Integrative Interpretation of Thermochronometric Data: Application to Inversion Tectonic Settings*

Richard A. Ketcham[1], Andrés Mora[2], Ariel Almendral[2], Mauricio Parra[2], Wilson Casallas[2], and Wilmer Robles[2]

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[1]Jackson School of Geosciences, University of Texas, Austin, TX, USA (ketcham@jsg.utexas.edu)
[2]Ecopetrol S.A. – Instituto Colombiano del Petróleo, Bucaramanga, Santander, Colombia

Abstract

Thermochronometric data provide a powerful way to build reliable time-temperature (t-T) histories in petroleum basins. Integrating information from multiple samples into a single modeling framework is a challenge, but is likewise a necessary step forward for providing refined and robust t-T histories. The challenges are particularly severe in inversion terranes where erosion has erased all synkinematic strata. Here we apply two new computational tools for interpreting thermochronometric data that facilitate the joint use of multiple samples, to obtain a continuous history of heating and cooling that would be extremely difficult to obtain using other tools. The first, Fetmove, is a finite element solver that takes as input a series of detailed balanced cross sections, and solves the heat flow equation in 2D along with predicted thermochronometric ages that can be compared against measured data. The key feature of Fetmove is a workflow that allows the interpreter to engage in successive refinements of the structural model using the inferences provided by thermochronometric data. The second is new functionality in the HeFTy software for inverse modeling of thermochronometric data that permits simultaneous modeling of samples down a well or borehole. This extension forces attention on issues that have previously been relatively neglected in thermochronometry-based modeling, in particular that of multiple provenance. The rewards in doing so include more robust modeling and interpretation and, in some cases, insights concerning the unroofing histories of the source rocks that contributed to a given sedimentary unit.

Our pilot cases show that Fetmove applied in the deeply exhumed inversion faults of the Cordillera is ideal for getting high resolution t-T histories along a 2d cross section, and the times at which potential petroleum source rocks were in the oil generation window. In contrast, the improved HeFTy fits more to the case of structures displaying only moderate inversion and post-inversion unconformities and quiescence based on borehole data. This is the case for the buried inverted half-grabens in the Magdalena Valley. In the first case, we found that oil generation stopped after the Oligocene whereas in the second case there might be generation even today.

Selected Reference

Caballero, V., M. Parra, A. Mora, C. Lopez, L.E. Rojas, and I. Quintero, 2013, Factors controlling selective abandonment and reactivation in thick-skin orogens; a case study in the Magdalena Valley, Colombia, *in* M. Nemcock, A. Mora, and J.W. Cosgrove, (eds.), Thick-skin-dominated orogens; from initial inversion to full accretion: Special Publication Geological Society of London, p. 377.

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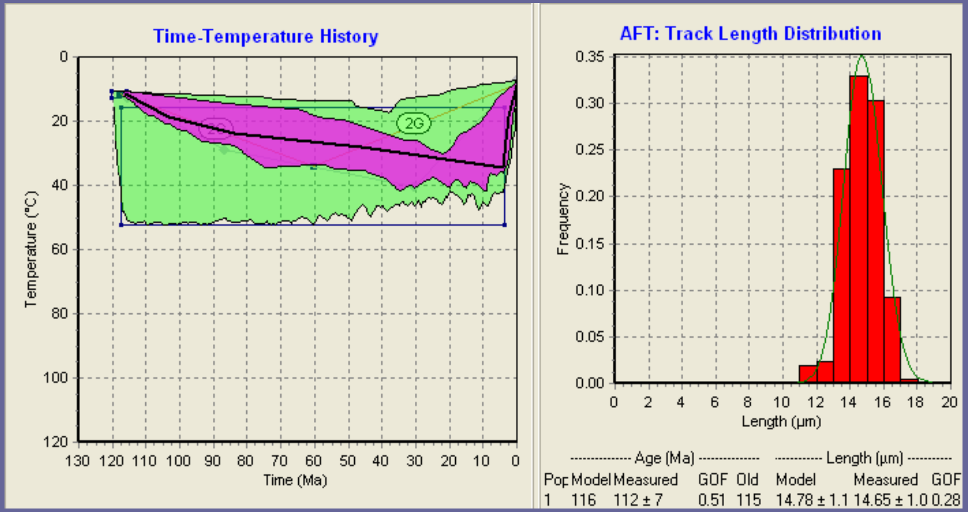
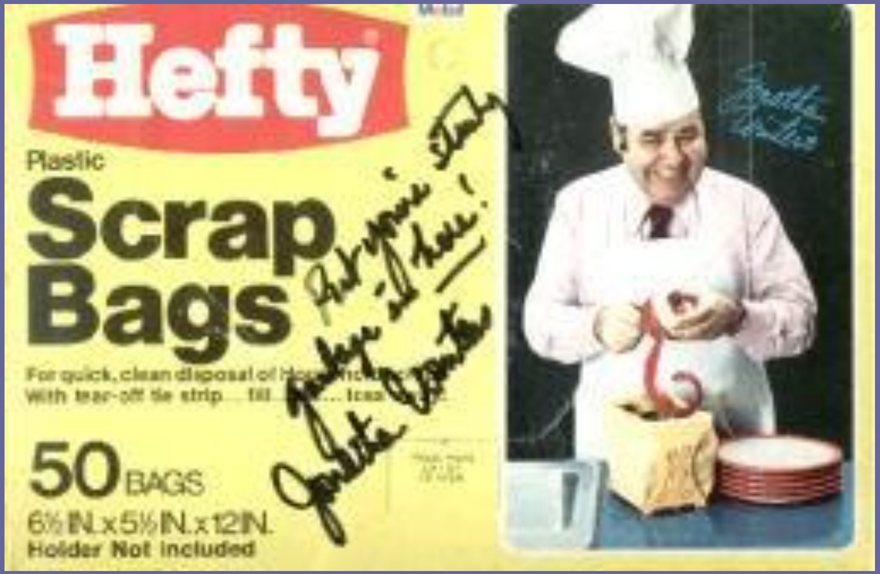
Thermal history modeling (with HeFTy)

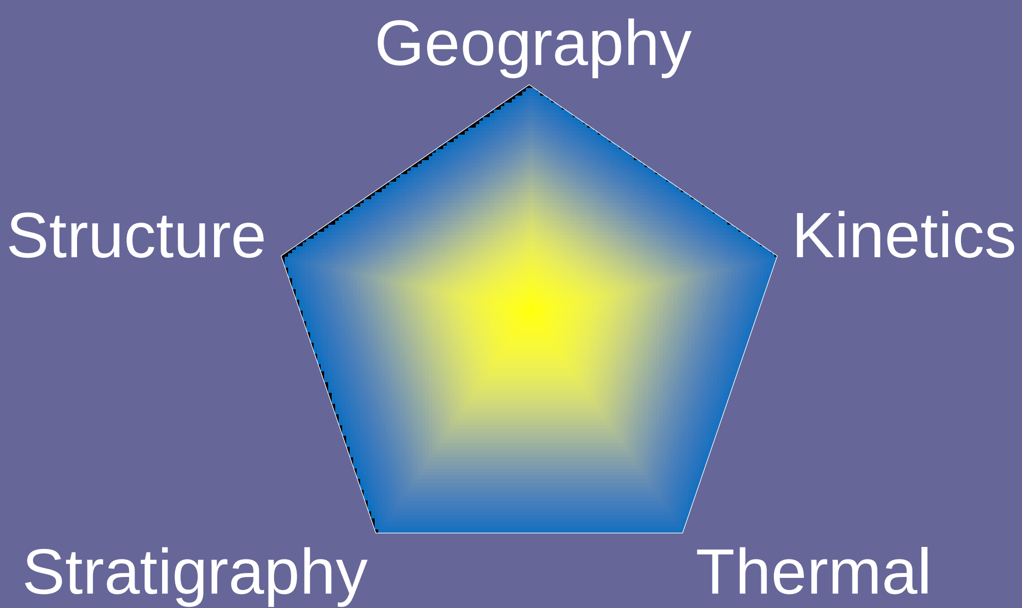
- To answer the general question: “What range of thermal histories is consistent with my data and my assumptions”
  - Fission-track
    - Apatite and zircon
  - (U-Th)/He
    - Apatite zircon, many others
    - Including ^{4}He/^{3}He
  - Vitrinite
- Some assumptions:
  - Data are good
  - Theory is good
  - Data and theory adequate to explain your sample
  - Geology is correctly, if loosely, constrained





The Many-Sided Multi-Sample Problem

How do samples relate to each other?



Position with respect to each other, and the earth surface, as f(t)

What are the intervening structures, what did they do, when did they do it?

Deposition, burial, unconformities, source/inheritance

Geothermal gradient; perturbations due to faults, erosion, burial

Characterize the thermochronometric systems, and their variation

How do we define these relationships simply and generally, but also realistically, or at least defensibly?

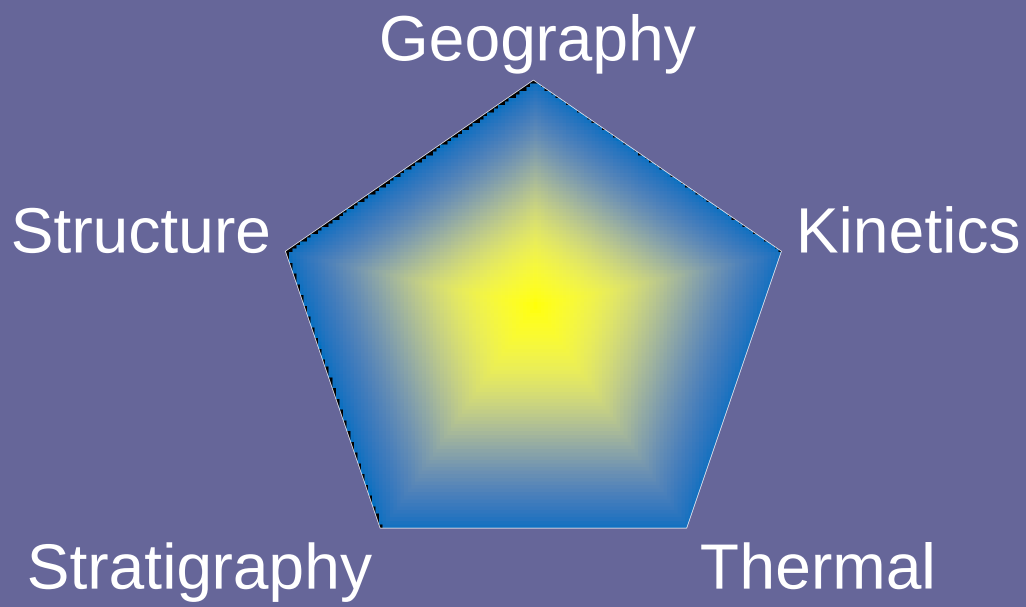
How do we make it easy?

Simplify

Match the tool to the job

New Tool #1: FETKIN

[Finite Element Thermo-KINematics]



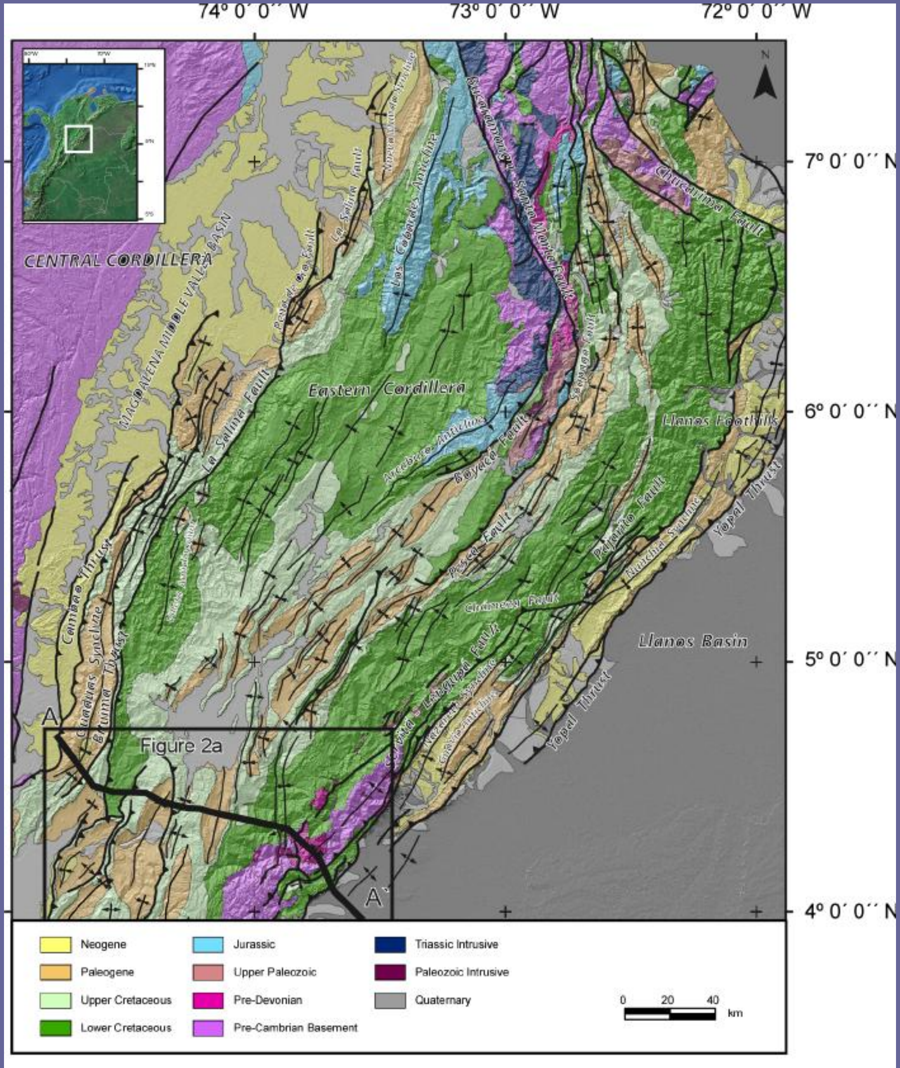
Based on Lock and Willet, 2008

Uses balanced cross section software (in this case, 2DMOVE, by Midland Valley) to generate kinematic history, uses 2D FE solver to calculate resulting temperatures.

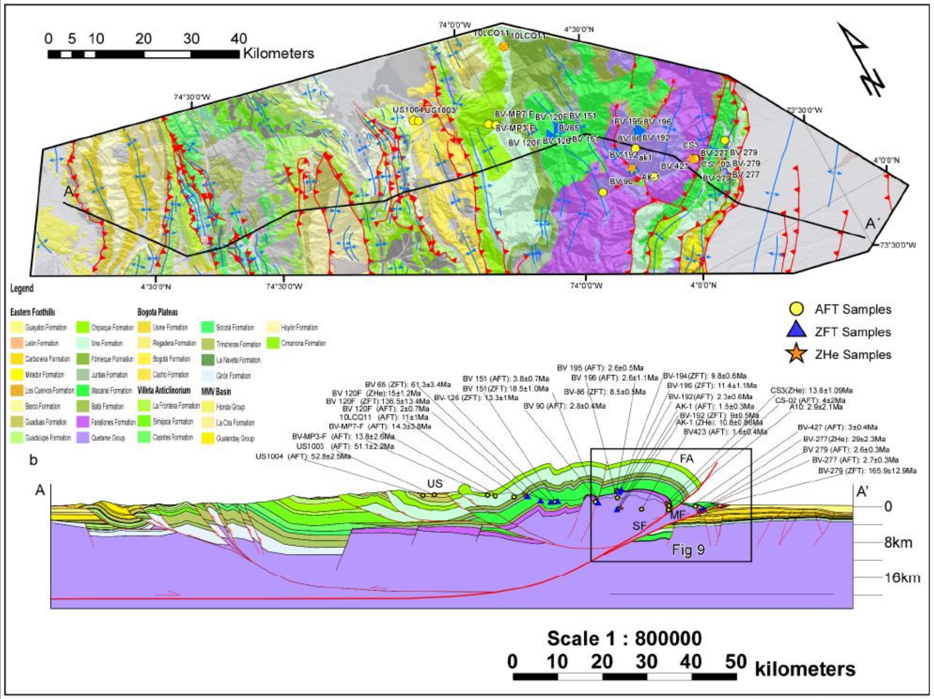
Could potentially be adapted to any reconstruction package.

A work-flow for using thermochronology to improve balanced cross section reconstruction

Colombian Eastern Cordillera



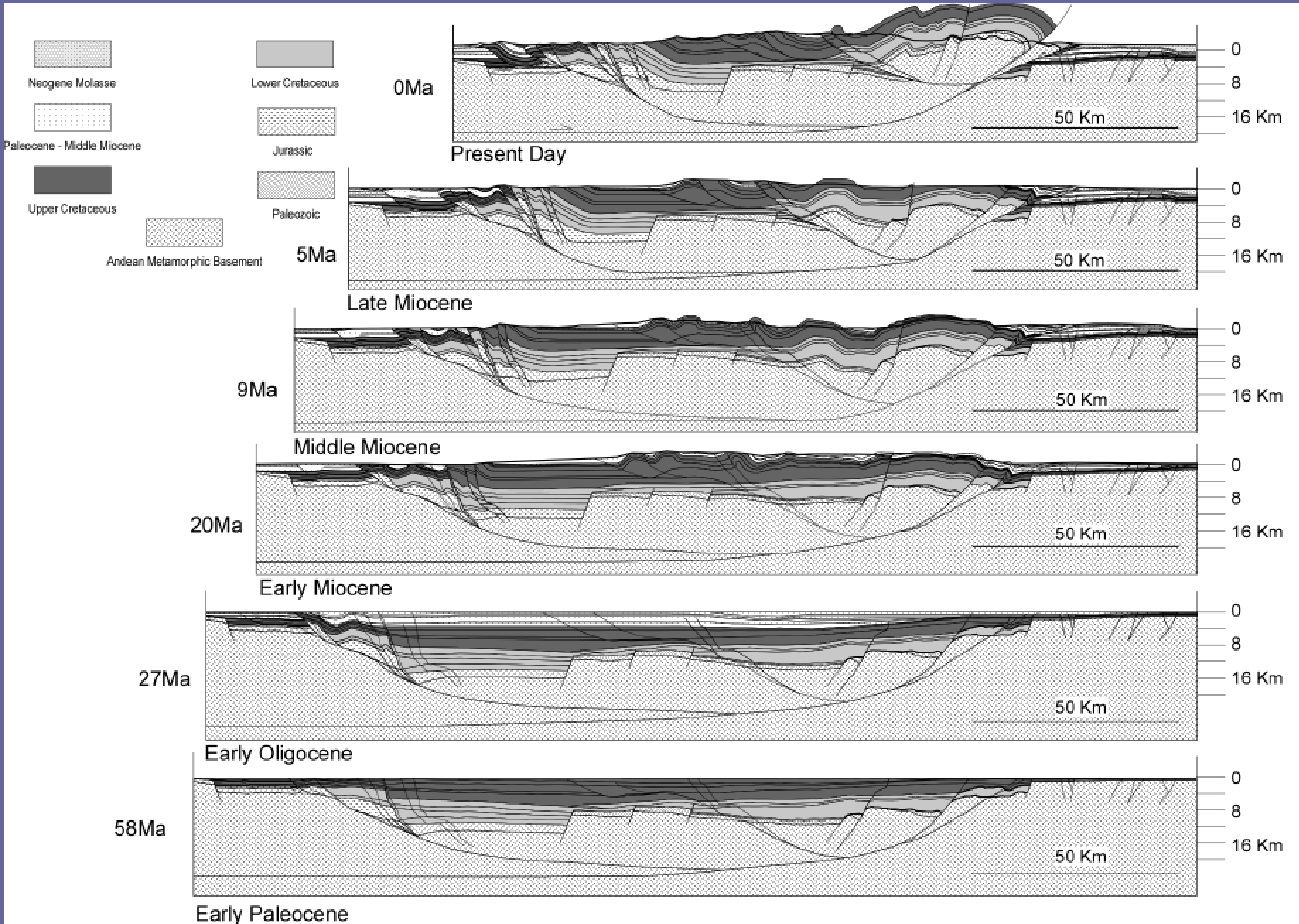
Casallas et al. Figure 1



Casallas et al. Figure 2

From Mora et al., in press, AAPG Bull.

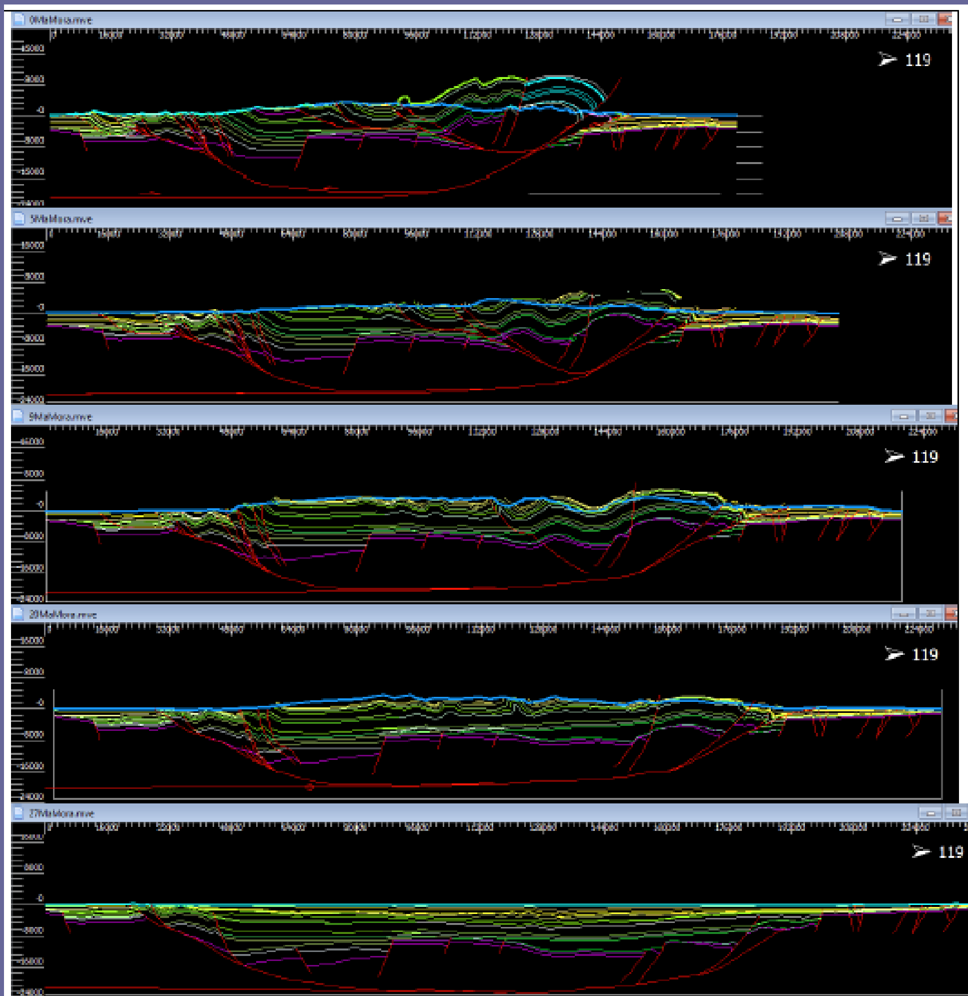
Step 1: Make and restore balanced cross sections



Casallas et al. Figure 5

Restoration incorporates a huge amount of geologic information
Timings only loosely constrained by stratigraphy

Step 2: Match horizons and faults, find where sections are out of balance



Matching and evaluation using Simulated Annealing algorithm (Ketcham and others, in prep.)

Table 3.1: Errors and warnings reported by FetmovePrep for initial “NamSurNew” cross sections.

Errors with horizon persistence:

Error: Horizon Guadalupe superior in section 20MaMoraDecompact not found in subsequent section 9MaMoraDecompact

Error: Horizon Cuervos in section 5MaMoraDecompact not found in subsequent section 0MaMora

Errors with fault uniqueness:

Error: Fault name Falla24 in section 27MaMoraDecompact is used more than once.

Error: Fault name Fallaservita in section 27MaMoraDecompact is used more than once.

Error: Fault name Falla22 in section 20MaMoraDecompact is used more than once.

Error: Fault name Falla23 in section 20MaMoraDecompact is used more than once.

Error: Fault name Fallaservita in section 20MaMoraDecompact is used more than once.

Error: Fault name Falla04 in section 0MaMora is used more than once.

Errors with fault persistence:

Error: Fault Fallaservita in section 20MaMoraDecompact not found in subsequent section 9MaMoraDecompact

Error: Fault Fallashortcut in section 20MaMoraDecompact not found in subsequent section 9MaMoraDecompact

Error: Fault Falla05 in section 9MaMoraDecompact not found in subsequent section 5MaMoraDecompact

Error: Fault Falla12 in section 9MaMoraDecompact not found in subsequent section 5MaMoraDecompact

Error: Fault Falla06 in section 5MaMoraDecompact not found in subsequent section 0MaMora

Error: Fault Falla26 in section 5MaMoraDecompact not found in subsequent section 0MaMora

Error: Fault Falla27 in section 5MaMoraDecompact not found in subsequent section 0MaMora

Errors with horizon net lengths:

Error: Horizon Guavio decreases in length from 79,384.5 in section 27MaMoraDecompact to 67,909.2 in section 20MaMoraDecompact without intersecting topography

Warning: Horizon Giron increases in length from 99,747.1 in section 27MaMoraDecompact to 103,977.7 in section 20MaMoraDecompact

Error: Horizon Simijaca decreases in length from 93,801.5 in section 27MaMoraDecompact to 84,551.1 in section 20MaMoraDecompact without intersecting topography

Error: Horizon Frontera increases in length from 71,847.8 in section 27MaMoraDecompact to 85,223.4 in section 20MaMoraDecompact

Error: Horizon Hoyon increases in length from 28,661.9 in section 27MaMoraDecompact to 33,244.0 in section 20MaMoraDecompact

Error: Horizon Cimarrona increases in length from 23,328.0 in section 27MaMoraDecompact to 26,554.5 in section 20MaMoraDecompact

Error: Horizon Farallones increases in length from 78,620.8 in section 27MaMoraDecompact to 83,969.3 in section 20MaMoraDecompact

Error: Horizon Trincheras decreases in length from 80,757.0 in section 27MaMoraDecompact to 69,477.7 in section 20MaMoraDecompact without intersecting topography

Error: Horizon Naveta decreases in length from 57,230.9 in section 27MaMoraDecompact to 51,257.1 in section 20MaMoraDecompact without intersecting topography

Error: Horizon Barco increases in length from 44,121.9 in section 27MaMoraDecompact to 46,966.2 in section 20MaMoraDecompact

Error: Horizon Une increases in length from 39,876.4 in section 27MaMoraDecompact to 147,033.9 in section 20MaMoraDecompact

Error: Horizon Gualanday increases in length from 21,027.8 in section 27MaMoraDecompact to 31,556.9 in section 20MaMoraDecompact

Error: Horizon Capotes decreases in length from 52,694.7 in section 27MaMoraDecompact to 46,553.9 in section 20MaMoraDecompact without intersecting topography

Error: Horizon Socota decreases in length from 56,149.4 in section 27MaMoraDecompact to 50,781.2 in section 20MaMoraDecompact without intersecting topography

Warning: Horizon Macanal decreases in length from 93,731.5 in section 27MaMoraDecompact to 89,997.1 in section 20MaMoraDecompact without intersecting topography

Warning: Horizon Fomeque decreases in length from 112,879.6 in section 27MaMoraDecompact to 108,489.3 in section 20MaMoraDecompact without intersecting topography

Error: Horizon Guadalupe Sup increases in length from 32,970.8 in section 27MaMoraDecompact to 95,208.1 in section 20MaMoraDecompact

Error: Horizon C1 increases in length from 1,195.1 in section 20MaMoraDecompact to 42,691.2 in section 9MaMoraDecompact

Error: Horizon C6 increases in length from 38,292.9 in section 20MaMoraDecompact to 47,002.8 in section 9MaMoraDecompact

Error: Horizon C7 increases in length from 47,008.9 in section 20MaMoraDecompact to 68,502.6 in section 9MaMoraDecompact

Warning: Horizon Capotes decreases in length from 46,553.9 in section 20MaMoraDecompact to 44,682.1 in section 9MaMoraDecompact without intersecting topography

Warning: Horizon Farallones decreases in length from 83,969.3 in section 20MaMoraDecompact to 81,481.5 in section 9MaMoraDecompact without intersecting topography

Error: Horizon Guadalupe Sup increases in length from 95,208.1 in section 20MaMoraDecompact to 208,873.1 in section 9MaMoraDecompact

Error: Horizon Gualanday increases in length from 31,556.9 in section 20MaMoraDecompact to 50,801.4 in section 9MaMoraDecompact

Error: Horizon Honda increases in length from 3,400.1 in section 20MaMoraDecompact to 6,817.7 in section 9MaMoraDecompact

Error: Horizon Hoyon increases in length from 33,244.0 in section 20MaMoraDecompact to 41,080.0 in section 9MaMoraDecompact

Error: Horizon La Cira increases in length from 13,323.3 in section 20MaMoraDecompact to 25,593.5 in section 9MaMoraDecompact

Warning: Horizon Naveta decreases in length from 51,257.1 in section 20MaMoraDecompact to 48,961.9 in section 9MaMoraDecompact without intersecting topography

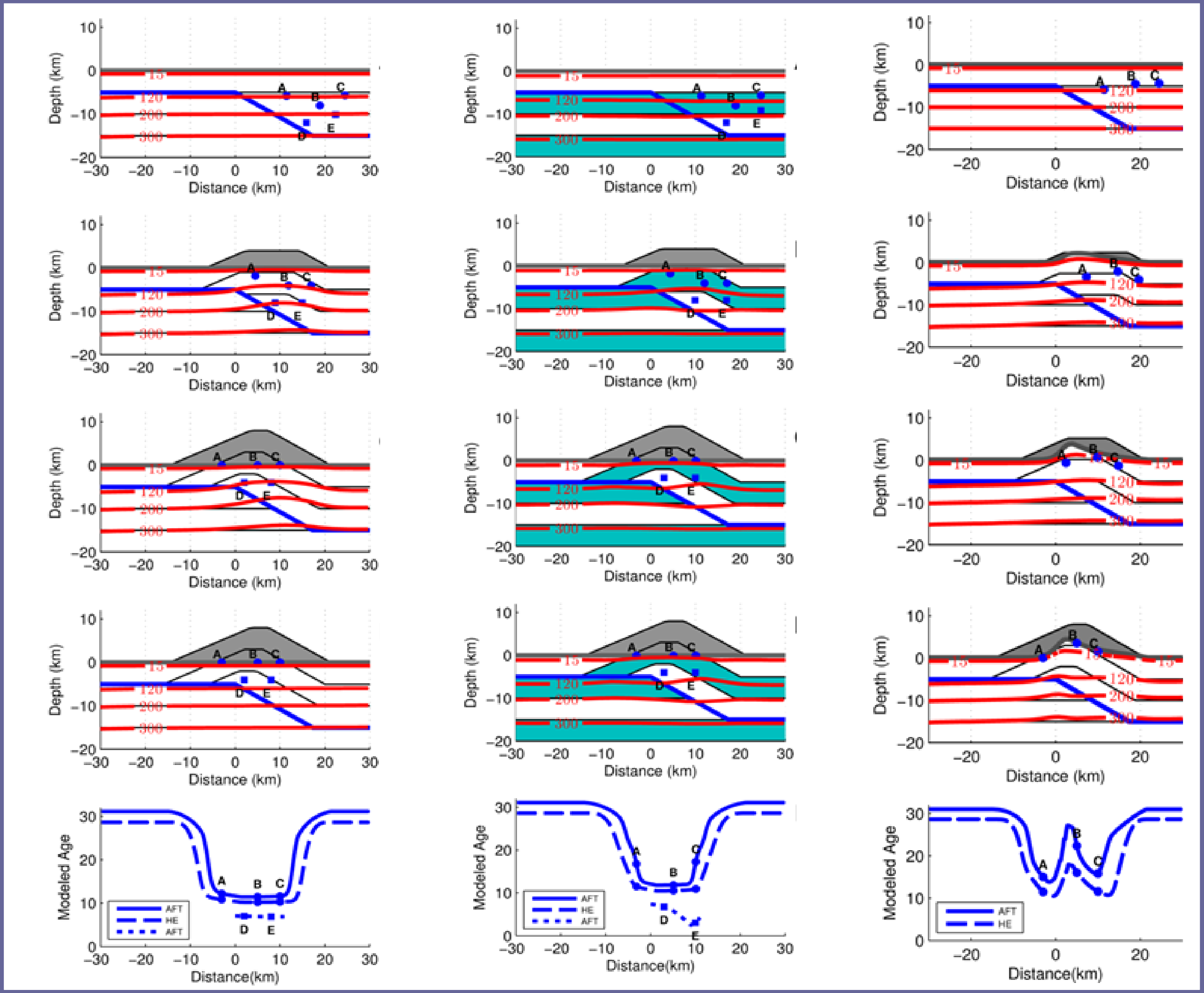
Error: Horizon Regadera increases in length from 45,558.9 in section 20MaMoraDecompact to 54,178.1 in section 9MaMoraDecompact

Warning: Horizon Socota decreases in length from 50,781.2 in section 20MaMoraDecompact to 48,368.9 in section 9MaMoraDecompact without intersecting topography

Warning: Horizon Trincheras decreases in length from 69,477.7 in section 20MaMoraDecompact to 66,832.4 in section 9MaMoraDecompact without intersecting topography

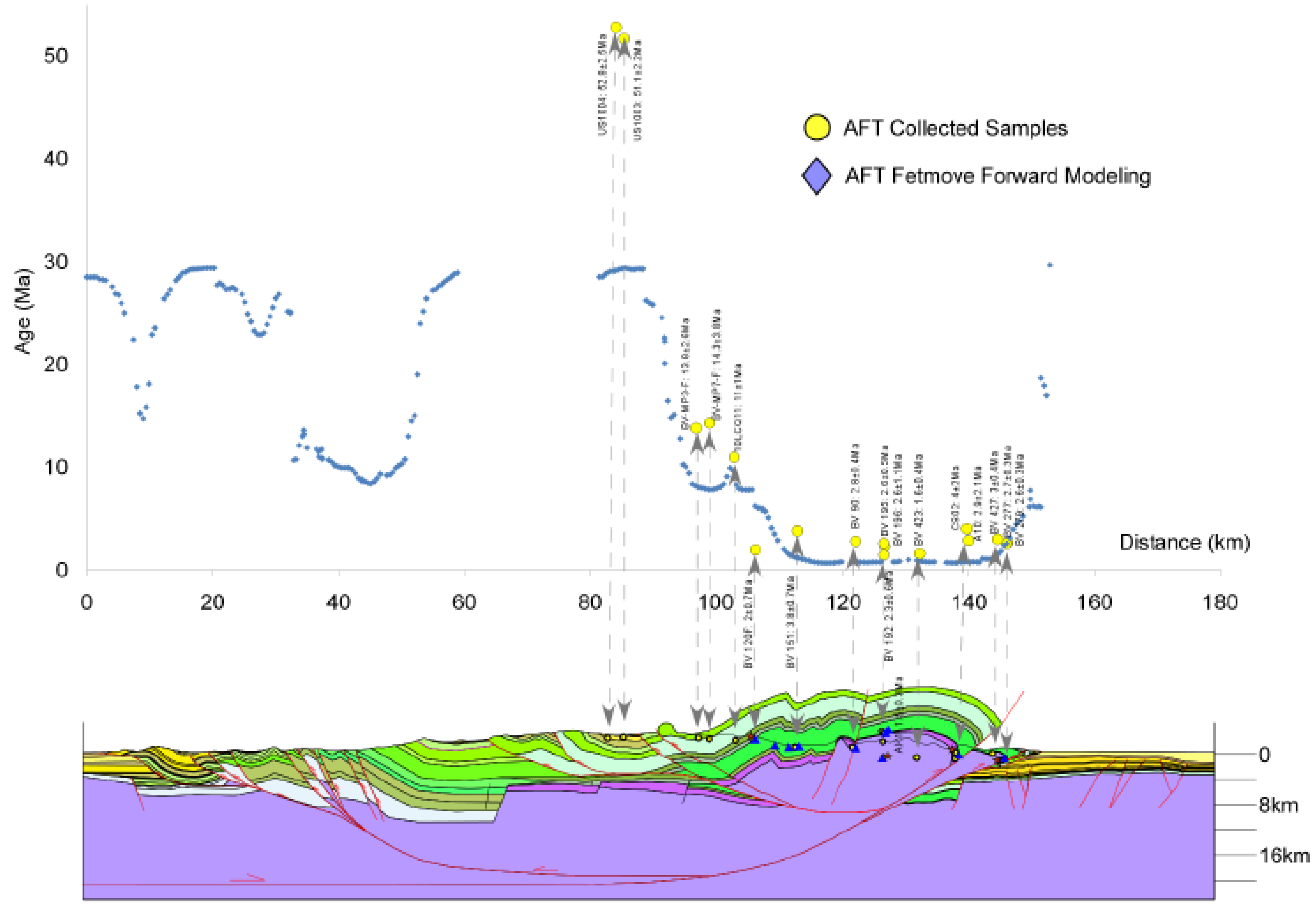
Error: Horizon Capotes decreases in length from 44,682.1 in section 9MaMoraDecompact to 40,599.4 in section 5MaMoraDecompact without intersecting topography

Step 3: Convert sections to vector fields, run thermal model

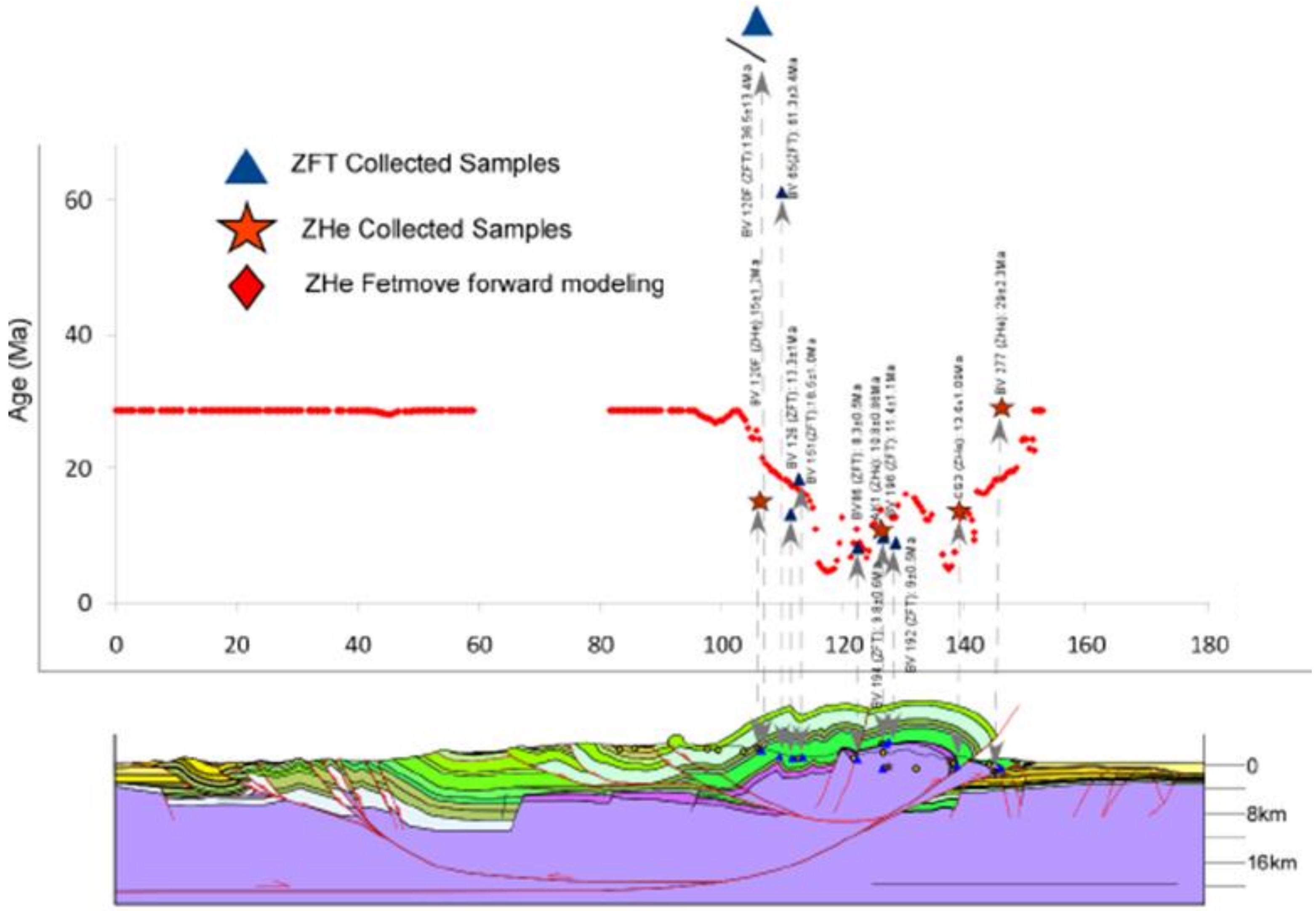


From Almendral et al., in review

Step 4: Compare with thermochon data

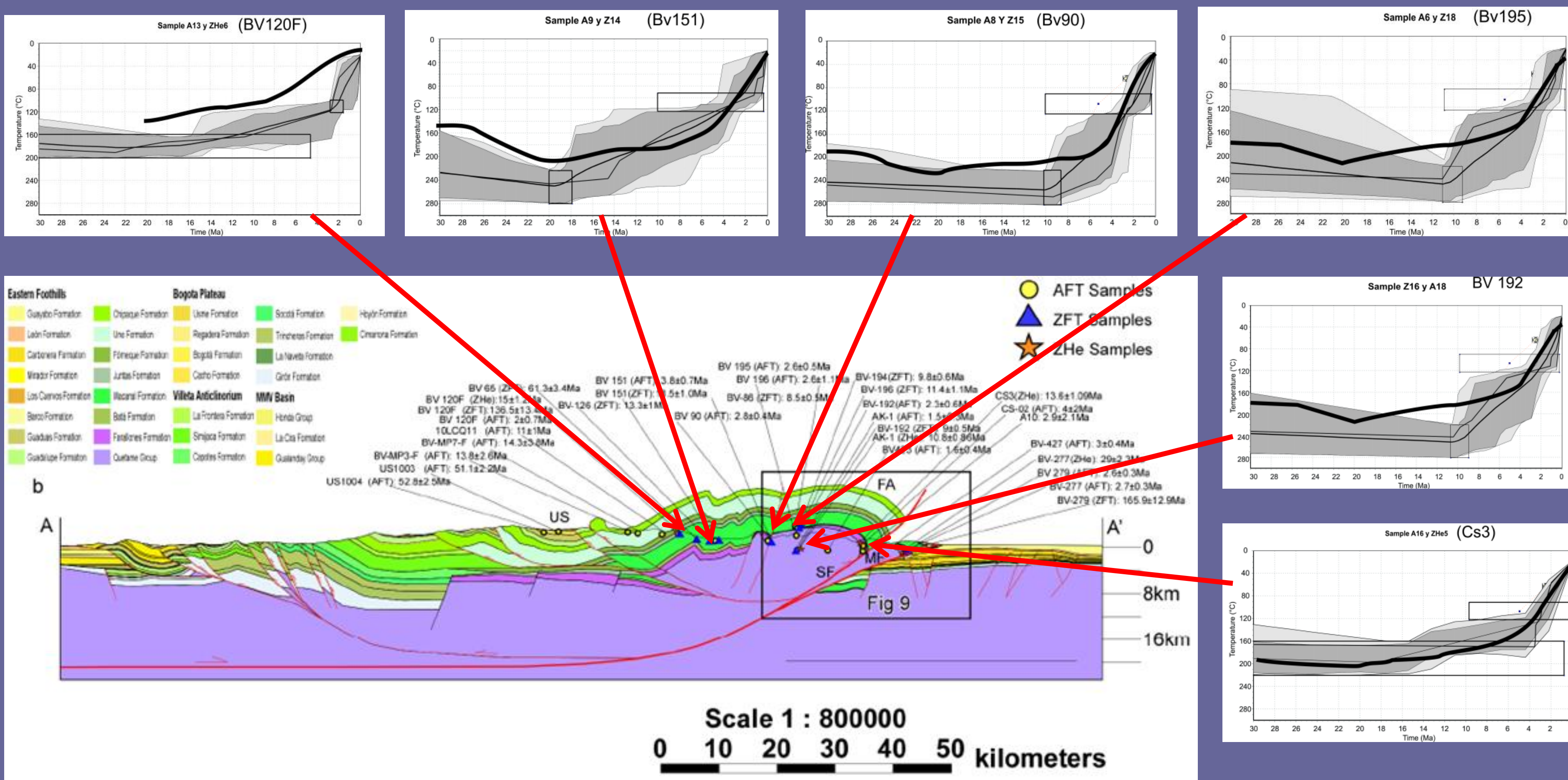


Casallas et al. Figure 7a



Casallas et al. Fig. 7b

Step 5: Back to step 1?

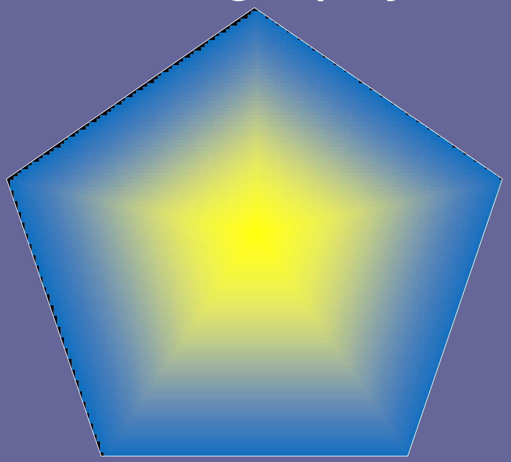


Adjust sections (or HeFTy models), repeat as necessary til done

Generate thermal solutions for petroleum system modeling

From Mora et al., in press, AAPG Bull.

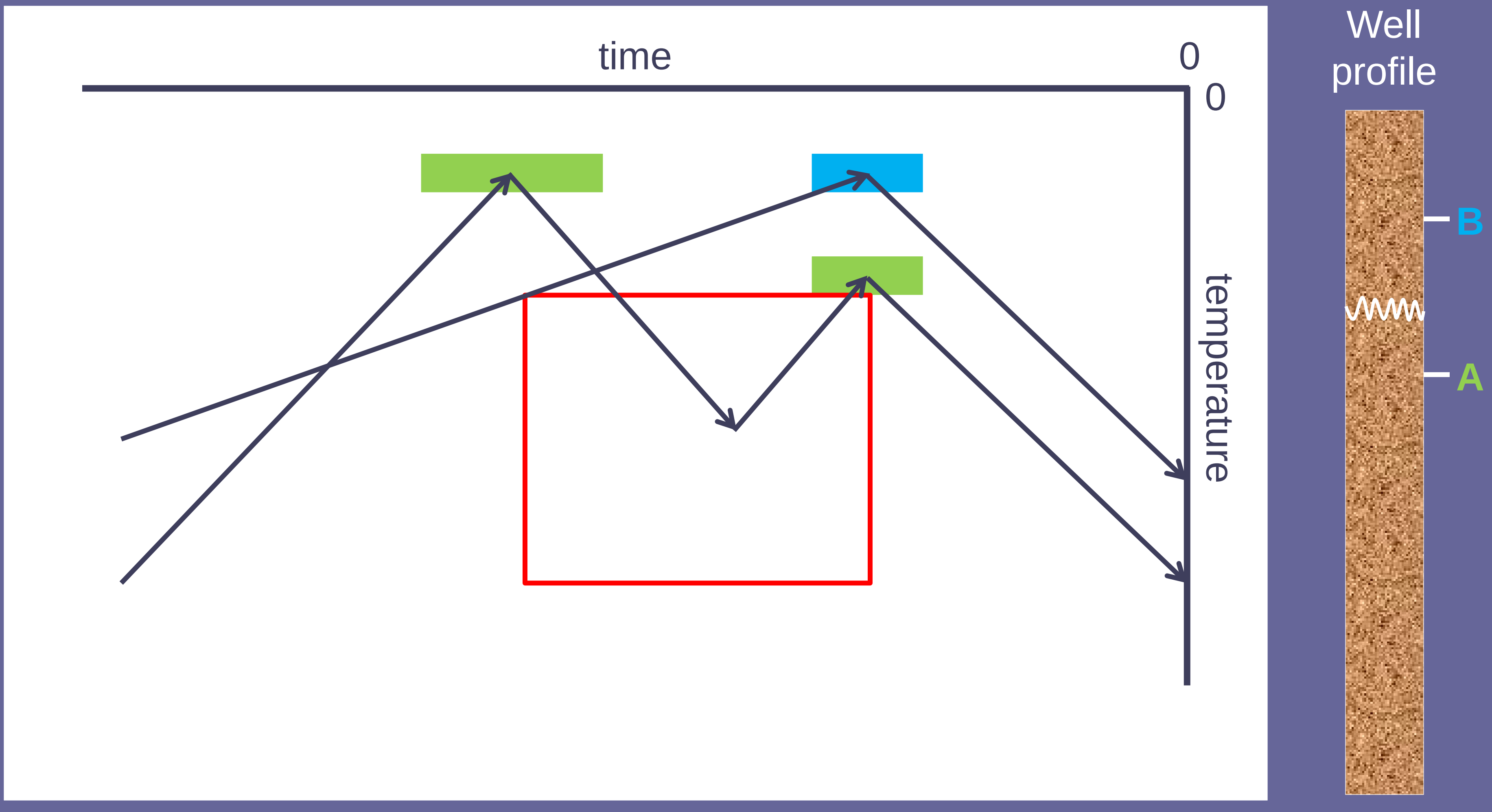
New Tool #2: Multi-sample HeFTy

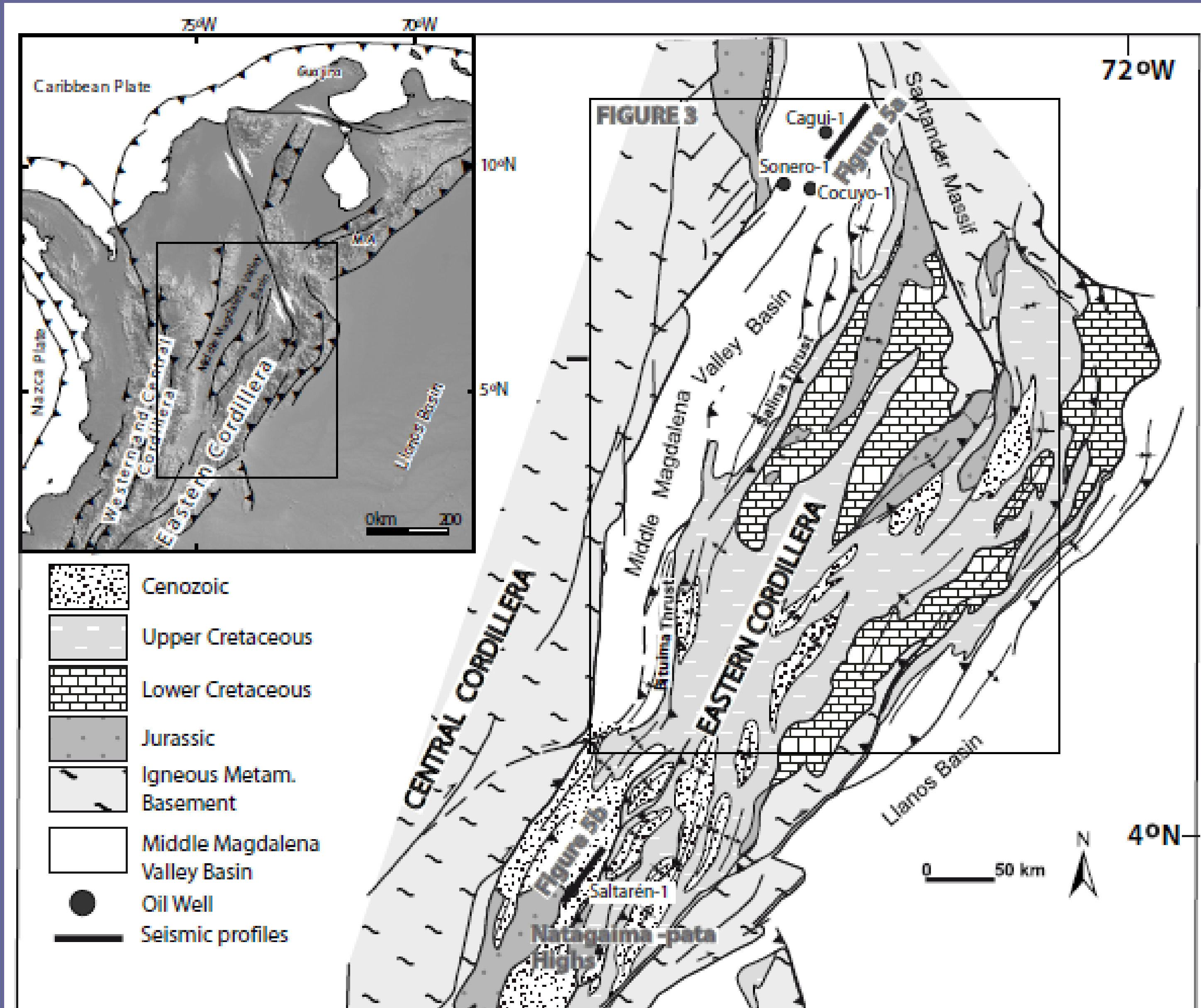


Mainly for samples down boreholes at this point.

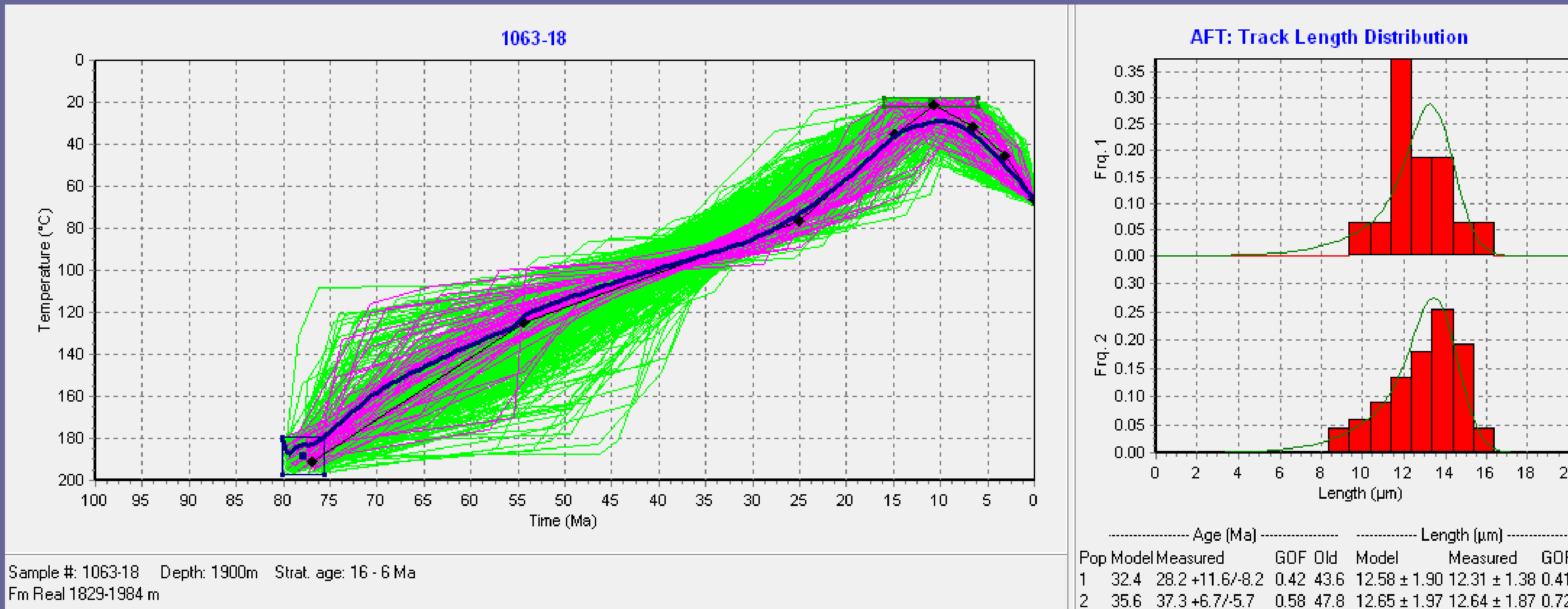
Principal issue addressed thus far is stratigraphic relationships: inheritance, burial, unconformities.

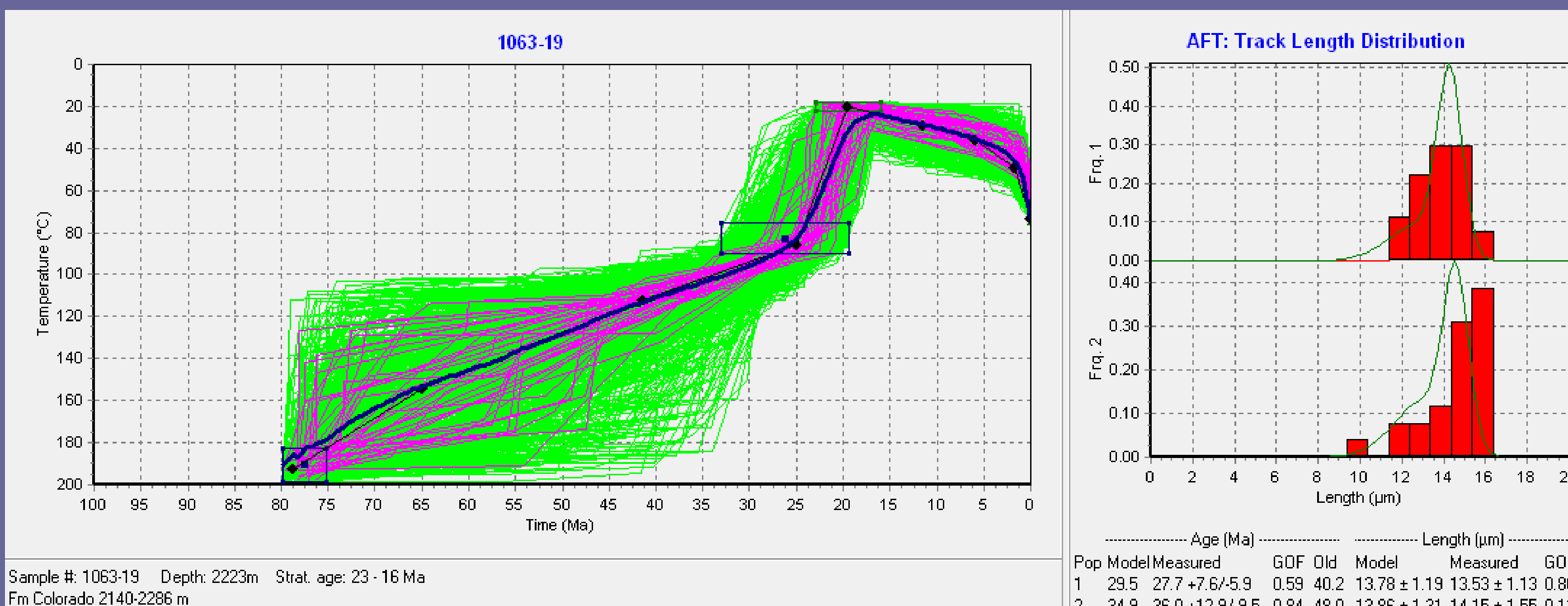
Samples down a well: Simple Strat

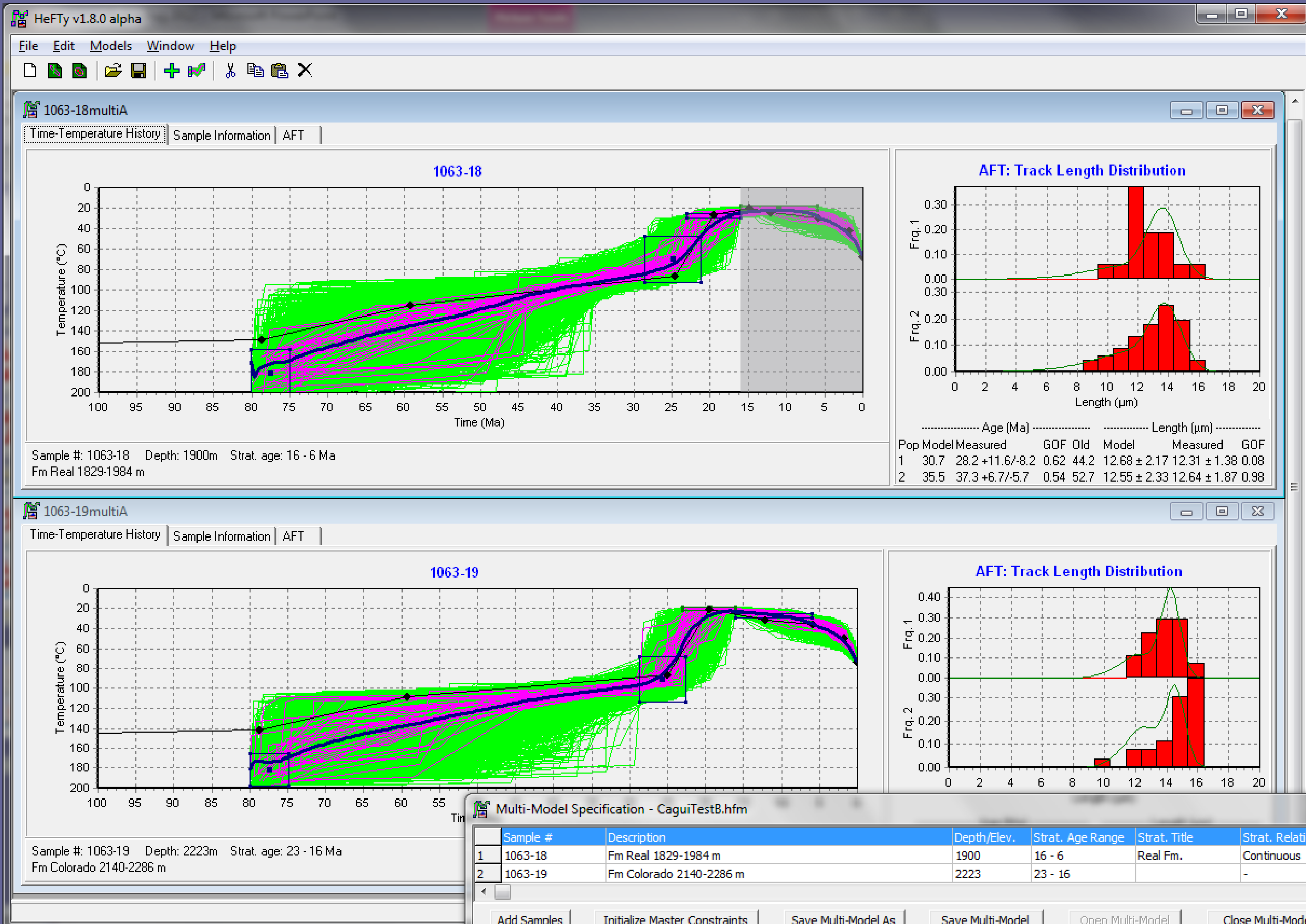




From Caballero et al., in review


1063-18
Temperature (°C)
Time (Ma)
AFT: Track Length Distribution
Frq. 1
Frq. 2
Length (µm)
Sample #: 1063-18 Depth: 1900m Strat. age: 16 - 6 Ma
Fm Real 1829-1984 m
------------ Age (Ma) ------------ ------------ Length (µm) ------------
Pop Model Measured GOF Old Model Measured GOF
1 32.4 28.2 +11.6/-8.2 0.42 43.6 12.58 ± 1.90 12.31 ± 1.38 0.41
2 35.6 37.3 +6.7/-5.7 0.58 47.8 12.65 ± 1.97 12.64 ± 1.87 0.72


1063-19
Temperature (°C)
Time (Ma)
AFT: Track Length Distribution
Frq. 1
Frq. 2
Length (µm)
Sample #: 1063-19 Depth: 2223m Strat. age: 23 - 16 Ma
Fm Colorado 2140-2286 m
------------ Age (Ma) ------------ ------------ Length (µm) ------------
Pop Model Measured GOF Old Model Measured GOF
1 29.5 27.7 +7.6/-5.9 0.59 40.2 13.78 ± 1.19 13.53 ± 1.13 0.80
2 34.9 36.0 +12.9/-9.5 0.84 48.0 13.86 ± 1.31 14.15 ± 1.55 0.13


HeFTy v1.8.0 alpha
File Edit Models Window Help
1063-18multiA
Time-Temperature History
Sample Information
AFT
1063-18
Temperature (°C)
Time (Ma)
AFT: Track Length Distribution
Frq. 1
Frq. 2
Length (µm)
------------- Age (Ma) -------------
------------- Length (µm) -------------
Pop Model Measured GOF Old Model Measured GOF
1 30.7 28.2 +11.6/-8.2 0.62 44.2 12.68 ± 2.17 12.31 ± 1.38 0.08
2 35.5 37.3 +6.7/-5.7 0.54 52.7 12.55 ± 2.33 12.64 ± 1.87 0.98
Sample #: 1063-18 Depth: 1900m Strat. age: 16 - 6 Ma
Fm Real 1829-1984 m
1063-19multiA
Time-Temperature History
Sample Information
AFT
1063-19
Temperature (°C)
AFT: Track Length Distribution
Frq. 1
Frq. 2
Sample #: 1063-19 Depth: 2223m Strat. age: 23 - 16 Ma
Fm Colorado 2140-2286 m
Multi-Model Specification - CaguiTestB.hfm
Sample # | Description | Depth/Elev. | Strat. Age Range | Strat. Title | Strat. Relation
1 | 1063-18 | Fm Real 1829-1984 m | 1900 | 16 - 6 | Real Fm. | Continuous
2 | 1063-19 | Fm Colorado 2140-2286 m | 2223 | 23 - 16 | | -
Add Samples
Initialize Master Constraints
Save Multi-Model As
Save Multi-Model
Open Multi-Model
Close Multi-Model

Discern provenance uplift rate
Estimate missing section

Implications for petroleum systems

- Fetkin
  - Ideal for high-resolution t-T histories, timing of source rocks in oil generation window
    - Eastern Cordillera
    - Oil generation stopped after Oligocene
- HeFTy
  - Better for moderate inversion with quiescence and post-inversion unconformities
    - Magdalena Valley
    - Oil generation possibly ongoing