3D Thermokinematic Modelling of the Colombian Eastern Cordillera: Refining the Timing of Oil Generation and Expulsion Using Multiple Thermochronometers*

Andrés Mora[1], Isaid Quintero[1], Richard Styron[1], Michael Raghib[1], Mauricio Parra1, and Richard A. Ketcham[1]

Search and Discovery Article #41222 (2013)**
Posted October 22, 2013

*Adapted from oral presentation at AAPG Annual Convention and Exhibition, Pittsburgh, Pennsylvania, May 19-22, 2013

[1]Ecopetrol-ICP (andres.mora@ecopetrol.com.co)

Abstract

The Colombian Eastern Cordillera of Colombia is a place where multiple shaly units with source-rock potential have been deposited since the Early Cretaceous. Traditionally, the generation and migration models for the region have only considered the Turonian shales coeval with the organic-rich La Luna Formation as the main source rock. Precise 3D time temperature conditions combined with a kinematic structural evolution of the basin are required in order to understand when the different potential source-rock intervals entered the oil window, and compare that with the presence and absence of traps in the adjacent foreland basins. Ecopetrol-ICP has acquired an unprecedented amount of thermochronometric data over the past several years (e.g., more than 3000 individual He ages, more than 600 apatite-fission track (AFT) and zircon-fission track (ZFT) analyses) and hundreds of vitrinite reflectance data. Here we present the results of 3D thermokinematic modeling supported on that data, using public domain and new in-house software tools. The modeling supports the presence of multiple generation and expulsion episodes starting in the Late Cretaceous. This information increases the potential to find further oil resources in the Llanos foreland basin, east of the Eastern Cordillera kitchens.

Selected References

Escalona, A., and P. Mann, 2011, Tectonics, basin subsidence mechanisms, and paleogeography of the Caribbean-South American plate boundary zone: Marine and Petroleum Geology, v. 28, p. 8-39.

ICP, 2009, Structural Geology Group: Ecopetrol Research Report, unpublished.

Mora, A., A. Reyes-Harker, G. Rodriguez, E. Teson, J.C. Ramierz-Arias, M. Parra, V. Caballero, J.P. Mora, I. Quintero, V. Valencia, M. Ibanez, B.K. Horton, and D.F. Stockli, 2013, Inversion tectonics under increasing rates of shortening and sedimentation: Cenozoic example from the Eastern Cordillera of Colombia, *in* M. Nemcok, A. Mora, and J.W. Cosgrove, (eds.), Thick-Skin-Dominated Orogens: From Initial Inversion to Full Accretion: Geological Society of London, Special Publication, v. 377, p. 411-442. doi:10.1144/SP377.6

Mora, A., M. Parra, M.R. Strecker, E.R. Sobel1, H. Hooghiemstra, V. Torres, and J. V. Jaramillo, 2008, Climatic forcing of asymmetric orogenic evolution in the Eastern Cordillera of Colombia: GSA Bulletin, v. 120, p. 930-049.

Restrepo-Pace, P.A., F. Colmenares, C. Higuera. and M. Mayorga, 2004, A Fold-and-thrust belt along the western flank of the Eastern Cordillera of Colombia—Style, kinematics, and timing constraints derived from seismic data and detailed surface mapping, *in* K.R. McClay, (ed.), Thrust Tectonics and Hydrocarbon Systems: AAPG Memoir 82, p. 598-613.

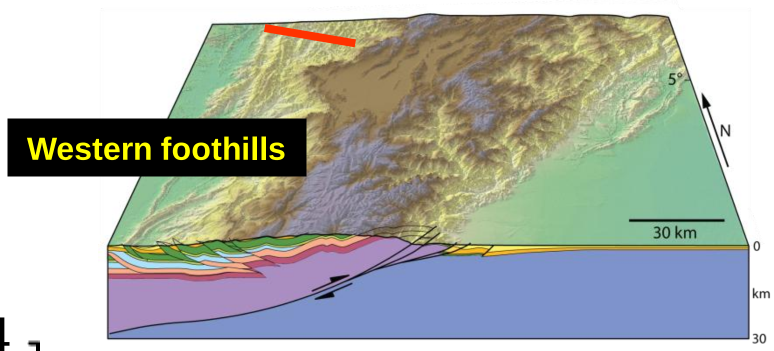
“3D Thermokinematic modelling of the Colombian Eastern Cordillera. Refining the timing of oil generation and expulsion using multiple thermochronometers.”

Andrés Mora, Isaid Quintero, Richard Styron, Michael Raghib, Mauricio Parra, Richard A. Ketcham

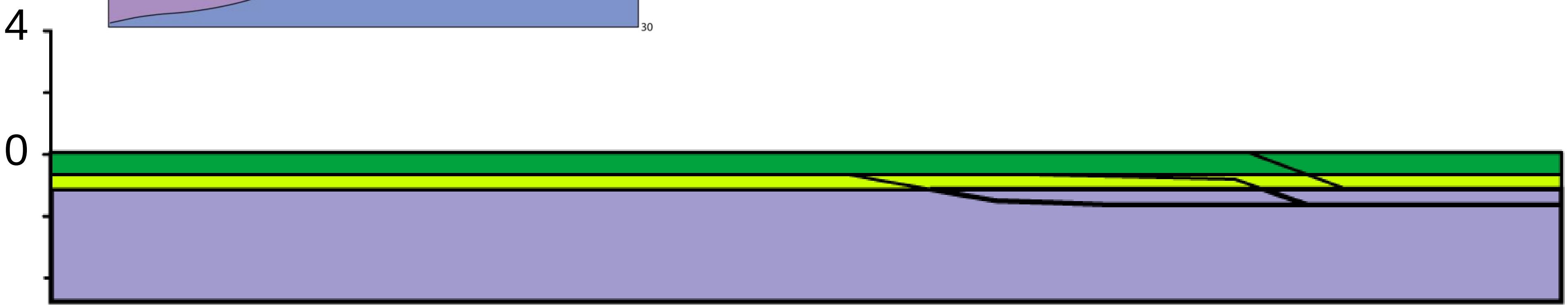
OUTLINE

- KINEMATIC RESTORATIONS.
- FROM AGES TO DEFORMATION HISTORIES.
- THERMOKINEMATIC MODELLING.
- CASE STUDY.
- CONCLUSIONS AND IMPLICATIONS.

KINEMATIC RESTORATIONS
Key tool for petroleum system modelling

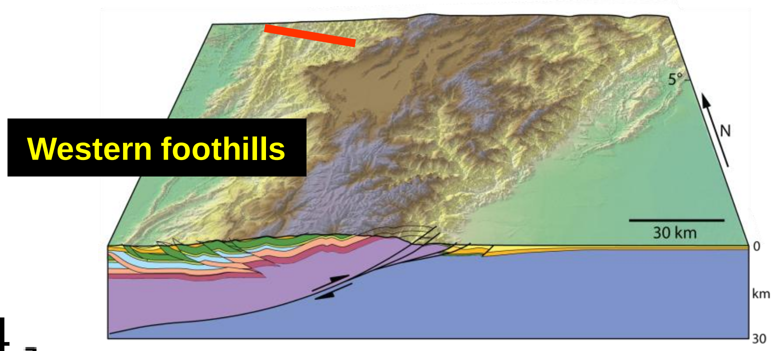


Maastrichtian retrodeformed state

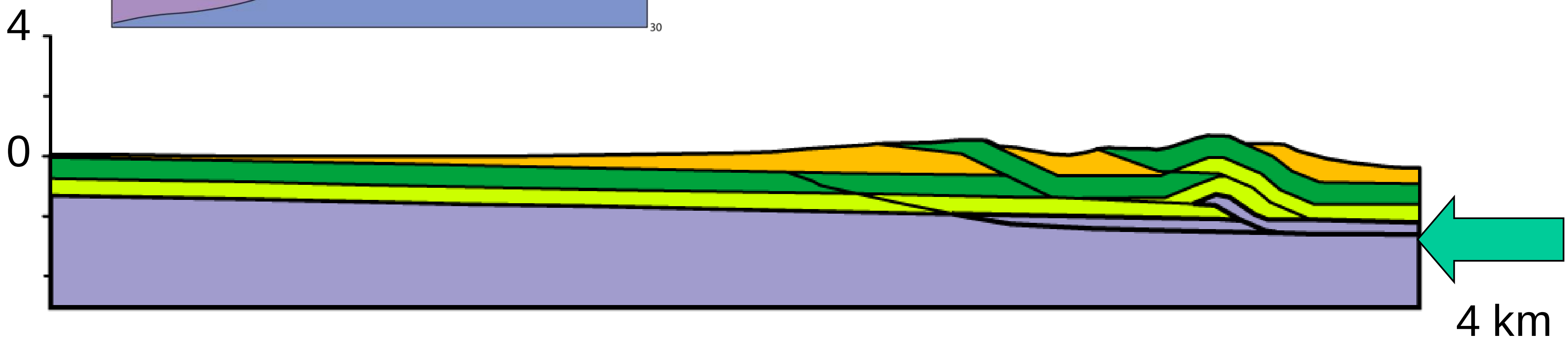


Restrepo-Pace et al., 2004

KINEMATIC RESTORATIONS
Key tool for petroleum system modelling

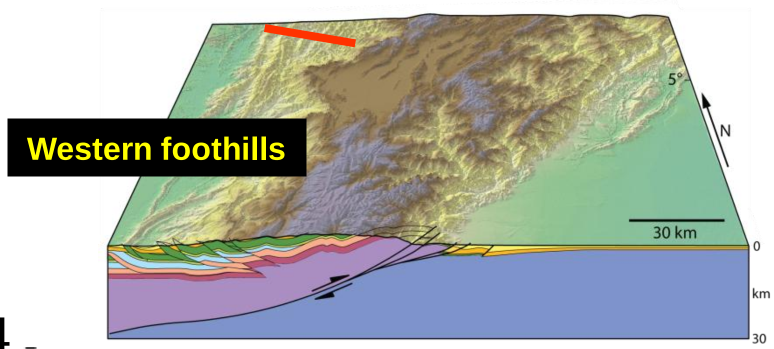


Paleocene

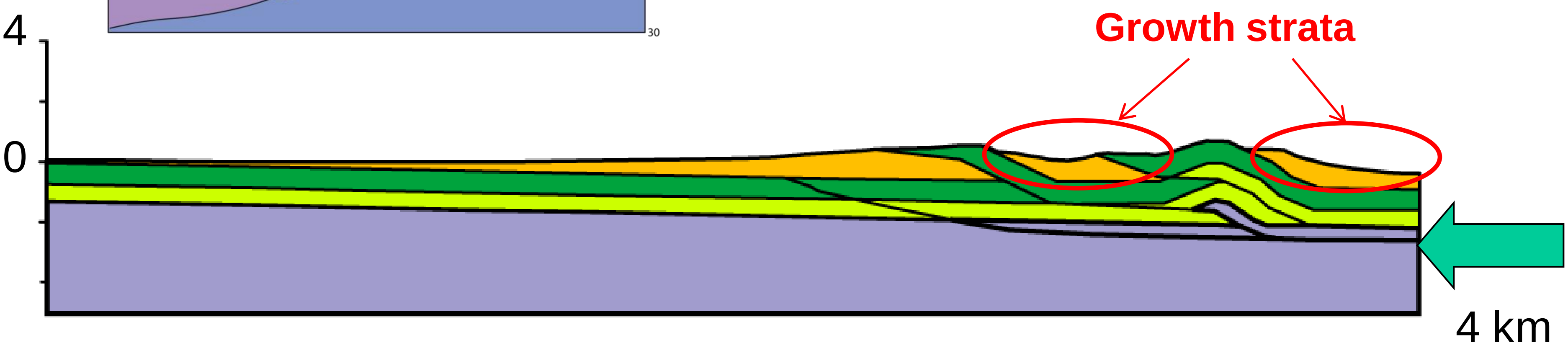


Restrepo-Pace et al., 2004

KINEMATIC RESTORATIONS
Key tool for petroleum system modelling

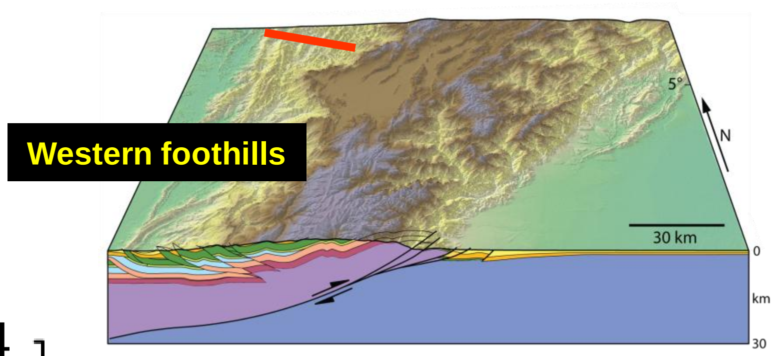


Paleocene

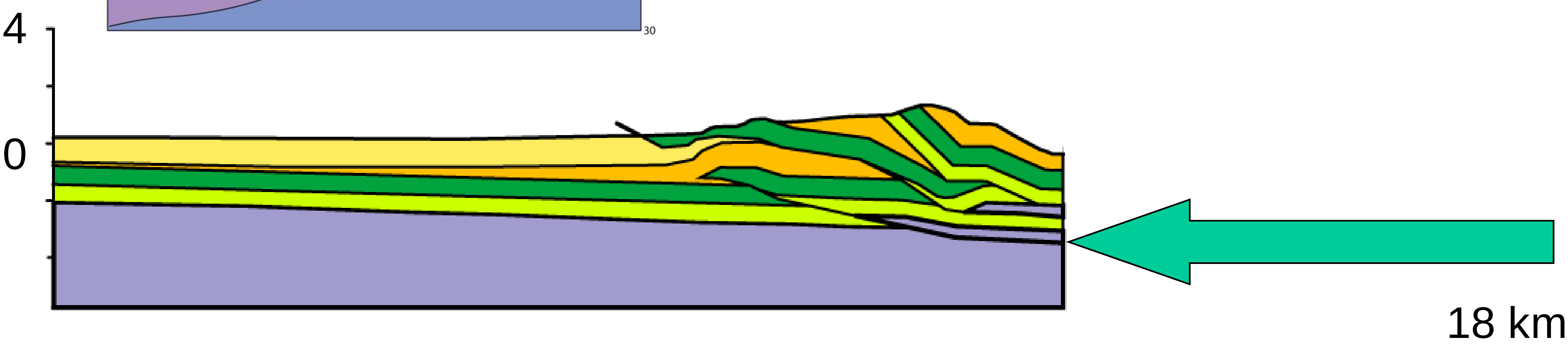


Restrepo-Pace et al., 2004

KINEMATIC RESTORATIONS
Key tool for petroleum system modelling

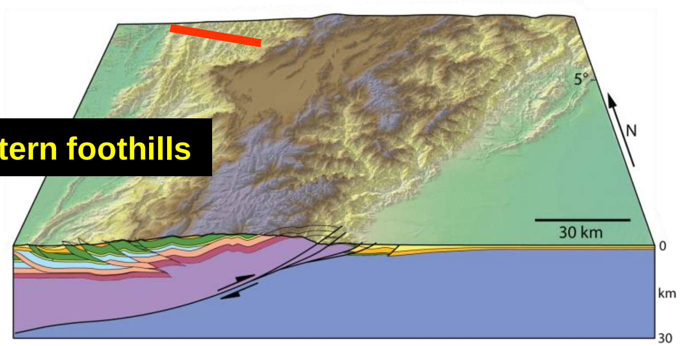


Late Oligocene

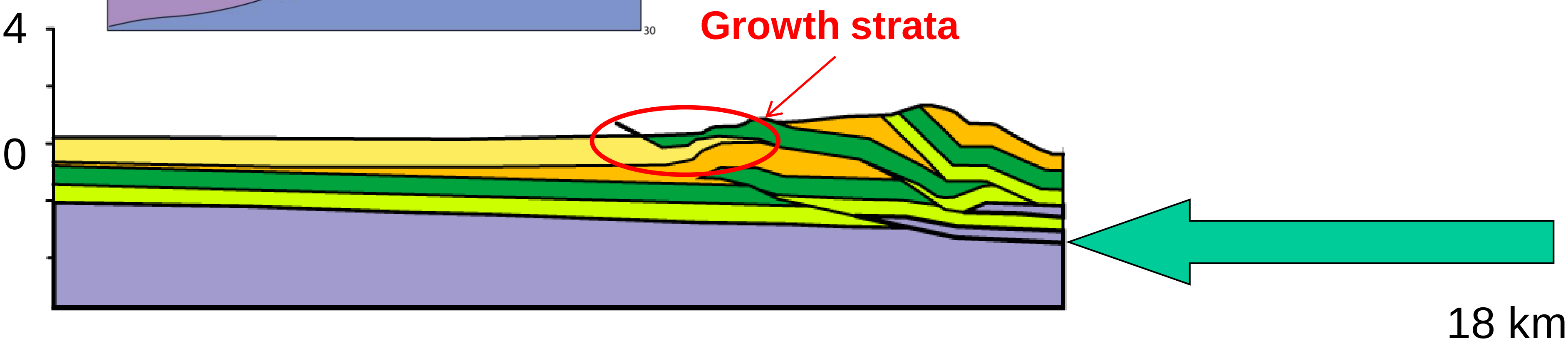


Restrepo-Pace et al., 2004

KINEMATIC RESTORATIONS
Key tool for petroleum system modelling



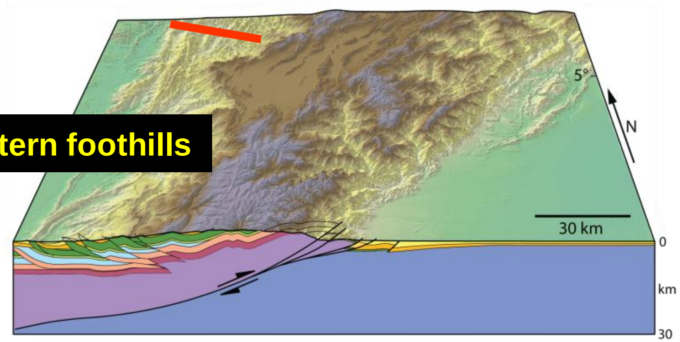
Late Oligocene



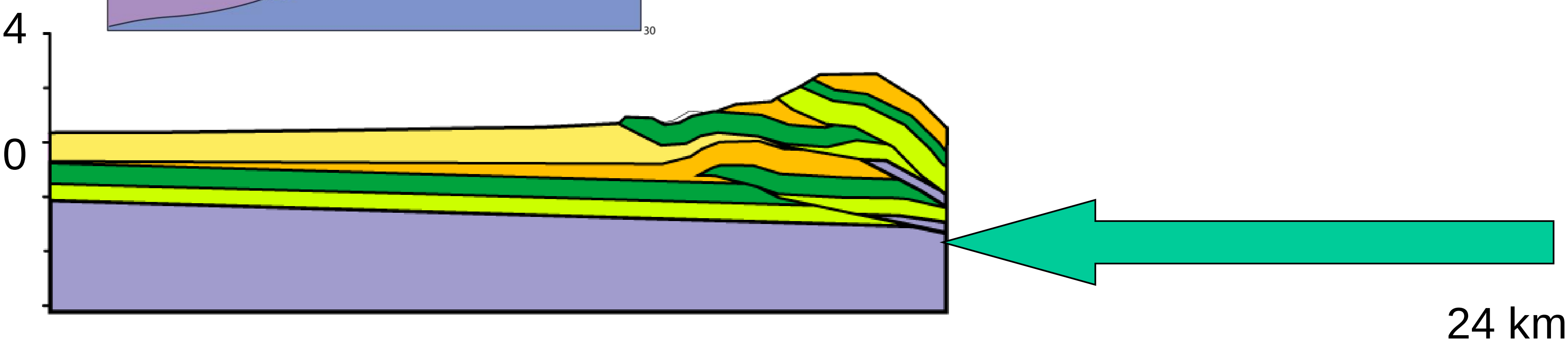
Restrepo-Pace et al., 2004

KINEMATIC RESTORATIONS
Key tool for petroleum system modelling

Western foothills

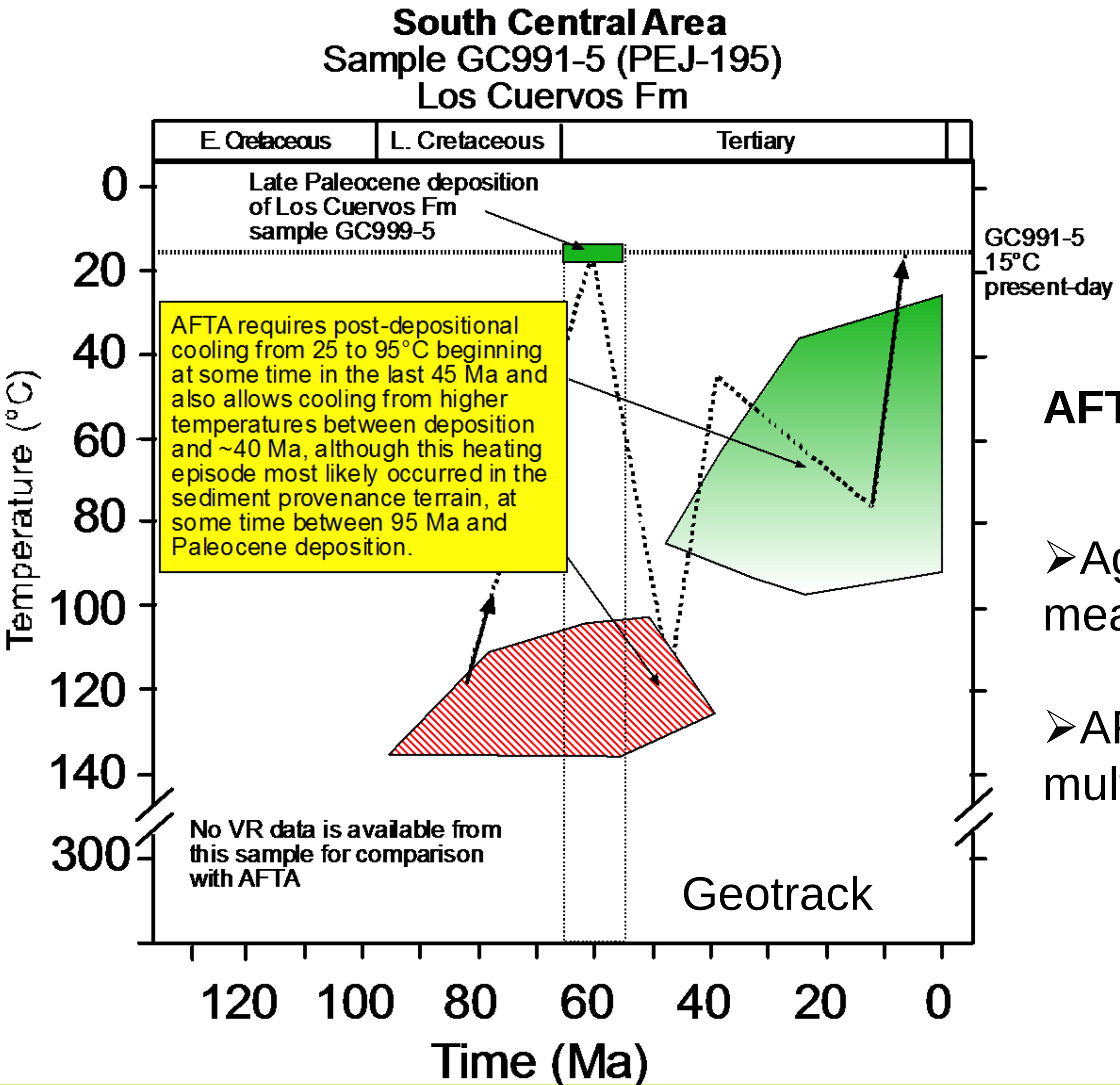


Present



KINEMATIC RESTORATIONS

In absence of growth strata thermochronometric data can be used

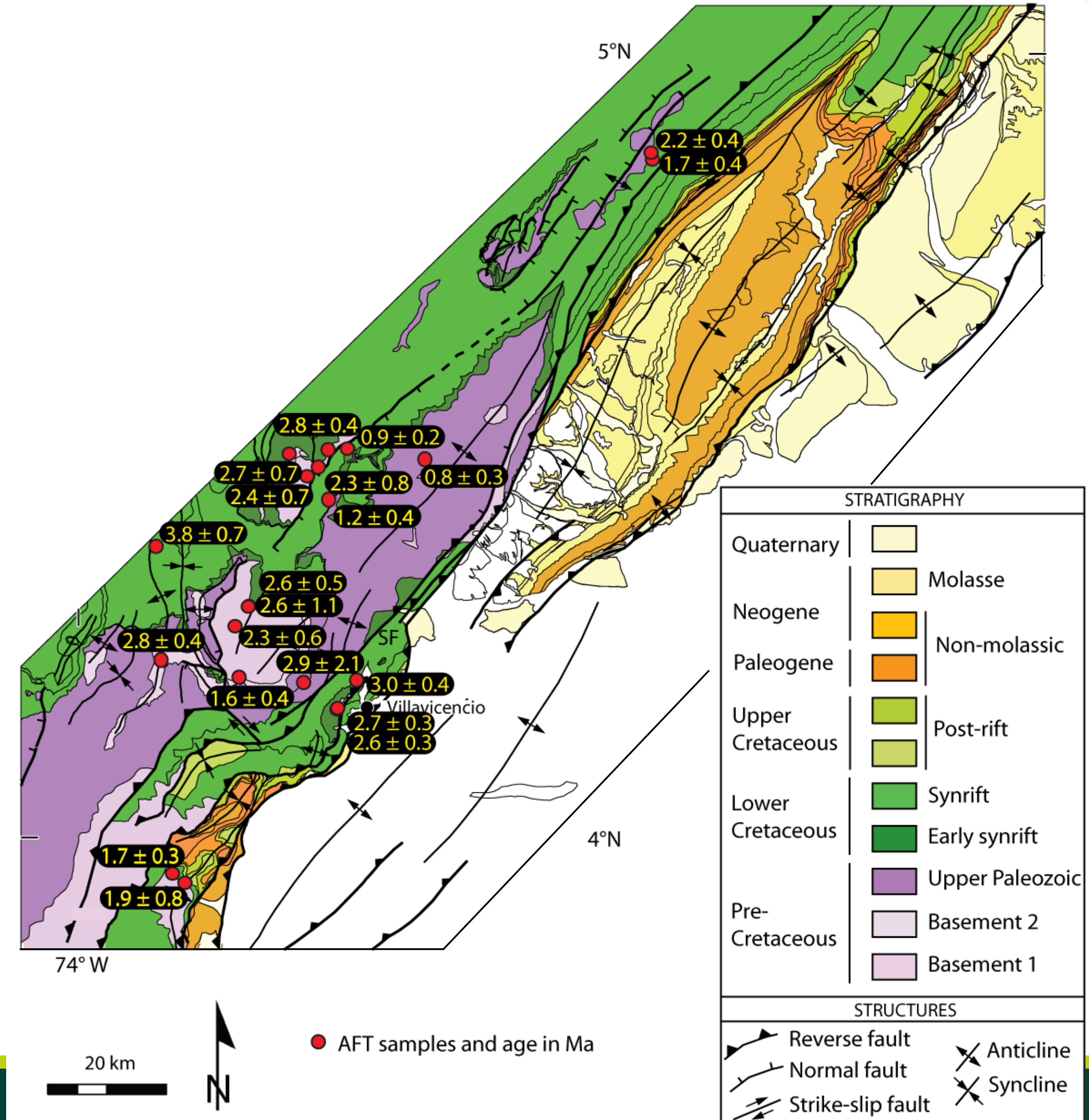


AFT age=30.0±10.2 Ma

- Ages rarely have geological meaning.
- AFTA modelling only gives multiple admissible solutions

KINEMATIC RESTORATIONS

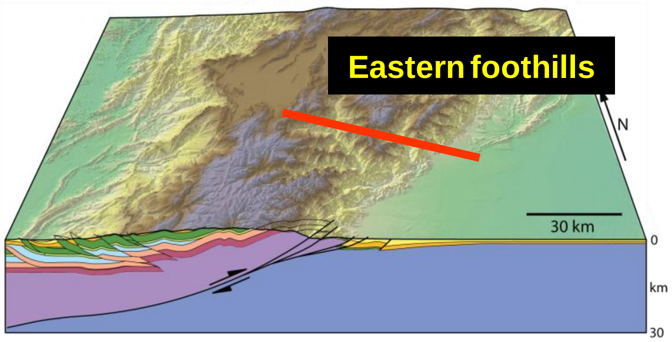
In absence of growth strata thermochronometric data can be used

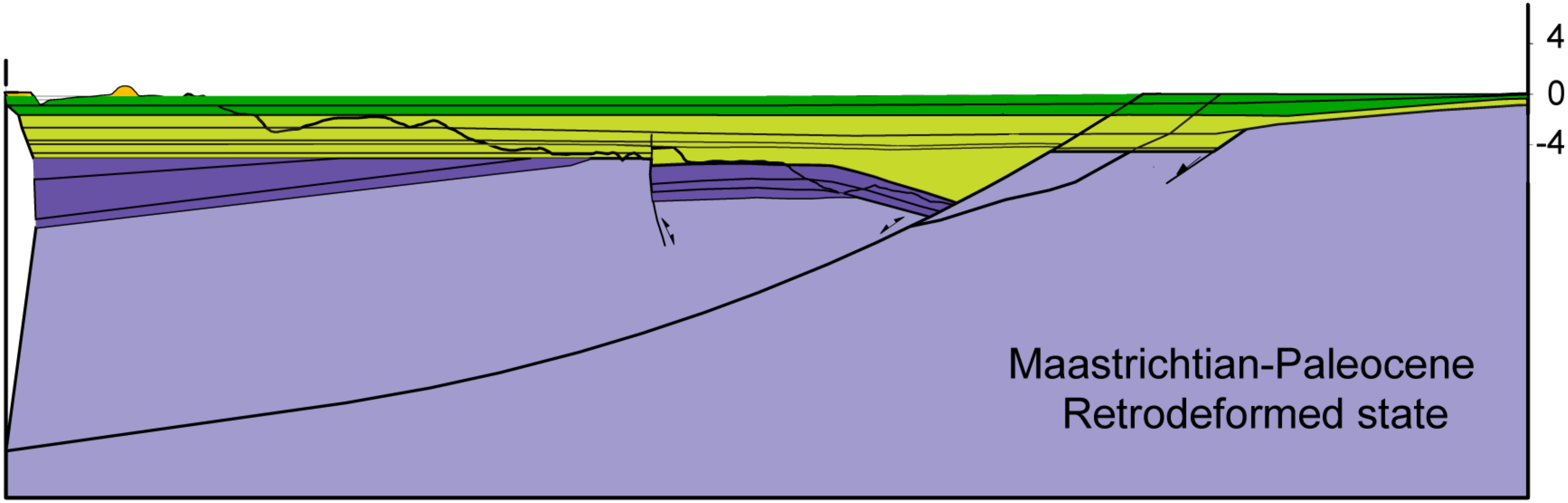


Mora et al. GSA bulletin 2008

KINEMATIC RESTORATIONS

In absence of growth strata thermochronometric data can be used

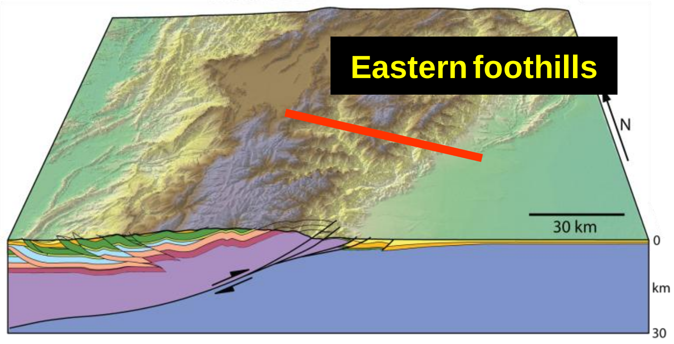


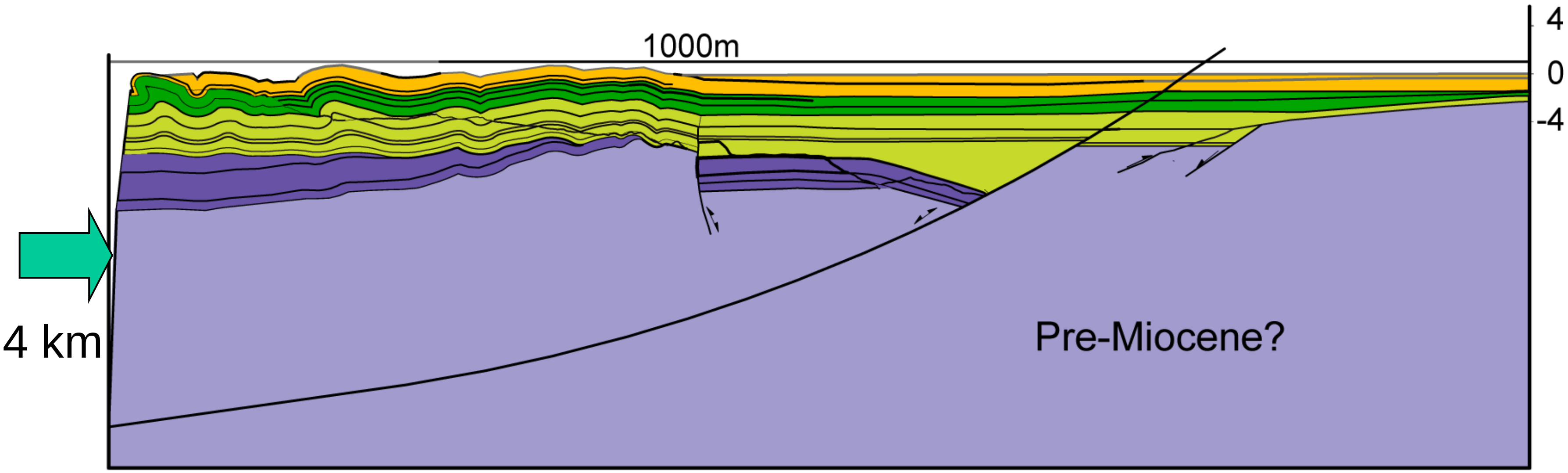


Mora et al. GSA 2008

KINEMATIC RESTORATIONS

In absence of growth strata thermochronometric data can be used

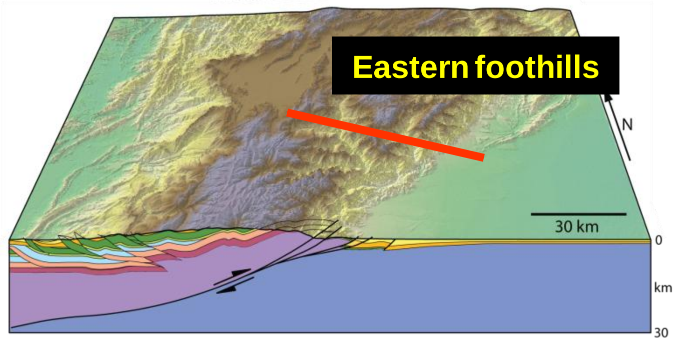


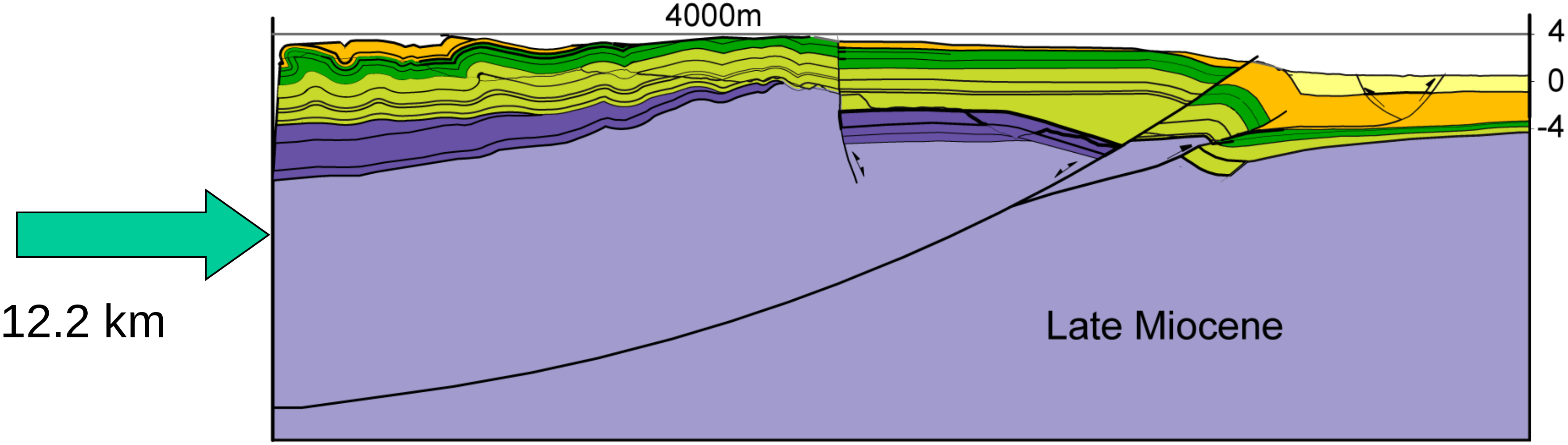


Mora et al. GSA 2008

KINEMATIC RESTORATIONS

In absence of growth strata thermochronometric data can be used



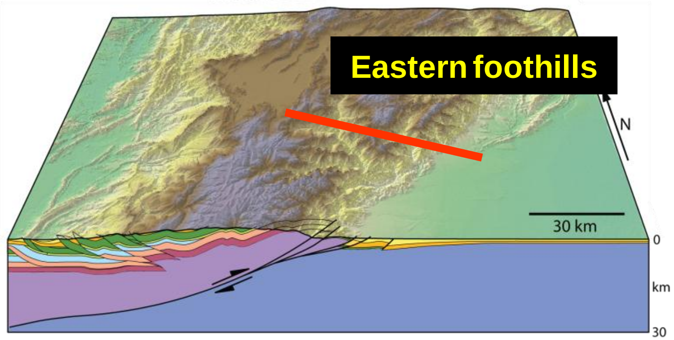


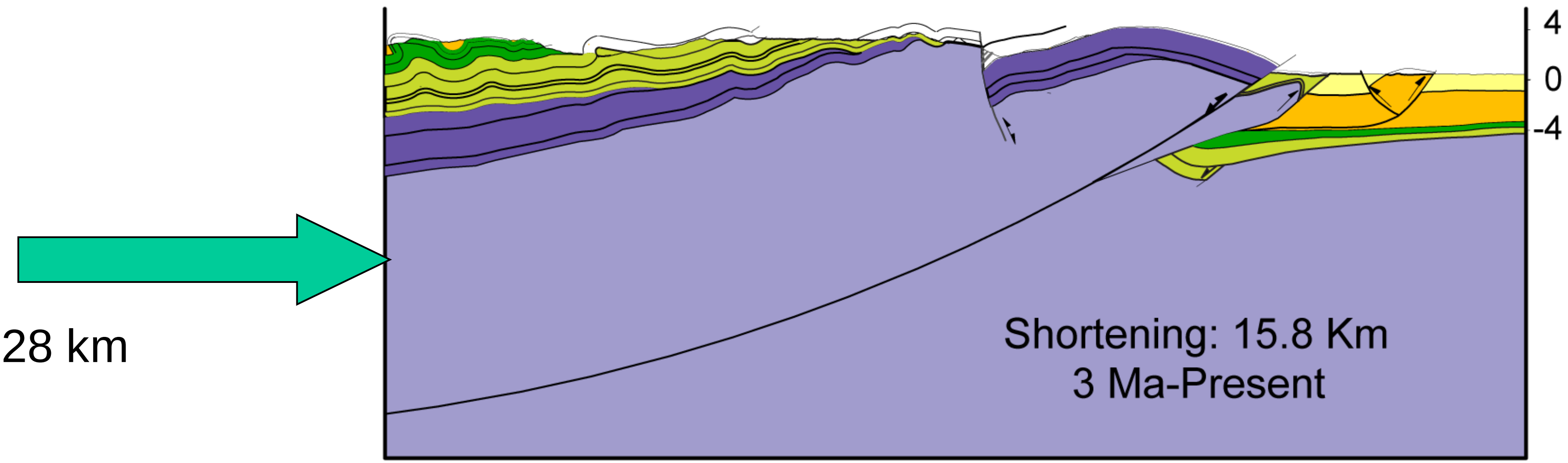
Mora et al. GSA 2008

KINEMATIC RESTORATIONS

In absence of growth strata thermochronometric data can be used

ca. 50% of shortening along the eastern flank may have occurred in the last 3 Ma, corresponding to ca. 25% of total orogenic shortening.





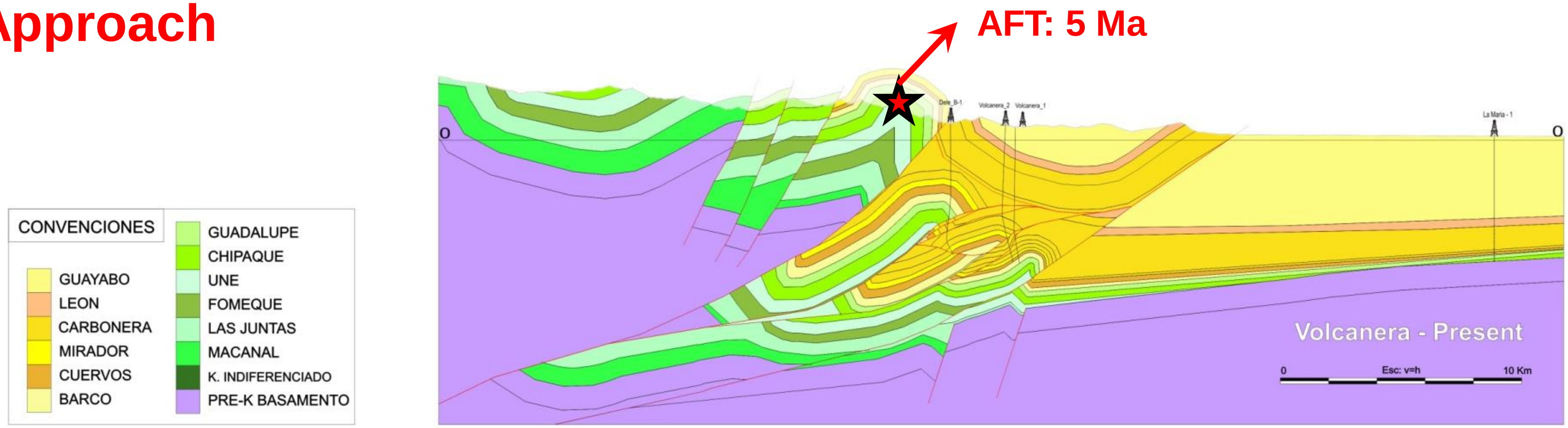
28 km

Total shortening: ca. 28 Km

Mora et al. GSA 2008

FROM AGES TO DEFORMATION HISTORIES

Average Closure Temperatures and present-day geotherm:
Manual Approach



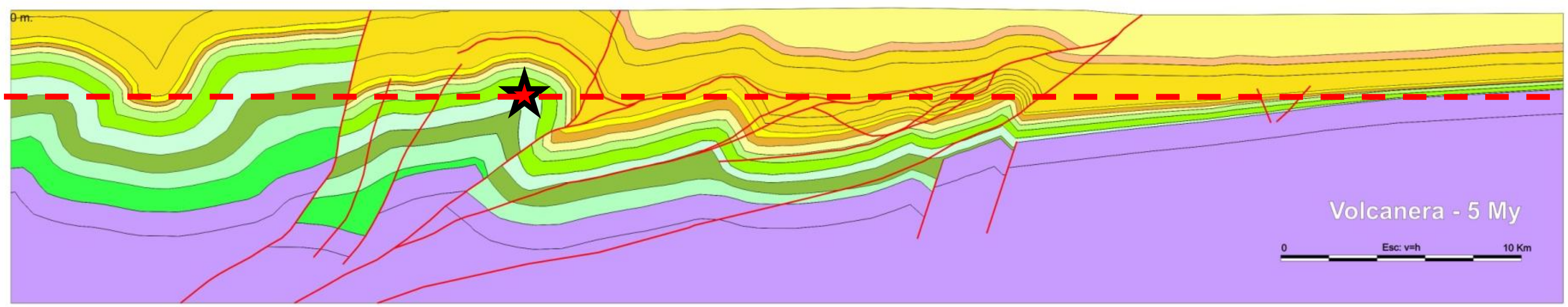
ICP (2009) Structural Geology Group

FROM AGES TO DEFORMATION HISTORIES

Reconstructing complete deformational histories: Manual Approach

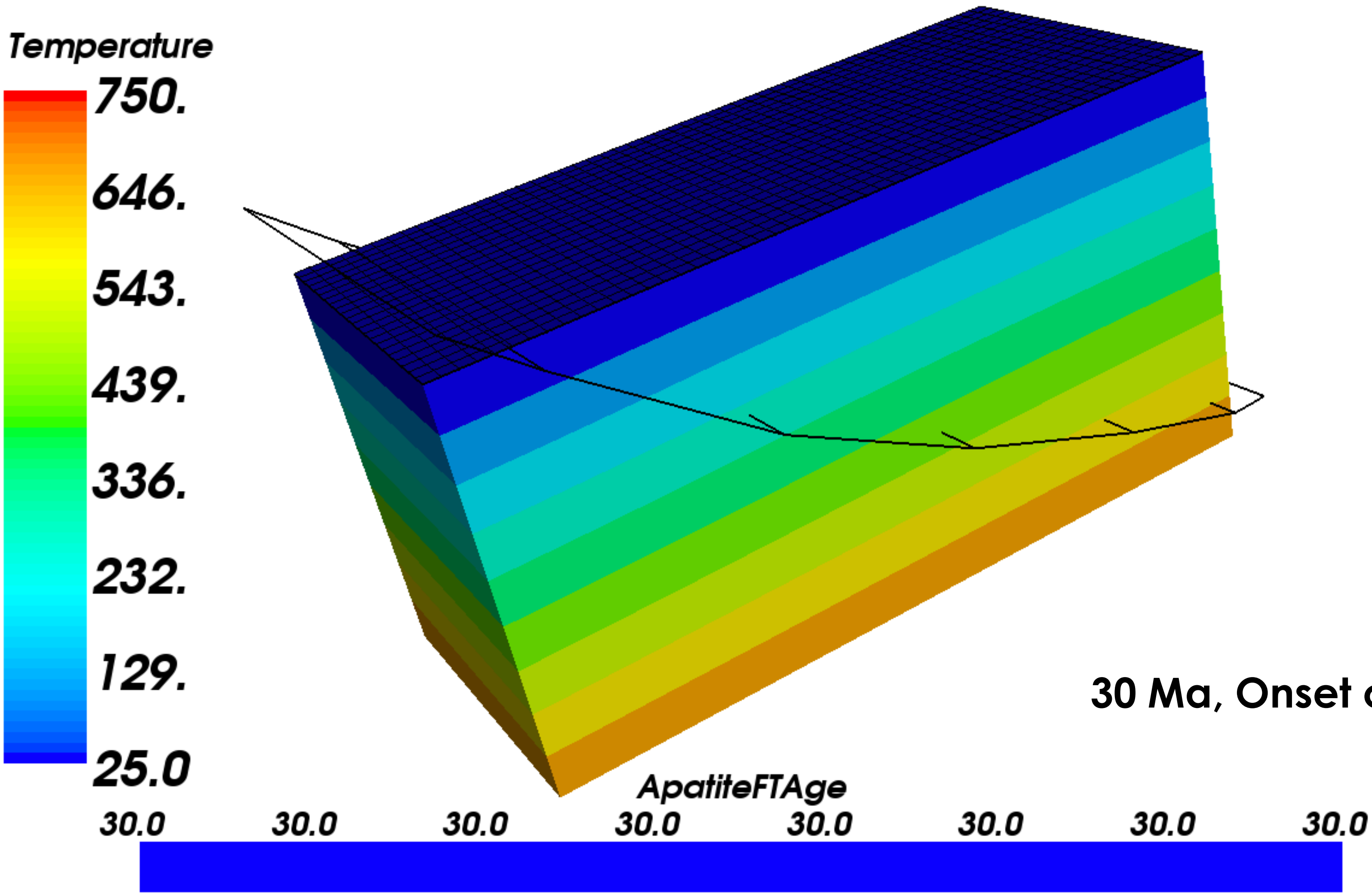
5 Ma

~4 km
~ 120°C
(@ 25°C/km)



ICP (2009) Structural Geology Group

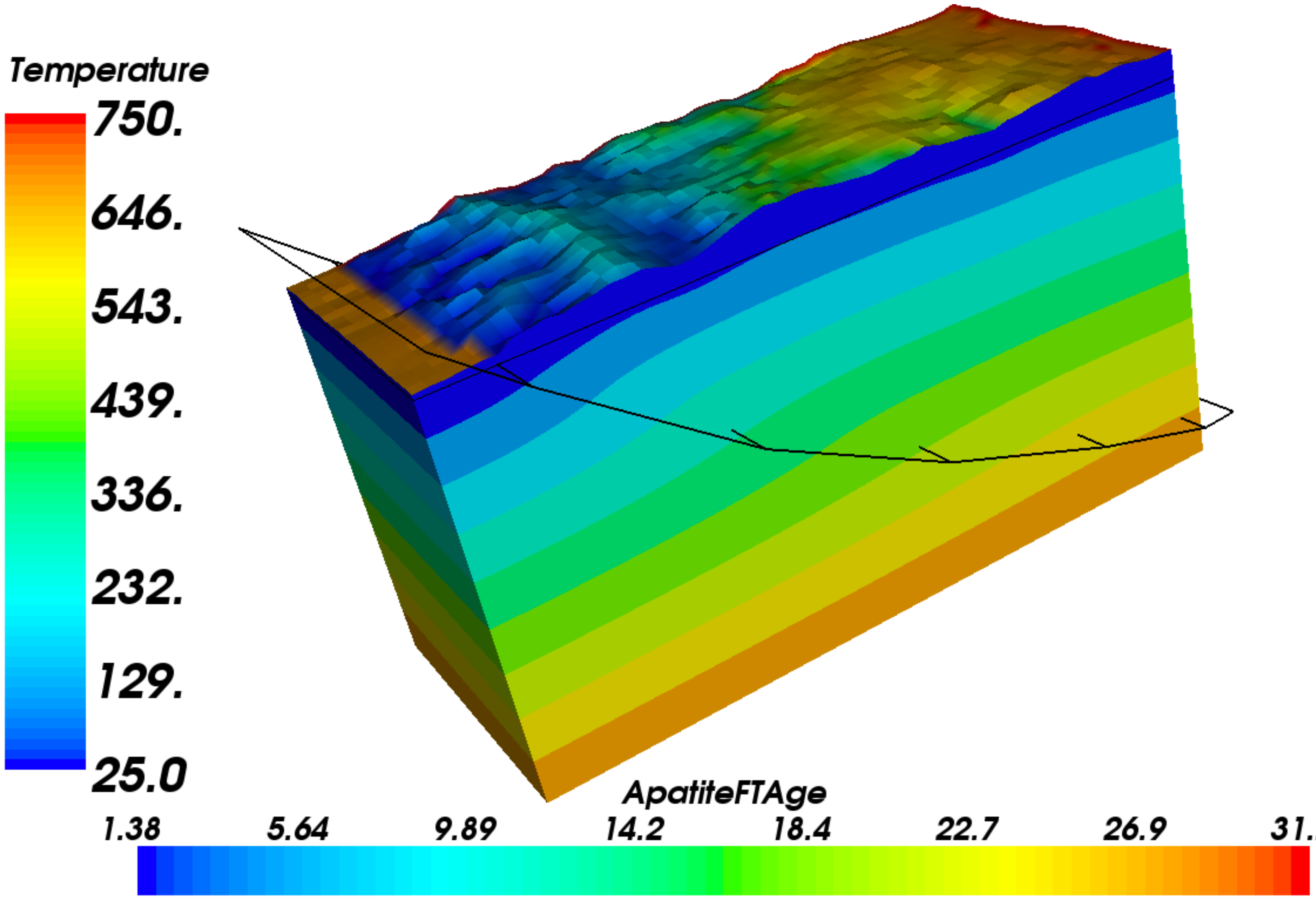
FROM AGES TO DEFORMATION HISTORIES



30 Ma, Onset of Model

FROM AGES TO DEFORMATION HISTORIES

Present (0Ma)



THERMOKINEMATIC MODELLING

- **SEISMIC: TIME TO DEPTH CONVERSION:**

  <u>PUNCTUAL DATA</u>: CHECK SHOT/VSP

  <u>3D DATA</u>: TOMOGRAPHY

- **thermochronology: TEMPERATURE TO DEPTH AND SHORTENING RATES.**

  <u>PUNCTUAL DATA</u>: thermochronoMETERS (AFT)

  <u>3D DATA</u>: THERMOKINEMATIC MODELLING

THERMOKINEMATIC MODELLING

What controls temperature through time?

Heat Equation (for two dimensions)

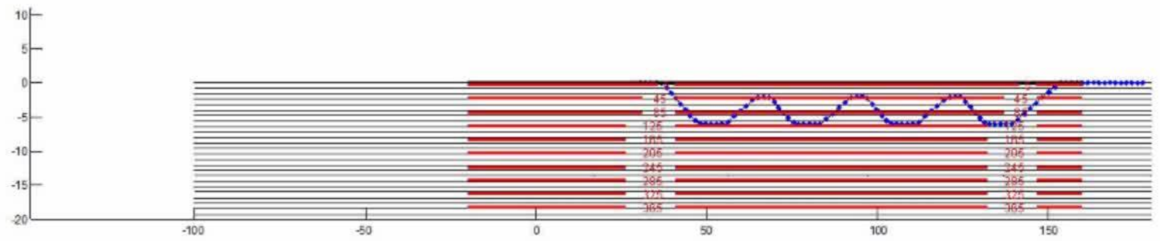
$$\rho c\left(\frac{\partial T}{\partial t} - v_x\frac{\partial T}{\partial x} - v_y\frac{\partial T}{\partial y}\right) = \frac{\partial}{\partial x}k_1\frac{\partial T}{\partial x} + \frac{\partial}{\partial y}k_2\frac{\partial T}{\partial y} + \rho H$$

Conduction
Advection
Production

ρ: density
c: heat capacity
κ: Thermal conductivity
v: velocity
H: Radiogenic heat production

UNKNOWN

Solving the equation allows transforming the depth into temperature in a cross section
(define boundary conditions)



FETKIN: Example

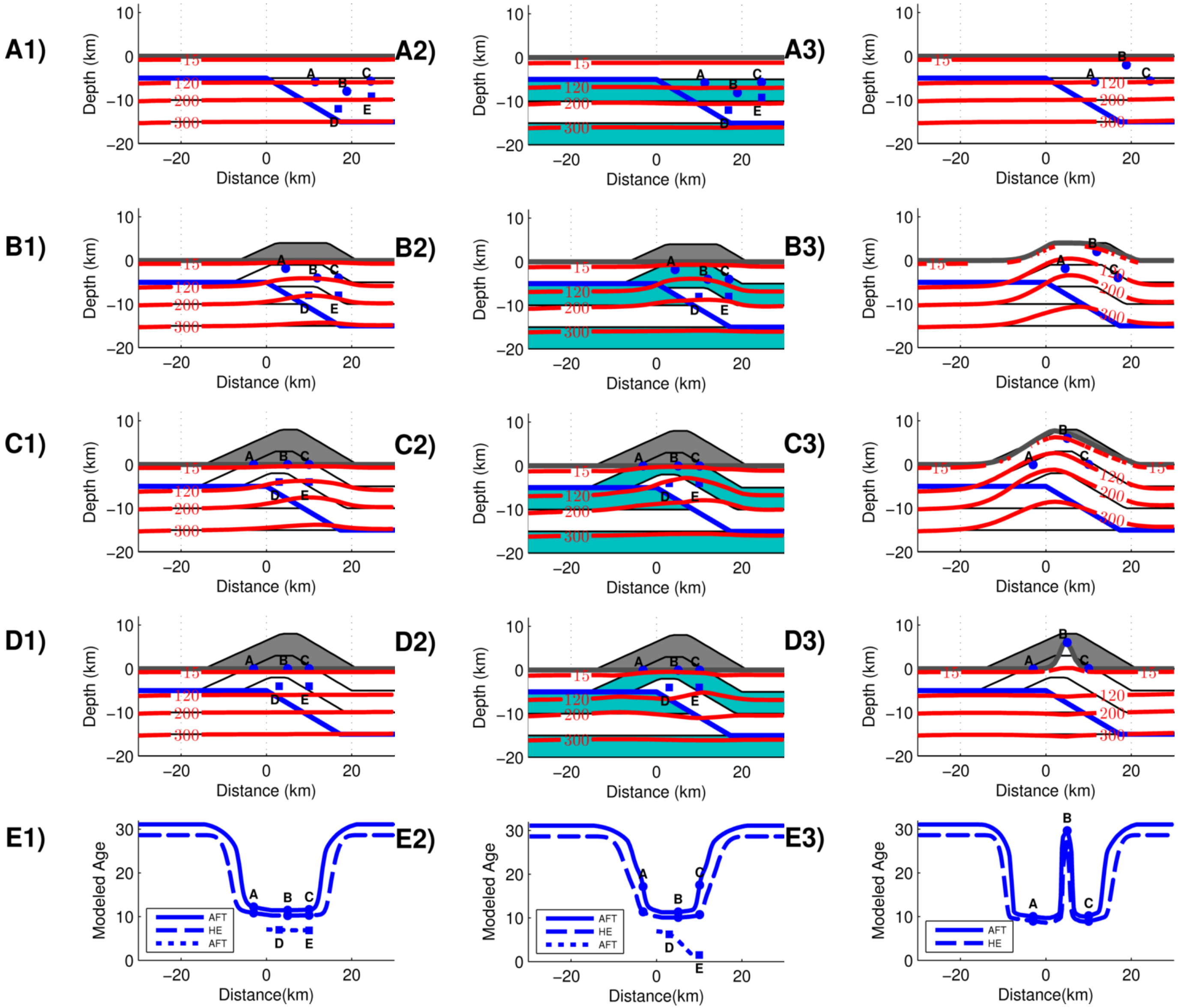
THERMOKINEMATIC MODELLING

12 Ma

11 Ma

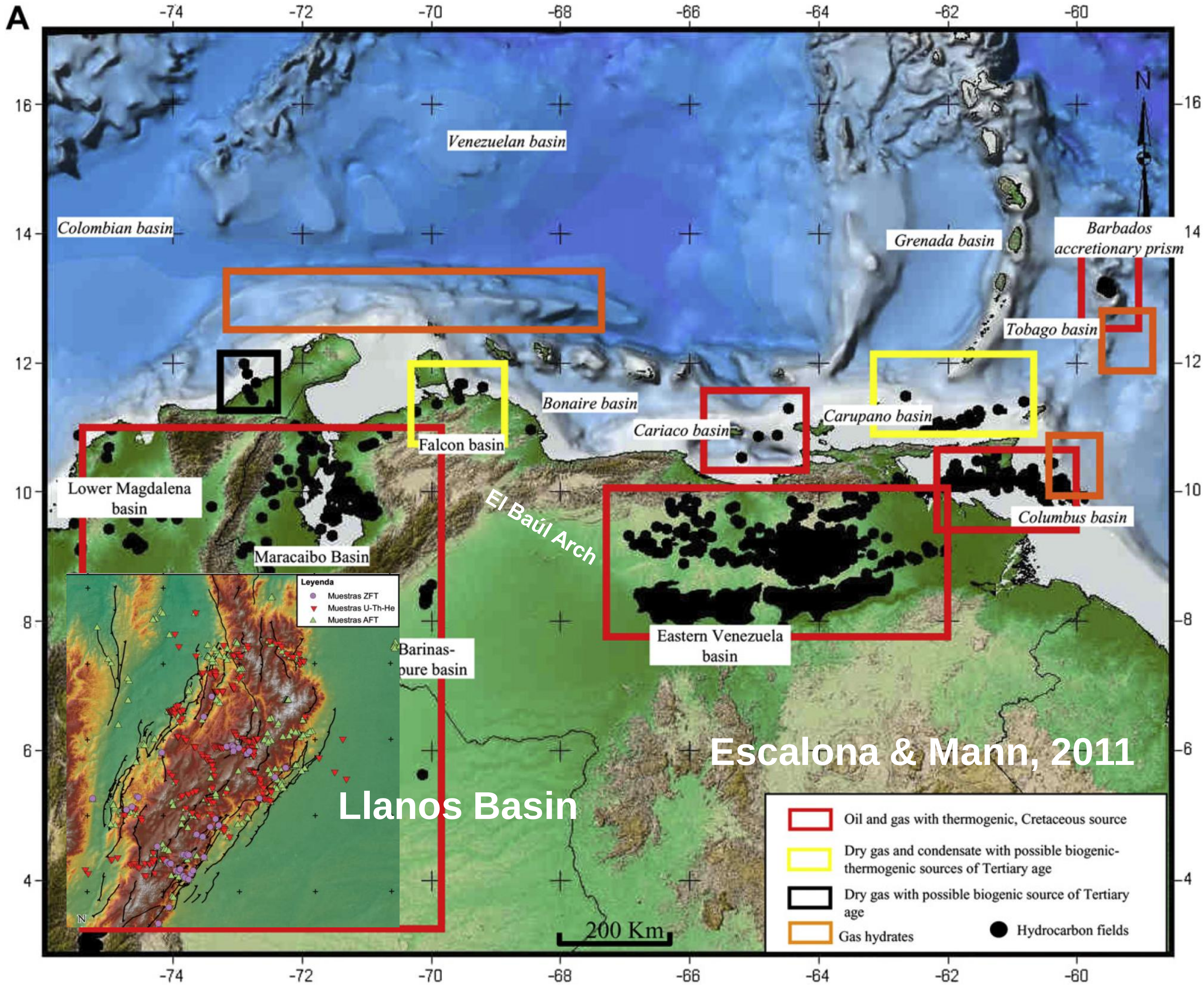
10 Ma

Present

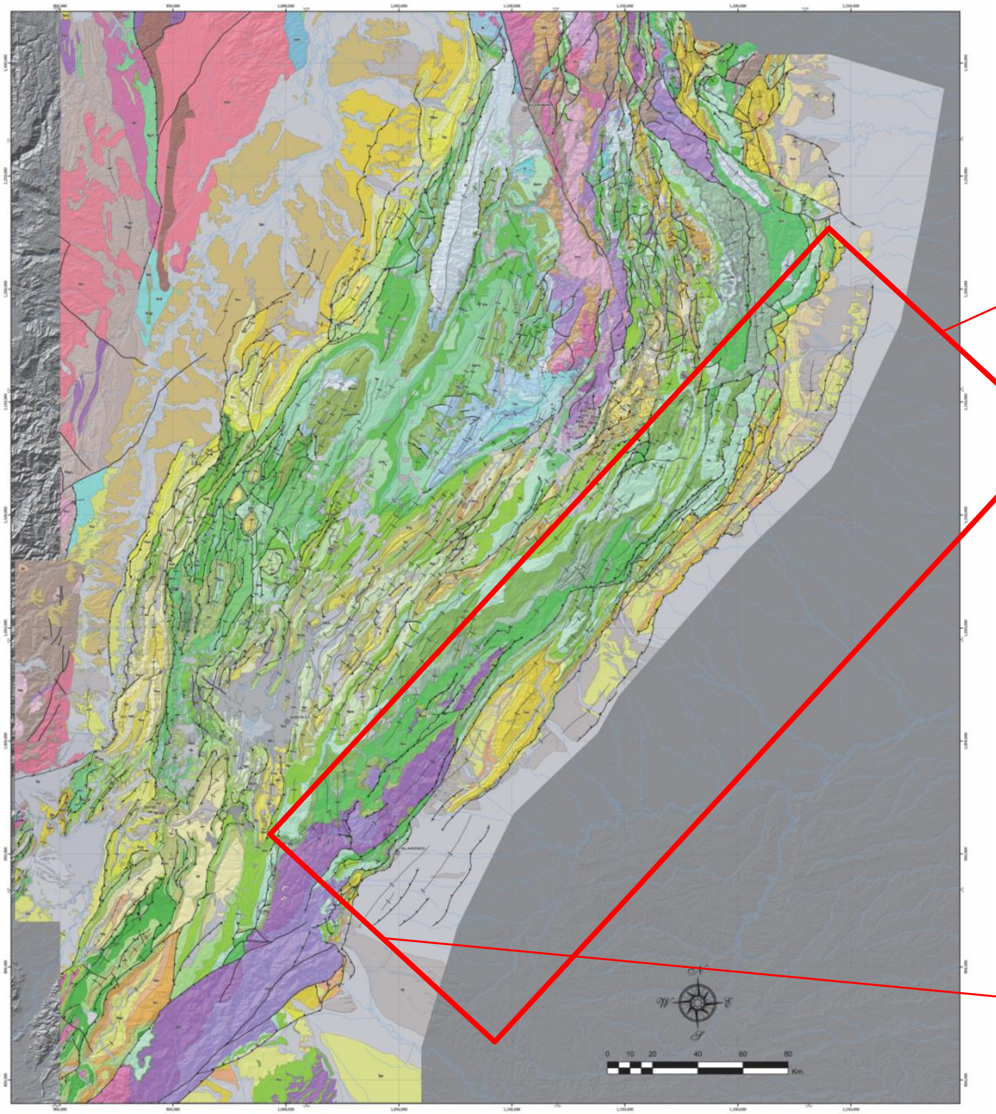


Almendral et al., in review

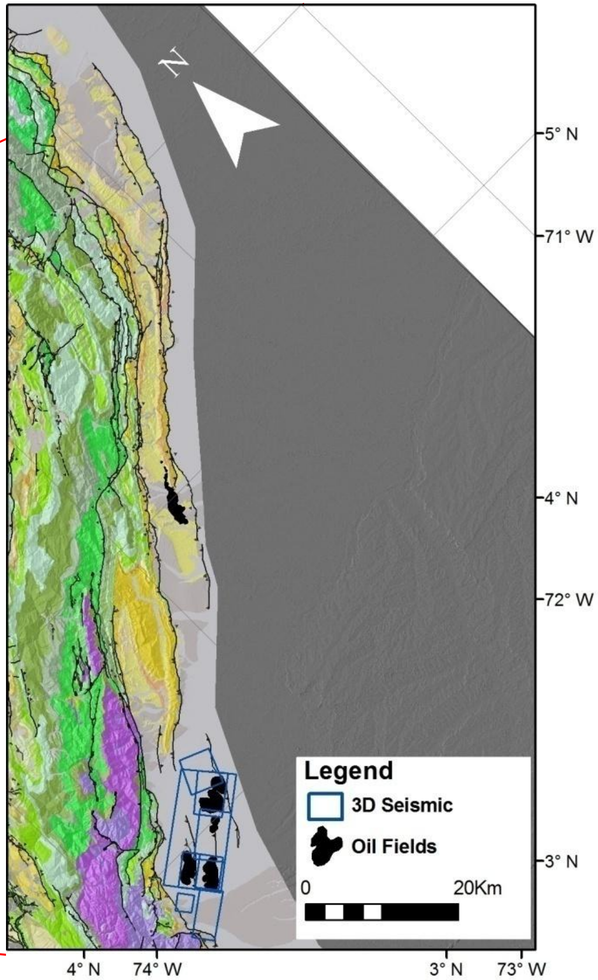
CASE STUDY: EASTERN CORDILLERA
No growth strata/ a lot of thermocron data



CASE STUDY



EASTERN CORDILLERA

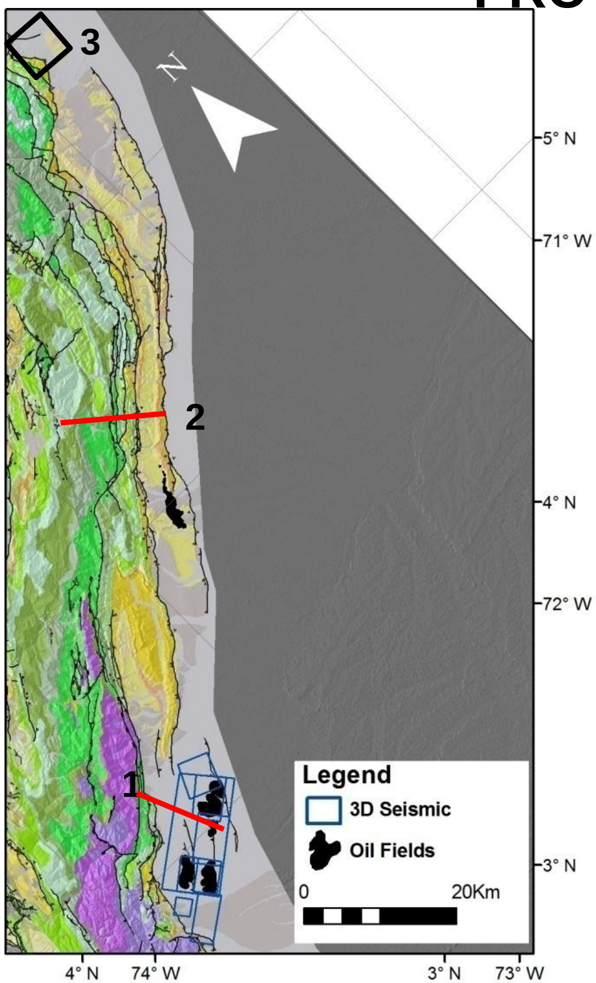


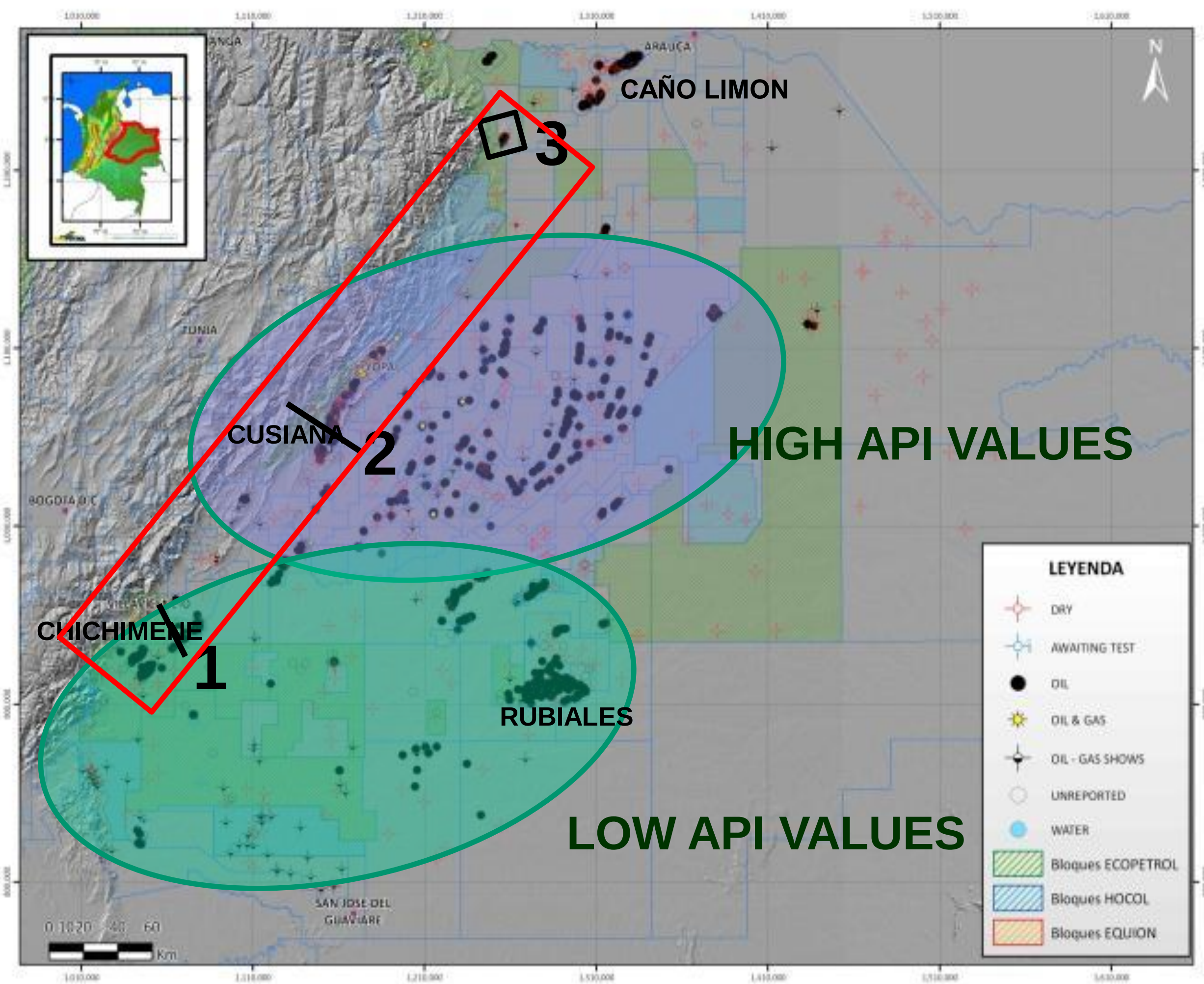
EASTERN FOOTHILLS

CASE STUDY

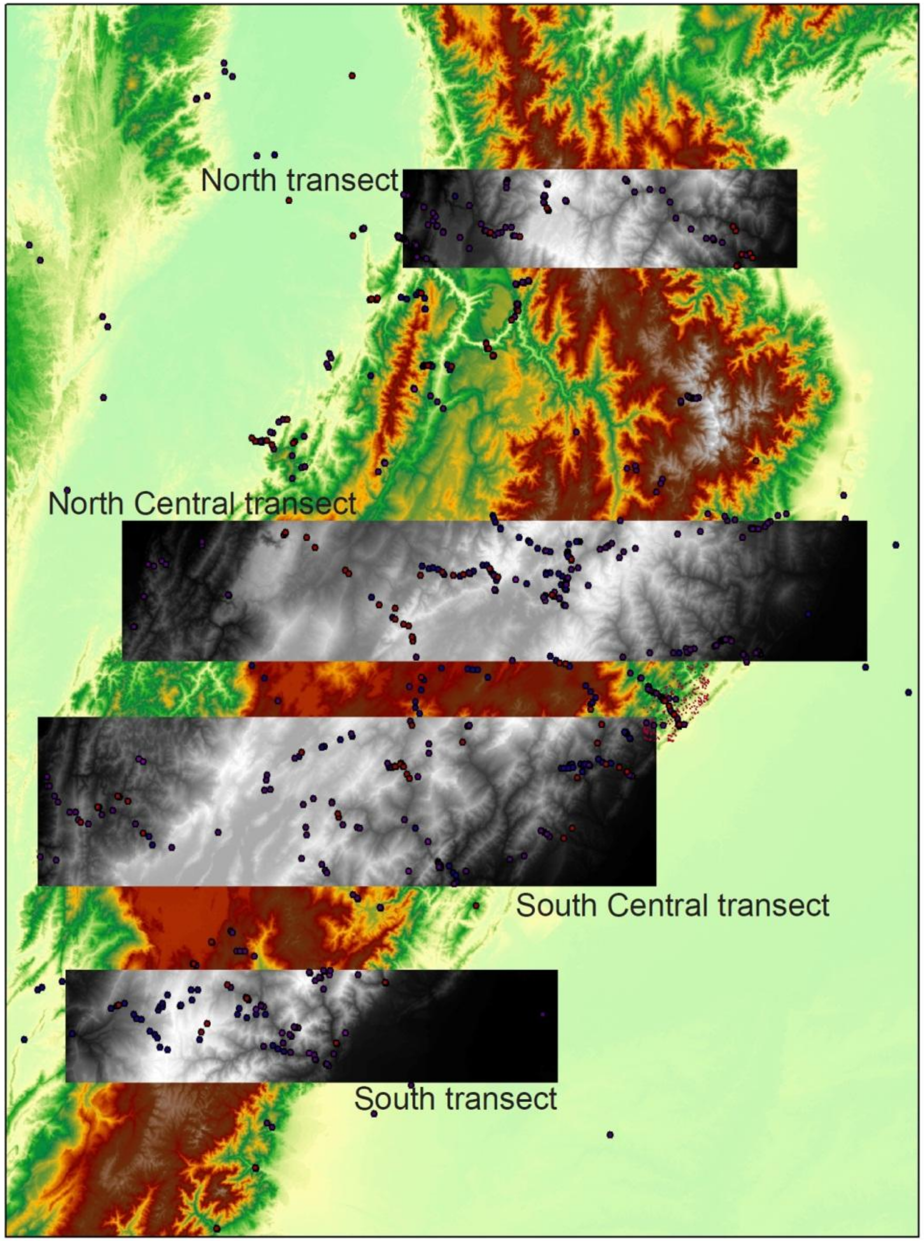
TIMING OF DEFORMATION AND HYDROCARBON PROVINCES

1. Chichimene
2. Cusiana
3. Tame

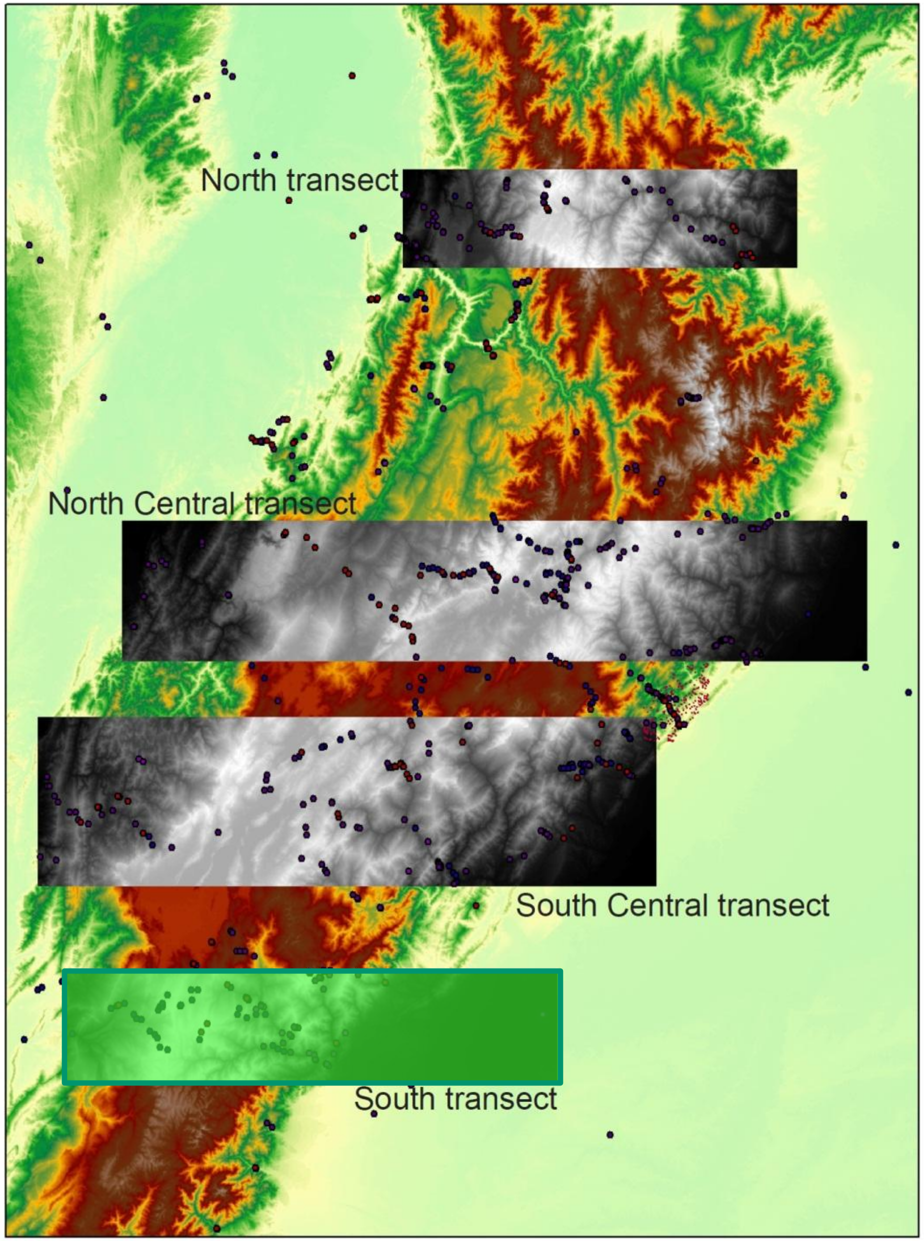




CASE STUDY: PECUBE (3D)

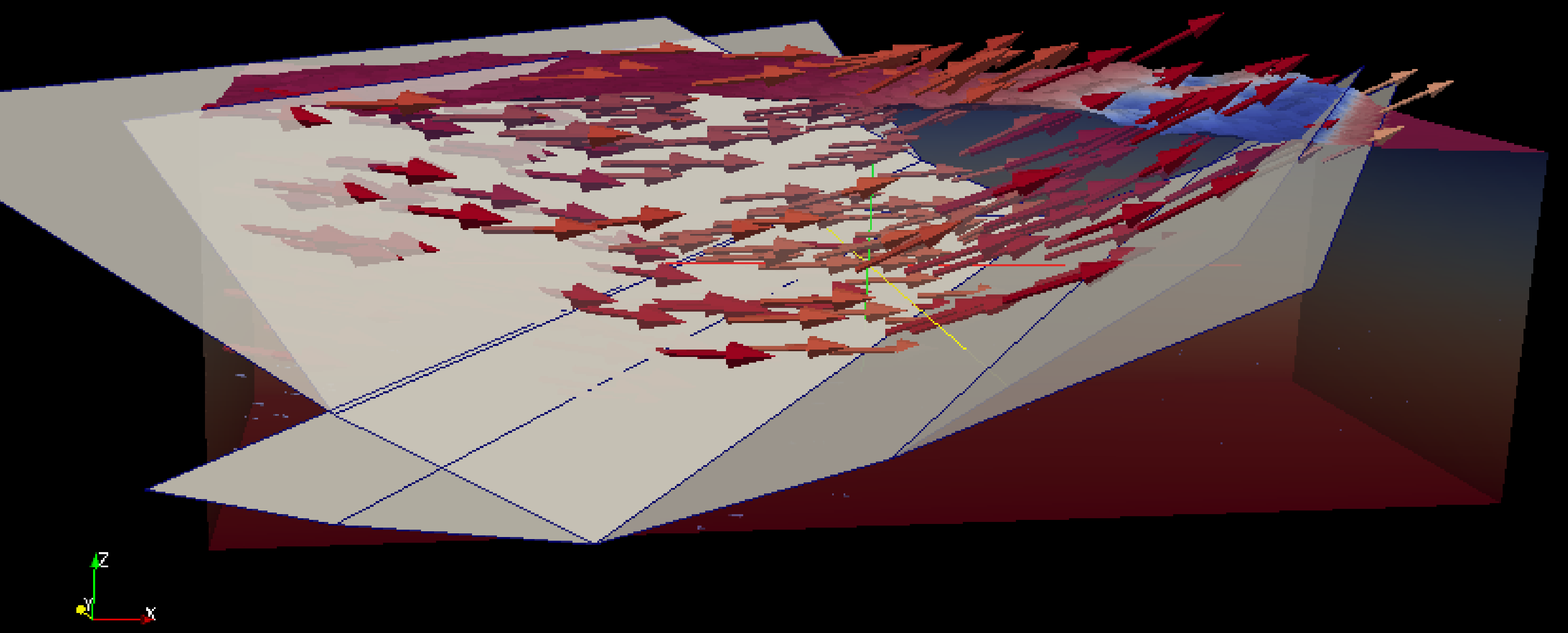


CASE STUDY: PECUBE (3D)



CASE STUDY: PECUBE (3D)
Cross section with velocities

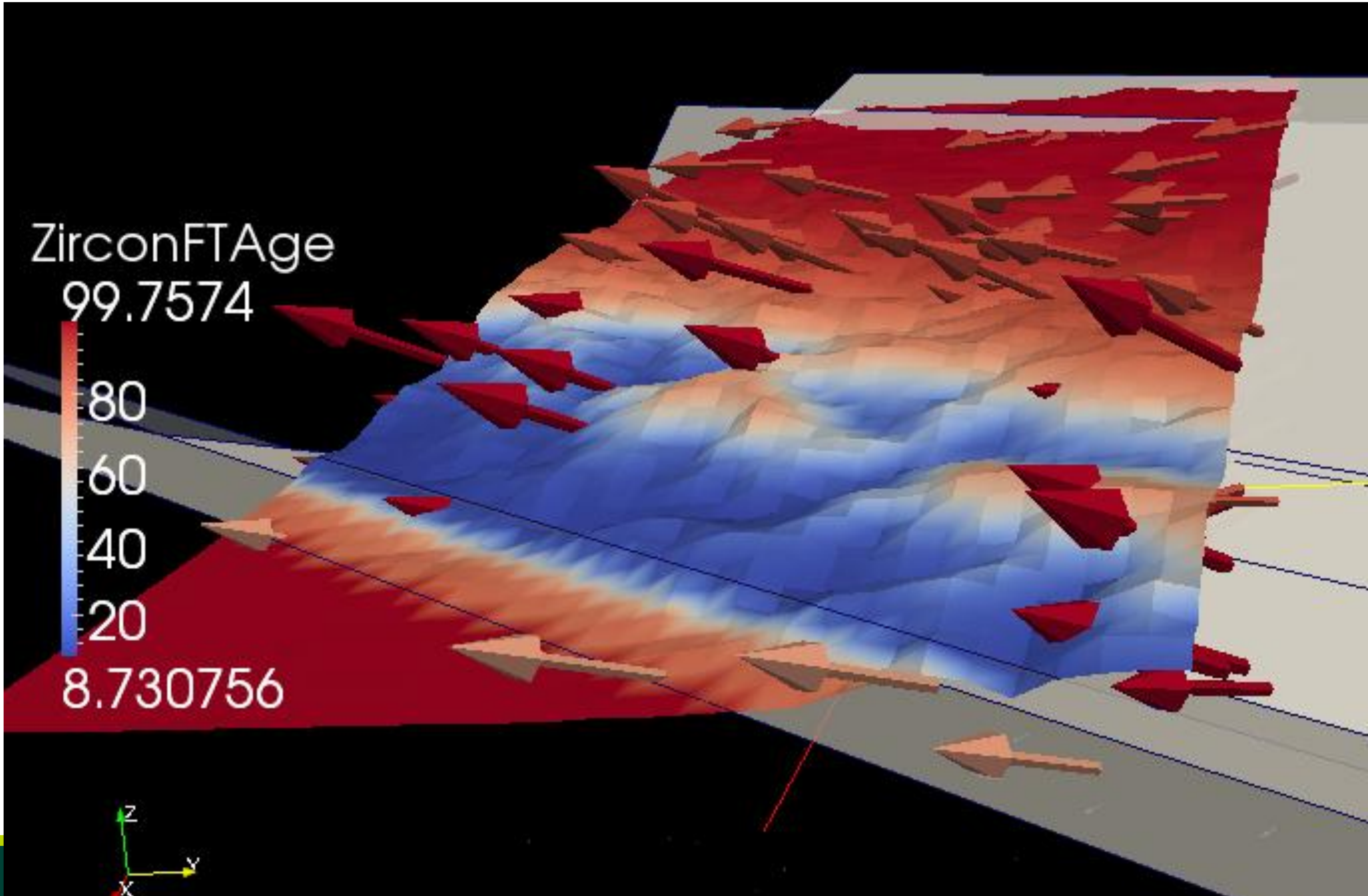
3D



CASE STUDY: PECUBE (3D)

Cooling ages on surface

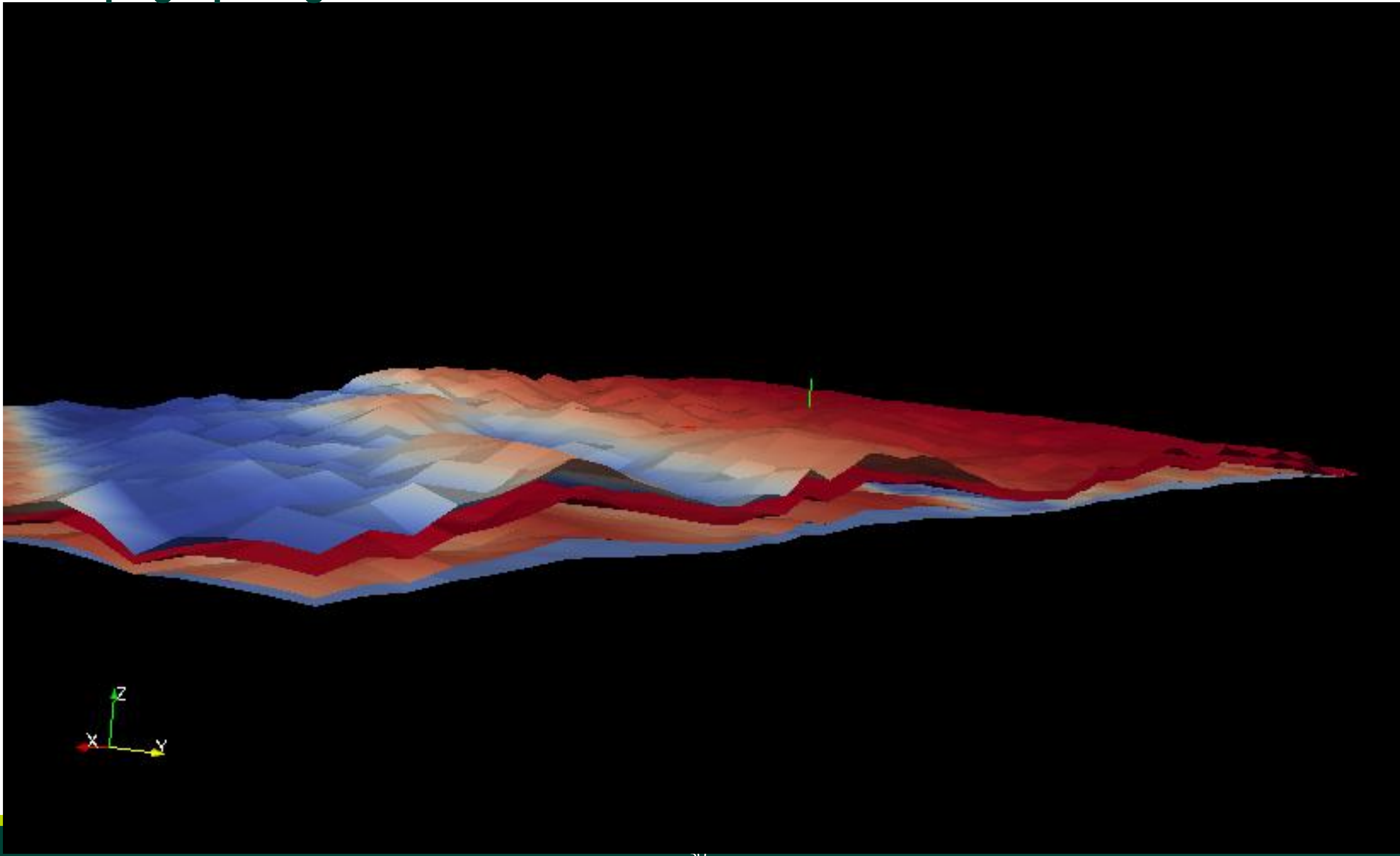
3D



CASE STUDY: PECUBE (3D)

3D

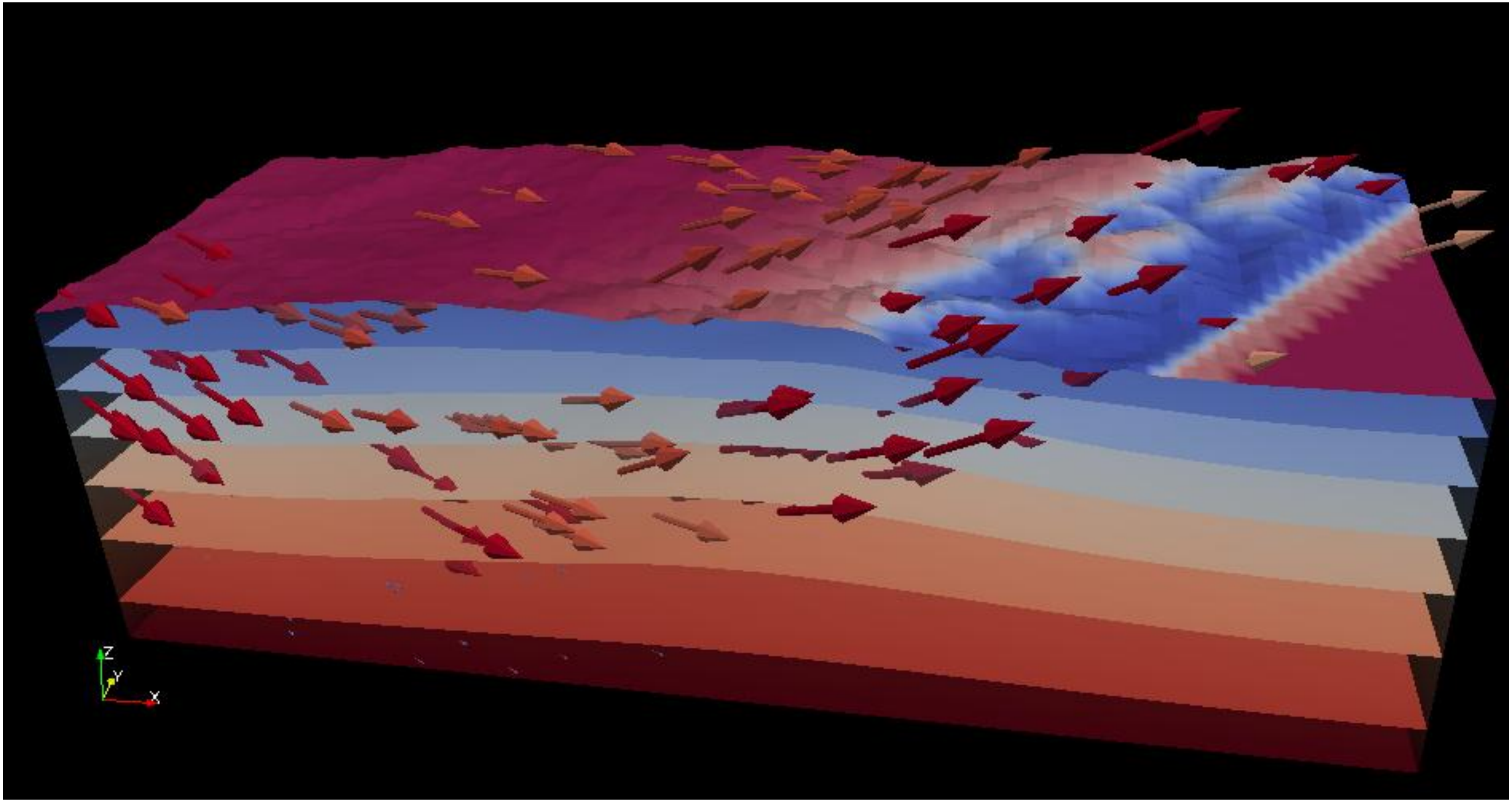
Topographic growth



CASE STUDY: PECUBE (3D)

3D

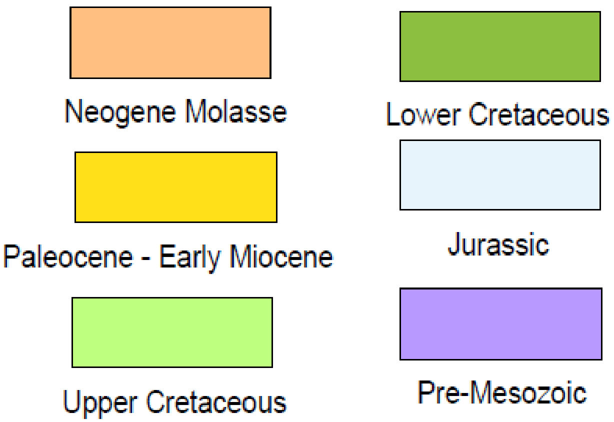
Isotherm advection



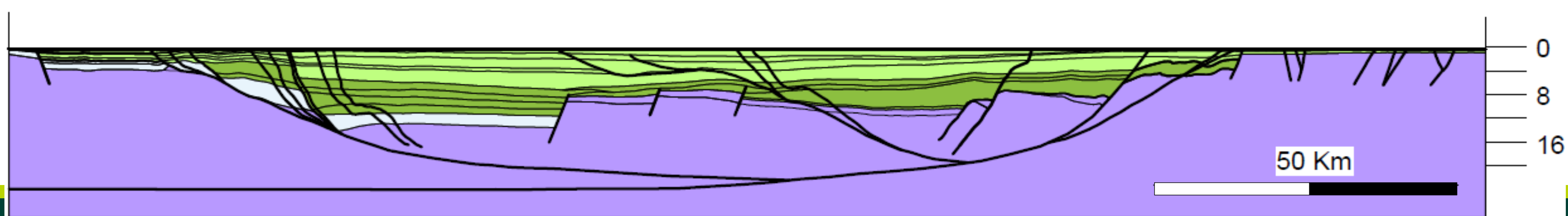
CASE STUDY

2D

1. 2D KINEMATIC RESTORATION: MANUAL APPROACH



Early Paleocene
(58 Ma)



CASE STUDY

2D

1. 2D KINEMATIC RESTORATION: MANUAL APPROACH

Neogene Molasse

Paleocene - Early Miocene

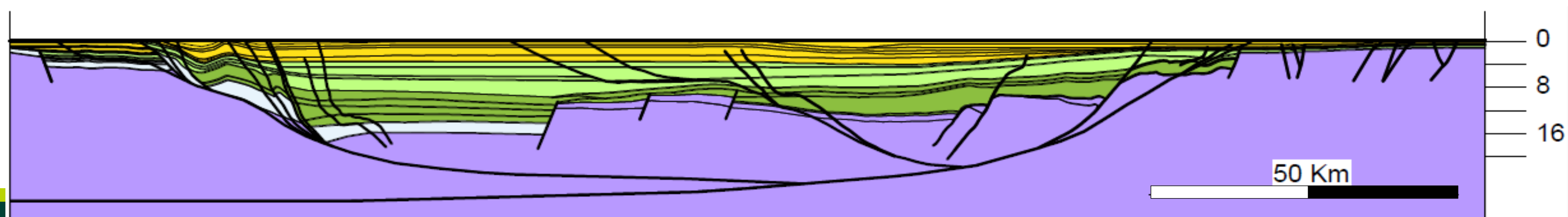
Upper Cretaceous

Lower Cretaceous

Jurassic

Pre-Mesozoic

Early Oligocene
(27 Ma)



CASE STUDY

2D

1. 2D KINEMATIC RESTORATION: MANUAL APPROACH

Neogene Molasse

Lower Cretaceous

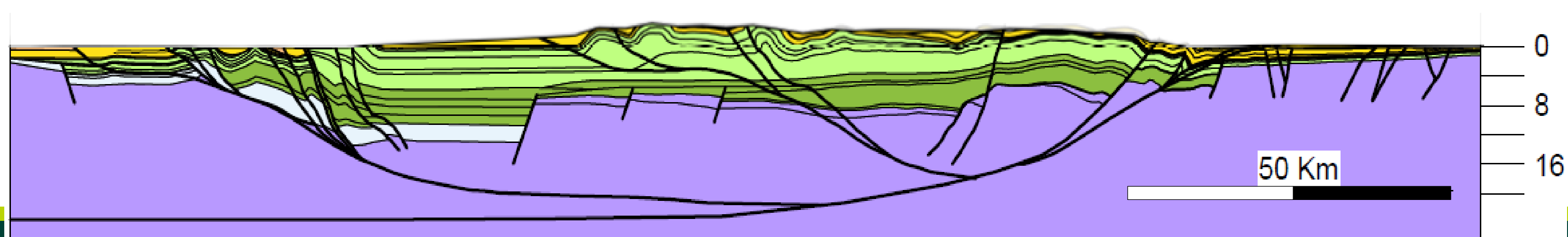
Paleocene - Early Miocene

Jurassic

Upper Cretaceous

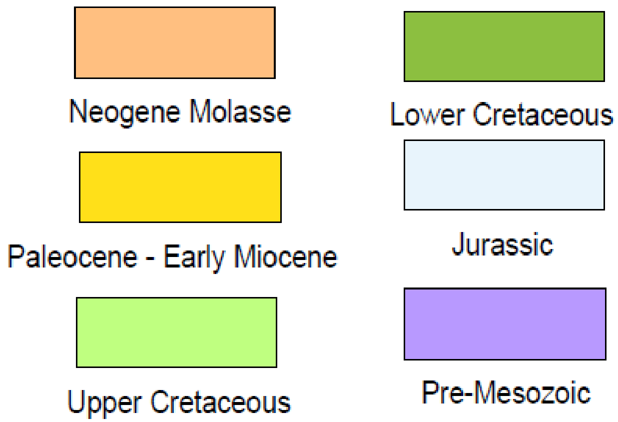
Pre-Mesozoic

Early Miocene
(20 Ma)

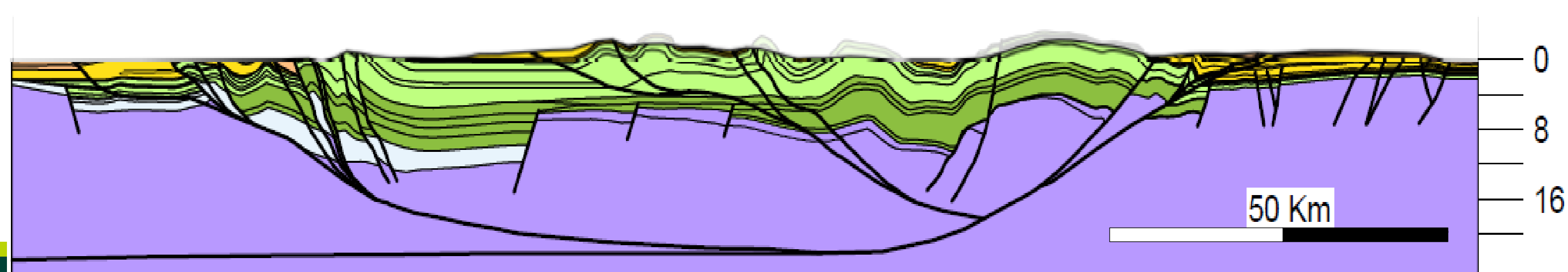


2D

1. 2D KINEMATIC RESTORATION: MANUAL APPROACH



Middle Miocene
(9 Ma)



CASE STUDY

2D

1. 2D KINEMATIC RESTORATION: MANUAL APPROACH

Neogene Molasse

Lower Cretaceous

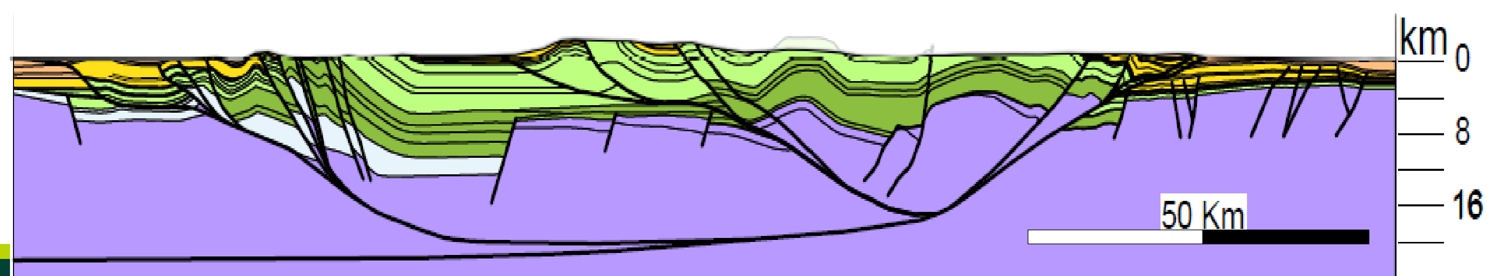
Paleocene - Early Miocene

Jurassic

Upper Cretaceous

Pre-Mesozoic

Late Miocene
(5Ma)



CASE STUDY

2D ECOPETROL

1. 2D KINEMATIC RESTORATION: MANUAL APPROACH

Neogene Molasse

Lower Cretaceous

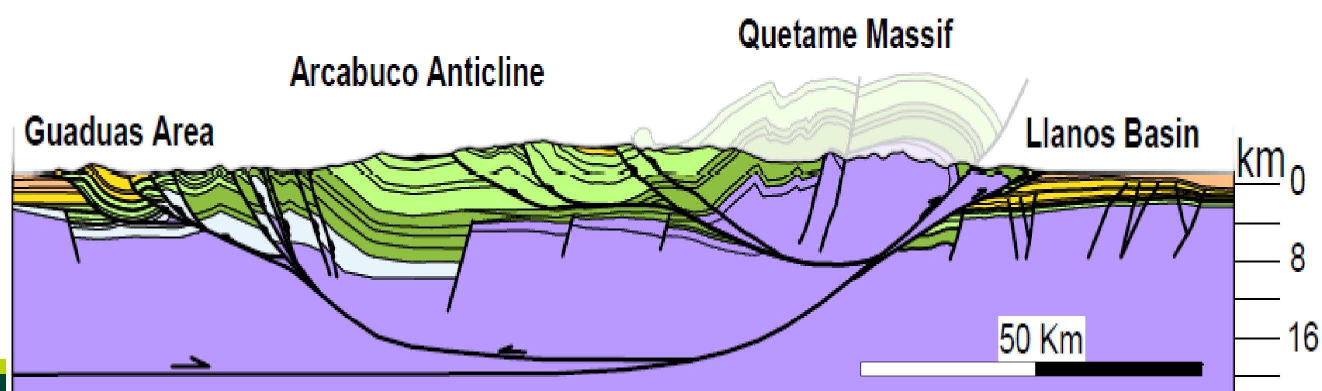
Paleocene - Early Miocene

Jurassic

Upper Cretaceous

Pre-Mesozoic

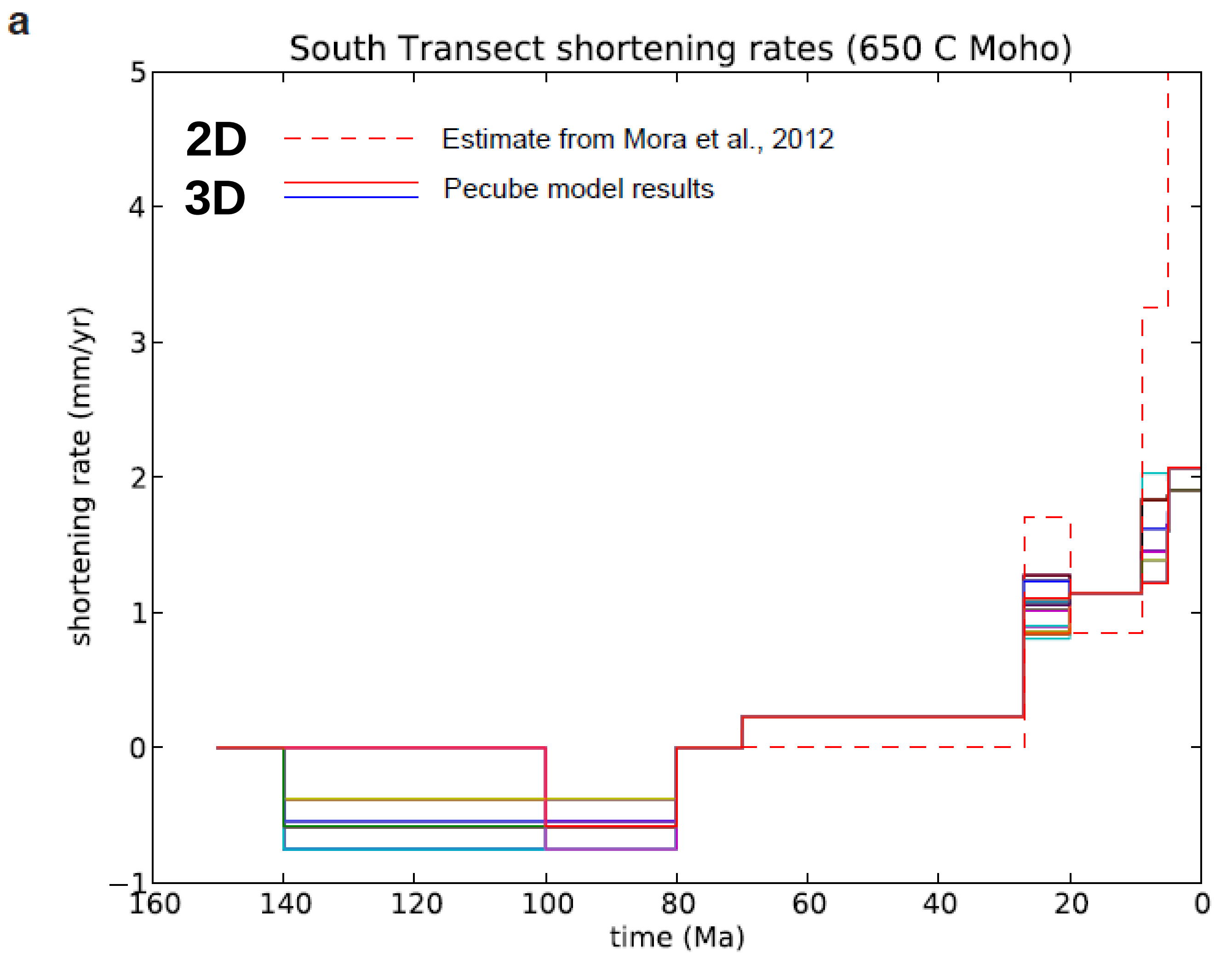
Present
(0 Ma)



CASE STUDY

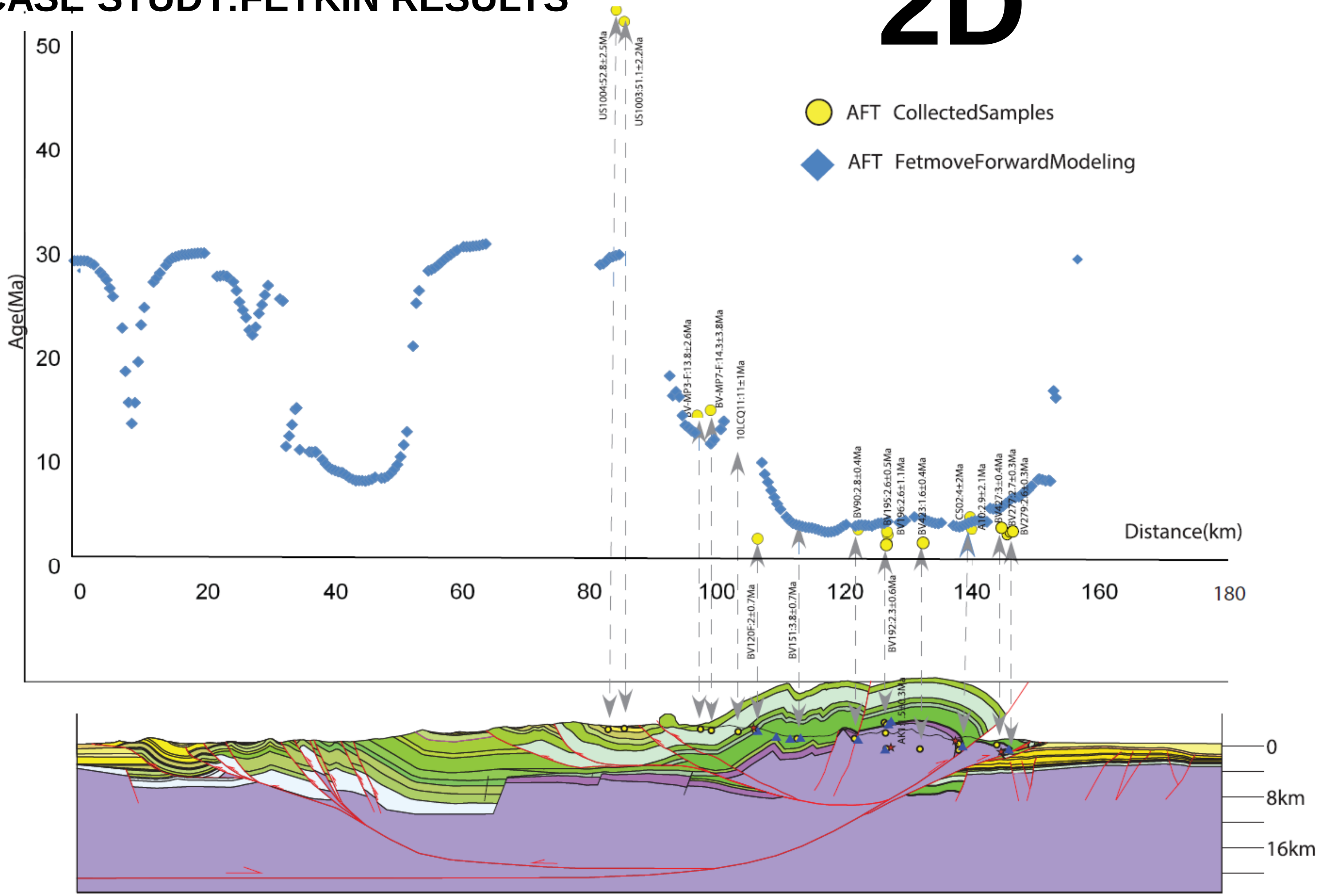
CALLIBRATION OF 2D&3D

COMPARING SHORTENING RATES



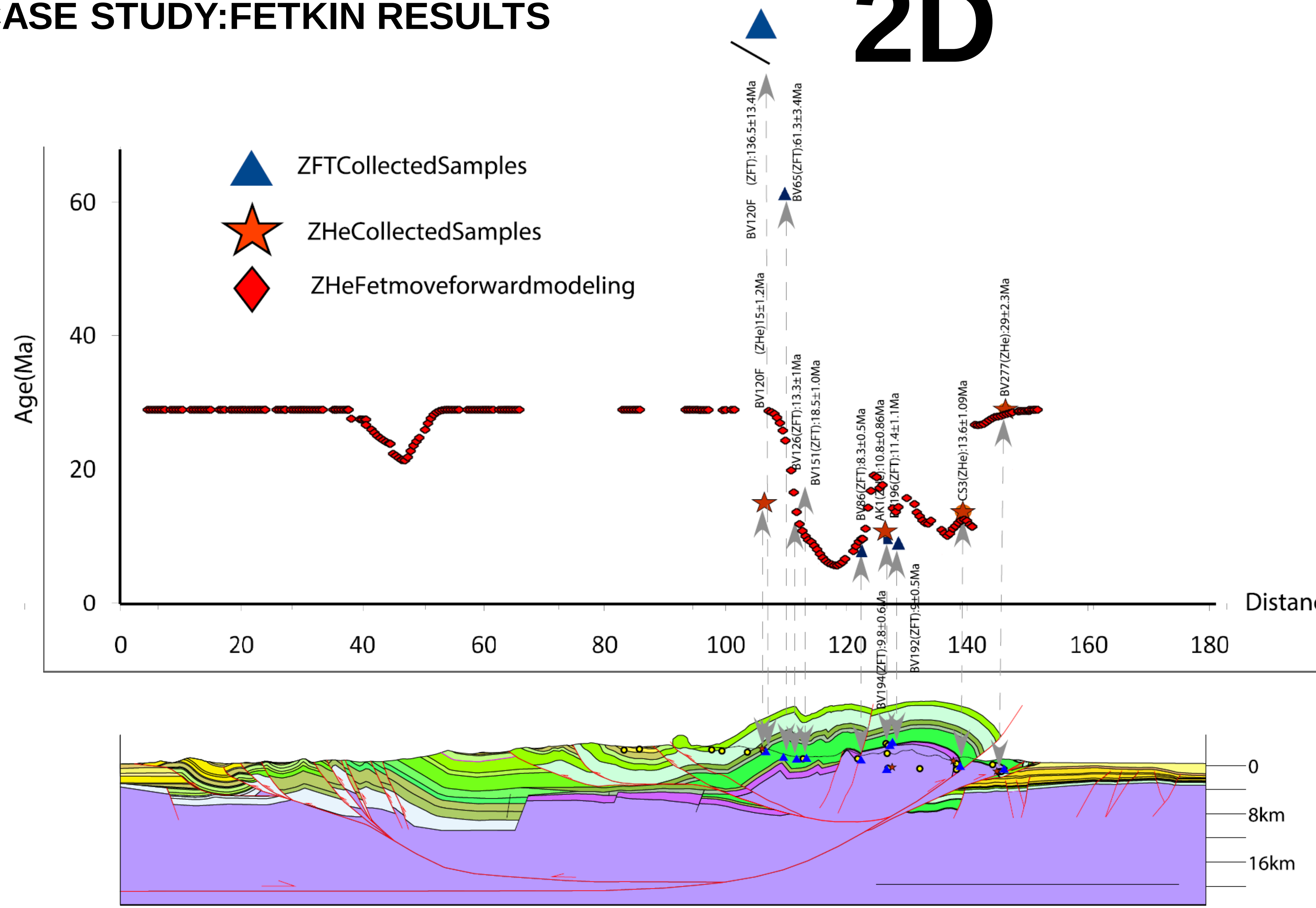
CASE STUDY:FETKIN RESULTS

2D



CASE STUDY:FETKIN RESULTS

2D



CASE STUDY:FETKIN RESULTS

2D

Lower Cretaceous source rocks in the oil window

Early Paleocene
(58 Ma)

50Km

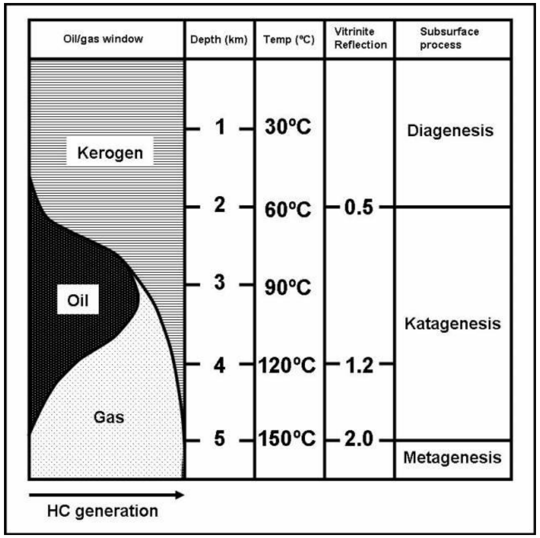
Samples

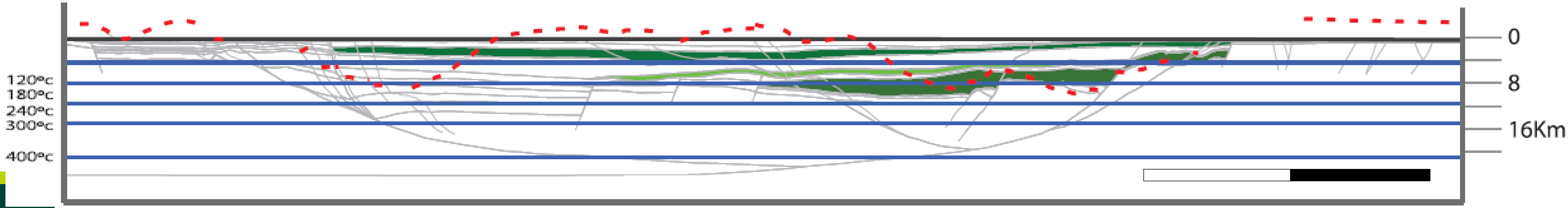
Isotherms

Chipaque Fm. (Upper Cretaceous Source Rock)

Fomeque Fm. (Lower Cretaceous Source Rock 1)

Macanal Fm. (Lower Cretaceous Source Rock 2)





CASE STUDY:FETKIN RESULTS

2D

Lower Cretaceous source rocks in the gas window. Upper Cretaceous in the oil window

Early Oligocene
(27 Ma)

50Km

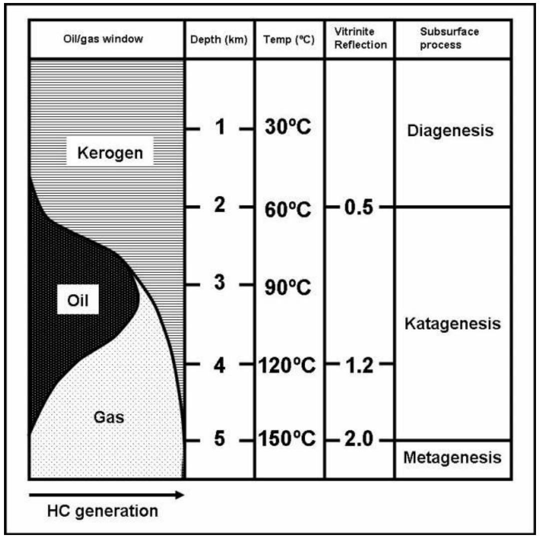
Samples

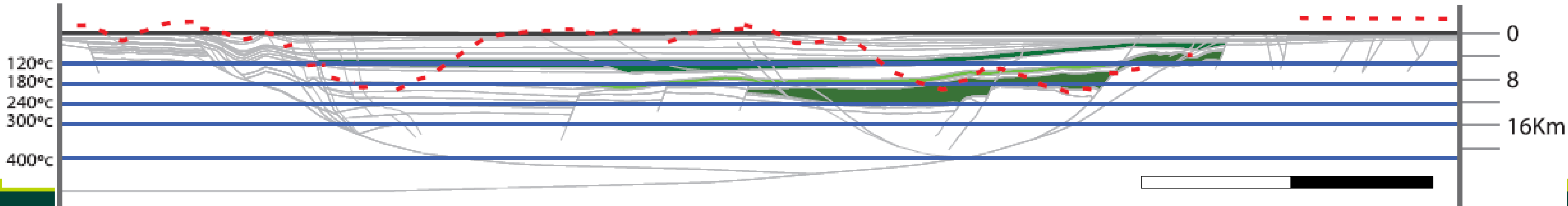
Isotherms

Chipaque Fm. (Upper Cretaceous Source Rock)

Fomeque Fm. (Lower Cretaceous Source Rock 1)

Macanal Fm. (Lower Cretaceous Source Rock 2)





CASE STUDY:FETKIN RESULTS

2D

Isotherm advection is not significant

50Km

Samples

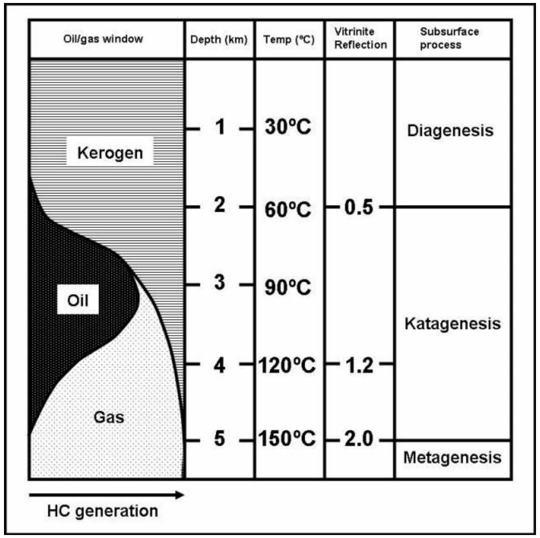
Isotherms

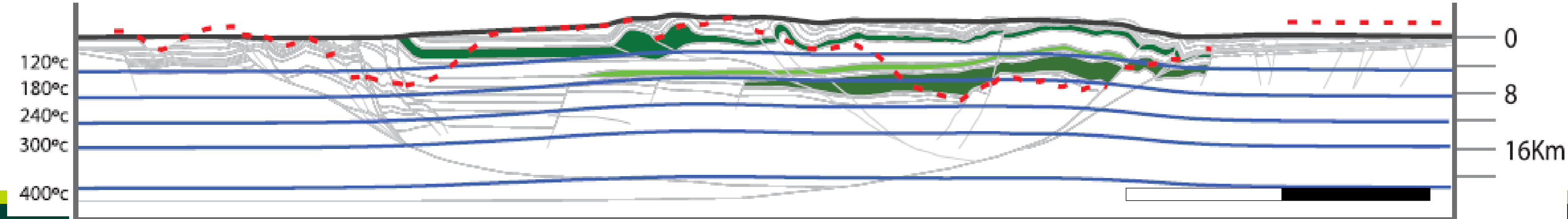
Chipaque Fm. (Upper Cretaceous Source Rock)

Fomeque Fm. (Lower Cretaceous Source Rock 1)

Macanal Fm. (Lower Cretaceous Source Rock 2)

Early Miocene
(20 Ma)





CASE STUDY:FETKIN RESULTS

Isotherm advection is not significant

50Km

Samples

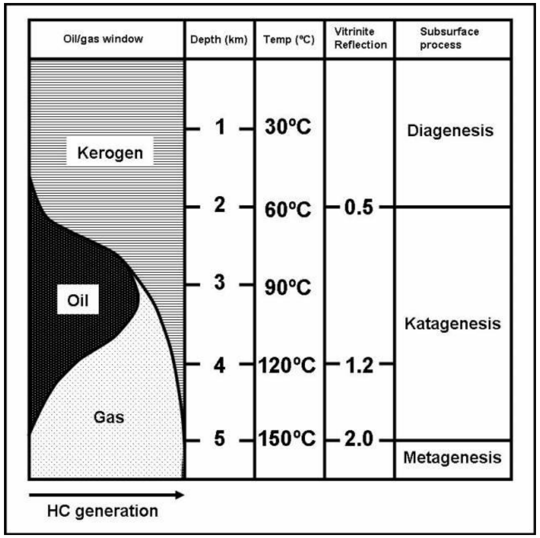
Isotherms

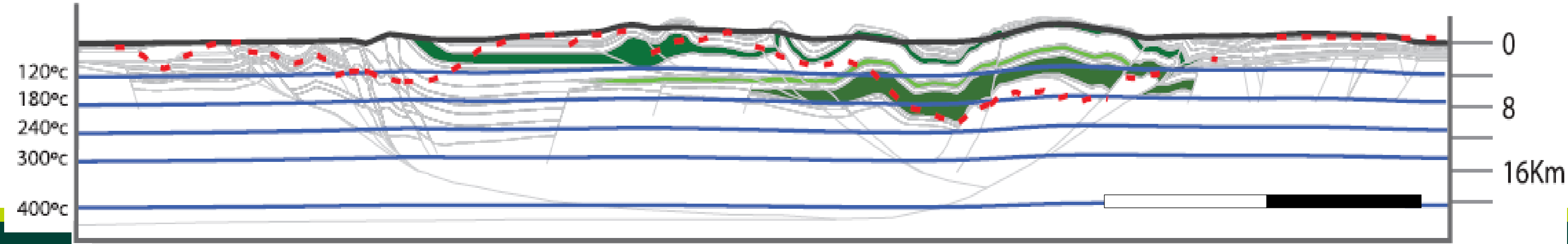
Chipaque Fm. (Upper Cretaceous Source Rock)

Fomeque Fm. (Lower Cretaceous Source Rock 1)

Macanal Fm. (Lower Cretaceous Source Rock 2)

Middle Miocene
(9 Ma)





CASE STUDY:FETKIN RESULTS

2D

Isotherm advection is not significant

50Km

Samples

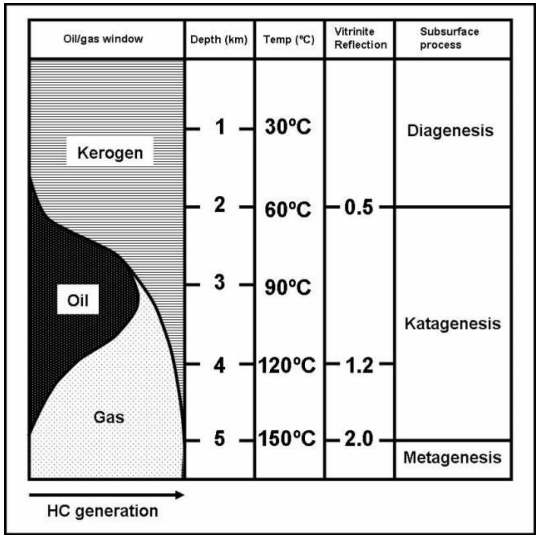
Isotherms

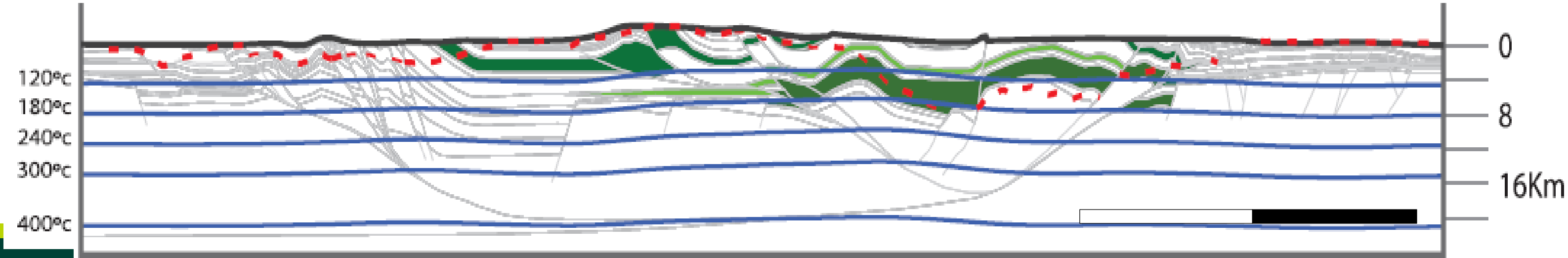
Chipaque Fm. (Upper Cretaceous Source Rock)

Fomeque Fm. (Lower Cretaceous Source Rock 1)

Macanal Fm. (Lower Cretaceous Source Rock 2)

Late Miocene
(5Ma)





CASE STUDY:FETKIN RESULTS

2D

The most important isotherm advection favors oil generation in the foothill areas

Present
(0 Ma)

50Km

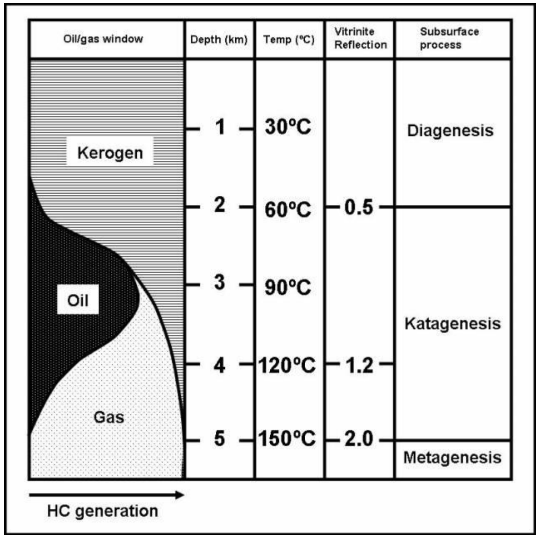
Samples

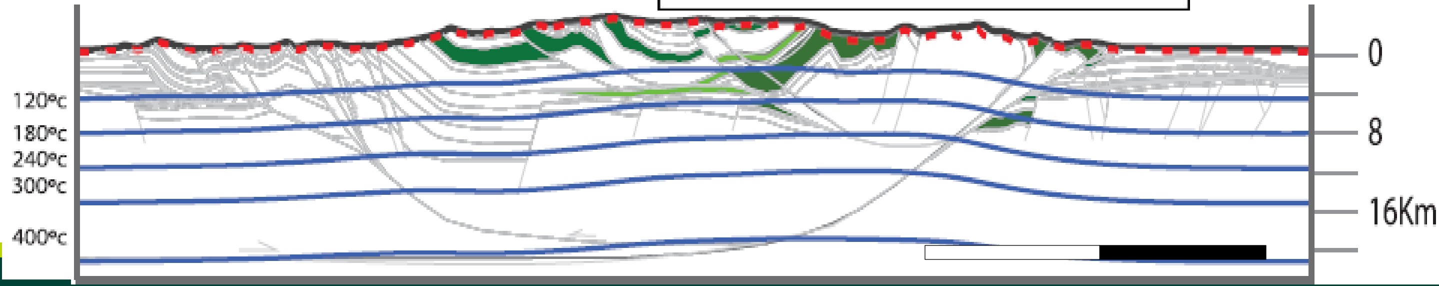
Isotherms

Chipaque Fm. (Upper Cretaceous Source Rock)

Fomeque Fm. (Lower Cretaceous Source Rock 1)

Macanal Fm. (Lower Cretaceous Source Rock 2)





CASE STUDY:FETKIN RESULTS

2D

The most important isotherm advection favors oil generation in the foothill areas

Present
(0 Ma)

50Km

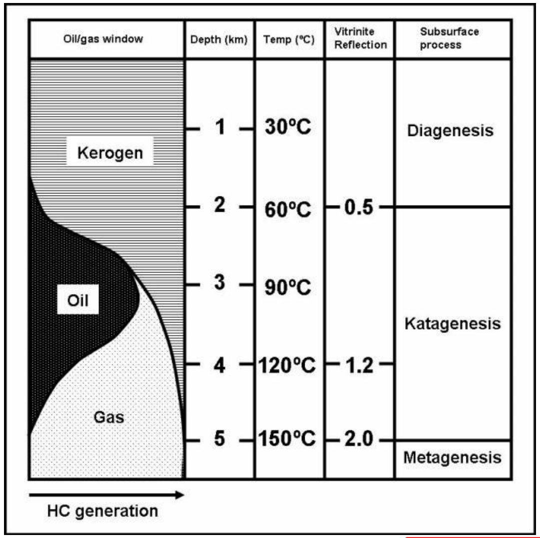
Samples

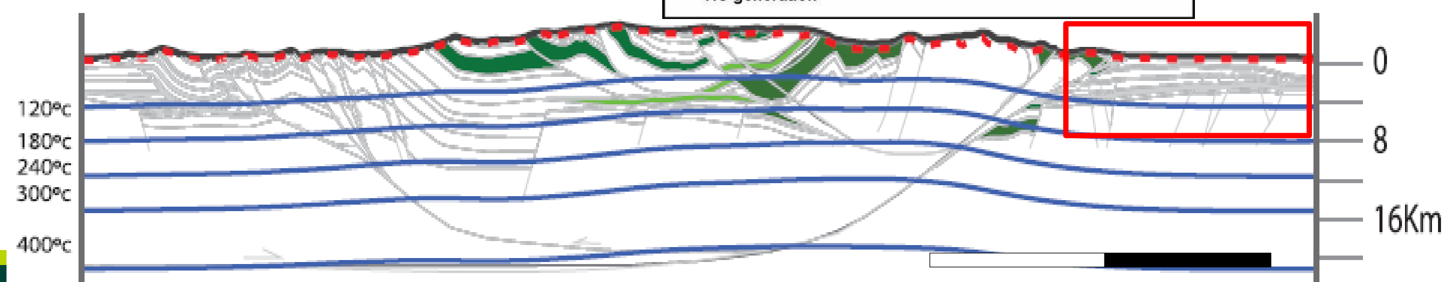
Isotherms

Chipaque Fm. (Upper Cretaceous Source Rock)

Fomeque Fm. (Lower Cretaceous Source Rock 1)

Macanal Fm. (Lower Cretaceous Source Rock 2)





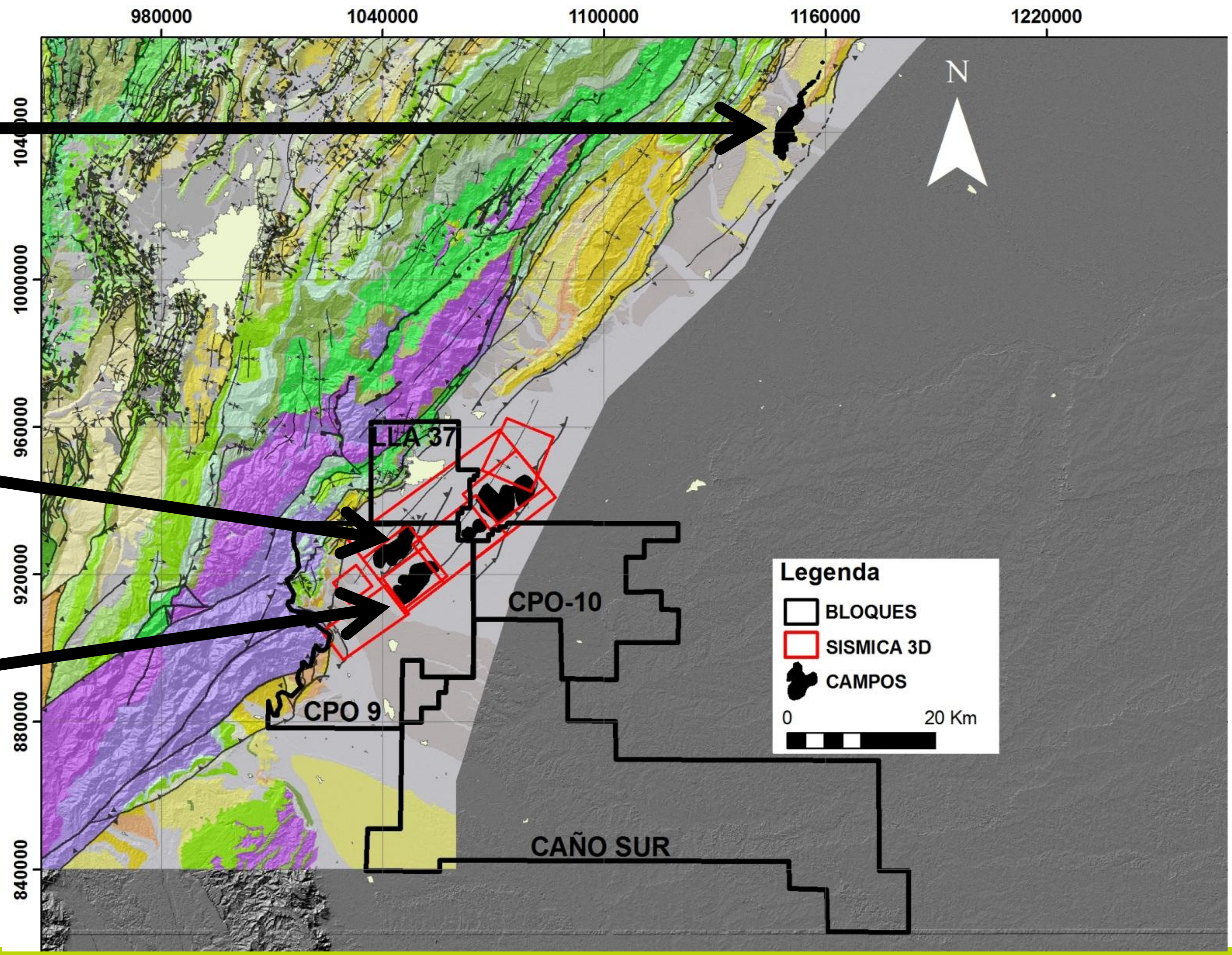
CASE STUDY

COMPARISON WITH THE AGE OF THE TRAPS

PIEDEMONTE
CUPIAGUA
CUSIANA
Mostly > 25° API

CHICHIMENE:
5000 MBO-OOIP
170000 BOD
< 15° API

CASTILLA:
5000 MBO-OOIP
100000 BOD
<15° API

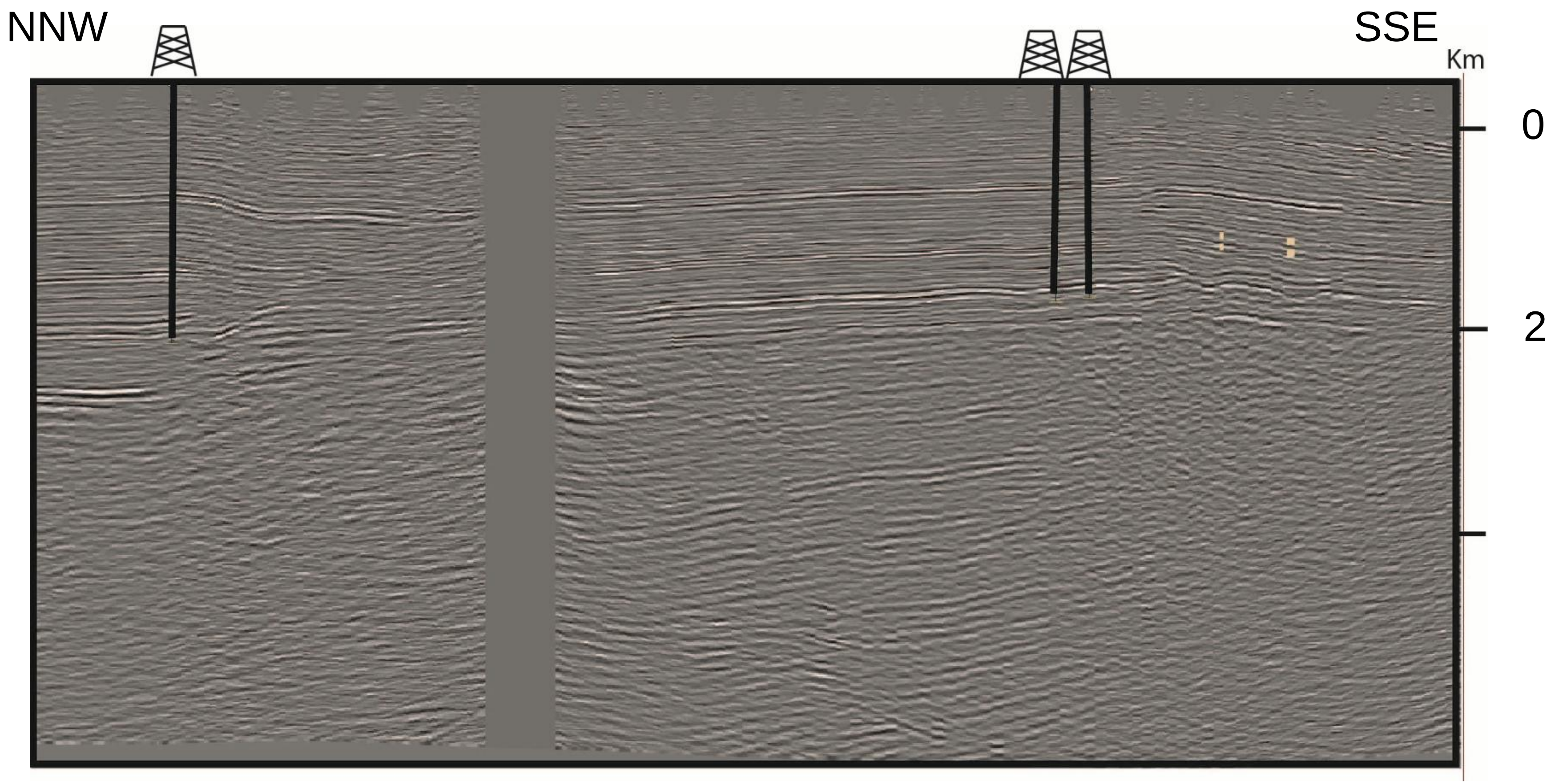


48

CASE STUDY

COMPARISON WITH THE AGE OF THE TRAPS

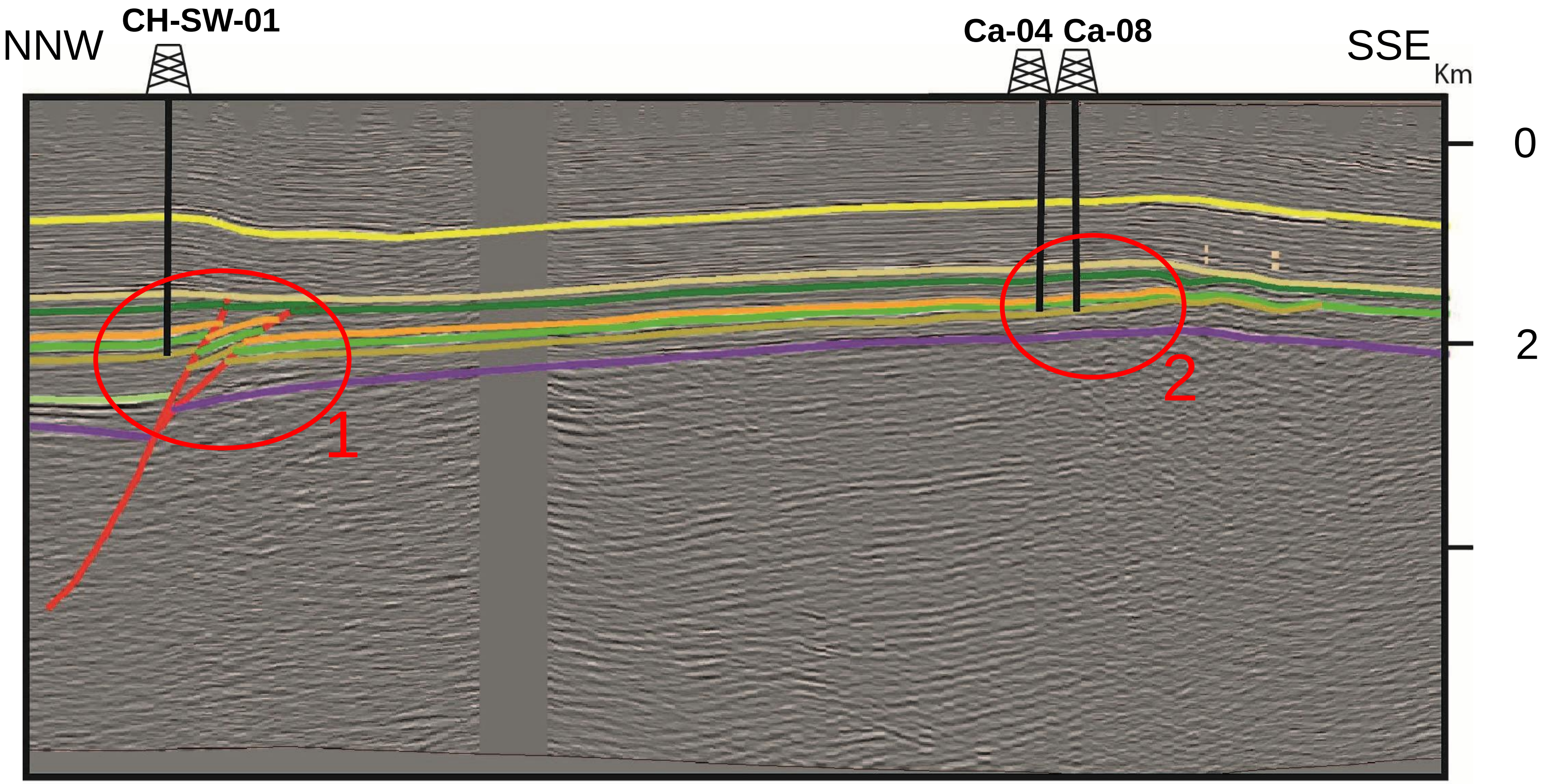
Chichimene and Castilla: Heavy Oil (Low API values <15)



CASE STUDY

COMPARISON WITH THE AGE OF THE TRAPS

Chichimene and Castilla: Heavy Oil (Low API values <15)

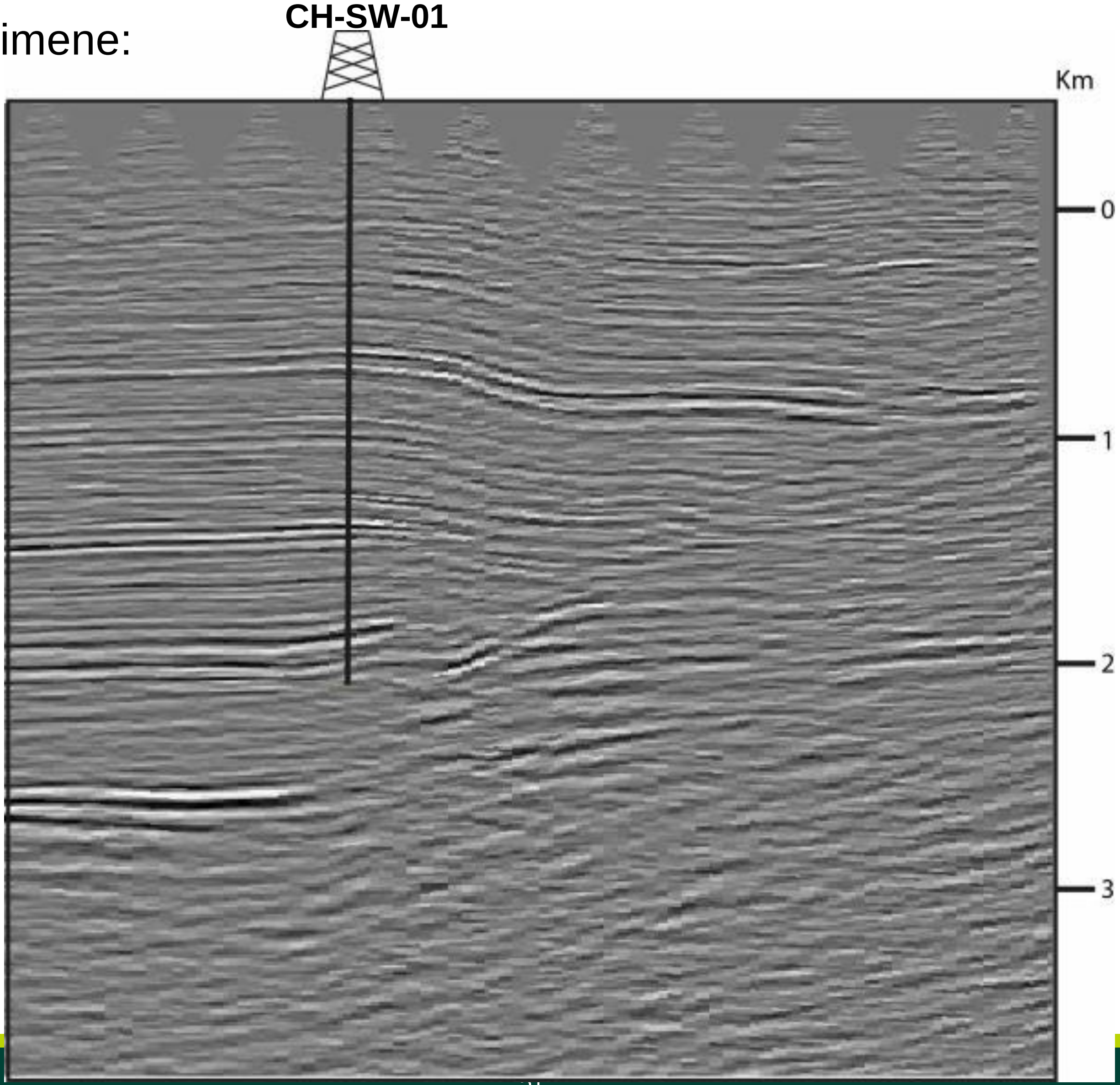


CASE STUDY

COMPARISON WITH THE AGE OF THE TRAPS

1. Chichimene:

1

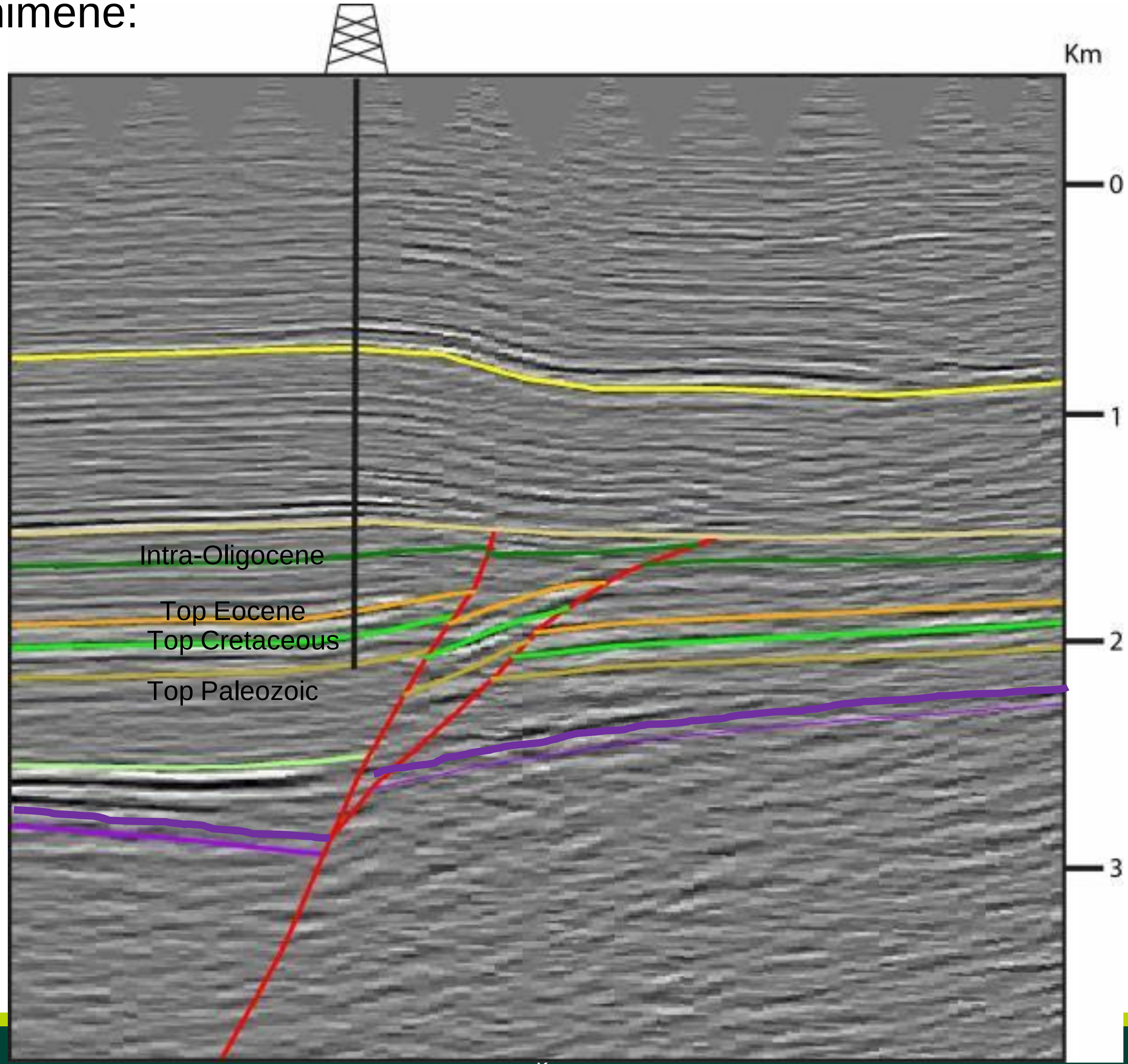


CASE STUDY

COMPARISON WITH THE AGE OF THE TRAPS

1. Chichimene:

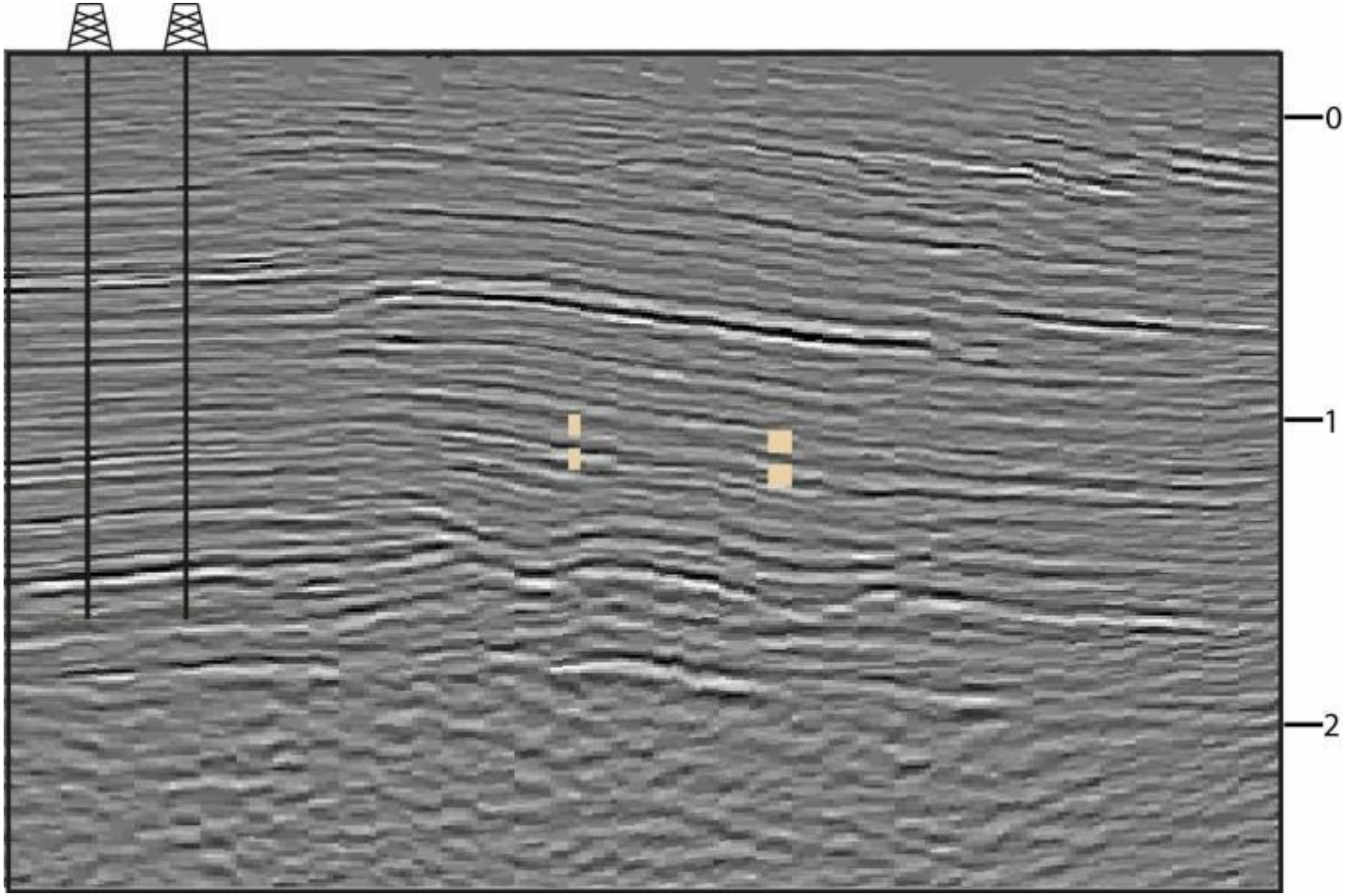
1



COMPARISON WITH THE AGE OF THE TRAPS

2. Castilla: Heavy Oil (Low API values <15)

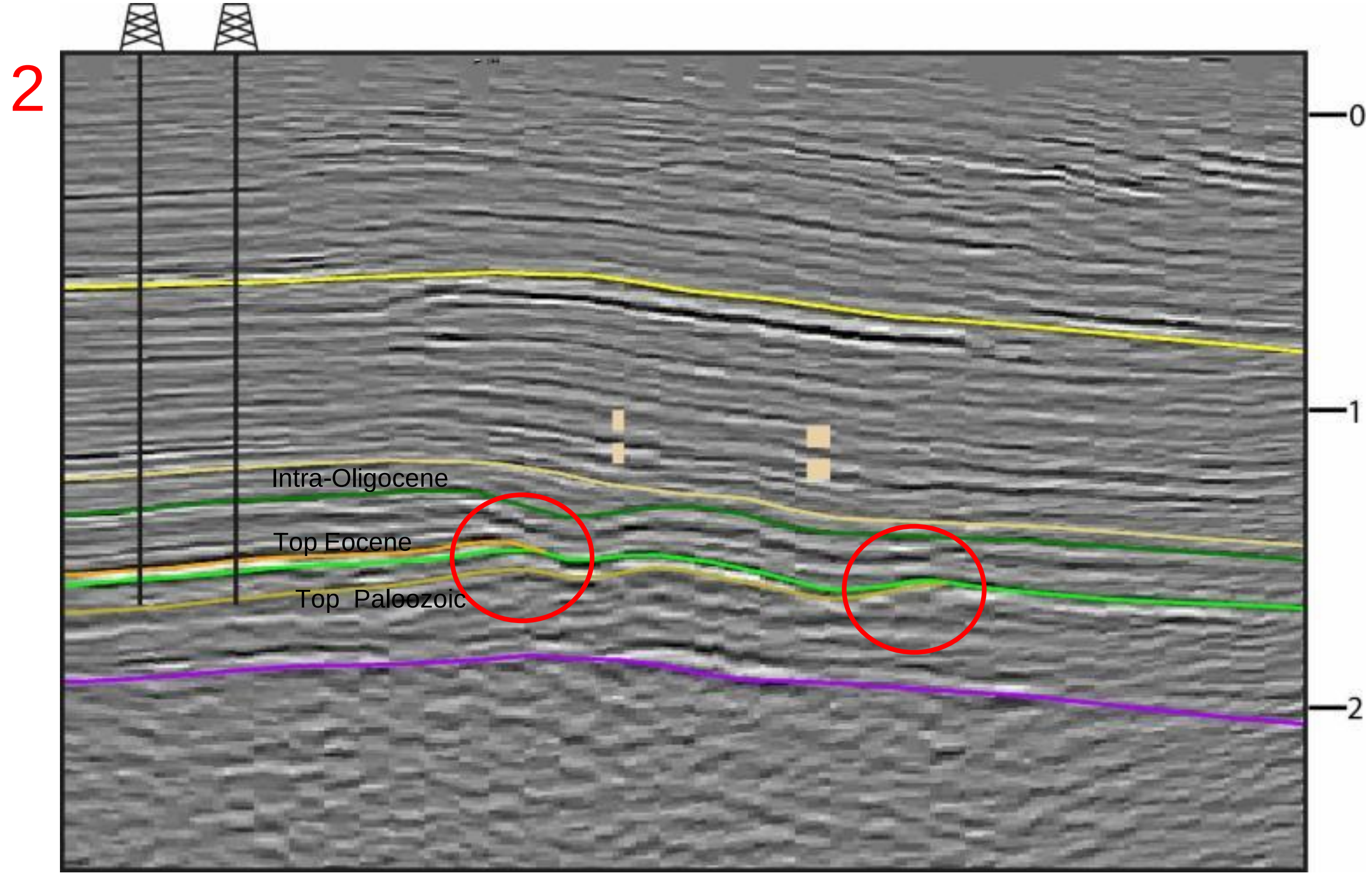
2



CASE STUDY

COMPARISON WITH THE AGE OF THE TRAPS

2. Castilla: Heavy Oil (Low API values <15)



CONCLUSIONS

- THERMOCHRONOLOGY MUST BE USED WITH CAUTION WHEN IT IS INTENDED TO INCORPORATE THESE TYPES OF DATA IN KINEMATIC RESTORATIONS.

- AGES RARELY HAVE GEOLOGICAL MEANING/ PROCESSING AND MODELLING IS NEEDED (1D).

- THERMOKINEMATIC MODELLING IS THE WAY TO PROCEED WHEN THERE IS NO GROWTH STRATA TO PRODUCE KINEMATIC RESTORATIONS BUT THERMOCHRON DATA IS ABUNDANT. (2D/3D)

- WE SHOW A CASE STUDY WHERE ISOTHERM ADVECTION IS SIGNIFICANT ONLY IN PRESENCE OF FAST DEFORMATION RATES.

- THERMOKINEMATIC MODELLING HELPS TO UNDERSTAND WHY OLDER (> 20 Ma) INVERSION TRAPS TEND TO HAVE HEAVY BIODEGRADED OILS (e.g. Chichimene, Castilla).

ENERGÍA PARA EL FUTURO

THANK YOU