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

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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


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

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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

Western foothills

Restrepo-Pace et al., 2004
**KINEMATIC RESTORATIONS**

Key tool for petroleum system modelling

Restrepo-Pace et al., 2004
KINEMATIC RESTORATIONS
Key tool for petroleum system modelling

Western foothills

Paleocene

Growth strata

Restrepo-Pace et al., 2004
KINEMATIC RESTORATIONS
Key tool for petroleum system modelling

Restrepo-Pace et al.,
2004
KINEMATIC RESTORATIONS
Key tool for petroleum system modelling

Western foothills

Late Oligocene

Growth strata

Restrepo-Pace et al., 2004
KINEMATIC RESTORATIONS
Key tool for petroleum system modelling

Western foothills

Present

24 km
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
KINEMATIC RESTORATIONS
In absence of growth strata thermochronometric data can be used
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.
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

Shortening: 15.8 Km
3 Ma-Present

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
Reconstructing complete deformational histories: Manual Approach

~4 km
~ 120°C
(@ 25°C/km)

5 Ma

ICP (2009) Structural Geology Group
FROM AGES TO DEFORMATION HISTORIES

Temperature

750.
646.
543.
439.
336.
232.
129.
25.0

ApatiteFTAge

30 Ma, Onset of Model
FROM AGES TO DEFORMATION HISTORIES

Present (0 Ma)
THERMOKINEMATIC MODELLING

- SEISMIC: TIME TO DEPTH CONVERSION:
  - PUNCTUAL DATA: CHECK SHOT/VSP
  - 3D DATA: TOMOGRAPHY

- thermochronology: TEMPERATURE TO DEPTH AND SHORTENING RATES.
  - PUNCTUAL DATA: thermochronoMETERS (AFT)
  - 3D DATA: THERMOKINEMATIC MODELLING
What controls temperature through time?

Heat Equation (for two dimensions)

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

\(\rho\): density
\(c\): heat capacity
\(\kappa\): 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)
THERMOKINEMATIC MODELLING

FETKIN: Example
THERMOKINEMATIC MODELLING

Almendral et al., in review
CASE STUDY: EASTERN CORDILLERA
No growth strata/ a lot of thermocron data

Escalona & Mann, 2011

Legend:
- Oil and gas with thermogenic, Cretaceous source
- Dry gas and condensate with possible biogenic-thermogenic sources of Tertiary age
- Dry gas with possible biogenic source of Tertiary age
- Gas hydrates
- Hydrocarbon fields
CASE STUDY

TIMING OF DEFORMATION AND HYDROCARBON PROVINCES

1. Chichimene
2. Cusiana
3. Tame

HIGH API VALUES

LOW API VALUES

Legend
- 3D Seismic
- Oil Fields

0 20Km
4° N 74° W
3° N 73° W
CASE STUDY: PECUBE (3D)
CASE STUDY: PECUBE (3D)
Cross section with velocities
CASE STUDY: PECUBE (3D)
Cooling ages on surface
CASE STUDY: PECUBE (3D)

Topographic growth
CASE STUDY: PECUBE (3D)

Isotherm advection
CASE STUDY

1. 2D KINEMATIC RESTORATION: MANUAL APPROACH

Early Paleocene
(58 Ma)
CASE STUDY

1. 2D KINEMATIC RESTORATION: MANUAL APPROACH

Early Oligocene
(27 Ma)
CASE STUDY

1. 2D KINEMATIC RESTORATION: MANUAL APPROACH

Early Miocene
(20 Ma)
CASE STUDY

1. 2D KINEMATIC RESTORATION: MANUAL APPROACH

Middle Miocene
(9 Ma)
CASE STUDY

1. 2D KINEMATIC RESTORATION: MANUAL APPROACH

Late Miocene (5Ma)
1. 2D KINEMATIC RESTORATION: MANUAL APPROACH

Present (0 Ma)

- Neogene Molasse
- Lower Cretaceous
- Jurassic
- Pre-Mesozoic

CASE STUDY

Arcabuco Anticline
Quetame Massif
Guaduas Area
Llanos Basin

km 0

50 Km
CASE STUDY

CALIBRATION OF 2D & 3D COMPARING SHORTENING RATES

South Transect shortening rates (650 C Moho)

2D

3D

Estimate from Mora et al., 2012

Pecube model results

shortening rate (mm/yr)

time (Ma)
CASE STUDY: FETKIN RESULTS

Lower Cretaceous source rocks in the oil window

Early Paleocene (58 Ma)

- 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

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

Early Oligocene (27 Ma)

<table>
<thead>
<tr>
<th>Depth (km)</th>
<th>Temp (°C)</th>
<th>Vitrinite Reflection</th>
<th>Subsurface process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30°C</td>
<td>0.5</td>
<td>Diagenesis</td>
</tr>
<tr>
<td>2</td>
<td>60°C</td>
<td>0.5</td>
<td>Katagenesis</td>
</tr>
<tr>
<td>3</td>
<td>90°C</td>
<td>1.2</td>
<td>Metagenesis</td>
</tr>
<tr>
<td>4</td>
<td>120°C</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>150°C</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

Isotherm advection is not significant

Early Miocene (20 Ma)

Samples

- Isotherms
- 50Km

- Chipaque Fm. (Upper Cretaceous Source Rock)
- Fomeque Fm. (Lower Cretaceous Source Rock 1)
- Macanal Fm. (Lower Cretaceous Source Rock 2)
CASE STUDY: FETKIN RESULTS

Middle Miocene (9 Ma)

Isotherm advection is not significant

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

Isotherm advection is not significant

Late Miocene
(5Ma)

Samples

50Km

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

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

Present (0 Ma)

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

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

Present (0 Ma)

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

Legend:
- BLOQUES
- SISMICA 3D
- CAMPOS

0 20 Km
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:
CASE STUDY

COMPARISON WITH THE AGE OF THE TRAPS

1. Chichimene:

- Intra-Oligocene
- Top Eocene
- Top Cretaceous
- Top Paleozoic
CASE STUDY

COMPARISON WITH THE AGE OF THE TRAPS

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

COMPARISON WITH THE AGE OF THE TRAPS

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

➢ THERMOCRONOLOGY 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 ISOETHERM 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).
THANK YOU