Confined fission track revelation: how it works and why it matters

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November 26, 2022

Abstract

Since the advent of particle-track methods, it has been understood that the energy loss rate of an ion changes continuously along the particle trajectory, and that energy loss rate in turn affects etching rate. As fission particles slow down and stop, their energy loss rate also drops, which in turn reduces their along-track etching velocity. Conversely, the conceptual model that underlies the way we interpret track length data is based on a more simplified paradigm of a constant along-track etching velocity, vT, with the track tip marking the transition to bulk crystal etching, vB, at its maximum etchable extent. We present a new model for the etching and revelation of confined fission tracks that incorporates and attempts to quantify variable along-track etching velocity, vT(x). The model attempts to fully represent the track-in-track (TINT) revelation process, consisting of etchant penetration along semi-tracks intersecting the polished grain surface, expansion of etchant channels to intersect latent confined tracks, etching of confined tracks, and finally selection by the analyst of tracks suitable for measurement. We successfully use the model to fit step-etching data for spontaneous and unannealed and annealed induced confined tracks in Durango apatite. All model fits support a continuous decrease in etching velocity toward track tips, and lead to a series of insights concerning the theory and practice of fission-track thermochronology. Etching rates for annealed induced tracks in Durango apatite are much faster than those for unannealed induced and spontaneous tracks, impacting the relative efficiency of both confined track length and density measurements, and suggesting that high-temperature laboratory annealing may induce a transformation in track cores that does not occur at geological conditions of partial annealing. However, we are still investigating to what degree that pattern holds for other apatite varieties. The model also quantifies how variation in track selection criteria by analysts, which we approximate as the ratio of along-track to bulk etching velocity at the etched track tip (vT/vB), is likely to play a first-order role in the reproducibility of confined length measurements, and may explain the bulk of the variability observed in inter-laboratory calibration exercises. The concept of a "fully etched track" is subjective. Finally, the model illustrates how a substantial proportion of tracks that are intersected are not measured, which in turn indicates that length biasing is likely to be an insufficient mathematical basis for predicting the relative probability of detection of different track populations.

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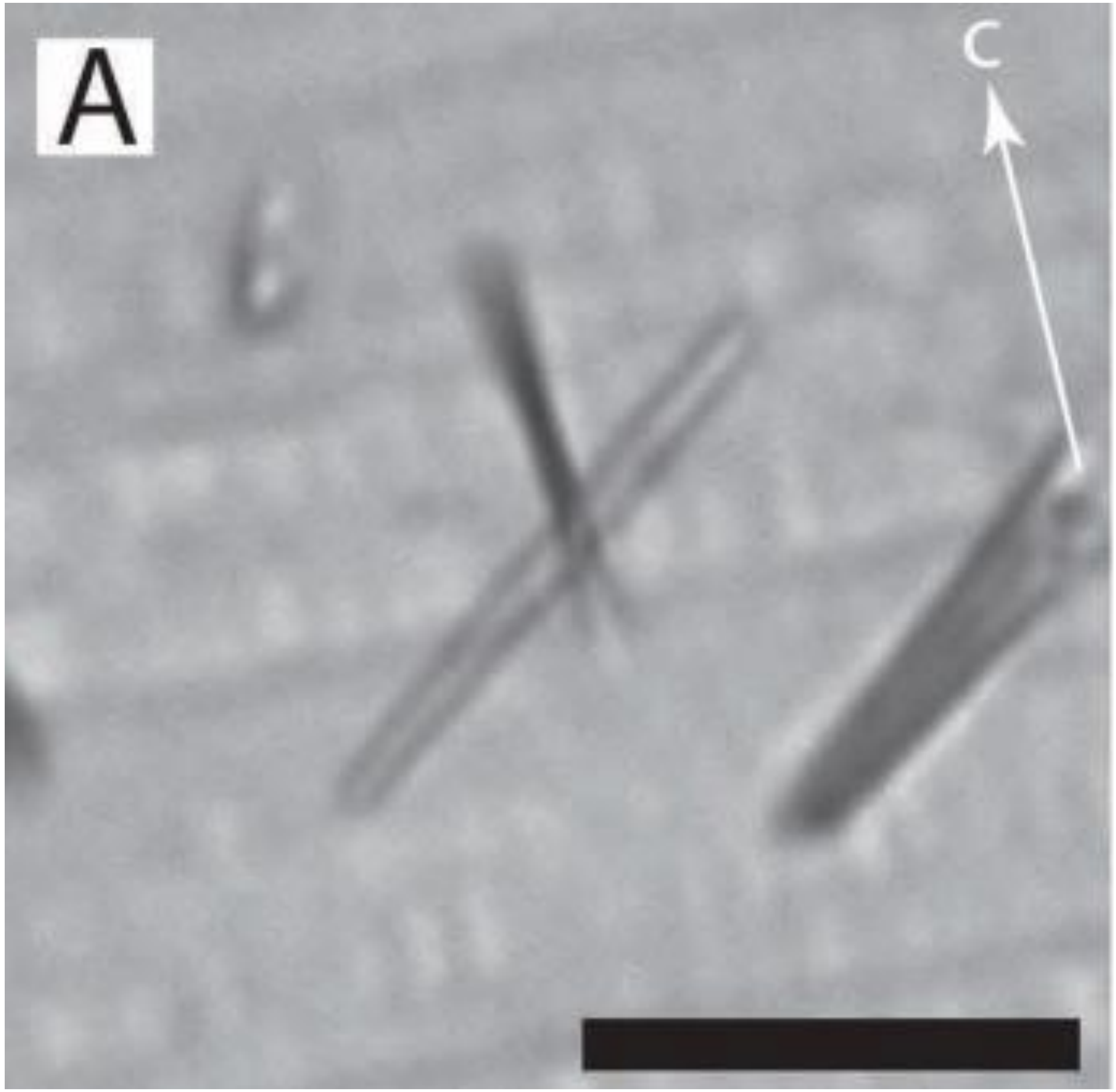
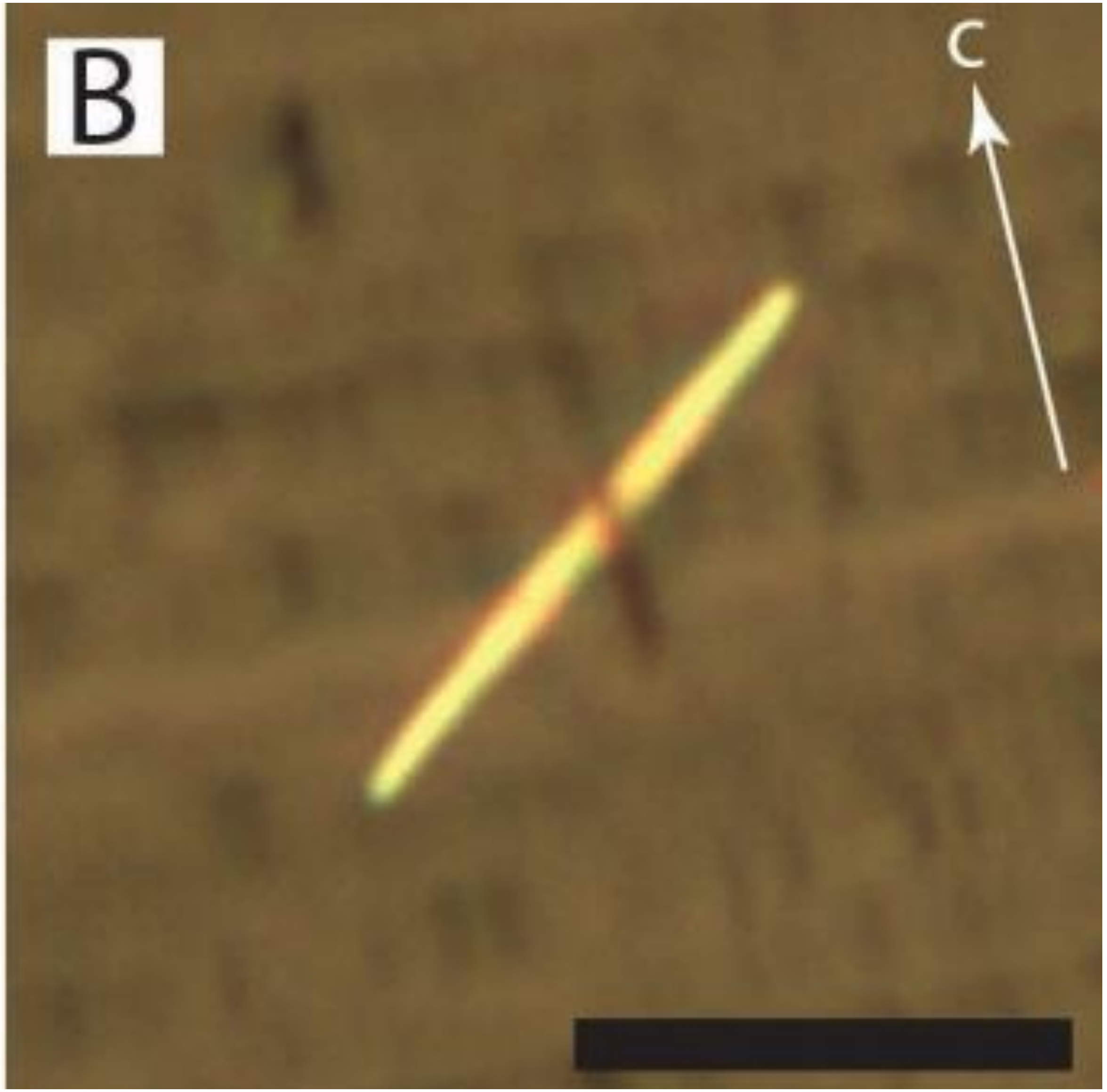
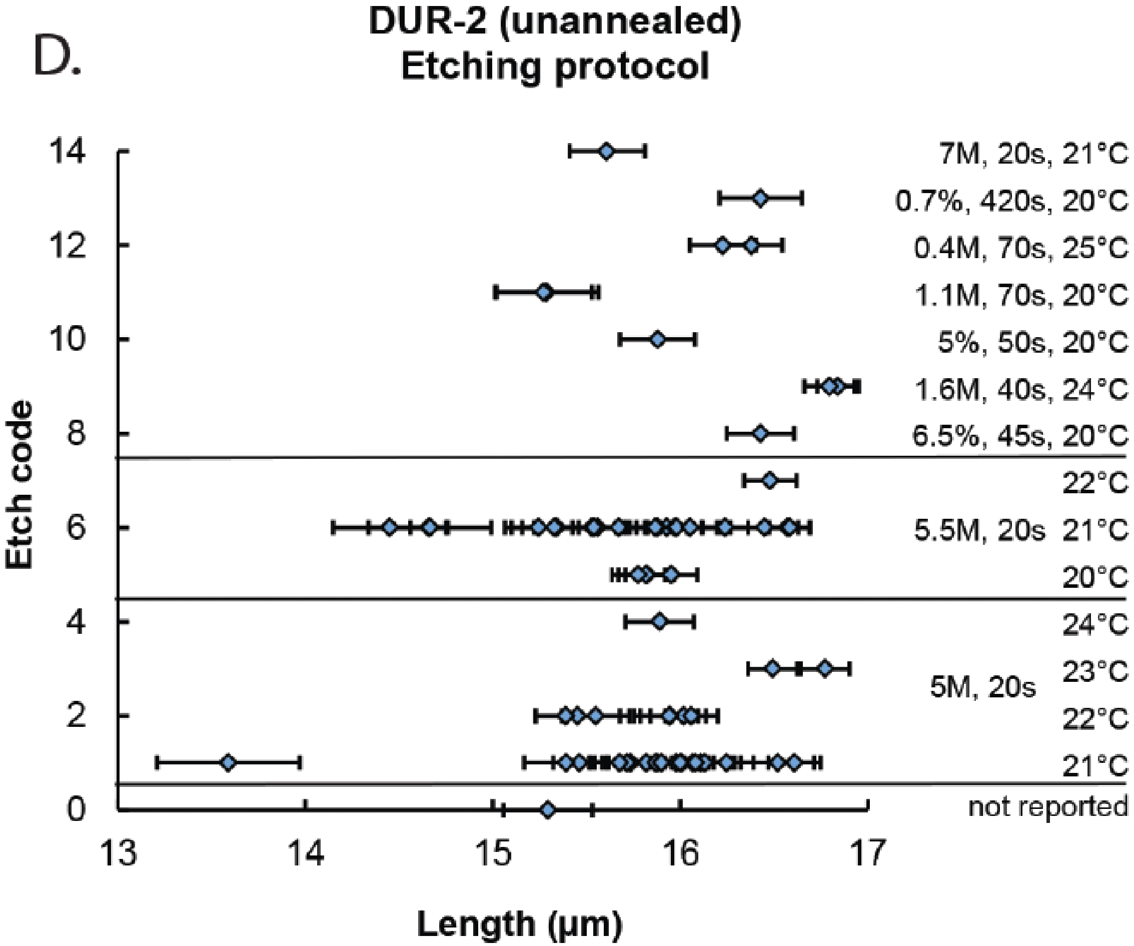
Or, What I did during COVID-19

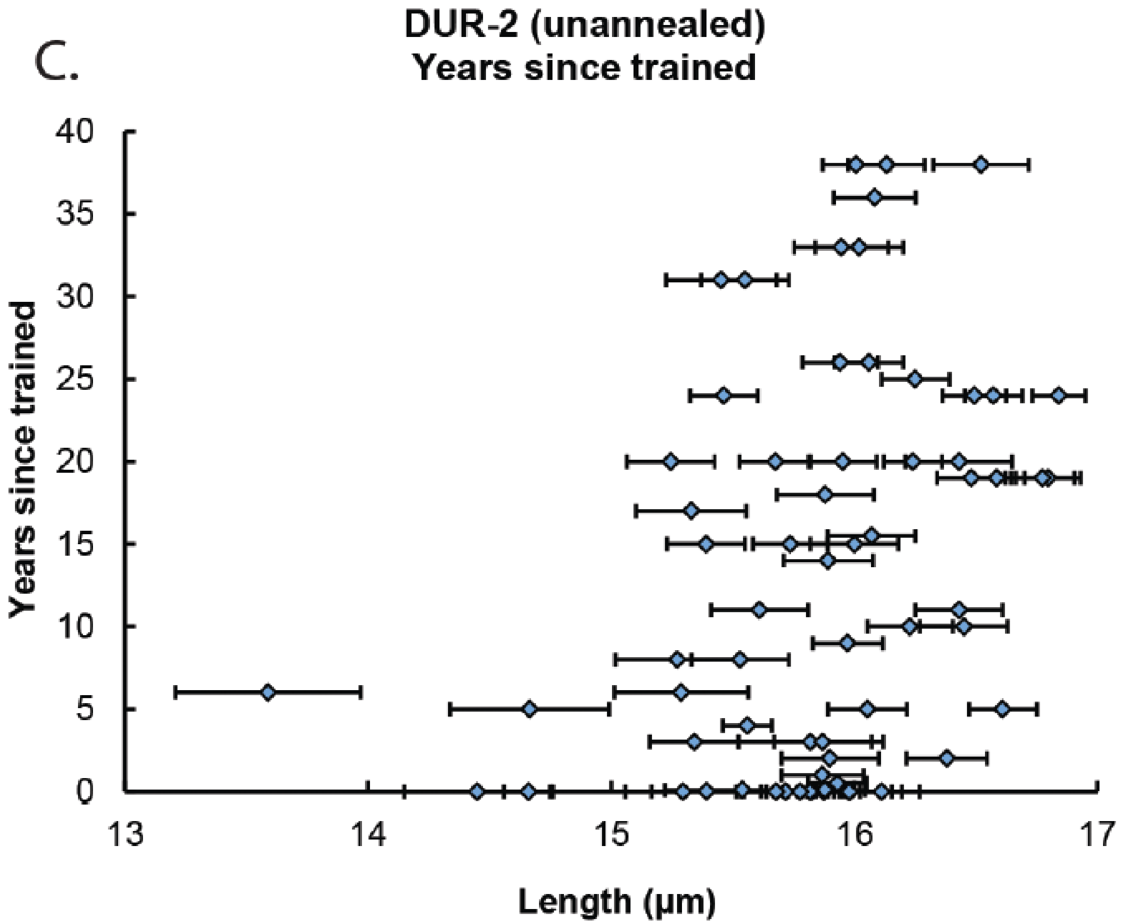




Ketcham, Carter and Hurford, 2015

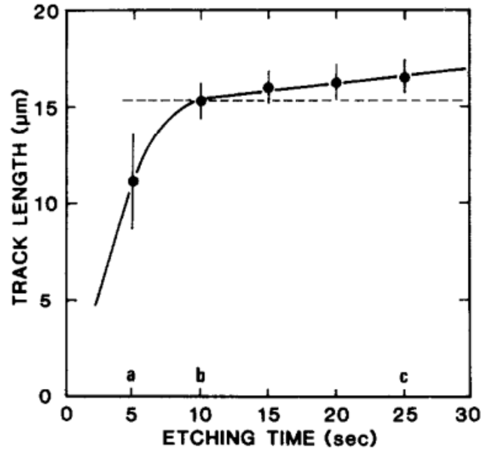
“The easiest length measurement there is”





Ketcham, Carter and Hurford, 2015

What does step etching tell us?

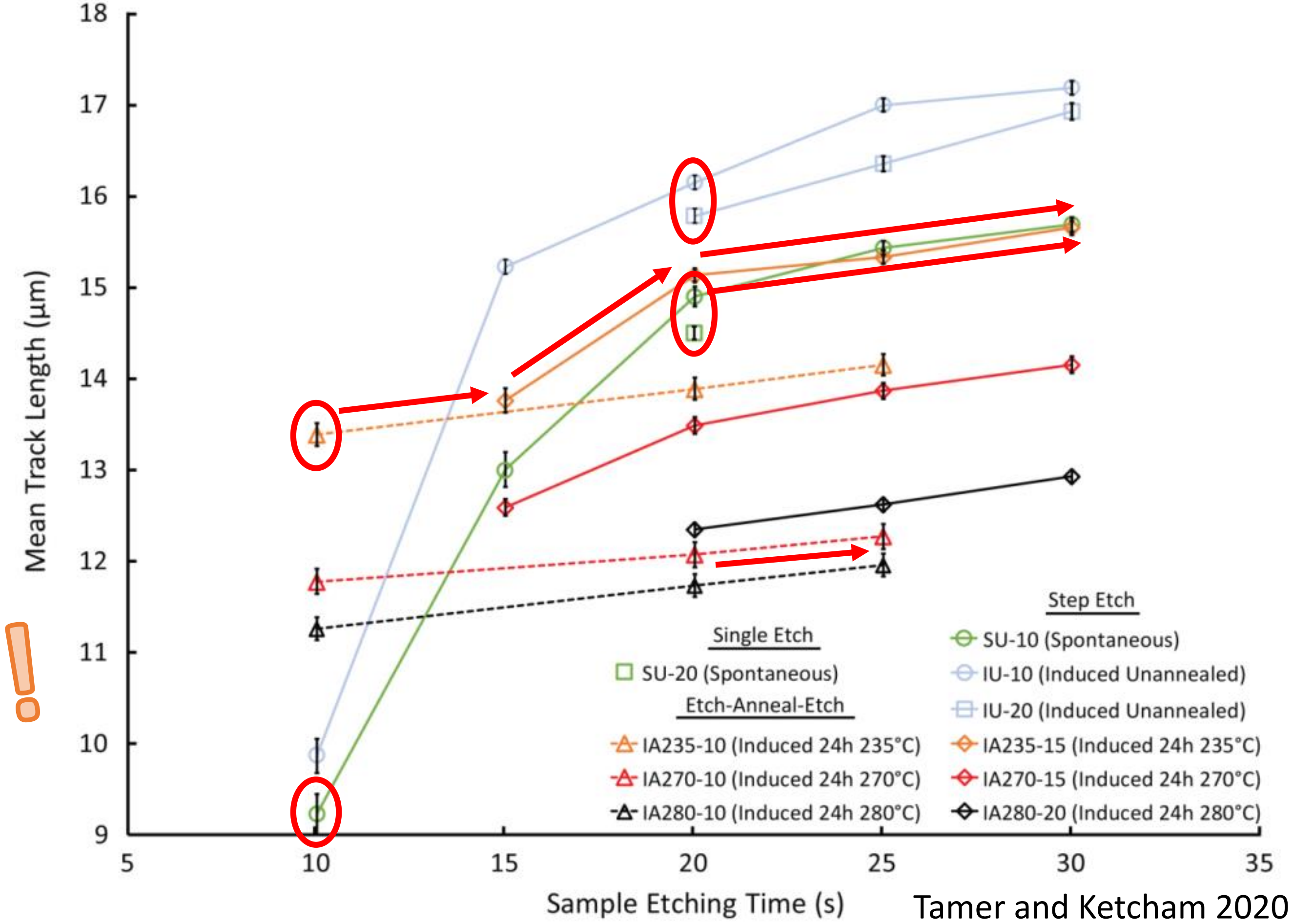


Laslett et al., 1984

Odd results from “follow-each-track” step etching…

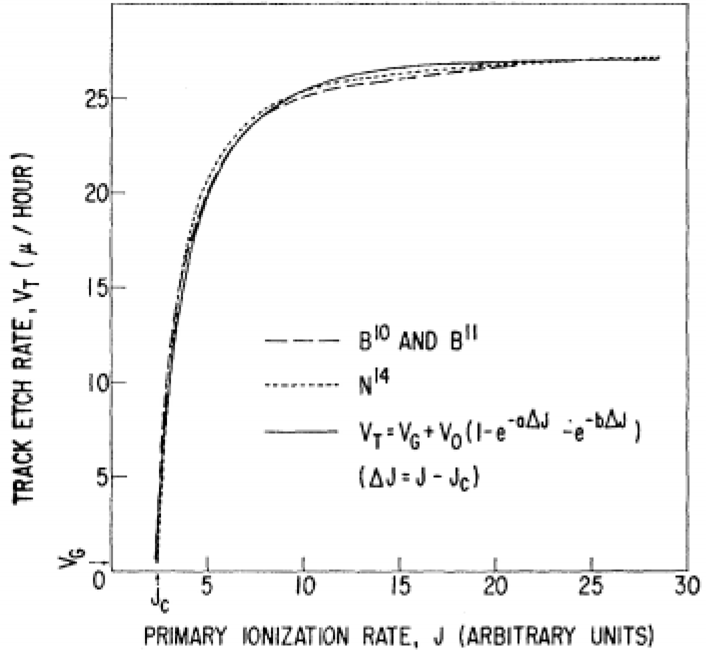
- Bulk etching velocity only reached after 25 seconds(!) in unannealed induced tracks
- Mean lengths 0.4 µm longer if detected after 10 vs. 20 seconds
- Spontaneous and annealed induced tracks very different at 10 s, indistinguishable after 25 s
- Apparent jump in etch rate

All can be explained!



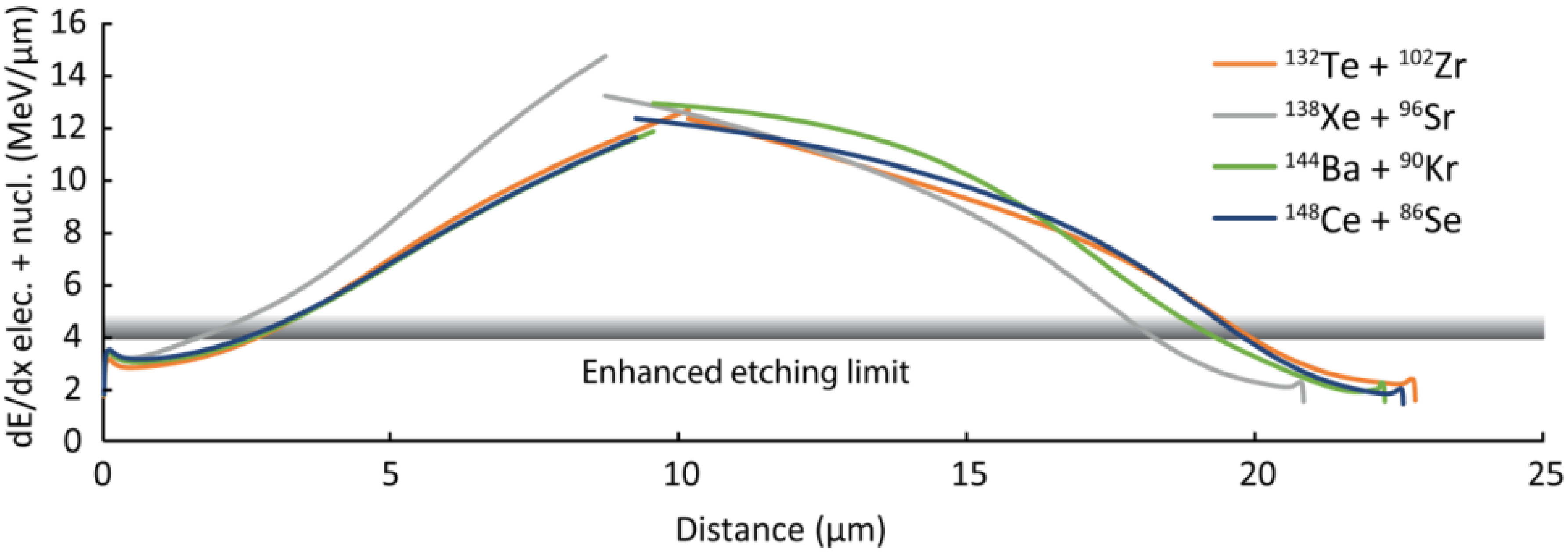
Tamer and Ketcham 2020

Etch rate along track is linked to energy loss rate



Price et al., 1967

Energy loss rates for various possible ^{238}U fission pairs



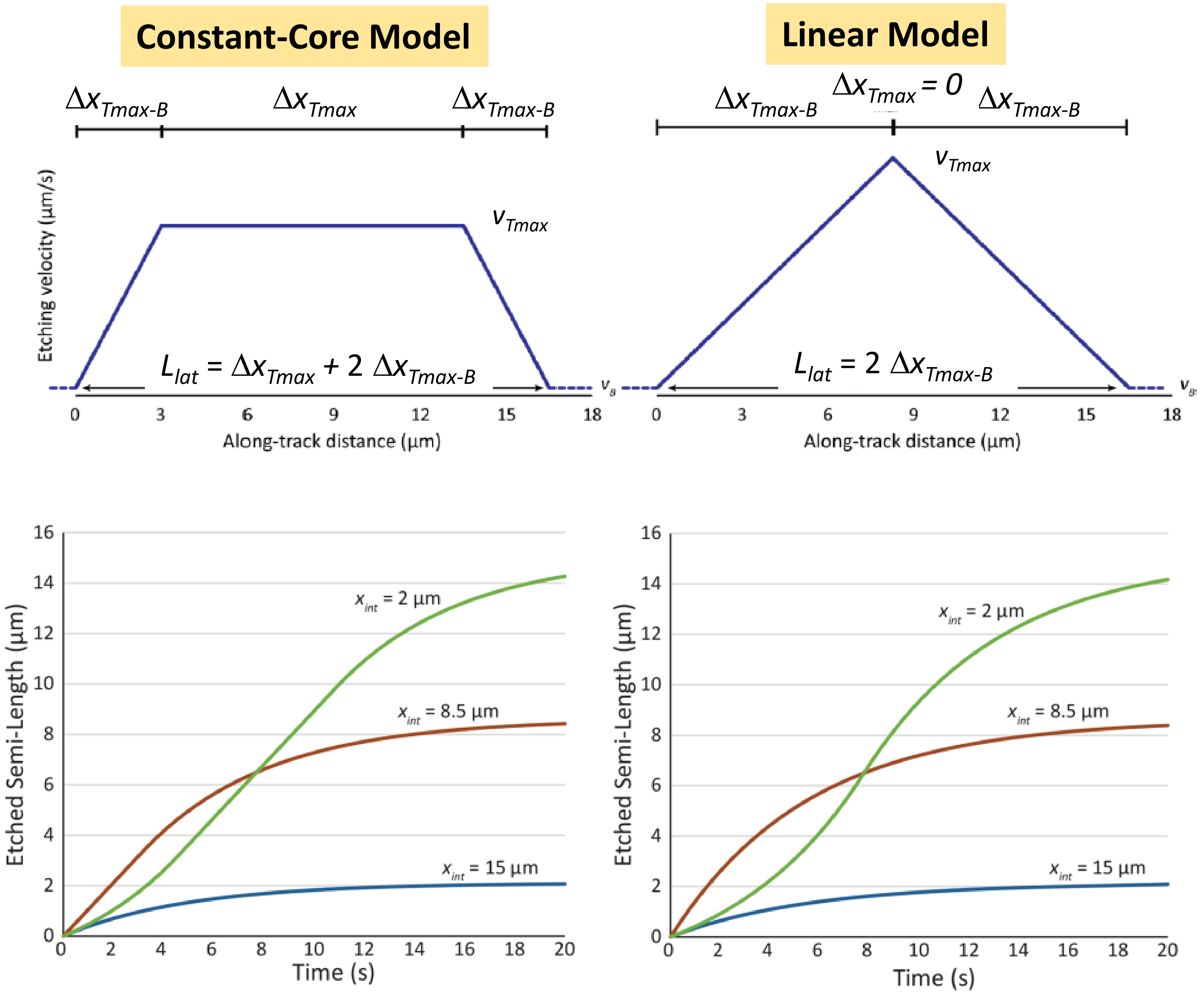
Calculated using SRIM (Ziegler et al. 2013)

Ketcham and Tamer 2021

Can we understand confined track etching better?

Two possible simplified etching structures

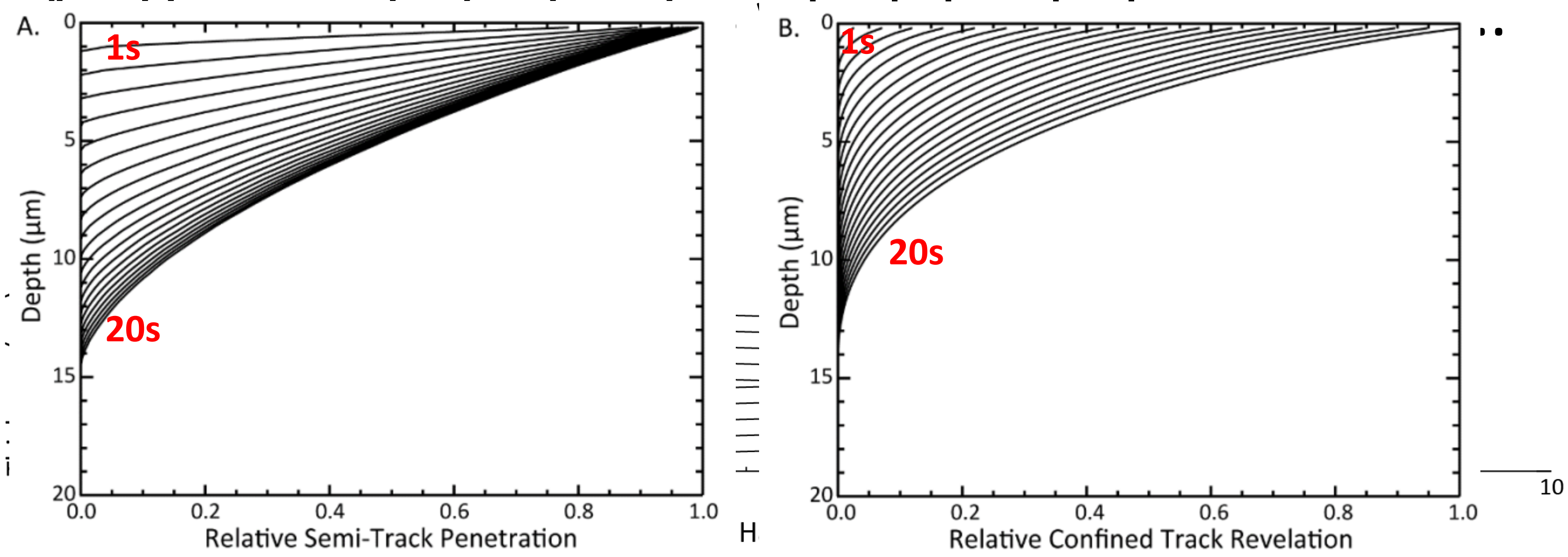
Half-track lengthening curves, depending on impingement point



From Ketcham and Tamer 2021

To figure out etching rates of TINT confined tracks, we need to model:

1. Penetration and then widening of semi-tracks
2. Intersection/revelation of confined latent tracks
3. Etching out of latent tracks



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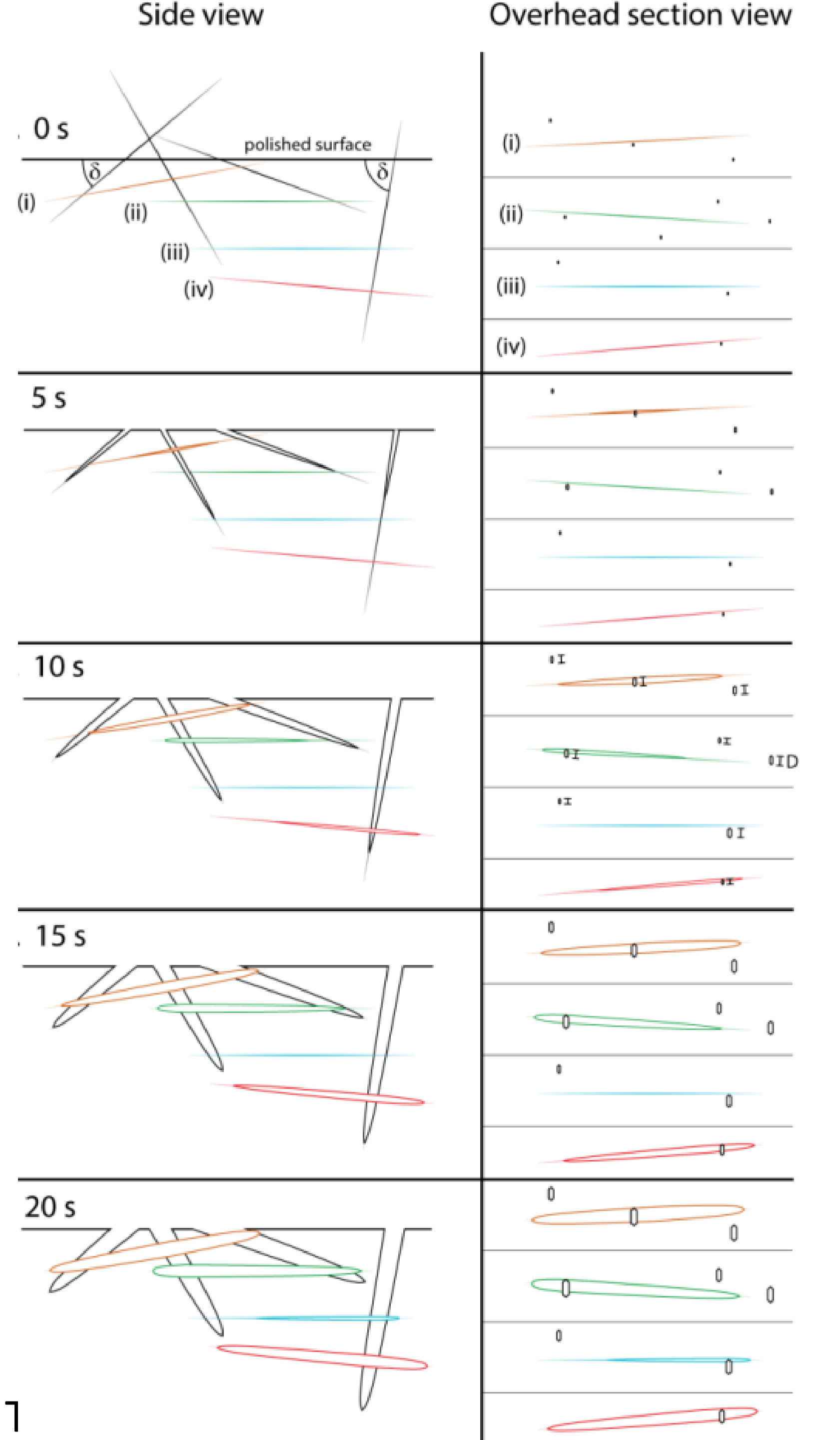

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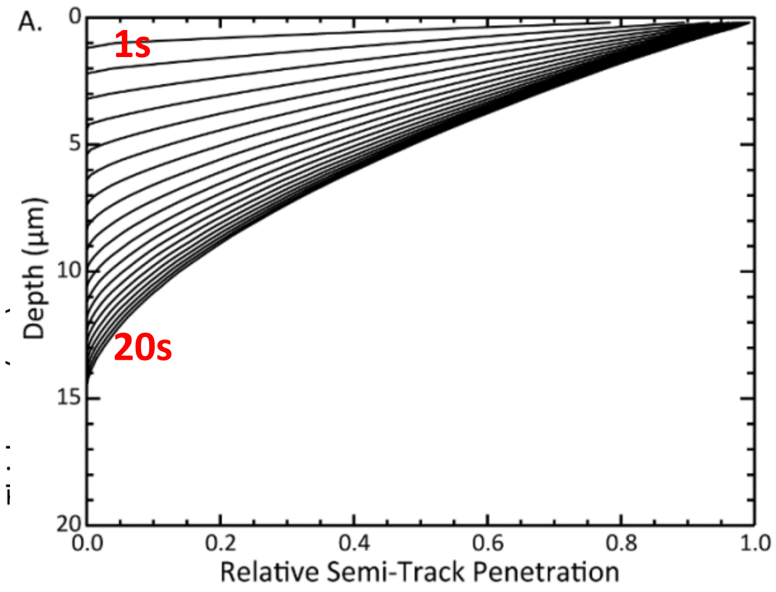

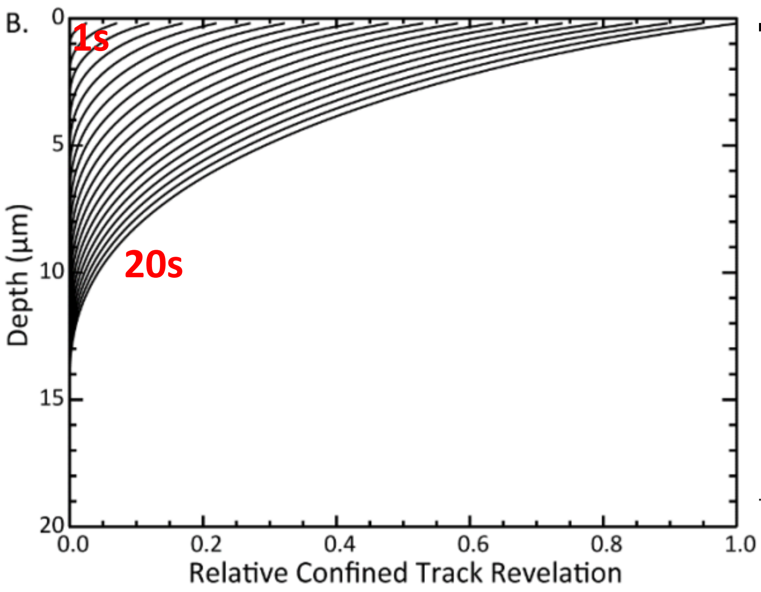

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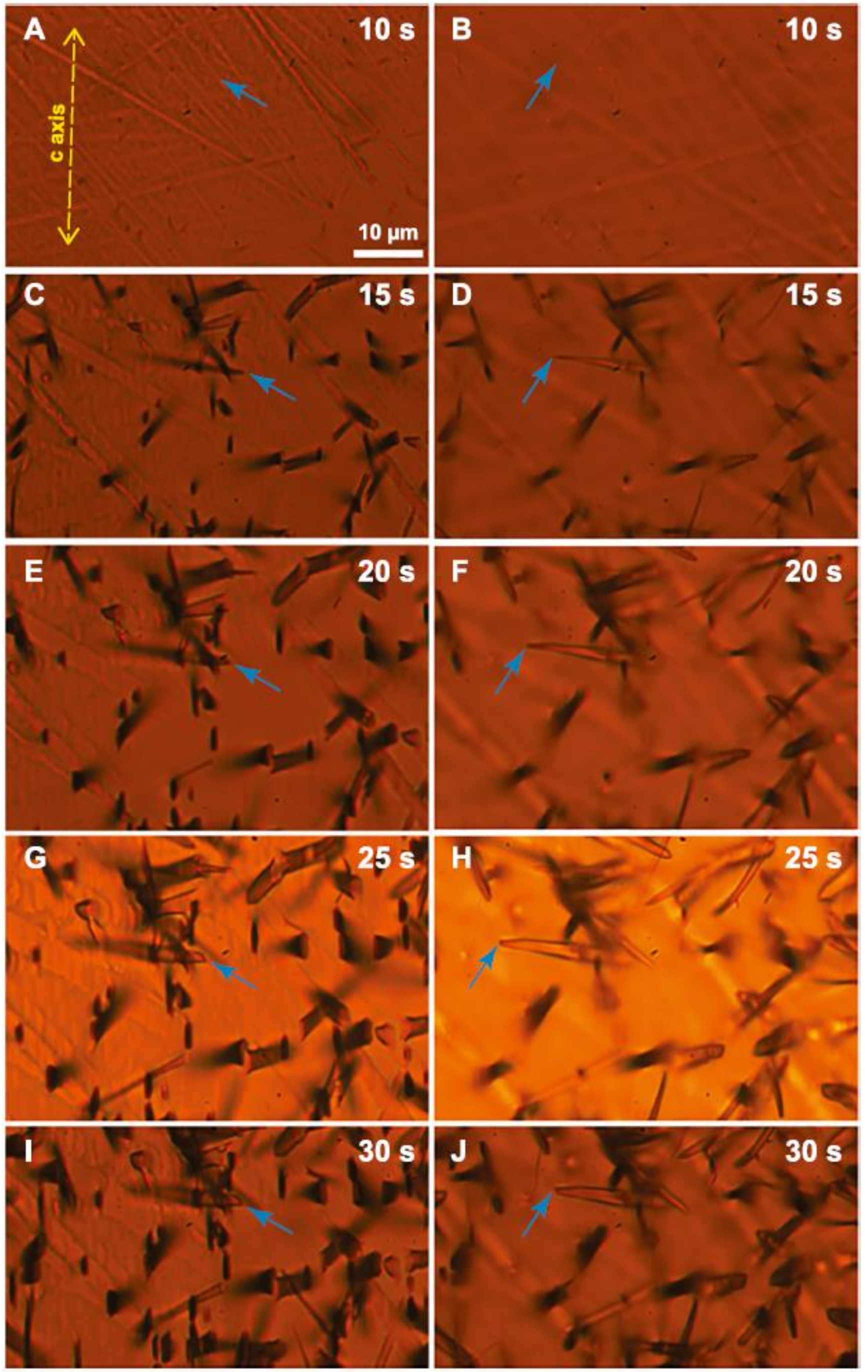
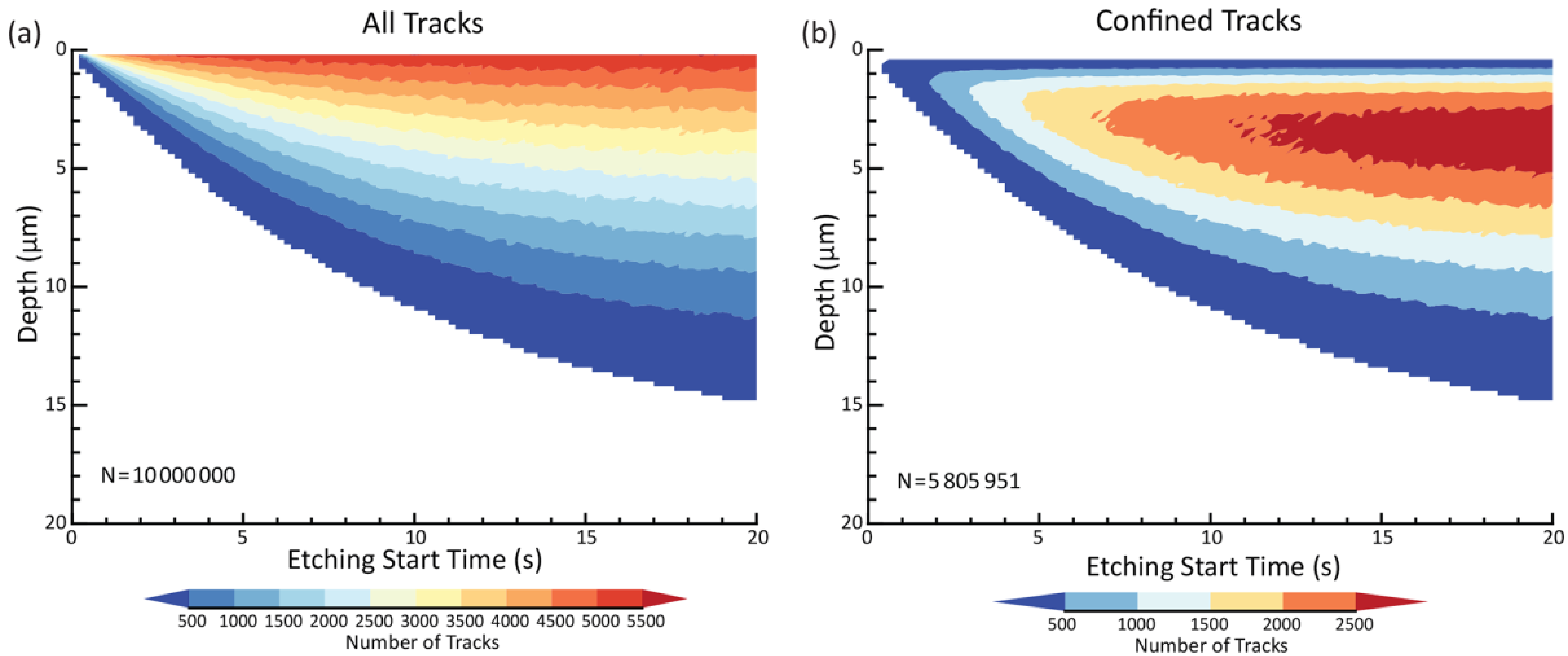
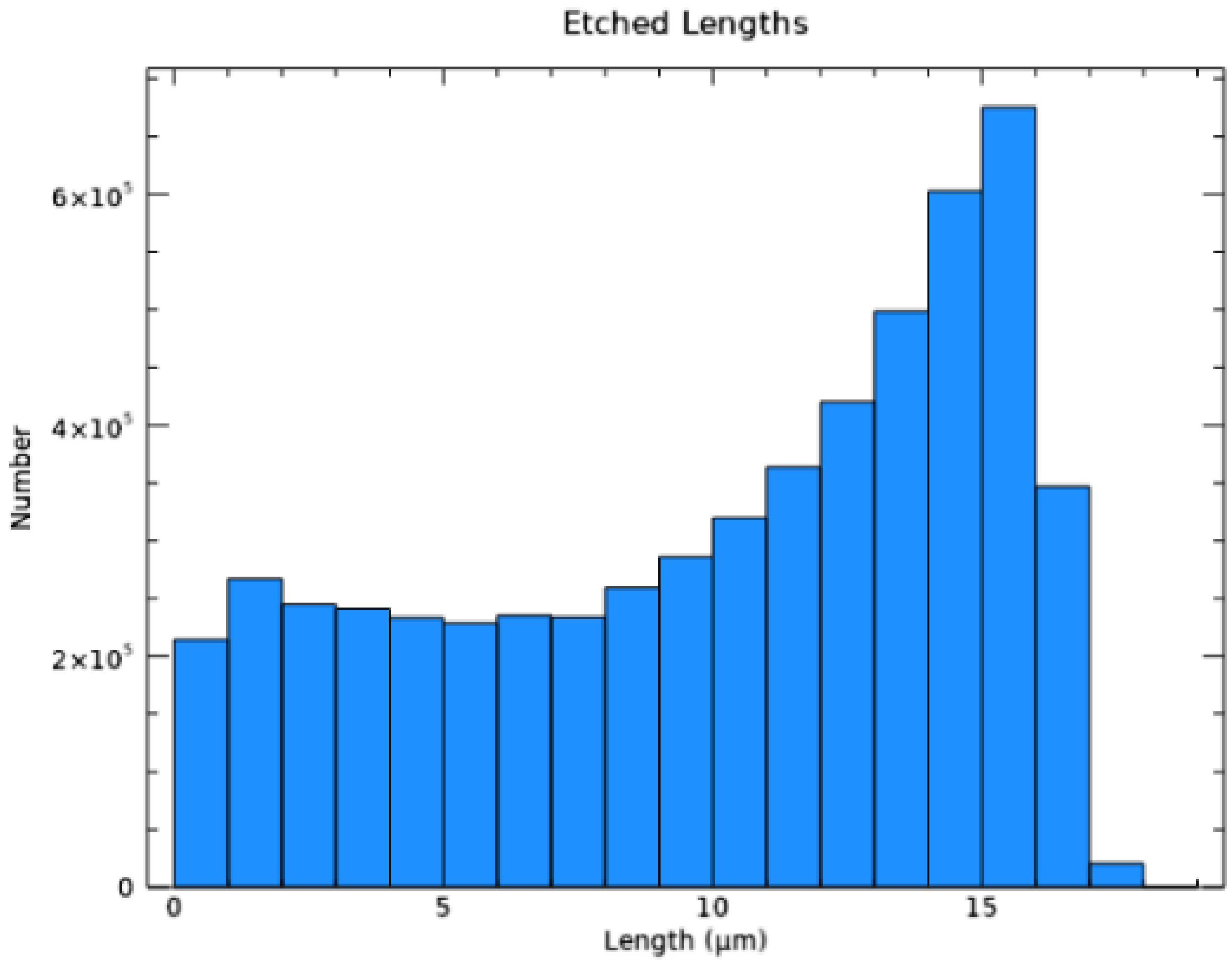


Tamer and Ketcham (2020, Chem Geol)

Generate lots of track intersections…



… and calculate the track length distribution…



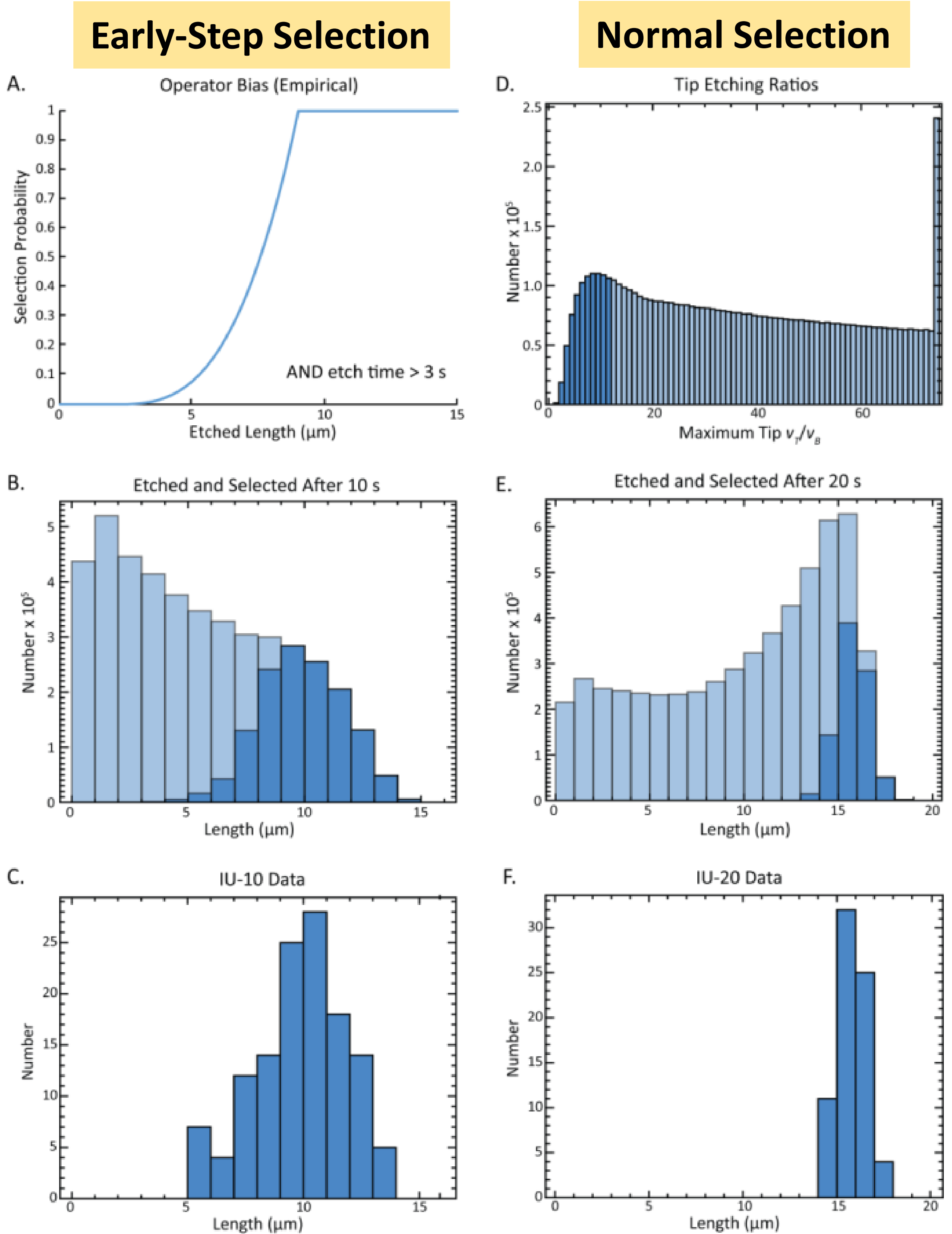
What measured length distributions really are

- Right side of length distributions: longest etched lengths
- Left side: which tracks analyst picks
  - 10-15 sec: visibility
  - 20 sec: shape, tips, etc.
- Grayed bars: tracks intersected but not selected.

Bias functions

Which are taken, which are not?

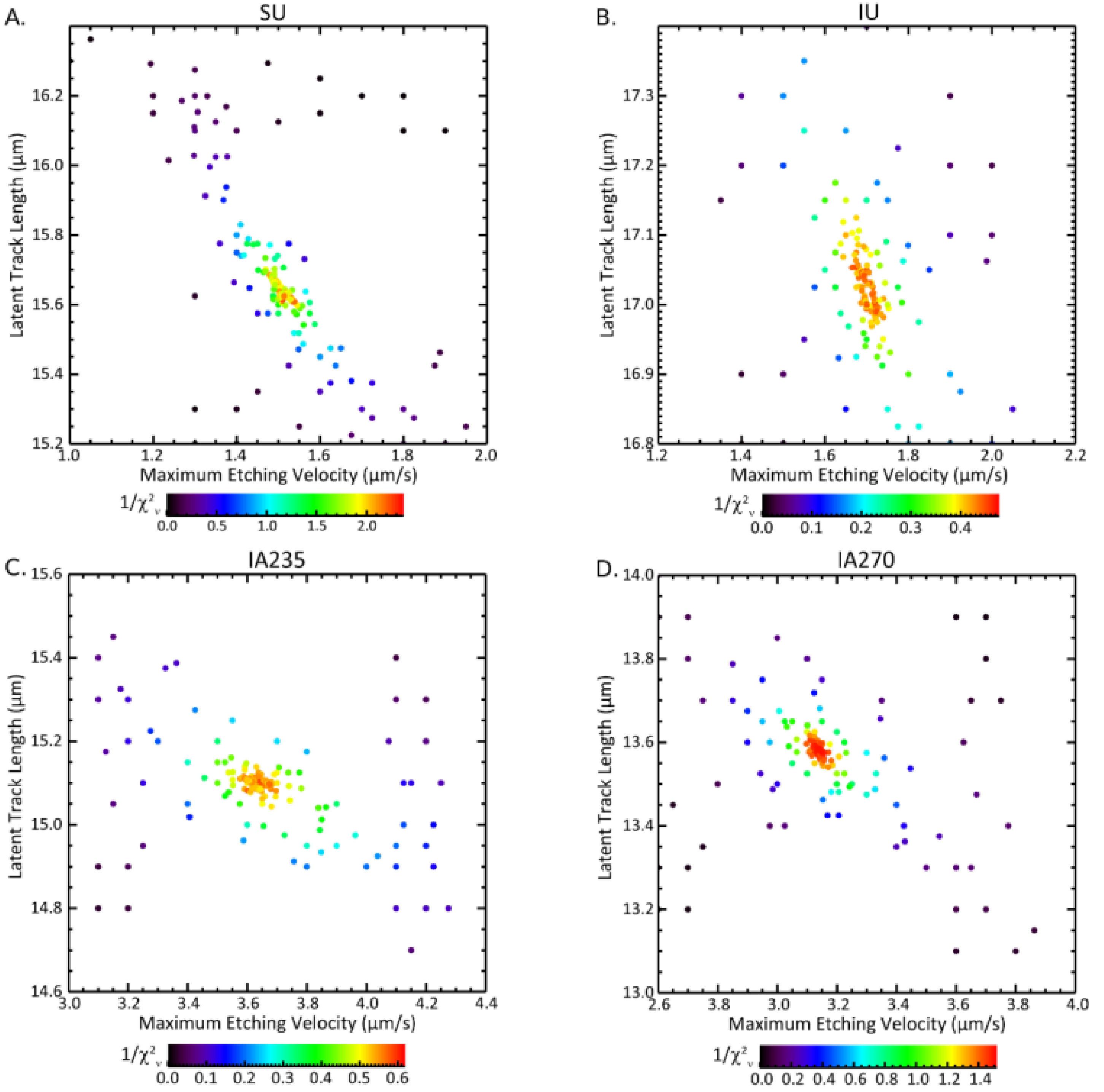
Measurements for these time steps



From Ketcham and Tamer, 2021

Fitting the models to the data

- Tricky, as much is randomized
  - Semi- and latent track L, ϕ, δ
  - Intersection time and depth
  - Impinged point along latent track
  - Leads to transitory minima
- Method: simplex, minimize χ_ν^2
  - Randomize 10^5-10^7 tracks
  - Use many starting points
- Fitted parameters:
  - Latent length
  - v_{Tmax}
  - Core length



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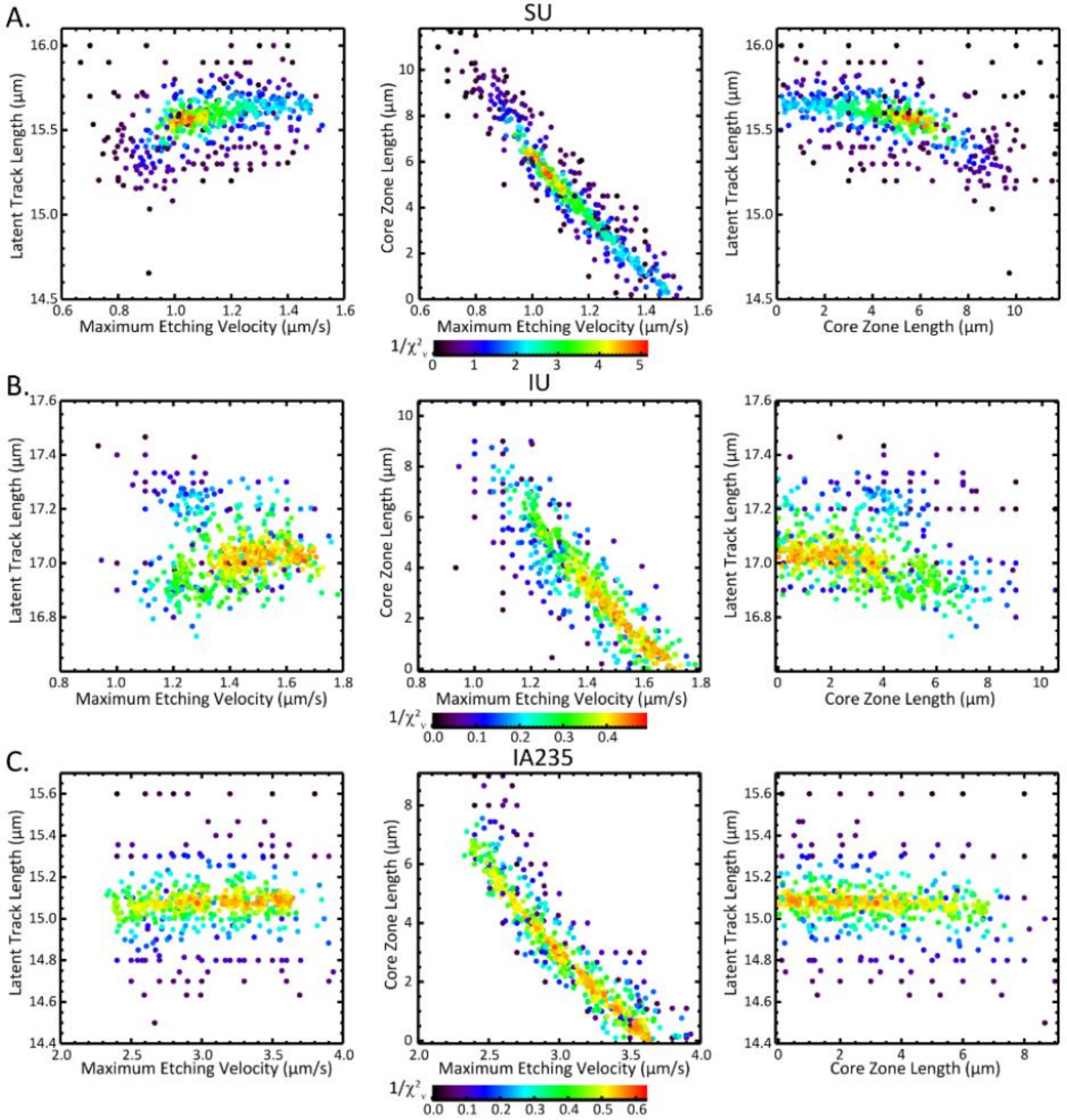

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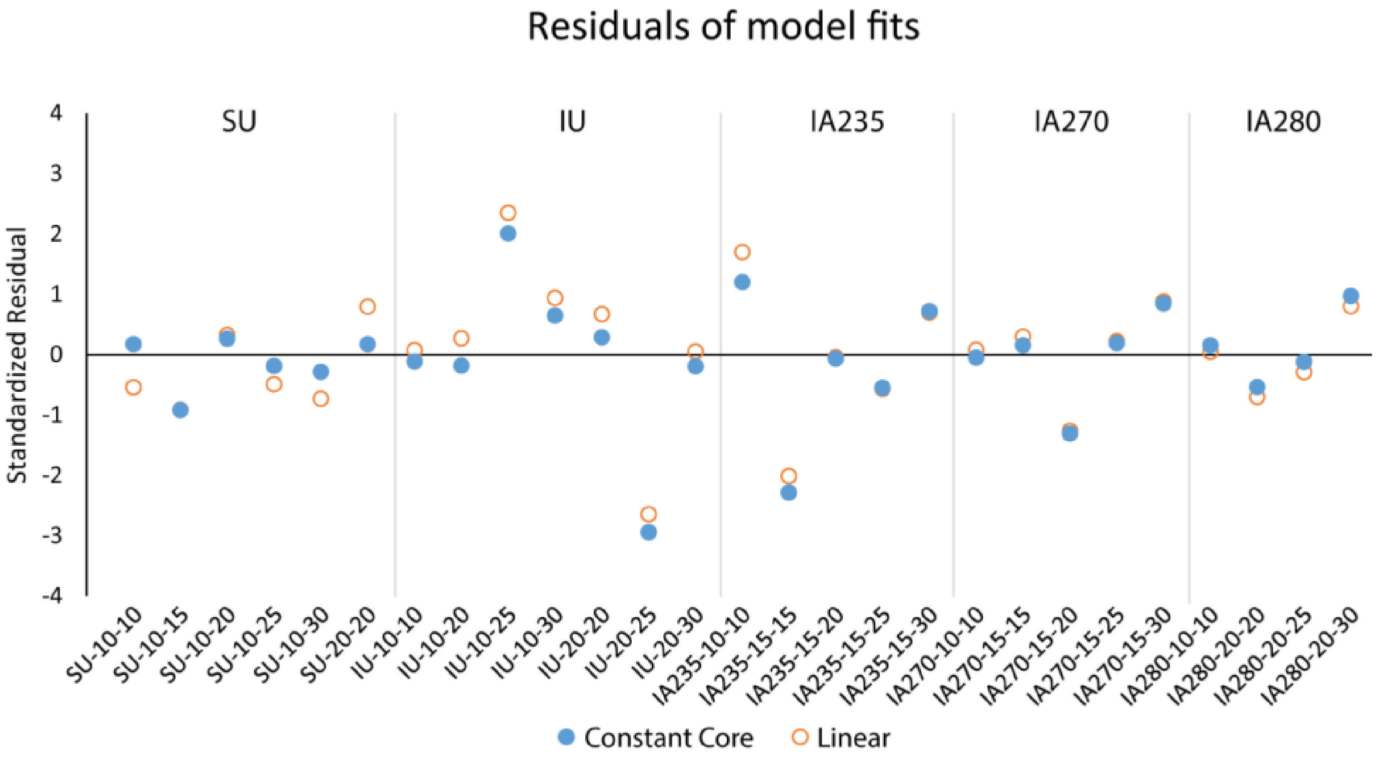
- Models fit pretty well



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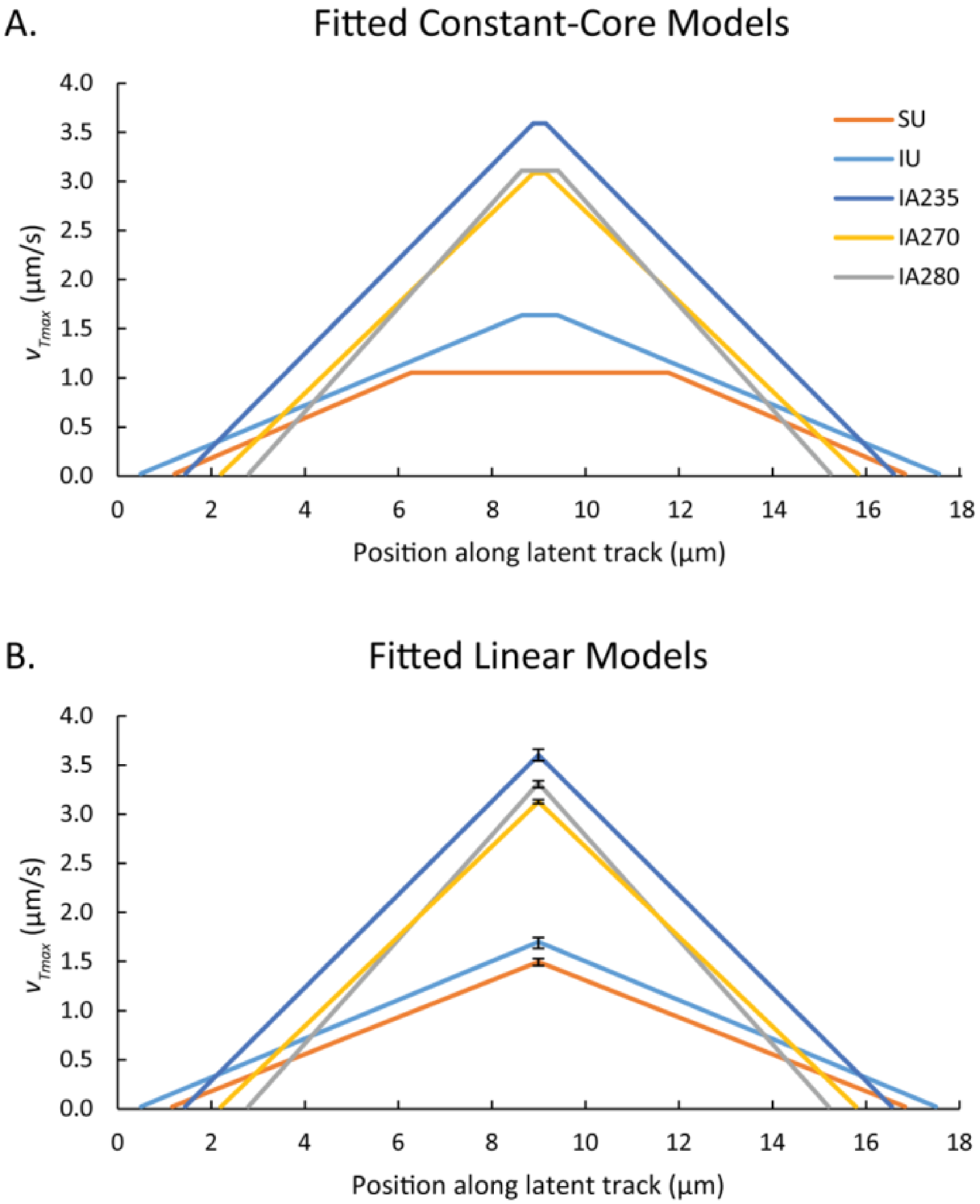
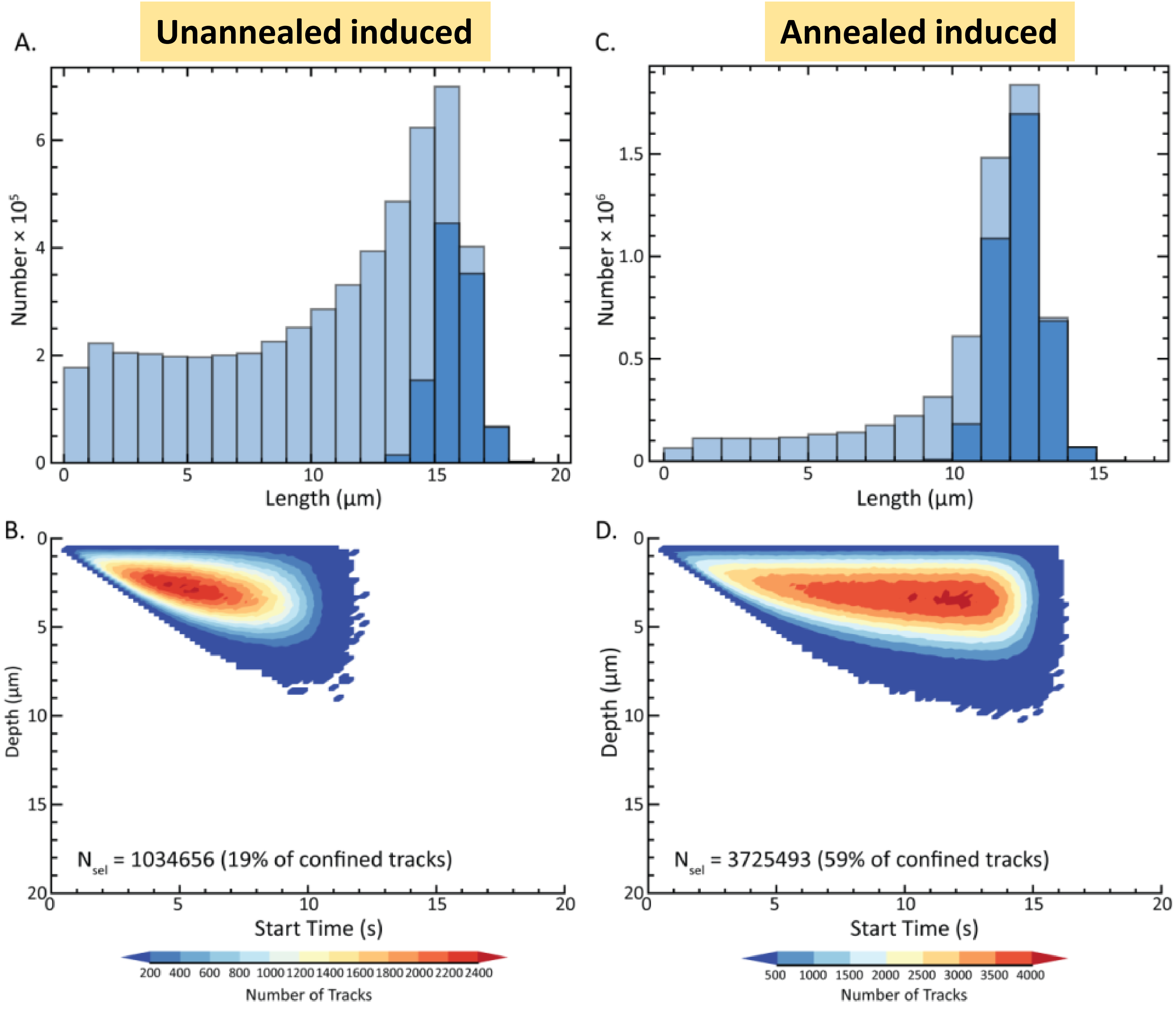
- Models fit pretty well
- Unannealed look different than annealed…

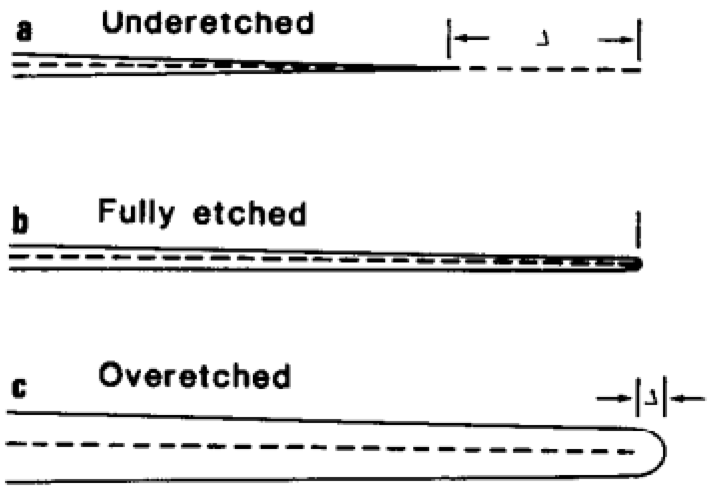


Anti-length biasing

- Shorter tracks are less likely to be intersected (length biasing), but…
- They also take less time to etch, and are more likely to etch completely



This contradicts how we've thought of tracks for >40 years



Laslett et al 1984

The "Fully etched tracks" model

LENGTH DISTRIBUTIONS OF FISSION TRACKS IN THICK CRYSTALS

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(*Received* 3 *January* 1978; *in revised form* 17 *March* 1978)

BIAS IN MEASUREMENT OF FISSION-TRACK LENGTH DISTRIBUTIONS

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(*Received* 19 *October* 1981; *in revised form* 21 *April* 1982)

THE RELATIONSHIP BETWEEN FISSION TRACK LENGTH AND TRACK DENSITY IN APATITE

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(*Received* 22 *February* 1983; *in revised form* 3 *January* 1984)

Apatite Fission Track Analysis: Geological Thermal History Analysis Based on a Three-Dimensional Random Process of Linear Radiation Damage

R. F. Galbraith; G. M. Laslett; P. F. Green; I. R. Duddy

Philosophical Transactions: Physical Sciences and Engineering, Vol. 332, Stochastic processes. (Sep. 15, 1990), pp. 419-438.

All assume that tracks are line segments in space, and p(intersection) = p(measurement)

Tamer et al. 2019

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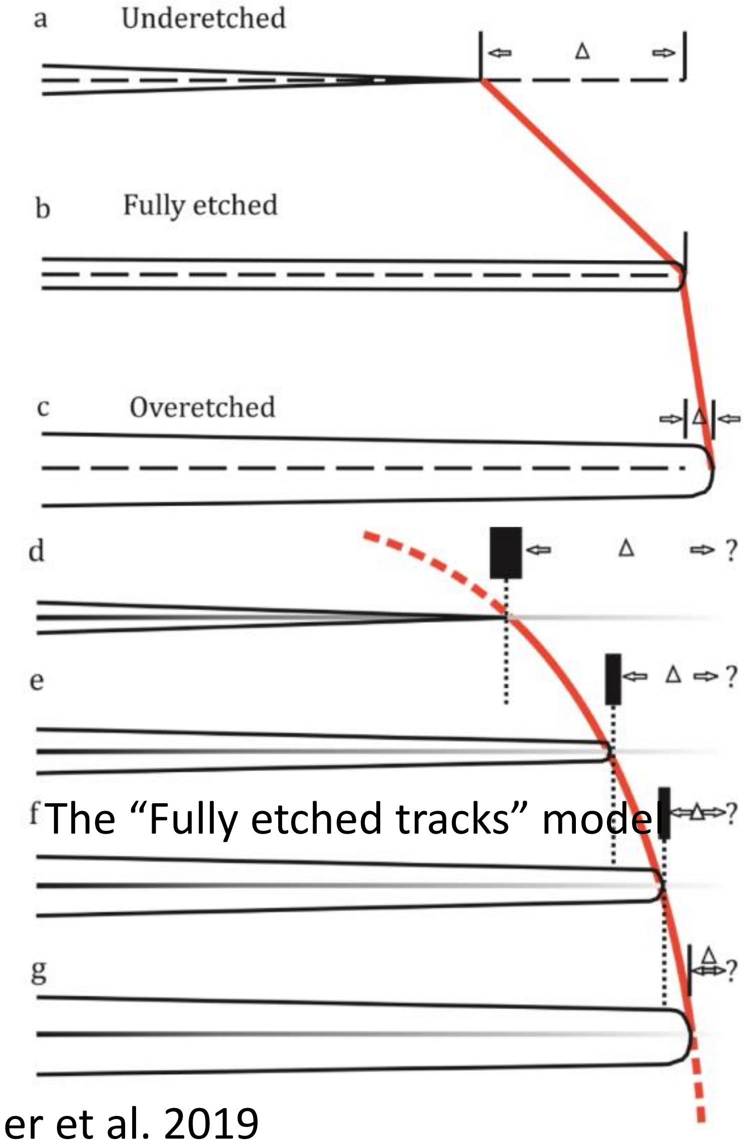
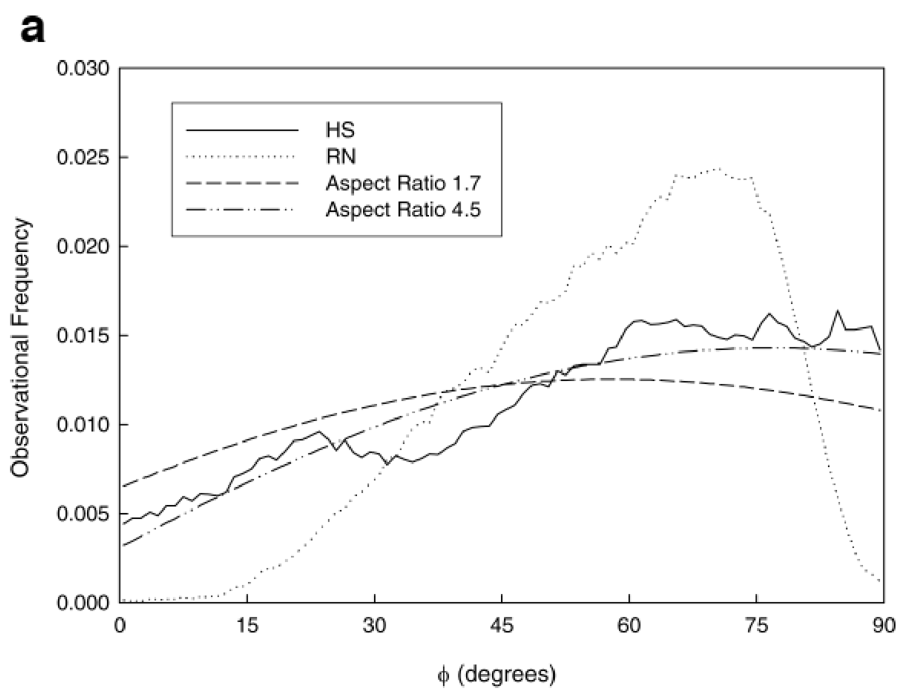


The "Fully etched tracks" model

Tamer et al. 2019



American Mineralogist, Volume 88, pages 817–829, 2003

Observations on the relationship between crystallographic orientation and biasing in apatite fission-track measurements

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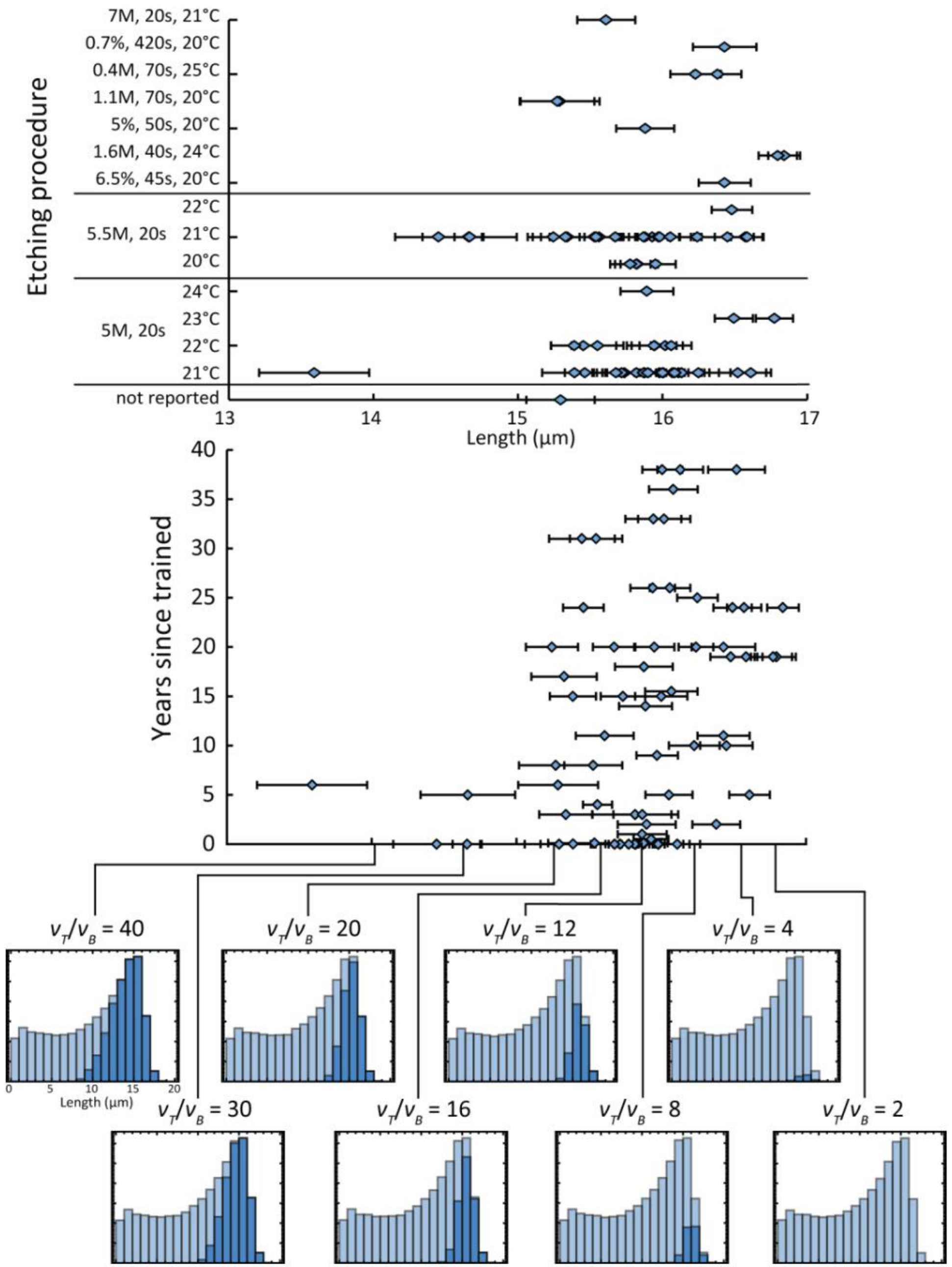
American Mineralogist, Volume 92, pages 789–798, 2007

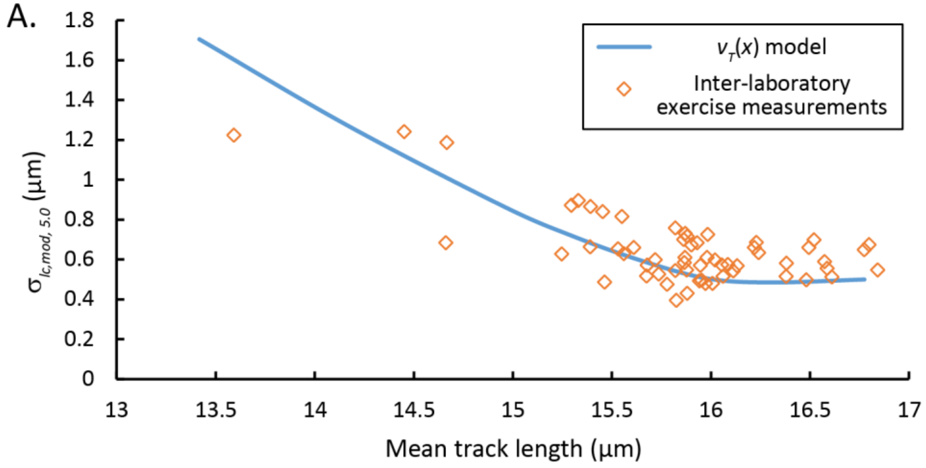
Improved measurement of fission-track annealing in apatite using c-axis projection

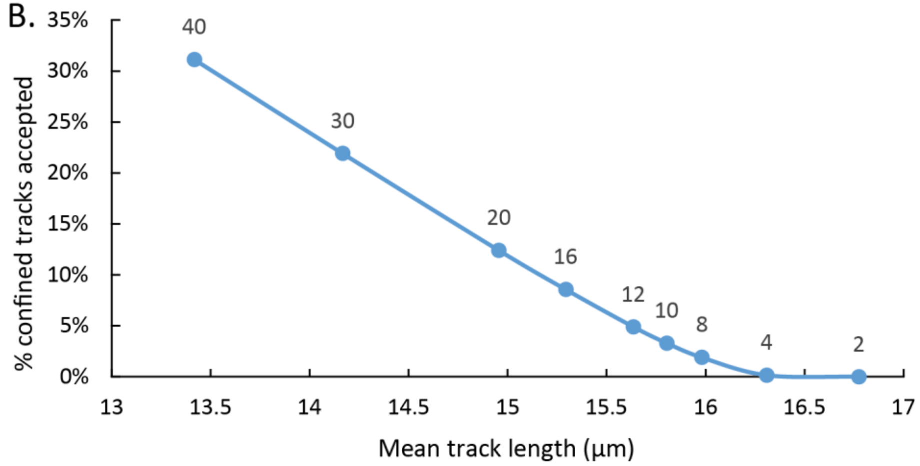
RICHARD A. KETCHAM,[1,*] ANDREW CARTER,[2] RAYMOND A. DONELICK,[3] JOCELYN BARBARAND,[4] AND ANTHONY J. HURFORD[2]

All assume that tracks are line segments in space, and p(intersection) = p(measurement)

Is track selection responsible for variation?



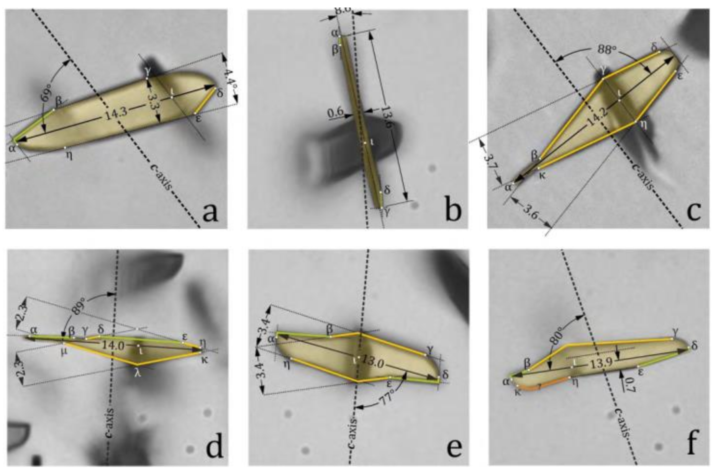




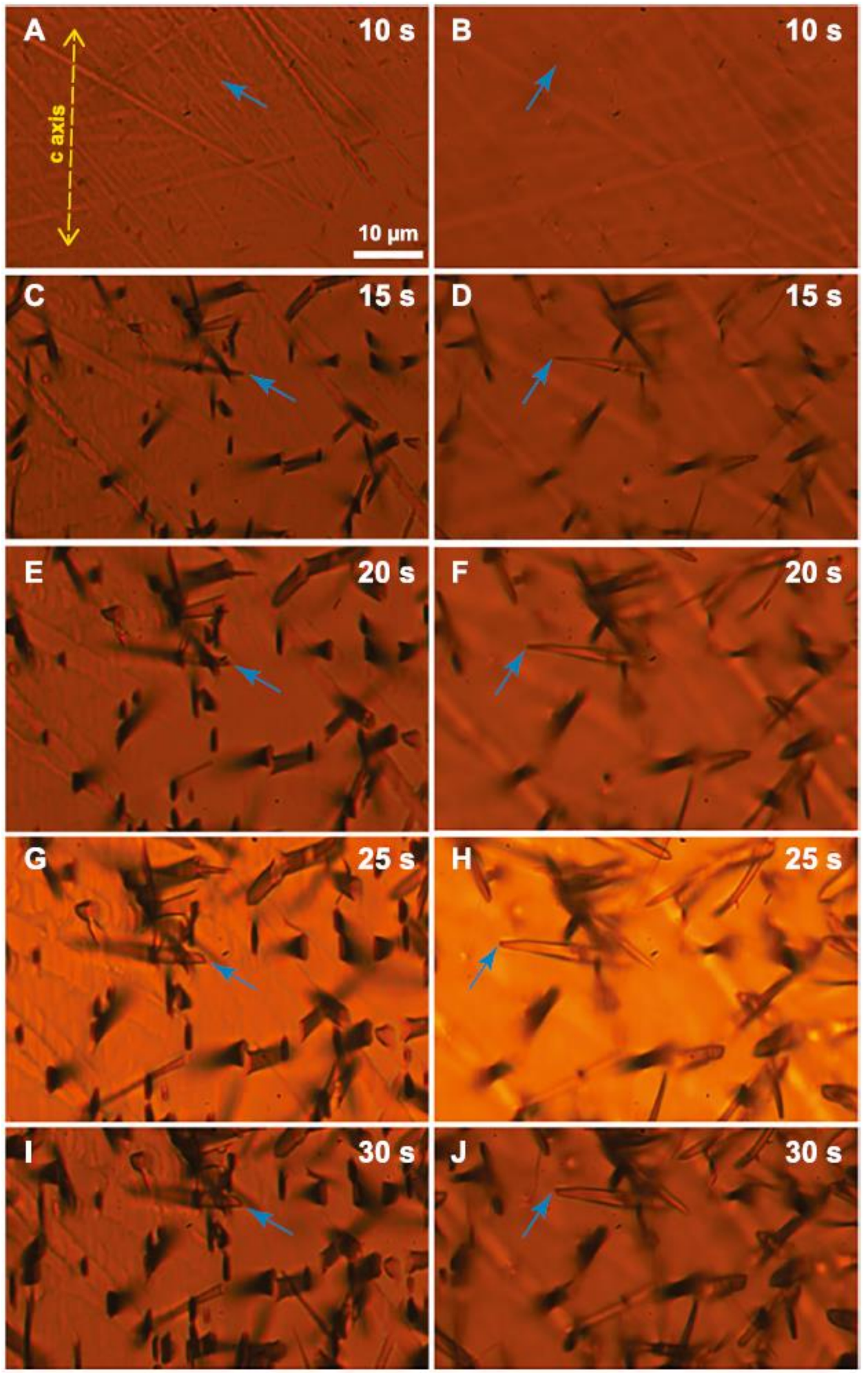
From Ketcham and Tamer, 2021

Why it matters

- Our conception of tracks comes closer to reality
  - Lo, Anti-length biasing, left vs. right
  - Focus on source of reproducibility
- It paves the way for redoing FT based on computer vision



From Jonckheere et al., 2021



Why it matters

- Our conception of tracks comes closer to reality
  - Lo, Anti-length biasing, left vs. right
  - Focus on source of reproducibility
- It paves the way for redoing FT based on computer vision
- But there's a LOT of work to do
  - More apatites with different etching
  - More levels of annealing
    - Both spontaneous and induced
  - Etching and annealing anisotropy