

Kinematic and Thermal Modeling of Contractual Belts. An Example from the Colombian Eastern Foothill Belt*

Andrés Mora¹, Richard Ketcham², Emili Carrillo¹, and Wilmer Robles¹

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Abstract

The evolution of the shape and geometry of geological structures through time has rarely been considered in detail in areas where growth strata are absent. This is a long-standing problem because in such cases, kinematic restorations have been mostly schematic in nature, and changes in shape and geometry were not realistically considered. As a result, vectors of movement for individual particles during deformation have been only carefully analyzed during analogue modeling. No real examples of the movement of most of the points in a cross section have been documented. In this context, actual rock properties cannot be tracked with confidence through geological time and petroleum systems modeling is therefore very speculative in many aspects. In this work, we show examples in the Colombian eastern foothill belt, of the application of a new tool (Fetkin-prep) which allows tracking of the position of individual points in the different steps of a kinematic restoration. In our examples, this procedure allows subsequent thermal modeling with Fetkin, where the kinematic restoration is calibrated with respect to thermochronometric data. There are many unexpected findings in this pilot study. The first is the fact that it is highly unlikely that the generation of structural relief and topography in the Colombian Eastern Cordillera is only related with brittle faulting. Instead, for most of the duration of the deformation in the Cenozoic we find evidence of homogeneous flattening. This means potentially that this mechanism must be considered during deformation in many other orogenic belts, wherever deformation happens at low rates. The second is that oil generation and migration could be as fast as trap formation, if deformation rates are fast. In such a context, prospectivity is reduced in those traps where homogeneous flattening was significant and in contrast, risk is reduced in those areas where structures appear to be very young.

References Cited

- Almendral, A., W. Robles, M. Parra, A. Mora, R.A. Ketcham, and M. Raghib, 2015, FetKin: Coupling kinematic restorations and temperature to predict thrusting, exhumation histories, and thermochronometric ages: AAPG Bulletin, v. 99, p. 1557-1573.
- Parra, M., A. Mora, E.R. Sobel, M.R. Strecker, and R. González, 2009, Episodic orogenic front migration in the northern Andes: Constraints from low-temperature thermochronology in the Eastern Cordillera, Colombia: Tectonics, v. 28, TC4004, doi: 10.1029/2008TC002423.
- Wilkerson, M.S., and C.L. Dicken, 2001, Quick-look techniques for evaluating two-dimensional cross sections in detached contractional settings: AAPG Bulletin, v. 85/10, p. 1759-1770.

Kinematic and thermal modeling of contractional belts. An example from the Colombian eastern foothill belt.

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***CALLIBRATING CROSS SECTIONS BEFORE
CORRECT PETROLEUM SYSTEMS MODELLING***



OUTLINE

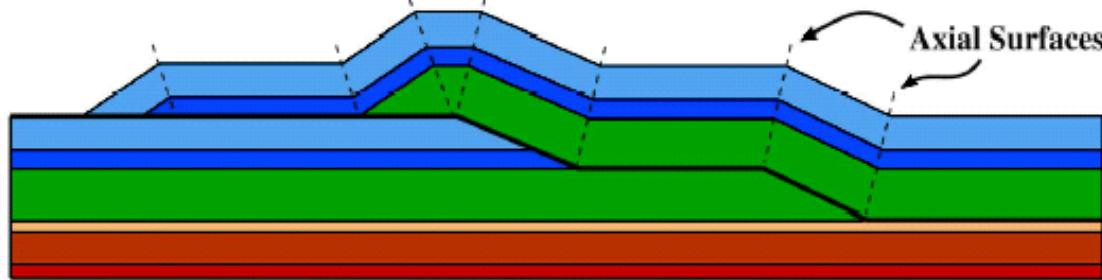
- 1. INTRODUCTION (THERMOKINEMATIC MODELING)**
- 2. OBTAINING MOVEMENT VECTORS**
- 3. CASE STUDY**
- 4. CONCLUSIONS**



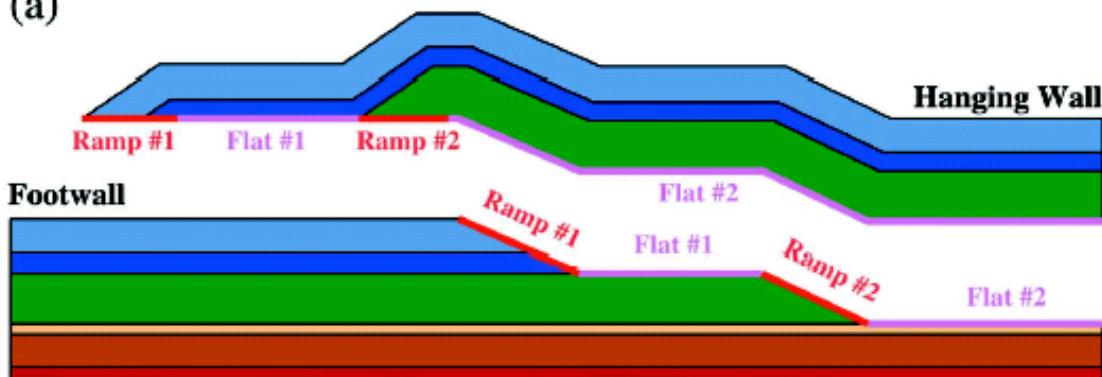
1. INTRODUCTION (THERMOKINEMATIC MODELING)



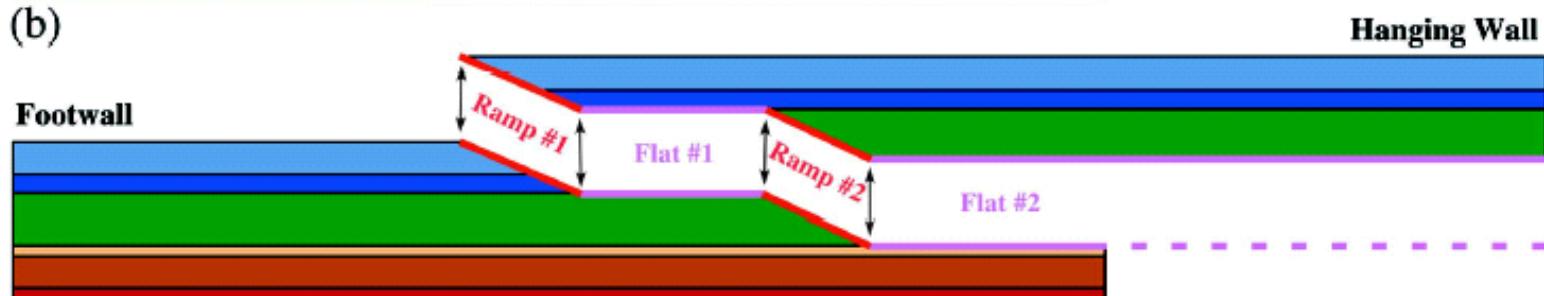
BALANCED CROSS SECTIONS ARE GEOMETRIC REPRESENTATIONS OF GEOLOGY WITHOUT MATERIAL PROPERTIES



(a)



(b)



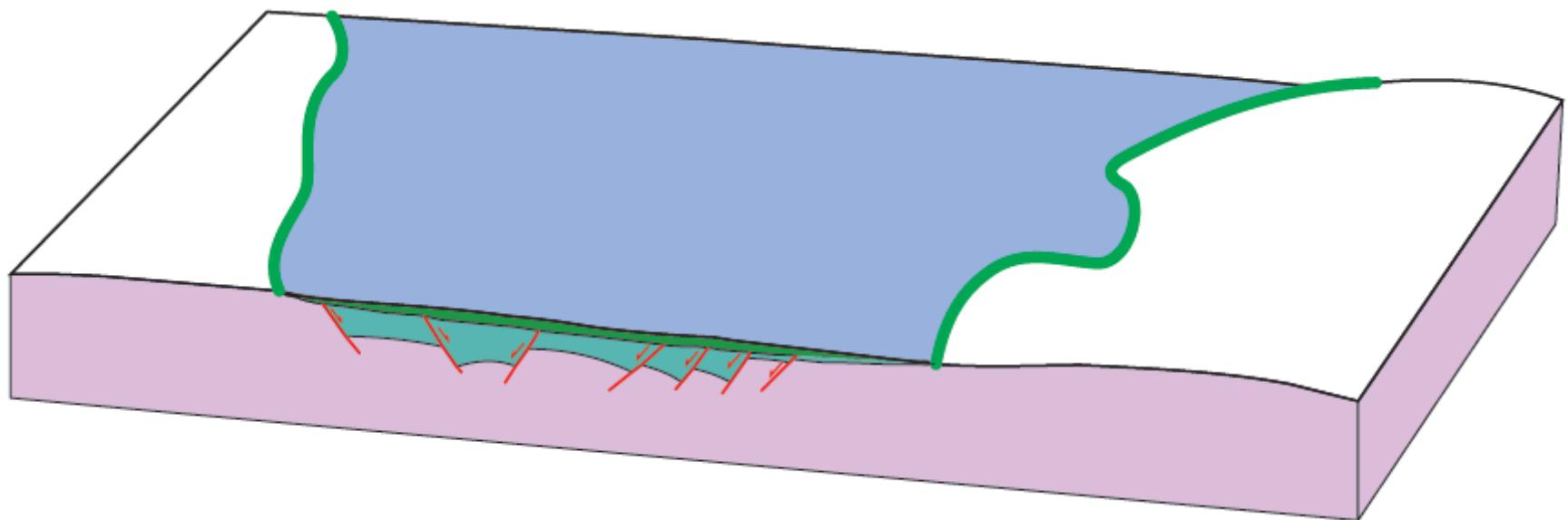
(c)

Wilkerson & Dicken, 2001

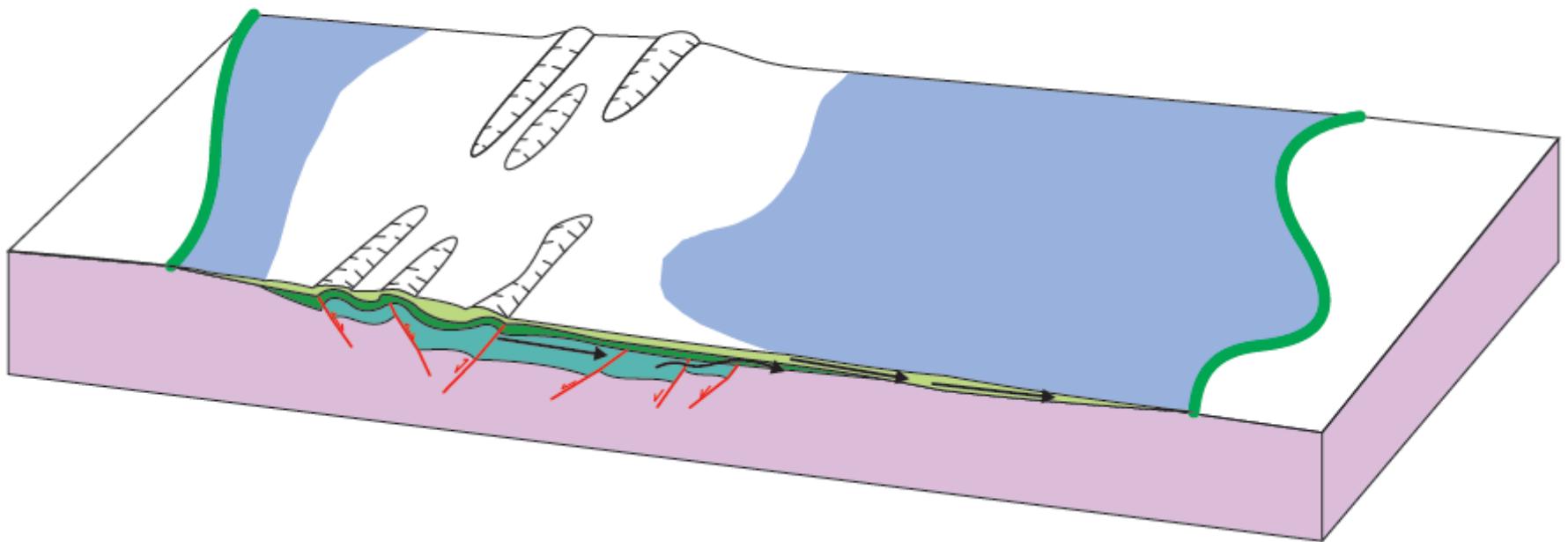


**AMOUNTS OF OVERBURDEN, EROSION AND TEMPERATURE MAKE THE DIFFERENCE
BETWEEN BASINS WITH OR WITHOUT OIL**

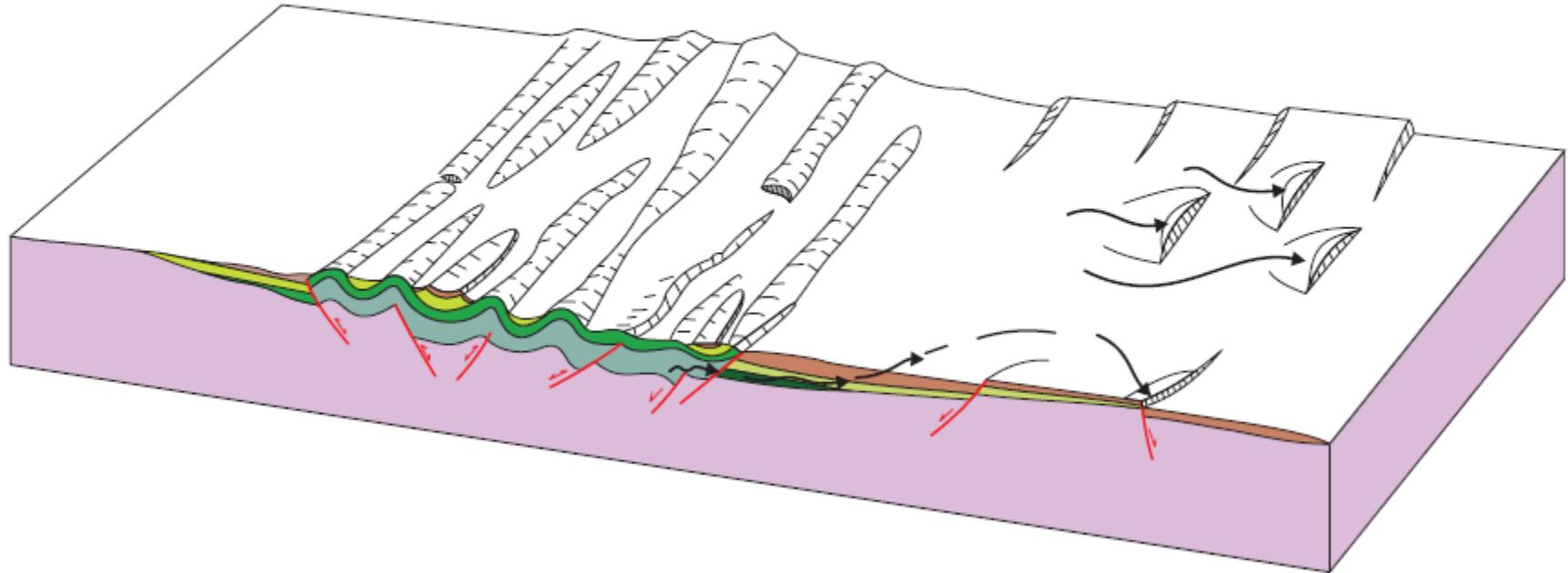
OVERBURDEN AND TEMPERATURE TRANSFORM KEROGEN INTO OIL



**TO SIMULATE PETROLEUM SYSTEMS, 2D KINEMATIC RESTORATIONS
IDEALLY SHOULD INCLUDE THE EVOLUTION OF
OVERBURDEN, EROSION AND TEMPERATURE THROUGH TIME
(i.e. CALIBRATED CROSS SECTIONS)**

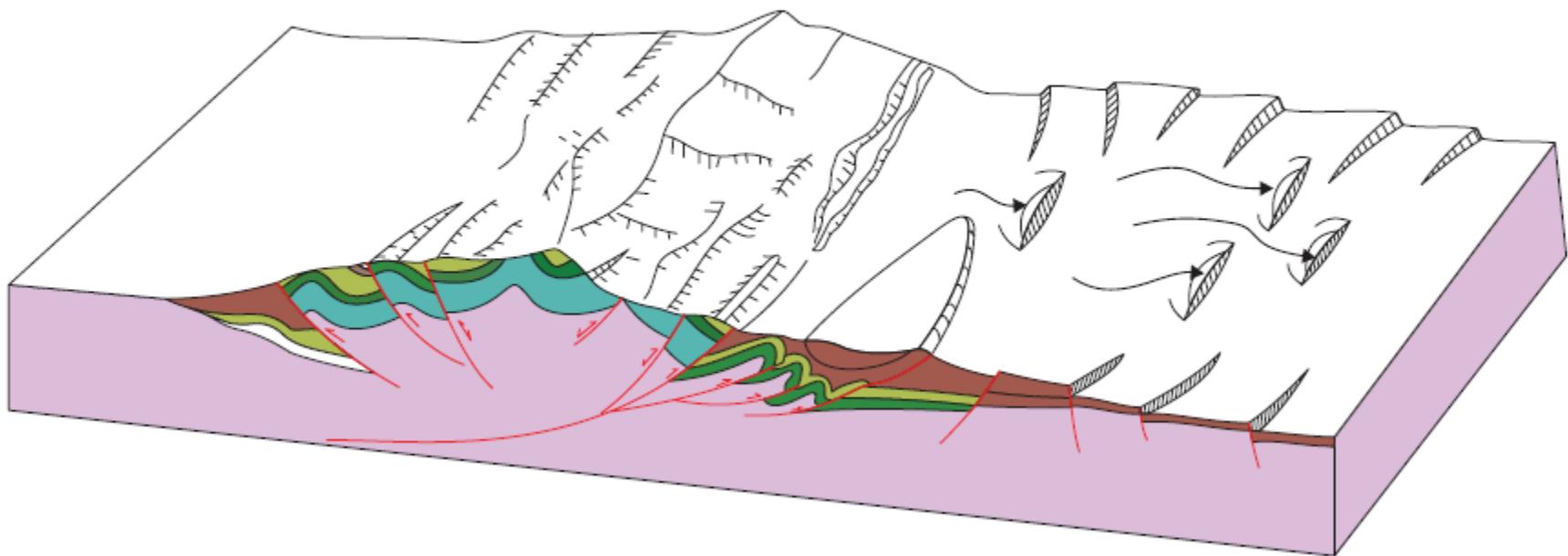


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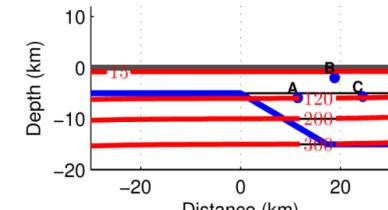
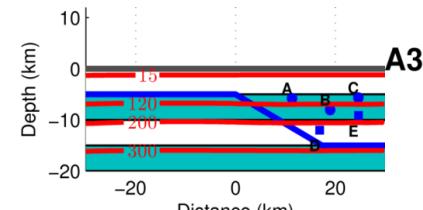
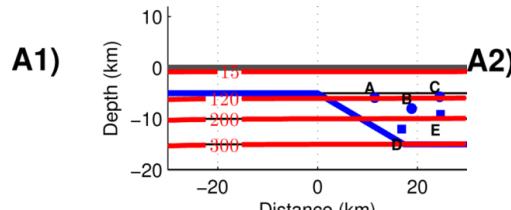
**IS IT ACTUALLY POSSIBLE TO OBTAIN RIGOROUS AND QUANTITATIVE
CALIBRATION OF KINEMATIC RESTORATIONS BEFORE PETROLEUM
SYSTEMS MODELLING?**

**HOW TO KNOW IN ADVANCE EROSION, OVERBURDEN AND TEMPERATURE
THROUGH THE GEOLOGICAL TIME?**

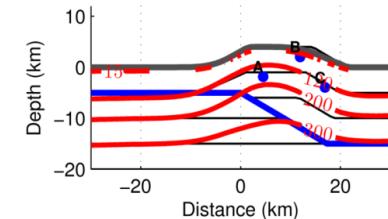
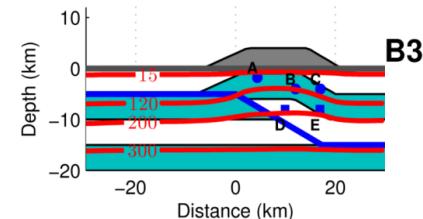
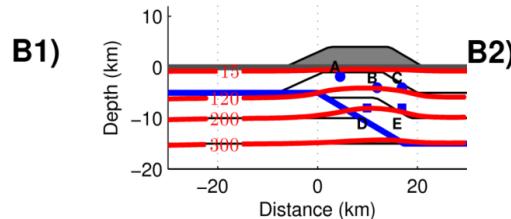


THERMOKINEMATIC MODELLING USING FETKIN SOLVES THE HEAT EQUATION IN 2D TO PREDICT EROSION, OVERBURDEN AND TEMPERATURE IN CROSS SECTIONS ALLOWING A CALIBRATION WITH ACTUAL DATA

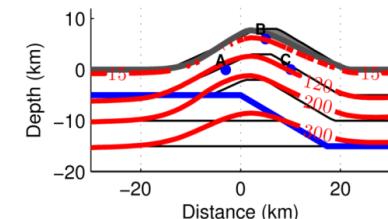
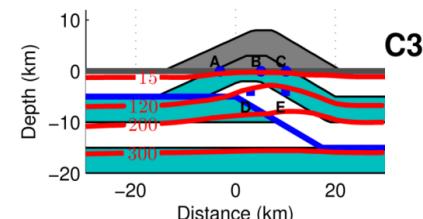
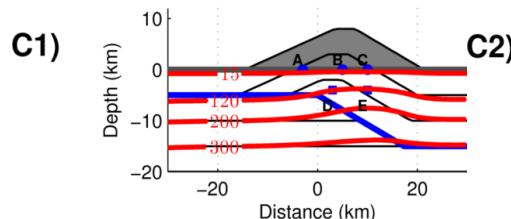
12 Ma



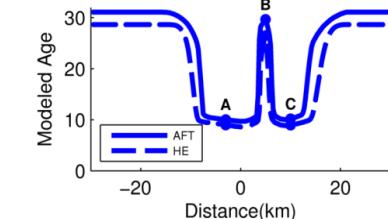
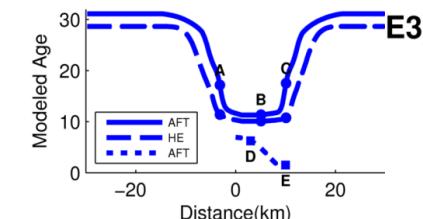
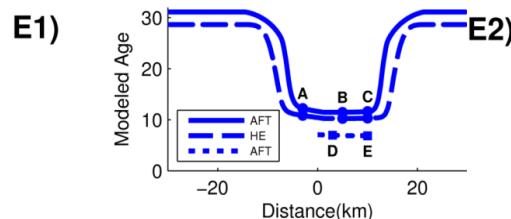
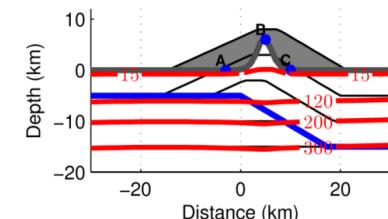
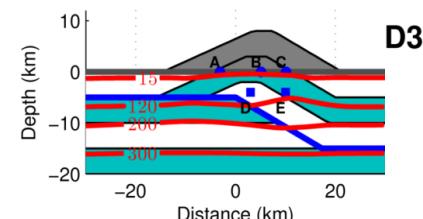
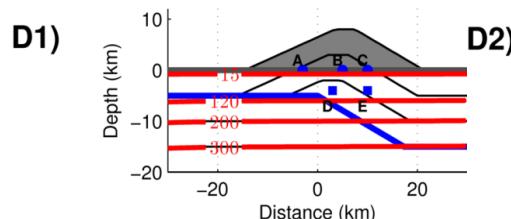
11 Ma



10 Ma



Present



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

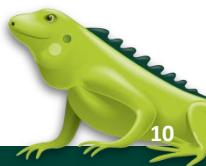
κ : Thermal conductivity

v: velocity

UNKNOWN: These requires to obtain movement vectors.

H: Radiogenic heat production

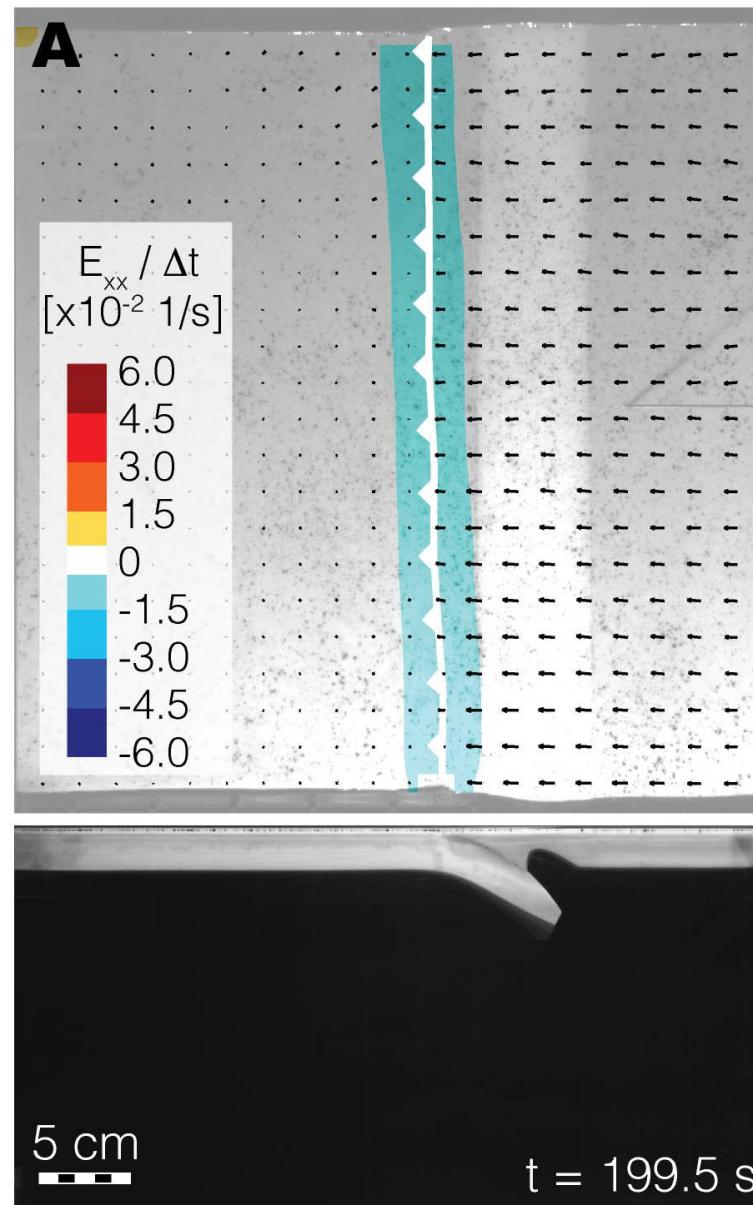
Solving the equation allows transforming the depth into temperature in a cross section
(define boundary conditions)



2. OBTAINING MOVEMENT VECTORS



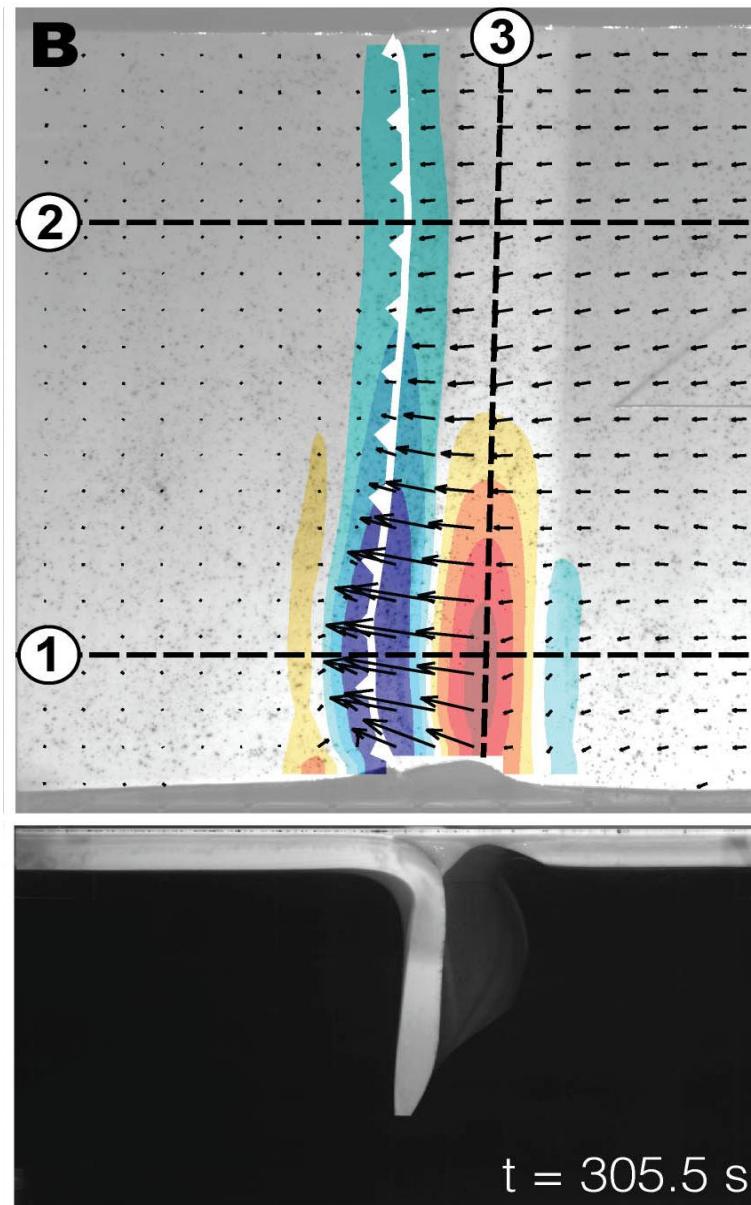
MOVEMENT VECTORS IN ANALOGUE MODELS (PLAN VIEW)



David Boutelier (New Castle)



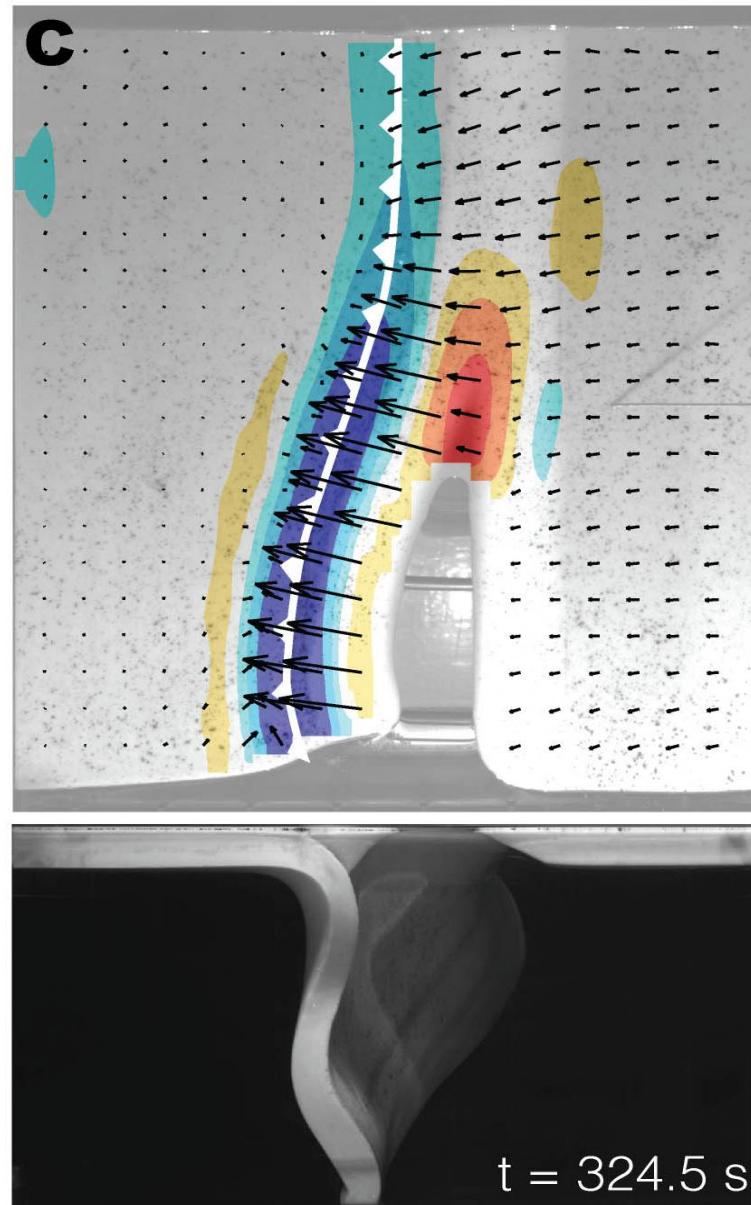
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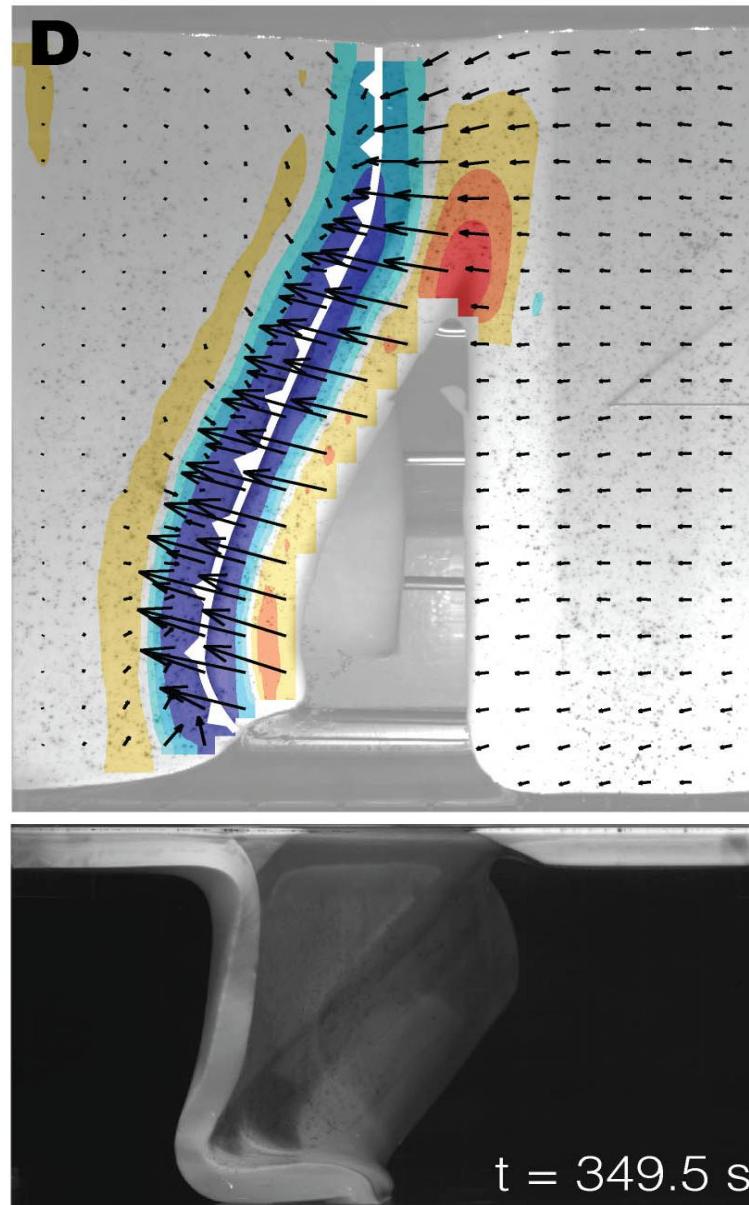
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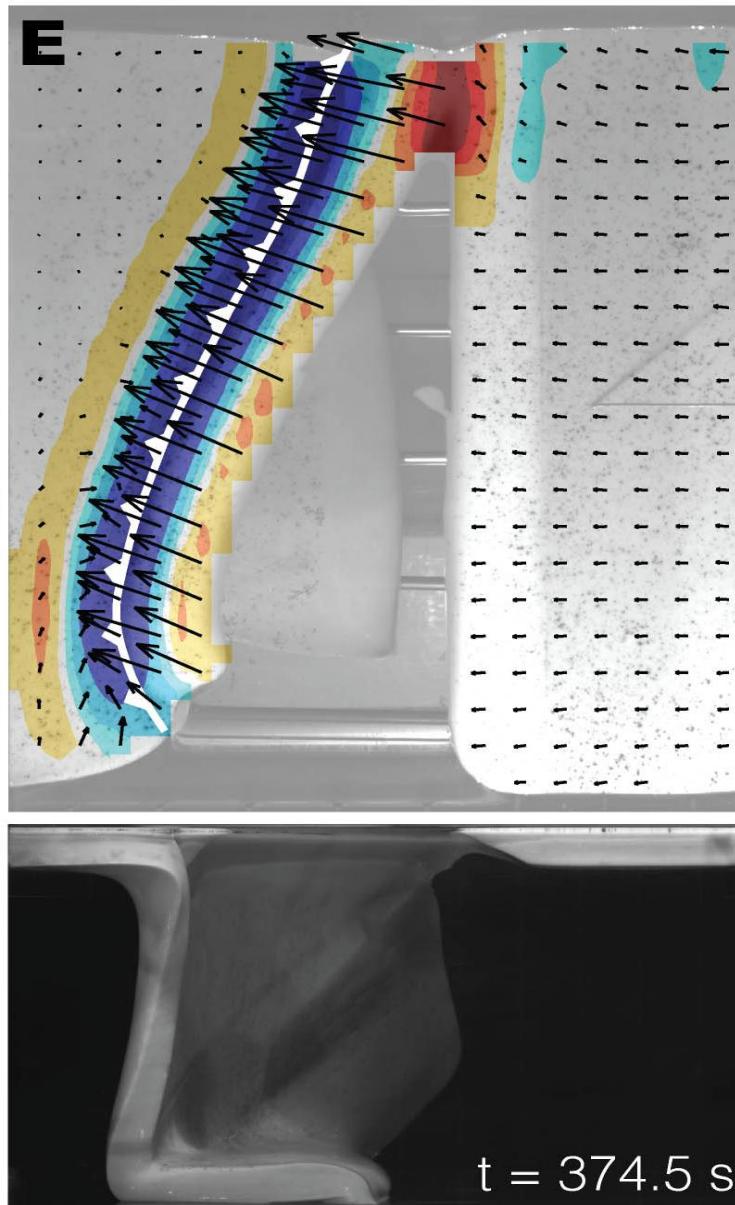
MOVEMENT VECTORS IN ANALOGUE MODELS (PLAN VIEW)



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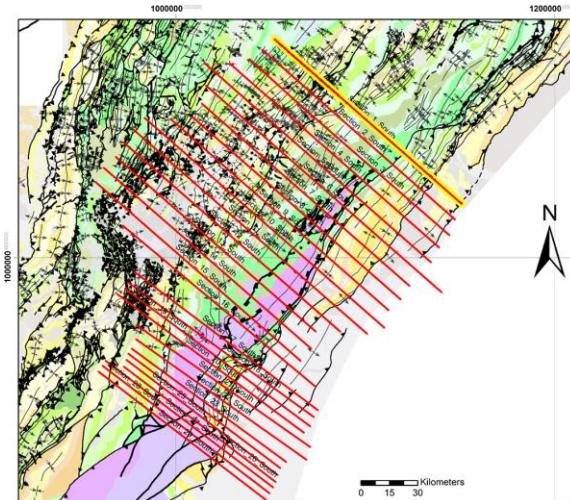
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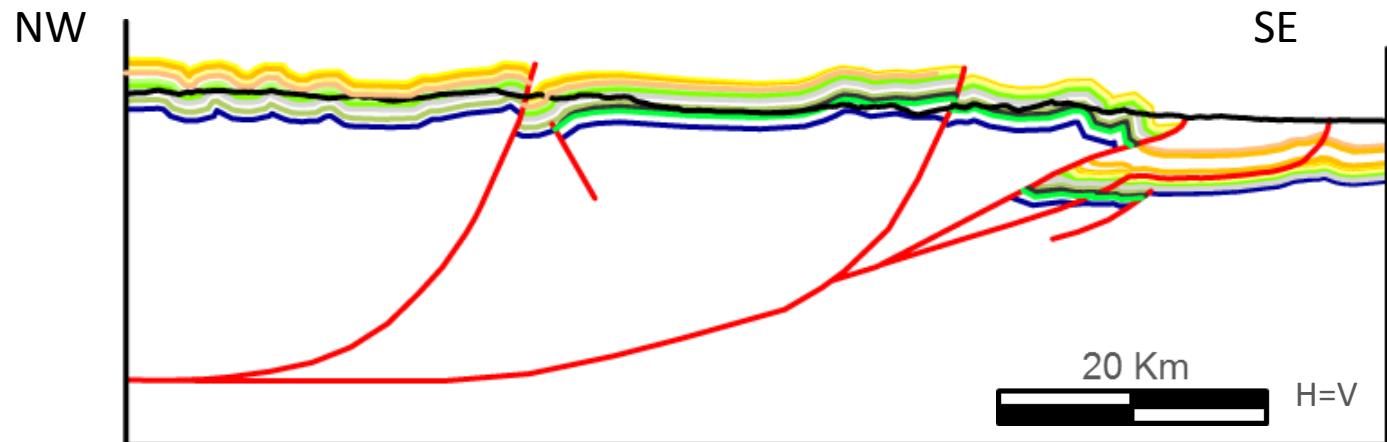


HOW TO OBTAIN THEM IN REAL SEQUENTIAL KINEMATIC RESTORATIONS?

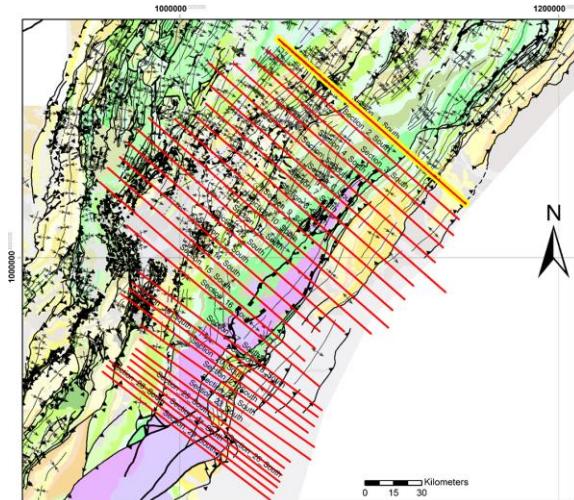


Section_1_South

0 Ma

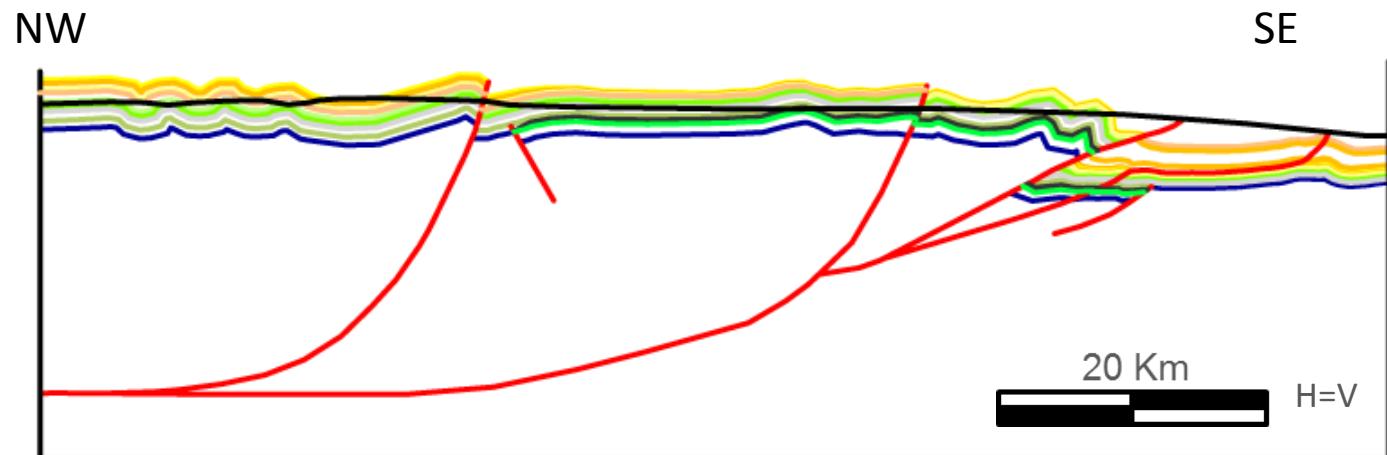


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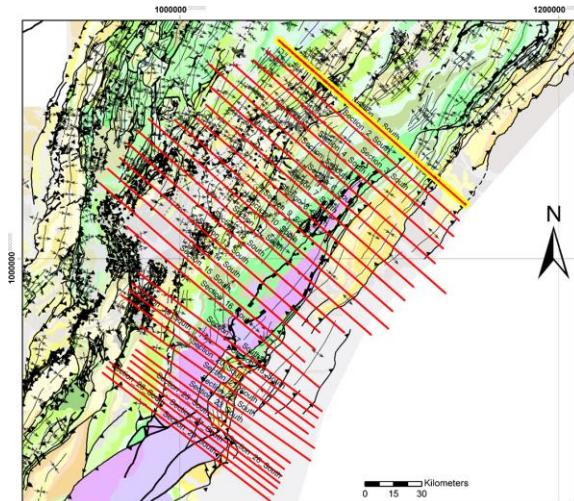


Section_1_South

3 Ma

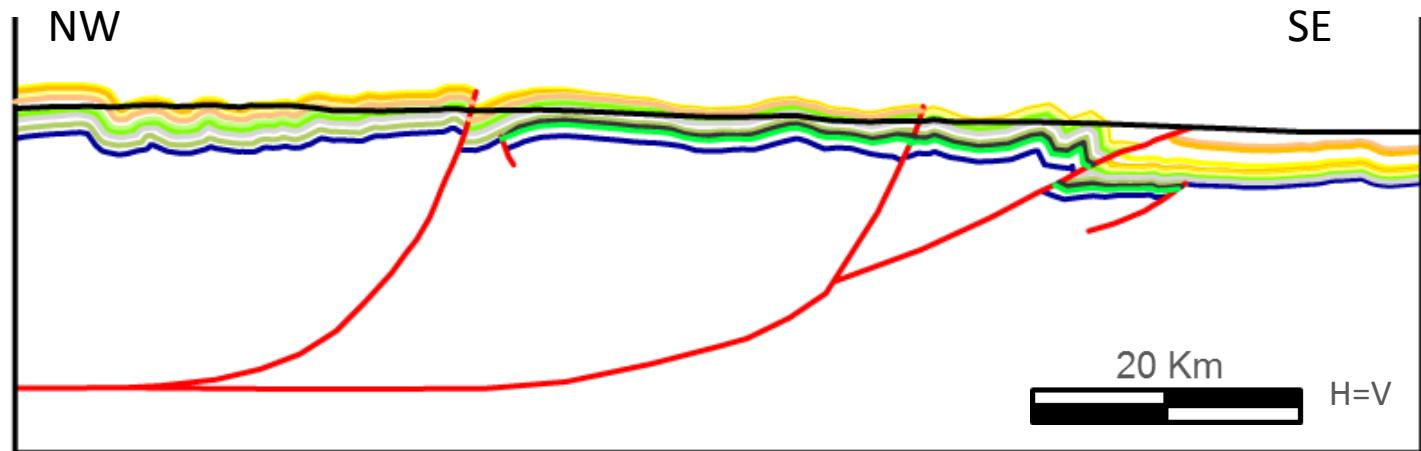


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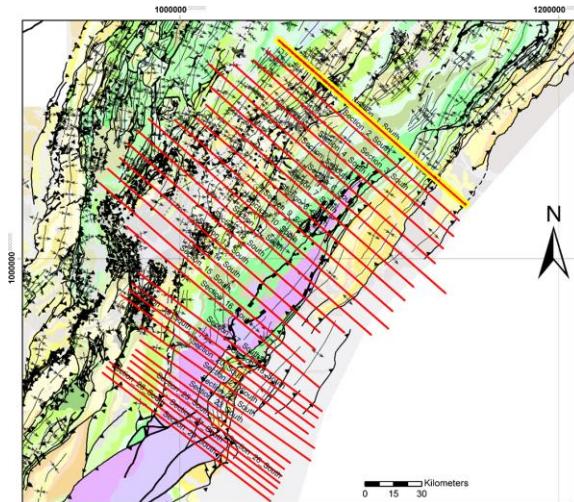


Section_1_South

5 Ma

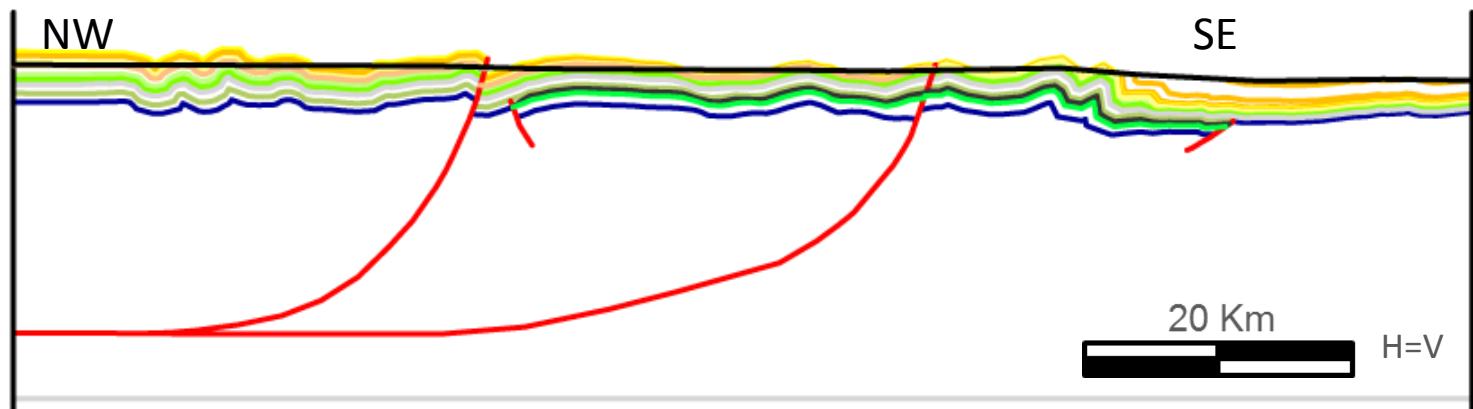


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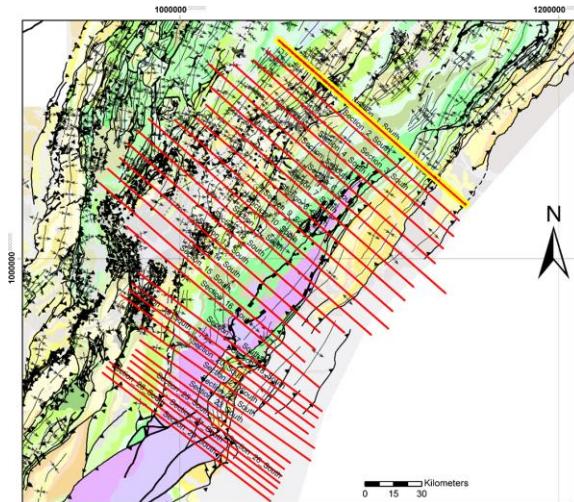


Section_1_South

11 Ma

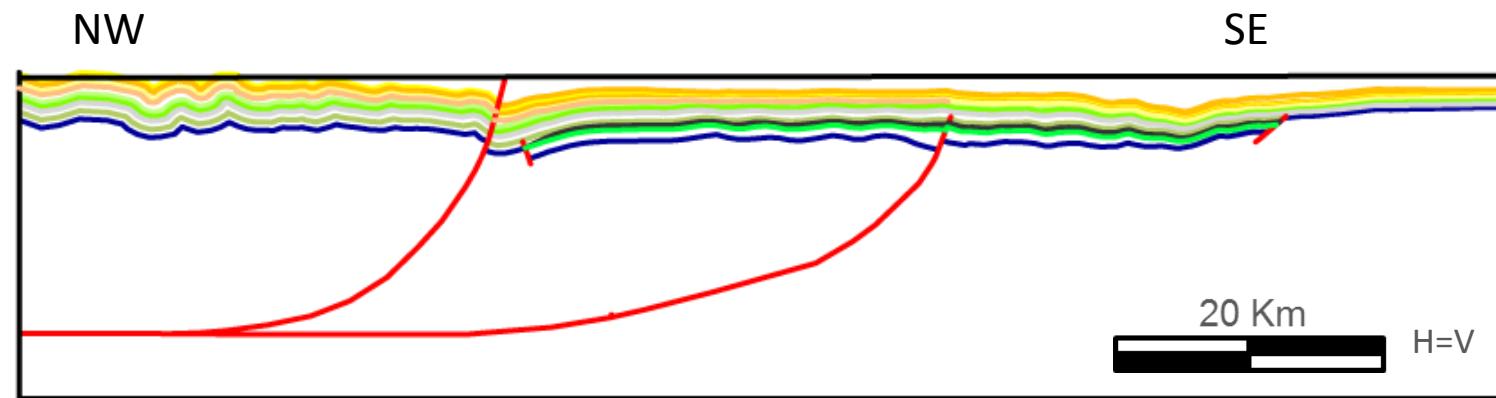


HOW TO OBTAIN THEM IN REAL SEQUENTIAL KINEMATIC RESTORATIONS?

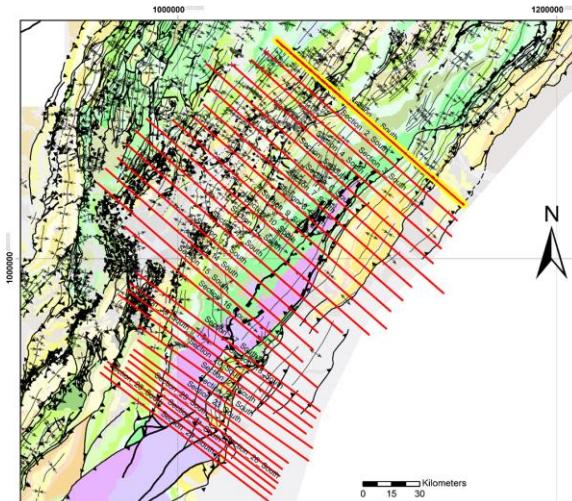


Section_1_South

23 Ma

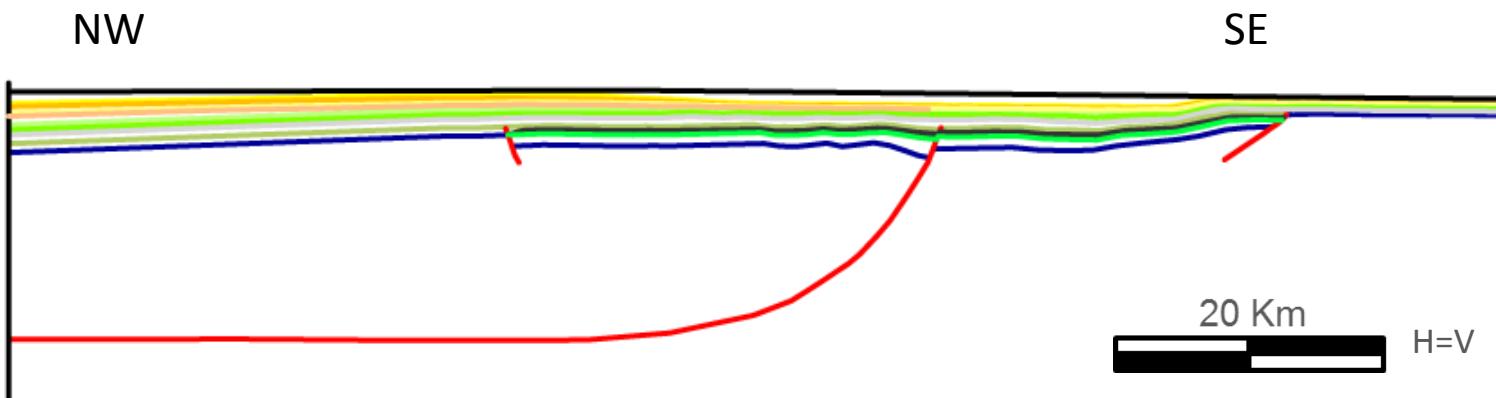


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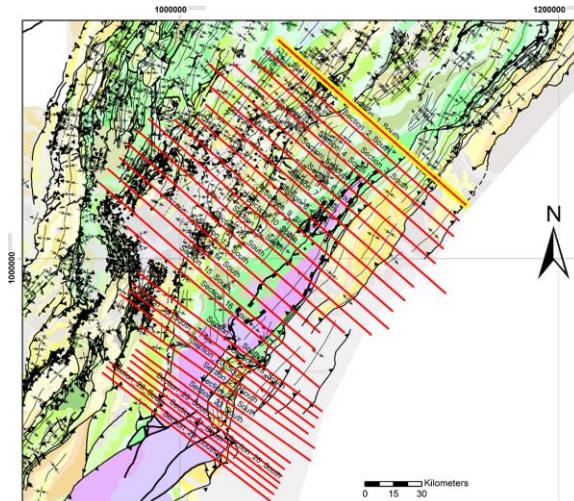


Section_1_South

33 Ma

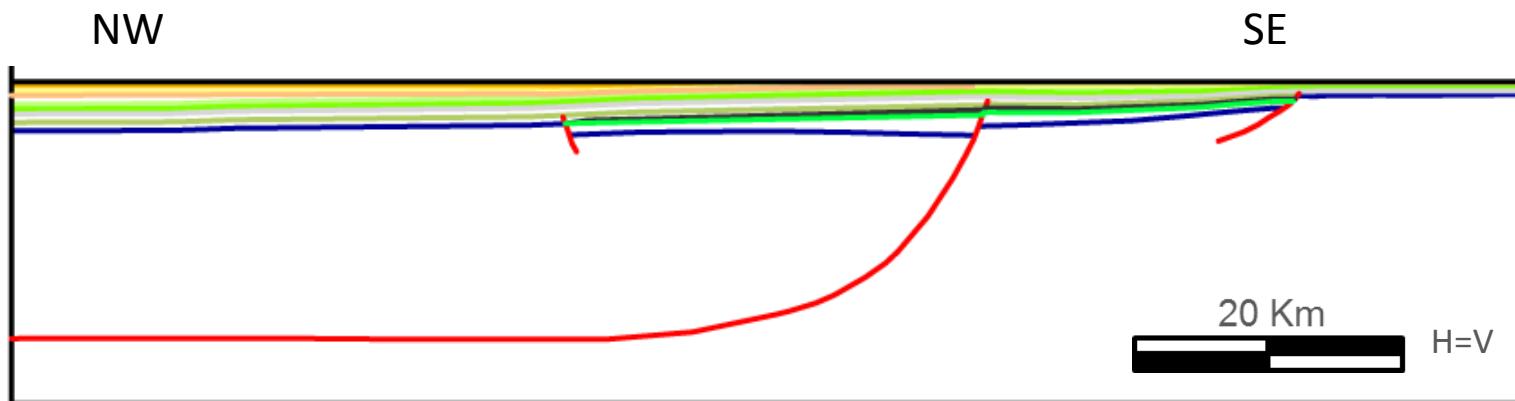


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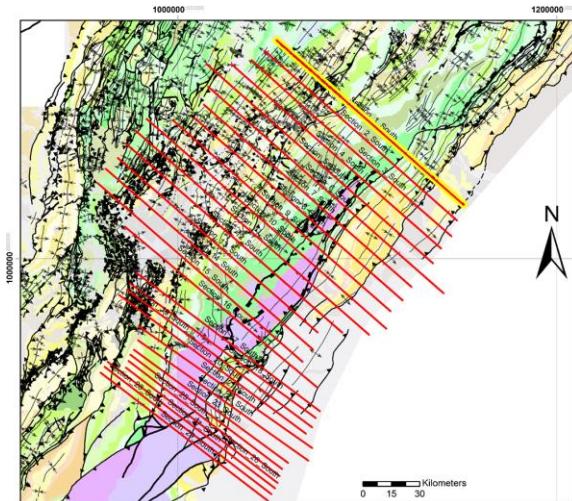


Section_1_South

40 Ma

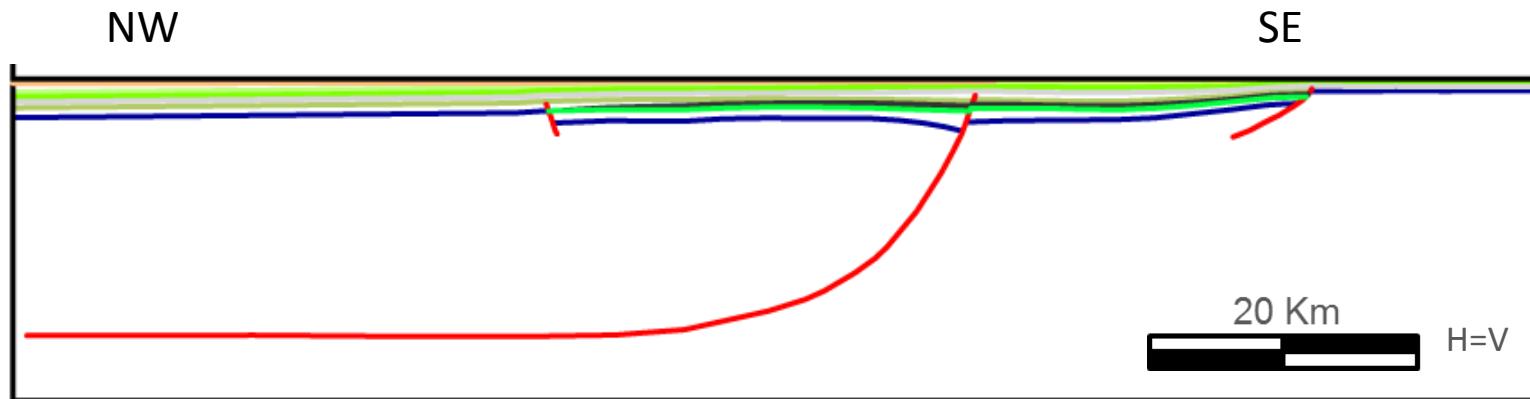


HOW TO OBTAIN THEM IN REAL SEQUENTIAL KINEMATIC RESTORATIONS?

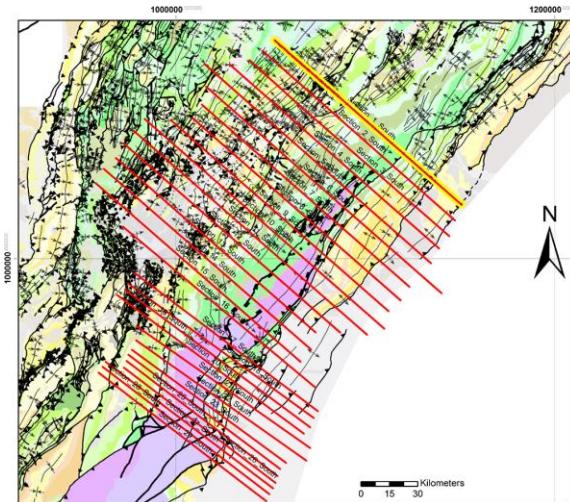


Section_1_South

55 Ma

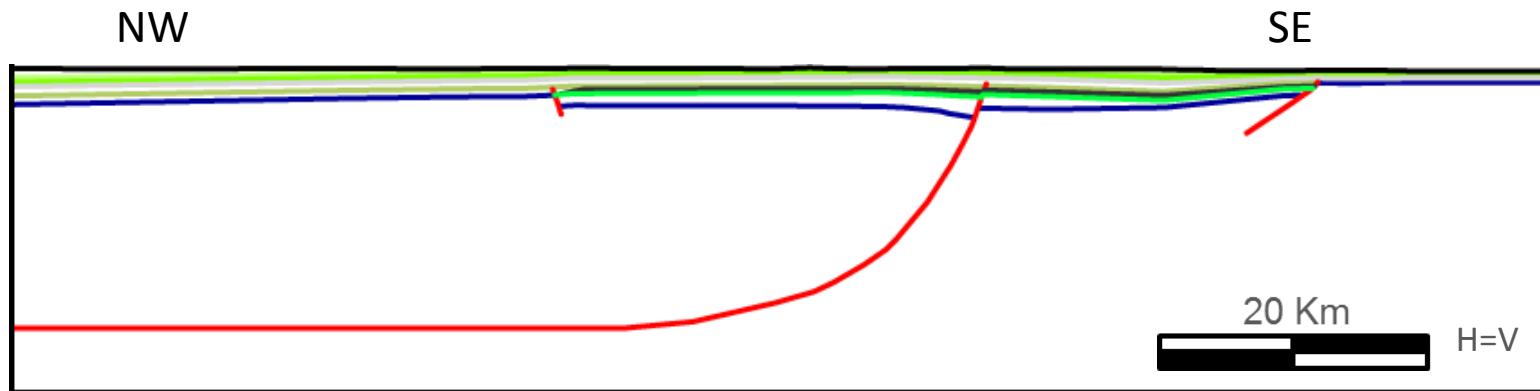


HOW TO OBTAIN THEM IN REAL SEQUENTIAL KINEMATIC RESTORATIONS?



Section_1_South

65 Ma



WHAT DOES FETKIN-PREP DO AND WHY (AND HOW)?

FetkinPrep

Step 1

Tolerances

- Anchor horizon segment to fault (m): 100
- Horizon length mismatch warning (%): 2
- Horizon length mismatch error (%): 5
- Connect separate horizon lines (m): 100

Step 2

Tolerances

- Horizon segment length mismatch (%): 5
- Horizon segment minimum mismatch (m): 250

Generic sequential file names

Sampling interval (m): 500

Status

```
Horizon: Macanal Fm. Line: 1 Id: 468 Left: Fault_02, Right: Fault_Pajarito
Horizon: Macanal Fm. Line: 2 Id: 486 Left: Truncated, Right: Truncated
Horizon: Macanal Fm. Line: 3 Id: 579 Left: Truncated, Right: Fault_04
Horizon: Las Juntas Fm. Line: 1 Id: 497 Left: Fault_02, Right: Fault_Pajarito
Horizon: Las Juntas Fm. Line: 2 Id: 578 Left: Truncated, Right: Fault_04
Horizon: Guadalupe Inferior Line: 1 Id: 559 Left: Truncated, Right: Model edge
Horizon: Fomeque Fm. Line: 1 Id: 572 Left: Truncated, Right: Fault_04
Horizon: 16180 Line: 1 Id: Line Left: Truncated, Right: Above topo
Finished loading section Miguel_65ma
```

Sections from oldest to youngest:

```
Miguel_65ma, Miguel_55ma, Miguel_40ma, Miguel_33ma, Miguel_23ma, Miguel_11ma, Miguel_05ma, Miguel_03ma, Miguel_00ma
```

Errors and Warnings:

```
Error: Horizon Mirador Superior increases in length from 12,013.1 in section Miguel_11ma to 13,471.8 in section Miguel_05ma
Warning: Horizon Chipaque Superior increases in length from 48,424.9 in section Miguel_11ma to 50,062.9 in section Miguel_05ma
Warning: Horizon Chipaque Inferior increases in length from 66,113.7 in section Miguel_11ma to 67,443.3 in section Miguel_05ma
Warning: Horizon Guadalupe Gr. increases in length from 12,580.8 in section Miguel_11ma to 12,870.9 in section Miguel_05ma
Warning: Horizon Las Juntas Fm. increases in length from 67,435.8 in section Miguel_11ma to 68,946.2 in section Miguel_05ma
Warning: Horizon Chipaque Fm. decreases in length from 88,199.4 in section Miguel_11ma to 86,407.2 in section Miguel_05ma without intersecting topography
Warning: Horizon Jurásico decreases in length from 46,400.3 in section Miguel_11ma to 44,841.9 in section Miguel_05ma without intersecting topography
Error: Horizon León Fm. increases in length from 4.4 in section Miguel_11ma to 28,800.2 in section Miguel_05ma
Warning: Horizon Jurásico decreases in length from 44,841.9 in section Miguel_05ma to 43,738.6 in section Miguel_03ma without intersecting topography
```

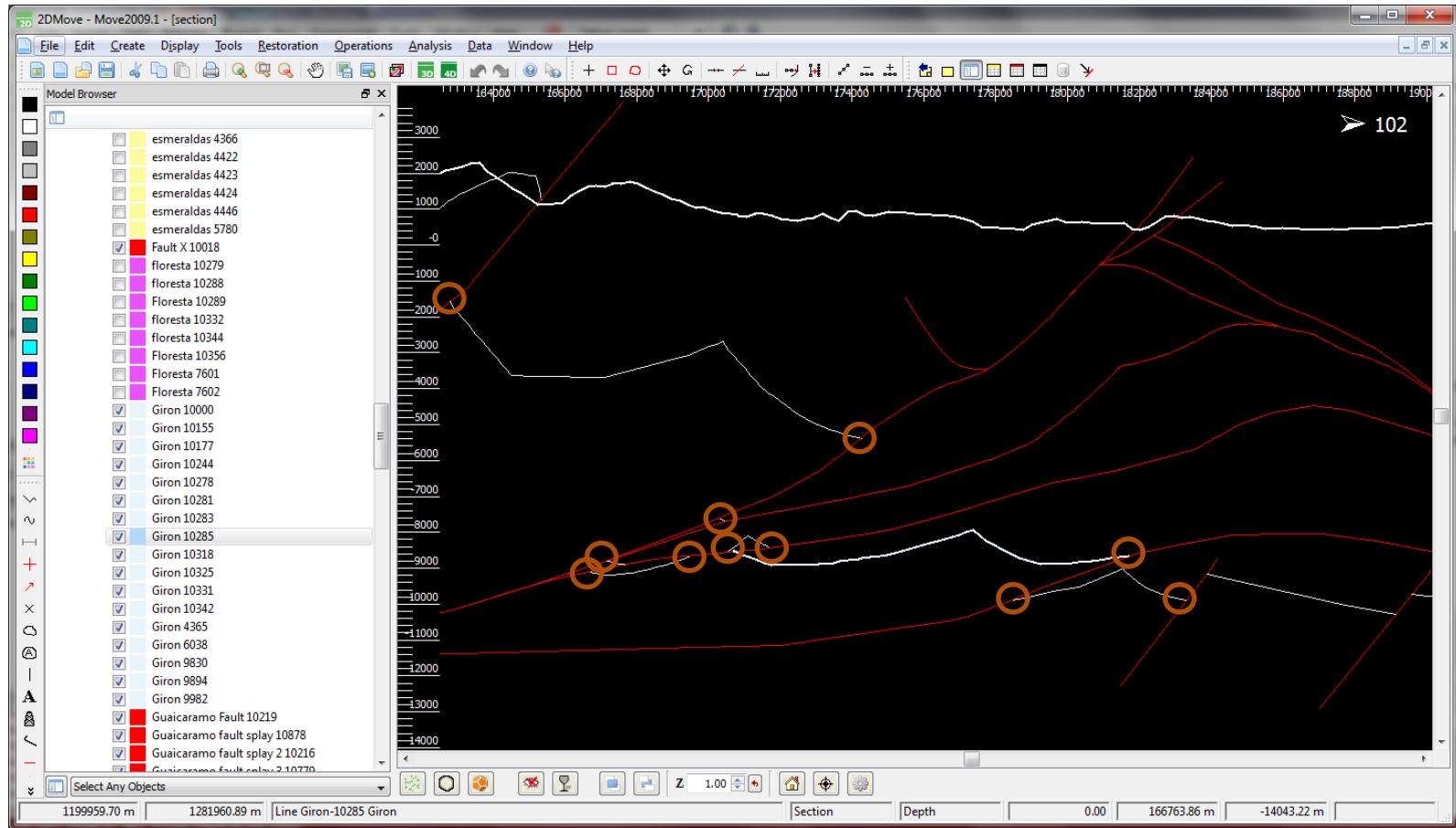


FETKIN-PREP STEPS

- **Read files**
 - **Checks for problems**
 - Line length changes a lot without a good reason
 - Horizons and faults do not persist from section to section
 - “Junk” lines (lines within other lines)
 - Disconnected lines that could be connect
 - **Figures out left-to-right order of lines in each horizon**
 - How?



ORDERING LINES FROM LEFT TO RIGHT



Lots of complexity; thrusting has changed ordering.

FetkinPrep makes sense of it with help of **anchor points**, where horizons intersect faults.

Gibraltar section, Giron Fm., Present-day



SIMULATED ANNEALING

* The Idea

- In natural processes (like crystallization), atoms try to reach their lowest-energy configuration.
- Here, we can give an “energy” to each arrangement of lines. Bad characteristics are given high energies, good characteristics are given low energies.
 - Example of bad: Line intersecting left side of model space is not in left-to-right list.
 - Example of good: One line has an anchor point on the left side of a fault, and the next one has an anchor point to the right of the same fault.

* The Algorithm

- Start with random arrangement.
- Allow lines to switch places; evaluate energy of each change
 - Changes that lower energy always accepted
 - Changes that raise energy are accepted with probability $\exp(-\Delta E/T)$
 - T = “Temperature”
- Start at high temperature, slowly “cool”



Vectors from one section to the next

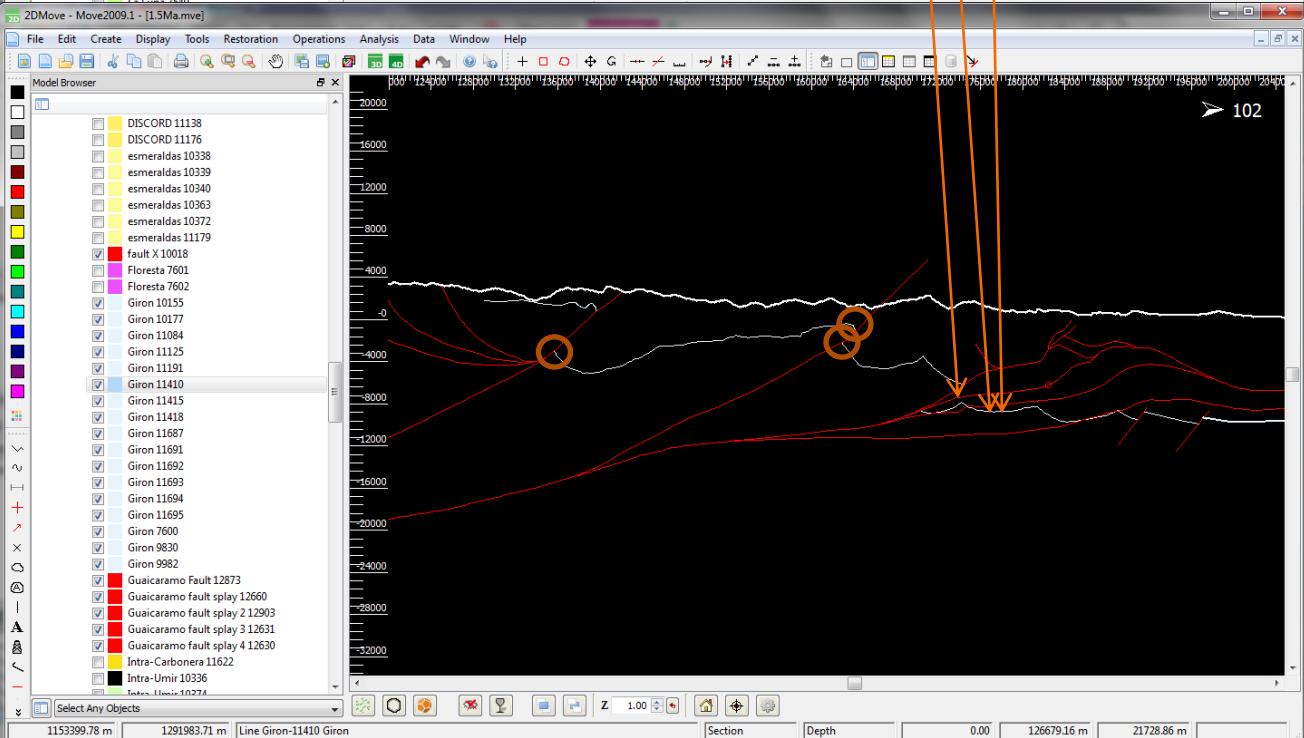
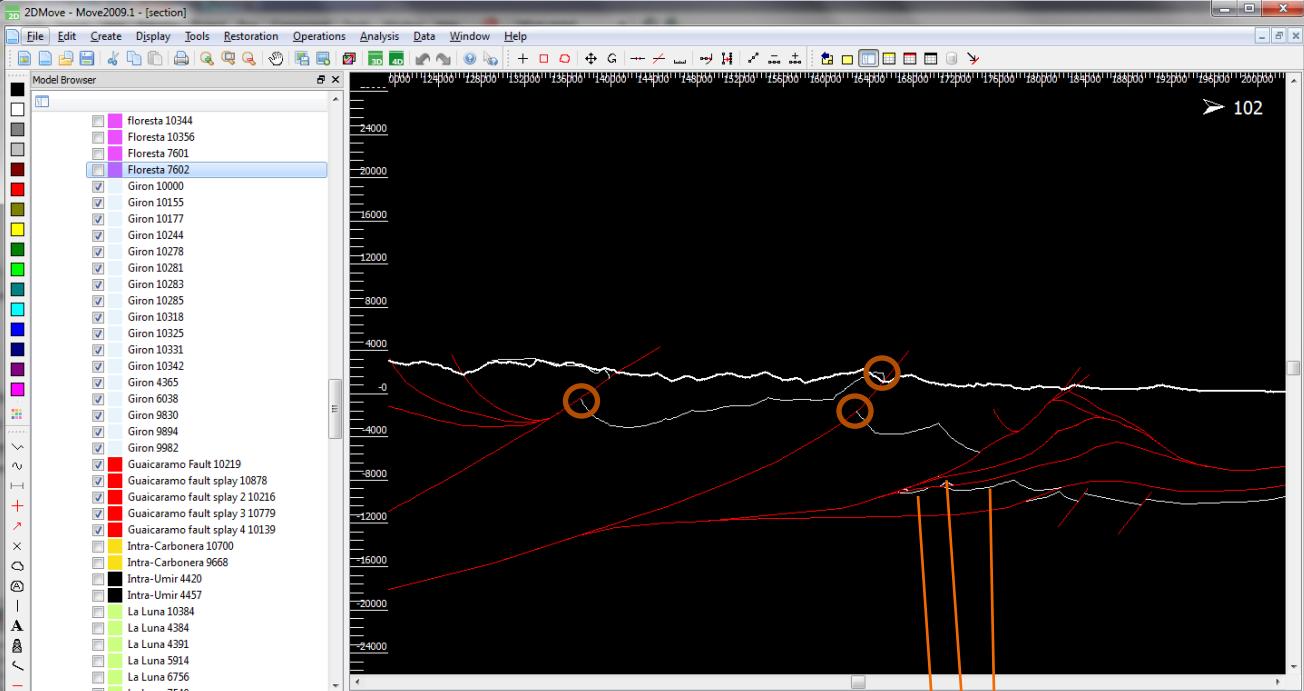
0 Ma

Use ordering and anchor points to match line-by-line.

Also uses simulated annealing

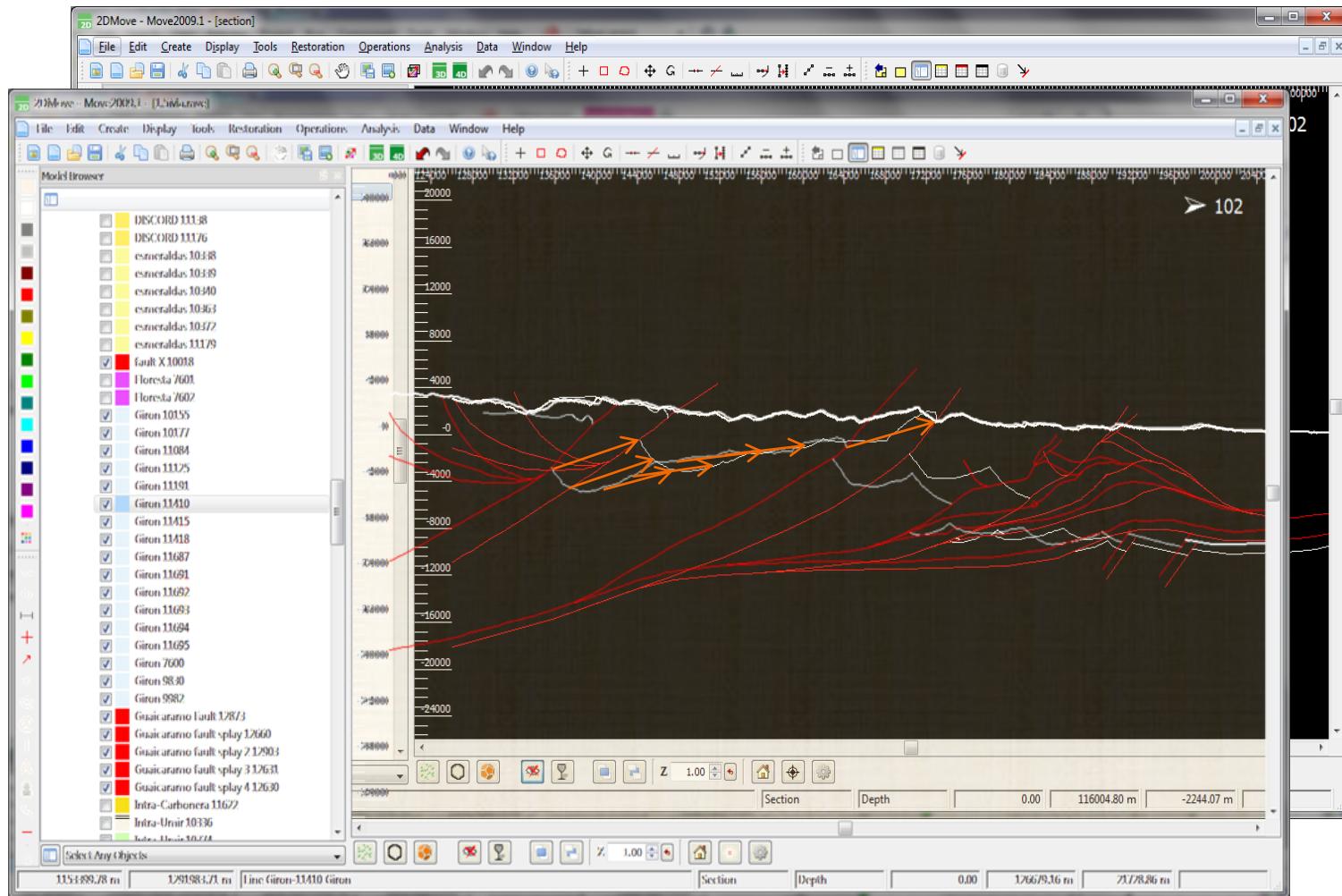
1.5 Ma

Move 2009 window
MidlandValley ©



CREATING VECTORS

Move 2009 window
MidlandValley ©



CREATING VECTORS

NOTICE THAT BY USING THIS PROCEDURE MOVEMENT VECTORS MAY NOT BE JUST GEOMETRIC ARTIFACTS.

IF: THEY ARE RESTRICTED BY ADDITIONAL KNOWLEDGE OF:

- *ROCK UPLIFT THROUGH TIME.**
- *COOLING THROUGH TIME.**
- *DENUDATION THROUGH TIME.**
- *SURFACE UPLIFT.**
- *HORIZONTAL SHORTENING**

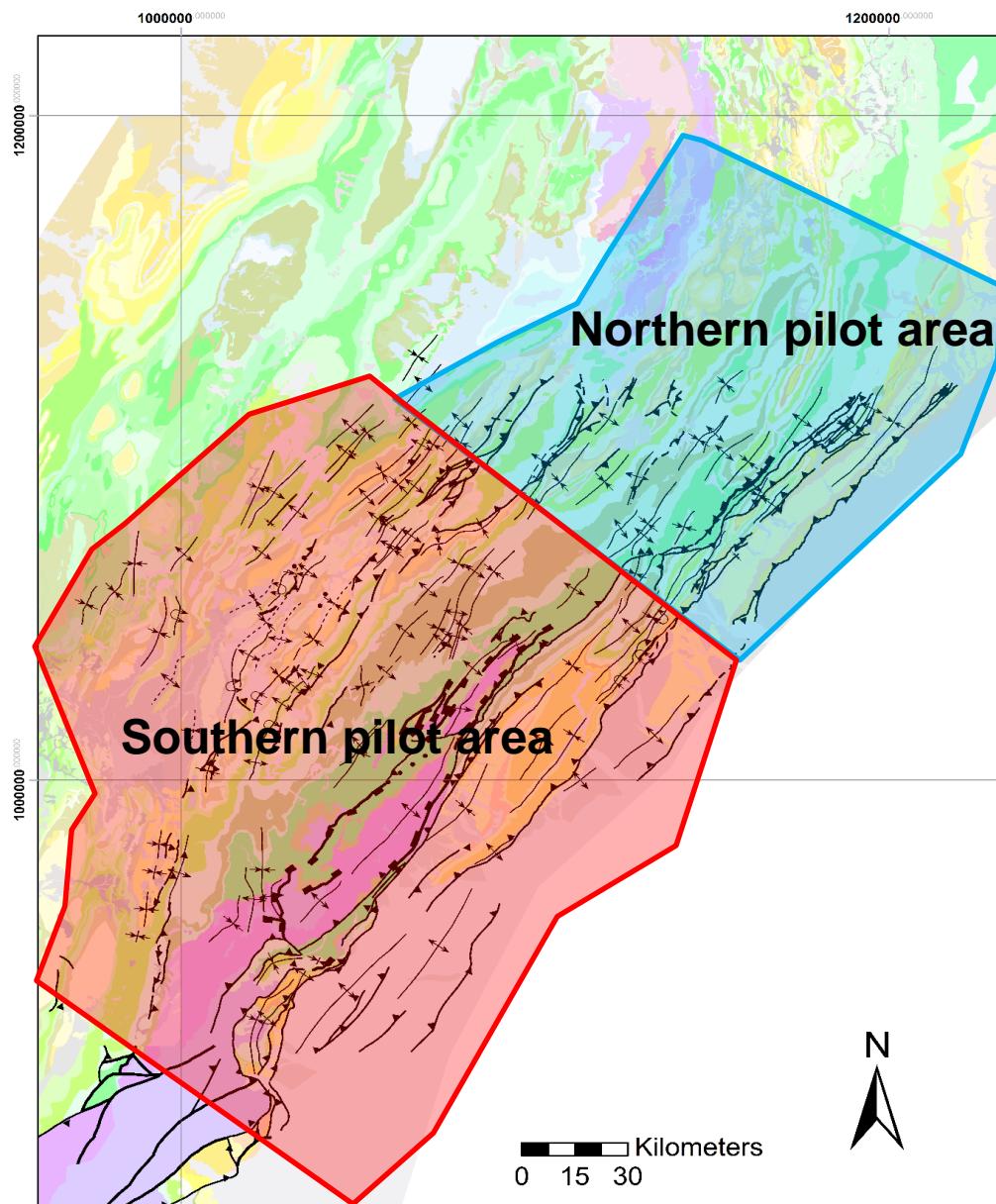
Which is obtained from cooling histories, paleoelevation, provenance data etc...



3. CASE STUDY

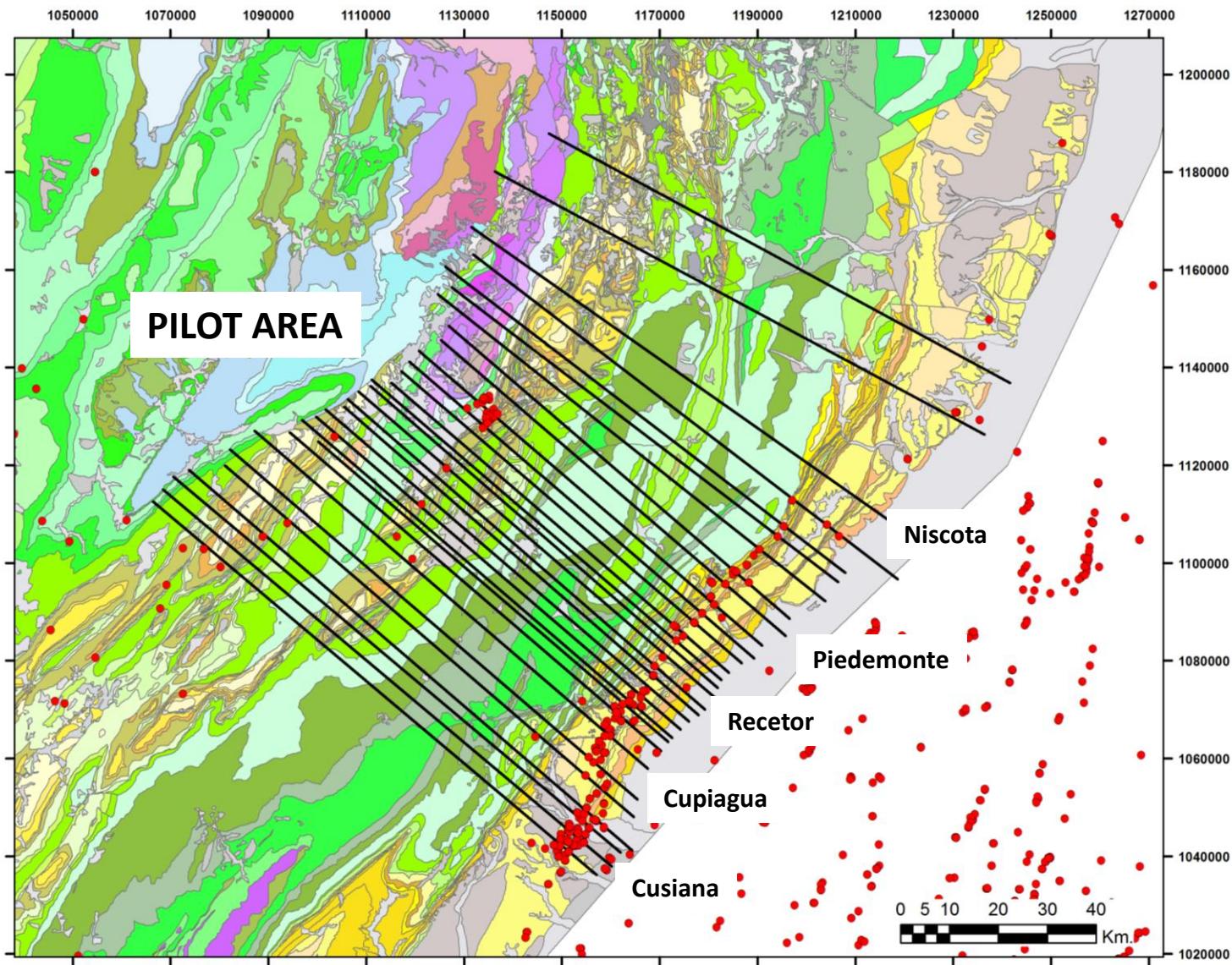


3. CASE STUDY



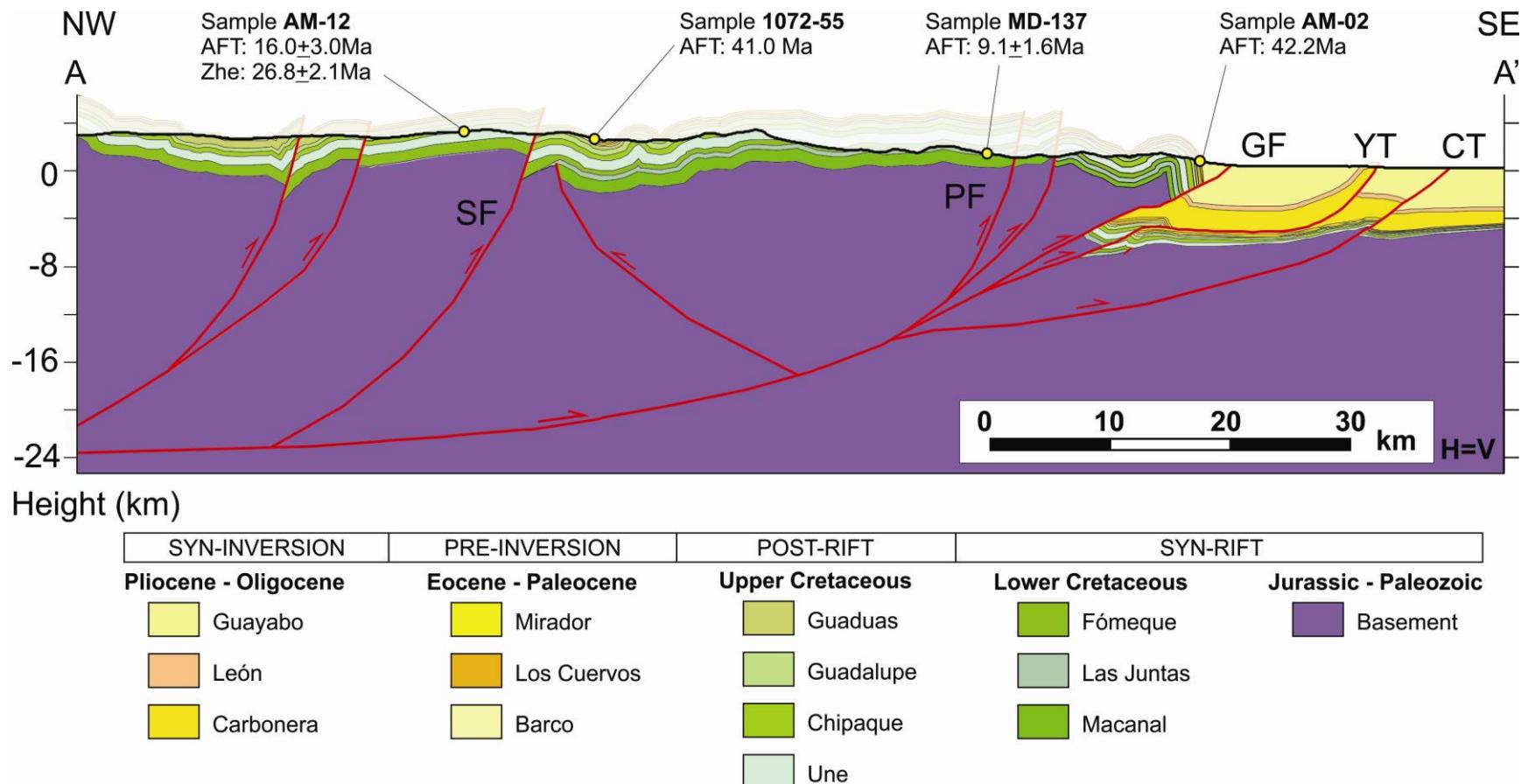
3. CASE STUDY

Fetkin/Fetkin-prep workflow applied to 30 2D cross sections in a pilot area



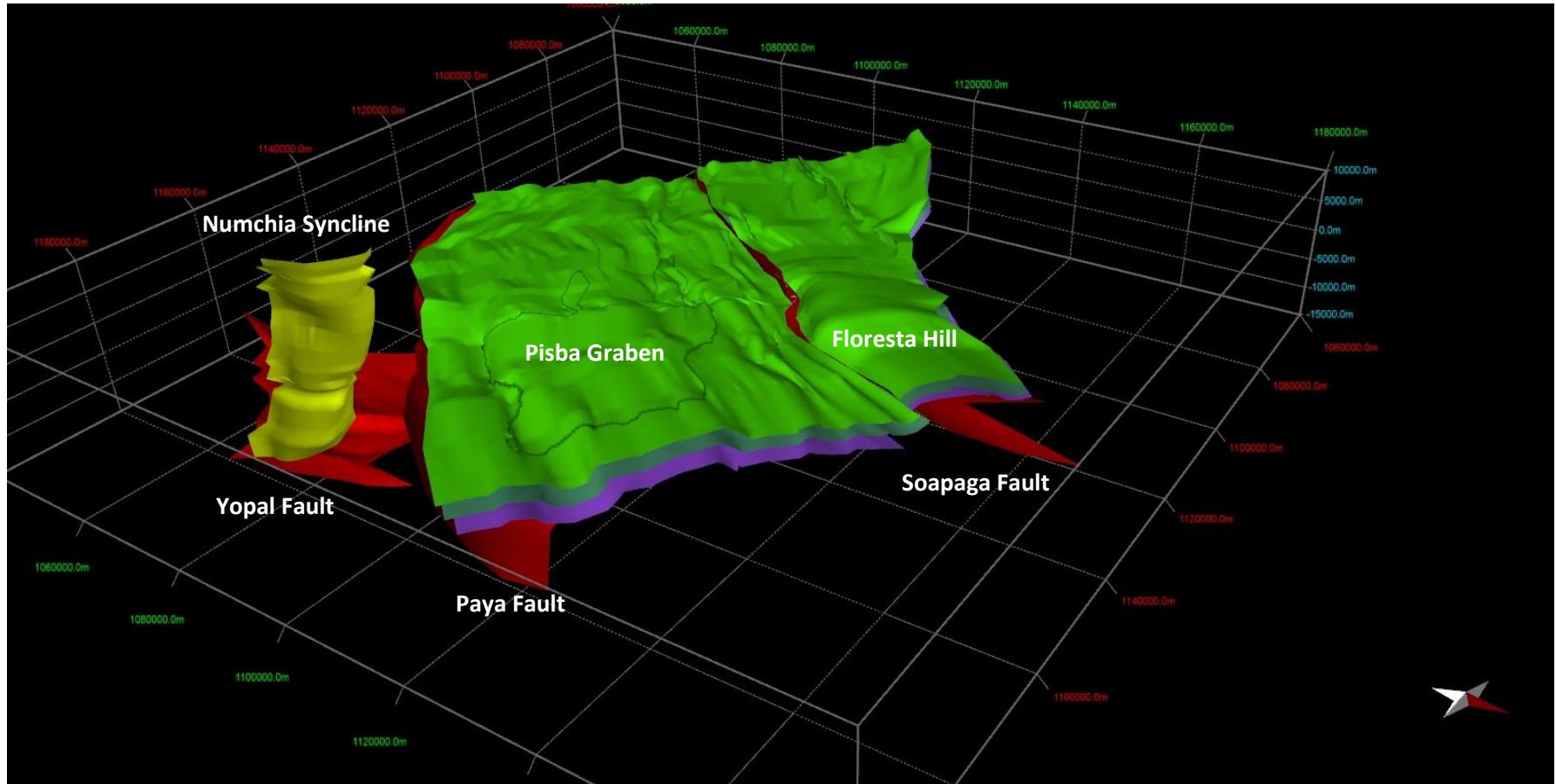
3. CASE STUDY

Example from one of the 30 cross sections



3. CASE STUDY

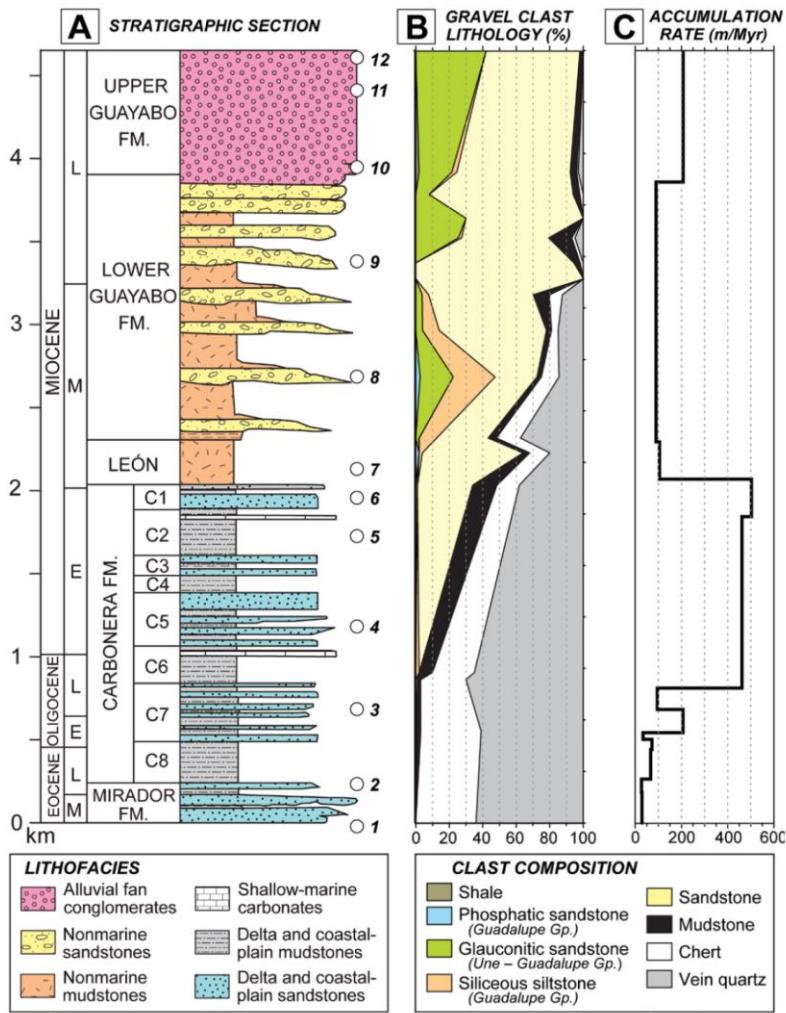
Preliminary 3D mapping



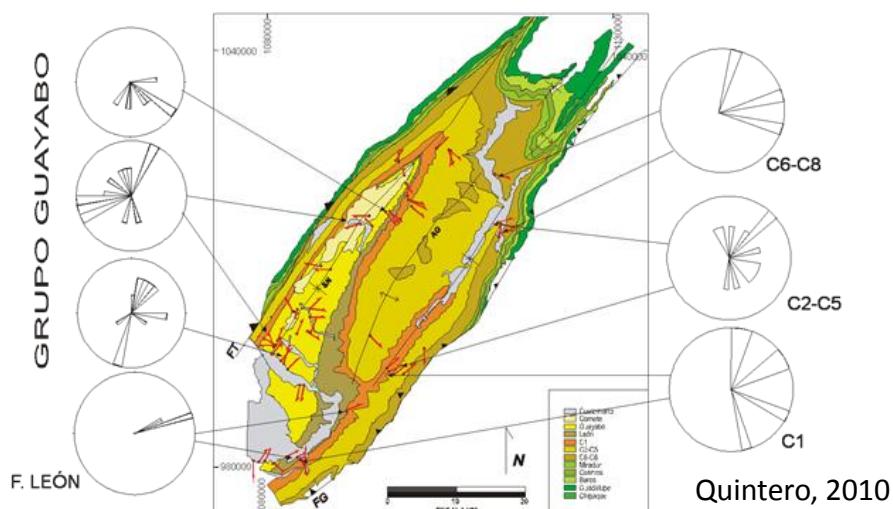
Assessment of relative sequence of deformation, sedimentation rates, paleoelevation, erosion and cooling history for sequential restoration

Paleocurrents

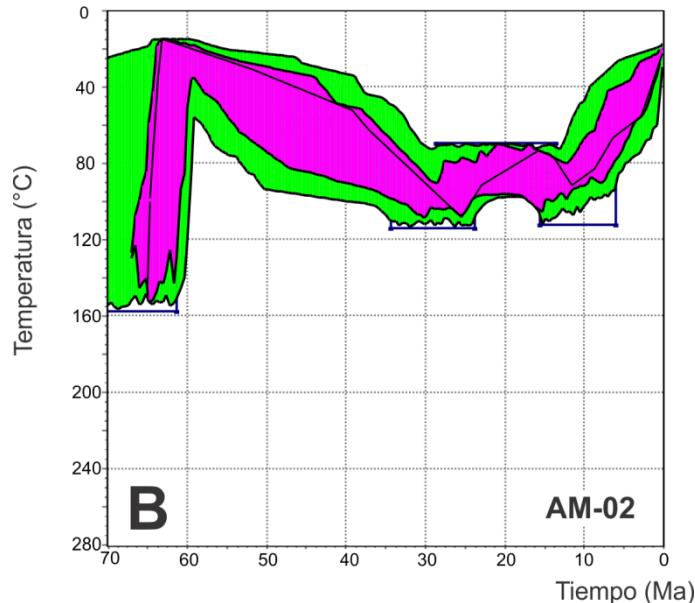
Provenance



Parra et al., 2009

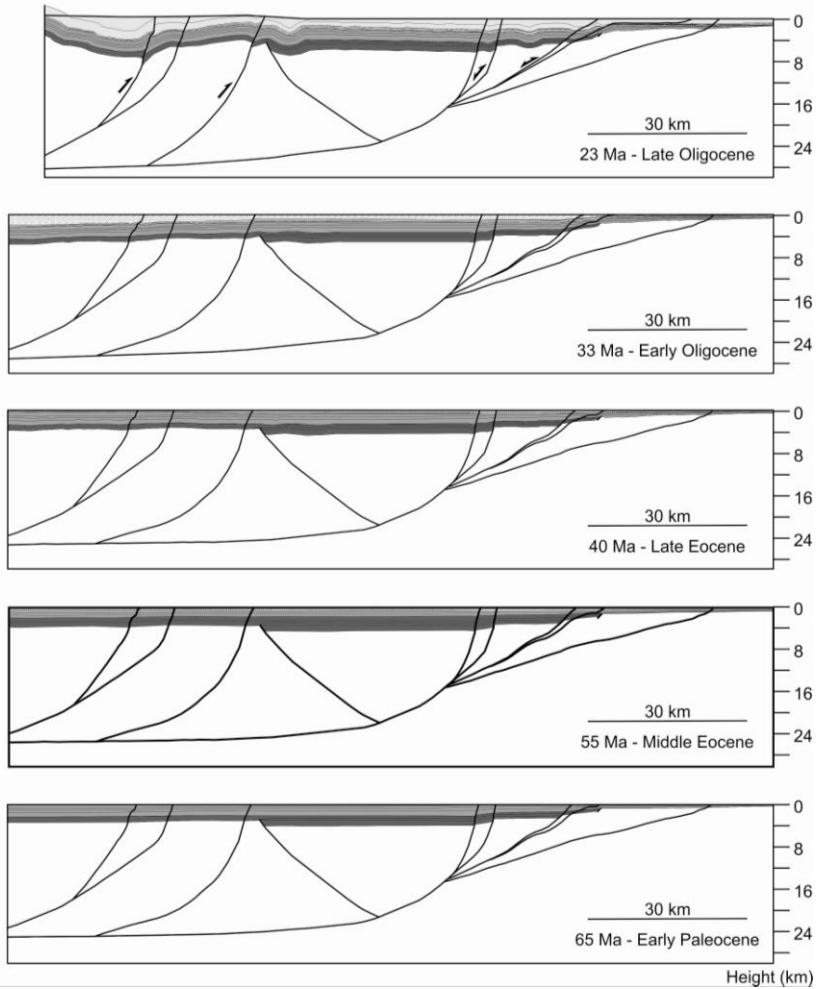
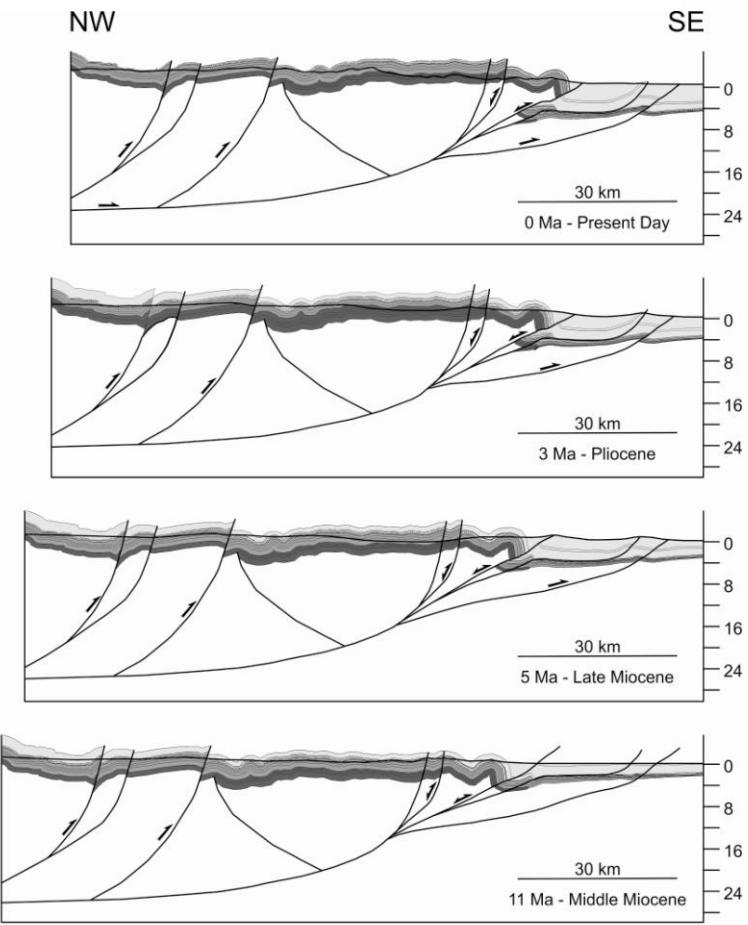
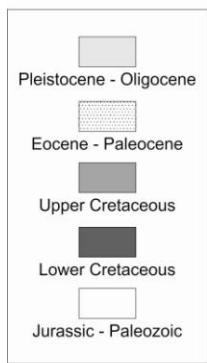


Thermochronology



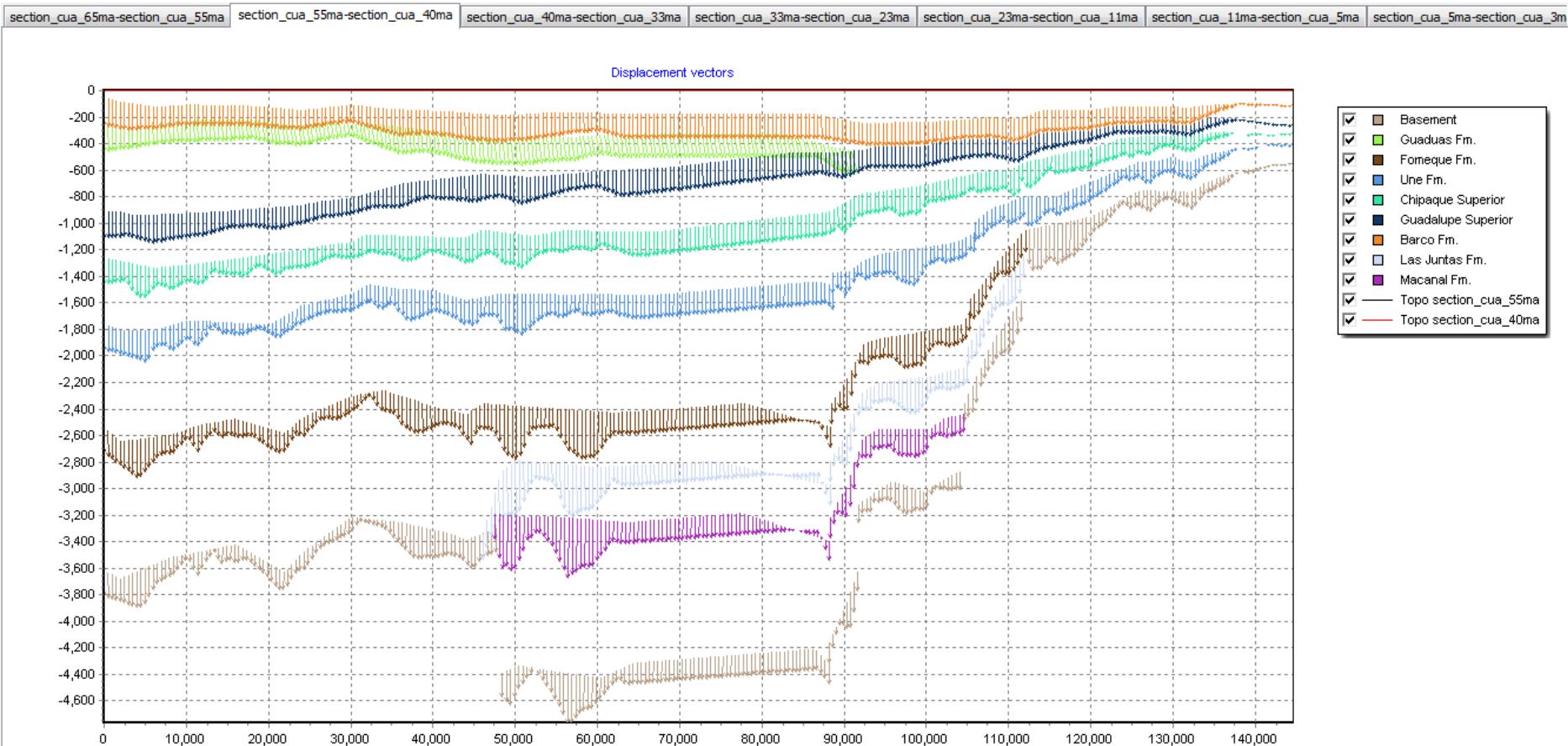
3. CASE STUDY

Sequential Restoration



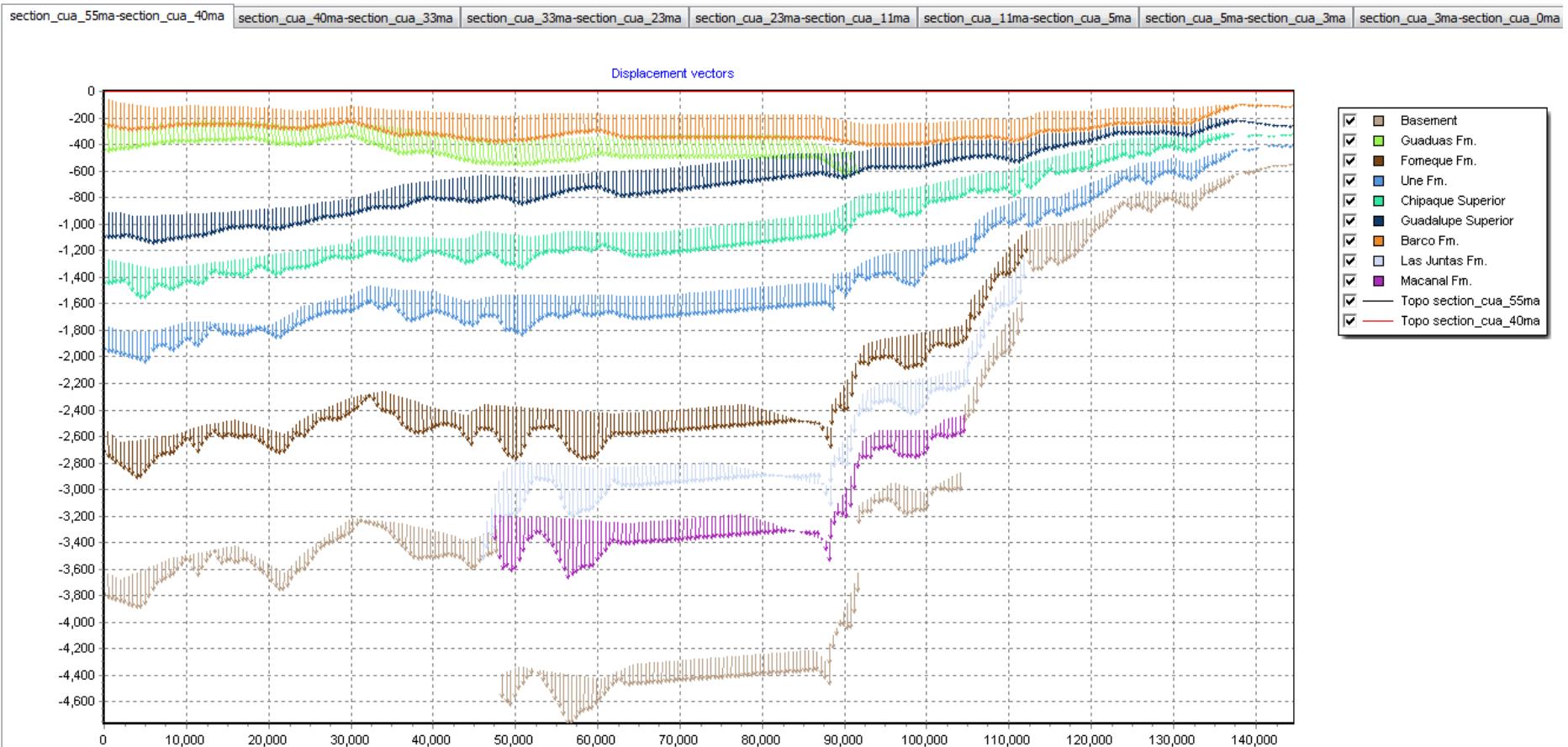
3. CASE STUDY

Movement vectors from Fetkin-prep



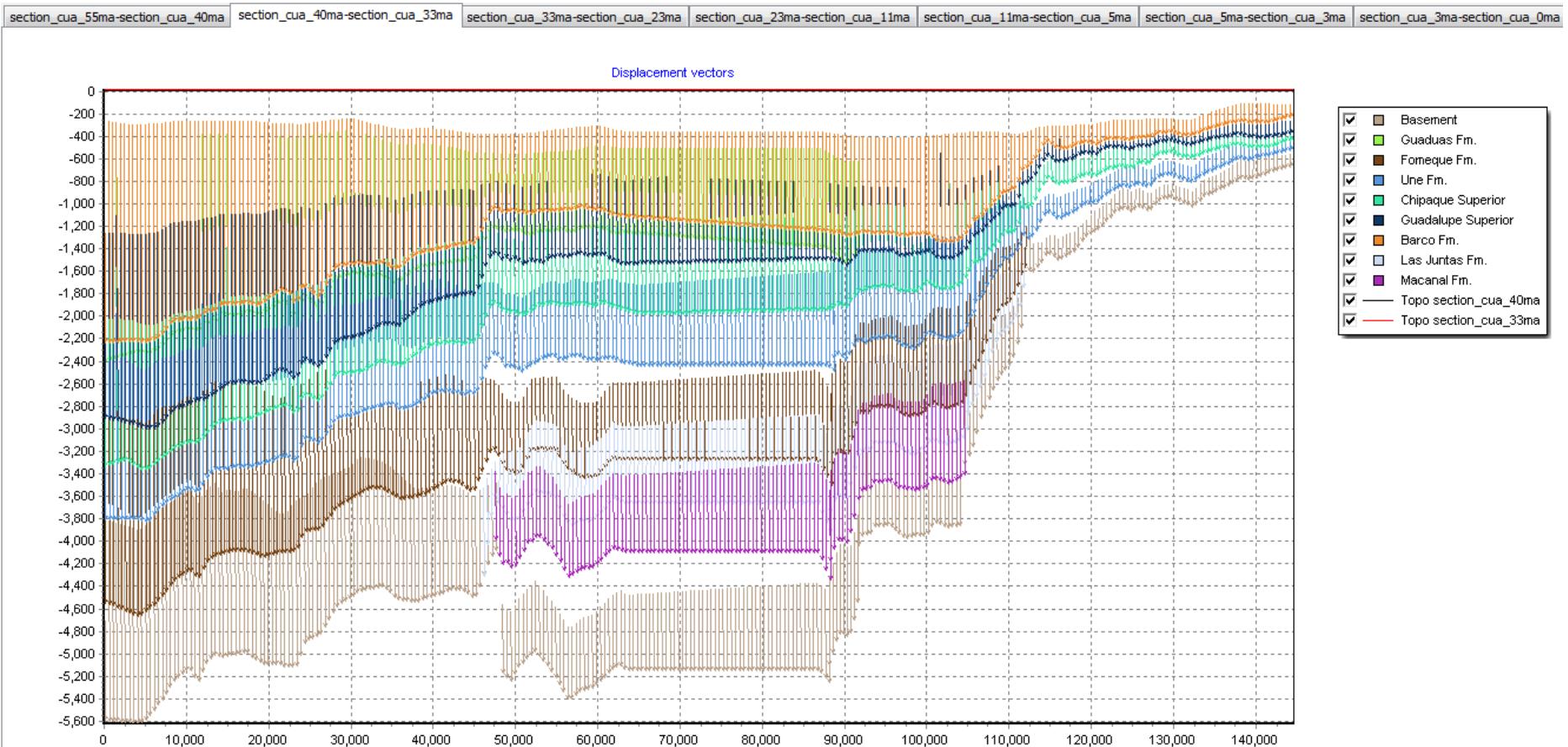
3. CASE STUDY

Movement vectors from Fetkin-prep



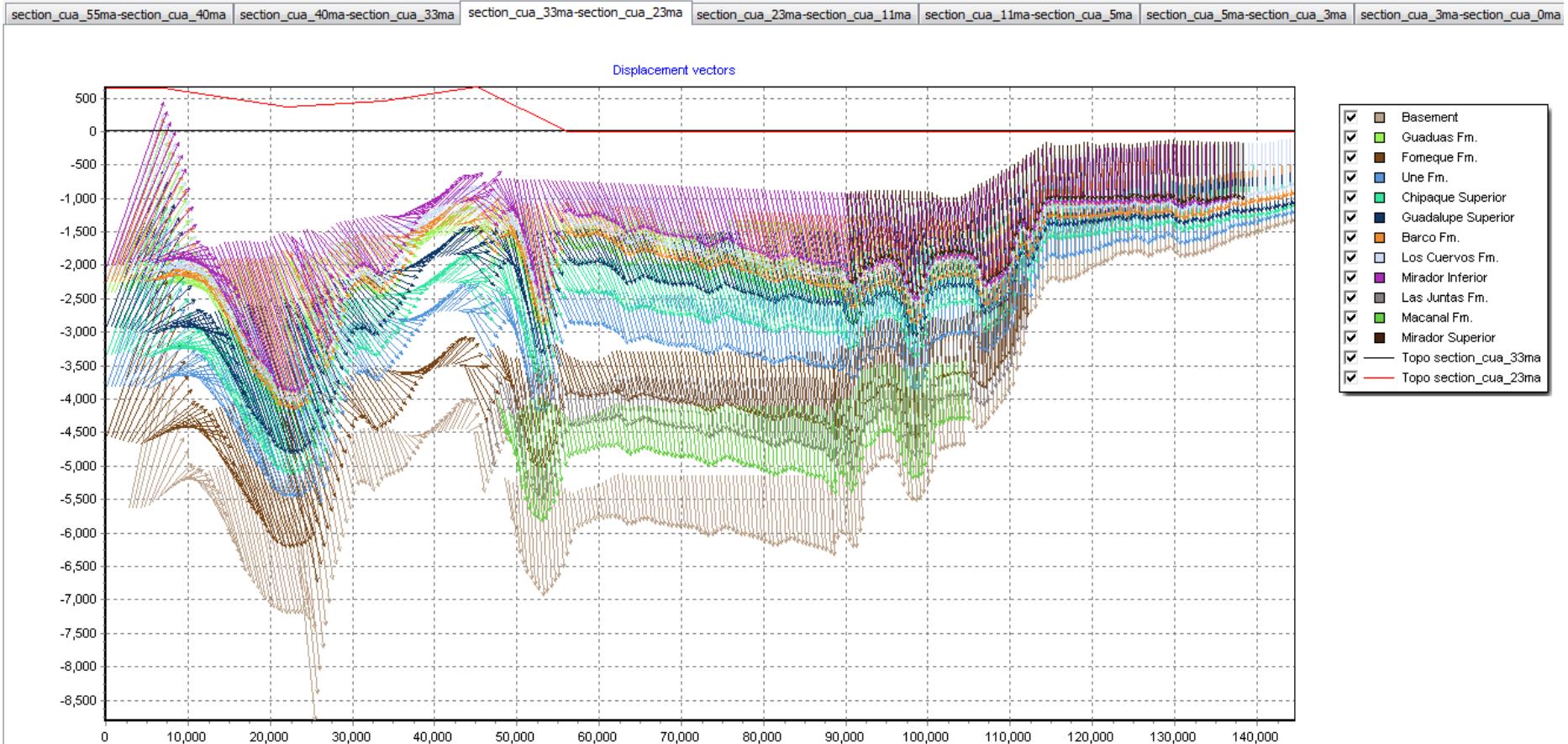
3. CASE STUDY

Movement vectors from Fetkin-prep



3. CASE STUDY

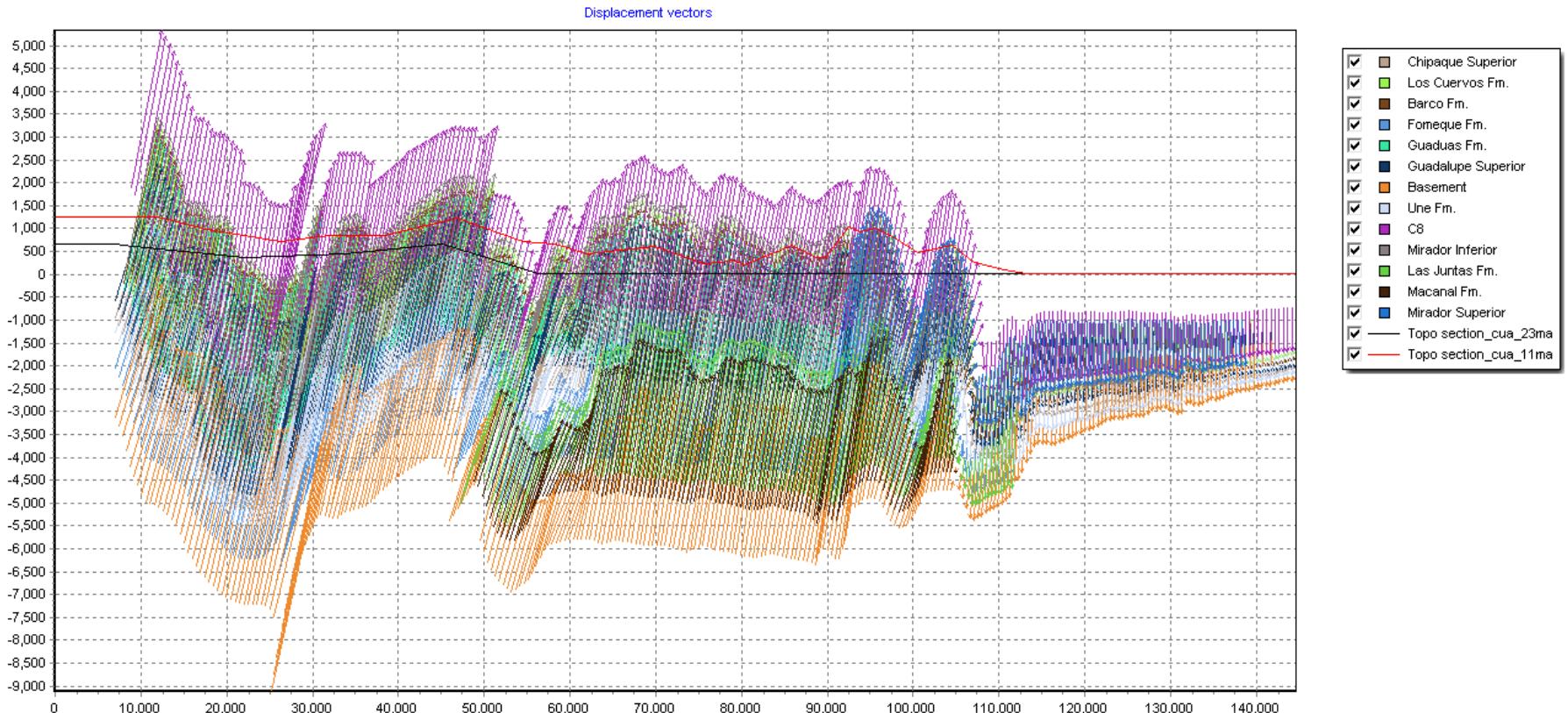
Movement vectors from Fetkin-prep



3. CASE STUDY

Movement vectors from Fetkin-prep

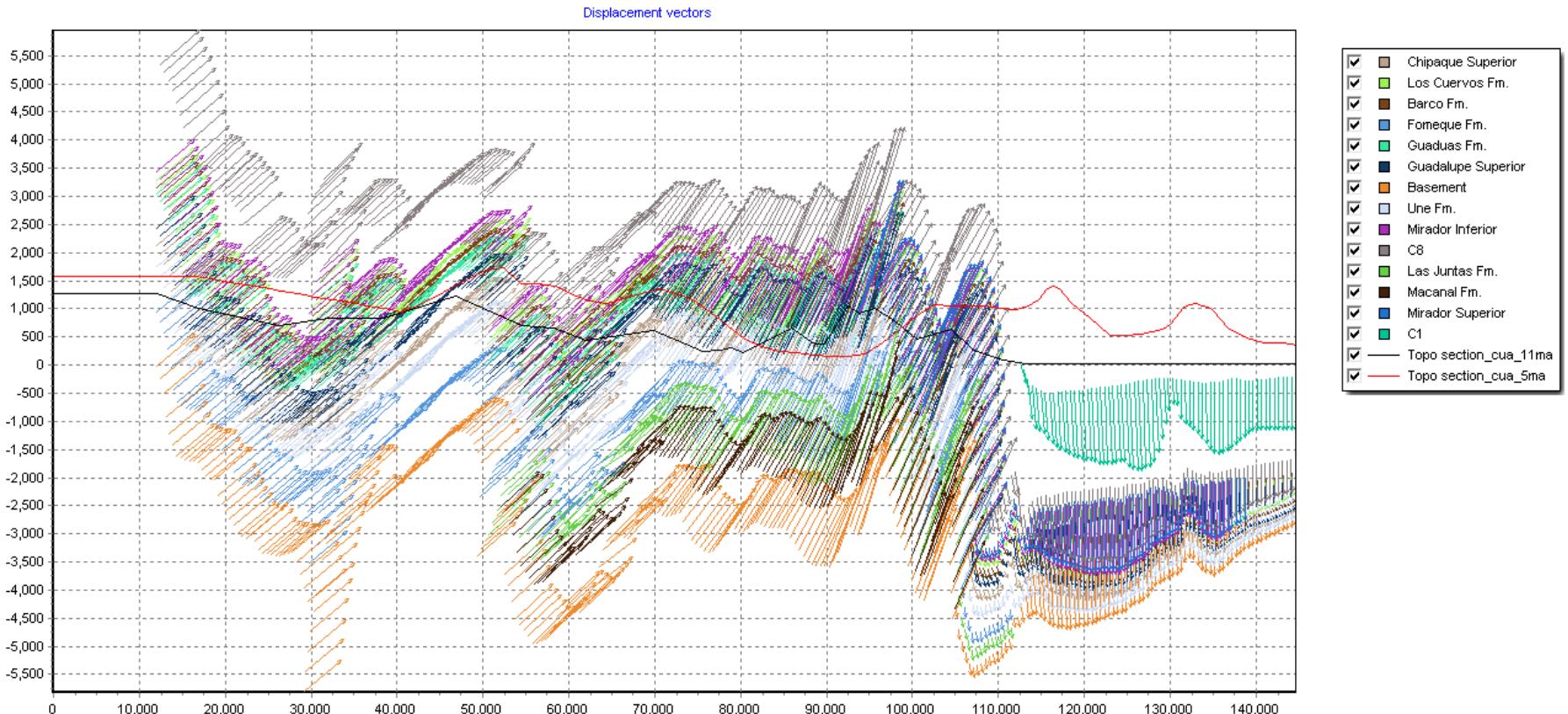
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3. CASE STUDY

Movement vectors from Fetkin-prep

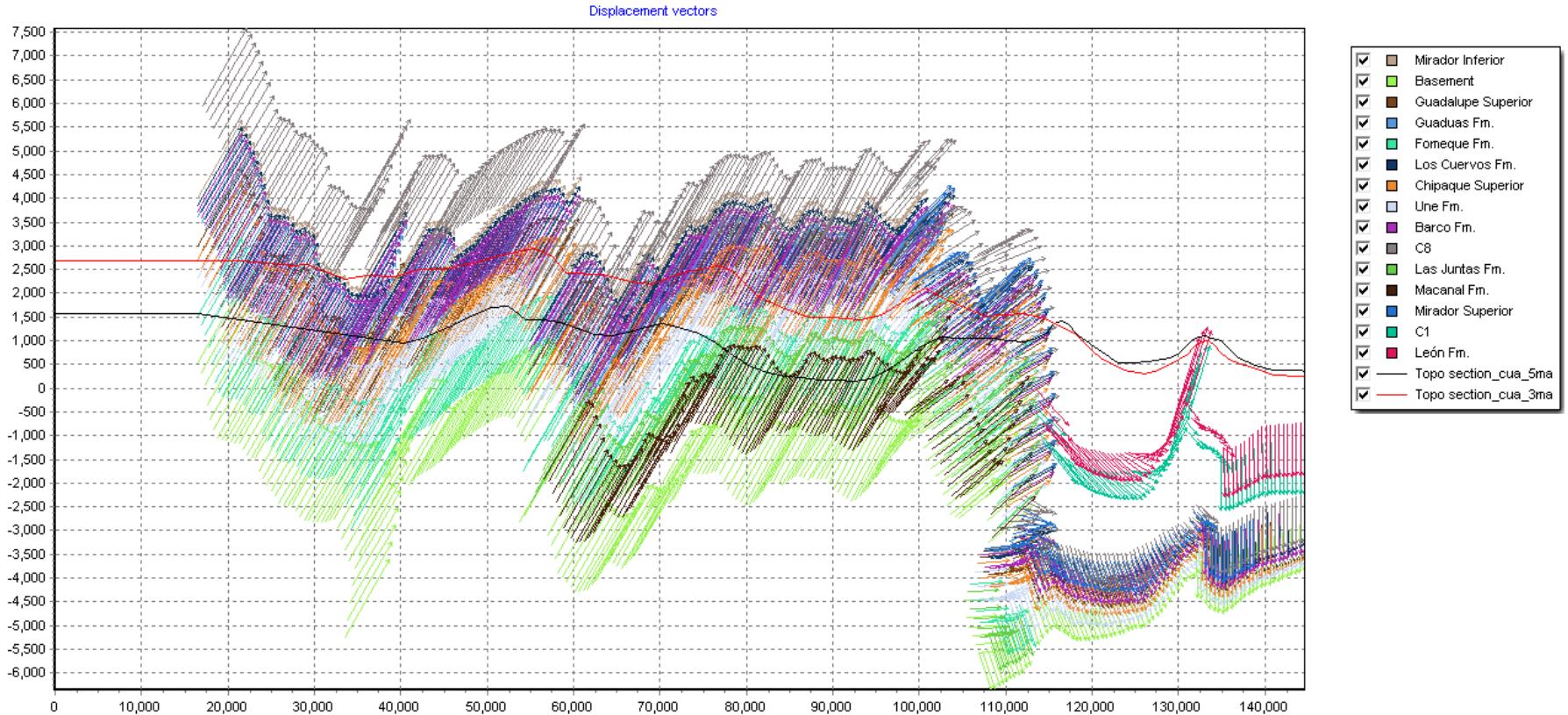
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3. CASE STUDY

Movement vectors from Fetkin-prep

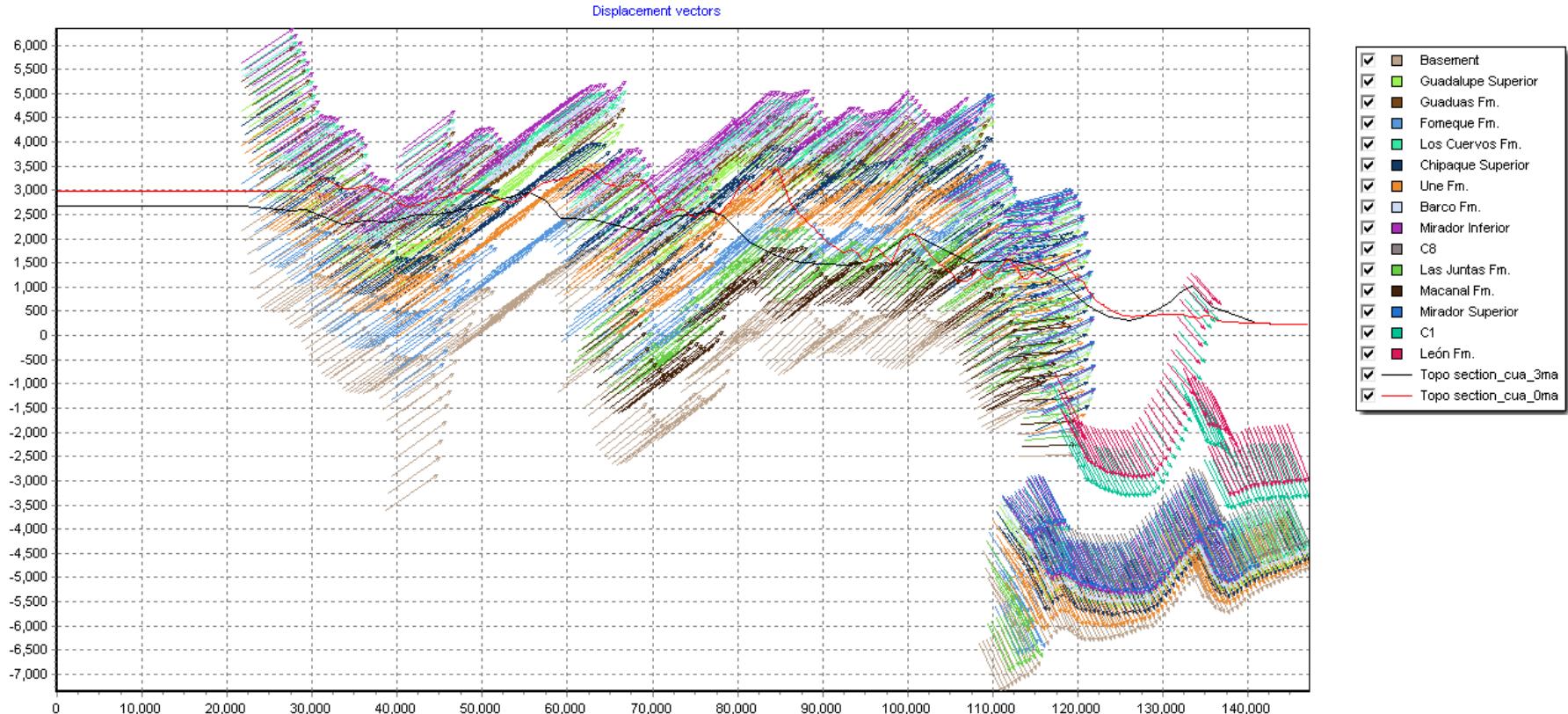
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3. CASE STUDY

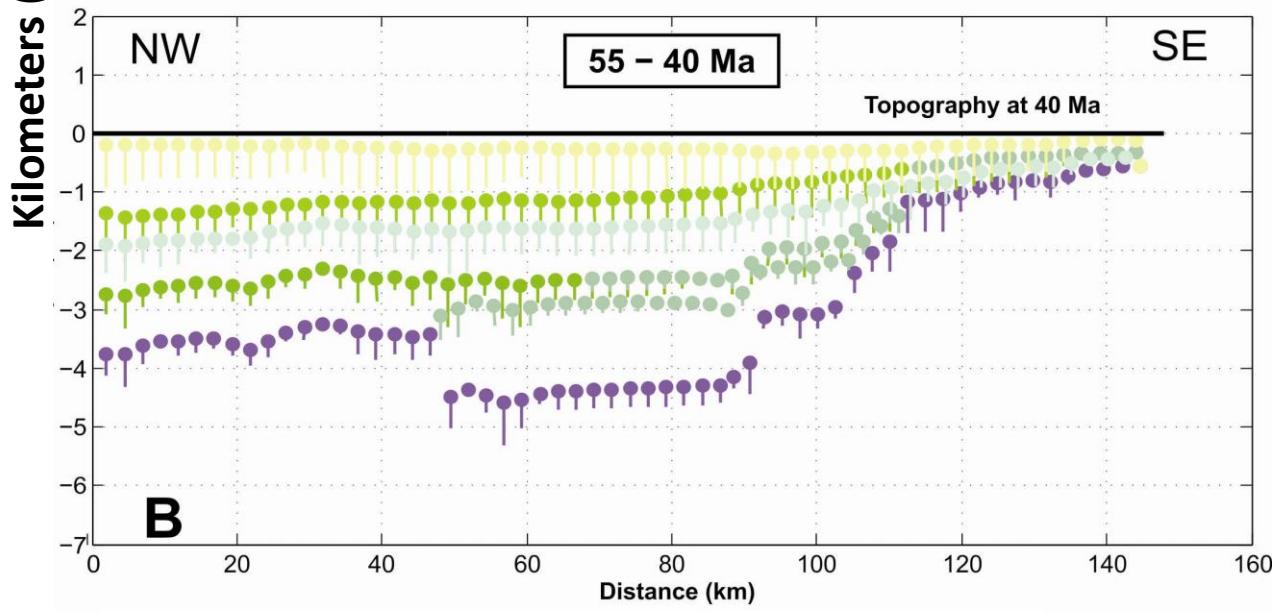
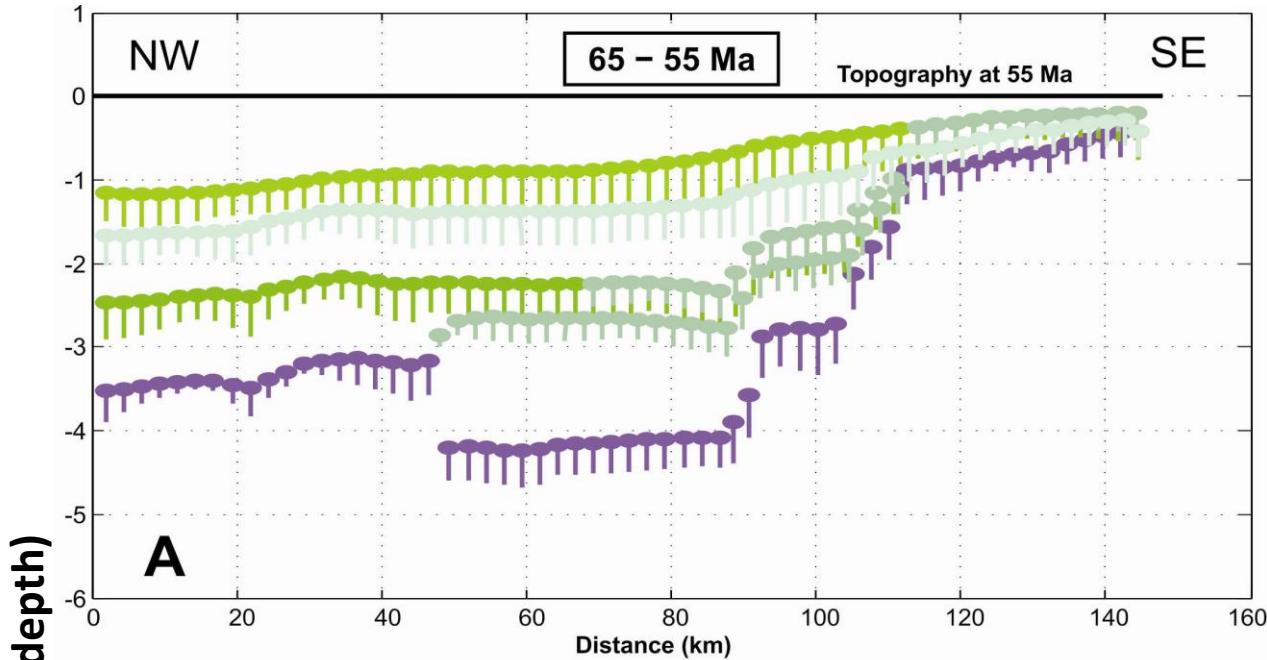
Movement vectors from Fetkin-prep

section_cua_55ma-section_cua_40ma | section_cua_40ma-section_cua_33ma | section_cua_33ma-section_cua_23ma | section_cua_23ma-section_cua_11ma | section_cua_11ma-section_cua_5ma | section_cua_5ma-section_cua_3ma | section_cua_3ma-section_cua_0ma



3. CASE STUDY:

Simplified representation of the movement vectors

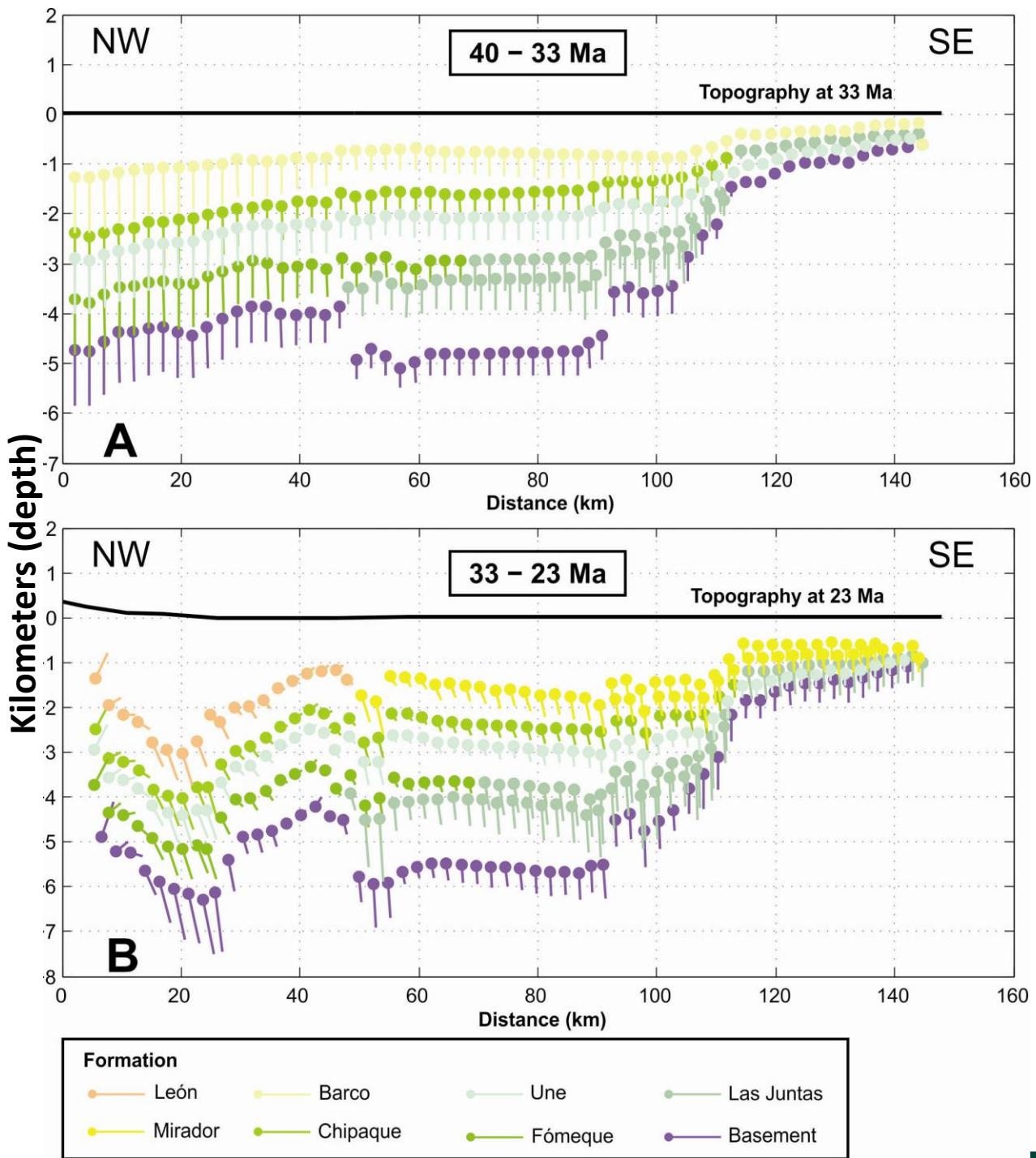


Formation	León	Barco	Une	Las Juntas
Mirador	●	●	●	●
Chipaque	●	●	●	●
Fómeque	●	●	●	●
Basement	●	●	●	●



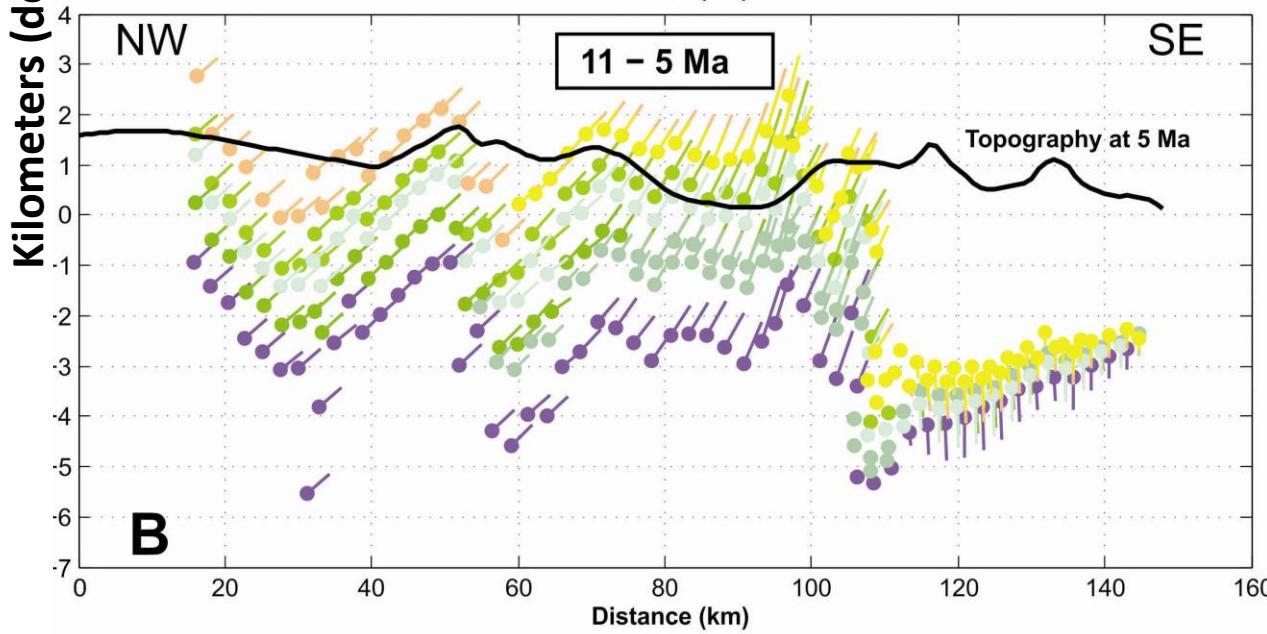
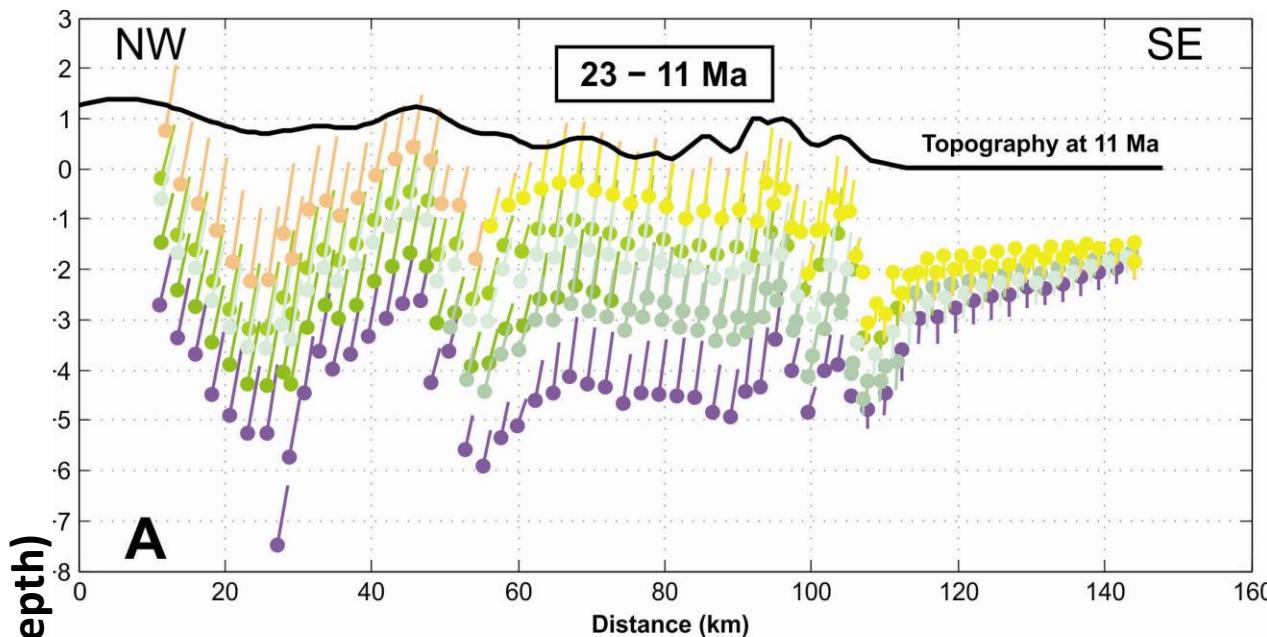
3. CASE STUDY:

Simplified representation of the movement vectors



3. CASE STUDY:

Simplified representation of the movement vectors

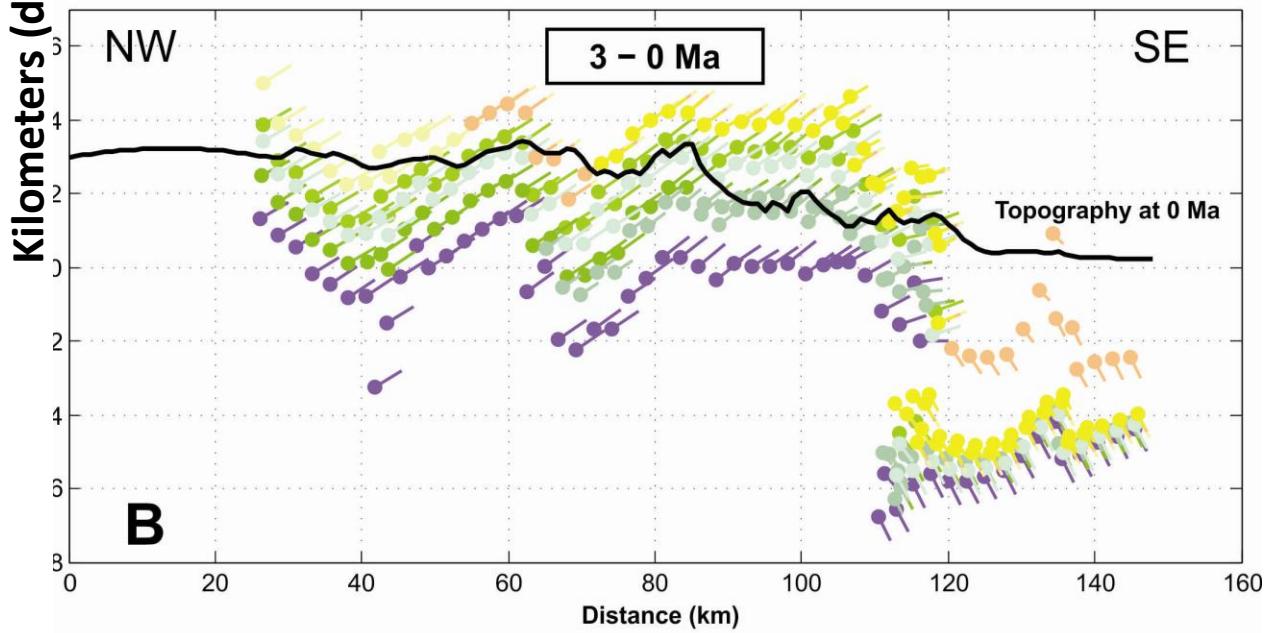
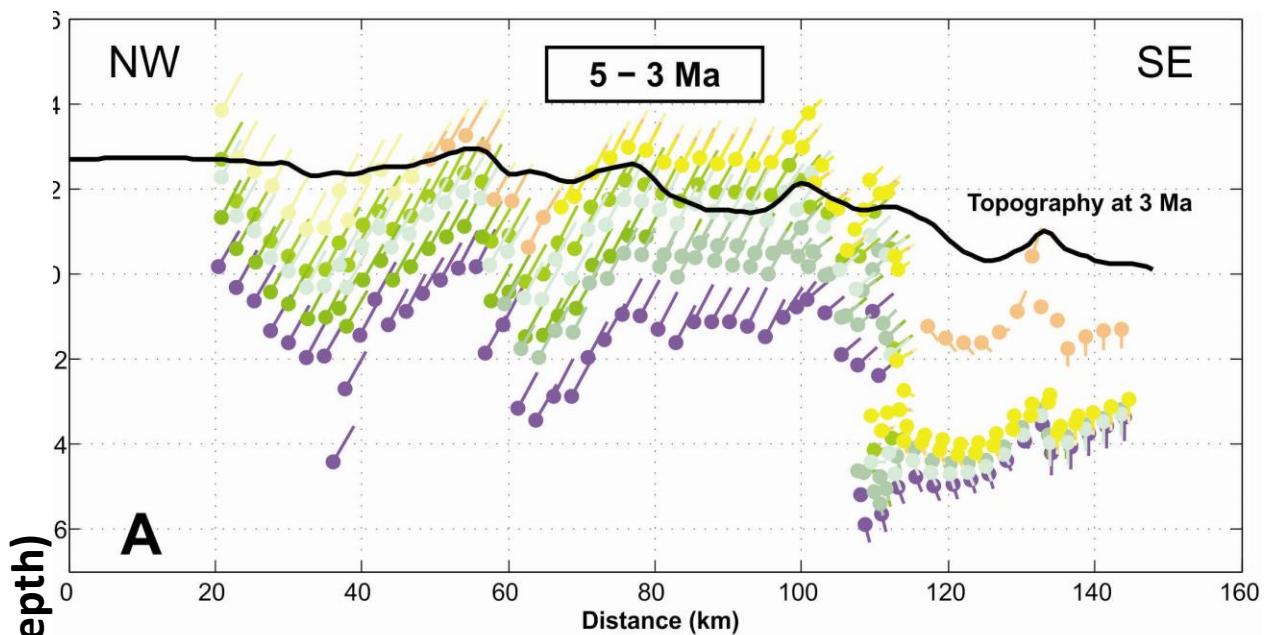


Formation				
León	Barco	Une	Las Juntas	
Mirador	Chipaqué	Fómeque	Basement	



3. CASE STUDY:

Simplified representation of the movement vectors

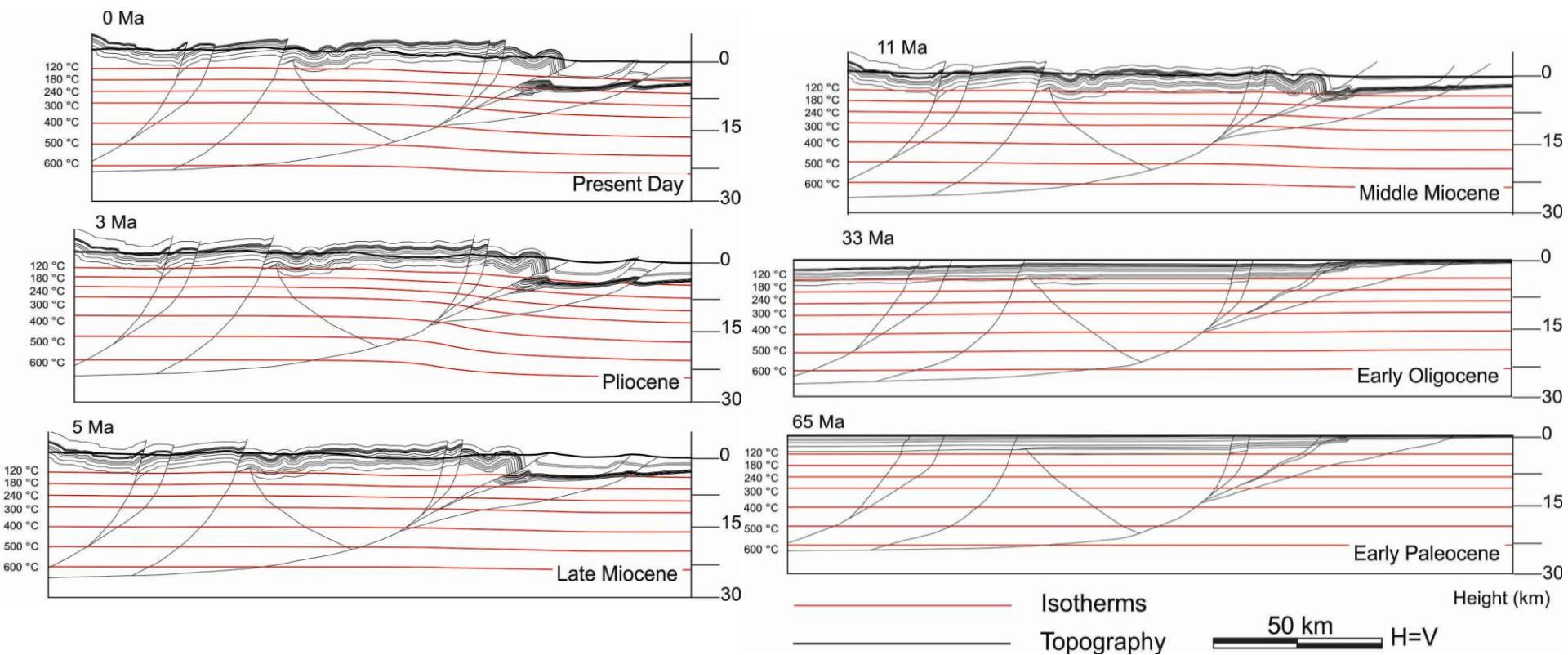


Formation	León	Barco	Une	Las Juntas
Mirador	●	●	●	●
Chipaqué	●	●	●	●
Fómeque	●	●	●	●
Basement	●	●	●	●



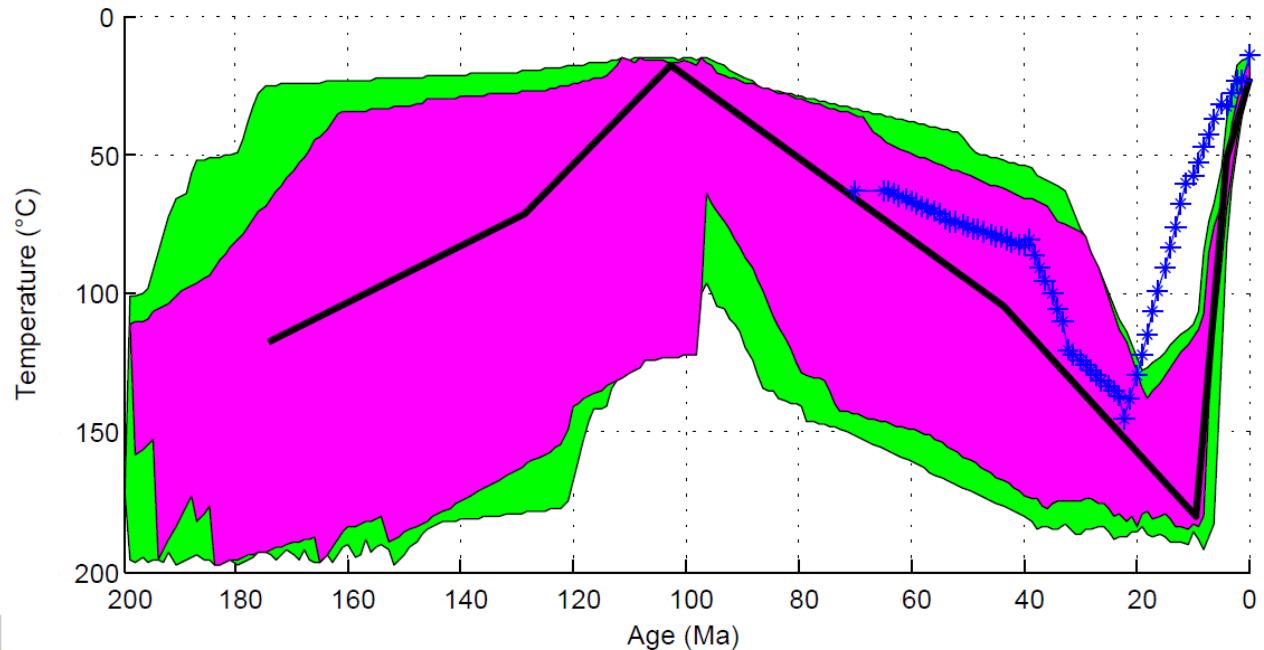
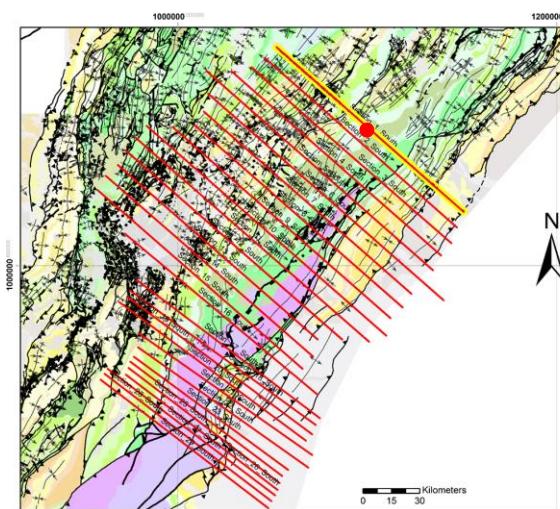
CASE STUDY

Isotherms derived in Fetkin from movement vectors obtained in Fetkin-prep



CASE STUDY

Comparison between AFT thermal models and forward modelled thermal histories in Fetkin

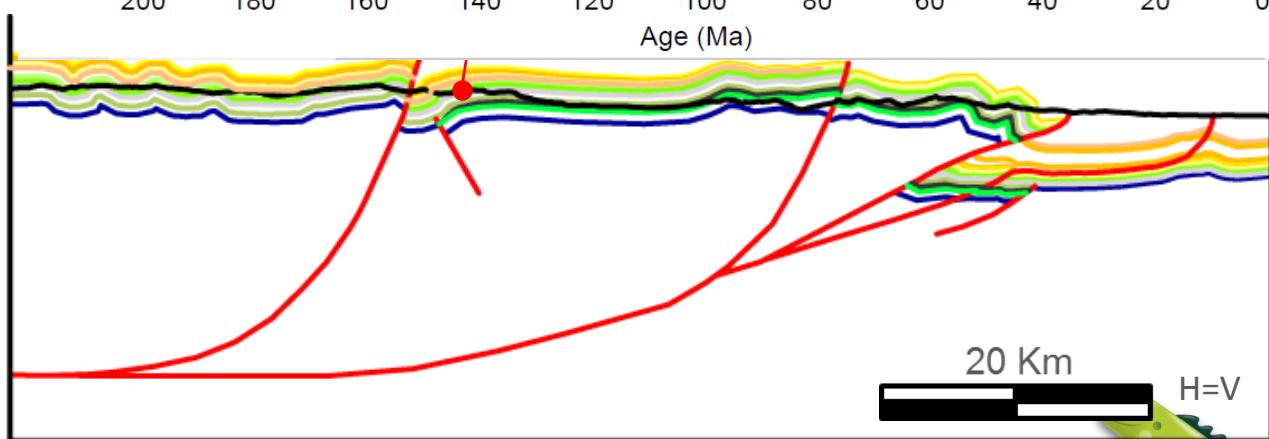


Section_1_South

NW

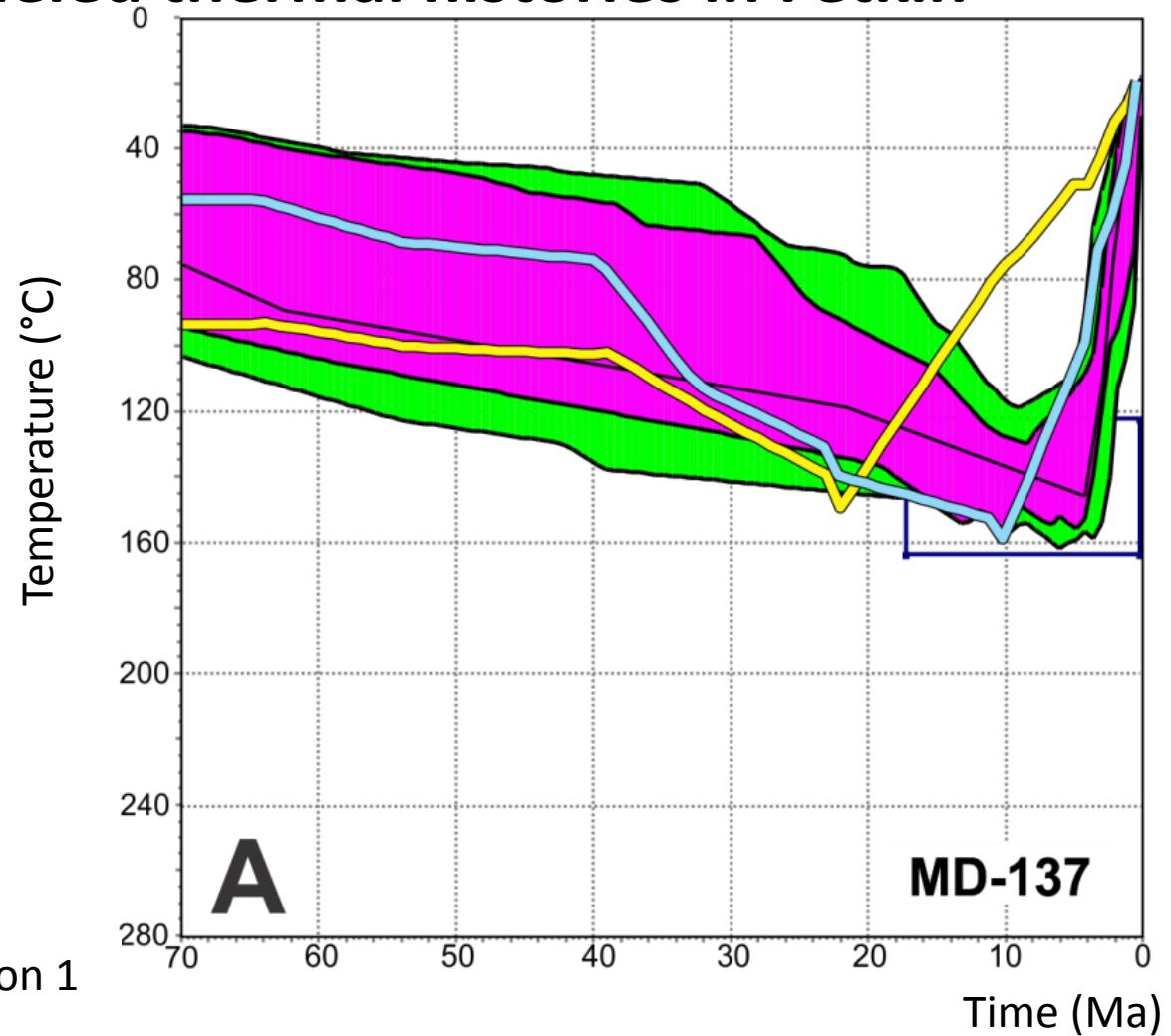
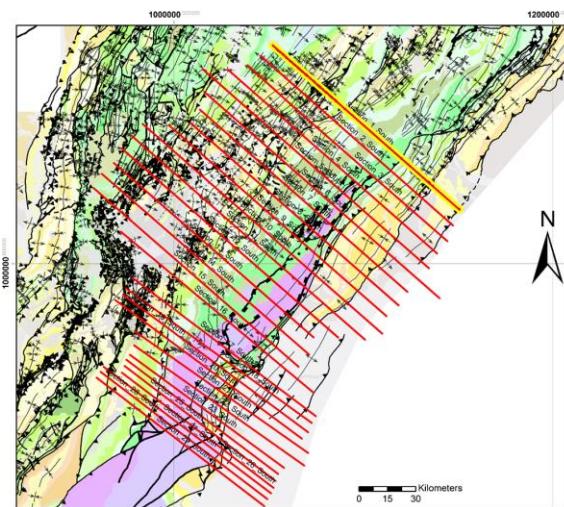
0 Ma

+ Fetkin forward
modelled sample



CASE STUDY

Comparison between AFT thermal models and forward modeled thermal histories in Fetkin



Fetkin forward model

Sequential restoration 1

Sequential restoration 2



4. CONCLUSIONS



4. CONCLUSIONS

- *FETKIN AND FETKIN-PREP PROVED TO BE A GOOD WAY TO CALIBRATE CROSS SECTIONS BEFORE PETROLEUM SYSTEMS MODELLING
- *FETKIN-PREP YIELDS MOVEMENT VECTORS RESTRICTED BY DENUDATION, ROCK AND SURFACE UPLIFT, HORIZONTAL SHORTENING AND COOLING HISTORIES. THEREFORE THEY CAN SHOW DEFORMATION PATHS.
- *UNEXPECTED VERTICAL UPLIFT PRESSUMABLY RELATED WITH HOMOGENEOUS FLATTENING CHALLENGE THE CONVENTIONAL WISDOM REGARDING DEFORMATION MECHANISMS IN CONTRACTIONAL SETTINGS.
- * THERE IS A LOT OF FUTURE USING THESE TECHNIQUES TO UNDERSTAND DEFORMATION MECHANISMS.





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