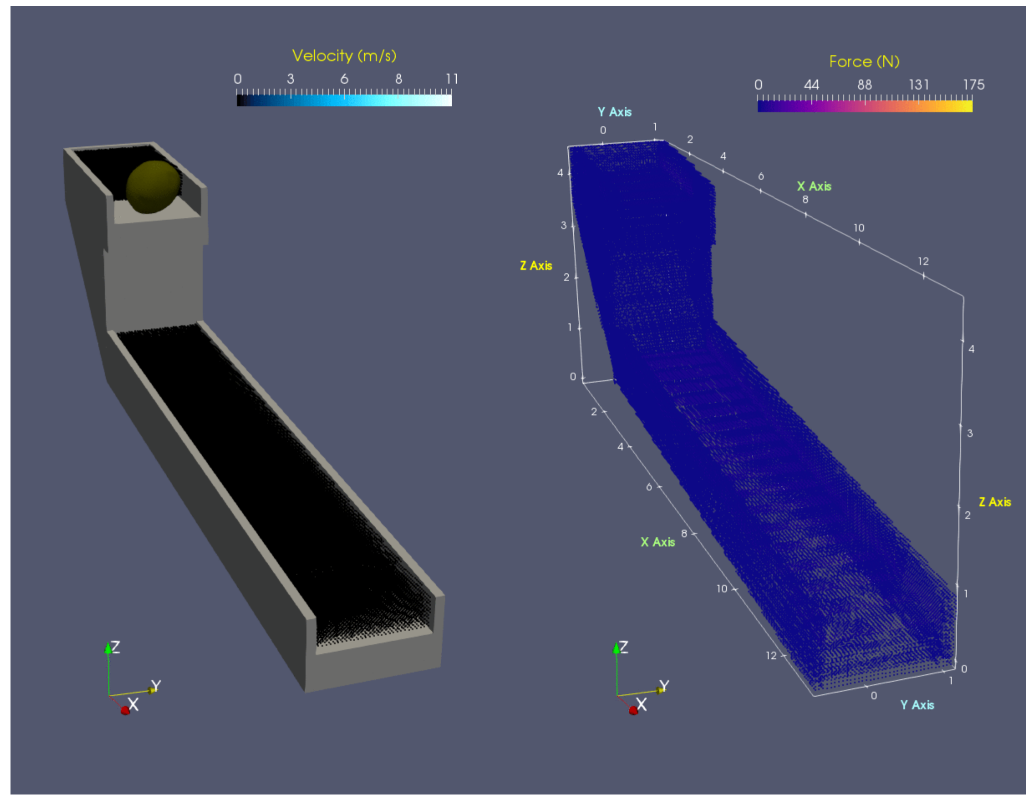

Some implications:

Topography records inherited mechanical anisotropy: valleys, cols are weak, high points are strong

Steep stress gradients at margins (eg ice/slope) lead to greater erosion/incision at these locations

Tectonic stresses and strain are modified by ice
- stablising effect of the ice load
- destablising effect of ice velocity increasing shear stresses

Glacial erosion in the presence of tectonic strain is more efficient that in non-tectonic regions – easier for the stresses to overcome the strength of the rock

Pore pressure fluctuations important and can be incorporated into FERM

Erosion rates are dominated by defect presence and exhumation.

Photo: Danilo Hegg, Southern Alps Photography