A new simulation approach for modeling inflated pahoehoe lava flows

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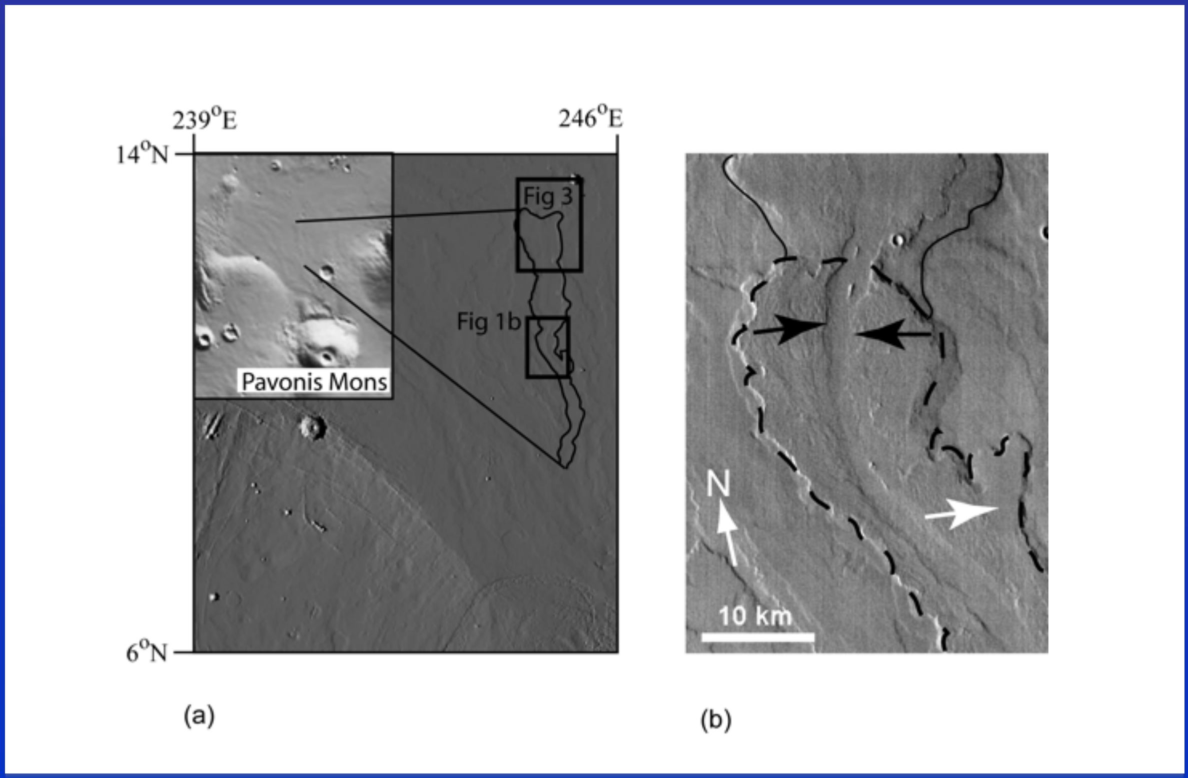
Basaltic Lavas

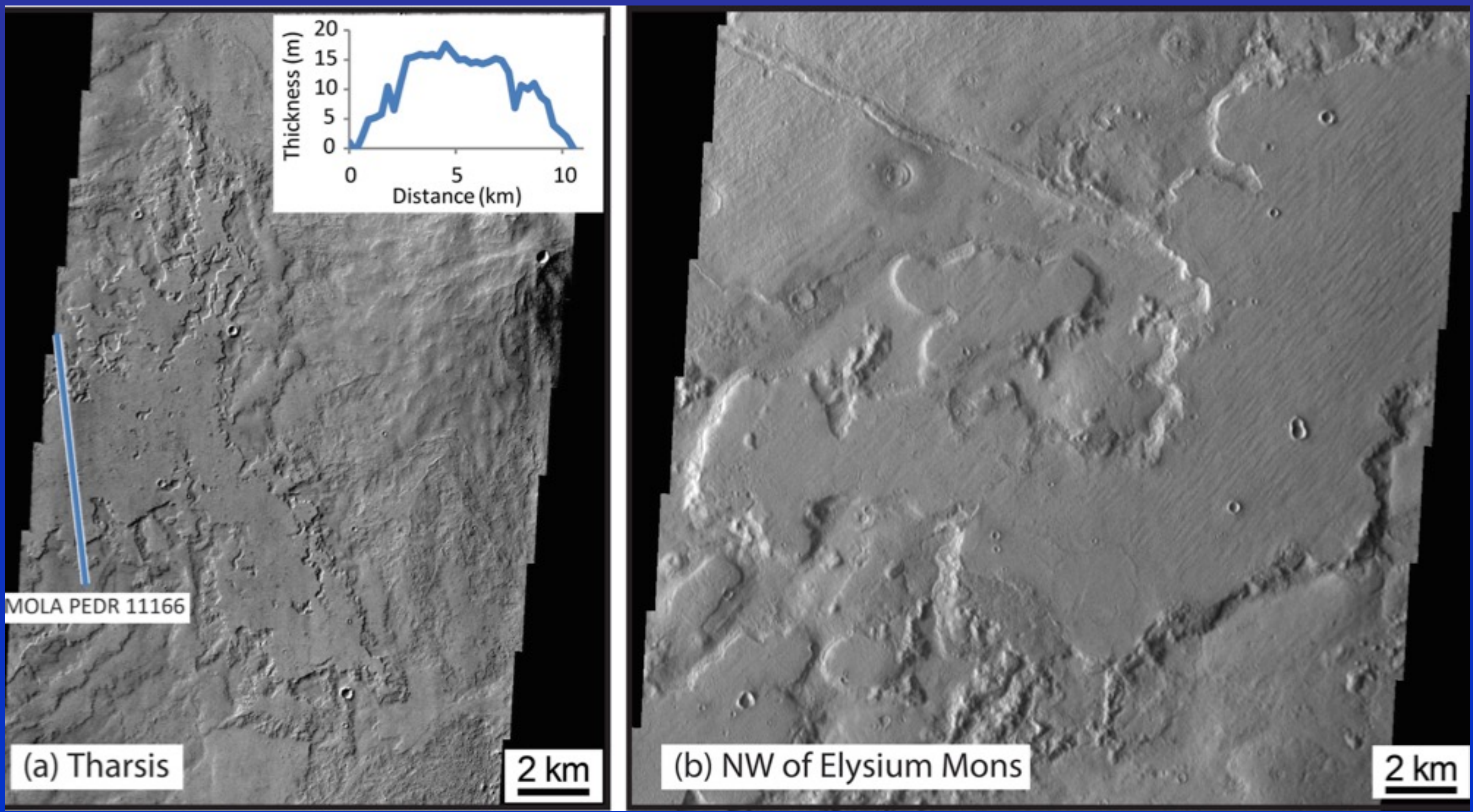
A`a

Pahoehoe

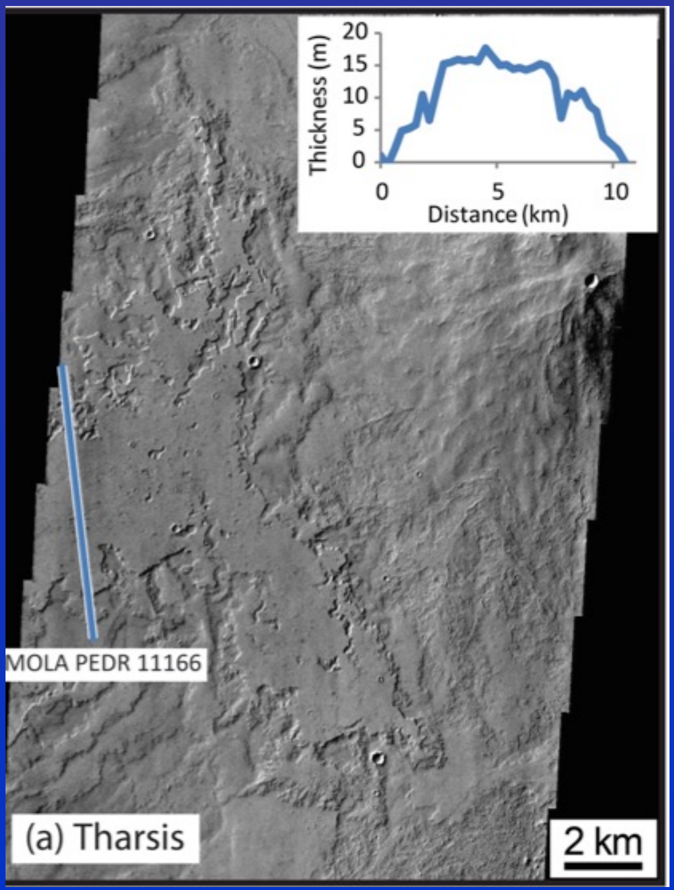
Lava flows on Mars: Channels = a`a



Evidence of pahoehoe on Mars



Lava flows on Mars: No channels?



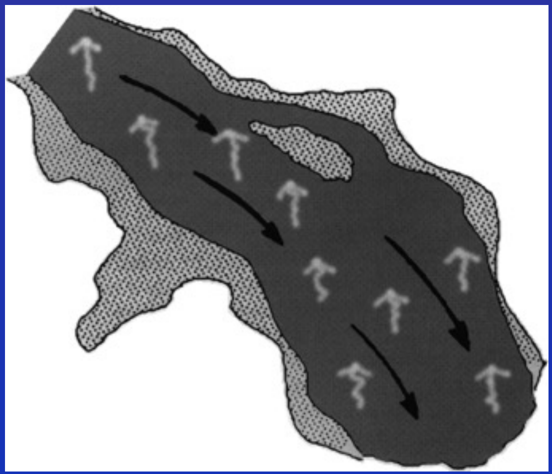
- Flat-topped flows resemble inflated pahoehoe sheet flows (coalesced lobes)
- Crenulated margins indicative of advance through pahoehoe lobes/toes
- Definitely not "channel-fed" a`a flows!

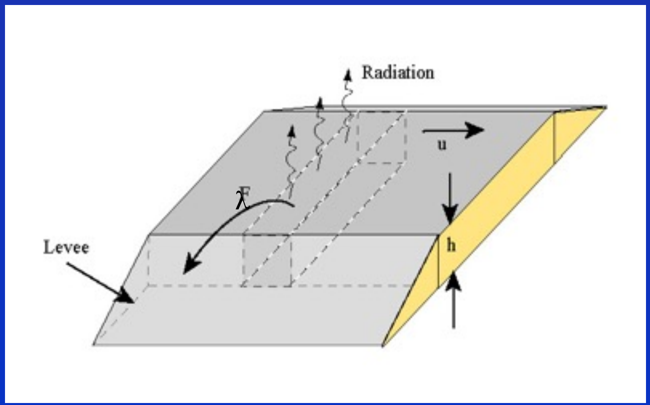
Introduction

- On Earth, pahoehoe flows typically occur on very low slopes (< 5˚) with very low effusion rates (< 10 m^3/s)
- Pahoehoe emplacement is often dominated by random effects
- Baloga and Glaze (2003) examined correlated random walk; complex scenarios were beyond computational ability at that time
- Can pahoehoe emplacement be "modeled"?
- If so, how?
- What field observations/measurements are needed?

"Modeling" 101

- All theoretical models begin as a cartoon:





- Leading to description of control volume physics

Typical Conservation Equations

- Volume

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} = -\lambda F$$

- Momentum

$$\frac{\partial (\rho u h)}{\partial t} + \frac{\partial (\rho h u^2)}{\partial x} = \rho g \sin(\theta) - \frac{\partial P}{\partial x}$$

- Heat

$$\frac{\partial (\rho h C_p T)}{\partial t} + \frac{\partial (\rho h C_p T)}{\partial x} = -\varepsilon \sigma T^4 h$$

Classic Physics Approach

- Gravity
- Slope
- Inertia
- Pressure
- Rheologic parameters
- Cooling
- Crystallization
- Strength of crust
- Lava supply

Predictable response ("deterministic") of bulk flow to limited number of well-characterized influences

Random Influences

- Pre-existing topography
- Skin formation and strength
- Self-induced topography
- Small-scale cooling and crystallization variations
- Lava discharge variations

Behavior of individual parcels must be considered and then aggregated together to understand the overall properties of the entire lobe

Emplacement dominated by Random Influences

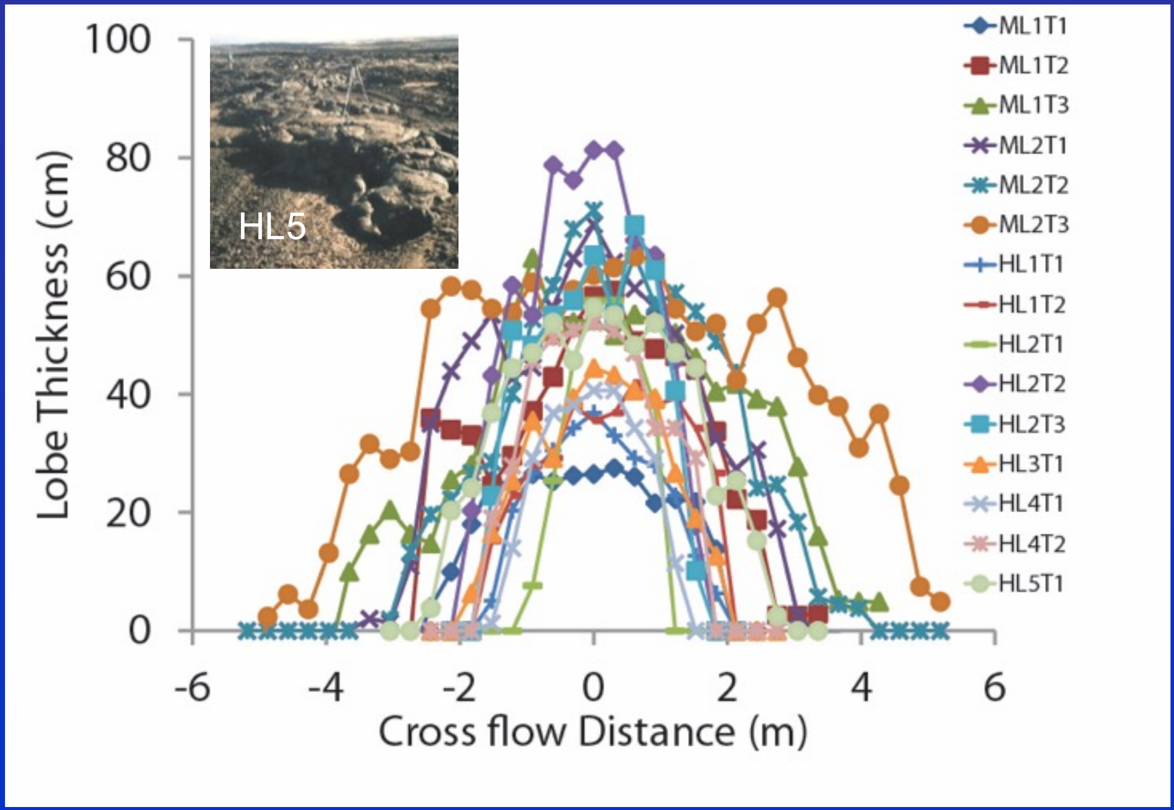
“Toe”

Typical Lobe and Flow Field

Key Observables

- Topographic profile shape
- Plan form variability
- Morphologic diagnostics
- Areal spreading rate
- Advance rate of the flow front
- Age distribution of the surface
- Flow directions on the surface

Key Observable: Lobe Topography



Key Factors Influencing Observables

- Topographic barriers
- Overall pre-existing slope
- Periods of inflation
- Channels, tubes, and preferred pathways
- Volumetric flow rate
- Durations of supply
- Growth and mechanical strength of the crust

Simulation Approach

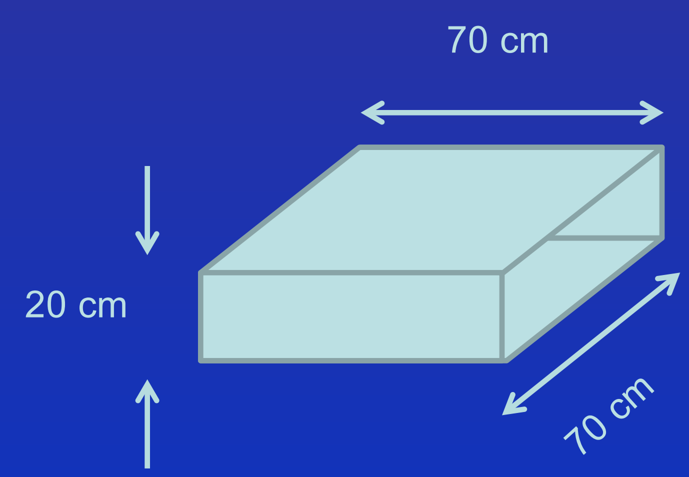
- Objective: Model basic factors and conditions that influence lobe dimensions and morphology
- Model based on:
  - Conservation of volume
  - Prescribed stochastic rules for lava movements within a pahoehoe lobe

What is a simulation?

- One or more quantities is a random variable that draws a particular value from a prescribed probability distribution.
- Each simulation represents a single trial or "realization" of the key observables.
- Due to randomness, each simulation produces a different set of outcomes depending on the underlying probability distributions.

A Lava "Parcel"

- Single parcel of volume, *V*, added at each time step, Γ
- For constant source of supply, volume flow rate, $Q = V/\Gamma$
- Parcel volume equivalent to a pahoehoe "toe"
- Parcel becomes a toe when affixed at the surface or margin of a lobe
- Parcels remain fluid and mobile in the lobe interior



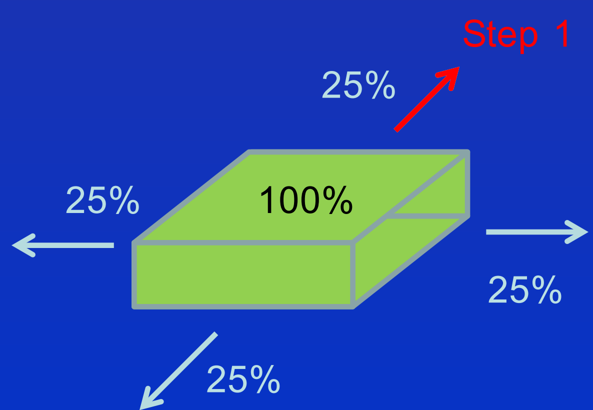
Crown and Baloga (1999):
Typical toe V = 0.09 m^3

Field Constraints

- Hamilton et al. [2013] supports constant volume flow rate assumption
  - For $Q = 0.006$ m^3/s, $\Gamma = 15$ s
- Not much in literature on lobe volumes
  - Hamilton et al. [2013] describes two small lobes with volumes of 10 m^3 and 60 m^3, respectively
  - Simulations explore lobe volumes from 5 – 225 m^3

Model Core

Two Choices (two random numbers*):
- Location of parcel transfer
- Direction of parcel transfer



*In simplest case, choices are equally probable

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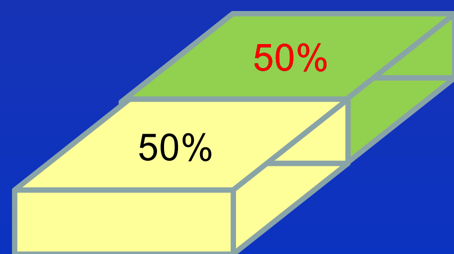

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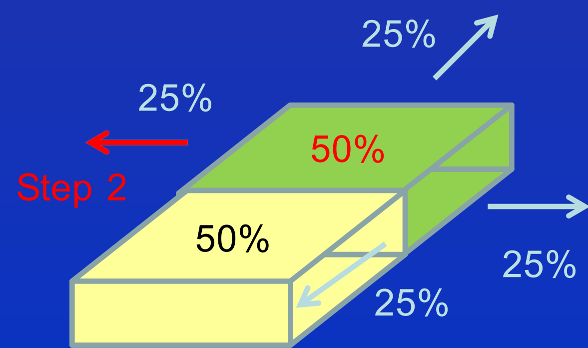

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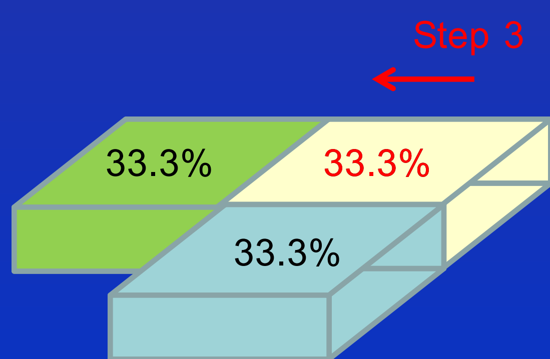

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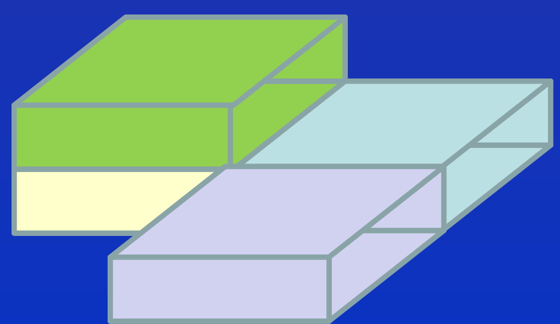
Model Core

Two Choices (two random numbers*):

•Location of parcel transfer

•Direction of parcel transfer



and so on…

*In simplest case, choices are equally probable

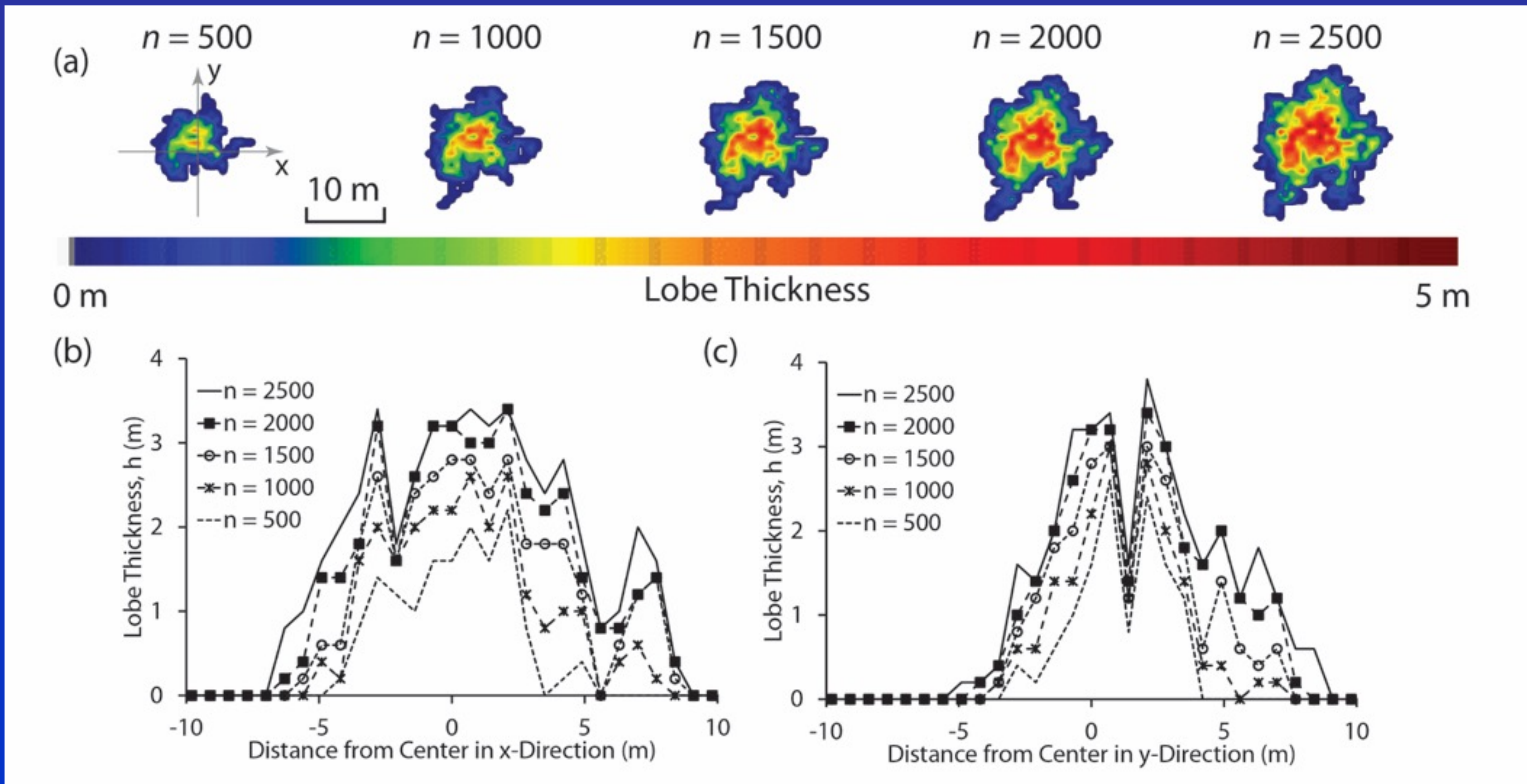
Example Realization

0 cm

550 cm

N = 2500

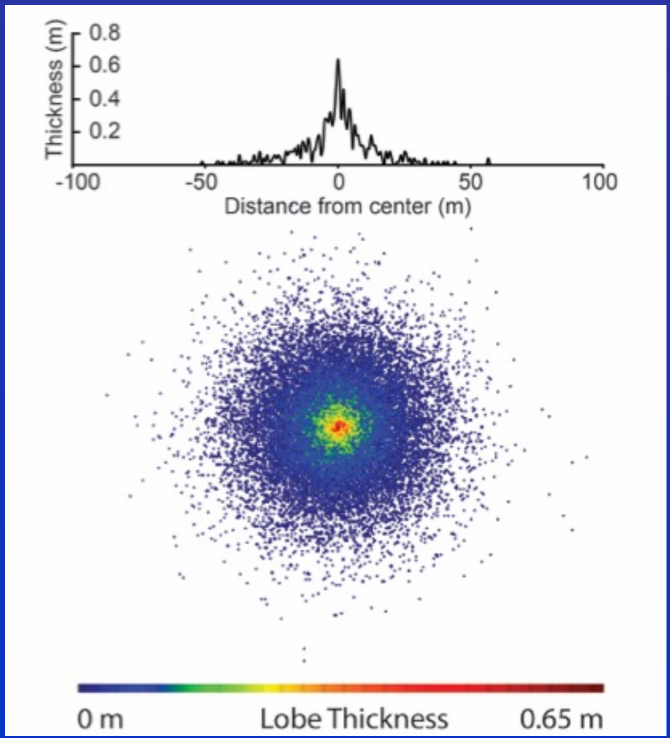
Reference Case: Equiprobable, Point Source



Difference from "Classical" random walk

- Classical: Every walker must move at every time step
  - diffuse distribution (100 m wide)
  - concave upper surface

- New: Walkers remain dormant but fluid for multiple time steps
  - Compact (15 – 20 m wide)
  - Concave down

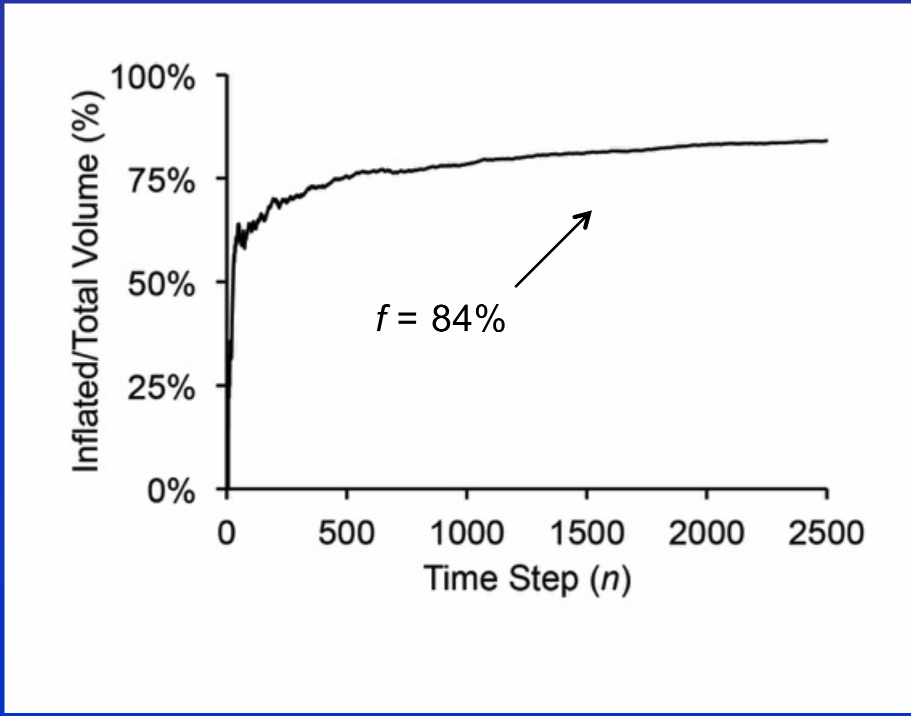


Average of 10 runs, N = 2500

“Inflation”

- Inflation: Increase in lobe volume *without* increase in lobe area
- Approach used here naturally includes inflation
- The percentage of lobe volume, *f*, contributing to inflation increases with the number of time steps

Reference Case: 84% of total lobe volume is from inflation



Framework to Explore Influences

- Using the basic simulation framework, we have looked at the influences of:
  - Number of parcels in a lobe
  - Source size (point vs. areal)
  - Source shape (point vs. linear)
  - Confinement by topographic barriers
  - Surface temperature distributions
  - Correlation (some degree of non-randomness)
- Each of these are discussed in Glaze and Baloga (2013)

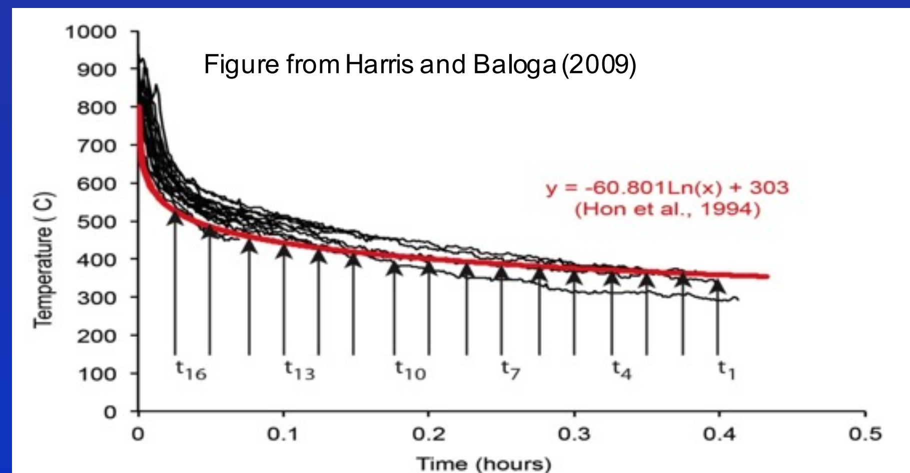
Correlation

- "Correlation" is a statistical term that describes the influence of prior steps
- Prescribes *different* probabilities for some parcel locations – in contrast to "equiprobable" case
- Glaze and Baloga [2013] used correlation to describe sequential breakouts at the margin
  - Somewhat arbitrary approach
- Glaze and Baloga [2015] used physical basis (surface temperature and internal pressure) to constrain correlation

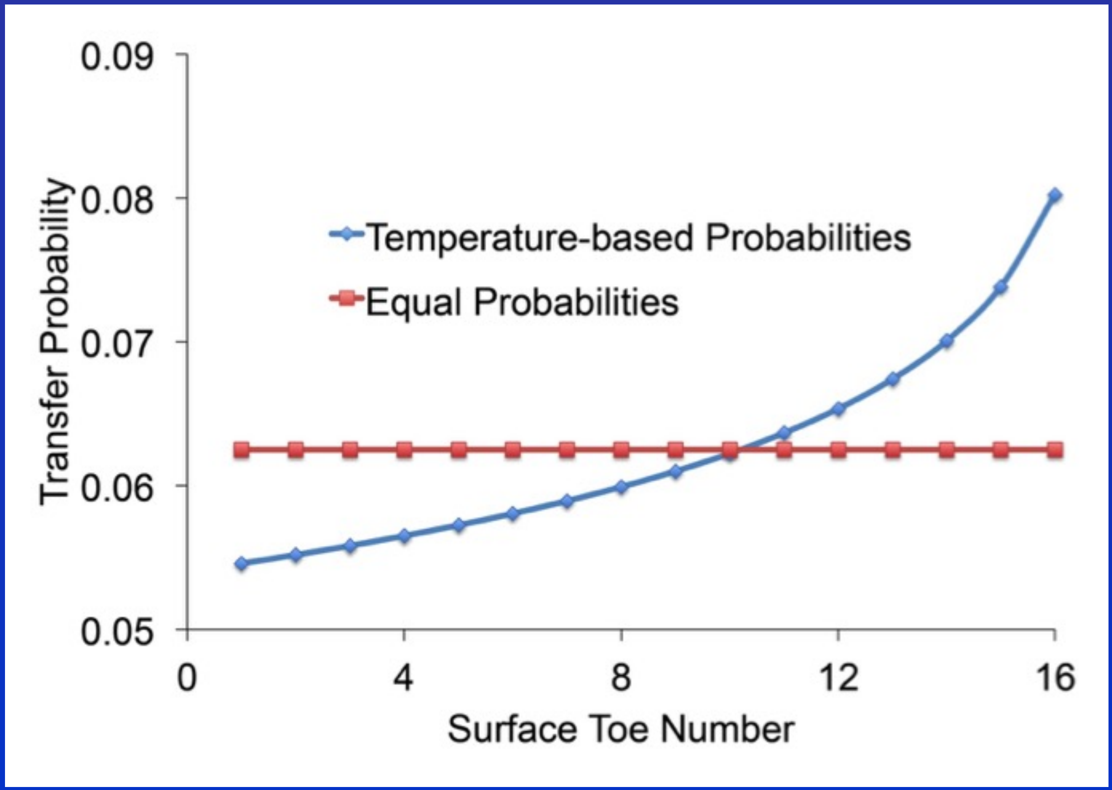
Correlation with Physics: Cooling

- Warmer parcels are more likely to breakout than cooler ones
- Mechanical strength of the crust increases with exposure time
- Cooling rate of pahoehoe is well-known (e.g., Harris and Baloga, 2009; Crisp and Baloga, 1990)

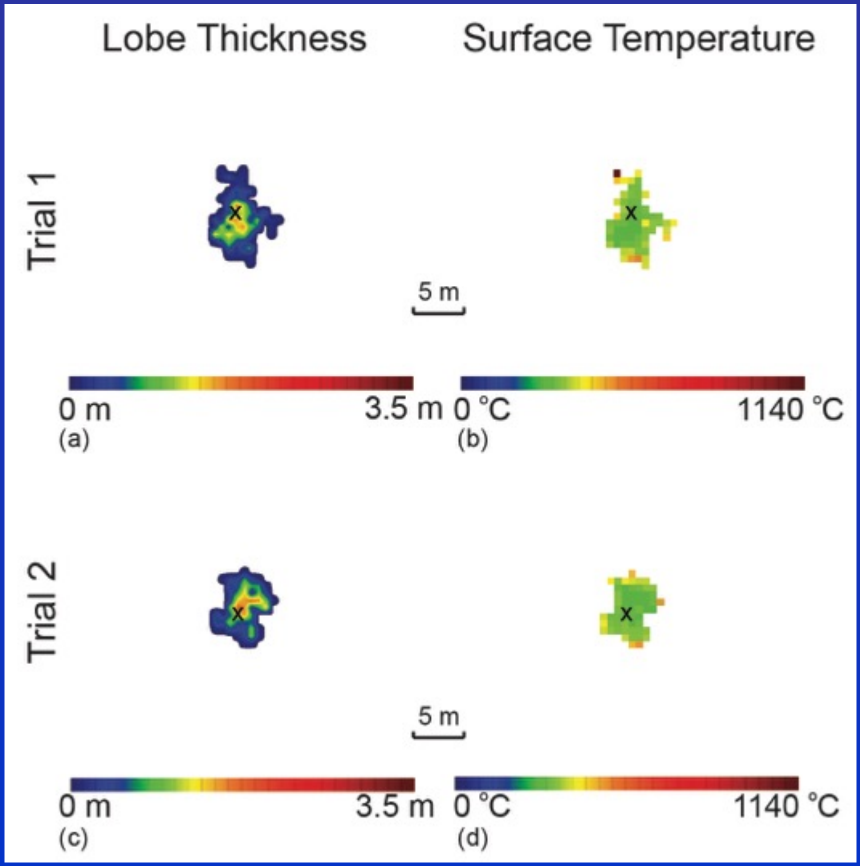
- Assume transfer probability is proportional to surface temperature



Cooling Probability Rules

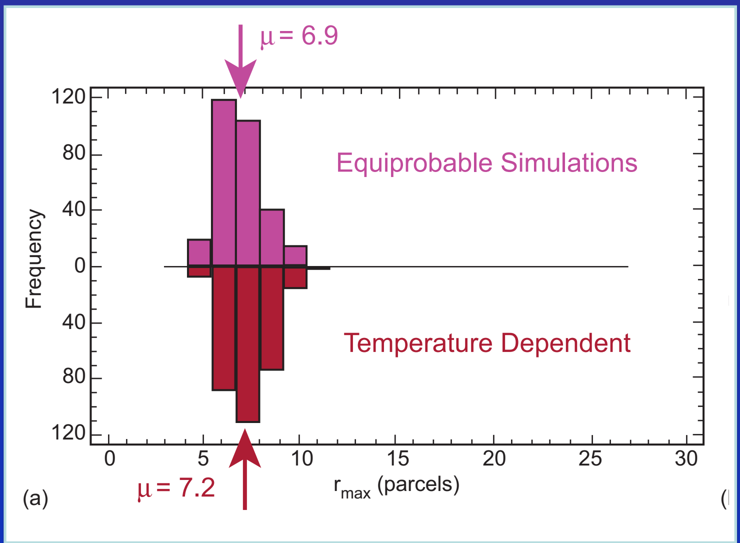


Temperature-dependent: 2 examples



- Point Source
- N = 200
- t = 15 s (observed flow rates)

r_{max} Comparison



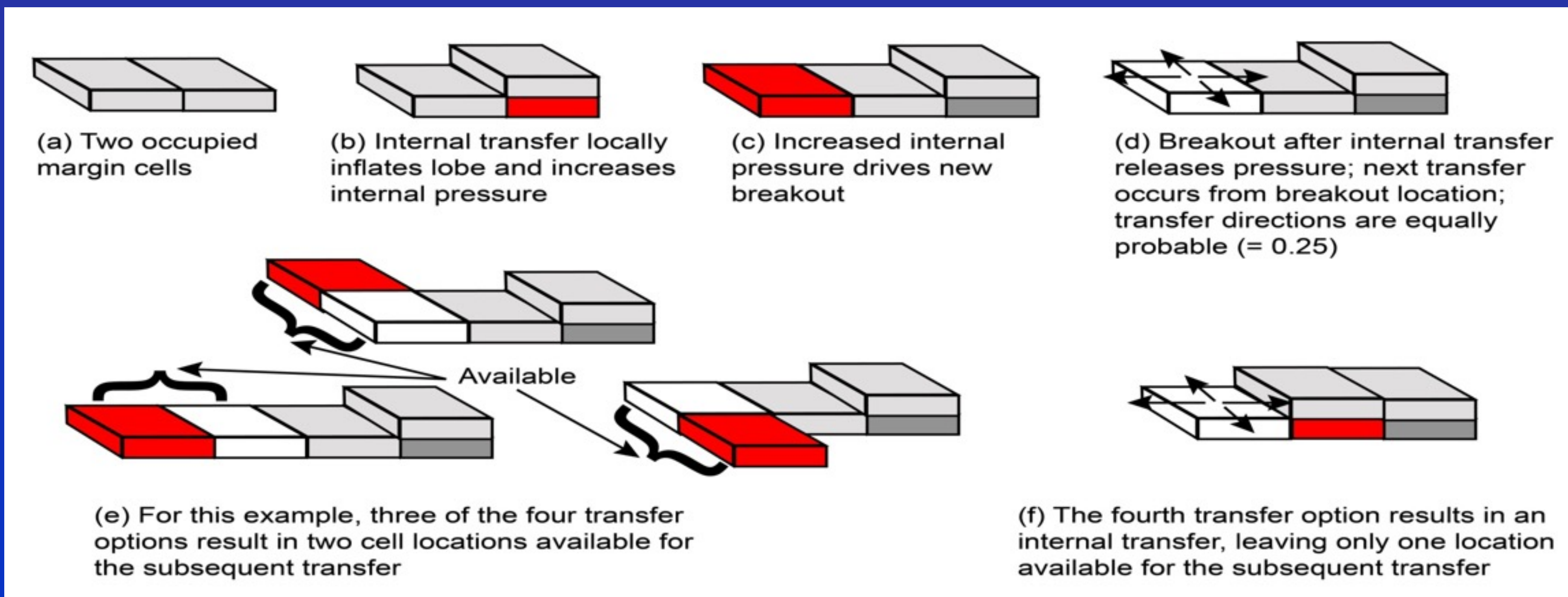
Comparison of maximum distance traveled by a parcel. Histograms show r_{max} from 300 simulations, each with 200 parcels, and 15 second time steps.

- Temperature dependence has a measurable effect on the r_{max}
- Effect decays rapidly to the equiprobable case
- Difference is probably not distinguishable in the field

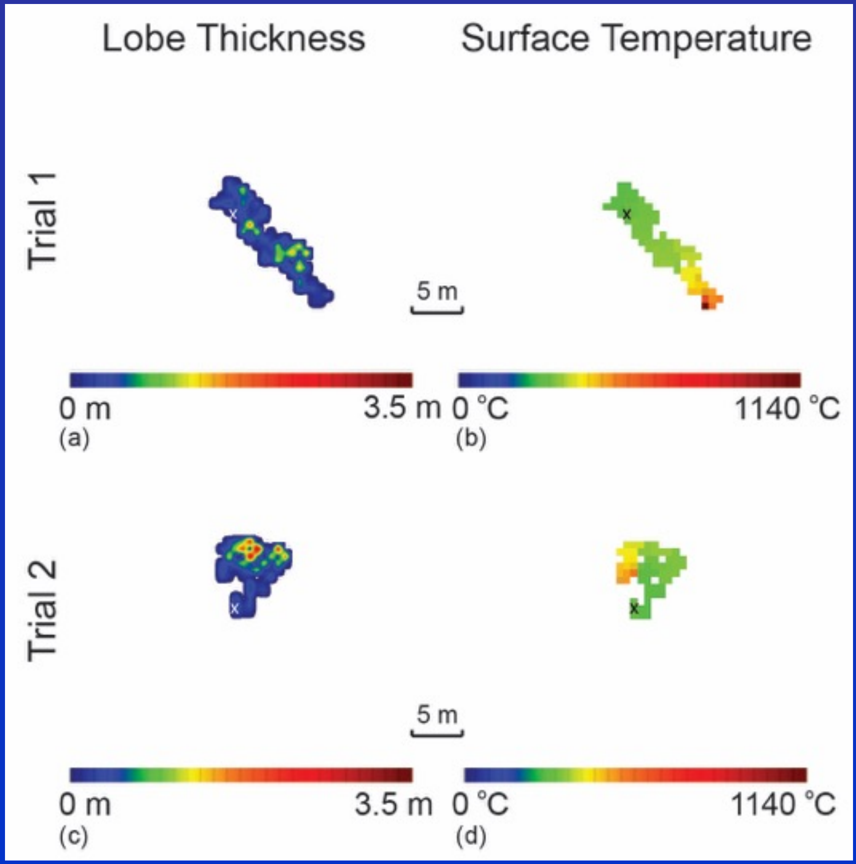
Temperature + Pressure

- The temperature effect can be amplified by adding pressure correlation when breakout occurs after internal transfers:
  - Internal transfers (i.e., inflation) result in a local increase in lobe thickness and a pressure gradient
  - A breakout following one or more internal transfers will become the “weakest” point in the lobe and the site of future transfers
- This is the essential stochastic rule for modeling the influence of internal inflation pressure
- The addition of internal inflation pressure produces dramatically different morphologies by magnifying the importance of breakouts at the margin

Pressure-dominated Correlation



Pressure – dominated: 2 examples



- Point Source
- N = 200
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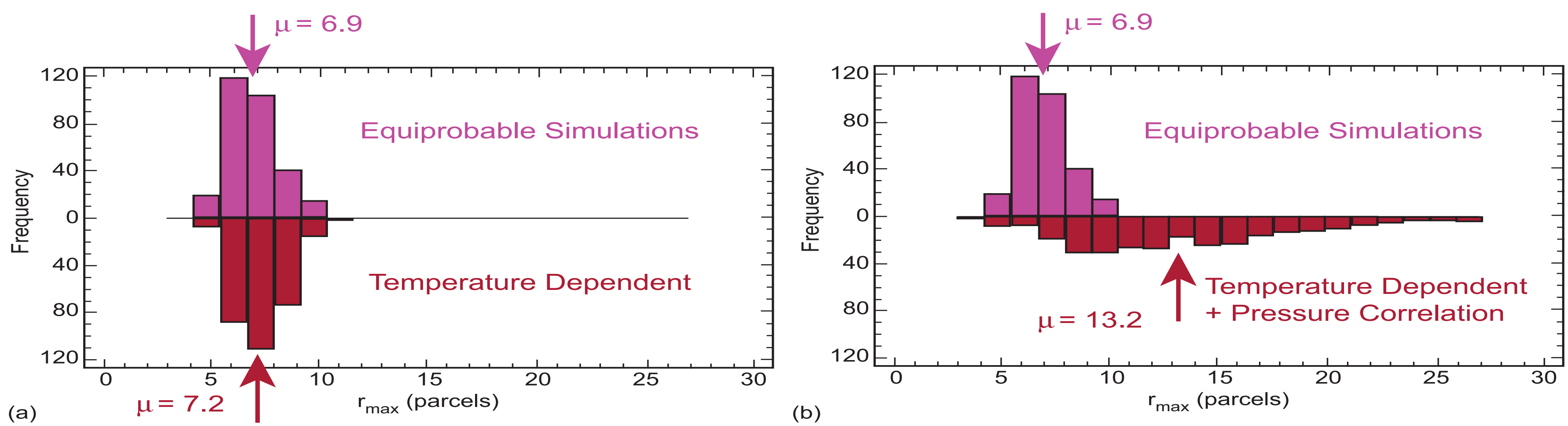
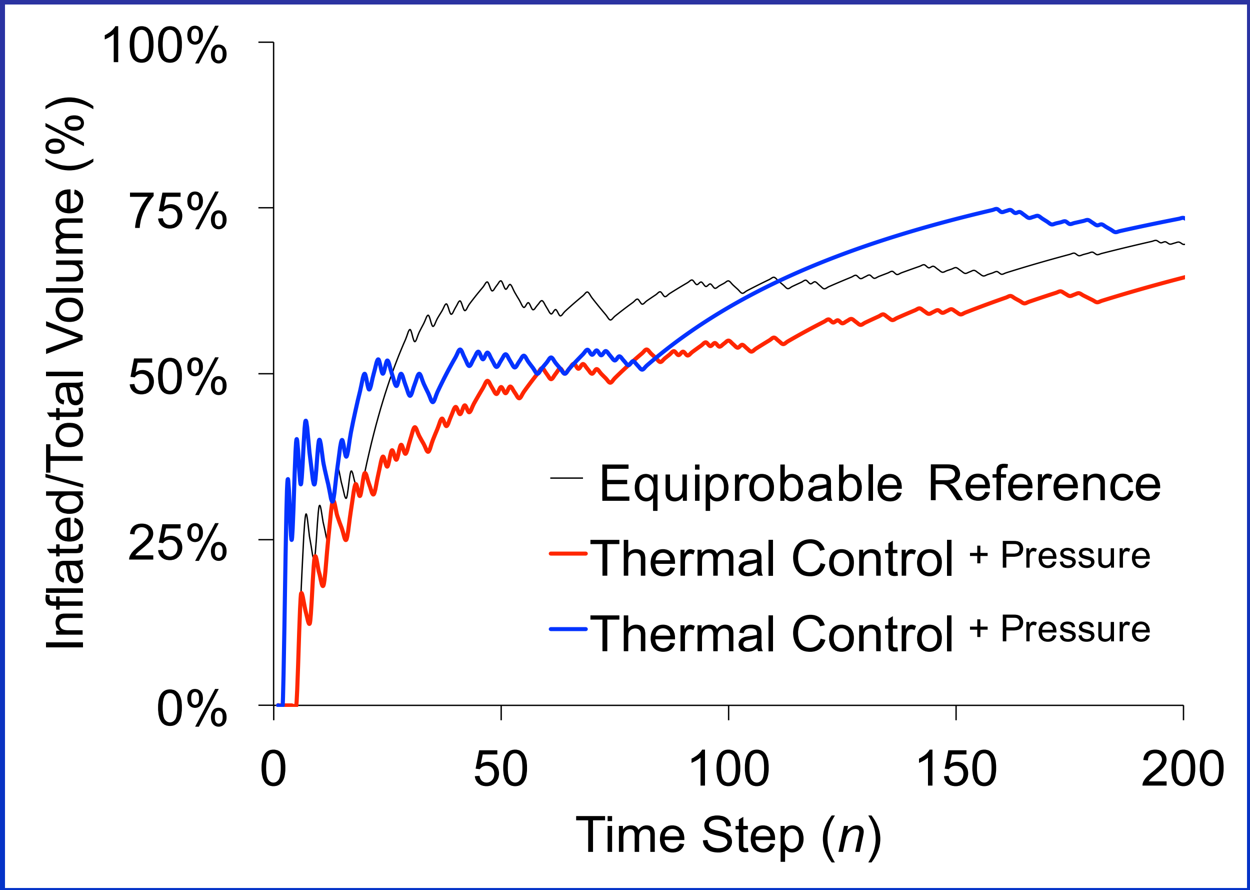
r_{max} Comparisons



Inflation Retained



Conclusions

- Pahoehoe emplacement is dominated by random effects, but they can be modeled and characterized by field studies.
- Conventional deterministic methods are not applicable to the dominant processes the govern overall emplacement.
- New random walk simulation approach
  - Qualitatively reproduces pahoehoe lobe topography and plan form,
  - Accommodates inflation and correlation observed in the field.
  - Cooling and is an independent physical process that enables calibration of the simulation model

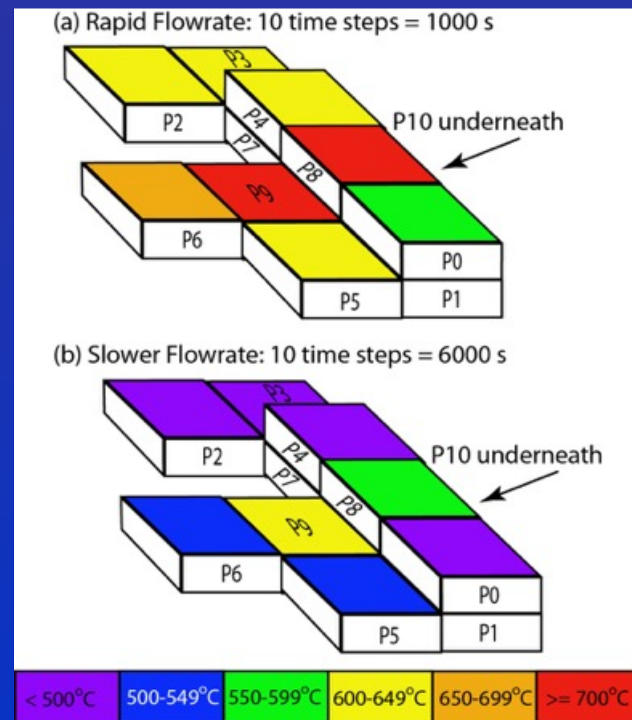
Conclusions – cont.

- Three types of simulations of parcel transfers have been explored:
  - Equiprobable,
  - Temperature-dependent, and
  - Pressure-dominated.
- All three types reproduce the lobe inflation observed in the field.
- Pressure-dominated lobes are generally highly lobate, asymmetric, significantly longer and thinner and would be readily distinguishable in the field.
- This NEW approach has tremendous potential for developing inferences for planetary pahoehoe flow emplacement.
- Next step: Exploring correlation due to slope

Backup

Surface Age

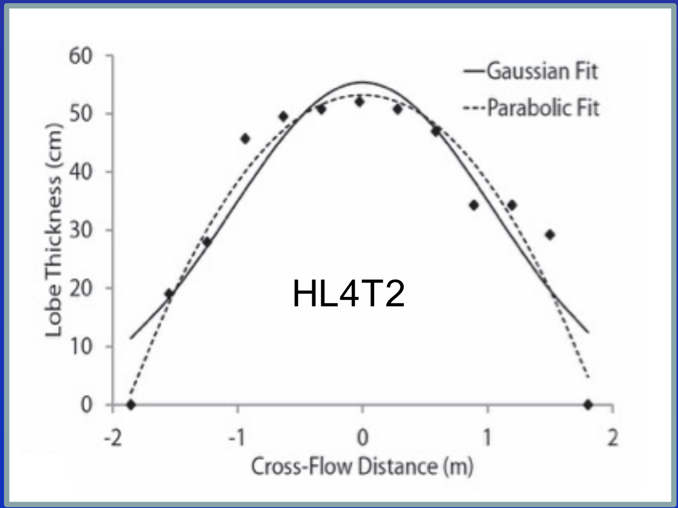
- Model can be used to track the temperature of each surface parcel as function of time
- Age of surface parcels depends on flow rate!!
- Comparisons can be made to thermal remote sensing data [Harris et al., 2007]



Crisp and Baloga [1990] used for temperature as a function of time

Fitting Profile Shape

- Most lobes have a medial ridge
- Explored Gaussian and Parabolic fits to data
- Gaussian: limit of classical random walks [Pearson 1905; Chandrasekhar, 1943]
- Parabola: pressure driven flow [Smith, 1973; Bruno et al., 1996]



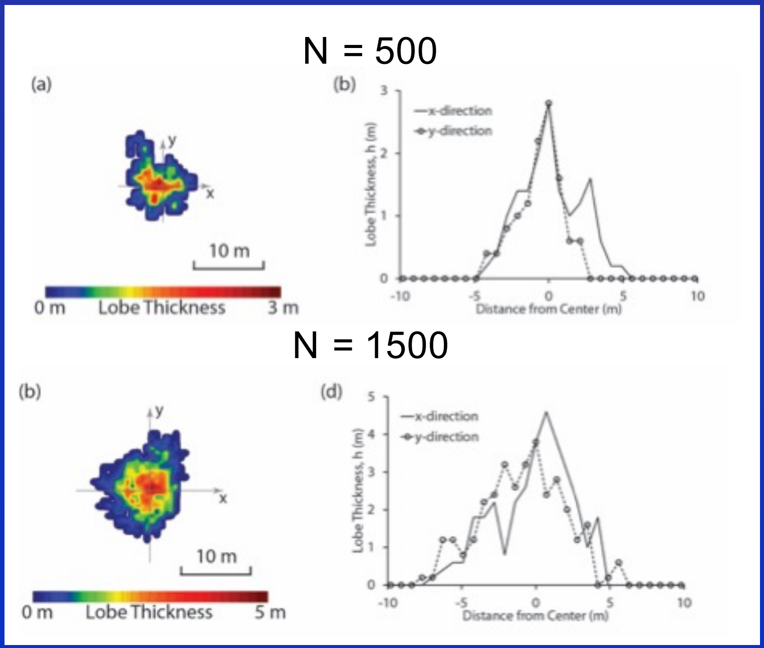
Measures of Fit

- R^2 is reasonably high for both models considering natural variability of data
- Durbin-Watson (D-W) measure of serial correlation varies
- Both Gaussian and parabola provide reasonable fits

	Gaussian		**Parabolic**	
Transect	**R^2**	**D-W**	**R^2**	**D-W**
ML2T2	95.4%	**1.6**	89.7%	0.9
ML2T3	82.6%	1.1	88.5%	**1.5**
HL1T2	77.8%	1.3	86.9%	**1.4**
HL2T1	92.5%	**2.1**	88.5%	**1.5**

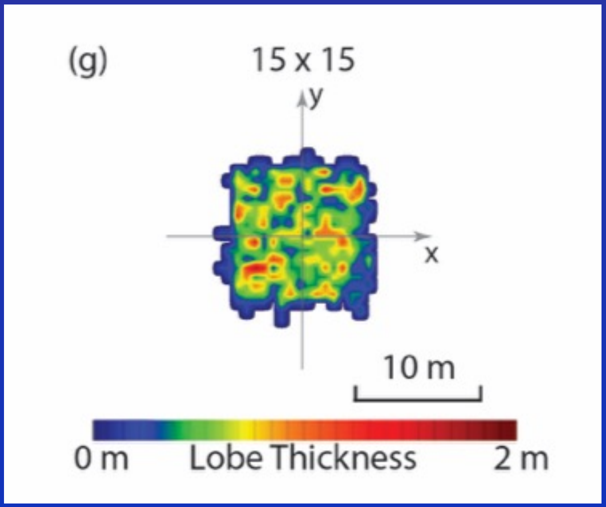
Influence of N

- N = number of parcels/time steps
- Equiprobable; point source
- Larger N results in:
  - Decreased planform variability,
  - More 'rounded' profile shape
  - Larger area and thicker flow



Influence of Source Size

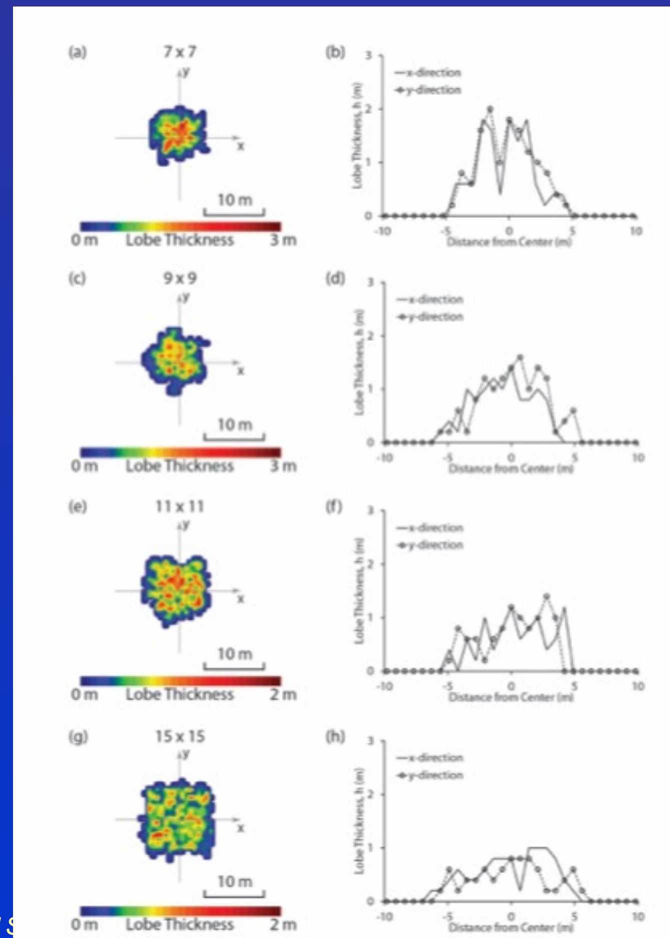
- Source is a sheet of thickness 20 cm (1 parcel)
- As source size increases, planform variability decreases
- As N increases, source appears more point-like
- $N/\sqrt{a}$ is a measure of this effect



N = 500

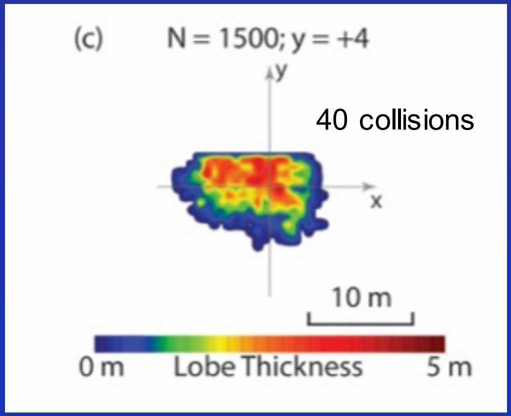
Influence of Source Size

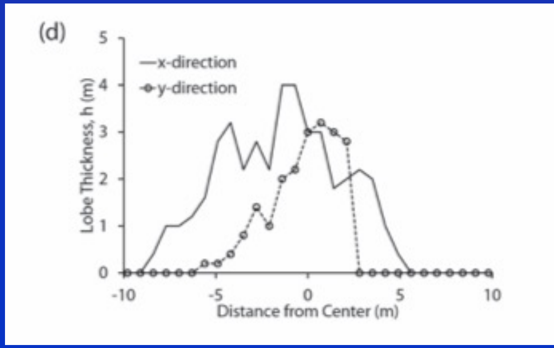
- Equiprobable
- Source is a sheet of thickness 20 cm (1 parcel), and √a = 7, 9, 11, 15
- As source size increases, planform variability decreases
- N/√a is a measure of this effect



Influence of Barriers

- Barrier defined as zero flux point; parcel volume added to the transfer parcel
- Few collisions with barriers relative to N
- Influence of barrier seen in topography of cross-flow profile – piling up of parcels at boundary





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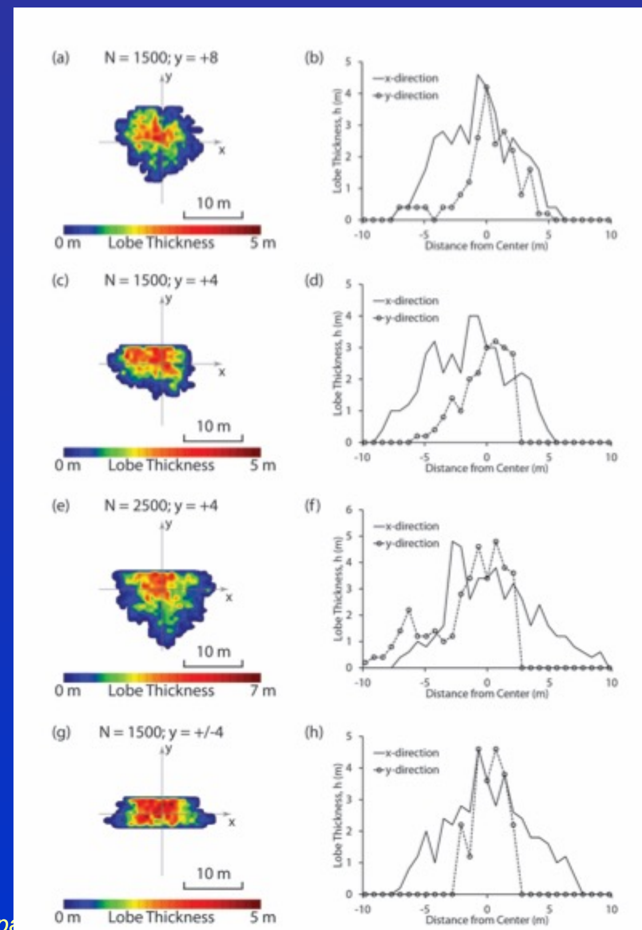
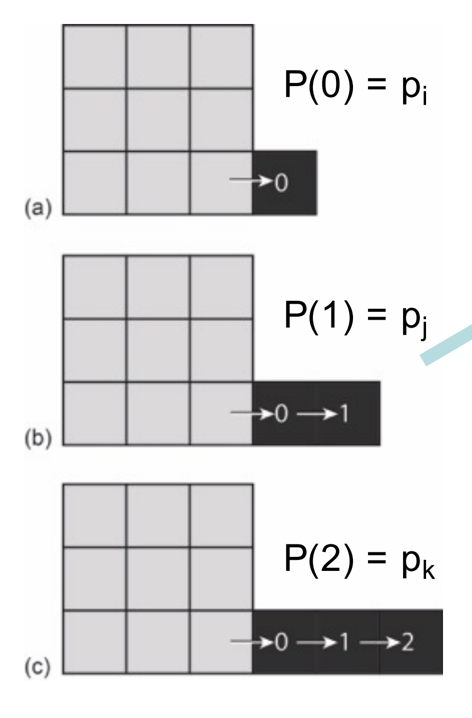
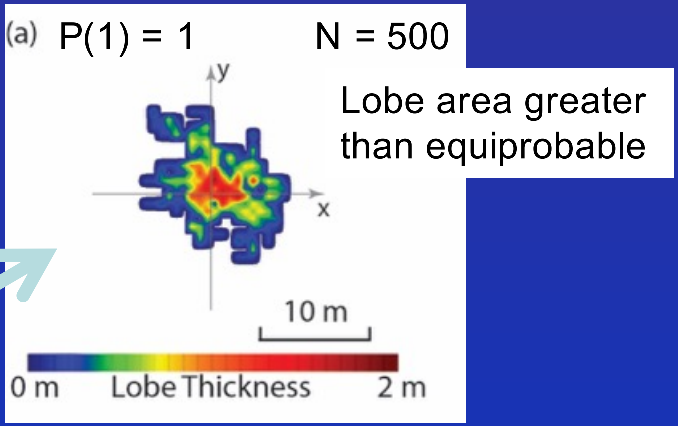
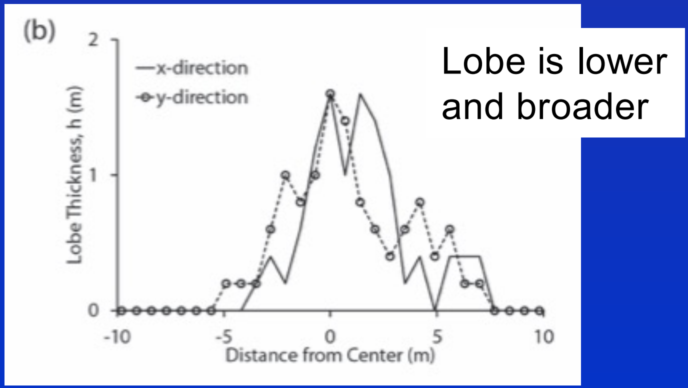


Correlation at Margin

$p_i + p_j + p_k \equiv 1.0$

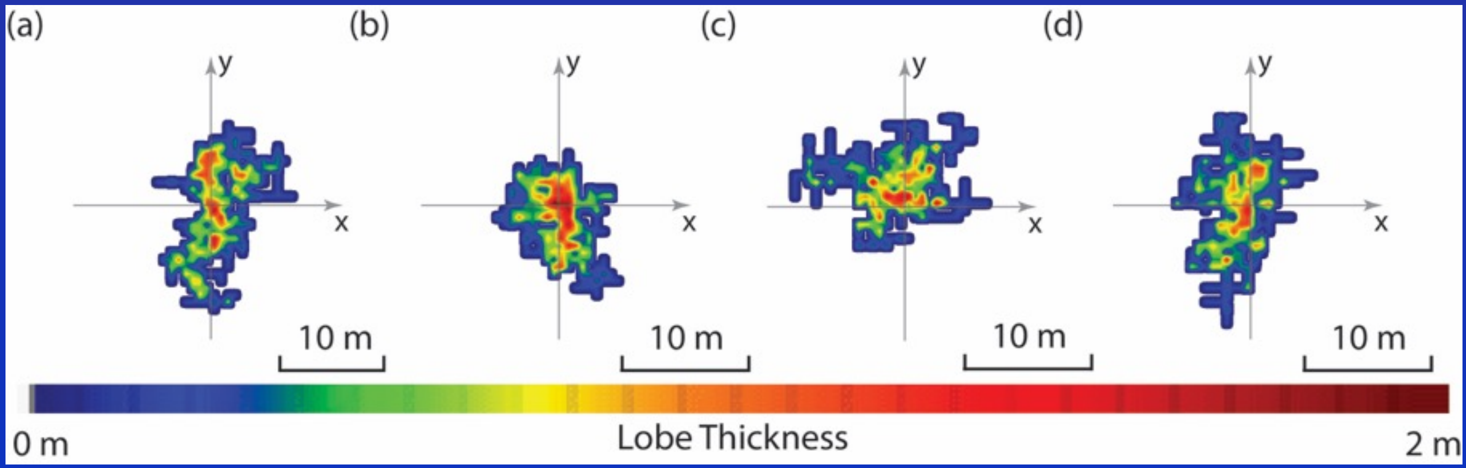






Correlation (N = 500)

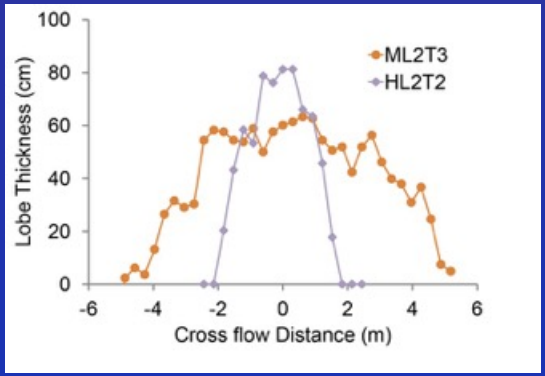
P(0) = 0.333	P(0) = 0.5	P(0) = 0.25	P(0) = 0.25
P(1) = 0.333	P(1) = 0.25	P(1) = 0.5	P(1) = 0.25
P(2) = 0.333	P(2) = 0.25	P(2) = 0.25	P(2) = 0.5



Area = 158 m^2	Area = 134 m^2	Area = 167 m^2	Area = 173 m^2

Comparison with Field Data

- Data:
  - Two example cross flow profiles



Comparison with Field Data

- Data:
  - Two example cross flow profiles
- Simulations:
  - (a) Point source + confined
  - (b) Sheet source
  - Correlation in both cases (50% chance of 2 extra xfers after breakout)