Models meet Data, Earth Surface meet Geodynamics

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GNS SCIENCE
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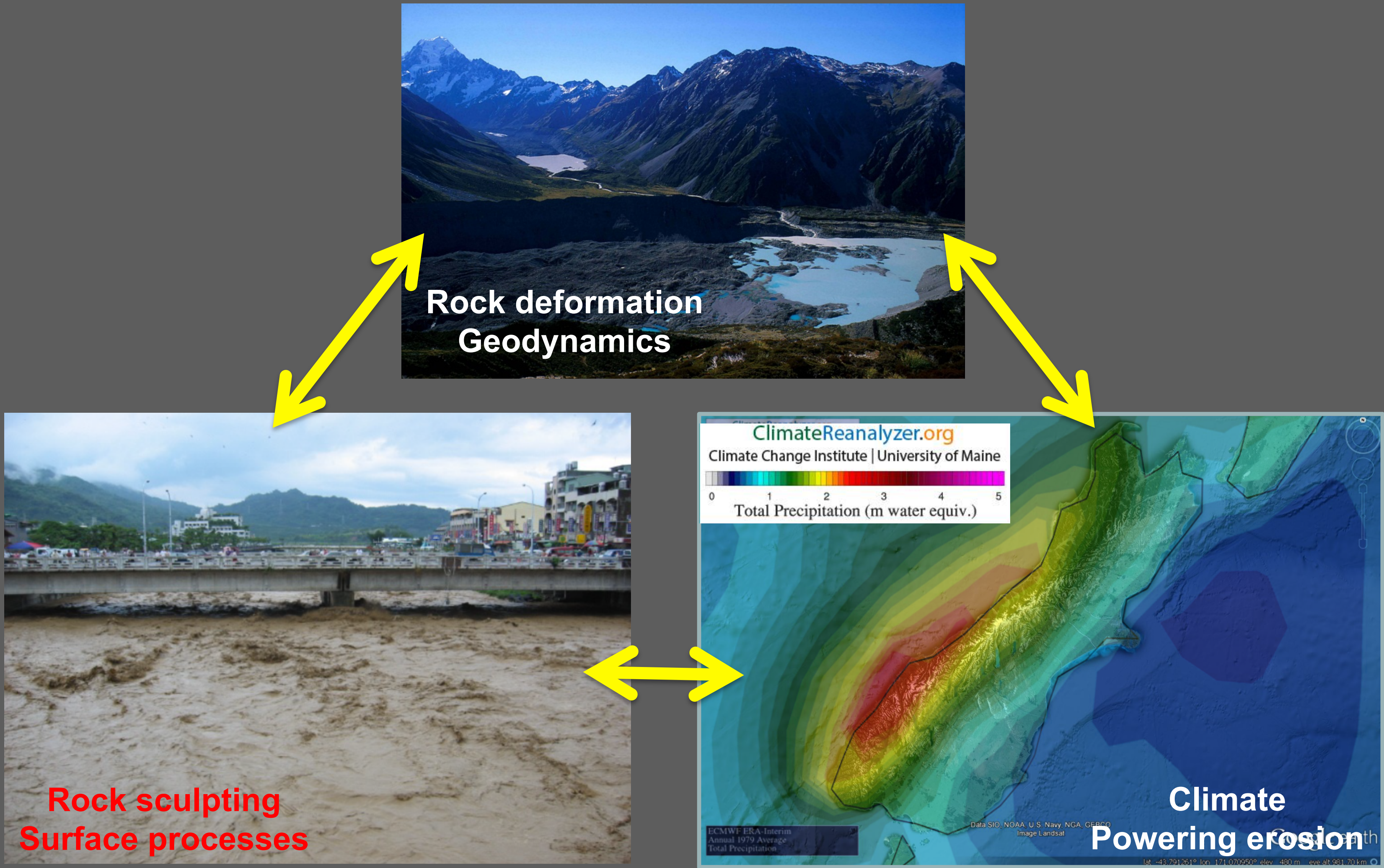
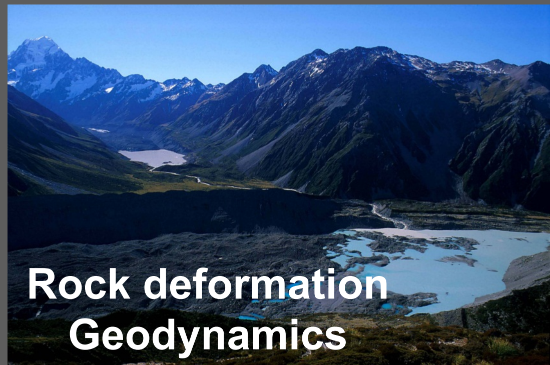
Geodynamics:Earth Surface Processes:Climate

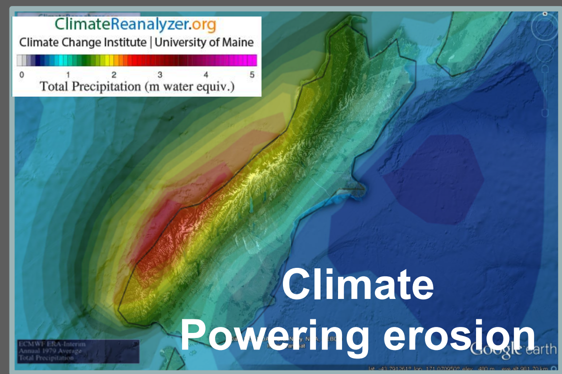


Geodynamics:Earth Surface Processes:Climate

tectonic uplift and subsidence
earthquakes, volcanic eruptions
deformation induced weakening
erosion
sediment/glacial loading/unloading
tectonic stresses
topographic stresses
fluvial/glacial stresses



fluid pressures
orographic rainfall
glaciations
silicate weathering



precipitation – water and ice
weathering rates

Geodynamics:Earth Surface Processes

tectonic uplift and subsidence
earthquakes, volcanic eruptions
deformation induced weakening
erosion
sediment/glacial loading/unloading
tectonic stresses
topographic stresses
fluvial/glacial stresses

No code or formulation can model all these features

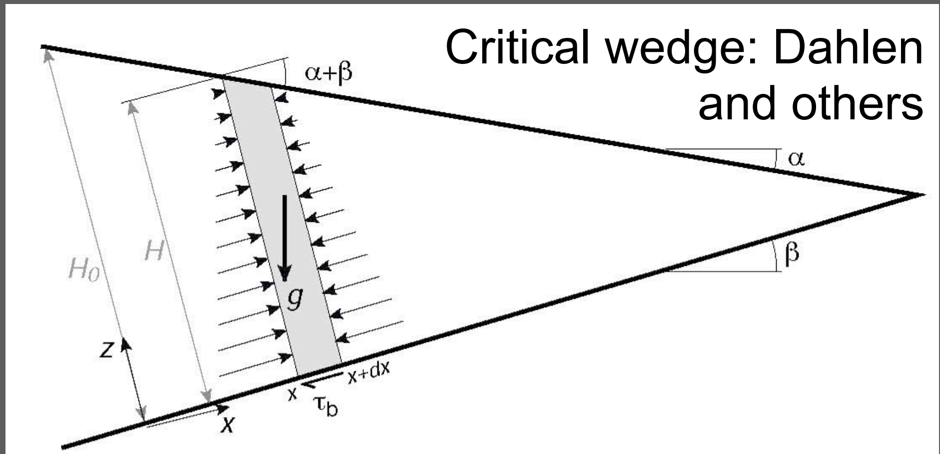
Three approaches that cover most current attempts
Add surface processes to geodynamics codes
Add geodynamic features to LEMs
Coupling existing geodynamic and surface process codes

What we are aiming for:
New conceptual framework and new codes with enhanced functionality

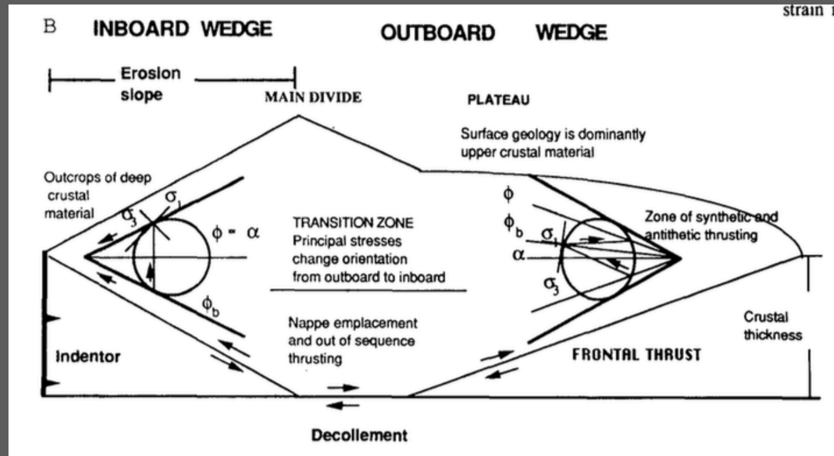
Adding surface processes to geodynamic codes:

e.g. simple erosion and/or sediment loading
inclusion of thermal effects

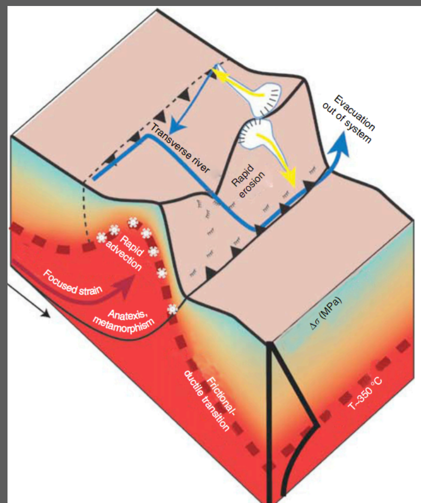
(Koons 1990)

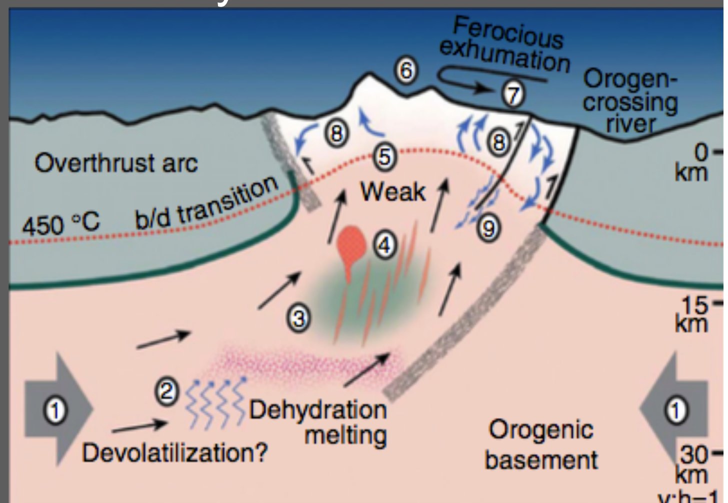


Critical wedge: Dahlen and others



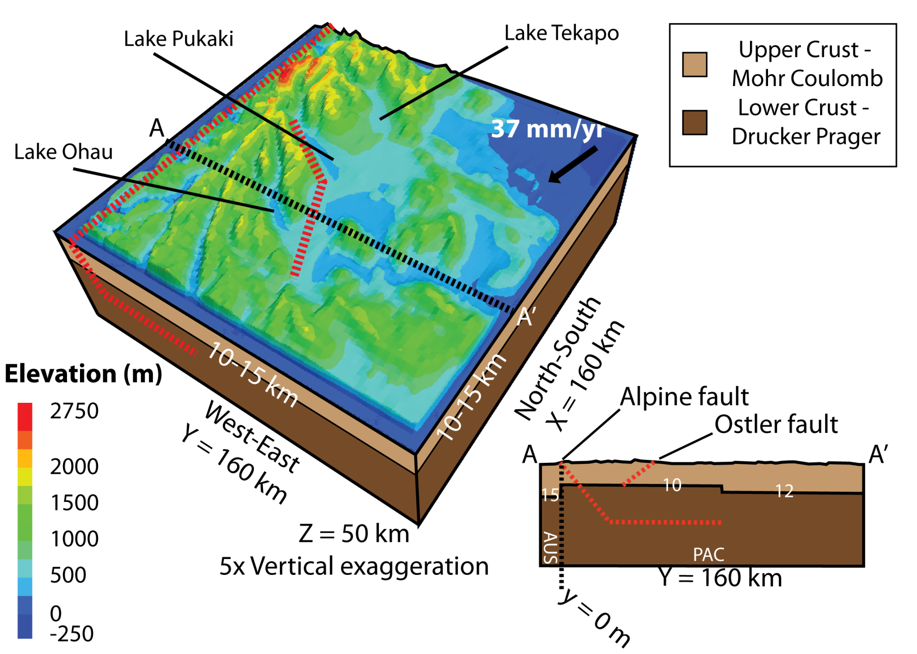
Tectonic aneurysm

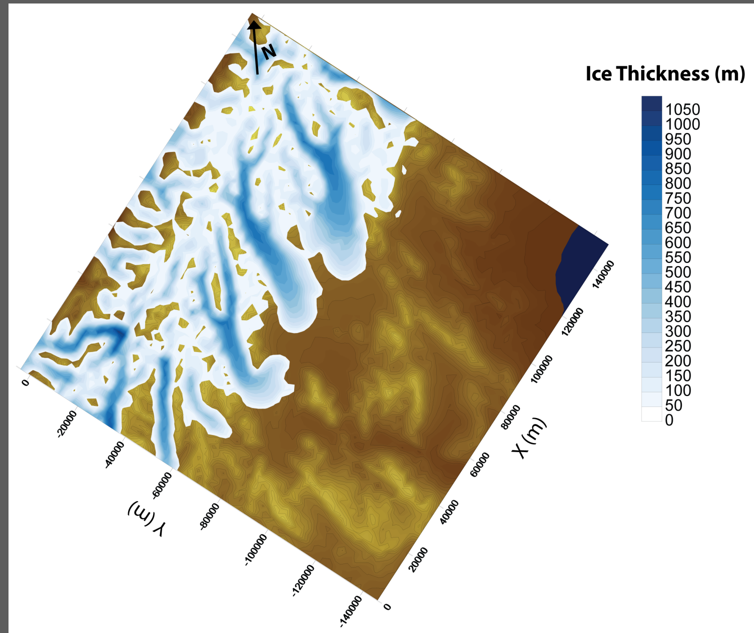




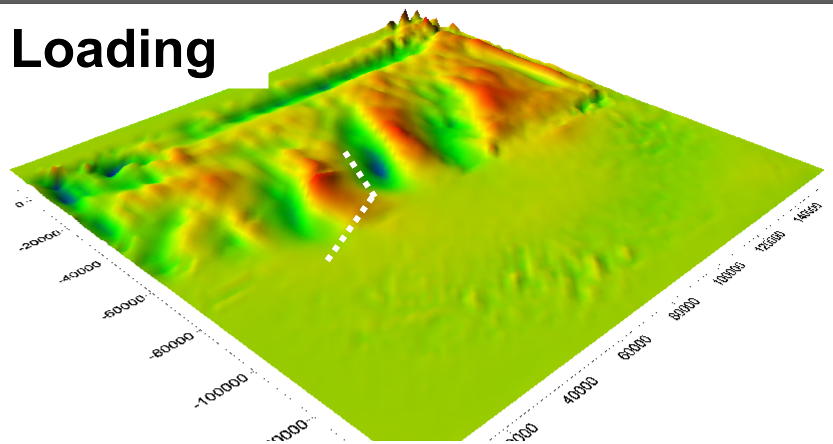
(Koons et al. 2013)

Model setup and LGM glacial load

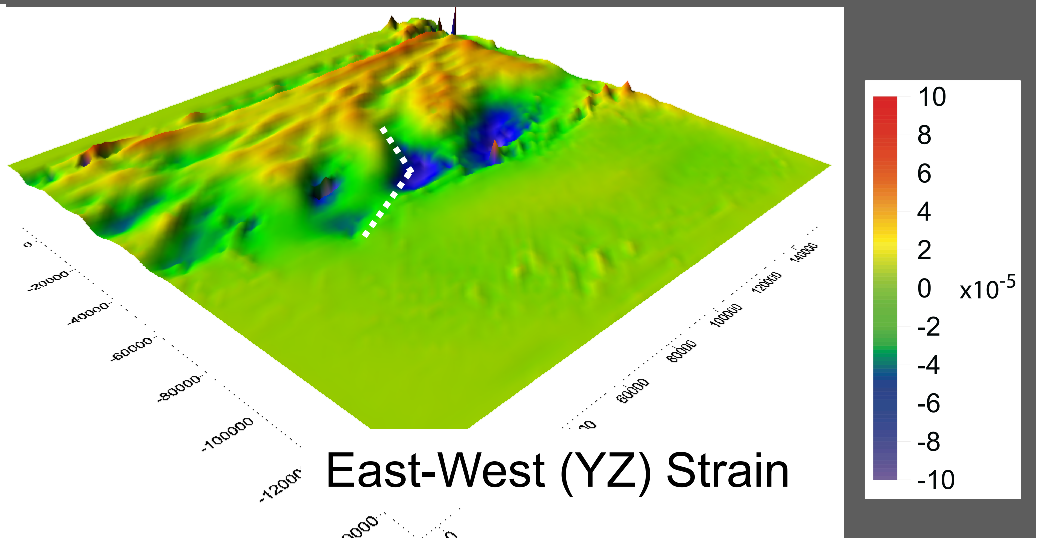




Loading



North-South (XZ) Strain



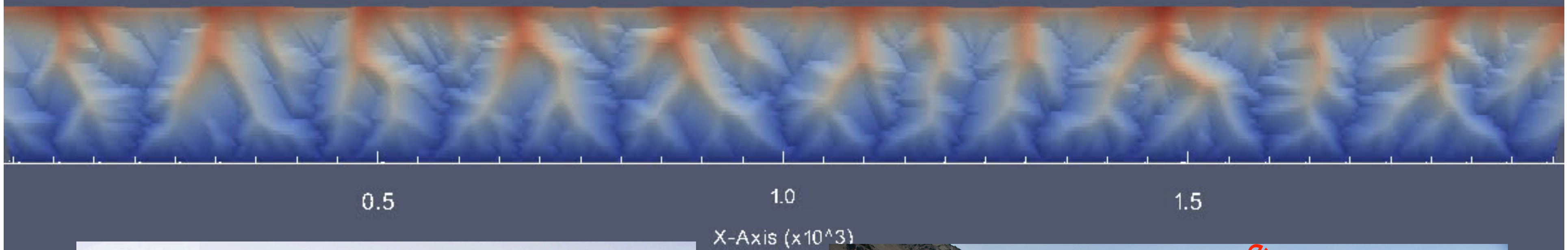
East-West (YZ) Strain

Images produced by Lauren Wheeler

GNS Science

Adding geodynamic features to surface process codes:

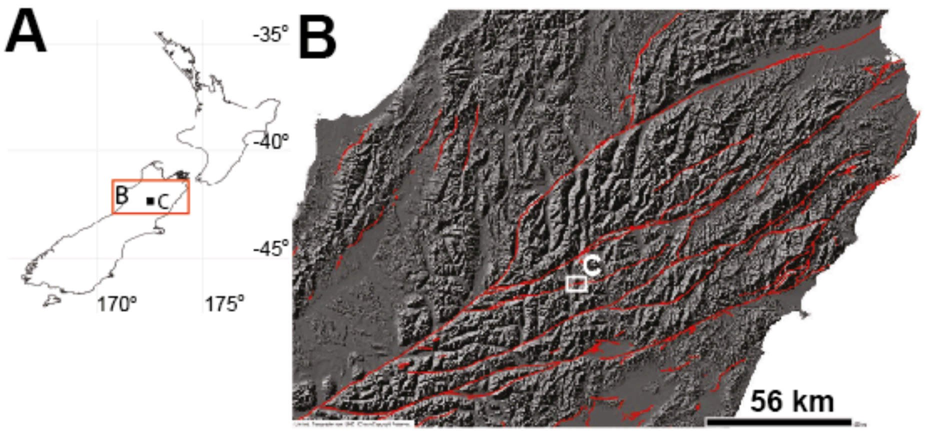
CHILD + lateral fault motion – from Sarah Harbert, University of Washington



Adding geodynamic features to surface process codes:

KCHILD: Sam Roy, University of Maine
"K" – kinematics and "K" – Kb, bedrock erodibility derived from cohesion

Fault damage → Erodibility link → put into CHILD



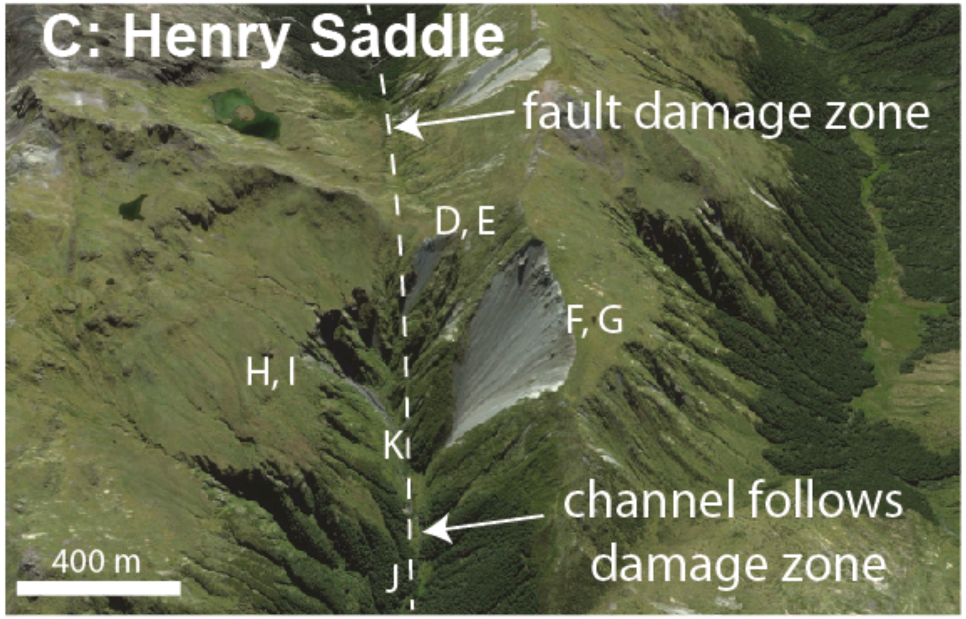
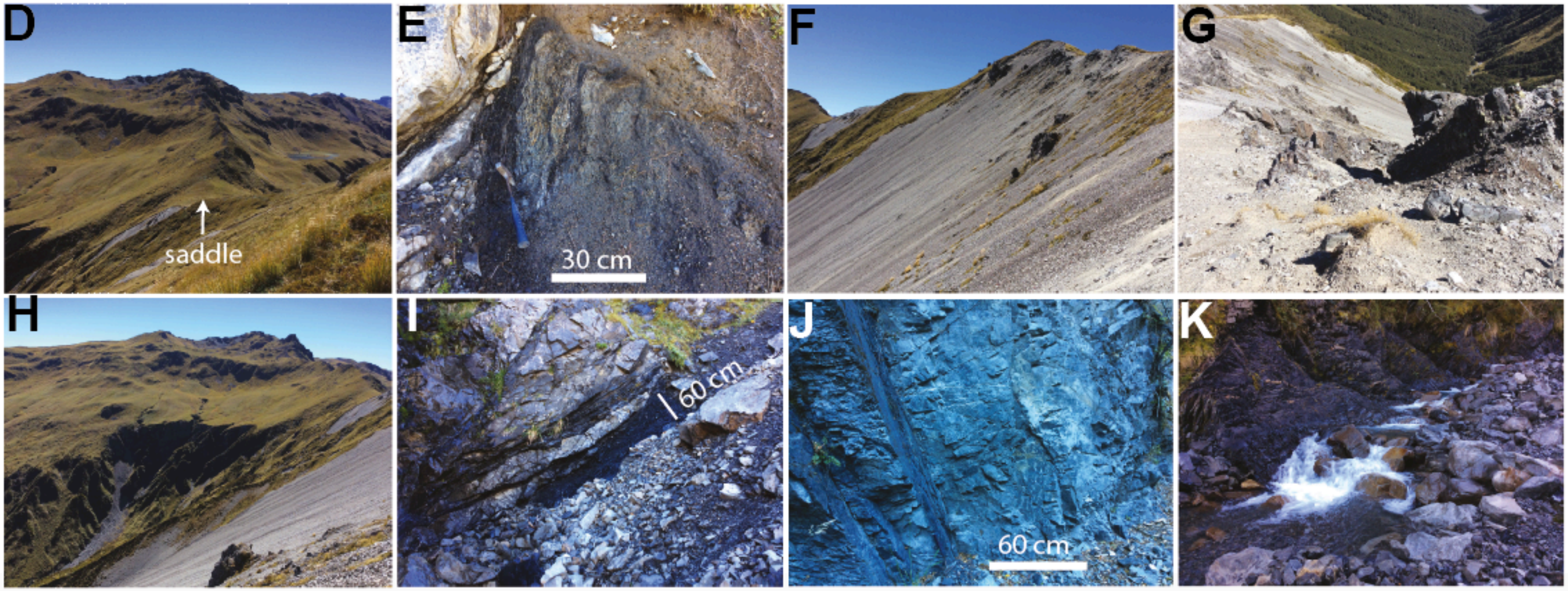
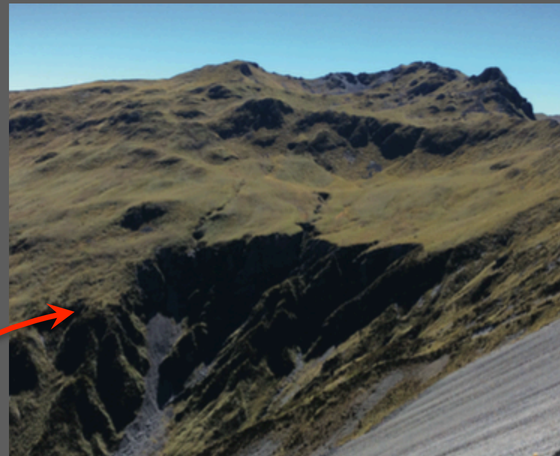


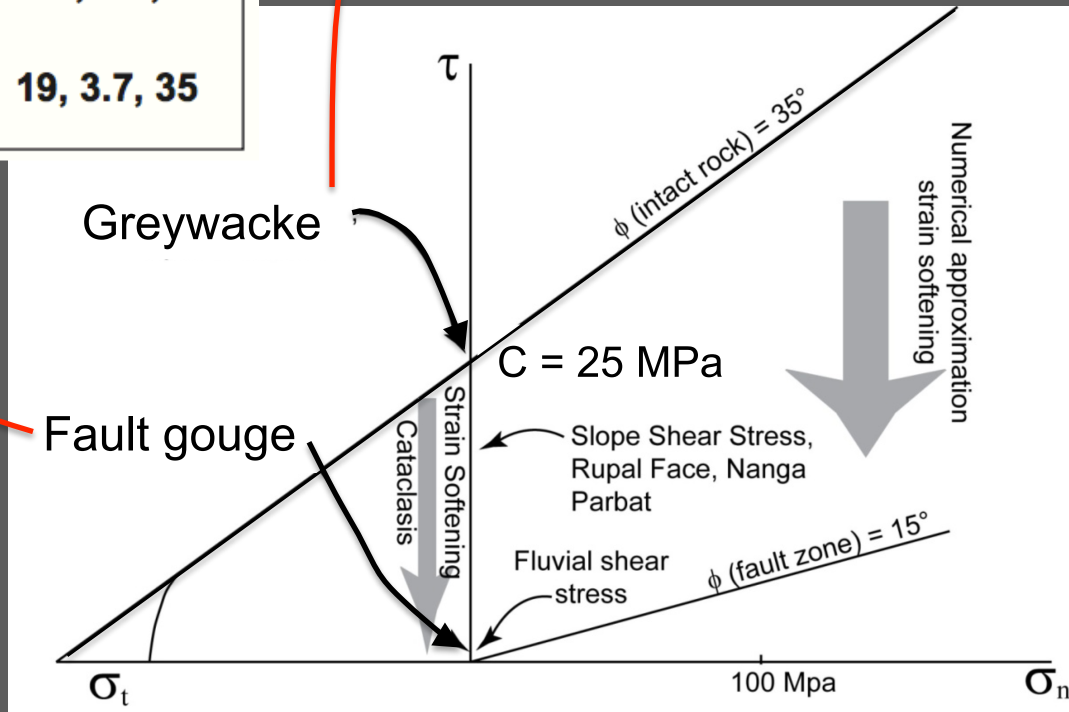
Figure 1: (A) New Zealand, red box: Lewis Pass, Marlborough regions. (B) Strong structure-valley correlation (GNS Science, data.gns.cri.nz/af/), white box: Henry Saddle region (C). Cont'd...



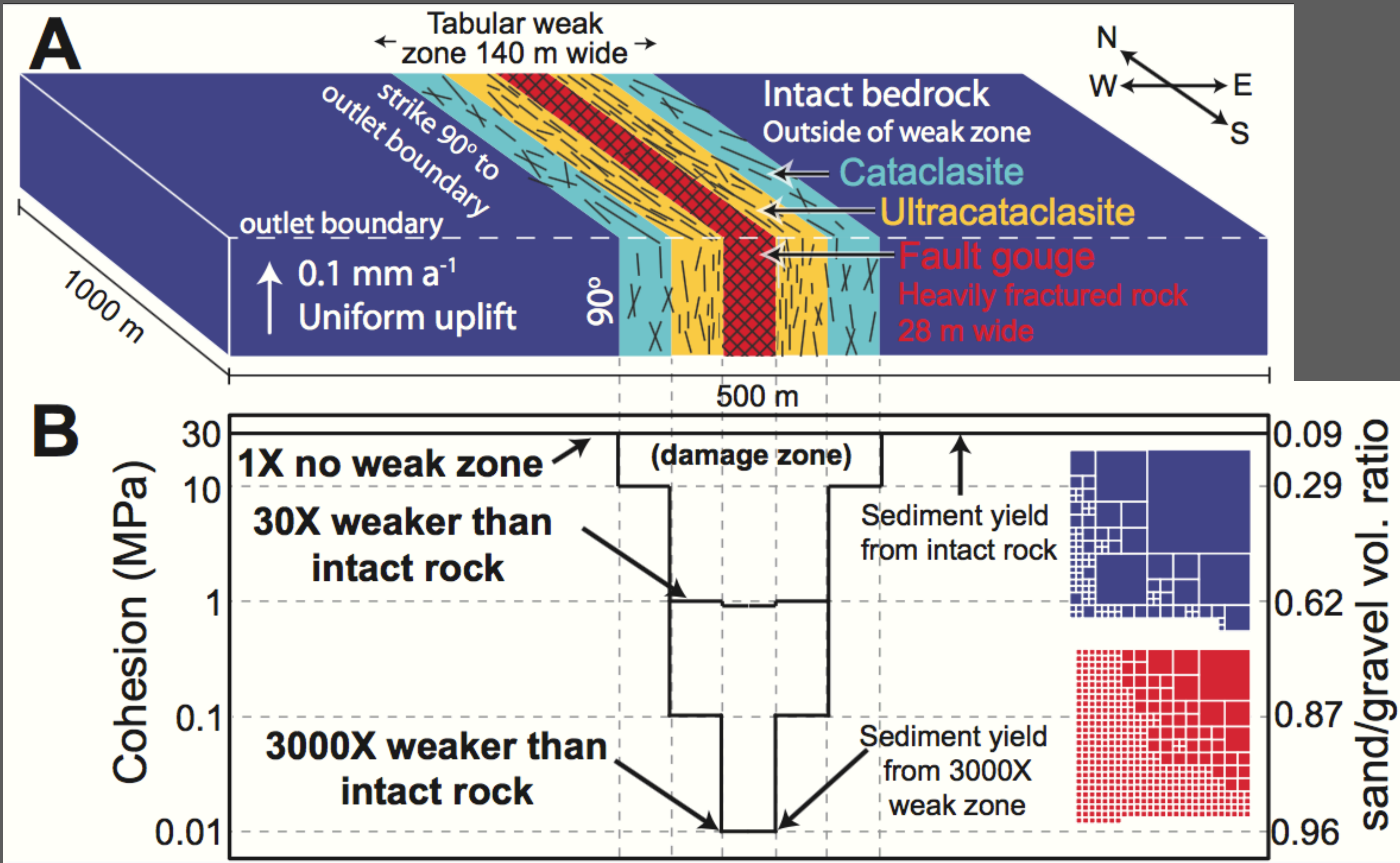
Model parameters constrained by field data

Table1: Mechanical parameters measured from outcrop			
Sample	Cohesion (MPa)	Joint spacing range (mm)	D_{50}, D_{16}, D_{84} (mm)
Jointed greywacke	8.5-25	200-800	189, 60, 318
Cataclasite	0.1-0.9	5-100	8.8, 1.9, 18.9
Gouge	0.003-0.02	<1	5.1, 0.3, 8
Downstream alluvium	n/a	n/a	19, 3.7, 35

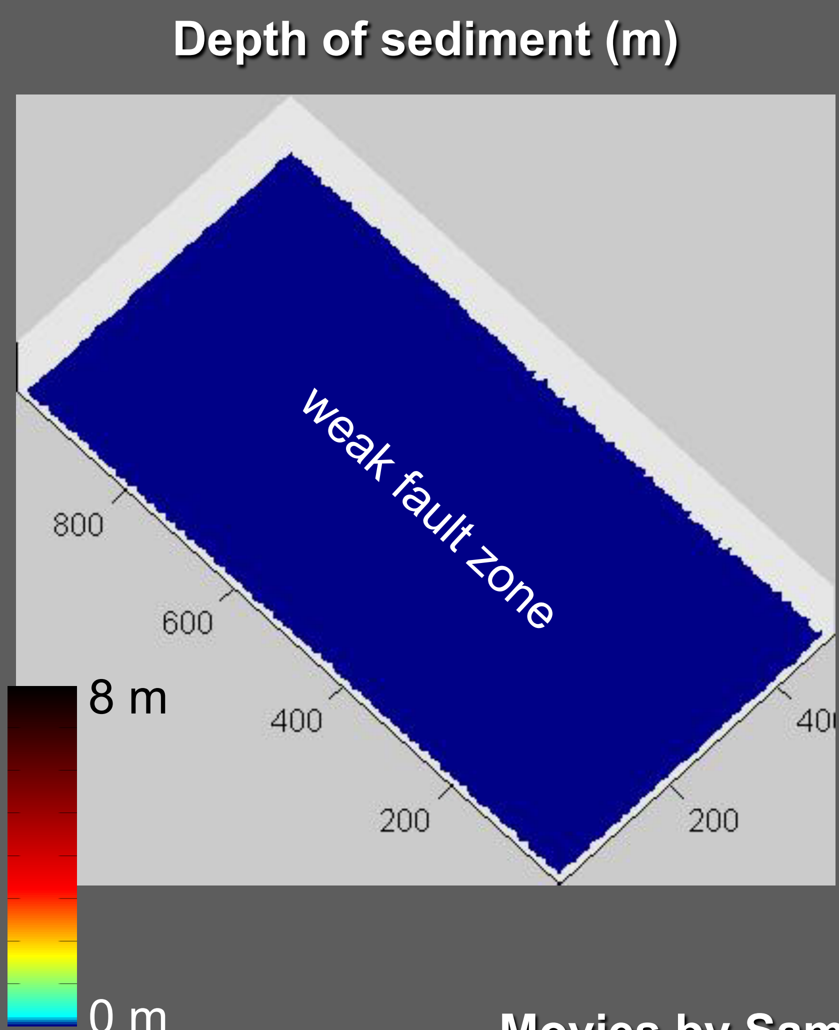


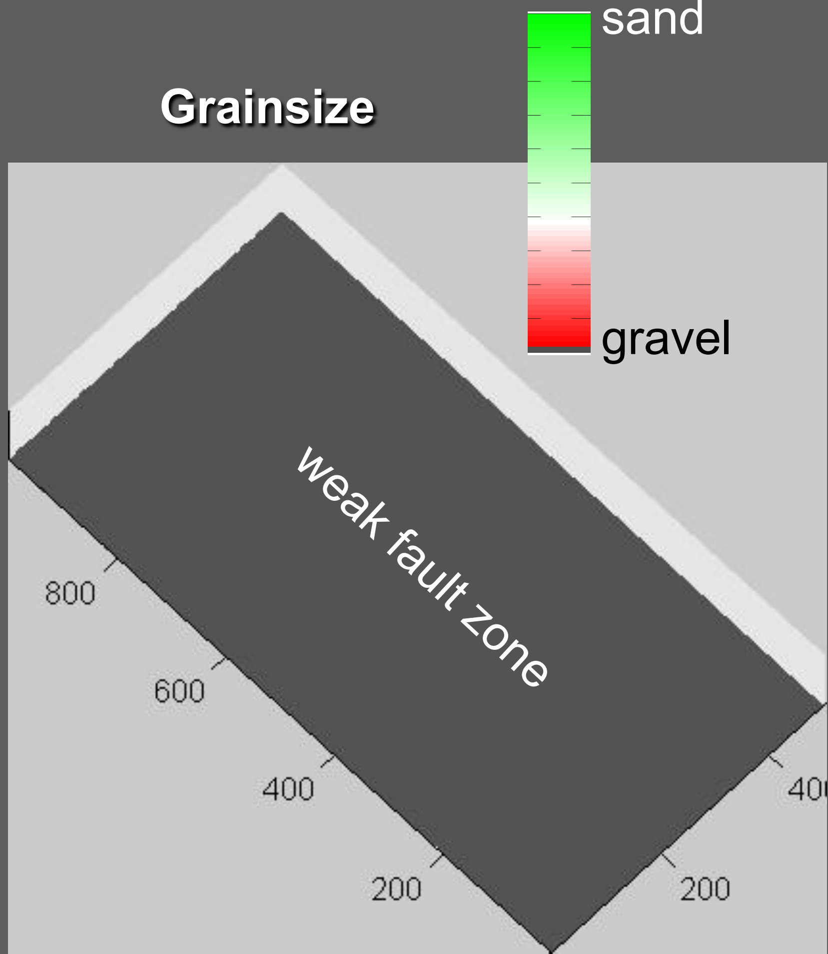


Model constrained by field data



Fluvial incision with sediments





Movies by Sam Roy, run in KCHILD

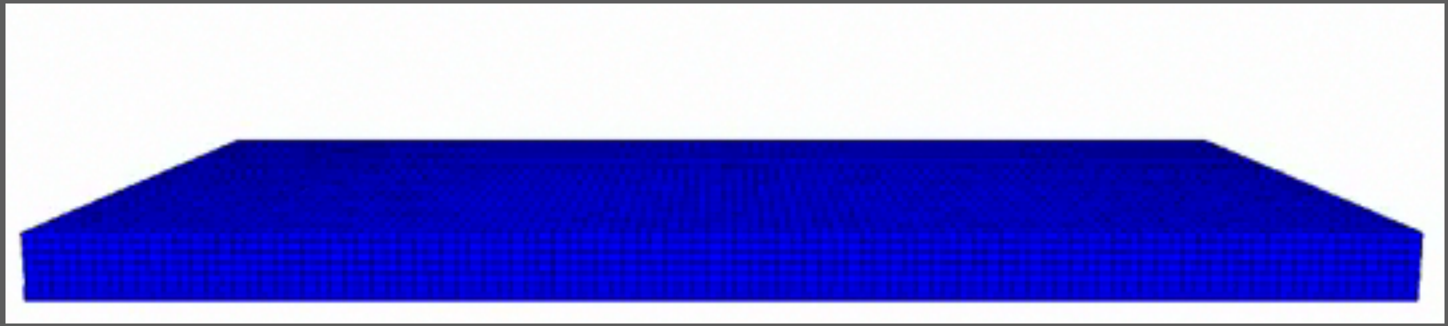
Coupling existing geodynamic and surface process codes:

For example:

FLAC^{3D} and CHILD (Roy, Upton, Tucker, Koons)

Uniform erodibility

Erodibility is a function of cohesion Incl. strain softening



Geodynamics with Underworld

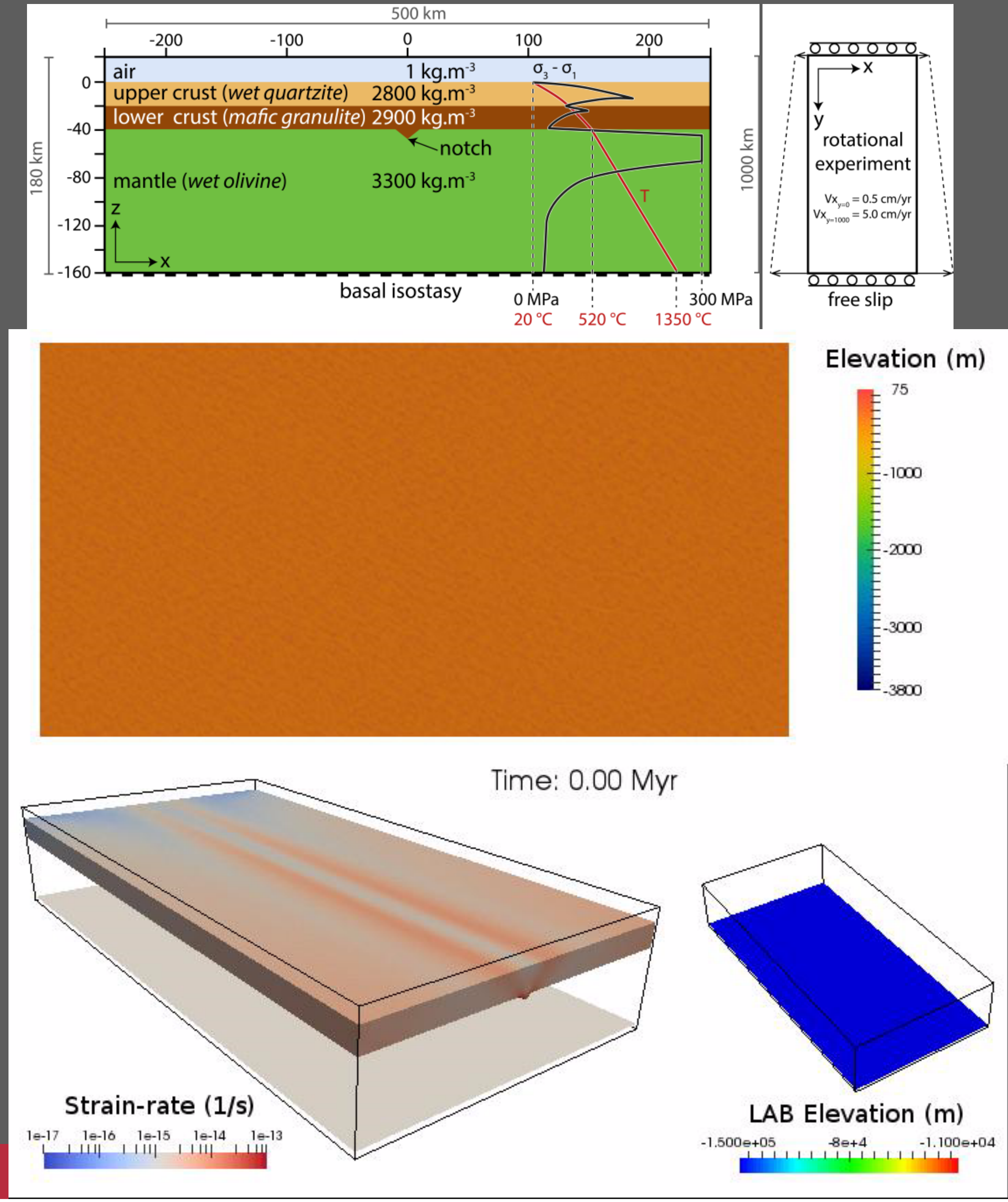
Underworld:

- Designed to model lithospheric and mantle scale deformation processes,
- Supports complex rheologies,
- Open source,
- Parallel computing and capable of modelling at high resolutions,

Underworld allows us to have a thermally and mechanically realistic lithosphere.

This allows us to study how landscapes influence tectonics, and vice versa.

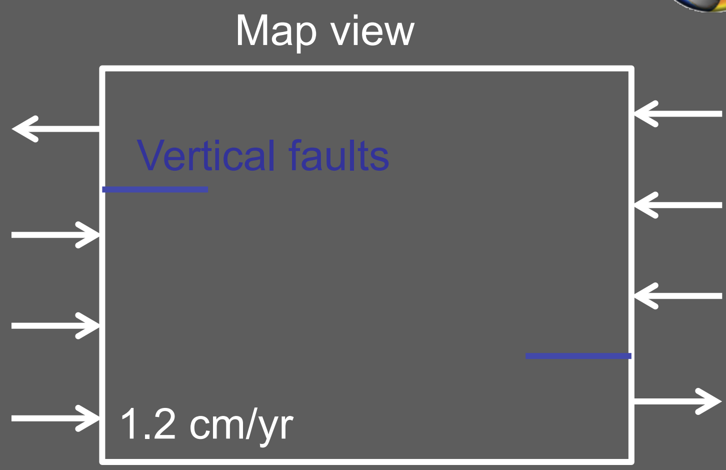
Continental Rifting near an Euler Pole

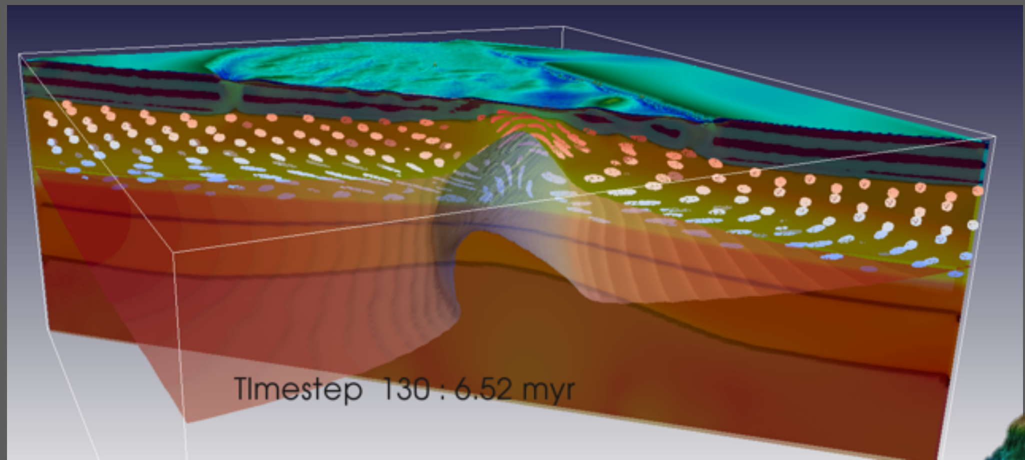


Coupling Underworld to BadLands

Pull-apart Metamorphic Core Complex experiment

Underworld output showing surface topography, strain-ellipsoids, and a melt contour after 6.5 Myr.



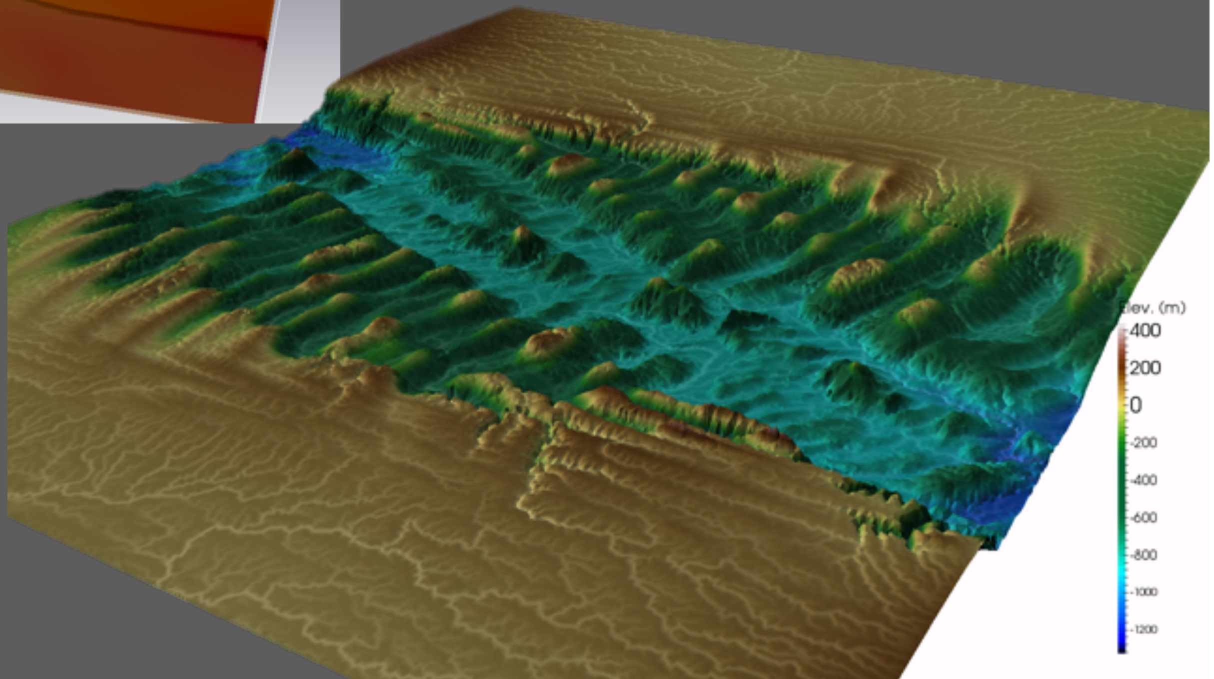


BadLands

BadLands is an open-source basin and landscape dynamics code.

BadLands advects surface nodes based on the velocity field from Underworld.

BadLands fills sinks/erodes highs to model the geodynamic influence of landscape evolution.



badlands-model / **Badlands-doc**

Watch 1 | Star 0 | Fork 0

Compilation of tests and documentation on the use of Badlands

11 commits | **1** branch | **0** releases | **3** contributors

branch: **master** | **Badlands-doc** / +

Code

Issues 0

Pull requests 0

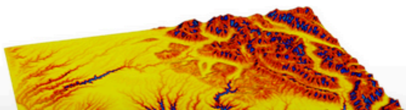
update manual

t-salles authored 19 days ago — latest commit 99d796840

example1	update XSD	a month
example2	update XSD	a month
example3	update XSD	a month
example4	update XSD	a month
README.md	Update README.md	2 months
manual.pdf	update manual	19 days
riseofthephoenix.png	get doc	2 months

README.md

Compilation of tests and documentation on the use of Badlands



Overview

Basin and **lan**dscape **d**ynamic**s** (**Badlands**) is a parallel TIN-based landscape evolution model, built to simulate topography development at various space and time scales. The model is presently capable of simulating hillslope processes such as **linear** & **nonlinear** diffusion, fluvial incision (**detachment-limited** & **under-capacity** laws), spatially varying surface uplift which can be used to simulate changes in base level, as well as effects of climate changes and sea-level fluctuations.

The specs...

The model is mainly written in fortran and takes advantage of the Earth Surface Modelling Framework (**ESMF**).

- The finite volume approach from Tucker et al. (2001) based on the dual Delaunay-Voronoi framework is used to solve the continuity equation explicitly,
- Node ordering is perform efficiently based on the work from Braun & Willett (2013),
- A Hilbert Space-Filling Curve method algorithm (Zoltan) is used to partition the TIN-based surface into subdomains,
- Drainage network partitioning is generated through METIS library.

Community driven

The code is conceived as an open-source project, and is an ideal tool for both **Research** and **Learning** purposes.

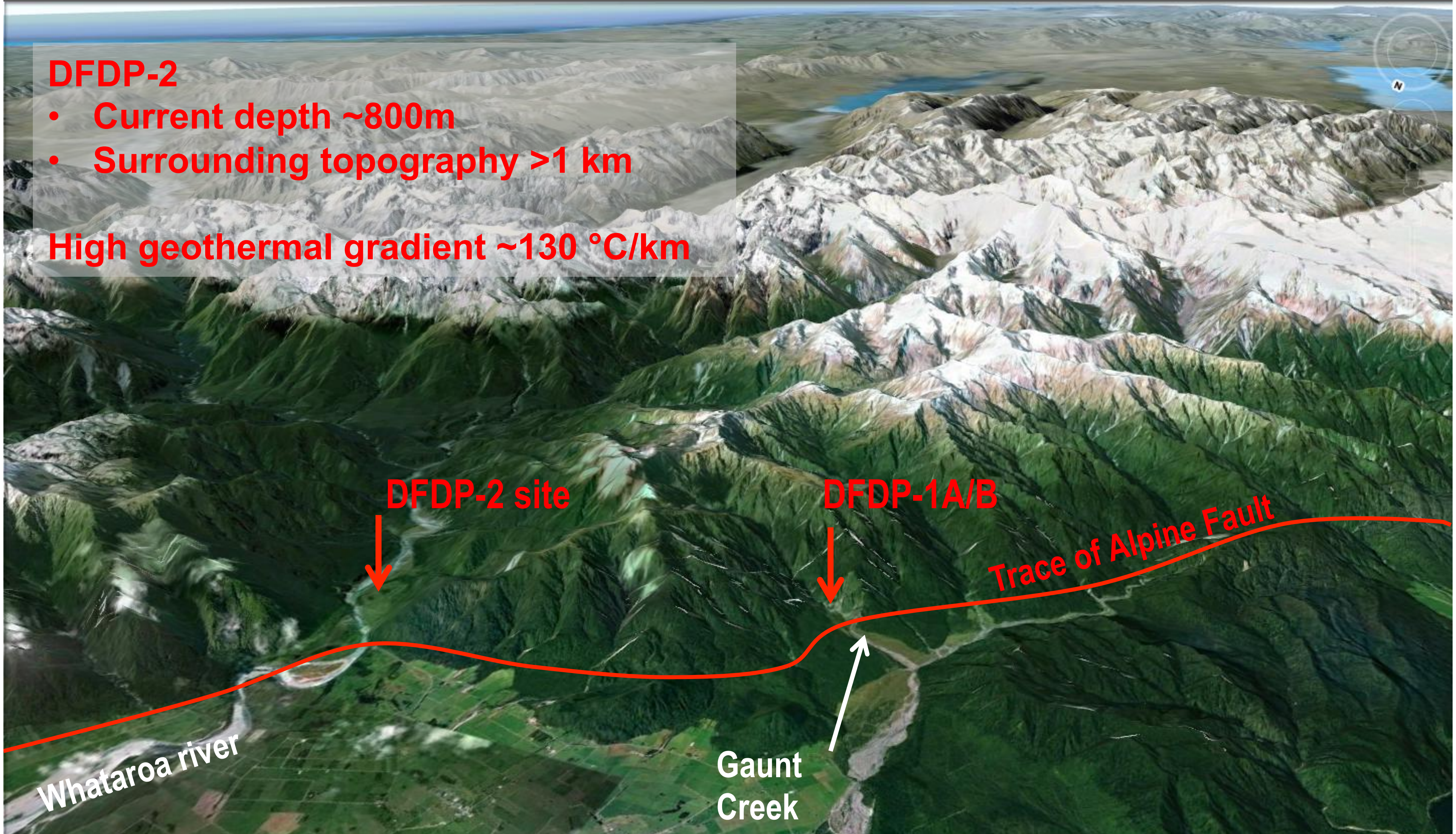
Getting the source code

The source code is available on github: here

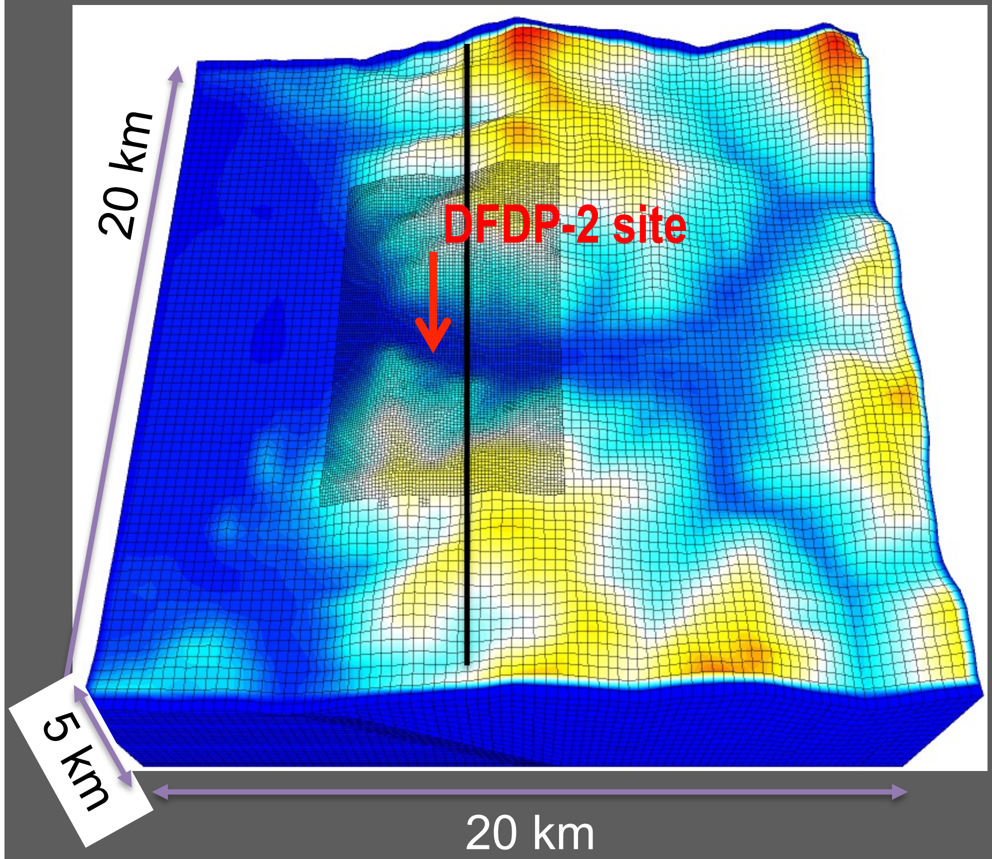
New conceptual framework: a single system for modeling Earth materials:

- Topography and the stress state
- Topography and strain partitioning
- FERM – Failure Earth Response Model

Importance of topography and relief to stress state – Deep Fault Drilling



Importance of topography and relief to stress state – Deep Fault Drilling



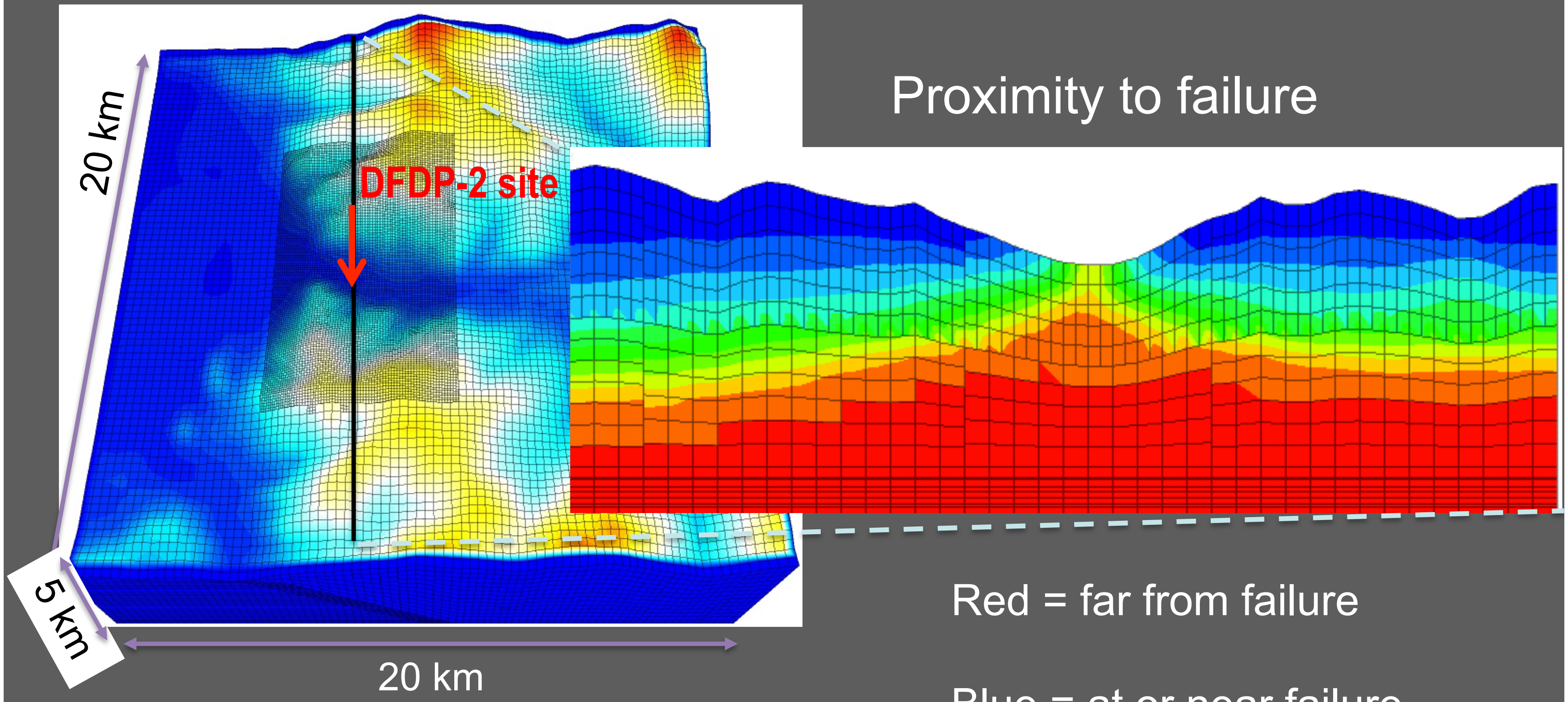
3D thermal/fluid flow model

Work in progress:
Exploring the permeability structure required to produce a 130°C/km geotherm in the near surface.

Previous work showed that the permeability structure in actively deforming regions is related to the stress state, or more specifically, the proximity to failure

(Upton & Sutherland, 2014, EPSL)

Importance of topography and relief to stress state – Deep Fault Drilling

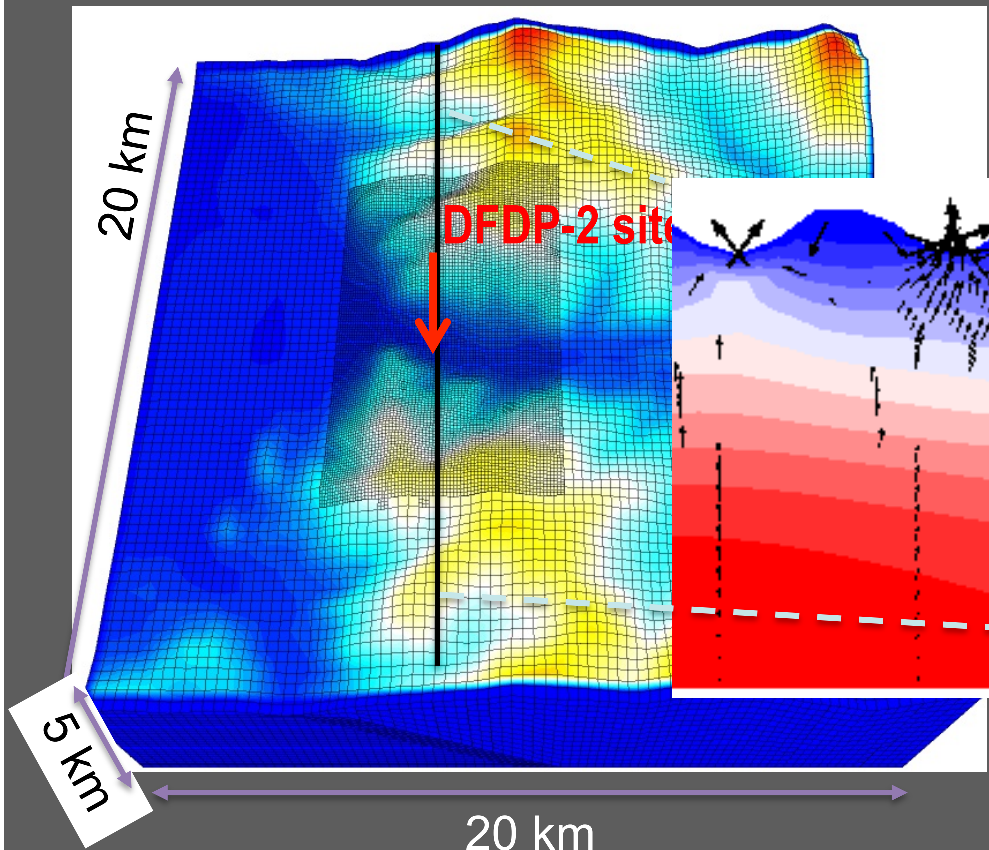


Proximity to failure

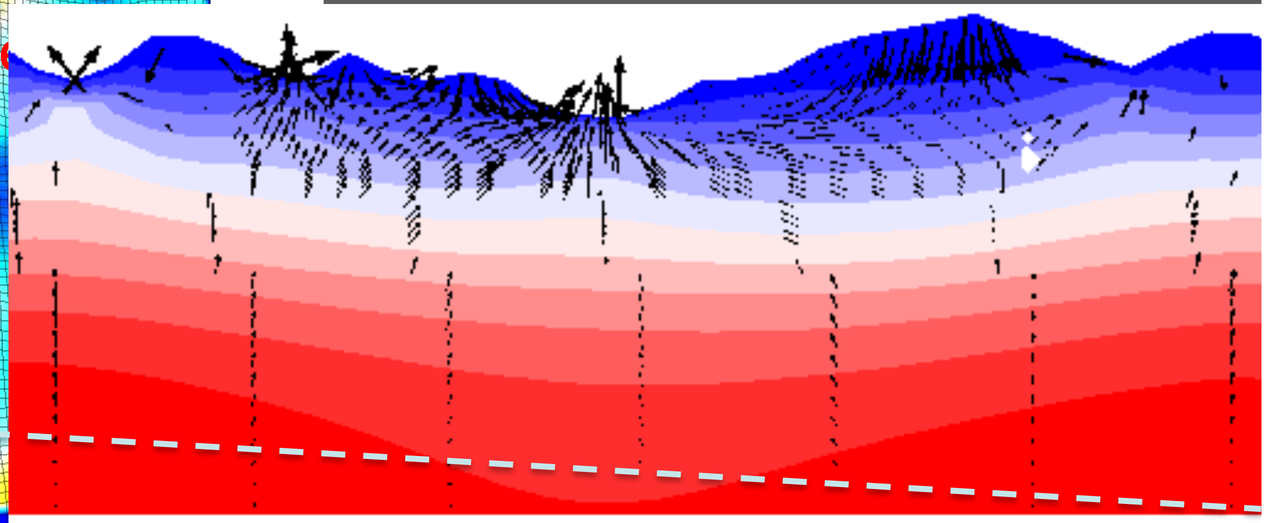
Red = far from failure

Blue = at or near failure

Importance of topography and relief to stress state – Deep Fault Drilling

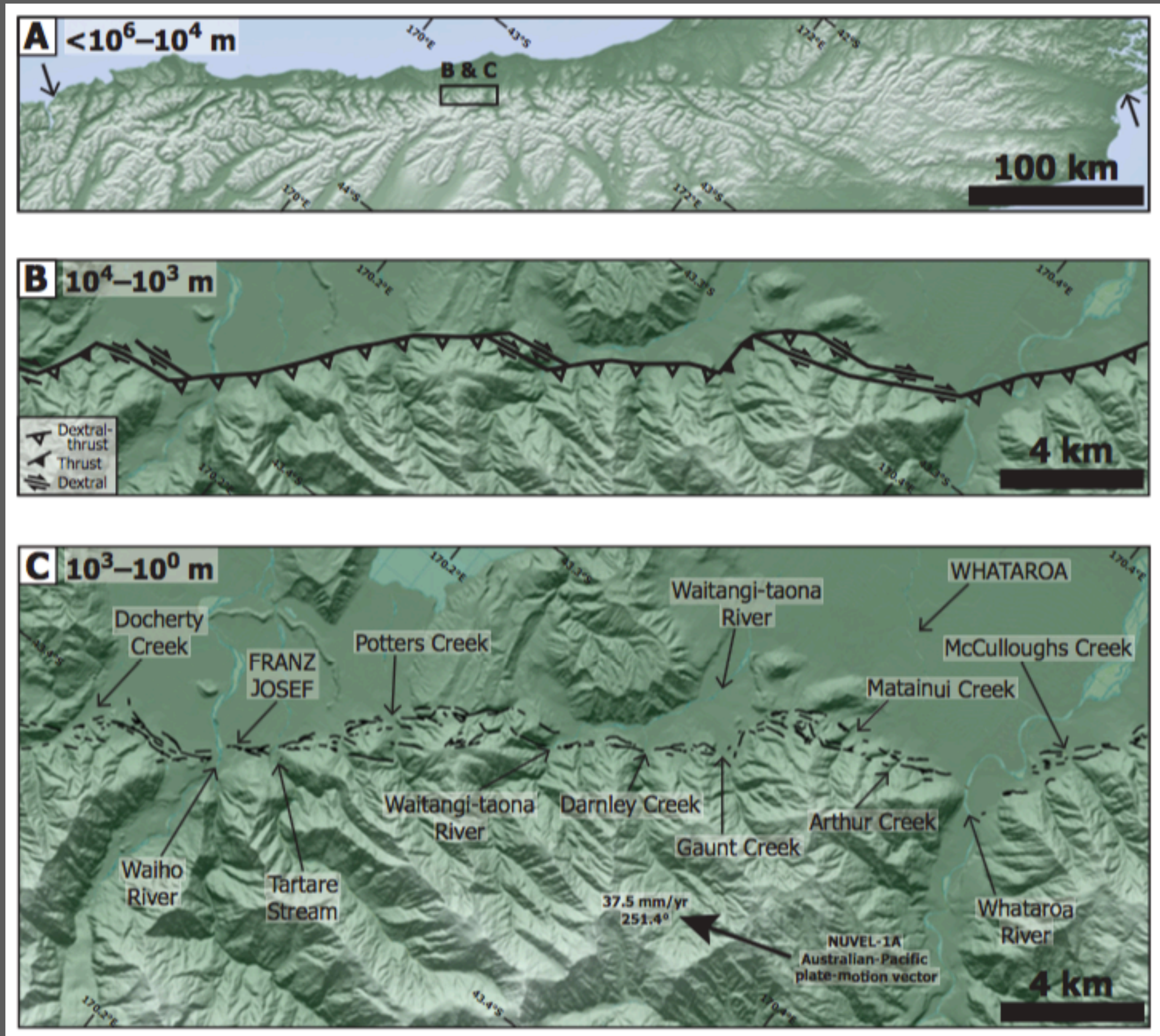


Temperature and fluid flow



Model permeability 10^{-15} m^2 to a depth of 2 km below sea level

Importance of topography and relief to stress state – strain partitioning



Barth et al. 2012

Importance of topography and relief to stress state – strain partitioning

- Alpine Fault fixed below 2 km
- Strain softening rheology
- Based on ϕ reducing from 30º to 5º

- Constraint of AF @ 2 km reflected in these results

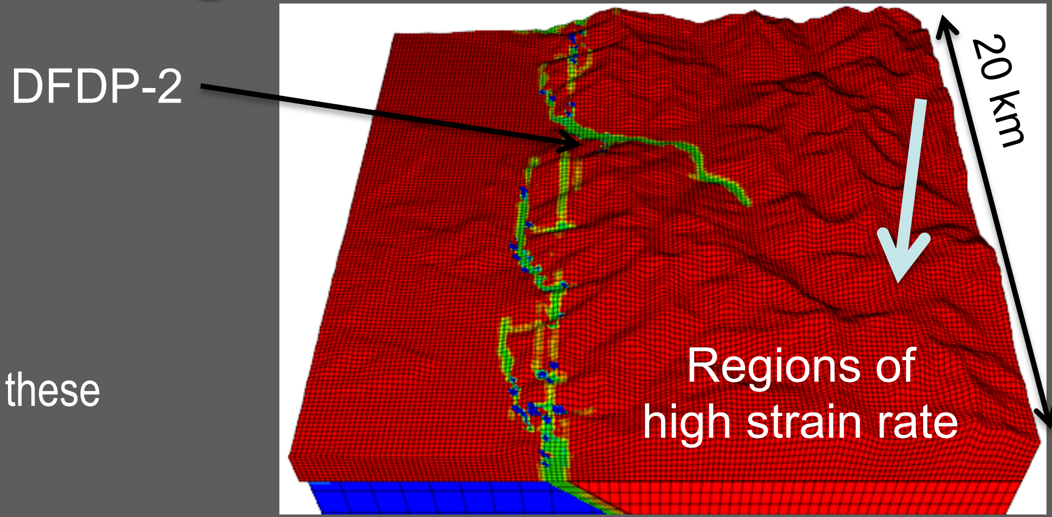


Plate normal velocity component

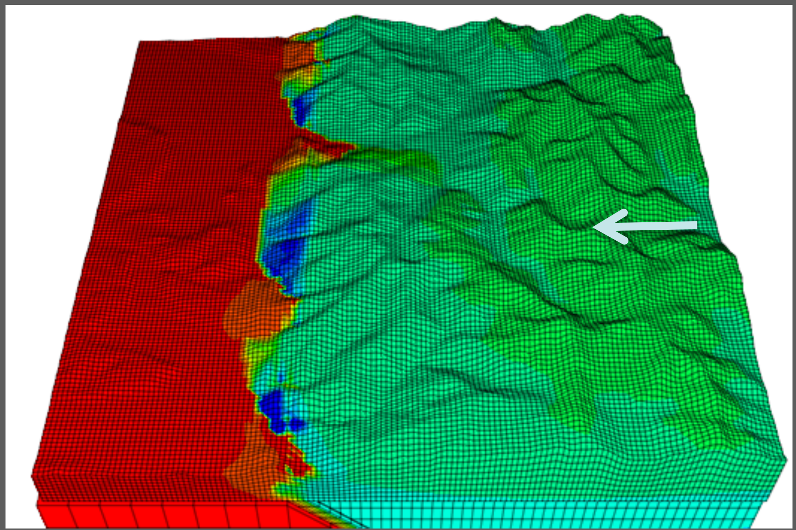
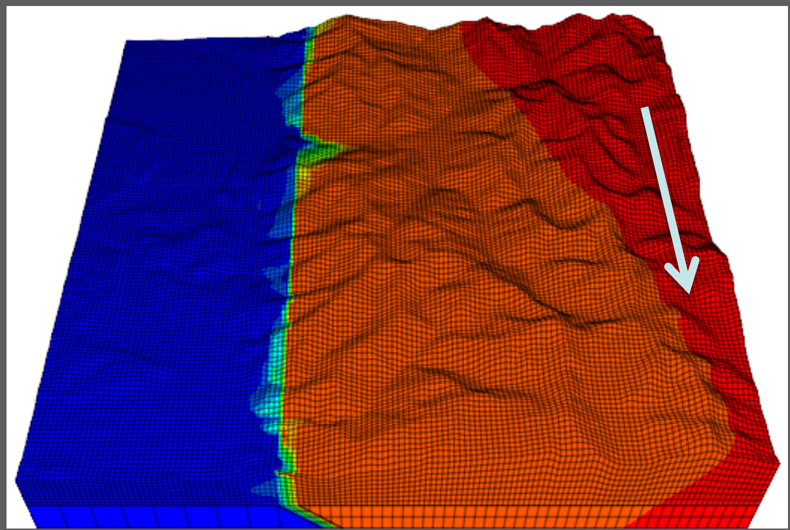


Plate parallel velocity component



FERM – failure earth response model

1: Material displacement, whether tectonic or geomorphic in origin, at or below Earth's surface, is driven by local forces overcoming local resistance.

2: Large displacements, whether tectonic or geomorphic in origin, irreversibly alter Earth material properties enhancing a long term strain memory mapped into the topography.

3: To implement we need the total stress state at each point on the Earth's surface

Determining the *Total Stress State*

$$\Sigma = \sigma_{fluvial} + \sigma_{glacial} + \sigma_{slope} + \sigma_{tectonic} + \sigma_{dynamic}$$

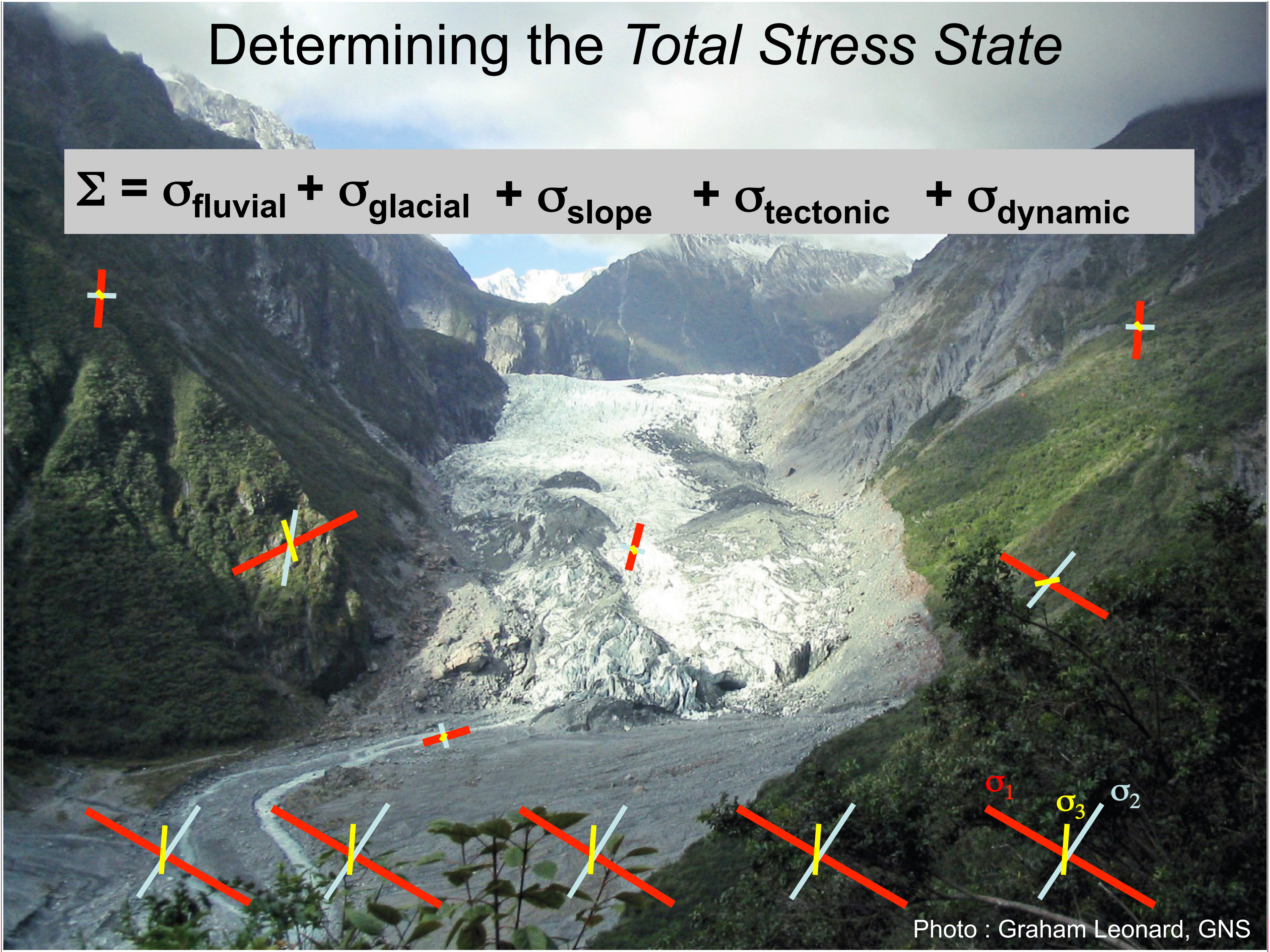
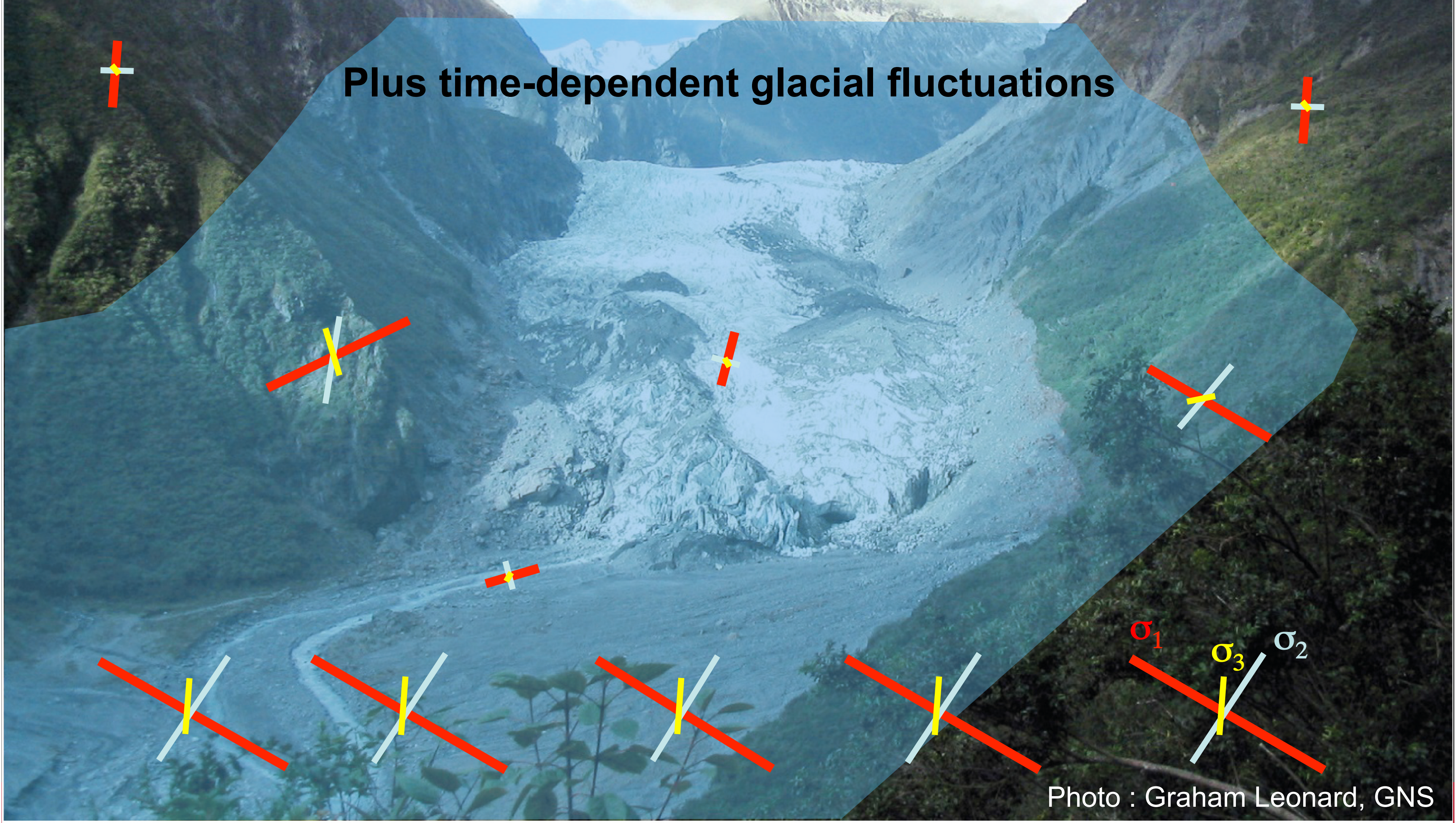


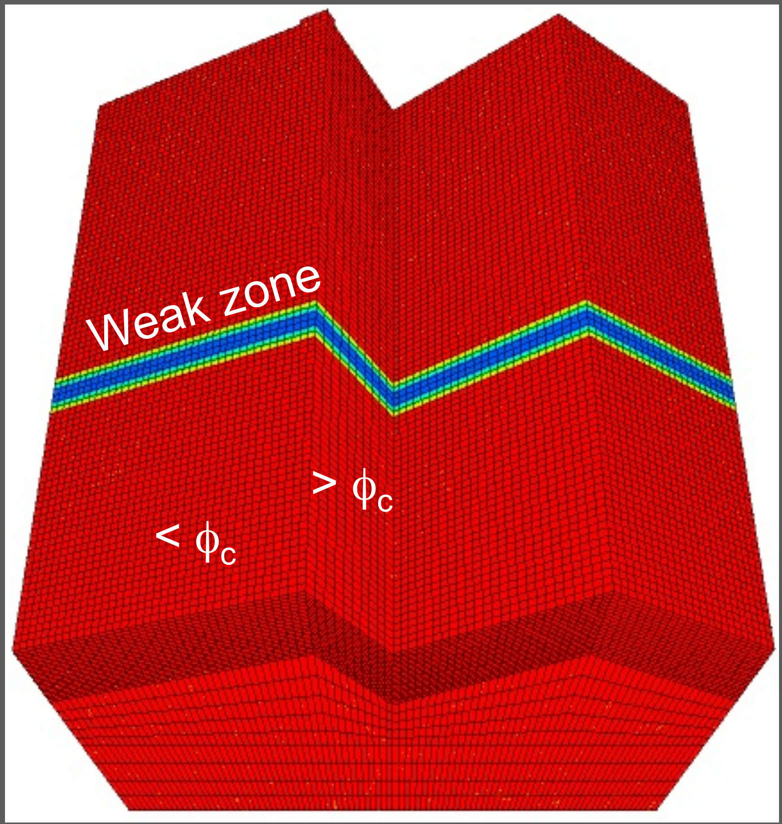
Photo : Graham Leonard, GNS

Determining the *Total Stress State*

$$\Sigma = \sigma_{fluvial} + \sigma_{glacial} + \sigma_{slope} + \sigma_{tectonic} + \sigma_{dynamic}$$



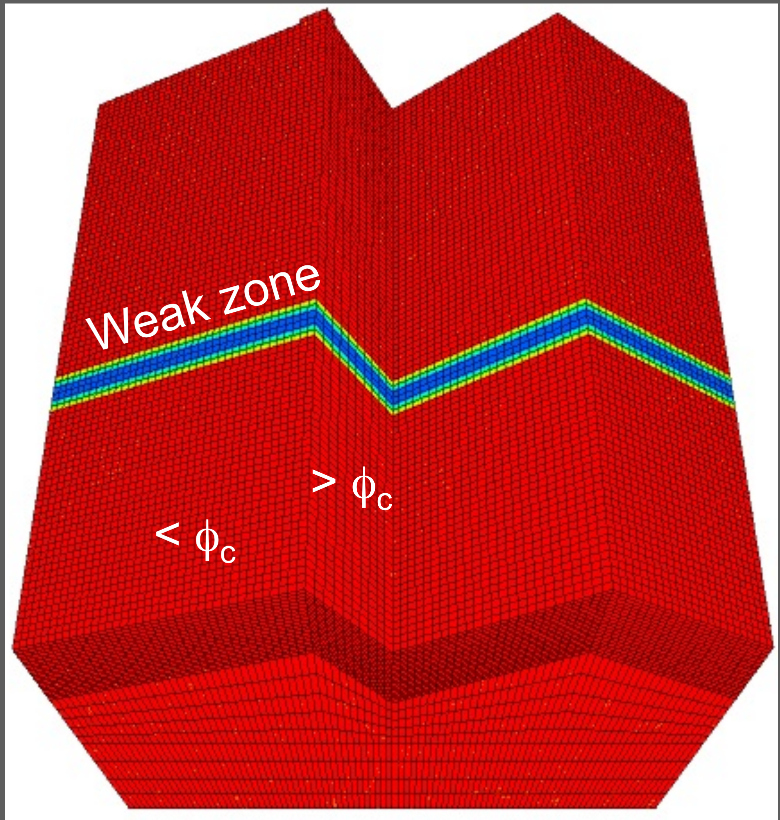
FERM – failure earth response model

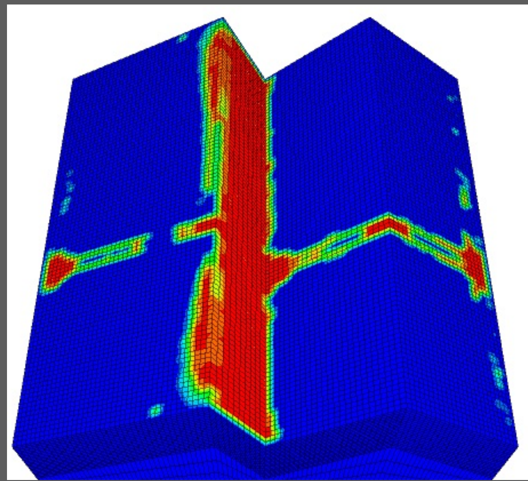


For each point:

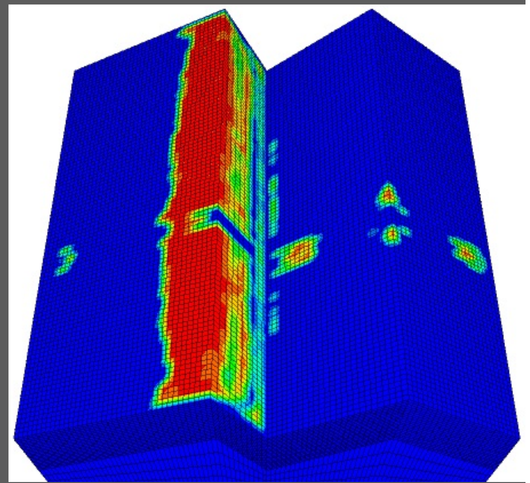
1. Sum all stresses: Geomorphic (slope and inertial), Tectonic (Static and potentially Dynamic) into a single **Total Stress** tensor
2. Describe Earth failure using effective stress formulation (potential to include local fluid pressure)
3. We can distinguish shear and tensile failure states
4. Solve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

FERM – failure earth response model



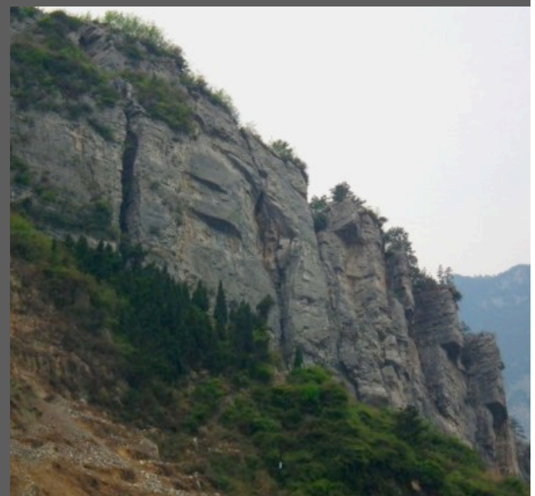


shear failure



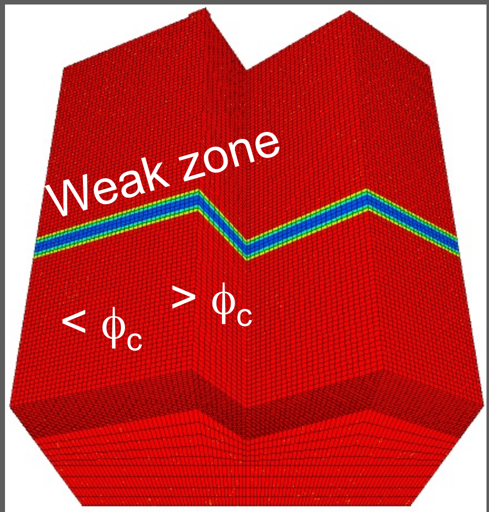
tensile failure

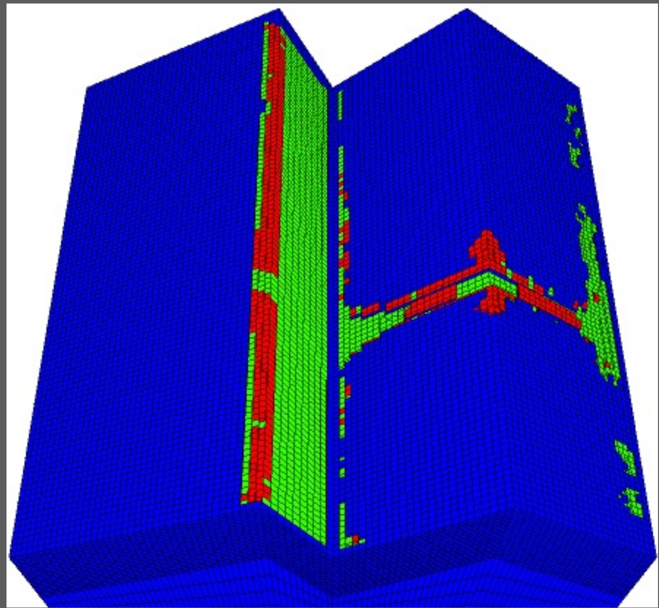
http://commons.wvc.edu/rdawes/



http://blogs.agu.org/landslideblog/

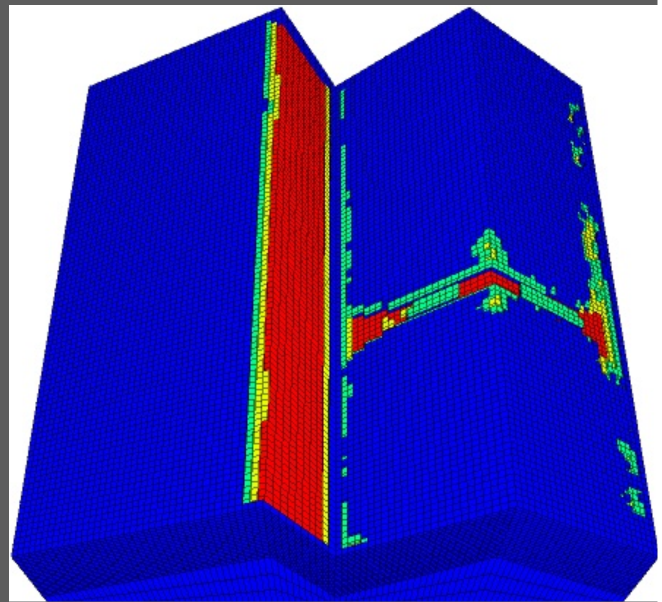
FERM – failure earth response model





Different failure modes

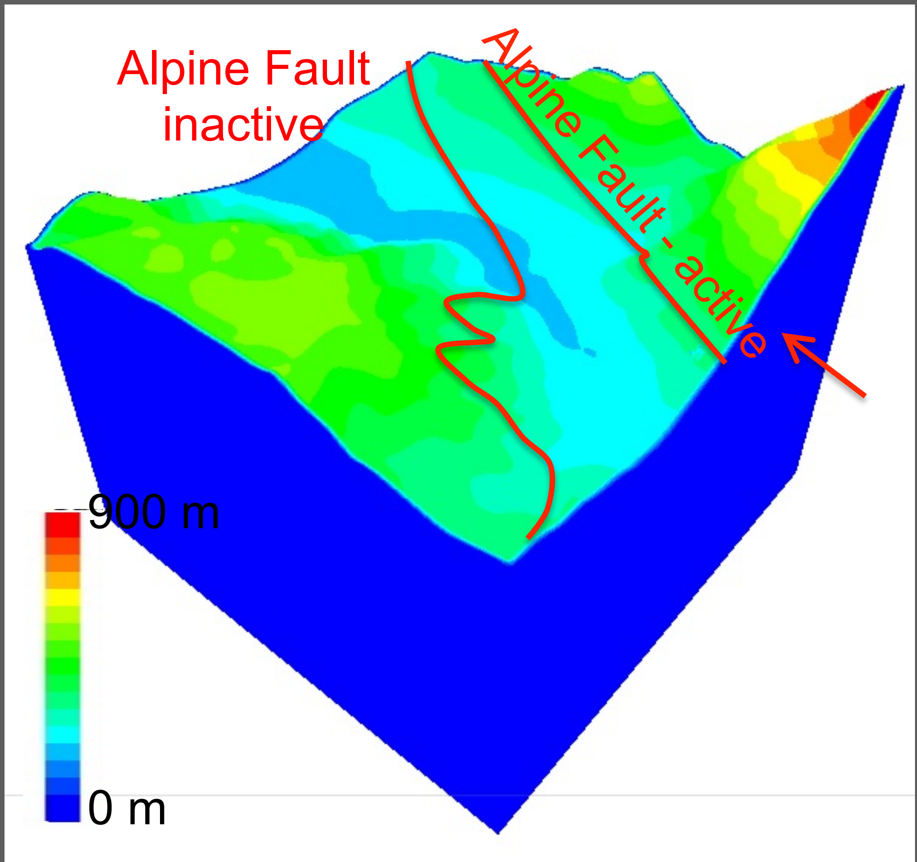
Green = shear
Red = tensile
Blue = none



Amount of material removed

Red = maximum
Blue = zero

FERM – example from the Waikukupa segment of the Alpine Fault



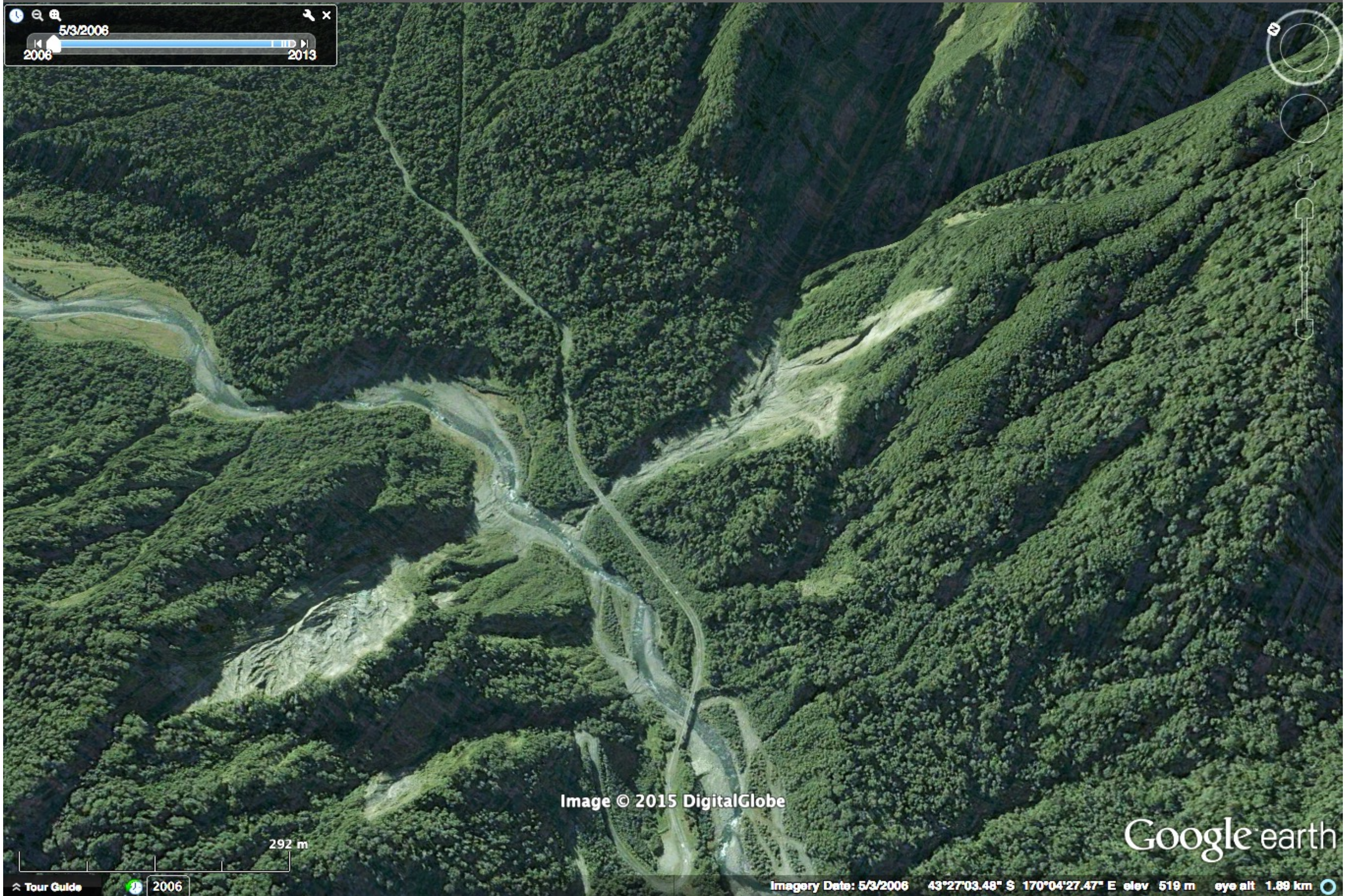

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Image © 2015 DigitalGlobe
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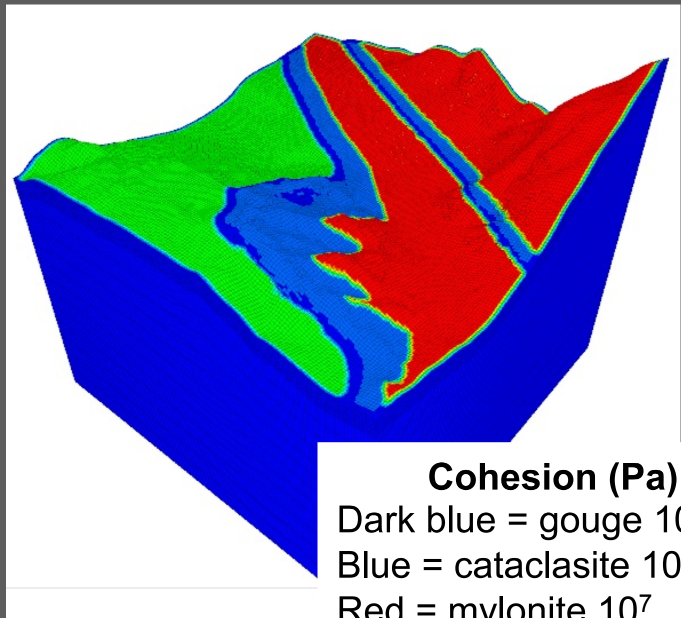
Imagery Date: 5/3/2006 43°27'03.48" S 170°04'27.47" E elev 519 m eye alt 1.89 km

10/17/2012
2006
2013
Image © 2015 DigitalGlobe
292 m
Google earth
Tour Guide
2006
Imagery Date: 10/17/2012 43°26'29.73" S 170°04'33.95" E elev 221 m eye alt 1.89 km

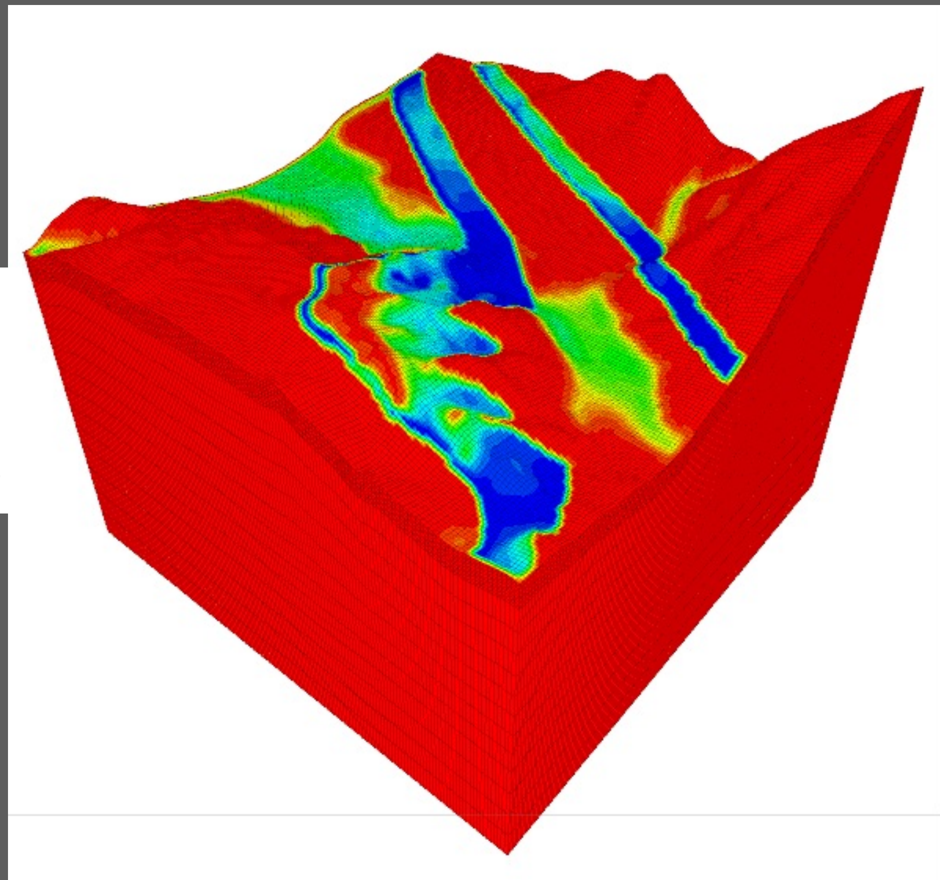
FERM – example from the Waikukupa segment of the Alpine Fault



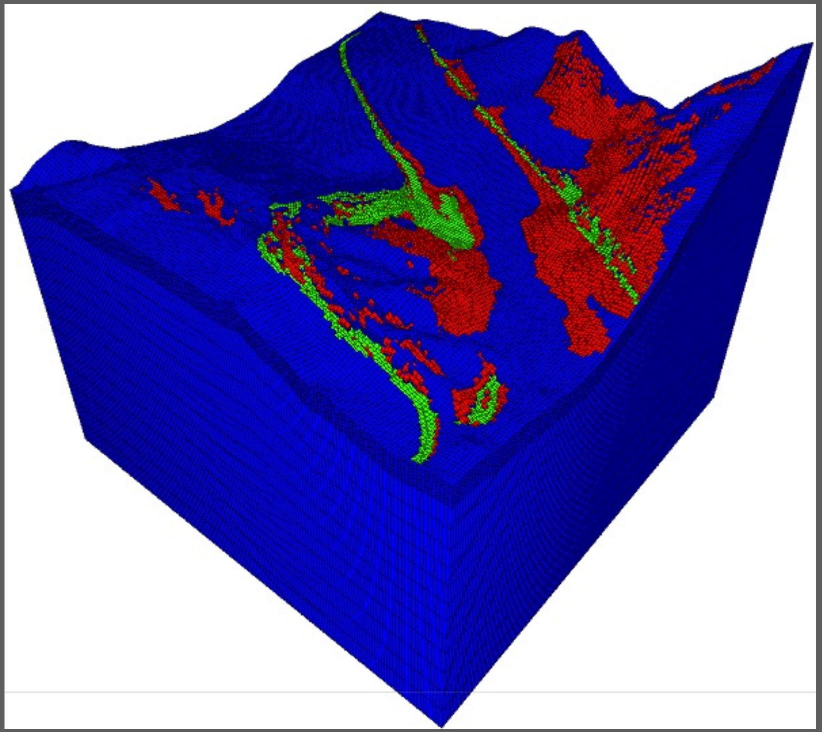
Cohesion (Pa)

- Dark blue = gouge 10^5
- Blue = cataclasite 10^6
- Red = mylonite 10^7
- Green = greywacke 5×10^6

Proximity to failure: dark blue at failure
topographic stresses only (no tectonic)

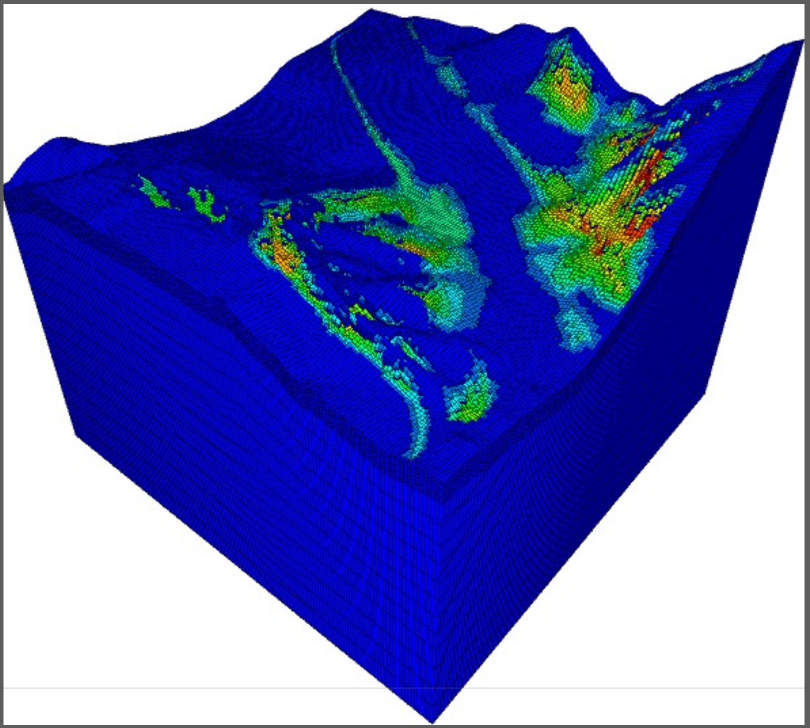


FERM – example from the Waikukupa segment of the Alpine Fault



Different failure modes

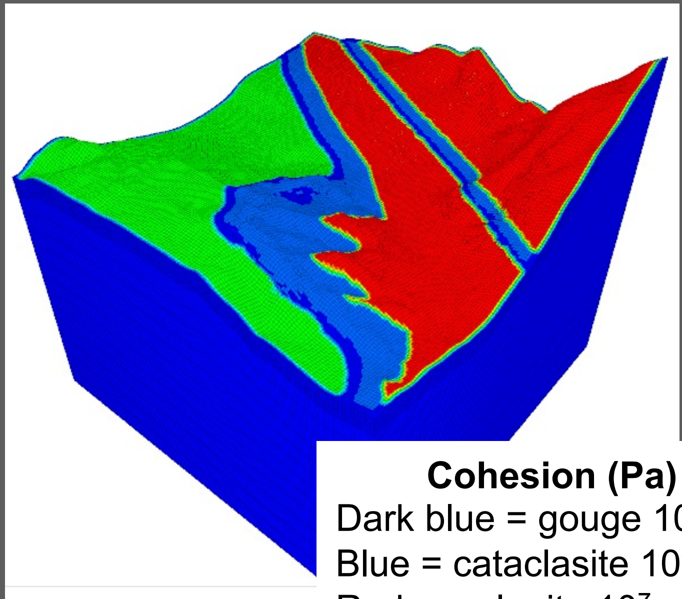
Green = shear
Red = tensile
Blue = none



Amount of material removed

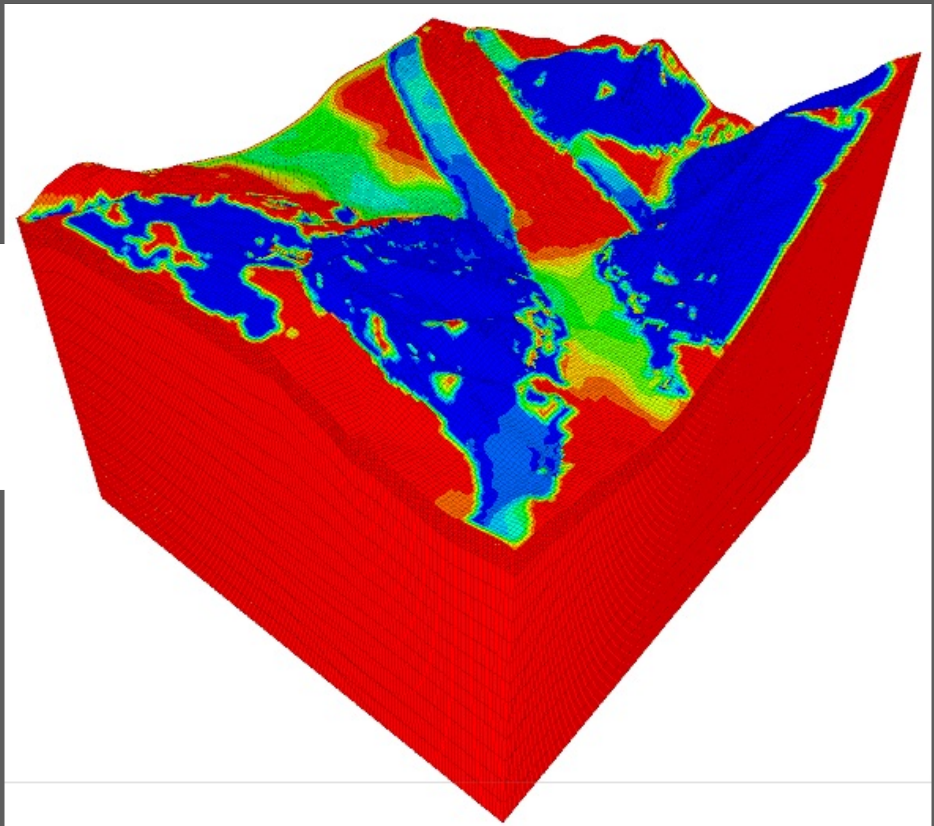
Red = maximum
Blue = zero

FERM – example from the Waikukupa segment of the Alpine Fault – add pore pressure



Proximity to failure: dark blue at failure
topographic stresses only (no tectonic)

Cohesion (Pa)
Dark blue = gouge 10^5
Blue = cataclasite 10^6
Red = mylonite 10^7
Green = greywacke $5x10^6$



Koons and Upton in prep

Challenges

Tectonics:
10^2 to 10^6 years

Extreme events at surface:
seconds, days, decades

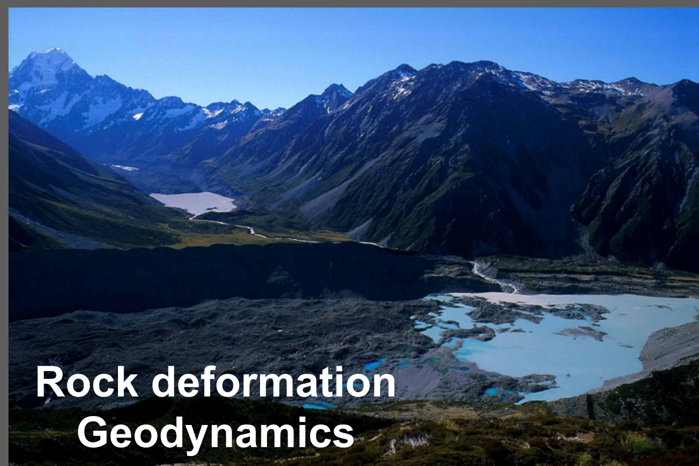
Geodynamics:Earth Surface Processes

Challenges cont.

Communication between the communities (see next slide)

Software:
Extending FERM to realistically model surface processes
Meshless methods
Hydrodynamics, describing particle transport

Hardware



Clarence River, New Zealand

Tectonics and geomorphology by raft