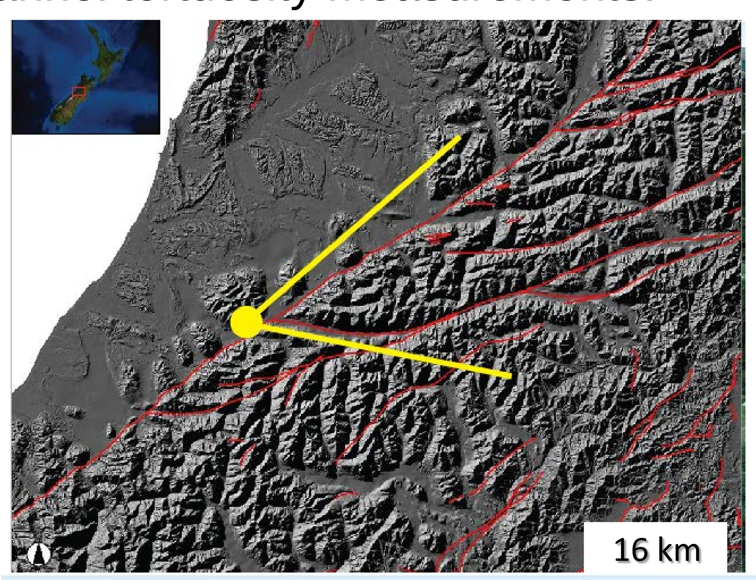
The influence of tectonic strain on landscape evolution

Samuel G. Roy[1] (samuel.g.roy@umit.maine.edu), Peter Koons[1], Greg Tucker[2], Phaedra Upton[3,1]
1) Earth and Climate Sciences, University of Maine; 2) Geological Sciences, CIRES fellow, University of Colorado, Boulder; 3) GNS Dunedin, New Zealand

1. Tectonic strain localization creates heterogeneous strength fields that influence erosion rate where exposed at the surface.

1. Tectonic strain localization creates heterogeneous strength fields that influence erosion rate where exposed at the surface. We use landscape evolution models to study topographic sensitivity to strain induced crustal strength fields for orogenic regions. We define strength fields using a Mohr-Coulomb model with non-associated strain softening of the crust and consider erodibility as a function of cohesion [Sklar & Dietrich, 2004; Koons et al., 2012]. Knickpoint migration rates are measured for multiple strength fields as a proxy for erosion rate in an orogen. Correlation between topographic and strength field orientations are determined using visual comparison and channel tortuosity measurements.



-**Figure 1:** Bird's eye view (yellow vectors denote position and view orientation) of the correlation between topography, runoff incision, and crustal failure, Alpine (left) and Hope (right) faults, New Zealand.

2. Methods

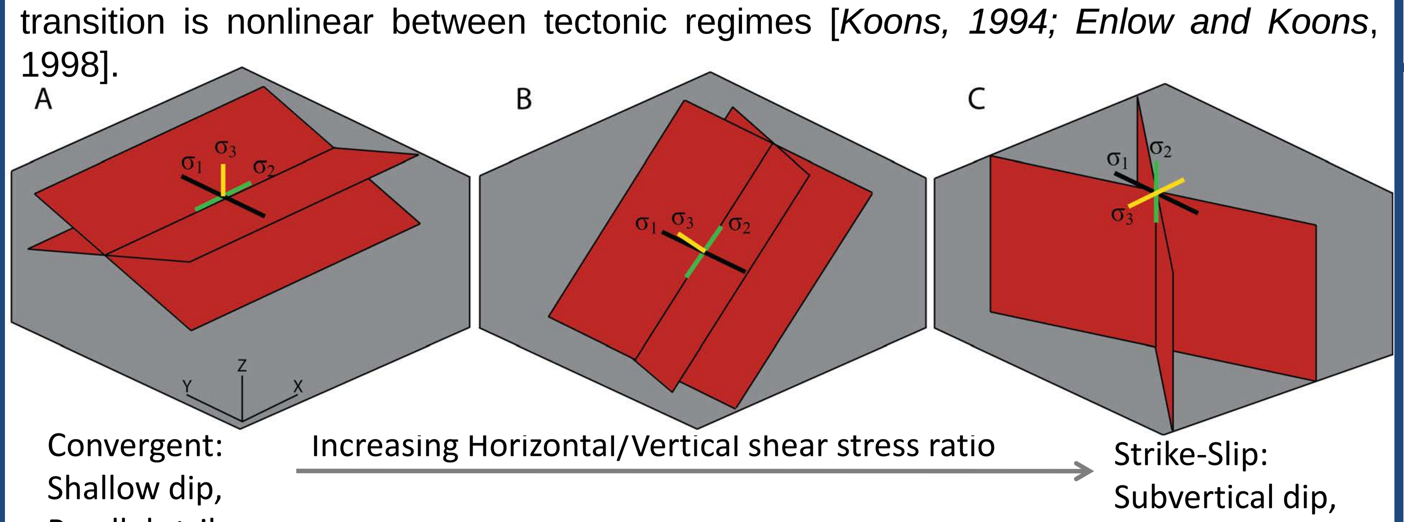
-We use the Channel-Hillslope Integrated Landscape Developmental model [CHILD, *Tucker et al.*, 2001] used to simulate topographic changes for detachment-limited orogenic watersheds. The Spatial pattern of finite volume detachment, transport, and deposition of material for gridded elements is controlled by a steepest descent routing algorithm and surface evolution takes the form [*Tucker et al.*, 2001; *Tucker and Hancock*, 2010]

$$\frac{\partial h}{\partial t} = k_b\left(k_t\left(\frac{Q}{W}\right)^{m_b} S^{n_b}\right)^{P_b} + k_d\nabla^2 h + U(x,y,t) \qquad k_b = 0.2C^{-0.5}$$

Basal shear stress; Topographic curvature; Transient elevation change; Erodibility; Shear stress coefficient; Flux/channel width; Slope; Hillslope diffusivity; Uplift; cohesion

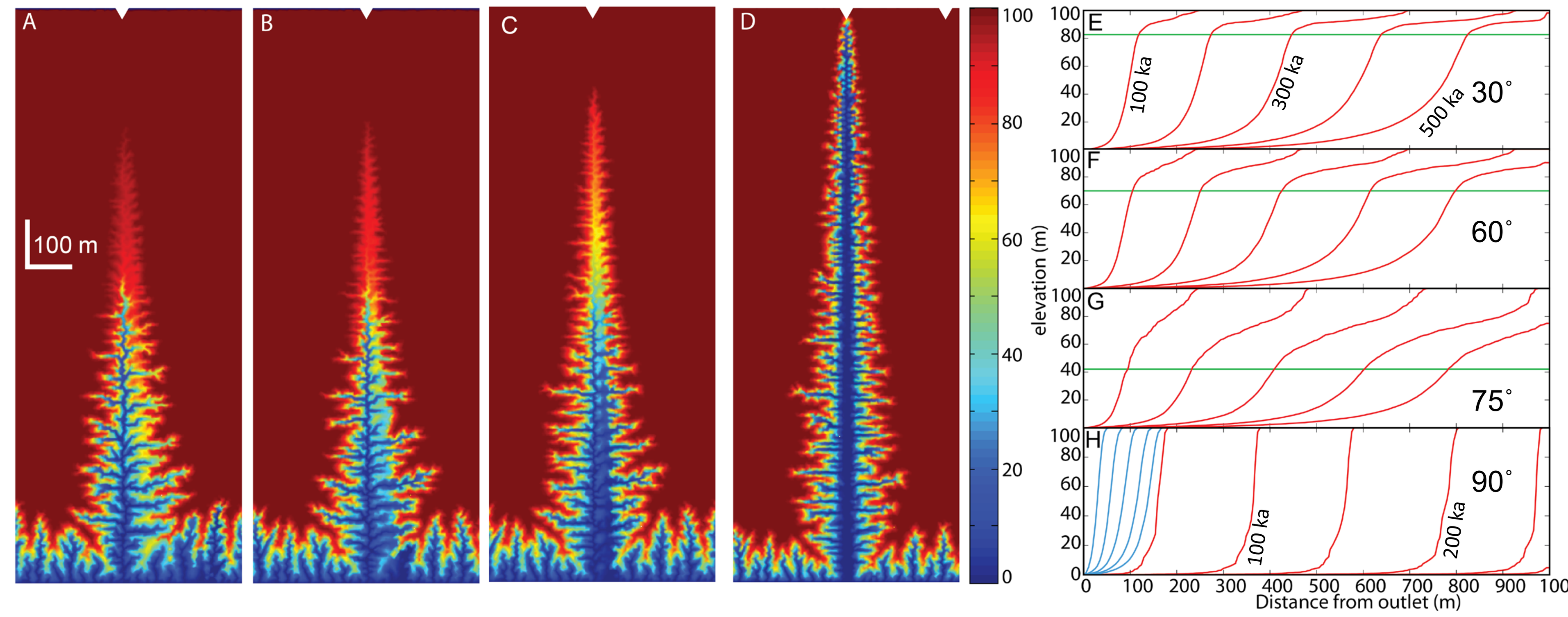
-We assume that uniaxial stress failure of the substrate by saltating bedload impact is the dominant mechanism of detachment [*Sklar and Dietrich*, 2001, 2004] and therefore assume that 1) bedload impact frequency and amplitude scales to basal shear stress and 2) substrate cohesion is proportional to erodibility by use of the above right equation [*Hanson and Simon*, 2001]. Host rock cohesion is $3x10^7$ Pa grading to a fault core cohesion of $5x10^5$ Pa, from measured values [*Thomson, 1992, Lockner et al., 2009*].

-**Figure 3** (below): Plastic behavior in a strained crust leads to localized failure distributed heterogeneously over Earth's surface. The orientation and distribution of 3D failure/fault sets are predictable by use of a Mohr-Coulomb rheological model of the crust for situations with known principal stress orientations. The shear stress transition is nonlinear between tectonic regimes [*Koons, 1994; Enlow and Koons*, 1998].

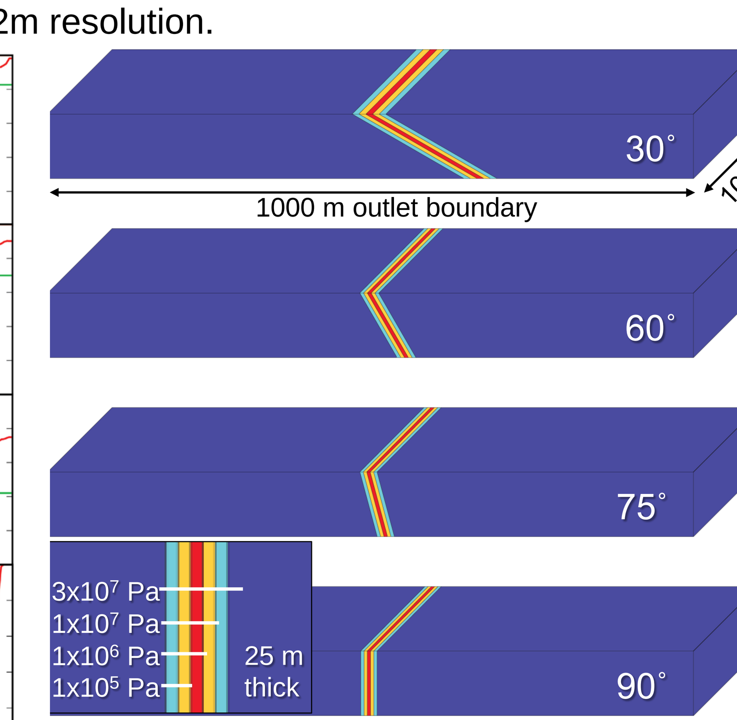


3. Knickpoint migration, fault dip sensitivity

Knickpoint migration rate is sensitive to heterogeneous strength fields and migration rate scales with fault dip. Knickpoints are a useful indicator of landscape evolution [*Crosby & Whipple, 2006*] and can be used to represent regional erosion rate. All models assume a single outlet boundary at sea level with a single fault striking orthogonally, 1.2 m a^{-1} precipitation, no uplift, 100 m initial elevation, 2m resolution.

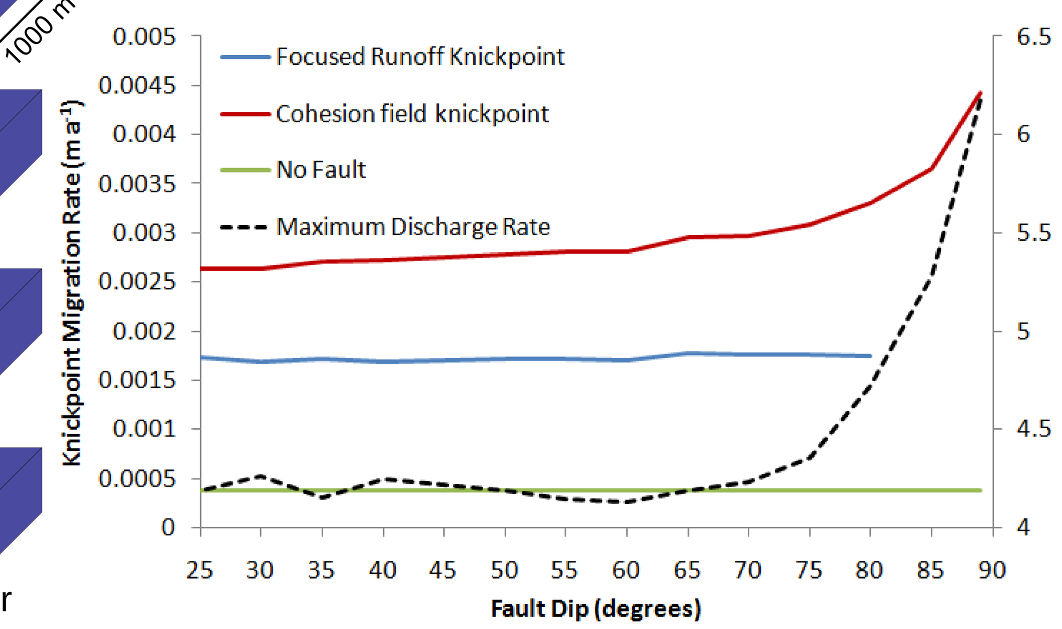


-**Figure 4** (upper left): map view of elevation, 250 ka (A-D) and channel elevation longitudinal profiles (E-H, red curves, orientation shown by white pointers orthogonal to the outlet boundary) for landscapes host to (A,E) 30˚, (B,F) 60˚, (C,G) 75˚, and (D,H) 90˚ dipping faults, with an example that erodes into strong host rock (blue curves, H). Profiles are taken at 100 ka time steps for all but the 90˚ fault at 50 ka steps. Knickpoint migration rates are sensitive to the existence of faults. The knickpoint on a shallow dipping fault is split into erosion into the fault, then erosion into the strong footwall (green line, E-G).



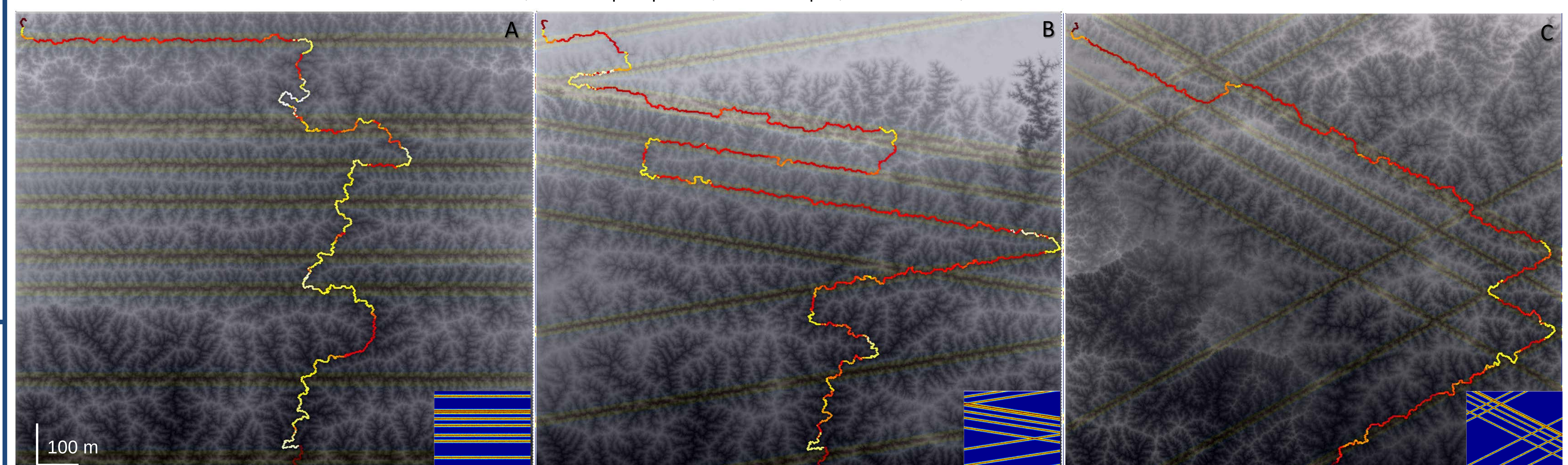
-**Figure 5** (above): Domain conditions for knickpoint models.

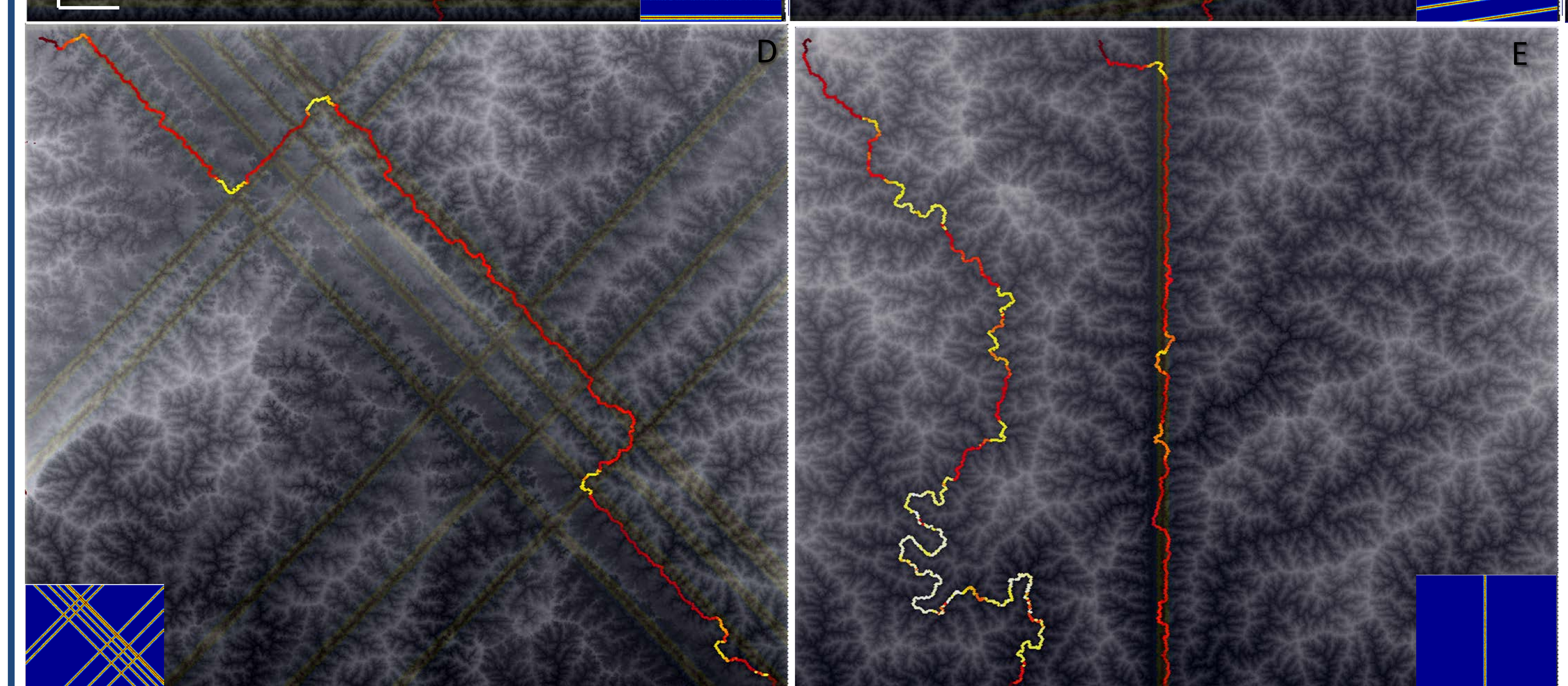
-**Figure 6** (below): Average knickpoint migration rate vs. fault dip. Knickpoint migration rate scales with fault dip, Order of magnitude range exists. Maximum discharge rate (secondary axis) increases with fault dip.

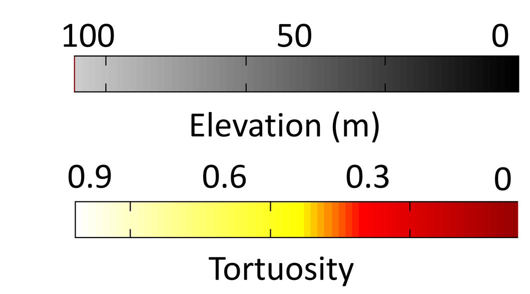


4. Topographic sensitivity to fault orientation

Topography assumes dominant orientations from the strength field. All models assume a single outlet boundary at sea level, fault sets assume orientations based on the Mohr-Coulomb crust model, 1.2 m a^{-1} precipitation, 1 mm a^{-1} uplift, 2m resolution, 1km² domain.



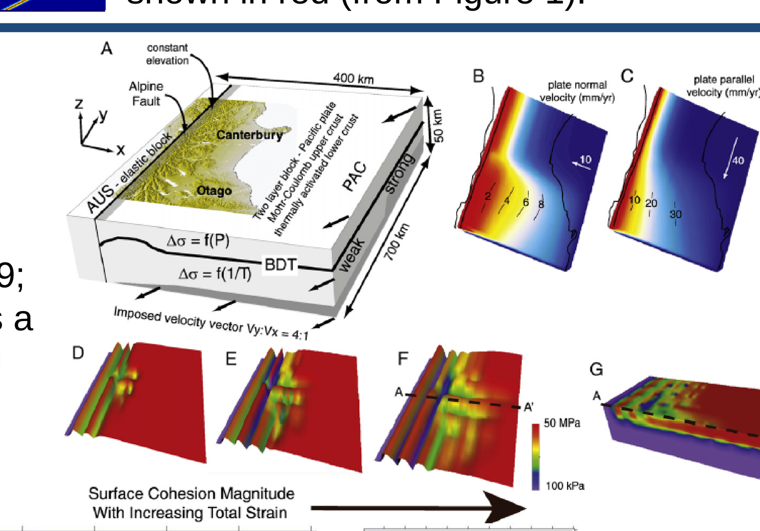


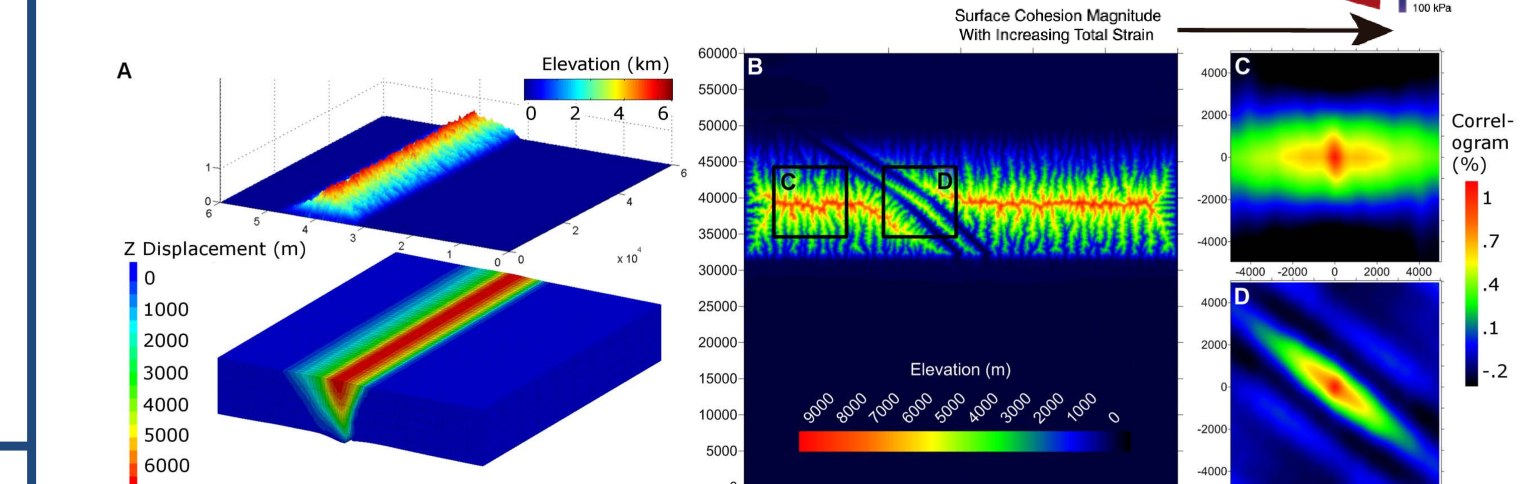


-**Figure 7** (left): Orogenic model topography (grey color scale) overprinted by cohesion (faint red: fault core, also inset) and tortuosity for a single channel path (red-yellow color scale). (A-E) Fault orientations shift from a purely convergent regime (A) to a purely strike-slip regime (E). Valleys tend to develop within exposed fault cores if they are connected to the outlet. Tortuosity, a measure of path straightness, is greatest where faults intersect or where channels cross homogeneous host rock, and is least where channels follow fault strike. Dominant ridge and valley orientations in New Zealand reflect the fault orientations shown in red (from Figure 1).

5. Coupling to large scale kinematic models

-**Figure 8** (left): Kinematic model of the lithosphere used to define surface displacement (B,C) and cohesion (D-G) for New Zealand (Upton et al., 2009; Koons et al., 2012). **Figure 9** (below): elevation as a function of displacement from kinematic model and erosion from surface model. (B) Faults alter topographic correlation (C,D).





6. Conclusions

-Knickpoint migration is sensitive to variations in naturally occurring strength fields with consequences for the rate of landscape evolution.

-Erosion into heterogeneous strength fields creates topography with dominant orientations determined by the tectonic history by fault orientation and therefore can control the drainage network geometry.

-Faults are ubiquitous at all scales in the crust and must impart a fundamental influence on landscape evolution

Crosby, B. T., and K. X. Whipple (2006), Knickpoint initiation and distribution within fluvial networks: 236 waterfalls in the Waipaoa River, North Island, New Zealand, *Geomorphology*, *82*(1-2), 16–38.; Enlow, R., and P. O. Koons (1998), Critical wedges in three dimensions: Analytical expressions from Mohr-Coulomb constrained perturbation analysis, *JOURNAL OF GEOPHYSICAL RESEARCH*, *103*, 4897–4914.; Hanson, G. J., and A. Simon (2001), Erodibility of cohesive streambeds in the loess area of the midwestern USA, , *38*(August 1999), 23–38.; Koons, P. O. (1994), Three-dimensional critical wedges: tectonics and topography in oblique collisional orogens, *JOURNAL OF GEOPHYSICAL RESEARCH*, *99*, 12,301–12,315.; Koons, P. O., P. Upton, and A. D. Barker (2012), The influence of mechanical properties on the link between tectonic and topographic evolution, *Geomorphology*, *137*, 168–180. ; Lockner, D. a., H. Tanaka, H. Ito, R. Ikeda, K. Omura, and H. Naka (2009), Geometry of the Nojima Fault at Nojima-Hirabayashi, Japan – I. A Simple Damage Structure Inferred from Borehole Core Permeability, *Pure and Applied Geophysics*, *166*(10-11), 1649–1667, doi:10.1007/s00024-009-0515-0.; Mooney, W., G. Beroza, and R. Kind (2007), Fault Zones from Top to Bottom: A Geophysical Perspective, in *Tectonic Faults Agents of Change on a Dynamic Earth*, edited by M. Handy, G. Hirth, and N. Hovius, pp. 24–61, MIT Press, Cambridge, MA, USA.; Thomson, R. (1993), *Clyde Dam engineering geological completion report volume 1: text and appendices*.; Tucker, G., S. Lancaster, and N. Gasparini (2001), The channel-hillslope integrated landscape development model (CHILD), in *Landscape erosion and Evolution Modeling*, edited by R. S. Harmon and W. W. Doe, Kluwer Academic/Plenum Publishers, New York.; Tucker, G. E., and G. R. Hancock (2010), Modelling landscape evolution, *Earth Surface Processes and Landforms*, *35*(1), 28–50, doi:10.1002/esp.