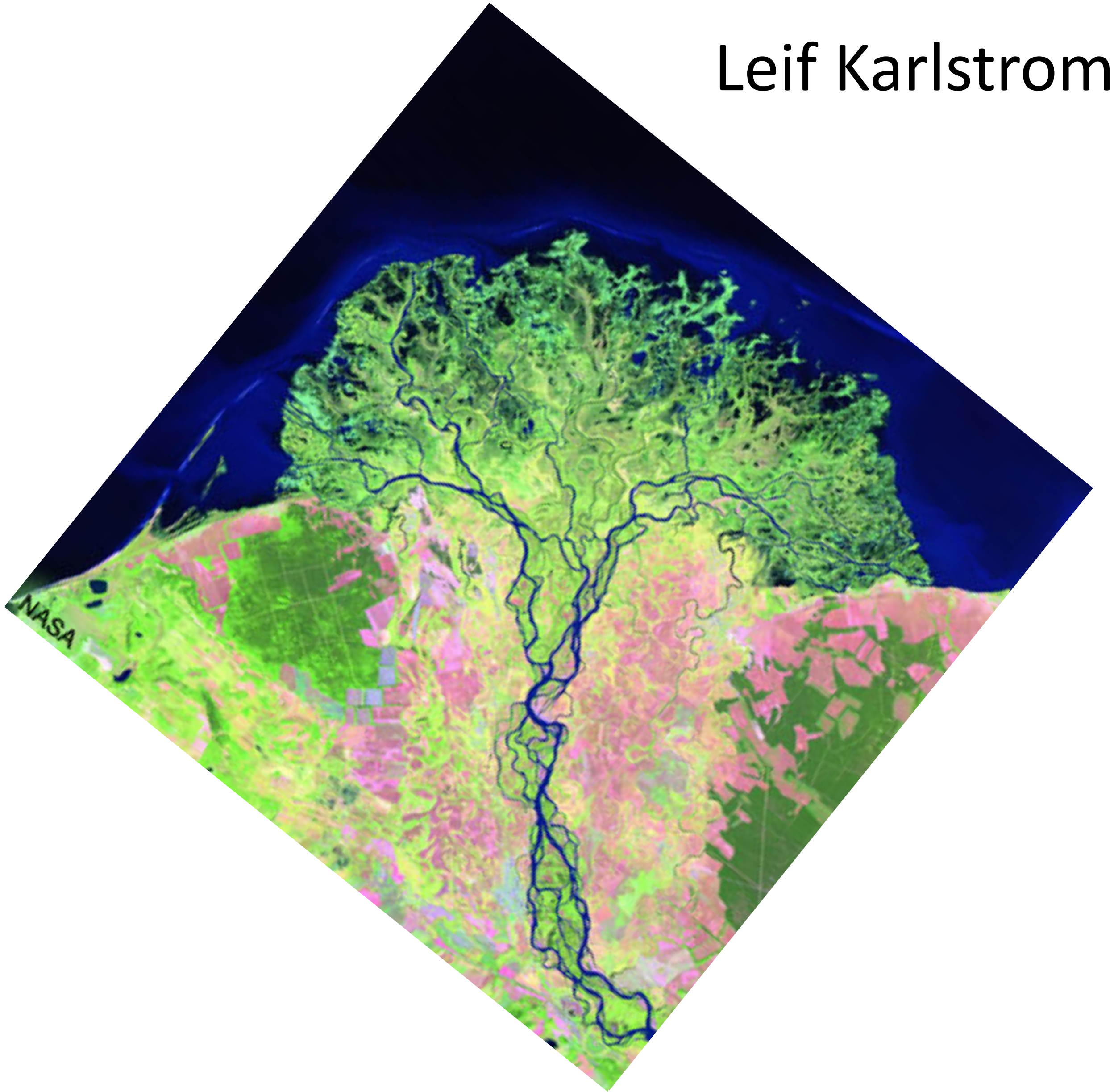
Volcanic Landscape Evolution



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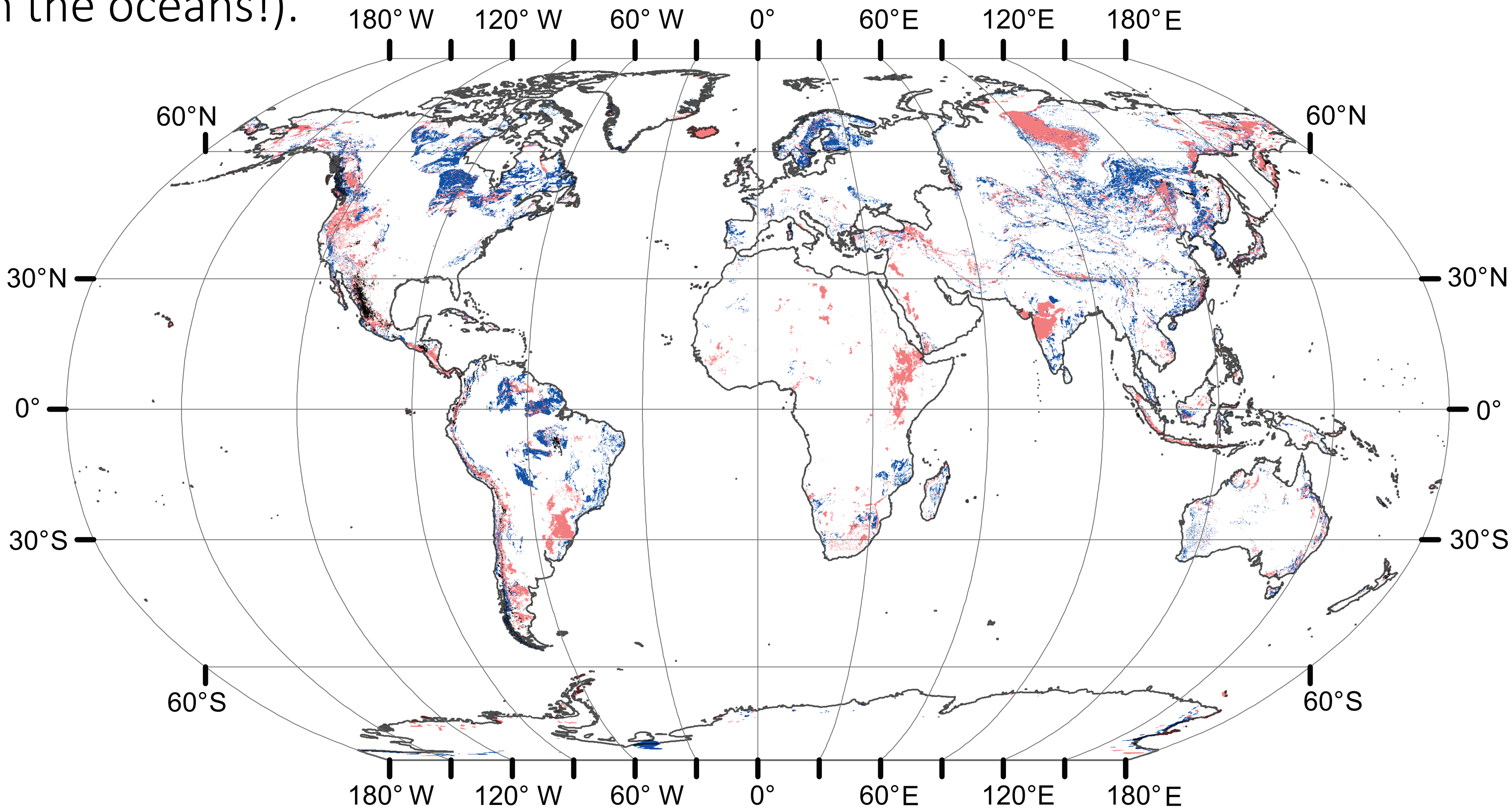
Volcanic/plutonic rocks occupy >13% of the Earth's landmass exposed at the surface.

Much higher percentage if we consider rocks buried by veneer of sediment (not to mention the oceans!).



Global distribution of volcanic/plutonic rocks (Karlstrom et al., 2018 JGR)

Statement of the problem

(this is not a talk about edifice or deposit classification)

Topographic change (i.e., landscape evolution) reflects a competition between processes that cause uplift or subsidence relative to some fixed reference, and processes that cause erosion (lateral transfer of material from one place to another).

A nonlinear advection-diffusion equation that encapsulates this at a point Z(x,y,t):

$$\frac{\partial Z(x,y,t)}{\partial t} = u(\mathrm{x,y,t}) - \mathrm{E(x,y,t)}$$

Rate of vertical topographic change

Rate of uplift/subsidence

Rate of erosion (lateral translation of topography that results in lowering)

+ initial conditions/boundary conditions (very important)

Statement of the problem

(this is not a talk about edifice or deposit classification)

In volcanic environments, what are the contributions to terms on the right hand side?

$$\frac{\partial Z(x,y,t)}{\partial t} = u(\mathrm{x,y,t}) - \mathrm{E}(\mathrm{x,y,t})$$

Eruptions, intrusions, caldera collapse, tectonic shortening/extension …

erosional processes (e.g., fluvial incision, debris flows, landslides, soil creep), + glaciers, + volcanic thermal/mechanical erosion …

What do we stand to learn? Why study this side of volcanology?

- **What are volcanoes?**

(ie, what are the characteristics of volcanic topography, how to relate to deeper transport, how they build and erode over time)

- **Does surface form encode time-averaged magmatic flux or intrusion/extrusion ratio?**

(ie, tectonic geomorphology applied to volcanic terrains)

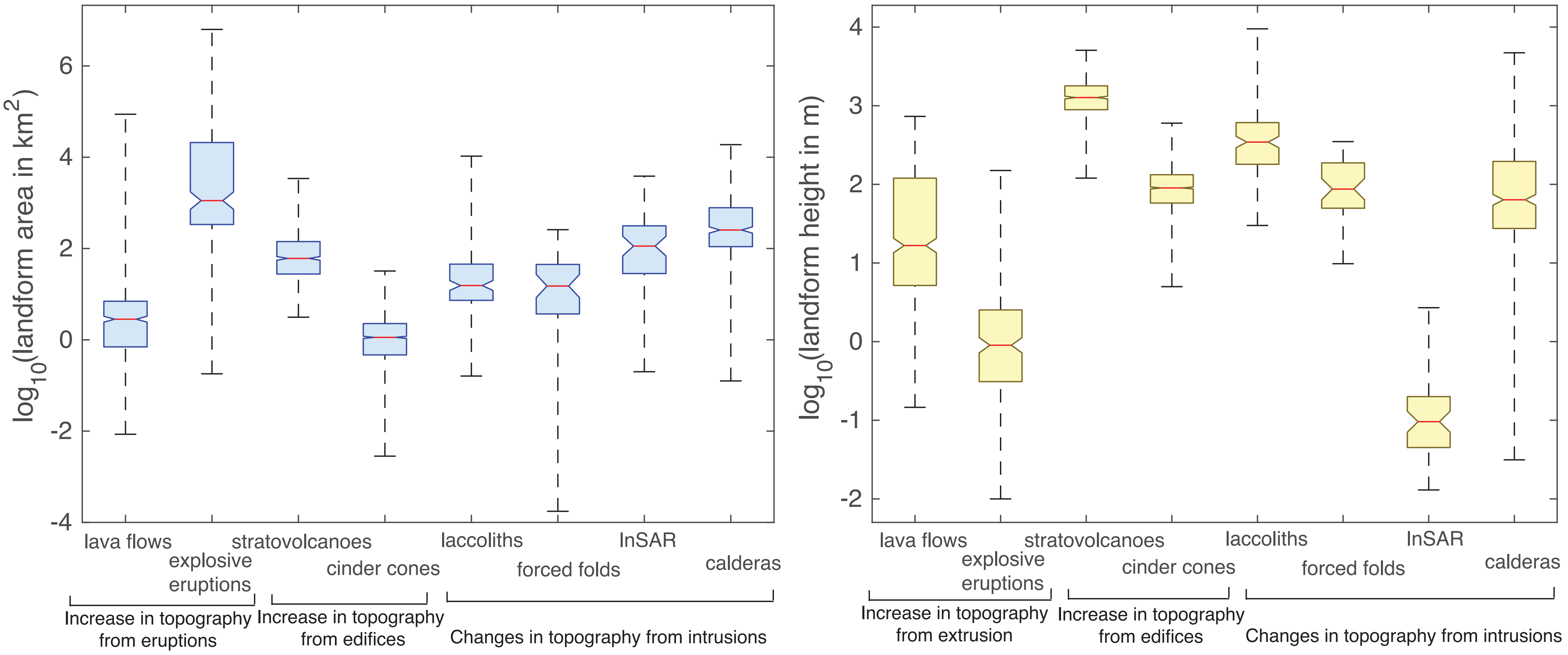
- **Planetary applications**

(often only see the surface)

- **Geomorph applications**

(sediment production rates and erosion rates, river longitudinal profiles, hillslope shape, etc…)

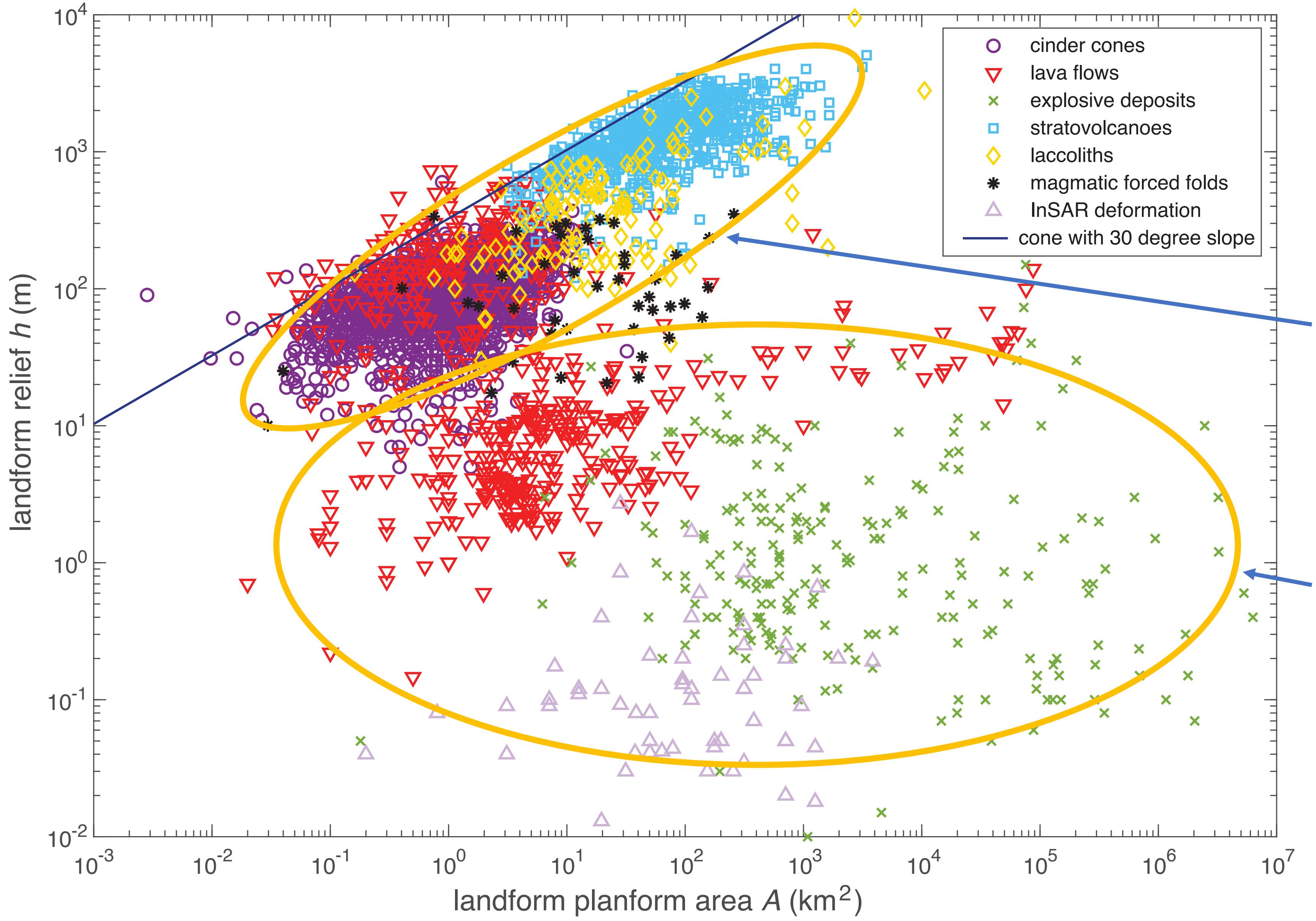
This is the range of volcanic landform geometry on Earth.



Global compilation of published landform heights and planform areas for deposits (lava flows, explosive eruptions), edifices, and intrusions (laccoliths, magmatic forced folds, InSAR, calderas)

Karlstrom et al., 2018 JGR

magmatic landform height compared to area

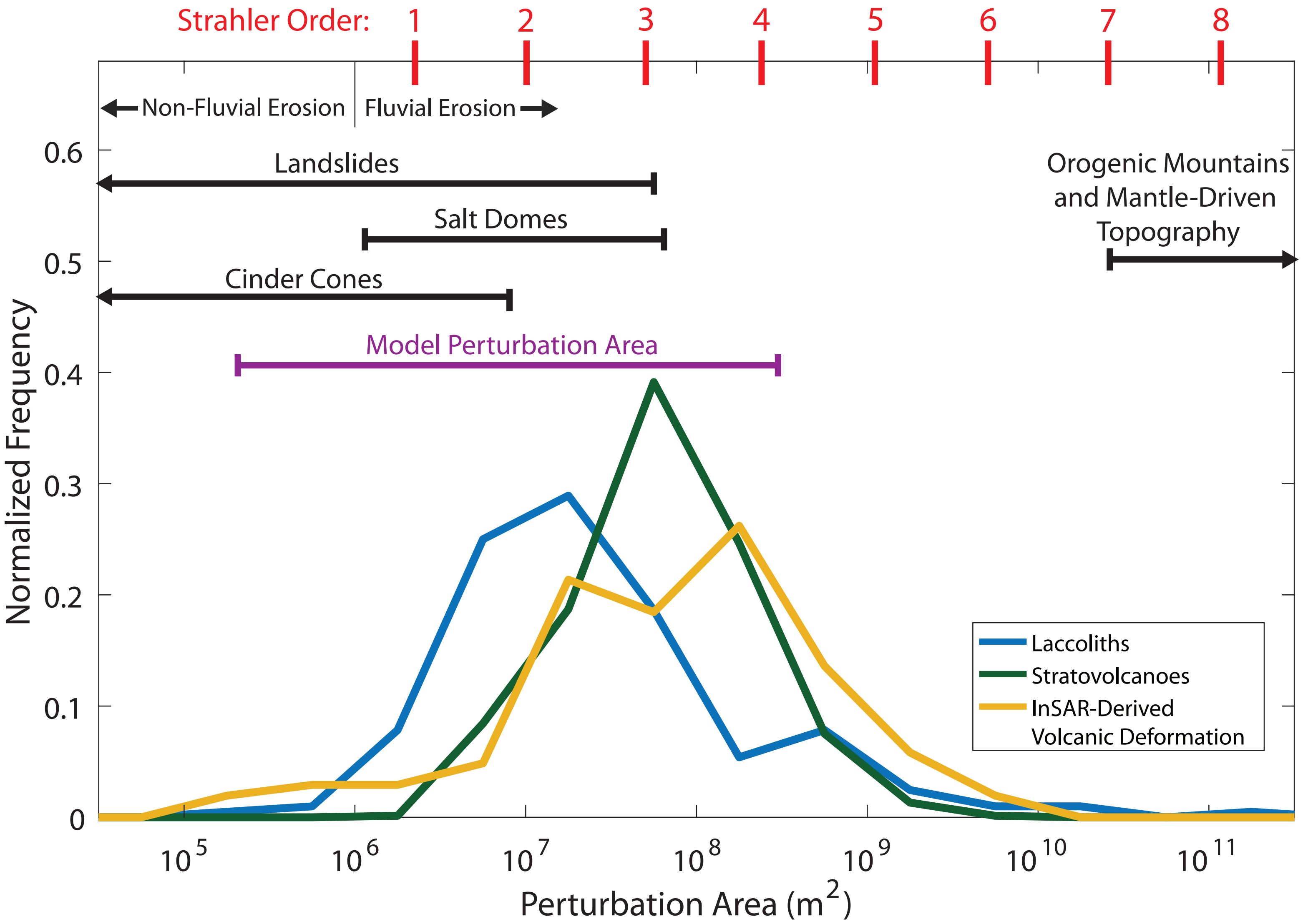


Class of landforms that grow “as high as they can” (angle or repose)

Class of landforms with areas much greater than height (flood basalt lavas, explosive deposits, active deformation)

Karlstrom et al., 2018 JGR

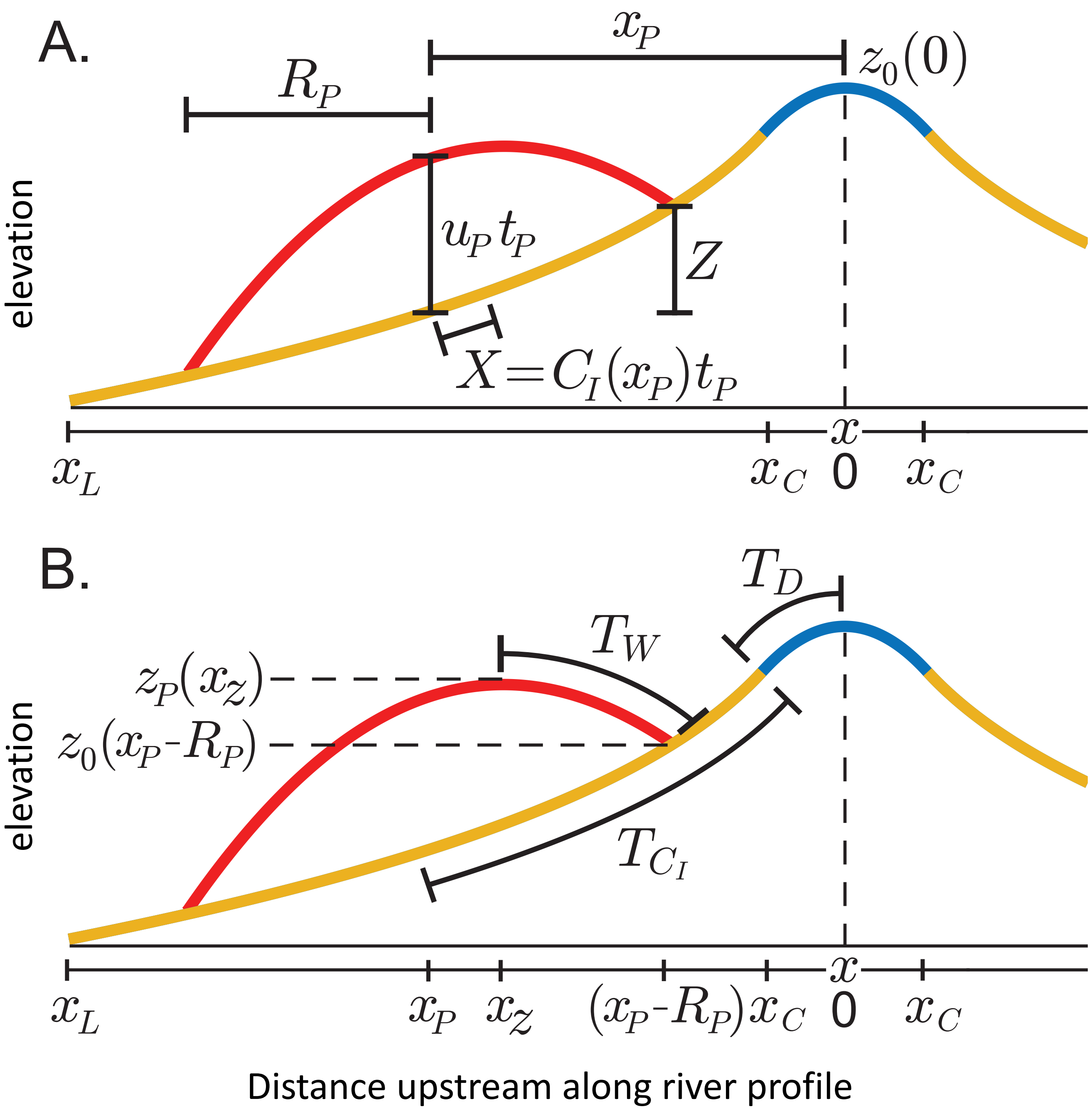
Together with a timescale of emplacement (harder to constrain), this helps define the "uplift" field from magmatism



Range of planform areas is smaller than tectonic scales (and shorter duration), more similar to large landslides and salt domes

Erosional processes typical for such areas include both "fluvial" and "hillslope" regimes

O'Hara et al., 2019 EPSL



O'Hara et al., 2019 EPSL

Transient uplift similar or smaller in size than typical drainage basins is an unexplored landscape evolution problem!

$$\frac{\partial z}{\partial t} = u - C_I |\nabla z| + D \nabla^2 z$$

Background uniform uplift + localized source

"stream power" fluvial erosion (n=1)

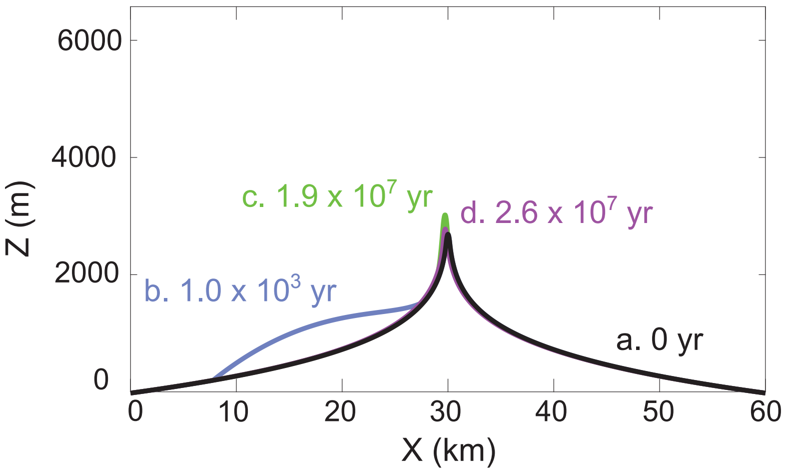
Linear hillslope diffusion (ridge tops)

$$C_I(x, y, t) = K A(x, y, t)^M$$

Wavespeed is nonlinear function of upstream drainage area A and erodibility K, raised to an empirical power M: this gives rise to nonlocal behavior

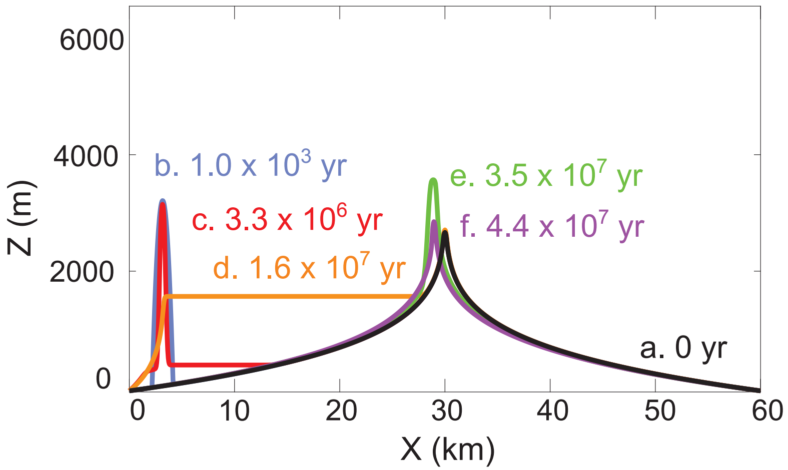
Three regimes of model behavior (not exploring hillslope dominated erosion yet)

A. Regime 1



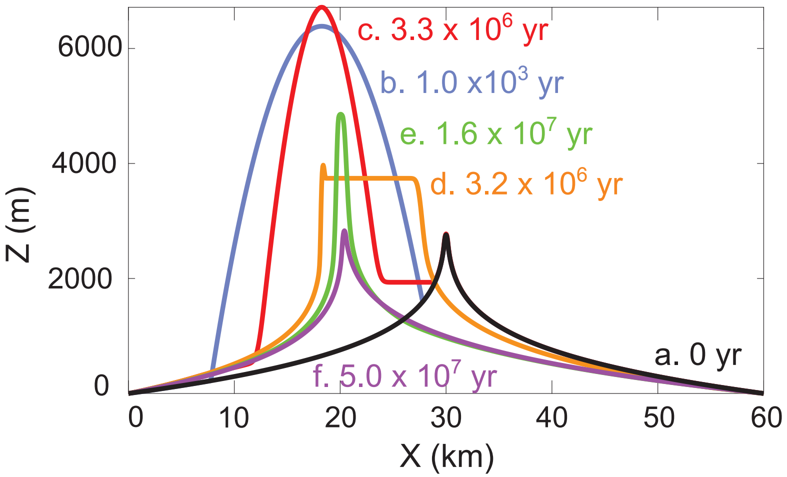
a. Initial steady state
b. Perturbation does not form minimum and advects upstream
c. Advection wave reaches ridge, amplifies topography
d. Ridge relaxes and migrates back to steady state

B. Regime 2



a. Initial steady state
b. Perturbation forms a local minimum
c. Minimum uplifts as plateau while perturbation erodes
d. Perturbation erodes to same elevation as plateau and is captured
e. Advection wave reaches ridges, amplifies topography
f. Ridge relaxes and migrates back to steady state

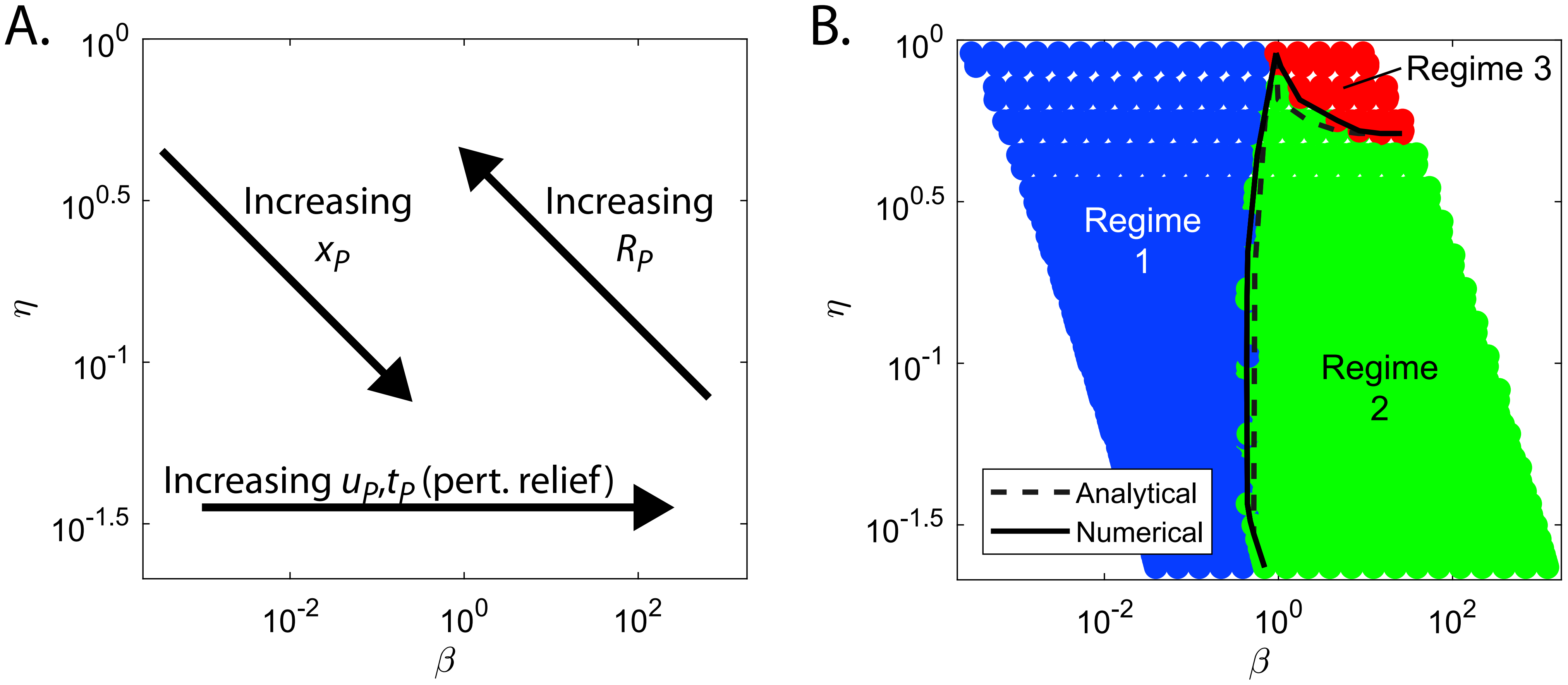
C. Regime 3



a. Initial steady state
b. Perturbation forms a local minimum
c. Minimum uplifts as plateau while perturbation erodes
d. Plateau reaches same elevation as initial ridge and captures it
e. Avection wave reaches new ridges, amplifying topography
f. Ridge relaxes and migrates back to steady state

O'Hara et al., 2019 EPSL

Model regimes are well explained by geometric control parameters that measure the uplift perturbation size and location in initial topography



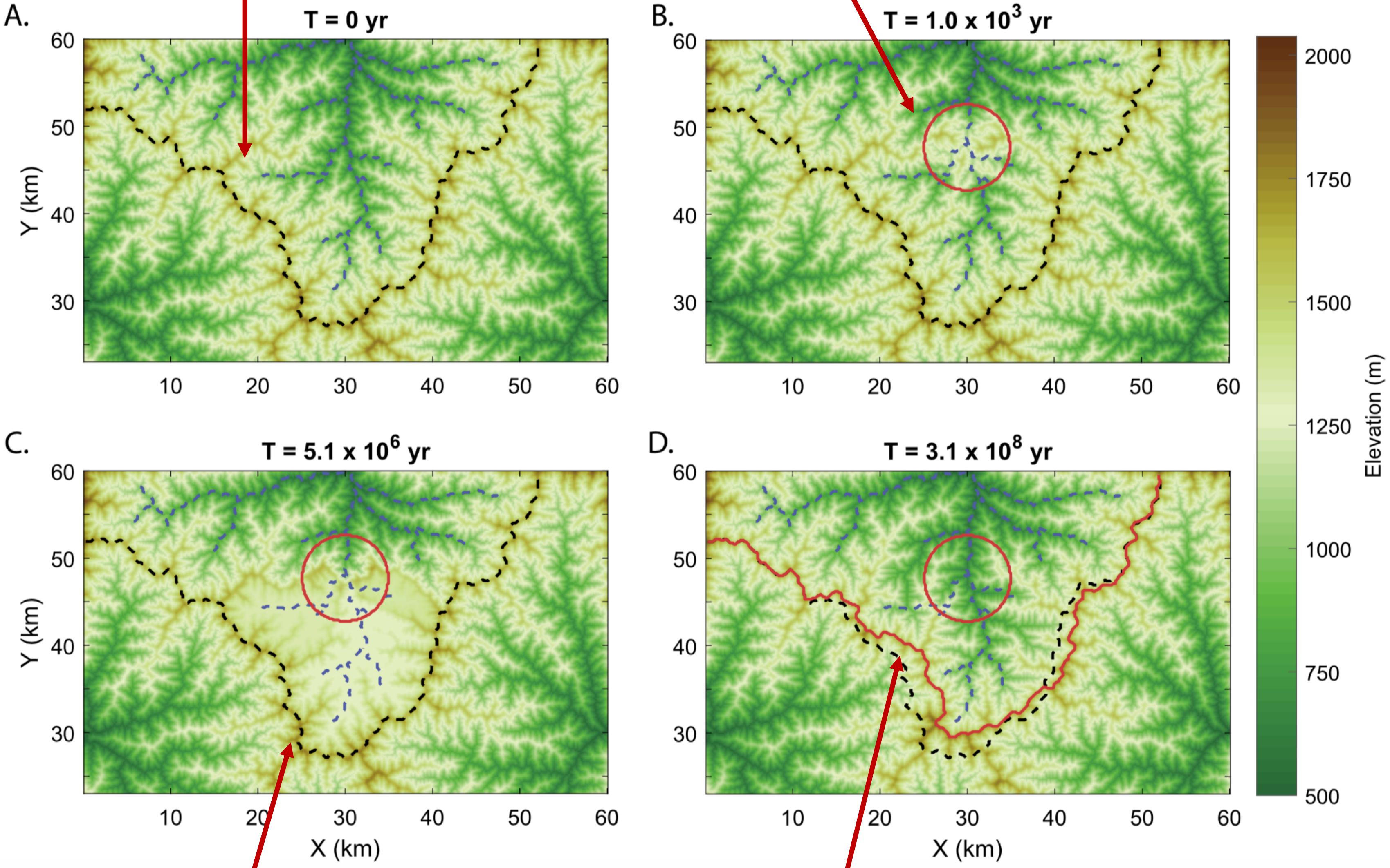
$$\beta = \frac{perturbation\ relief}{initial\ local\ relief}$$

$$\eta = \frac{drainage\ area\ of\ perturbation}{initial\ local\ upstream\ drainage\ are}$$

O’Hara et al., 2019 EPSL

Initial topographic steady state

After localized uplift (red circle)



Transient plateau construction due to beheading channels

Permanent “lensing” of ridge towards intrusion location. Topography reaches a different steady state!

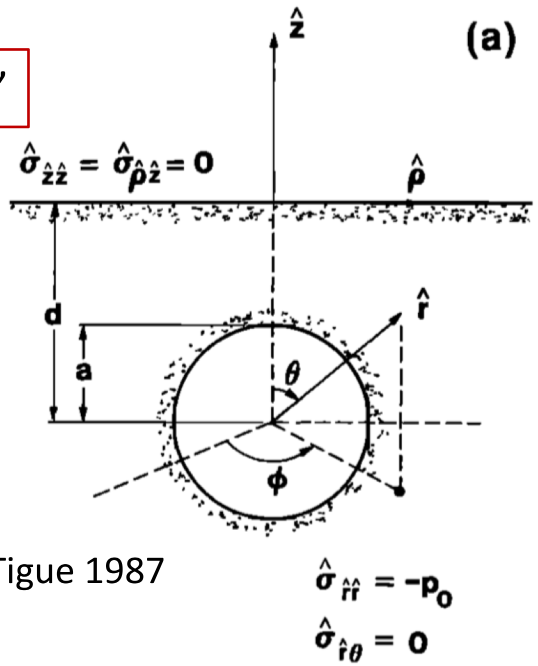
Same regimes hold for models done in 2D, but added complexity due to new spatial degrees of freedom: no longer one unique steady state solution!

Of course, real volcanic provinces involve many intrusions and eruptions over extended time.

O’Hara et al., 2019 EPSL

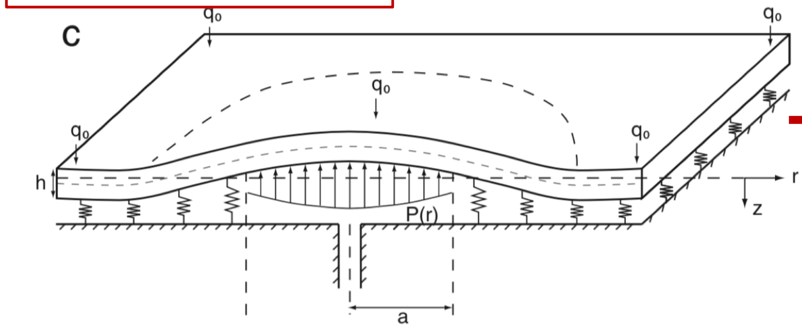
Next steps: Model landscape response to a stochastic (Magnitude/frequency) distribution of intrusions at a range of depths

"deep"

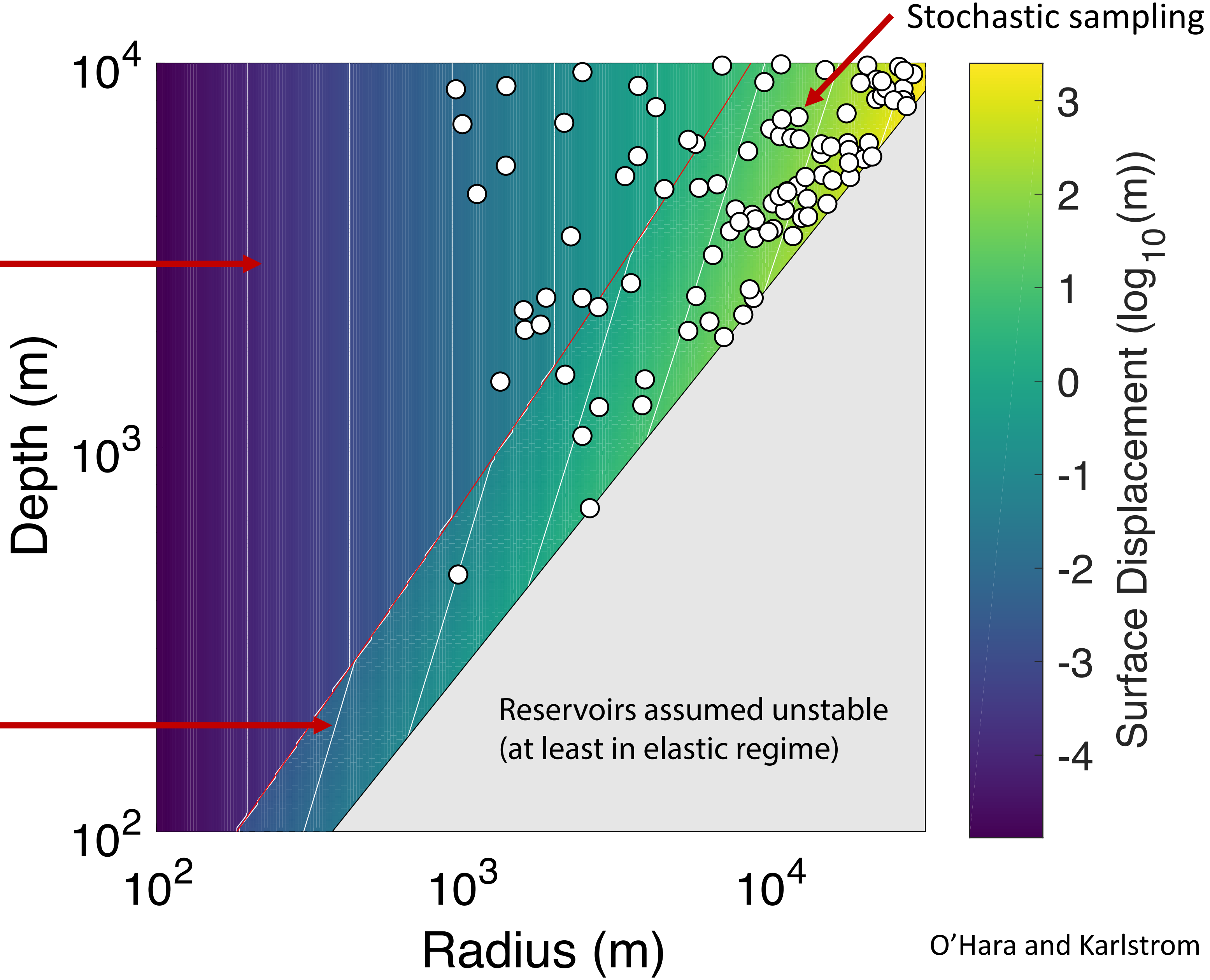


McTigue 1987

"shallow" (R>5 D)

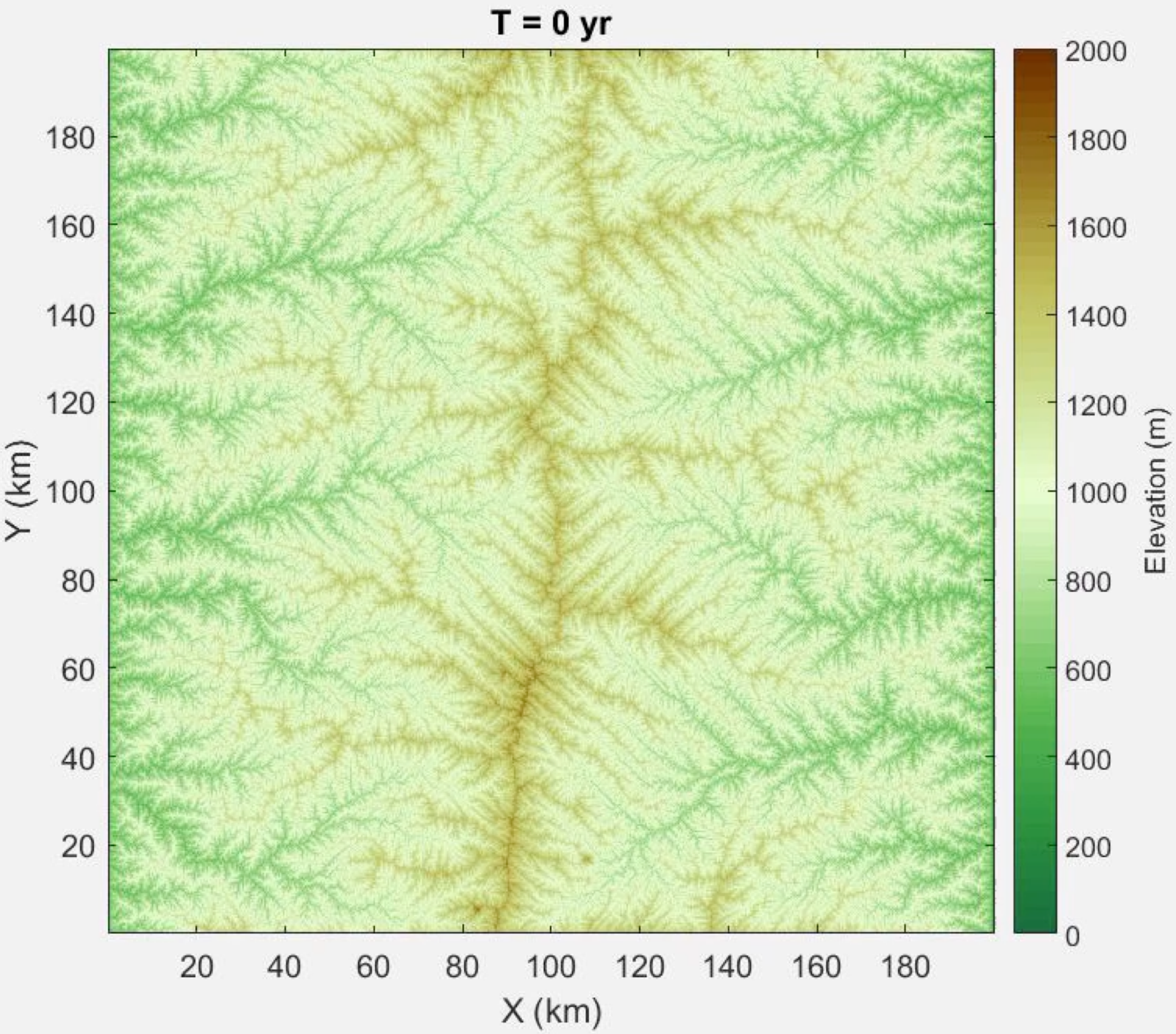


Galland and Scheibert, 2013



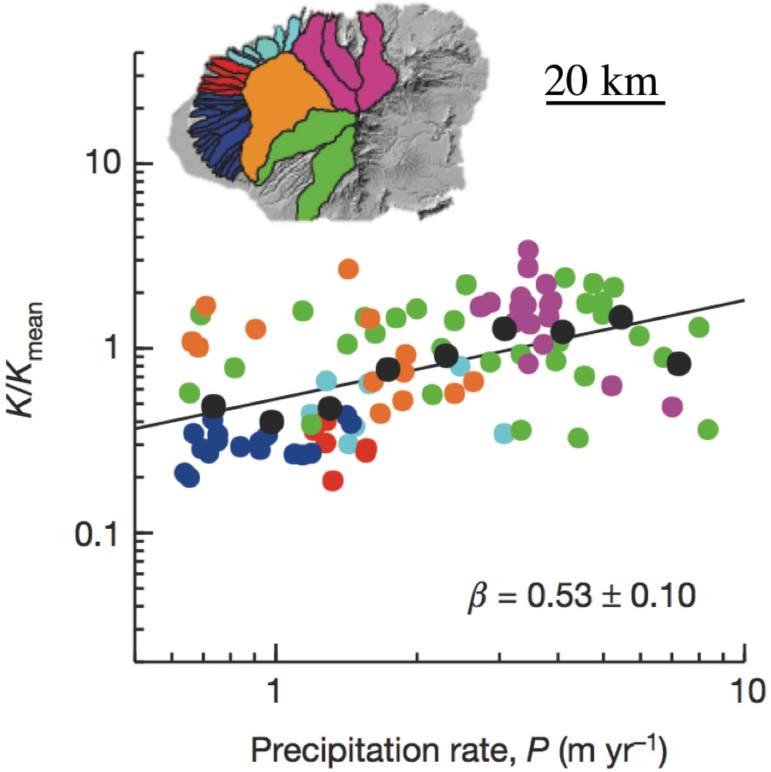
Reservoirs assumed unstable
(at least in elastic regime)

O'Hara and Karlstrom (in prep)

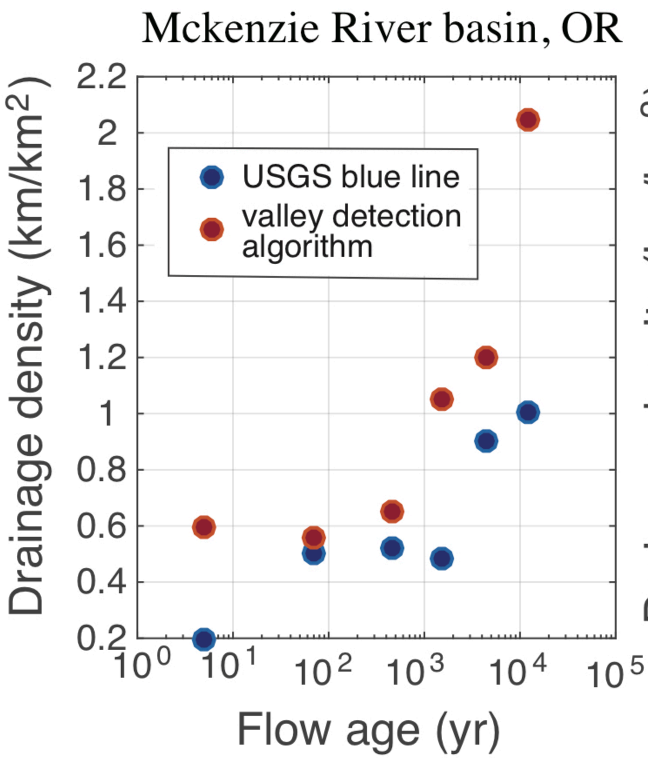


Simulation starts at topographic steady state with uniform uplift, then magma intrudes. Fluvial erosion + linear hillslope diffusion

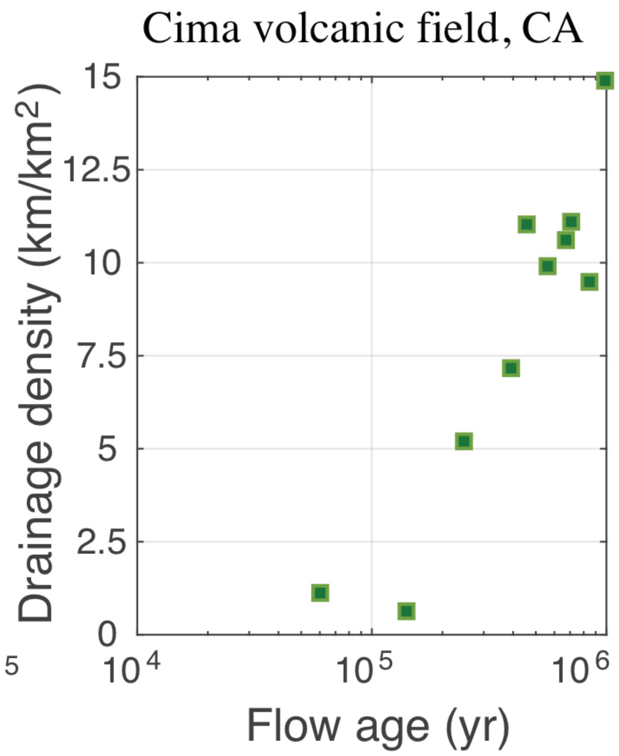
Next steps: Study the (probably 1st order!!) effect of time varying erodibility of volcanic deposits



Ferrier et al., 2013

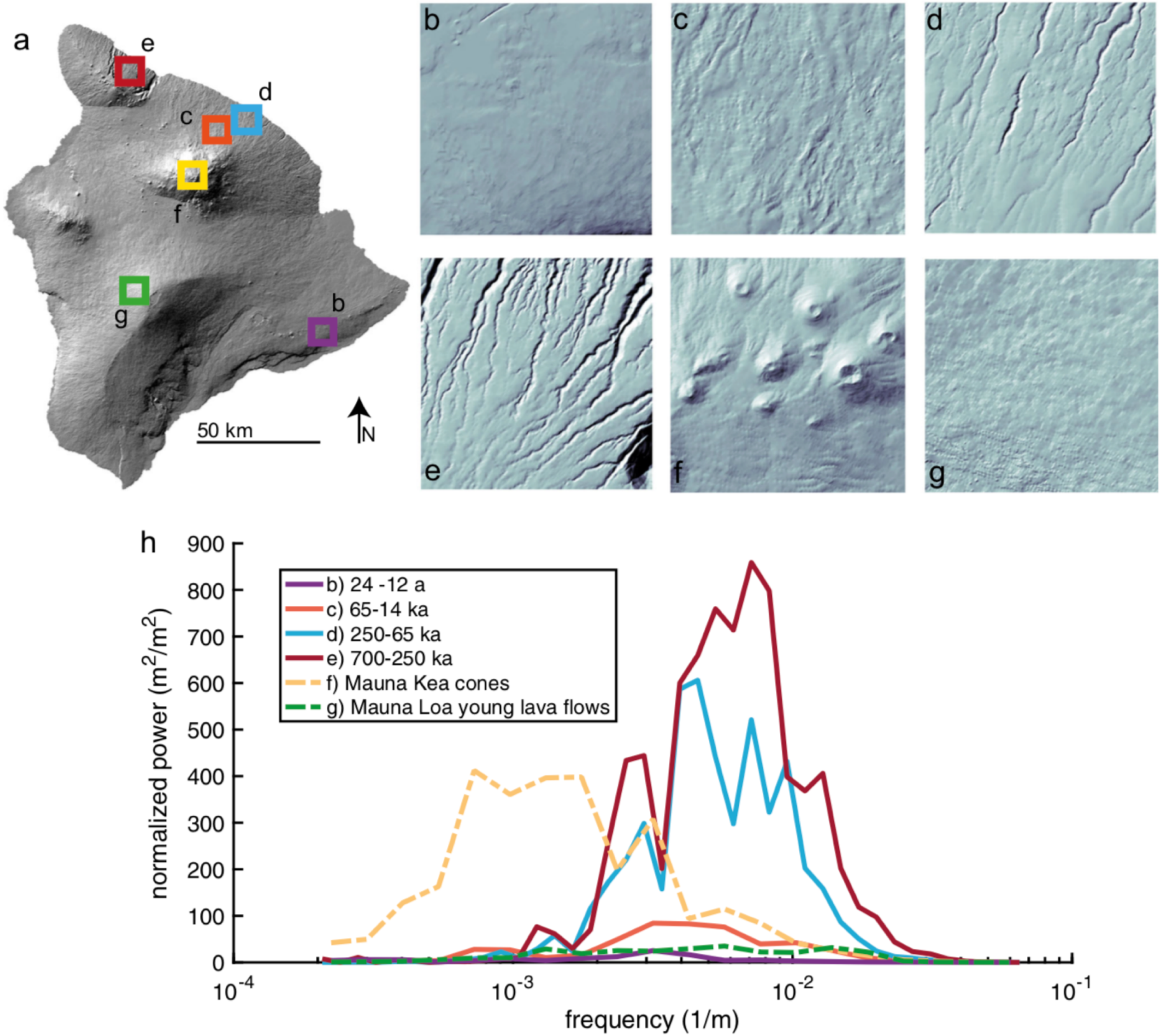


Jefferson et al., 2010



Wells et al., 1985

Lava flows initially armor the landscape and promote subsurface flow. It takes 10s-100s kyr (depending on climate?) to establish surface drainage networks



On Hawaii, lava flows of increasing age have systematically increasing roughness at wavelengths that corresponds to spacing of fluvial channels.

Surfaces dominated by cones (summit of Mauna Kea) have characteristic power at different wavelengths

→ Spectral signatures of different magmatic/erosional processes?

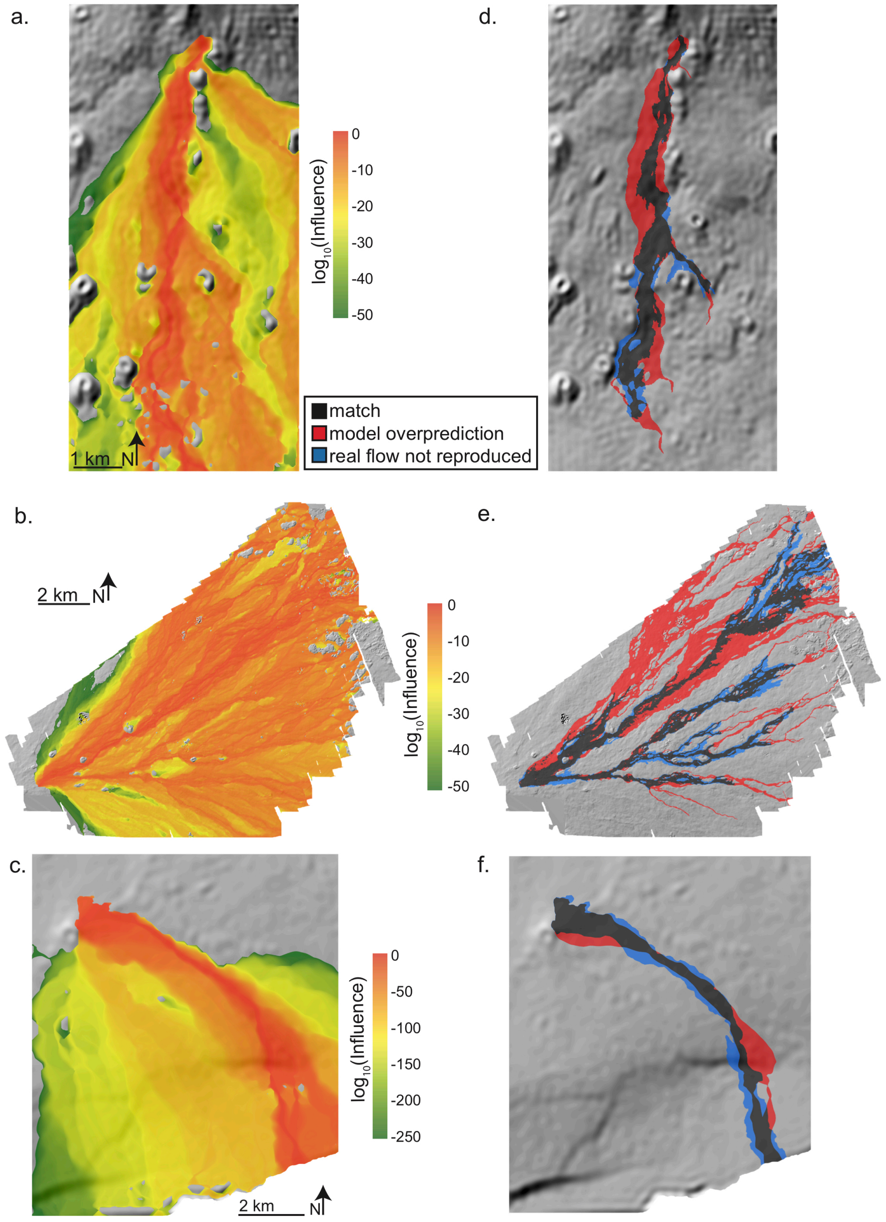
Richardson and Karlstrom (2019) Bull. Volc.

A current project: volcanic landscape construction (and erosion)

Mt Etna 2001

Mauna Loa 1984

Kilauea 2011



All possible downslope paths (weighted by slope)

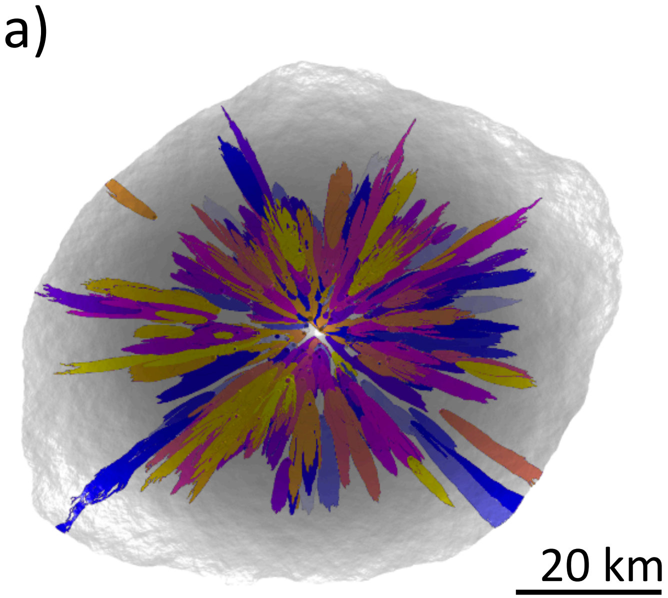
Match to known flow outlines

Its fairly simple to produce lava flow pathways that match real flows (the physical details are much more complicated and interesting!)

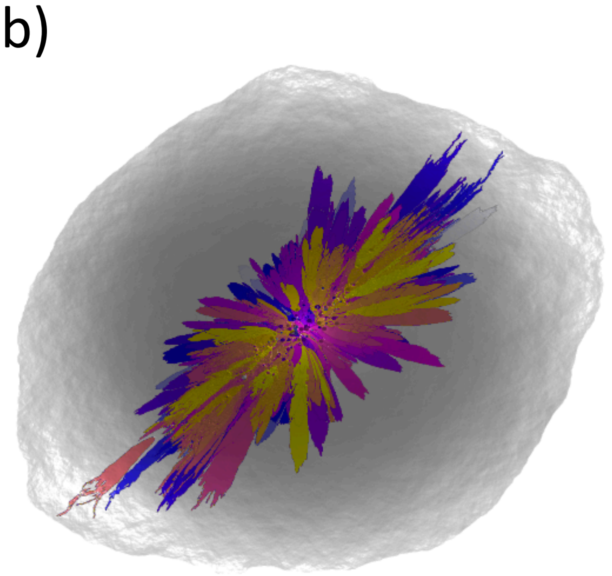
Flow routing + thresholding incorporates the complexity of real landscapes (red noise spectrum of topography).

Goal: Use this MULTIFLOW model (Richardson and Karlstrom, 2019) or something similar to study construction and erosion of landscape through time.

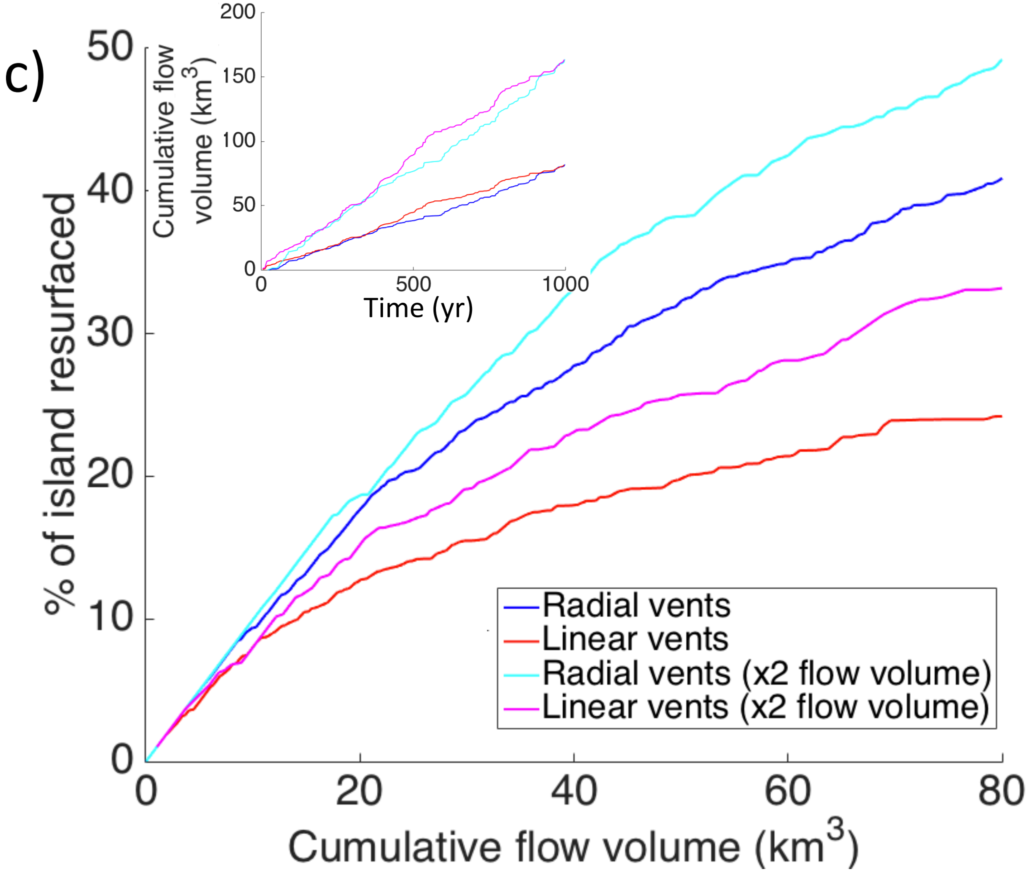
Richardson and Karlstrom (2019) Bull. Volc.



Radial distribution of vents around summit



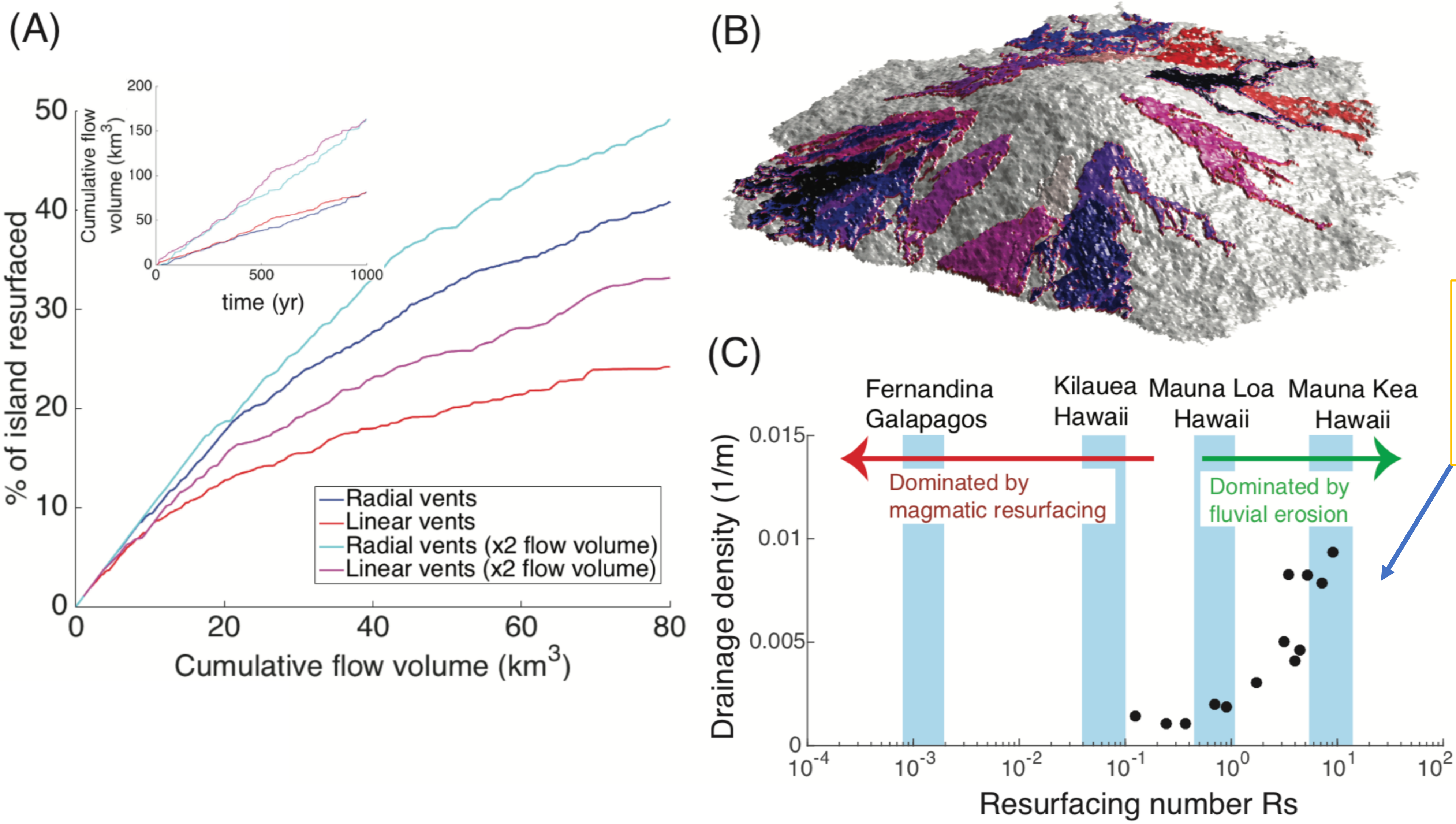
Quasi-linear distribution of vents around summit



If we emplace a sequence of flows with MULTIFLOW on a red-noise, cone-shaped “island” with volumes partitioned according to a Magnitude-Frequency distribution, the pattern of flows and ‘resurfacing efficiency’ varies systematically.

Does the topography of the current surface encode 1-10 kyr averaged effusion rate and vent distribution?

Richardson and Karlstrom, unpublished



This figure is pure speculation! Could be a good CIDER group project …

Add erosion back in… there will be a time-lagged response due to erodibility evolution. Can we map global ocean islands on to a climate/magmatic flux parameter space?

Questions?