Unifying Tectonics & Surface Processes in Geodynamics

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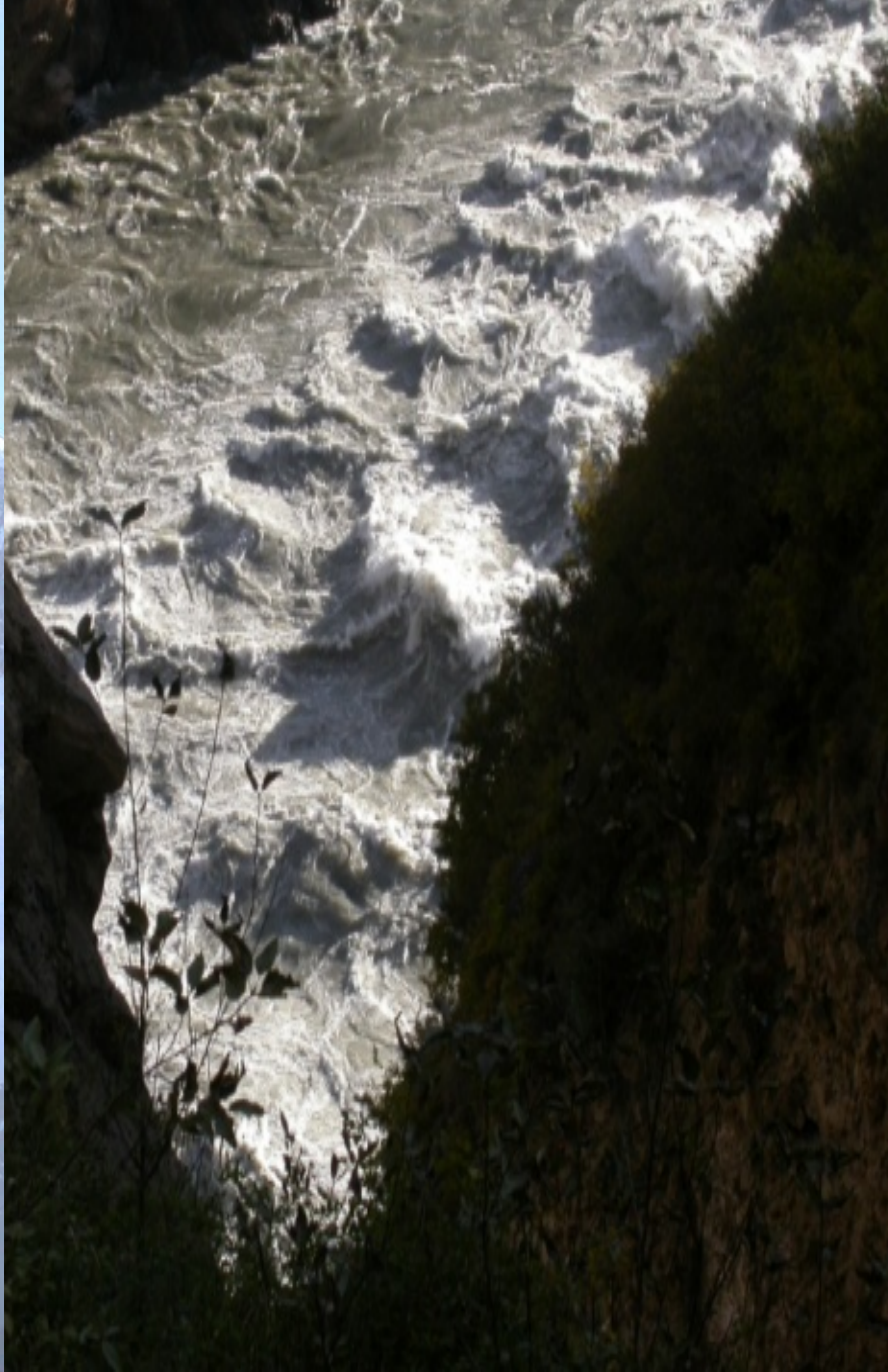
Funding through NSF *Continental Dynamics, CDI, GeoPrism , Tectonics and GLD* Programs



Motivation and Route Map

FERM = Failure Earth Response Model

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

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

Motivation

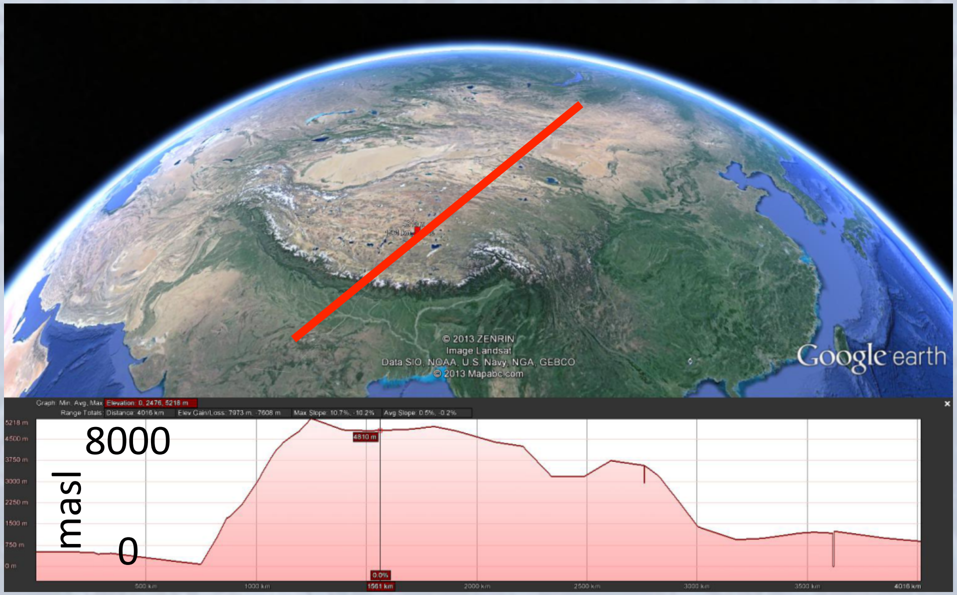
- To identify and use information of multiple temporal frequencies captured in topography
- To generate an additional link of tectonics and topography at high spatial frequencies
- To produce theory based on widely observed physical behavior and material parameters
- To view tempo of earth evolution within a different paradigm

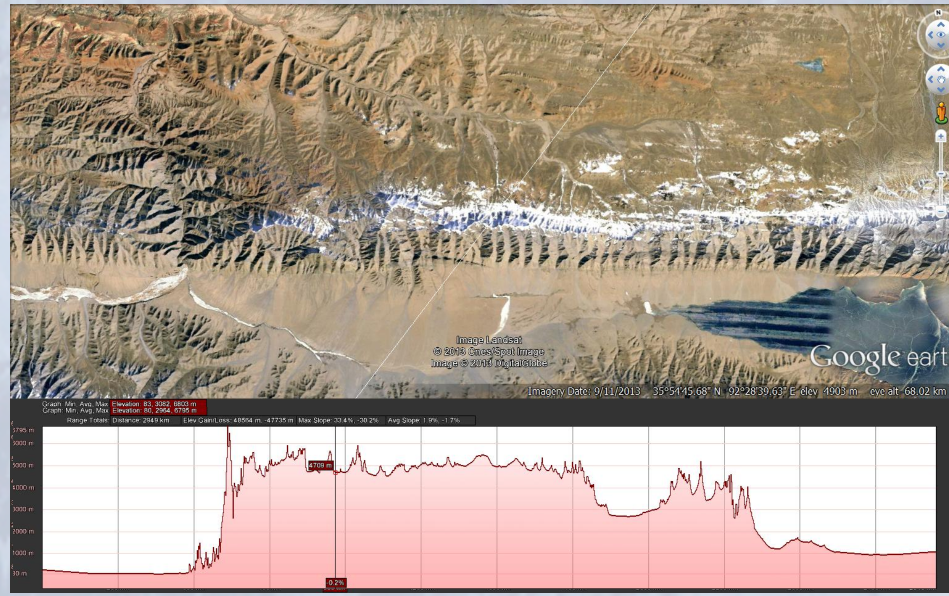
Route: Examine strength:strain relationship at increasing spatial frequencies

- Examine strength:stress relationship for deforming Earth for elevated pore pressures
- Examine strength:stress relationship for deforming Earth at increasing temporal frequencies (plate boundary strain rates to seismic strain rates)

Broadband Earth; Space and Time

- Topography at all frequencies contains critical information on cooperation among tectonic and geomorphic processes.





- Low frequencies are well described in current theory of cooperative phenomena.

- High frequency information is difficult or impossible to extract through conventional theory that does not explicitly permit cooperation.

- Existing landscape theory struggles to incorporate multi-scale cooperation among tectonic and geomorphic processes.

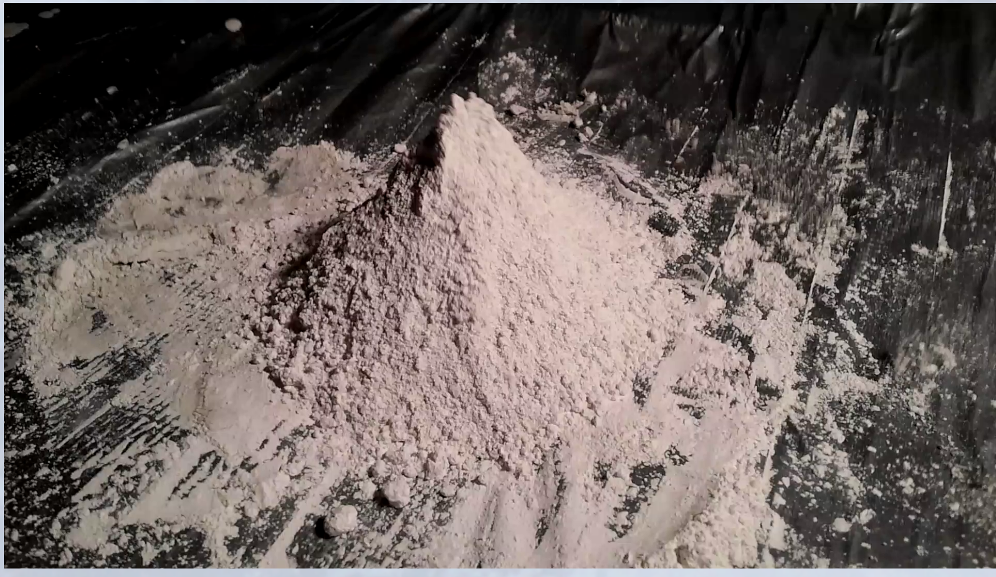
Why Bother?

Modern conventional solutions produce realistic model landscapes with testable solutions *(and great graphics)*.

- Most obvious drawback in conventional solution is that any individual piece of Earth's surface has different physical formulation for the same behavior depending on whether it is seen from above or below.
- Material parameters in conventional theory are difficult or impossible to quantify leading to Rampant Parameterization
- Computational advances are permitting resolution of rapidly varying dynamic 3D fields, Including dynamic stresses associated with varying stream velocities; i.e. the world of theory is changing

Why Bother? (cont):

Recognized components of landscape evolution can not be incorporated within conventional theory; e.g. Seismically Generated Landslides



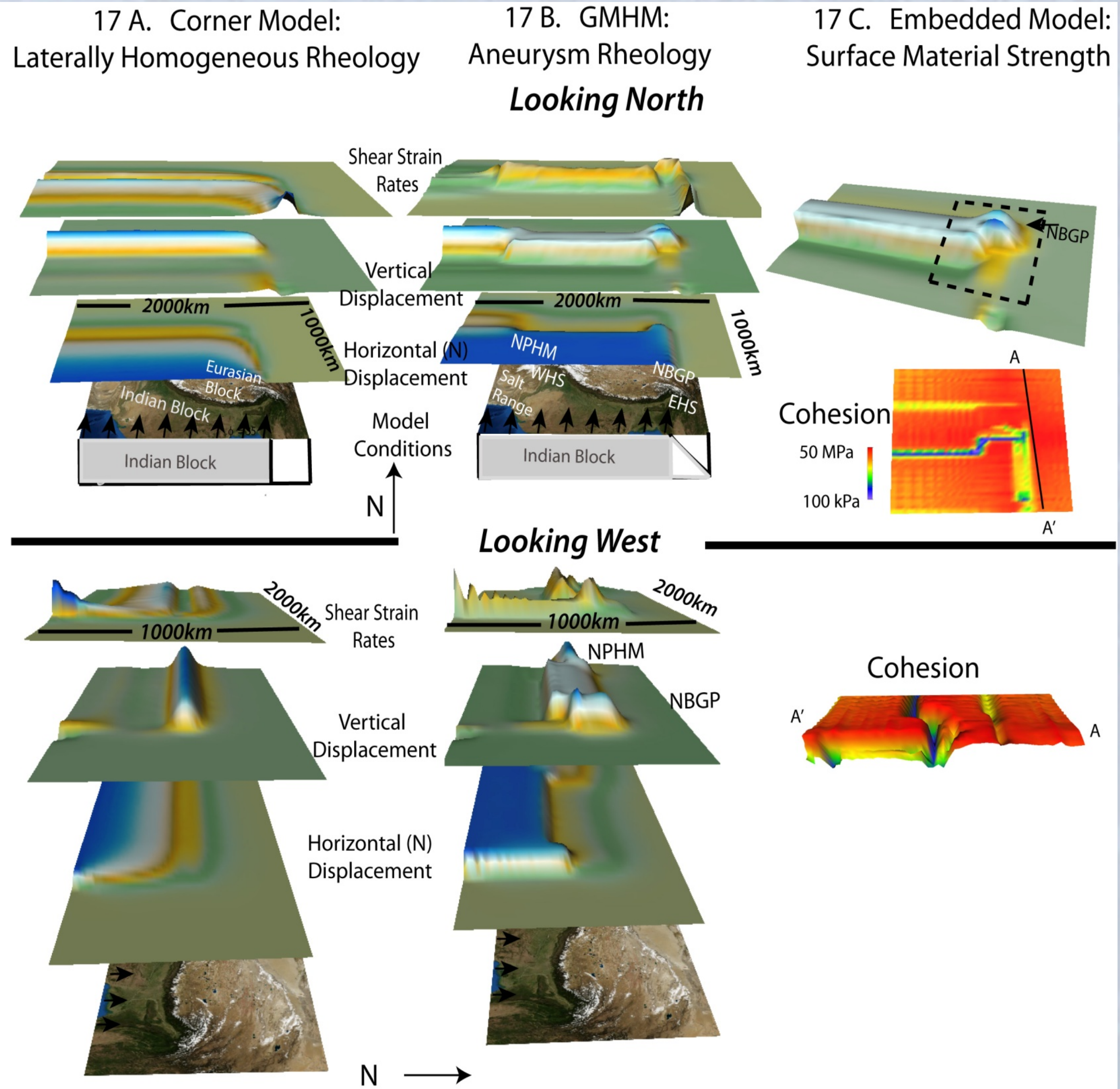
$t_{characteristic}$ = f(Local Seismic Accelerations)

Why Bother? (cont):
Recognized components of landscape evolution can not be incorporated within conventional theory;

e.g. Pore pressure instabilities

$t_{characteristic}$ = f(Effective Stress Transients) = f(Hydrological Regime)

Low Frequency Tectonic Geomorphic Links ~ Advection



After Koons, Zeitler and Hallet, 2012

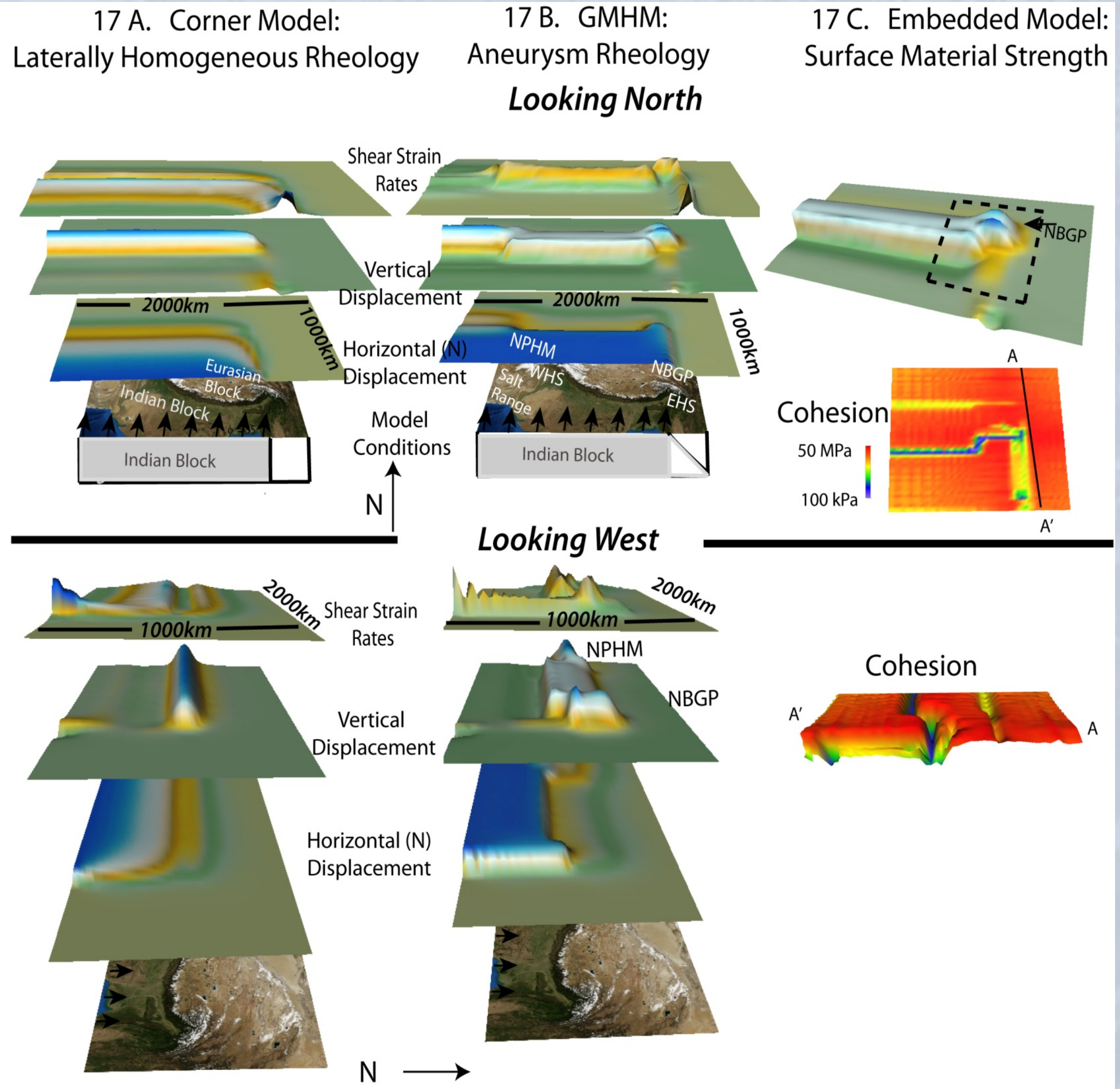
Model Class: Macroscale

<u>Tectonic</u>: Mantle-driven; Strain transmission through thermally-sensitive lithosphere, Pressure-dependent upper crust

<u>Atmospheric:</u> Homogeneous or Orographic precipitation

<u>Interaction</u> = Advection and Mass distribution >~50km (lithospheric scale)

Intermediate Frequency Cooperation = Advection cooperates with Rheology



After Koons, Zeitler and Hallet, 2012

Model Class: <u>Tectonic Aneurysm;</u>
Lithospheric strength= f(Advection);
Advection = f(Lithospheric strength)

<u>Tectonic</u>: As above, + Exhumation-related thermal thinning of Pressure-dependent upper crust

<u>Atmospheric:</u> As above, + Vigorous and vicious spatially-concentrated fluvial and glacial erosion.

<u>Interaction</u> = As Above, + Thermal weakening and strain concentration in regions of concentrated erosion: Result: association of highest peaks with biggest rivers.
>~20km (crustal scale)

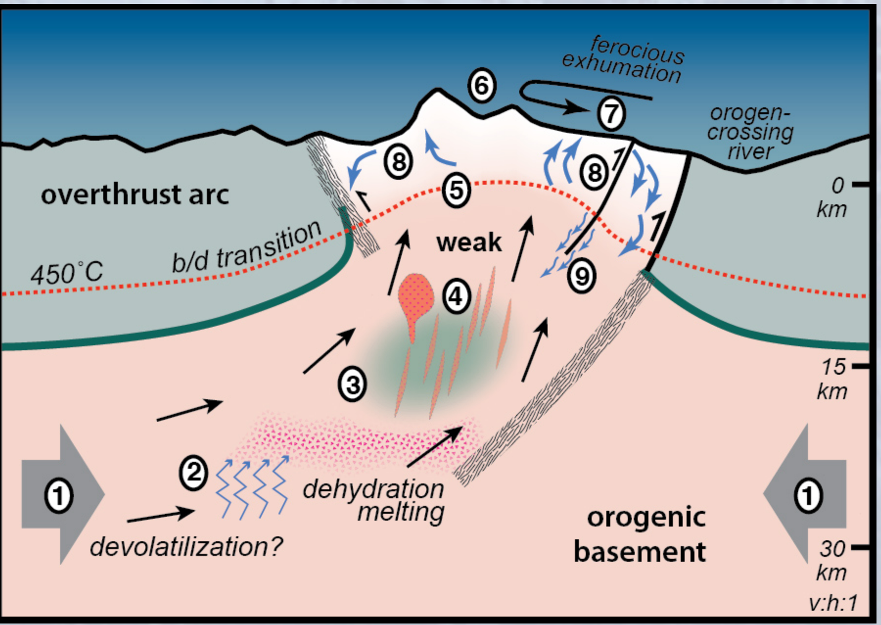
Intermediate Frequency Example of Tectonic Geomorphic Cooperation Make *Strength* a function of Kinematics and *Kinematics* a function of Strength and erode the beast

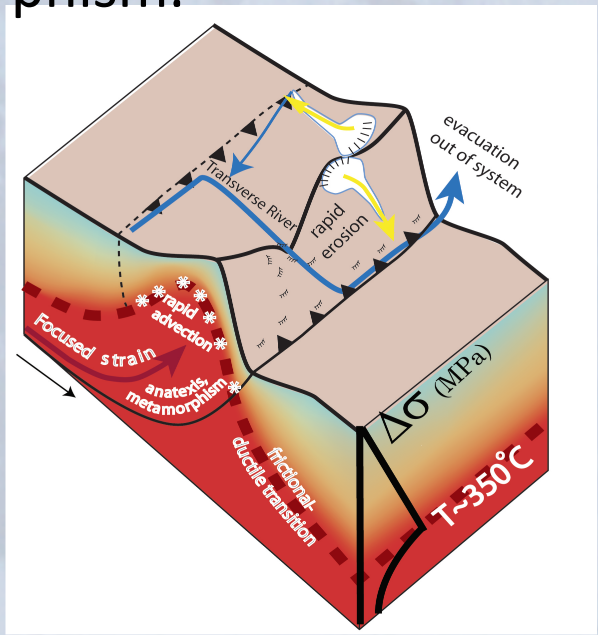
(Velocity)= f(Erosion); Temperature =f(Velocity)

Strength = f(Temperature); ∴ Strength = f(Velocity)

Resulting Tectonic Aneurysm

incorporates surface processes as a major driver of kinematics and metamorphism.





In: Koons, Zeitler and Hallet, 2012
Compiled from work of thousands plus Craw

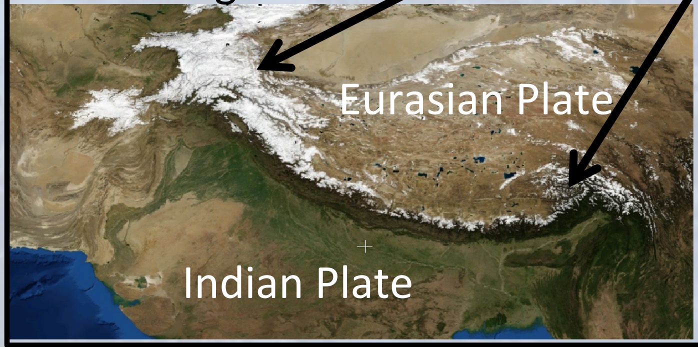
3 Tectonic Aneurysms:

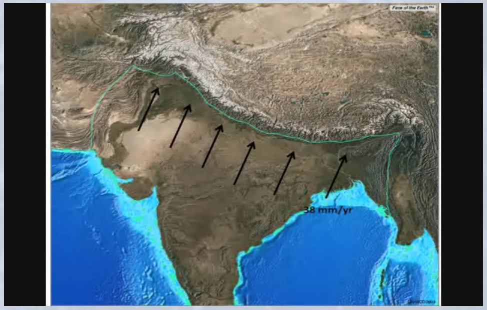
Erosion Influences Velocity - Influences Strength - Influences Velocity

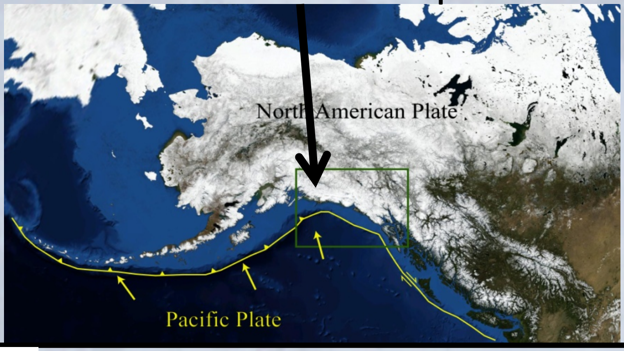
Nanga Parbat : Indus

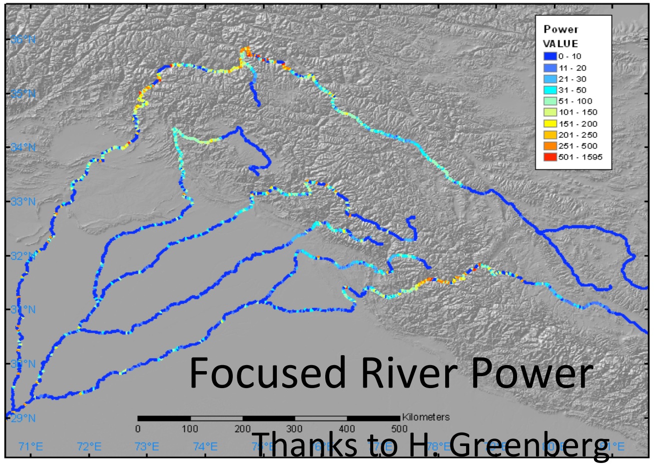
Namche Barwa : Tsangpo

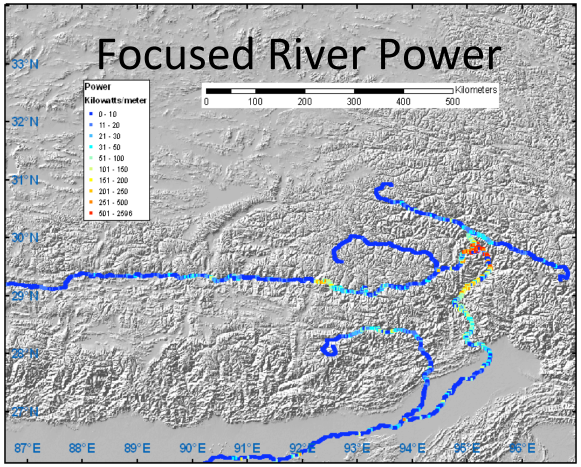
St Elias : Malaspina

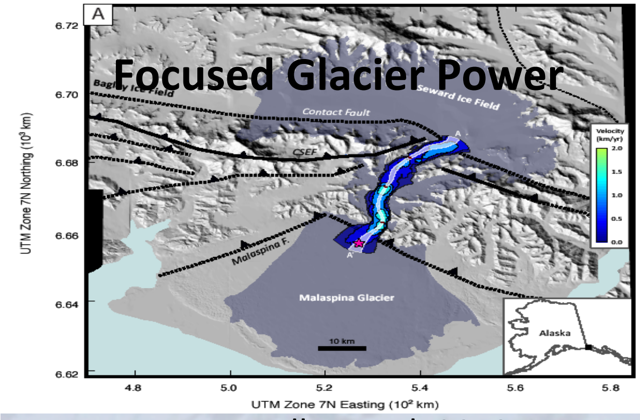








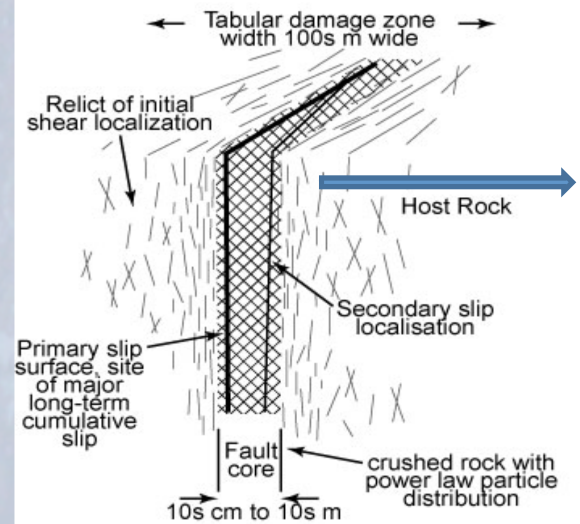




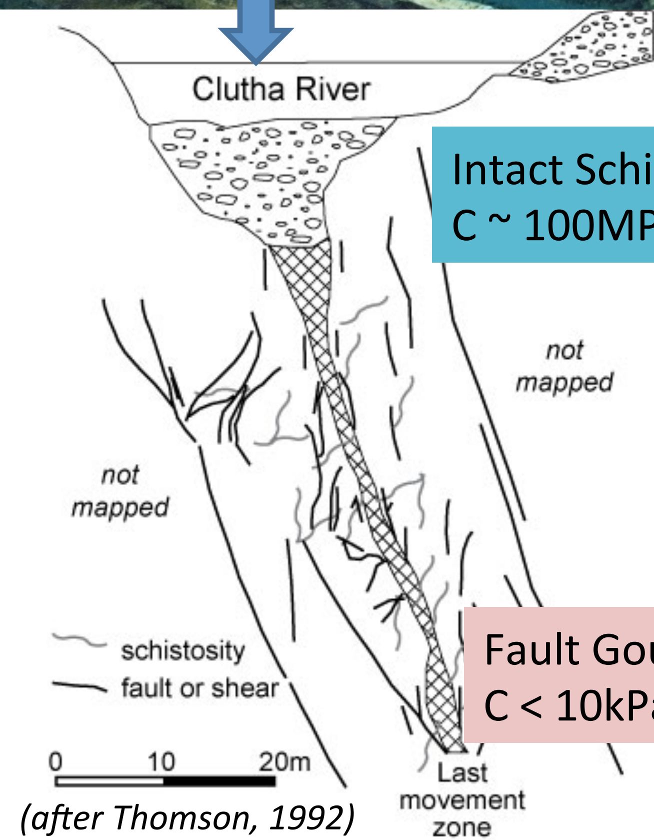
From Headley et al. 2013

Higher Frequency: Strength = f(Strain)

Natural Example: River Channel Fault Zone, Clyde Dam, South Island, N.Z. from Geology, Drilling, Excavation



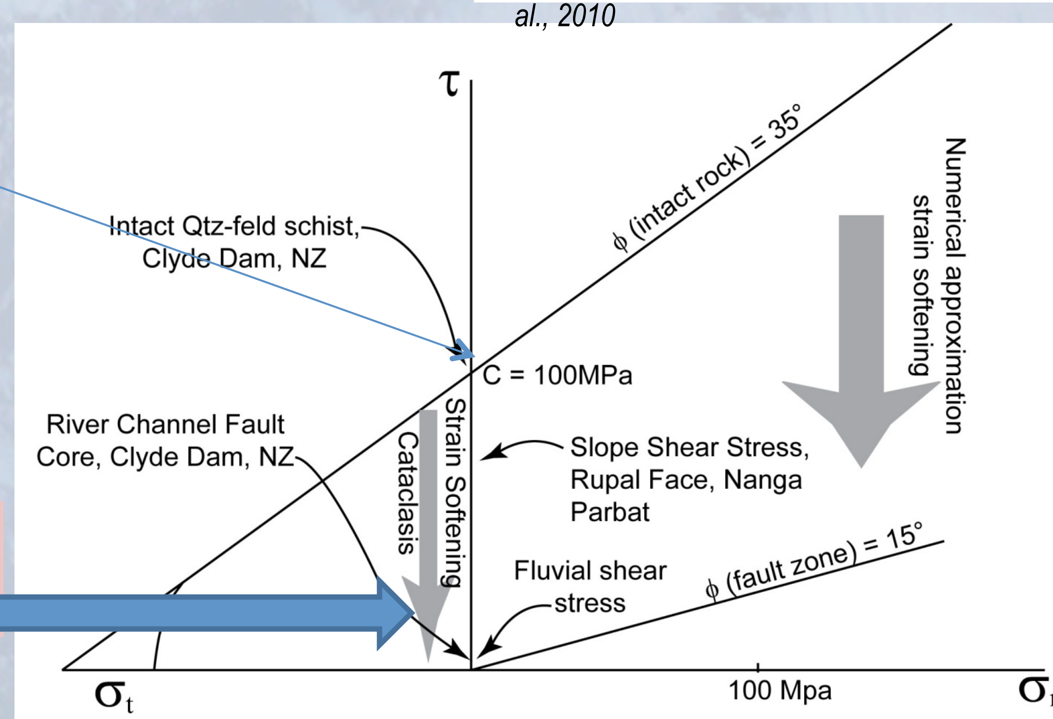
After Chester and Logan, 1986; Ben Zion and Sammis, 2003; Mooney et al 2007; Koons et al., 2010



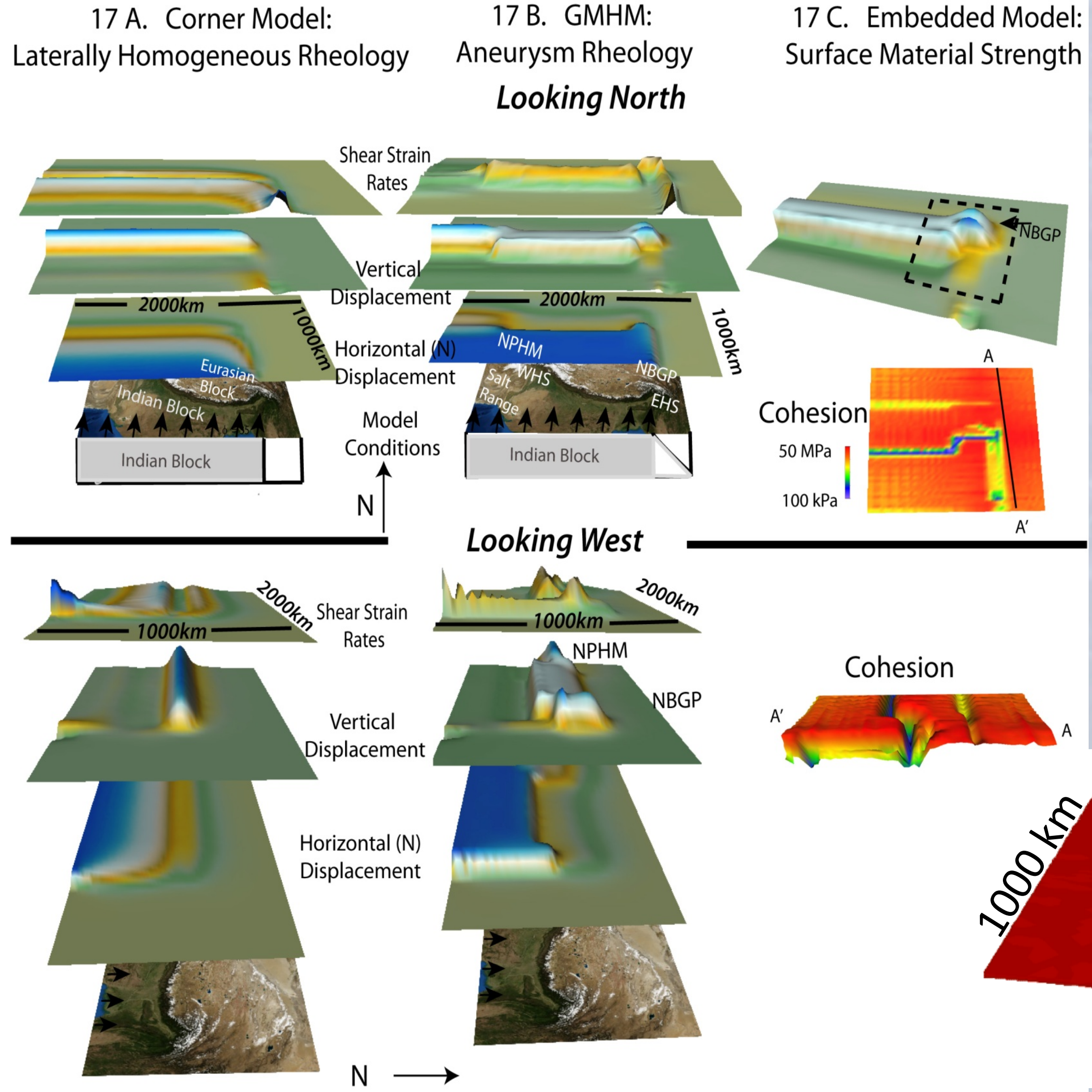
(after Thomson, 1992)

Intact Schist
C ~ 100MPa

Fault Gouge Core:
C < 10kPa



High-Frequency Cooperation: 1a
Strength= f(Strain)



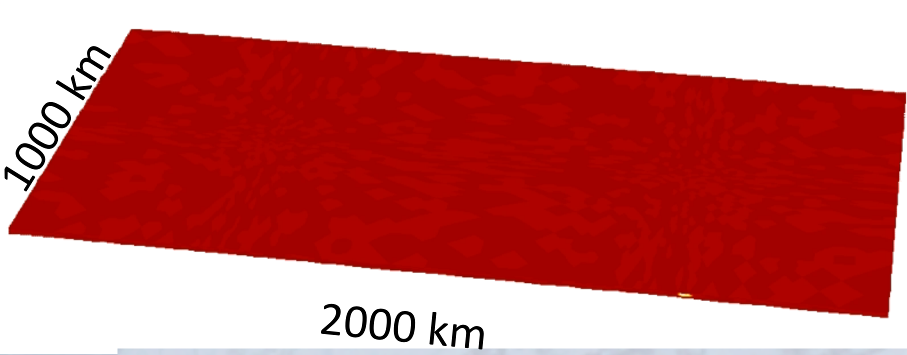
After Koons, Zeitler and Hallet, 2012

Model Class: Strain softening: Earth as Memory Material

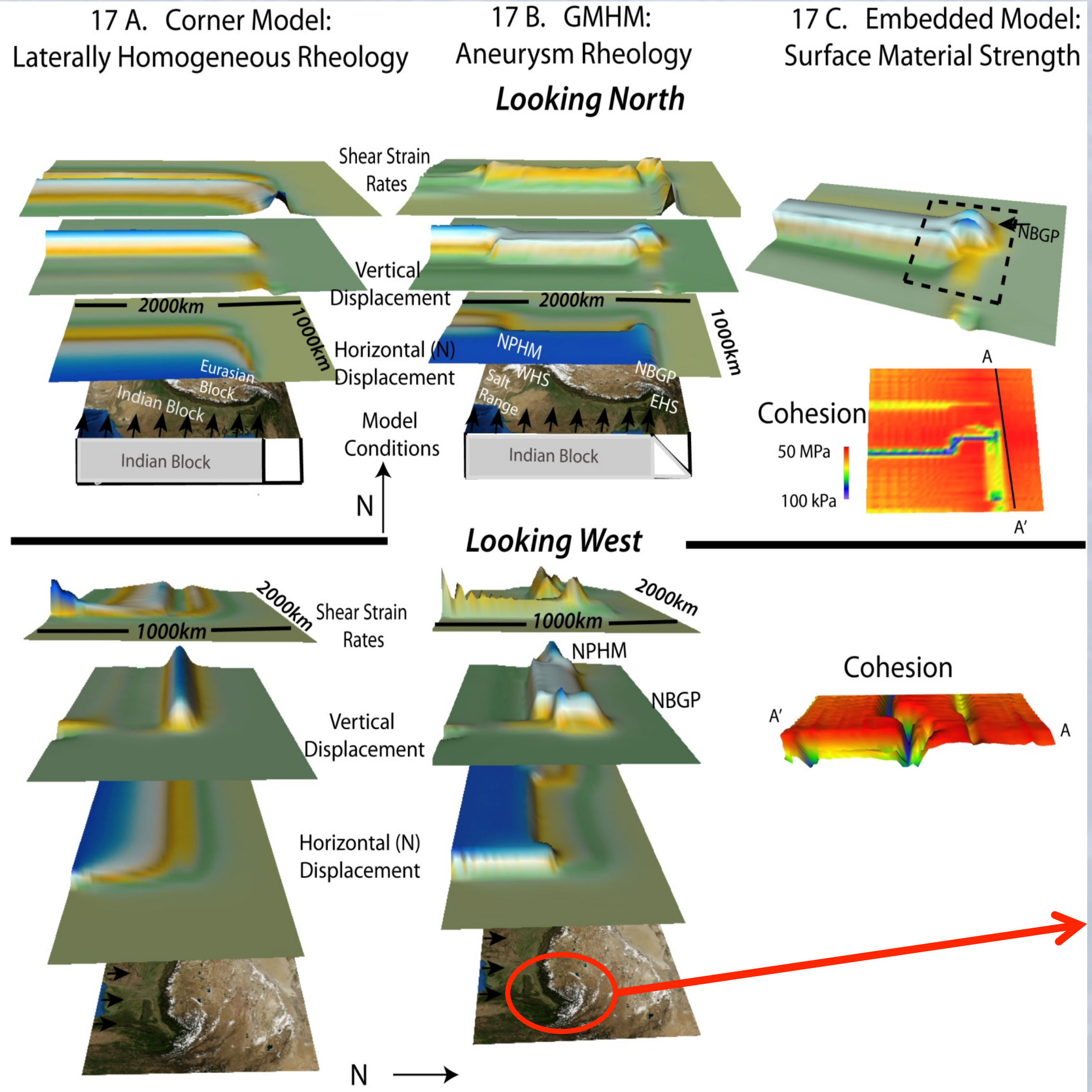
Tectonic: As above, + Strain-weakening along fault damage zones in upper crust

Atmospheric: As above, + Material properties are spatially and temporally variable and a function of far field plate kinematics

Interaction = As Above, + Topographic fabric reflects tectonic fabric at all scales >~1m.



High-Frequency Cooperation: 1b
Strength= f(Strain)



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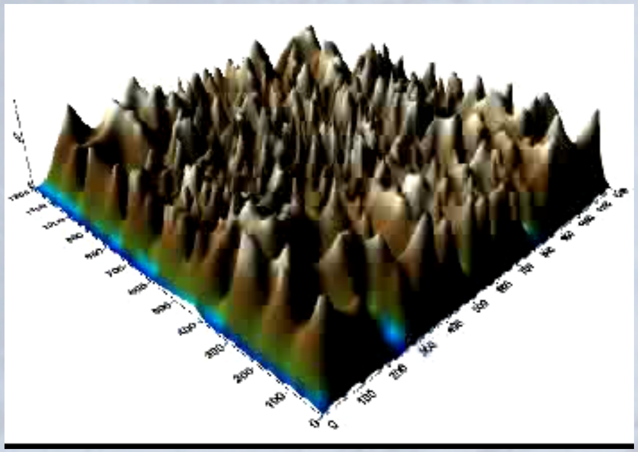
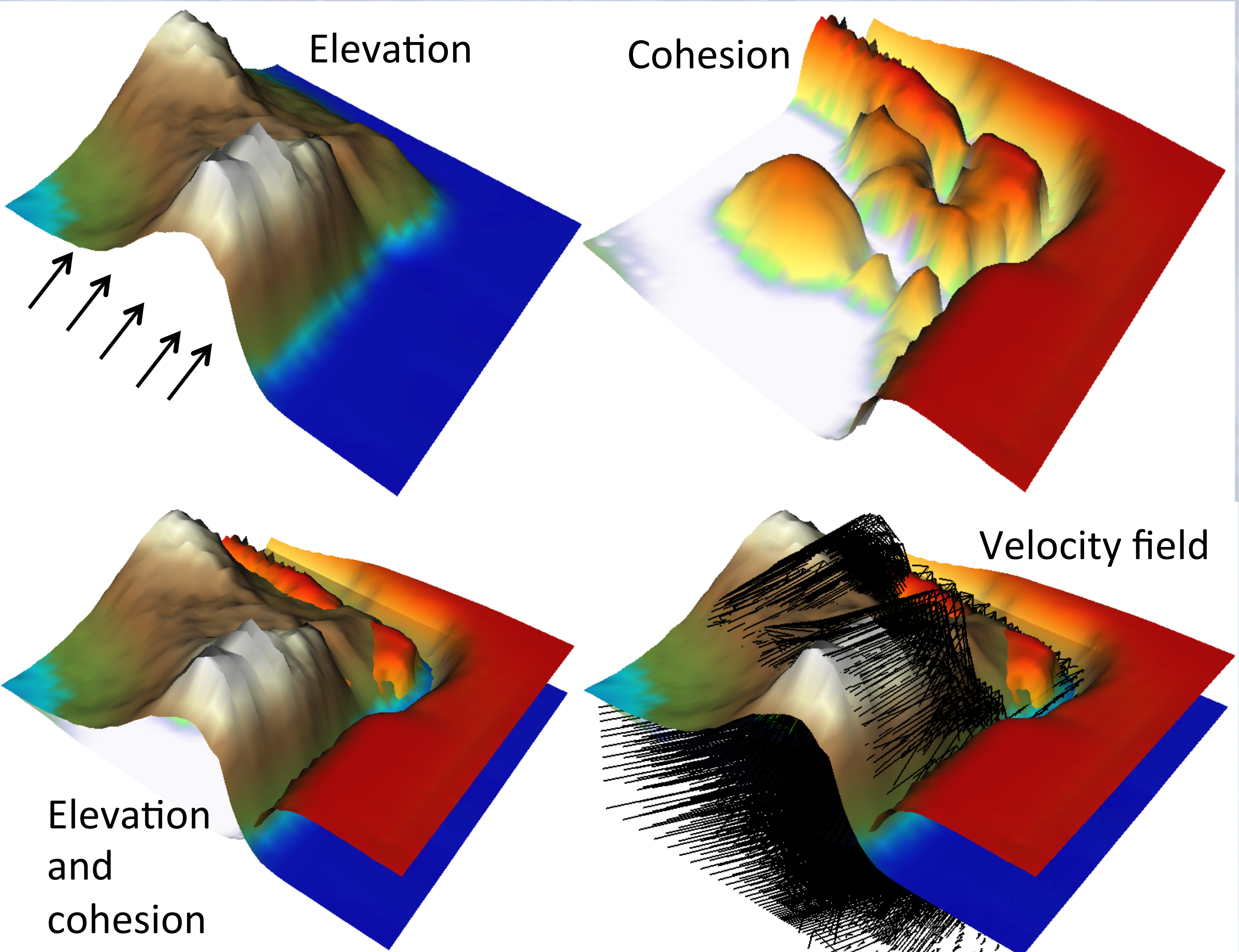
<u>Tectonic</u>: As above, + Strain-weakening along fault damage zones in upper crust

<u>Atmospheric:</u> As above, + Material properties are spatially and temporally variable and a function of far field plate kinematics

<u>Interaction</u> = Fully coupled



Intermediate Implications of Strain:Strength Cooperation



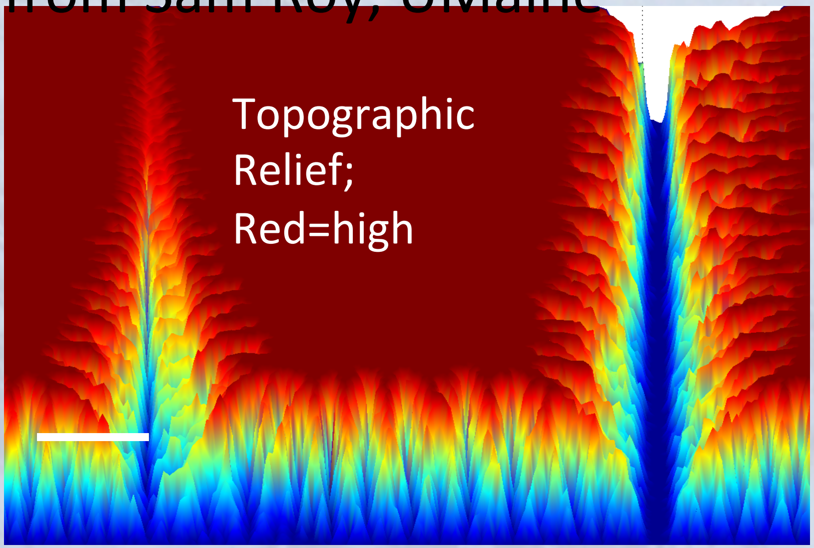
Both strain and erosion avoid the high strength blocks

Evolution toward a pattern of isolated high-strength massifs surrounded by shear zones is an inherent characteristic of the coupling of strain and strength

These patterns are very persistent

At moderate to high frequencies, Strength structure rules

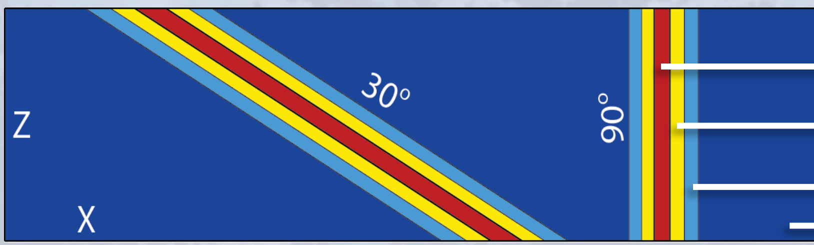
Example of Strength:Strain link from Sam Roy, UMaine



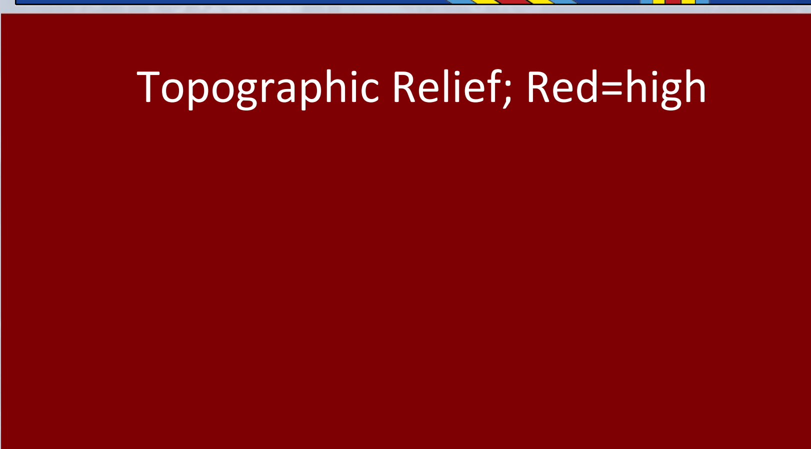
Hypothesis: Fault orientation Influences stream incision rates
(therefore influences all dependent features e.g. hillslope orientation etc…)

Test using CHILD (Tucker, 1999) Surface Process model modified by Roy (2013) to permit fault plane strain softening to material properties.

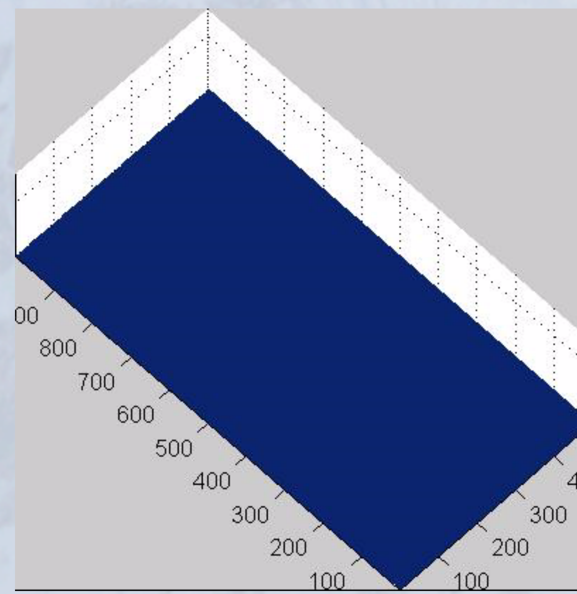
Simplifications for this specific model are:
Detachment-limited, Constant precip…



Cohesion gradient:
100 kPa
1 MPa
10 MPa
30 MPa



Dipping fault lateral migration
(see SG Roy; Umaine Geodynamics



Intermediate Conclusions

Valleys are weak; Ridges are strong *(*Cols are weak- Buttresses are strong…….)

∴ *Heterogeneity from the beginning*

Strength anisotropy is a fundamental landscape control in all Orogens and *reduces* complexity of surface

∴ *Topography and Rates are, consequently, anisotropic*

3D strength structure contains a dominant record of Strain history

∴ *Provides a long lived landscape memory of mantle kinematics*

Still some problems and opportunities:

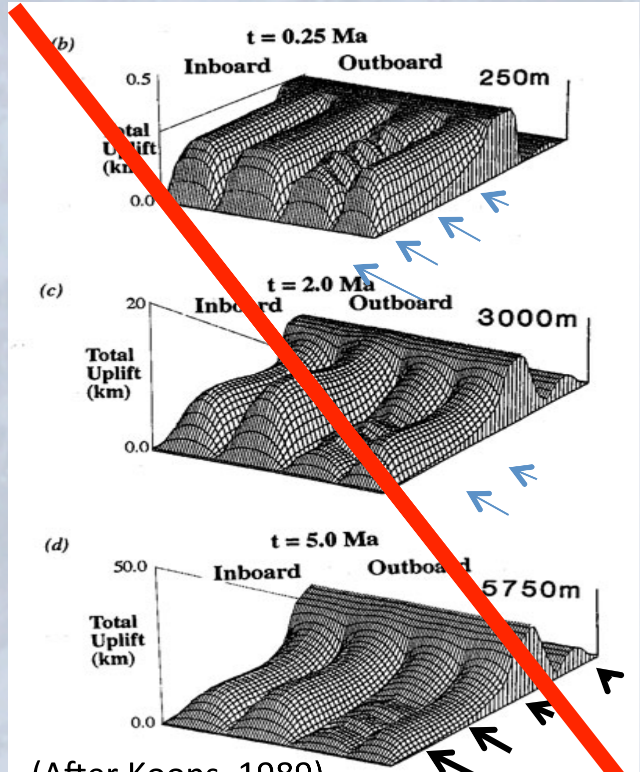
Physics of Earth dependent on whether viewed from below or above.

i.e. Same Earth: Multiple formulations.

Onto Ferm I. *Material displacement, whether tectonic or geomorphic in origin, at or below Earth's surface, is driven by local forces overcoming local resistance.*

<u>3D Strength:Stress</u> field and its time-evolution are the critical controlling parameters of unified model

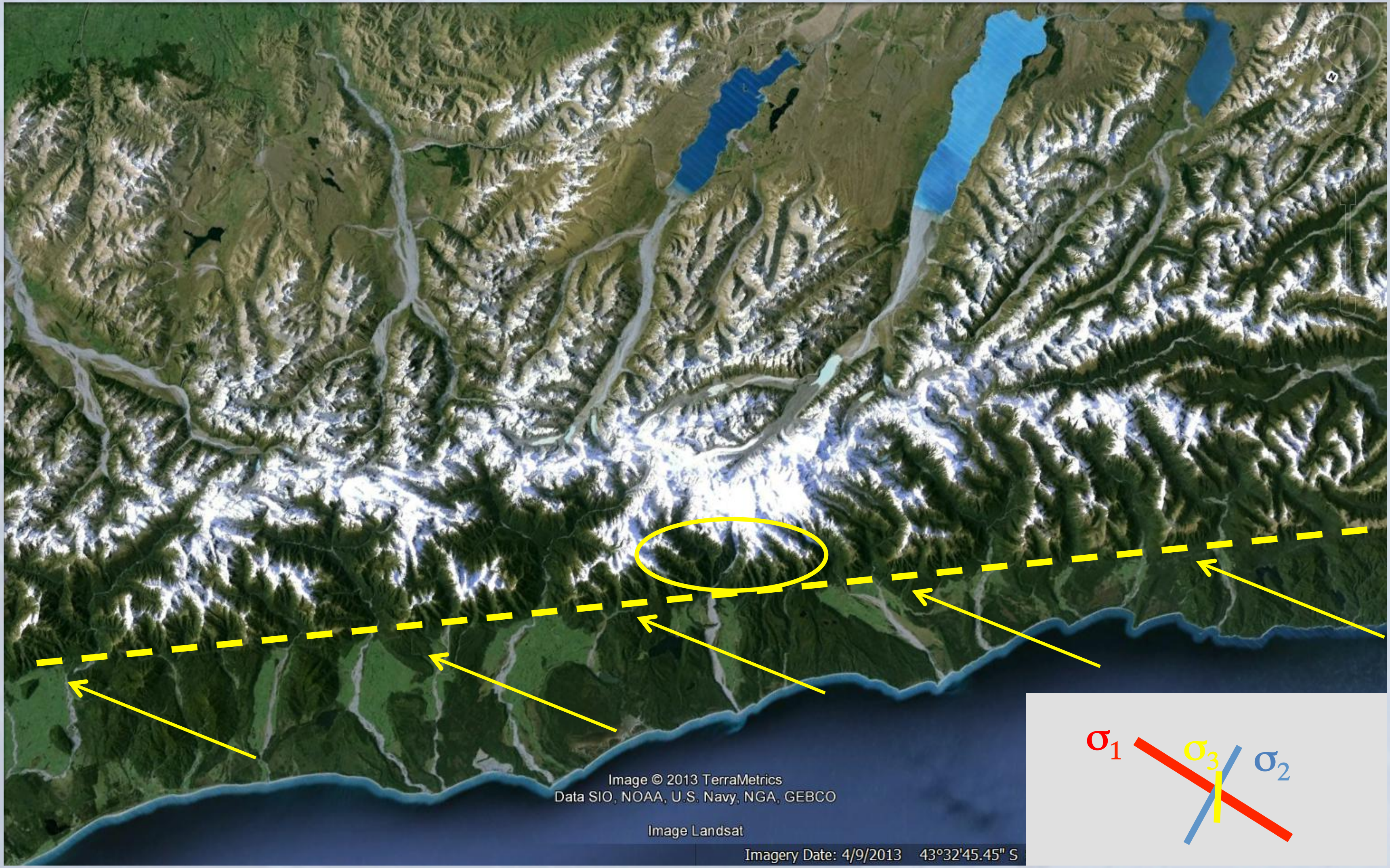
(Photo by E. Fordyce)



(After Koons, 1989)

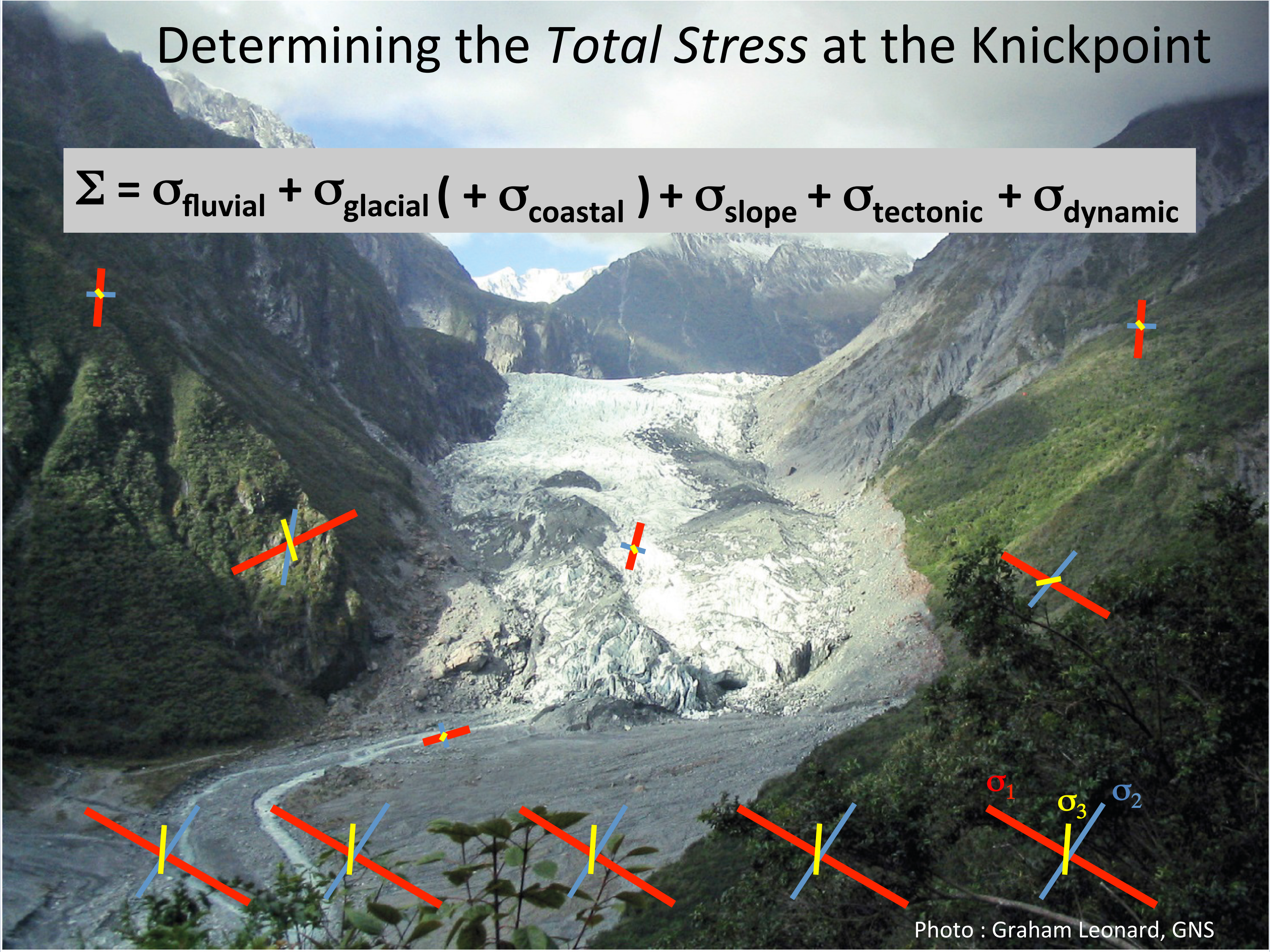
Determining the State of Stress at a Knickpoint

i.e.; In conventional theory, geomorphic stress > threshold strength for detachment



Determining the *Total Stress* at the Knickpoint

$$\Sigma = \sigma_{fluvial} + \sigma_{glacial} \; (+ \sigma_{coastal}) + \sigma_{slope} + \sigma_{tectonic} + \sigma_{dynamic}$$



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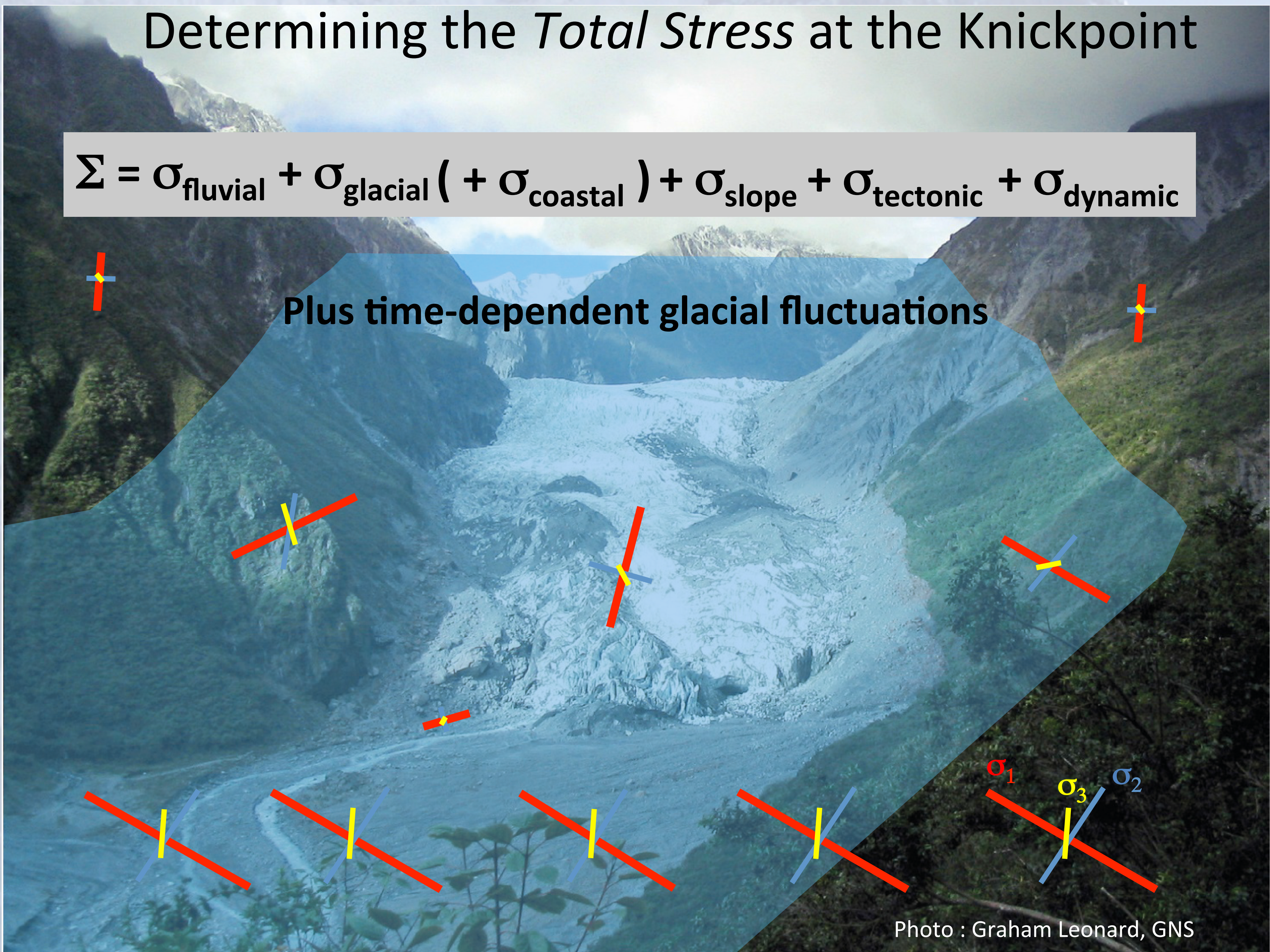


Photo : Graham Leonard, GNS

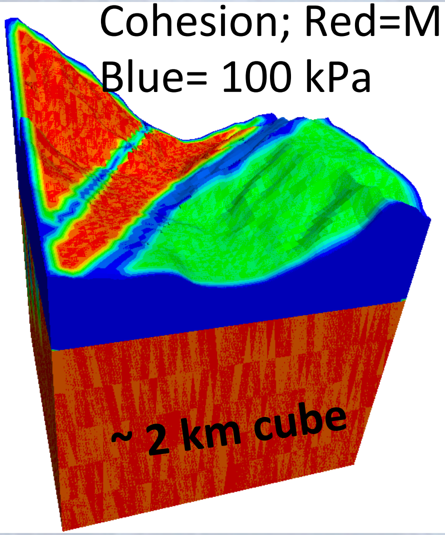
Construction of *FERM*

For each point:

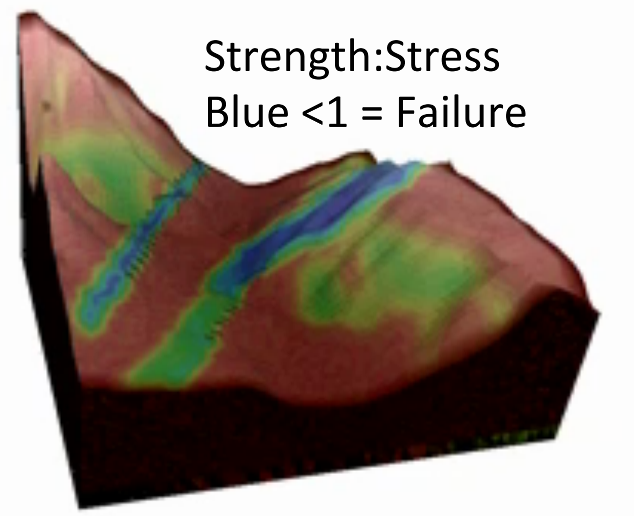
1. Re-formulate failure criteria in single, Geo-referenced (Cartesian) coordinate frame.
2. Sum all stresses: Geomorphic (slope and inertial), Tectonic (Static and Dynamic) into a single ***Total Stress*** tensor
3. Describe Earth failure using effective stress formulation, incorporating local fluid pressure
4. Allow *time-dependent* strength material behavior
5. Solve in 3D with a mesh/meshless method. *(no transport in these models)*

FERM Example: Waikakupa Landslide: Alpine Fault West Coast N.Z. *From Phaedra Upton's poster*

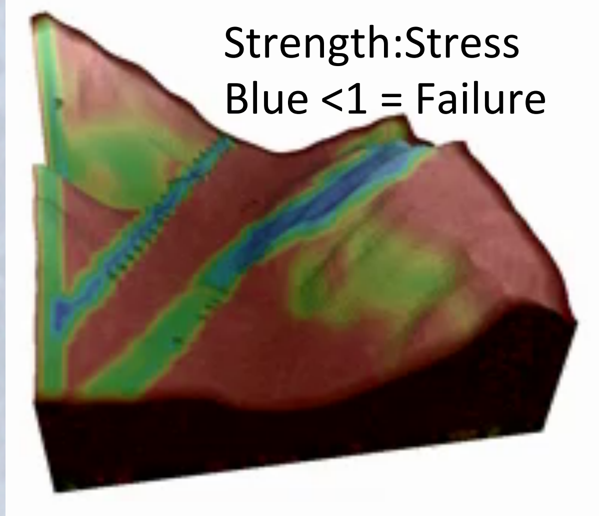
Strength



Add Fluid Pressure

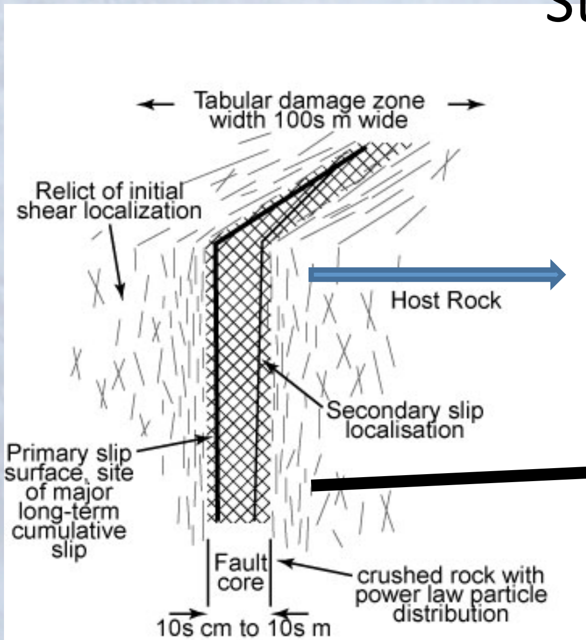


Add Tectonic Stress

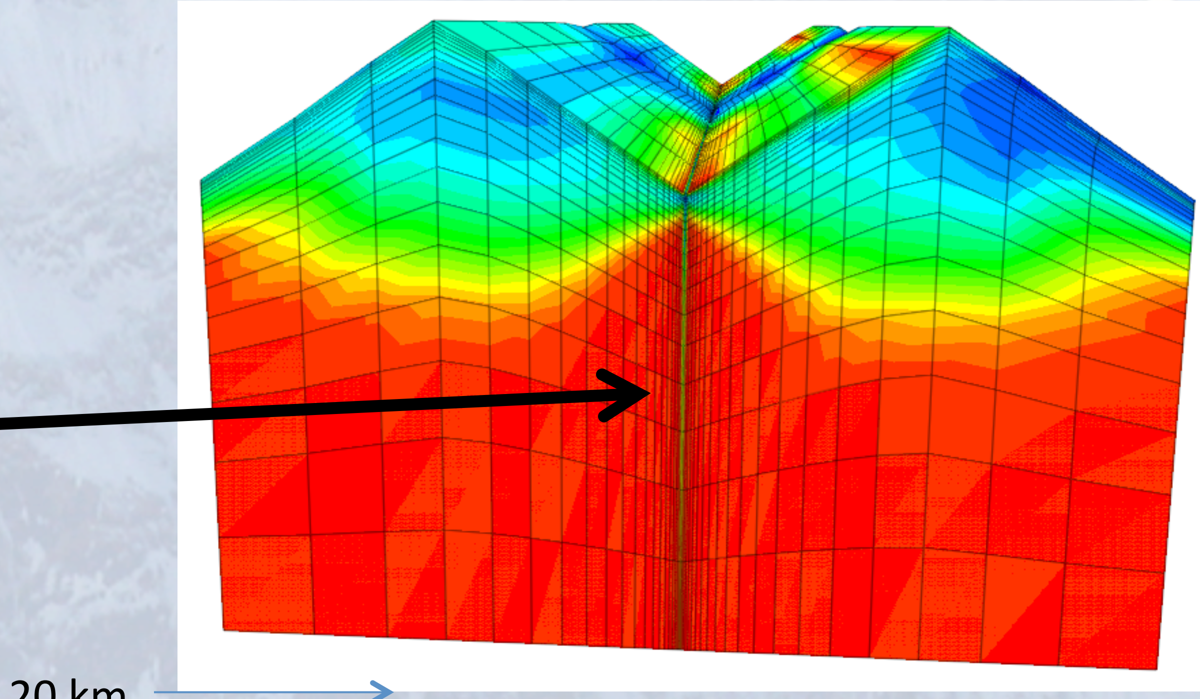


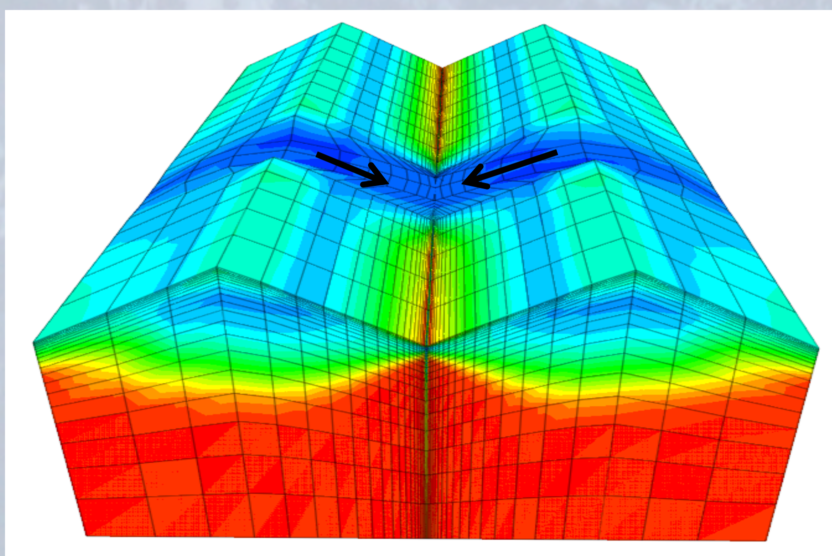
The shape of the Strength:Stress field in 3D and t reflects the source of perturbations

Strength: Stress Ratio : Blue ~1 = Failure; Red ~ 10



After Chester and Logan, 1986; Ben Zion and Sammis, 2003; Mooney et al 2007; Koons et al., 2010





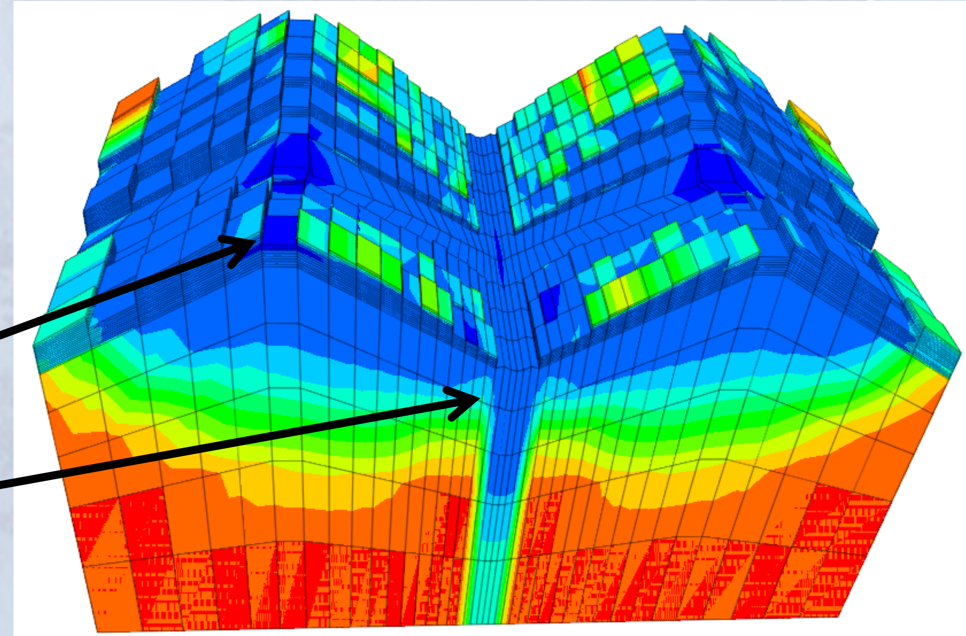
Alter the Strength:Stress ratio by:

1) Pre-existing weaker material
2) Fault damage (strain weaken)
3) Elevate Pore Pressure (Effective Stress formulation)
4) Alter Tectonic Stresses
5) Introduce Dynamic Stress due to Seismic Acceleration
6) All of the above

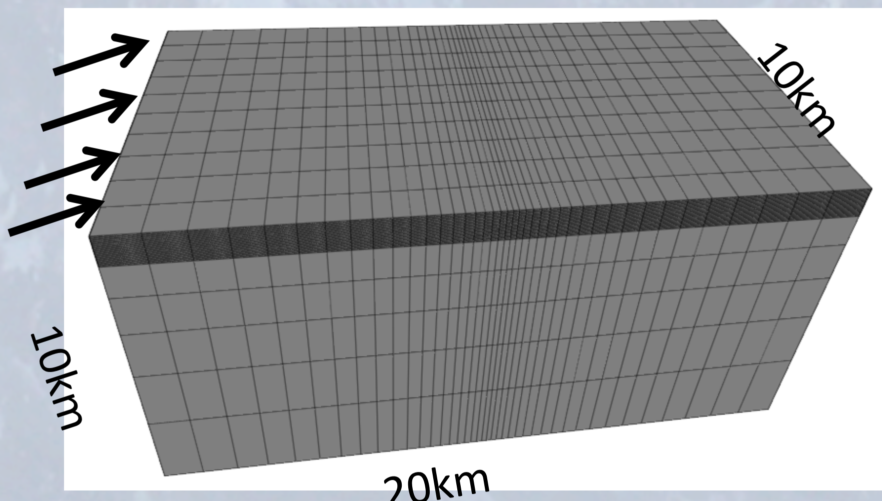
And the results are predictable

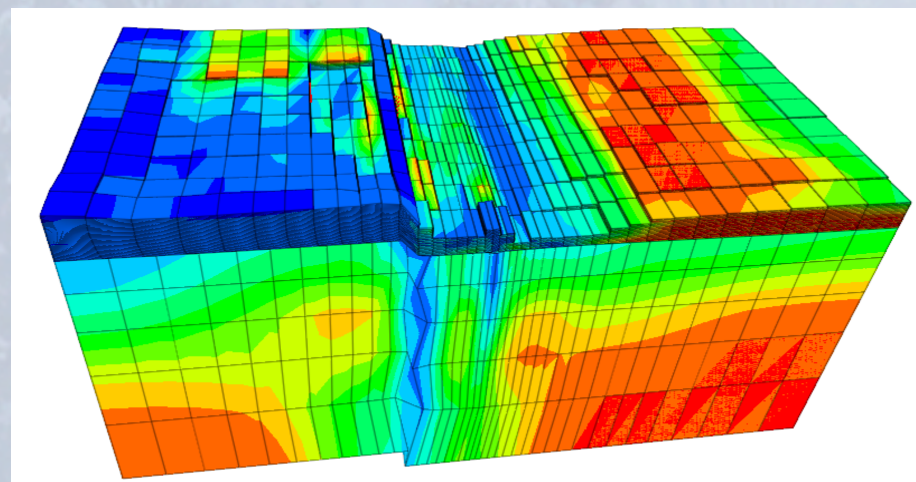
Introduce Normal and Shear Stresses (*Coordinate*) along valley floor:

- Tensile failure along ridge summits and steep faces
- Stress State of incising valley/slope ensemble is continuous and physically reasonable



Introduce Oblique convergence

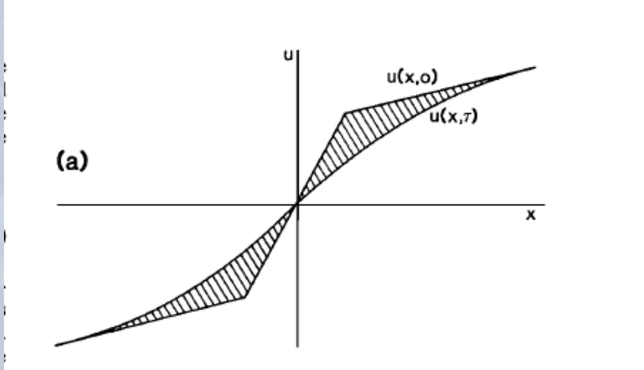




Strength: Stress Ratio : Blue ~1 = Failure; Red ~ 10

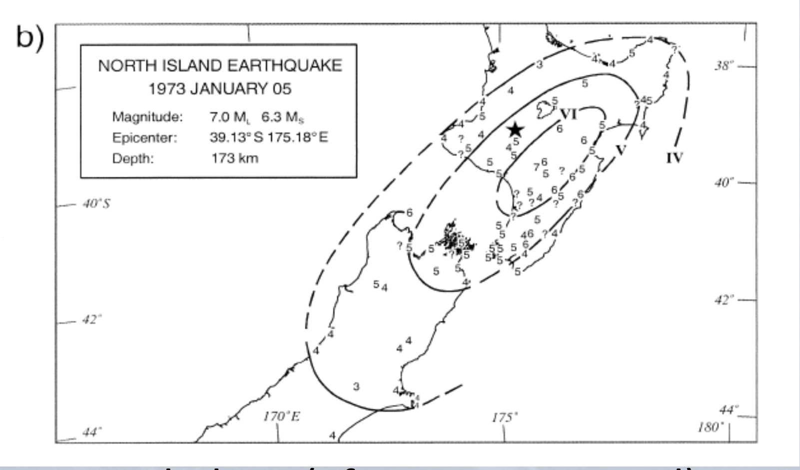
Dynamics: Earth Acceleration Response Spectra

Return to one historical motivation of all this
Landscape evolution and seismic hazard.
Scarp diffusion (here from Andrews and Hanks, 1985)

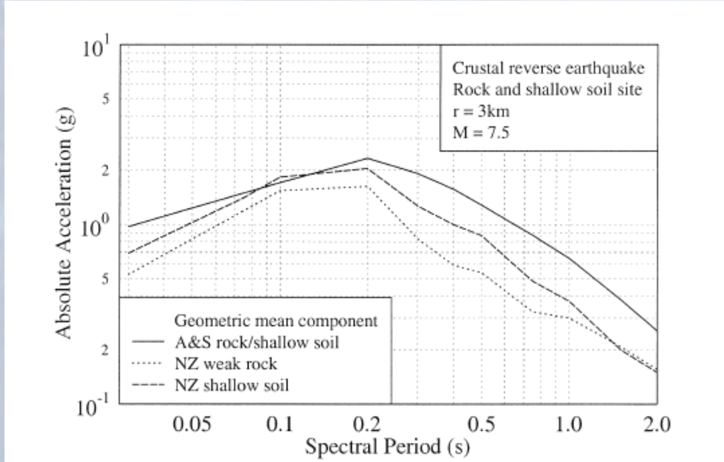


FERM view of Seismic Hazard

I. Stress:Strength relationship influenced by seismic acceleration
II. Earth response = f (local stress state, 3D acceleration as f(period)
III. Time and space pattern of acceleration field contains information on nature, proximity and timing of source



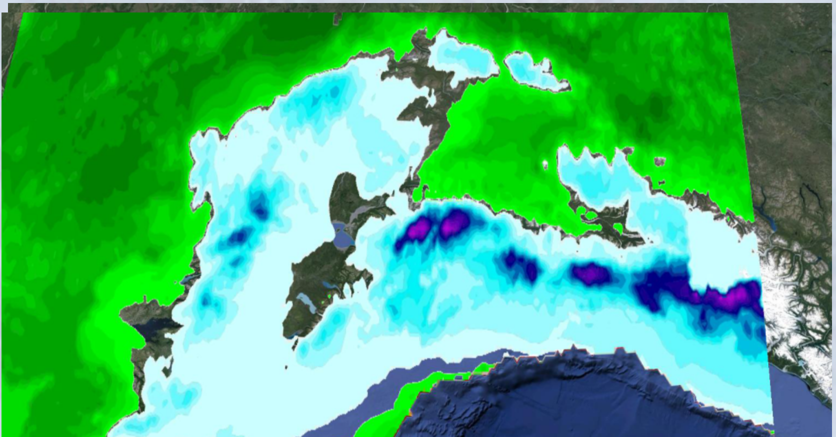
MM shaking (after McVerry et al)



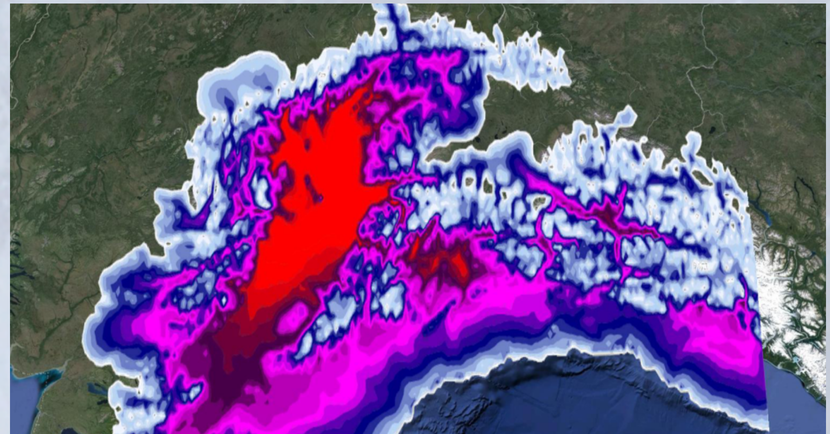
NZ Spectral response after Abramson and Silva, 1997

FERM Example: Last Glacial Maximum Load and Velocities, Southeast Alaska;

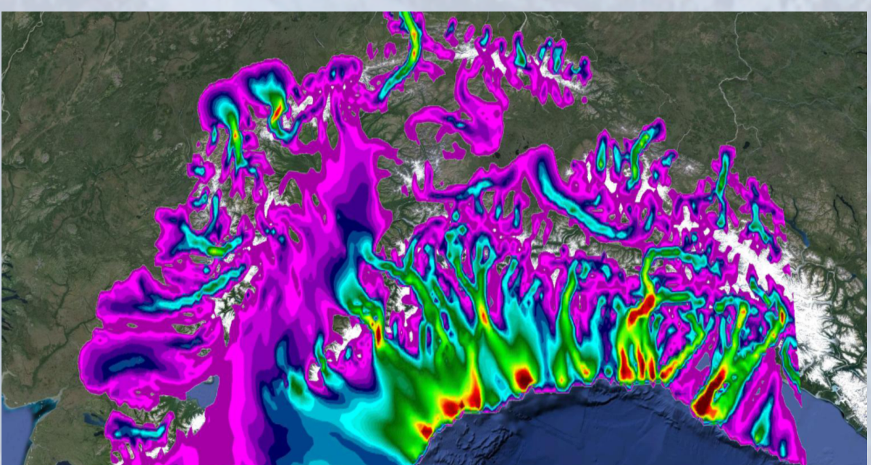
Climate and Glacier Models by Sean Birkel, Geodynamics by Lauren Wheeler, Upton, Koons, U Maine
In cooperation with B. Hallet, A. Barker, U.Washington



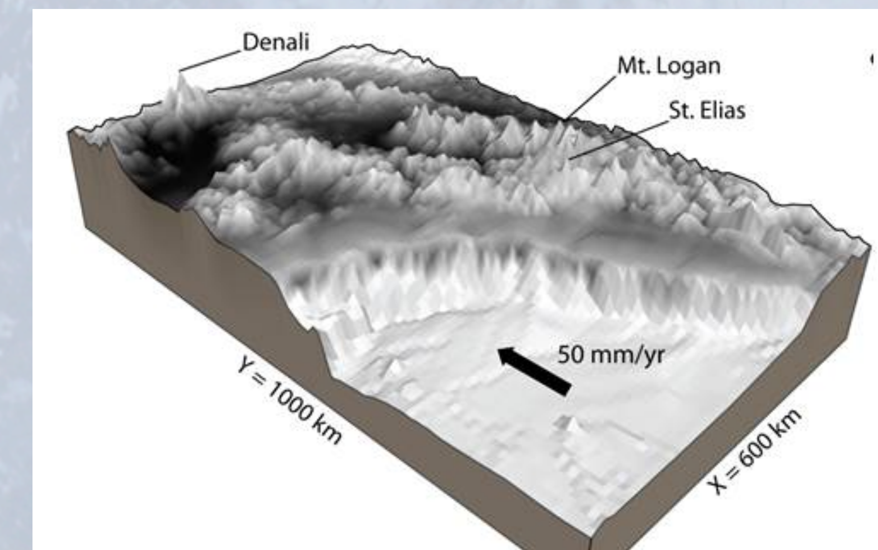
LGM Mass Balance; Blue=high



LGM Ice Thickness; Red=high



LGM Ice Velocity; Red=high



LGM Geodynamic Model; Vertical Stress

Some Implications

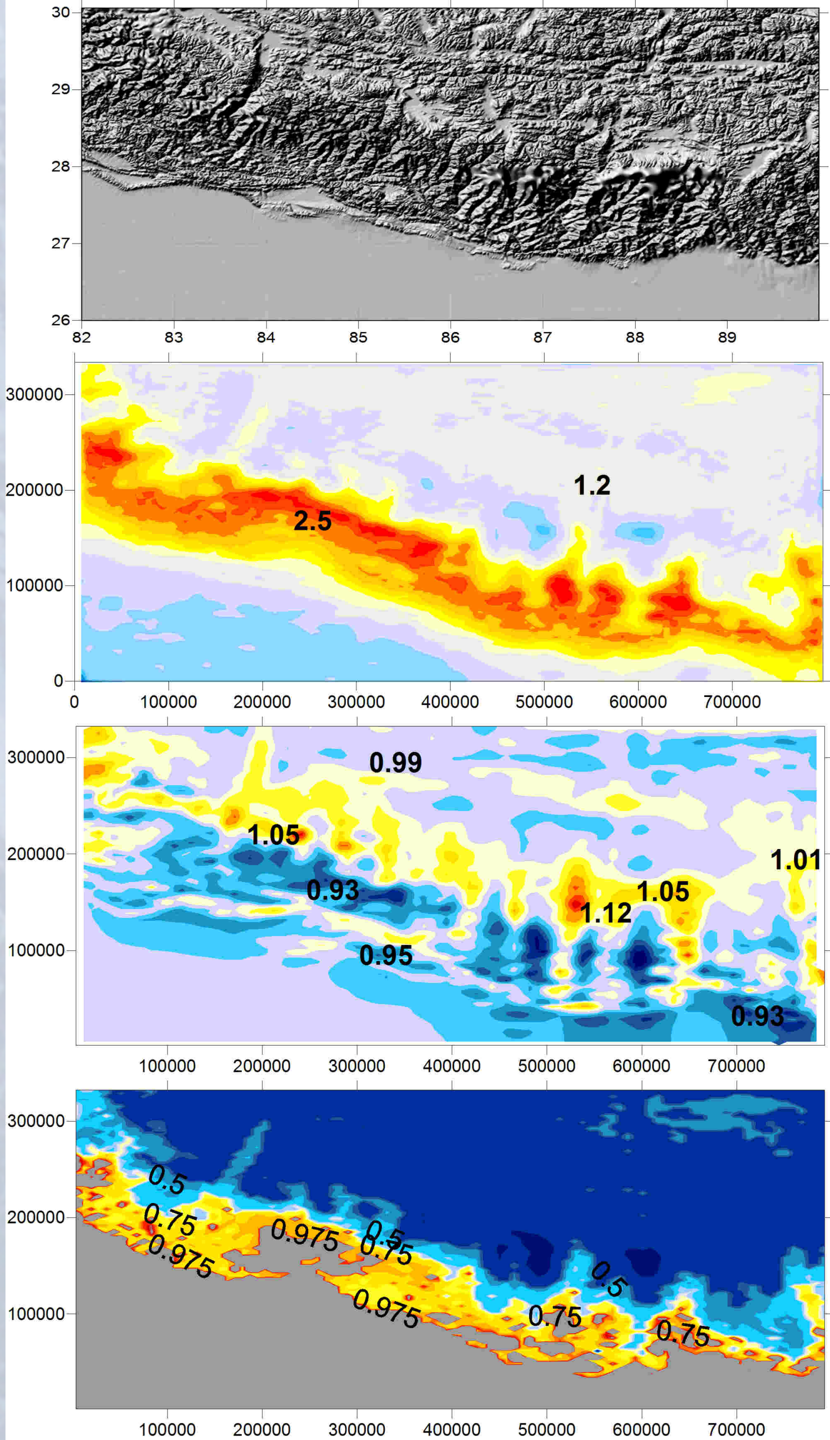
- Critical parameters of ***FERM*** (Cohesion, Tensile Strength, Pore Pressure etc) can be measured (*and have been for > 100years)*.
- Valleys and Ridges consist of fundamentally different stress and strength states with very different response rates.
- Non-linear sensitivity of incision rate on **Strength** means that strength differences (isolated massifs) are inescapable and persist for long times.
- <u>Landscape Tempo</u> is not controlled by diffusion decay and is defined by evolution of Strength/Stress field (i.e. seismic accelerations, climatic fluctuations) that are recorded at high frequencies.
- Geomorphic and Tectonic failure <u>are</u> the same; Broadband topography contains vast untapped information on surface, and .
- Unification within the stress:strain framework of ***FERM*** offers the means to unwrap the broadband signal of Tectonic:Geomorphic cooperation contained in topography

Challenges and Future Directions

- Computational: Hardware GPU- assisted
- Software: FERM, Meshless Methods, Particle in Cell …
- Part of our contribution: Calculate and provide 3D Stress Tensor derived from global DEM and Topographic Stress Index for terrestrial Earth

Enough

Photo by J. Alean



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