Energy & Geoscience Institute
AT THE UNIVERSITY OF UTAH

IN DEVELOPMENT

Petroleum Migration History Models for Foreland Basins: Colombian Foreland

Evaluation of the timing, paths & mixing locations of hydrocarbon migration events affecting the Llanos foreland basin, Colombia

Principal Investigator:

Michal Nemčok, Ph.D.
Research Professor

Email: mnemcok@egi.utah.edu
Phone: +421-2-2062 0781

Investment per Sponsor
$57K (USD)

Duration
12 months

Project I 01286

VALUE

- Determination of the flexural forebulge location of the Llanos foreland basin in time.
- Determination of the flexure-driven normal fault patterns of the Llanos foreland basin in time and space.
- Determination of major mountain building events of the Eastern Cordillera in time and space.
- Determination of the major advance events of the Eastern Cordillera in time and space.
- Determination of the expulsion timing in the hydrocarbon kitchens of all recognized oil families.
- More detailed determination of the spatial distribution of results of each individual migration pulse.
- Determination of lateral and vertical migration segments of each migration pulse.

KEY DELIVERABLES

1. Arc GIS project including all data, profiles and maps addressing problems to be solved, which are listed in the Task list.
2. Written report with accompanying graphic documentation on the results of the tasks focused on individual open problems listed in the Task list.

EMAIL:
ContactEGI@egi.utah.edu

PHONE: (801) 585-3826

Data Sources

Type of Data	Quantity
Reflection seismic profiles for geoseismic trace sections and geological cross sections	20,000 km of 2D images tied to a larger number of wells not specified for confidentiality reasons (Figure 1A)
Gravity data	Coverage of the whole study area by the Free-air and Bouguer gravity anomaly maps
Magnetic data	Coverage of the whole study area by the Total magnetic intensity map (Figure 2)
Geochemical data	Initial dataset contains (Figure 1B): -479 crude oil bulk analyses -461 oil GCs -305 extract GCs -151 oil biomarkers -19 extract biomarkers -4876 TOC measurements -2079 pyrolysis measurements -1004 reflected light organic petrography analyses -519 transmitted light organic petrography analyses In-project analytical work is expected to contain: up to 15 GC-MSMS analyses of oil, 10-15 extract GC-MS analyses of source rocks

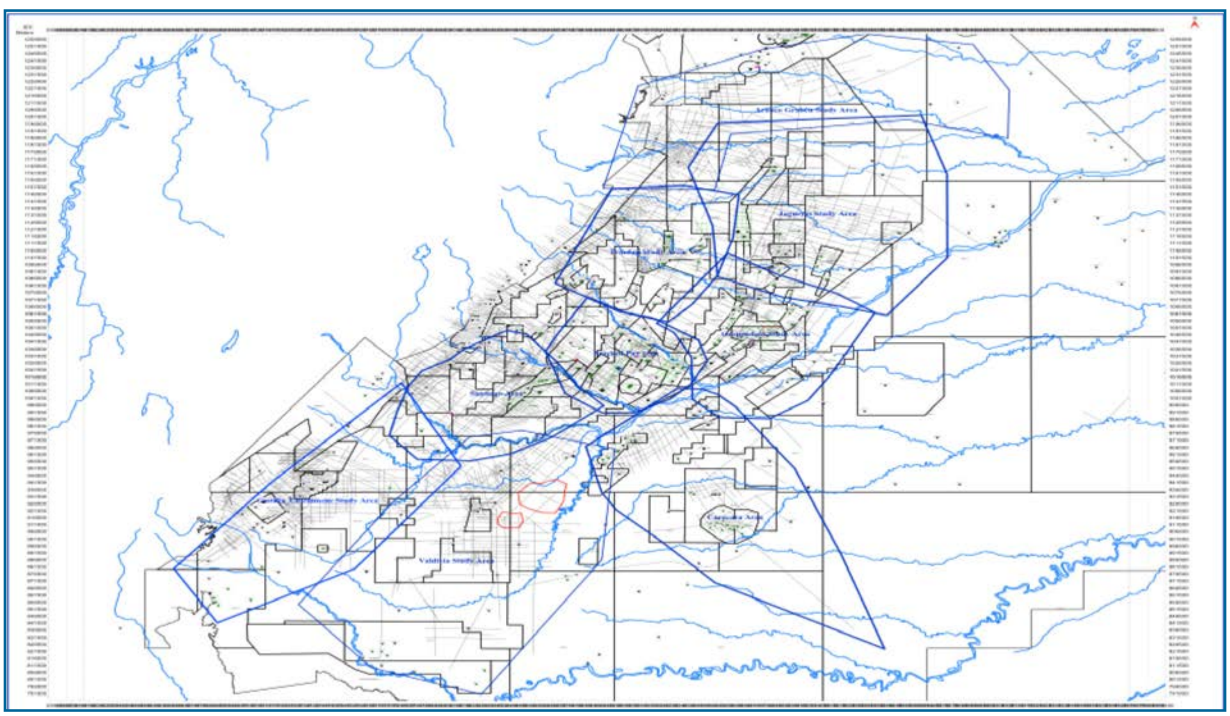


Figure 1A: Map of the provinces used for spatial differentiation in the Llanos foreland basin with location of studied seismic profiles and wells (provided by Remora for Nemčok et al., 2009, 2010).

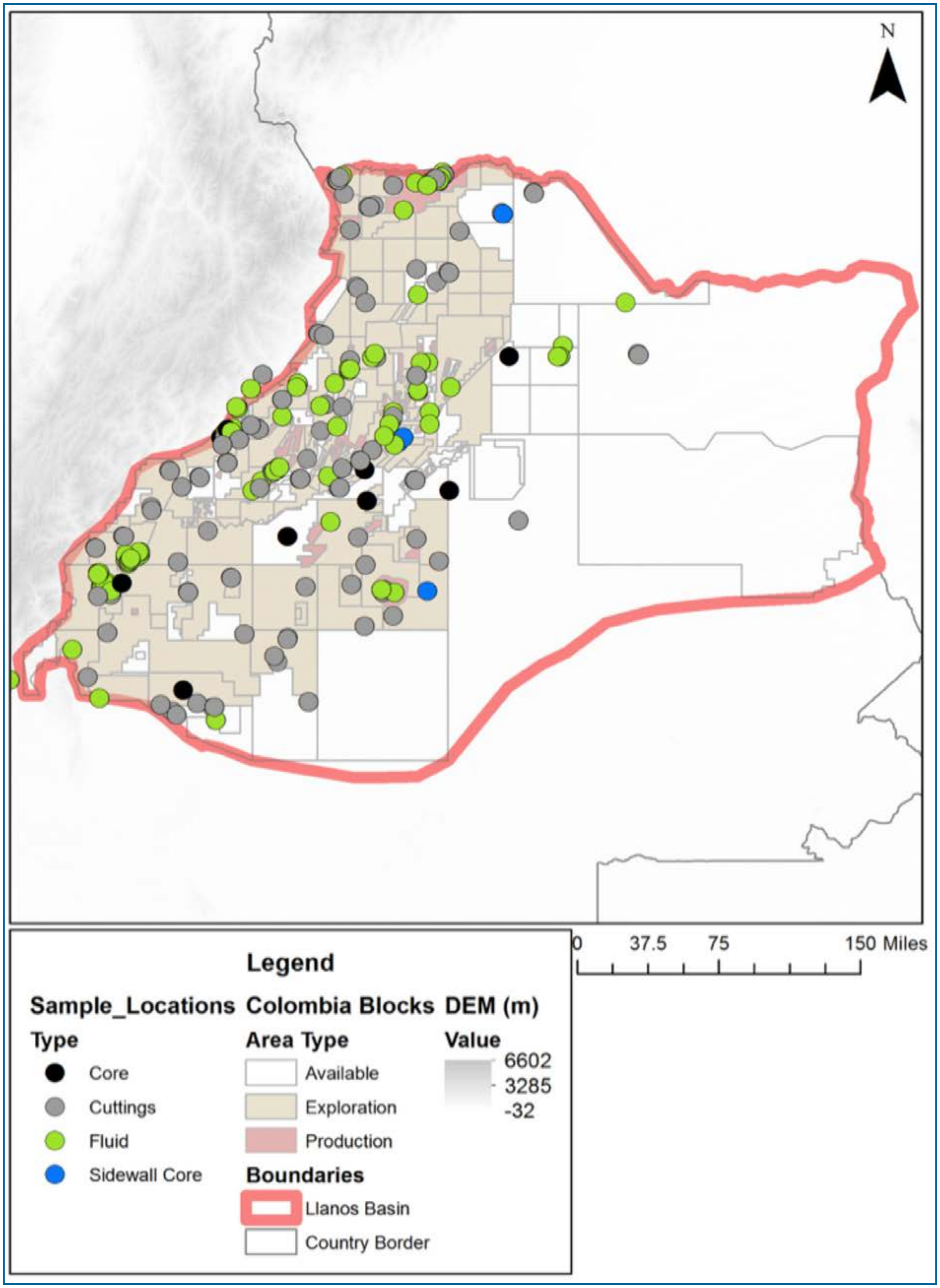


Figure 1B: Location map of samples already taken from the Llanos foreland basin.

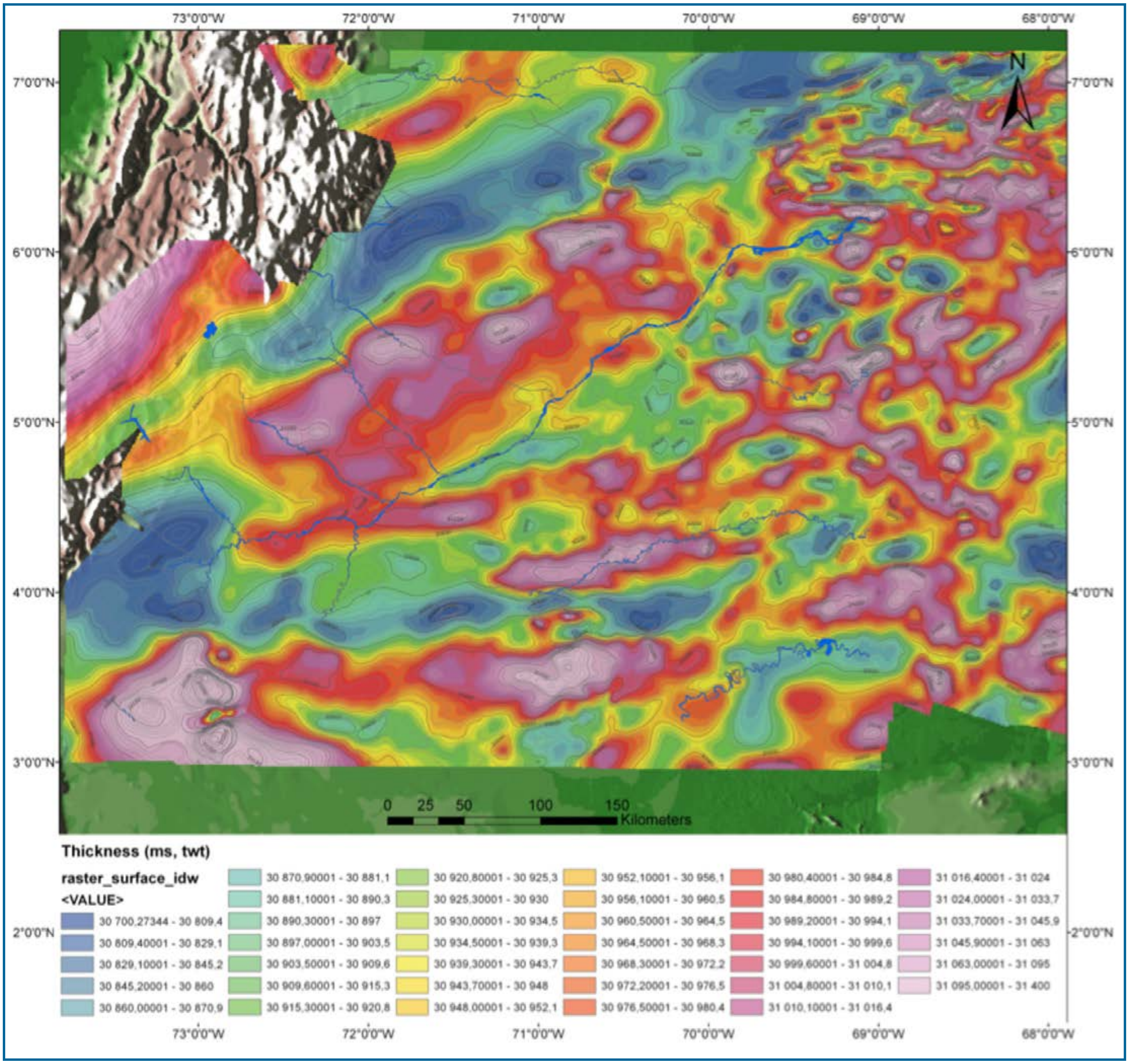


Figure 2: Total magnetic intensity map of the study area (Hermeston et al., 2011).

Significance & Rationale

Foreland strata accretion into the developing thrustbelt taper (Figure 3A and 2) accelerated sediment transport from the emergent portion of the orogen undergoing mountain building (Figure 3B) control a relatively rapid burial of the proximal portion of the foreland basin. They are the most prominent factors affecting the expulsion timing from the organic rich strata residing under and inside the foreland basin fill.

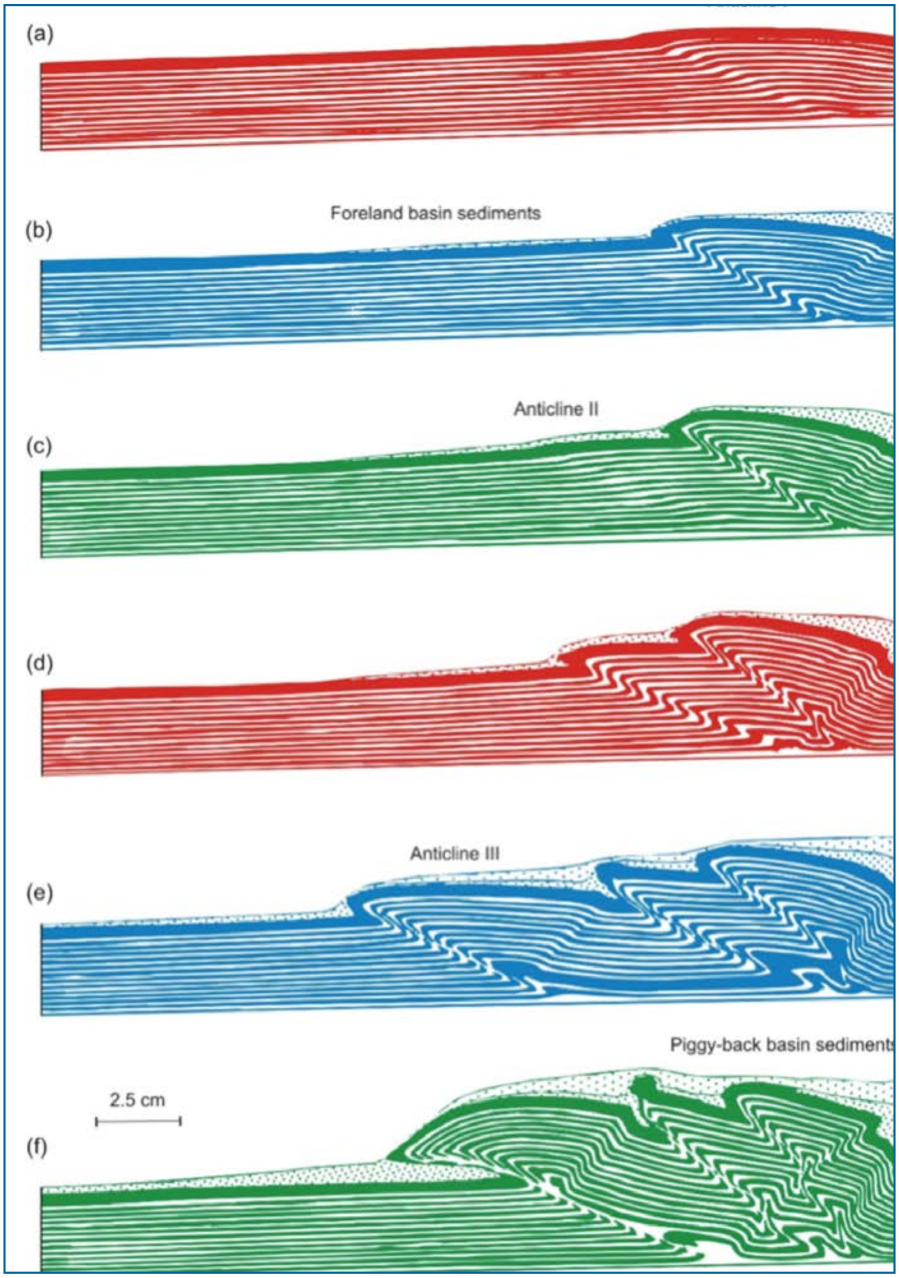


Figure 3A: Line drawings from time-lapse photographs of a sandbox model with syn-tectonic deposition, after contraction of a) 6 mm, b) 14 mm, c) 22 mm, d) 30 mm, e) 54 mm and f) 90 mm (Storti et al., 1997). Black layer indicates top of the pre-tectonic sediments.

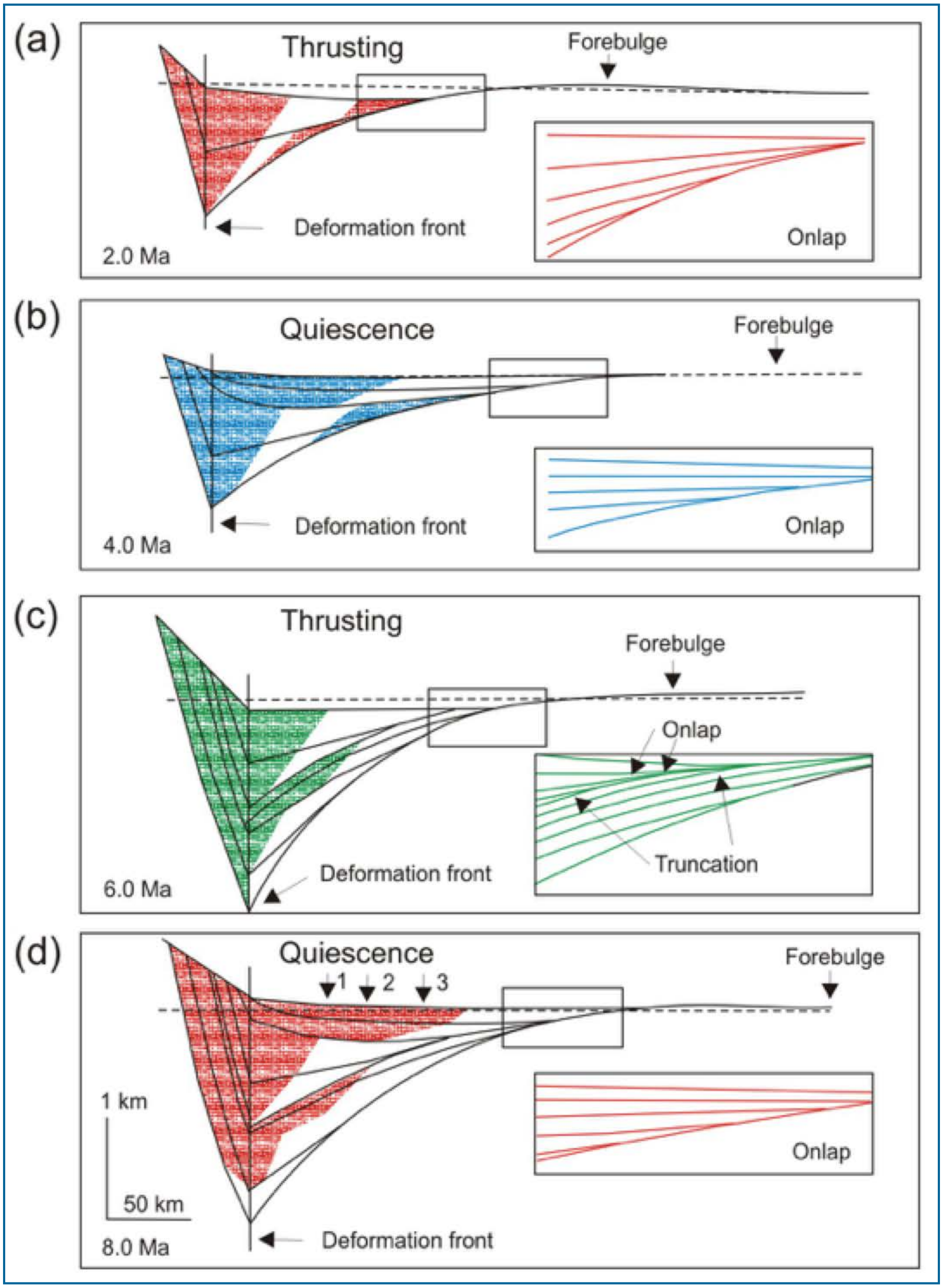


Figure 3B: Stratigraphic evolution of a foreland basin during 8 Ma, shown at 2 Ma intervals (Flemings and Jordan, 1990). Time lines show 1 Ma intervals. Vertical exaggeration is 40 times. Shading indicates basin margin facies, which were deposited at a gradient greater than 0.0005. Basin-axis facies, accumulated at a smaller gradient are unshaded. Right margin of the basin is amplified in boxes and 200,000 year lines are used to illustrate onlap and truncation at vertical exaggeration of 100 times. Bedding on the left side has been uplifted and deformed by leading edge of the thrust belt. Thrust belt advance was 20 km during the second phase of thrusting.

If the contraction driving the thrustbelt and foreland basin development is orthogonal to thrustbelt and basin axes, hydrocarbon expulsion from source rocks of the same stratigraphic age is more-or-less synchronous along strike. However, the timing can quickly gain more complex character if the contraction is either oblique to the axis of linear thrustbelt-foreland basin system or fanning inside of salients and reentrants of the curved thrustbelt-foreland basin system.

Starting with simpler of the two systems, the Phase 1 study focuses on the Llanos foreland basin of Colombia (Figure 4), while the second system is planned to be covered by subsequent Phase 2 and 3 studies that would focus on Andean foreland basins of Argentina and Peru-Bolivia, respectively.

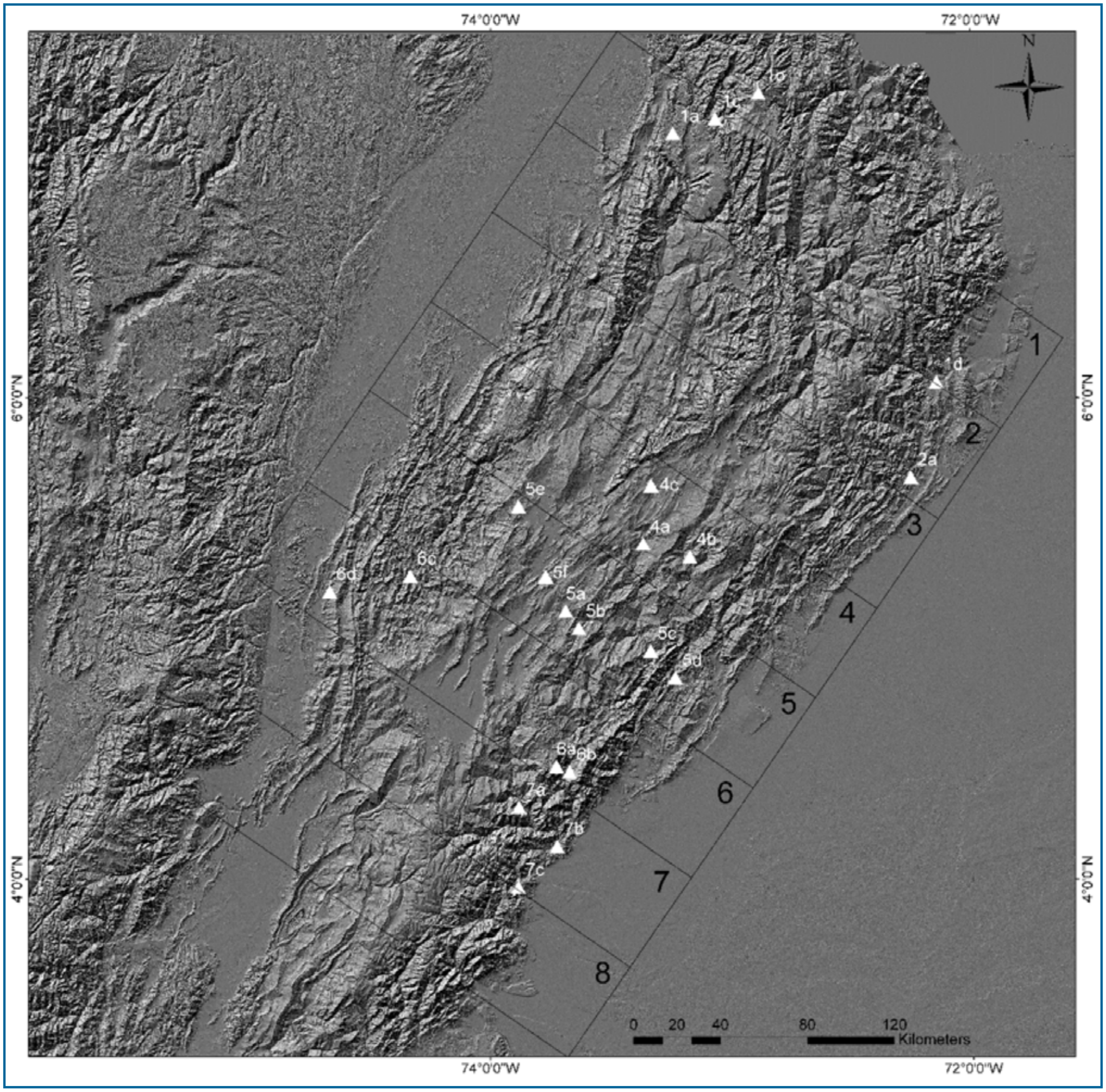


Figure 4A: Study area with map of the Eastern Cordillera, studied portion of the Colombian segment of the Andes, together with location of exhumation timing data (Hermeston and Nemčok, 2013).

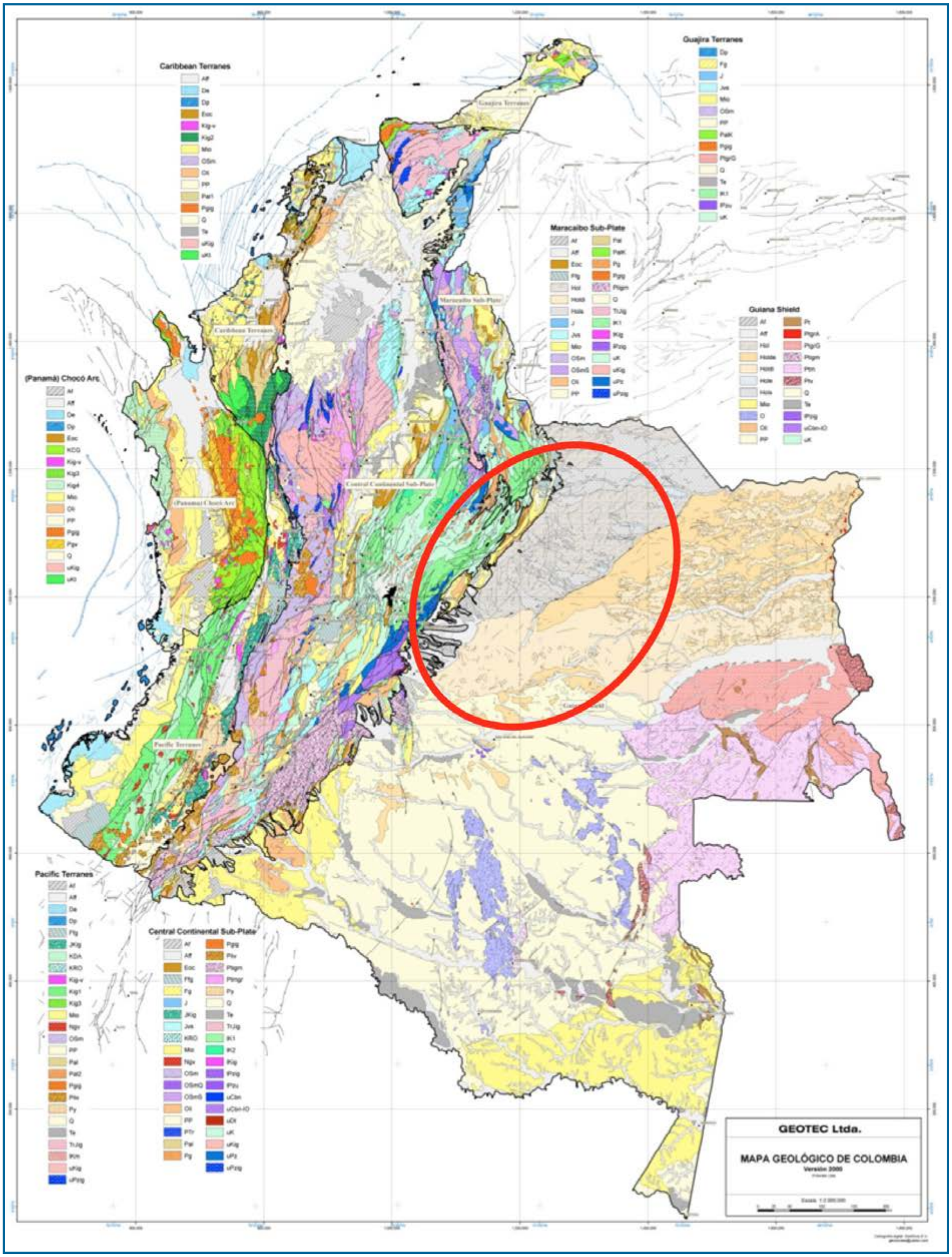


Figure 4B: Study area with geological map of Colombia showing the Llanos foreland basin (red ellipse) adjacent to the Eastern Cordillera shown in (Figure 4A) (Geotec in Hermeston et al., 2011).

There are multiple lines of evidence documenting oblique plate convergence driving the development of the Colombian segment of Andes and their adjacent foreland basin from Paleocene till present, including:

1. plate reconstructions (e.g., Pindell, 1993; Figure 5, Scotese, 1998; Golonka, 2000; Dalziel et al., 2001);
2. paleostress data calculated from shear fractures at outcrops (Cortés and Angelier, 2005a);
3. present-day stress field interpreted from earthquake and bore hole data (e.g., Arcila et al., 2000; Cortés and Angelier, 2005b; Figure 6);
4. along-strike migration of the foreland basin depocenters (Hermeston and Nemčok, 2013); and
5. orogen structural architecture analogy with architecture of analog material models (Macedo and Marshak, 1999).

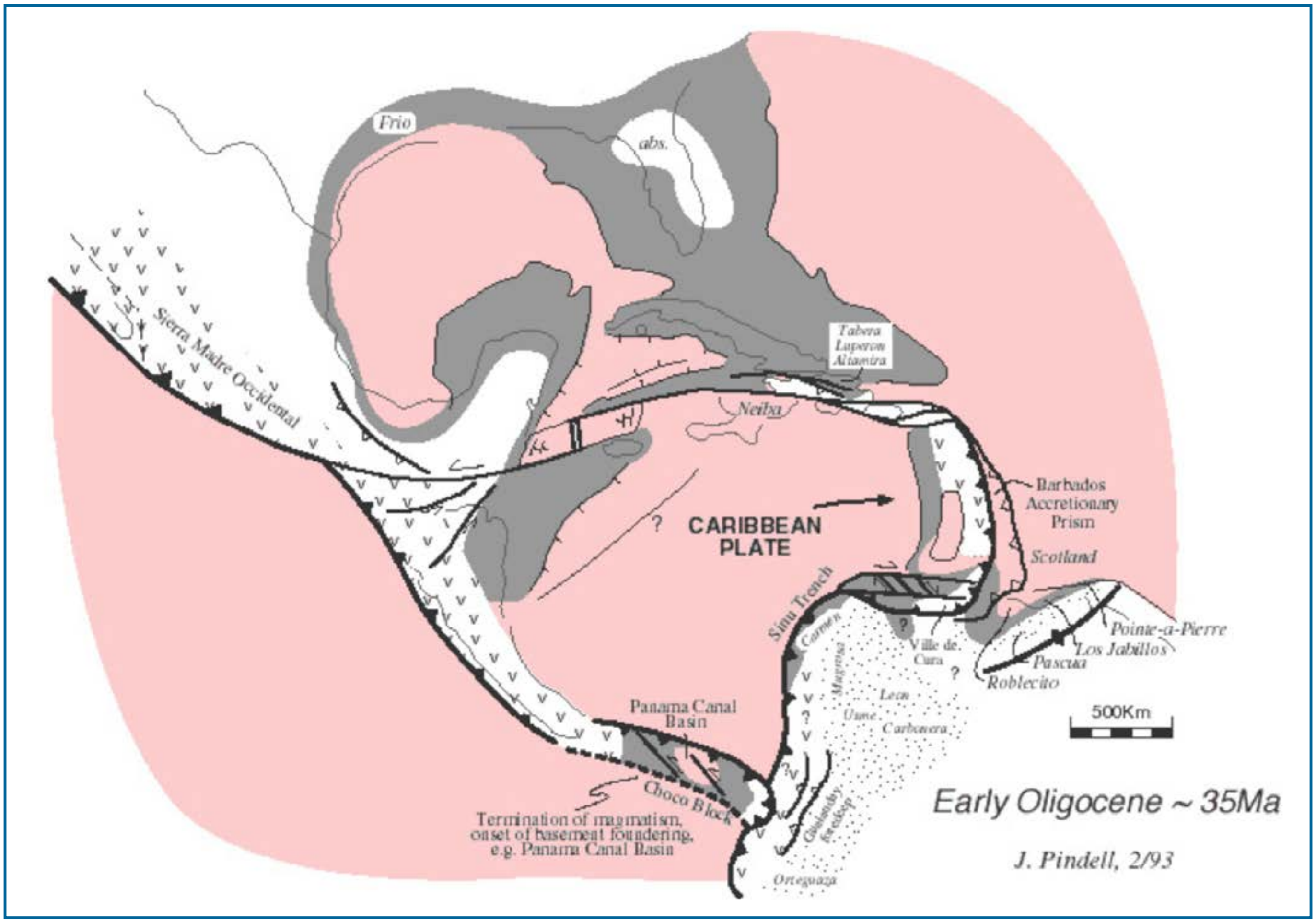


Figure 5: Early Oligocene stage (35 Ma) of the plate reconstruction done for the circum-North Andean region (Pindell, 1993).

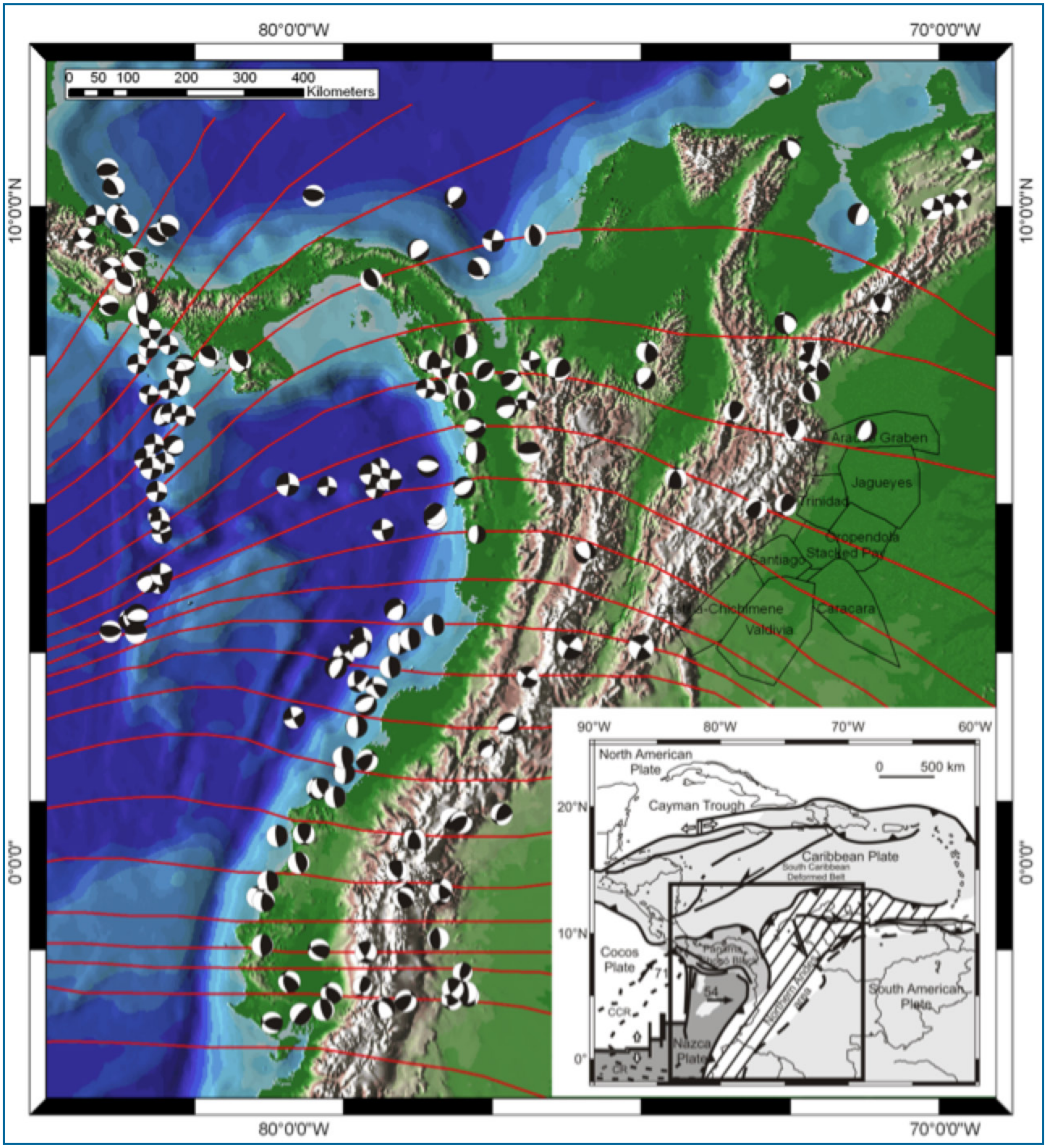


Figure 6: Extrapolated in situ σ1 stress trajectories (red) based on earthquake focal mechanism data in circum-North Andean region (Arcila et al., 2000) together with map of provinces from Figure 1. Note that the Eastern Cordillera is affected by dextral transpression, the strike-slip component of which decreases from S to N. Inset shows major tectonic elements of the Caribbean Region and Northern Andes (Cortés & Angelier, 2005a). Rectangle indicates the location of main figure.

In theory, the oblique convergence in the study area should drive the S-to-N zipper-like closure of the orogen-foreland system. Such closure should control the S-to-N younging of accelerated sediment transport into the proximal foreland basin. This effect was documented by S-to-N transfer of thickness maxima in the Carbonera Formation, Leon Formation and 4 sedimentary packages of the Guayabo Formation (Hermeston and Nemčok, 2013; Figure 7A-C). Furthermore, such closure should control the S-to-N younging events of internal orogen deformation and its advance towards the foreland. This effect is yet to be documented by structural and exhumation data collected and calculated from the Eastern Cordillera.

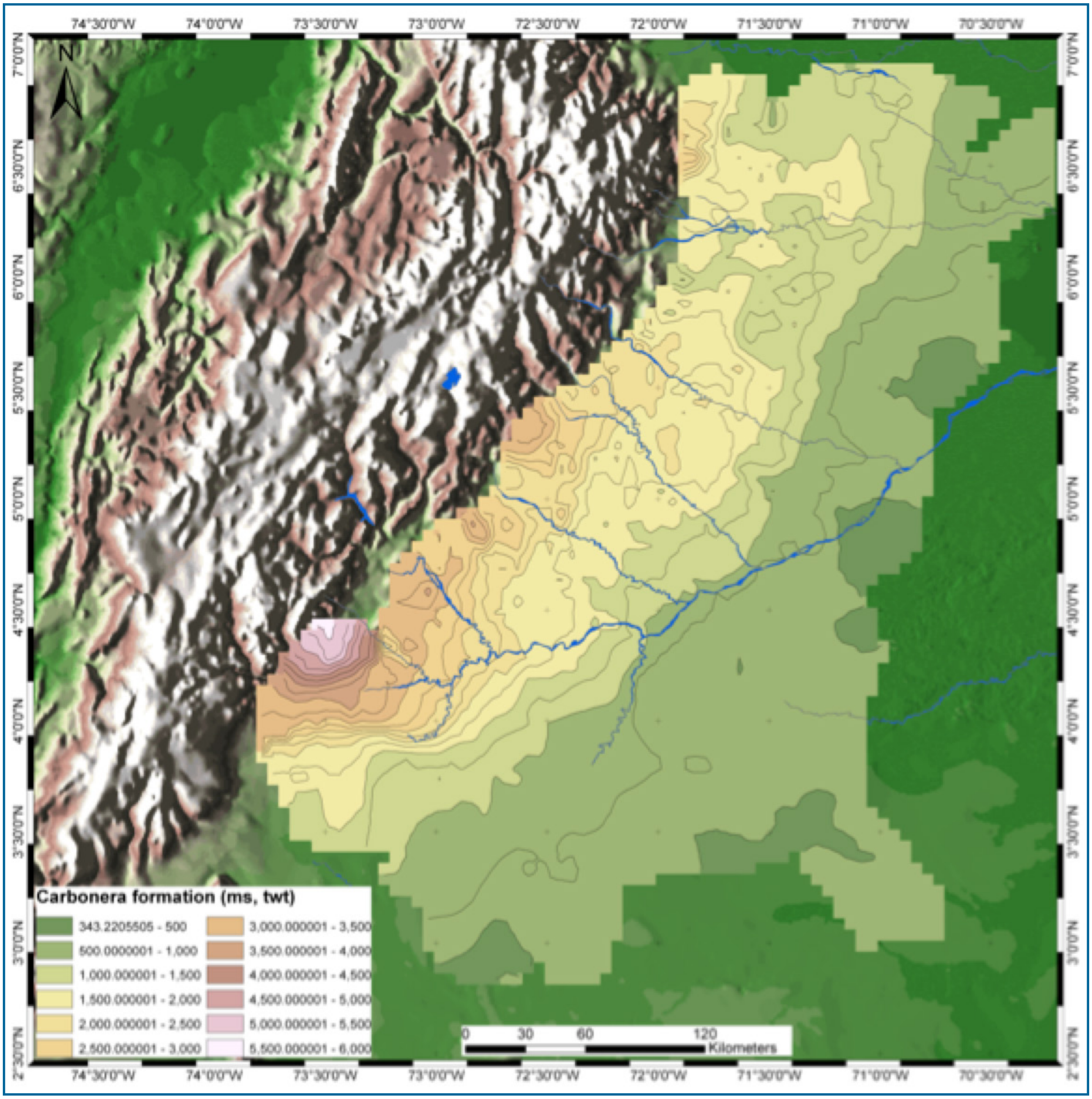


Figure 7A: Thickness distribution of the Carbonera Formation, (Hermeston and Nemčok, 2013).

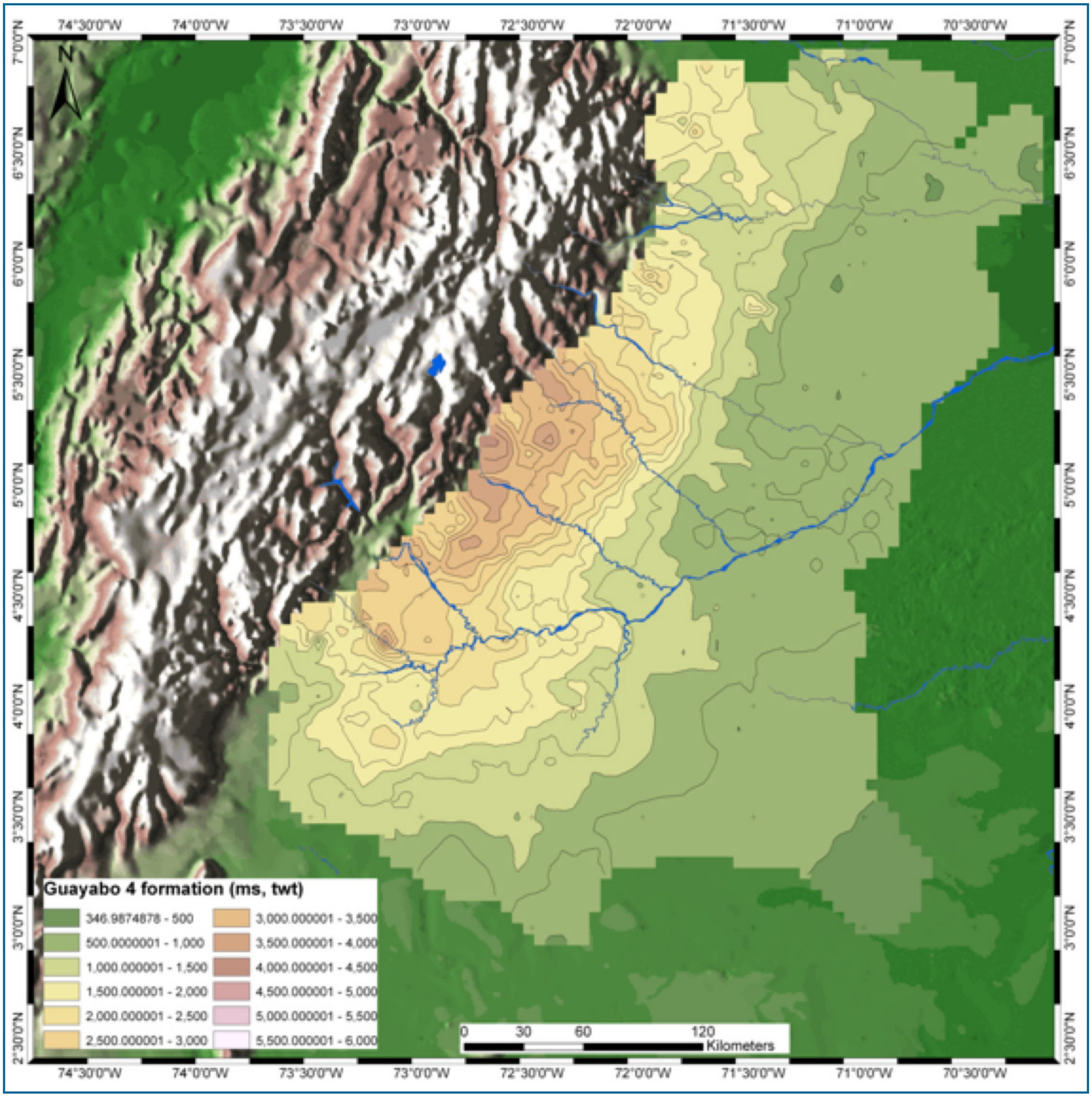


Figure 7B: Part 4 of the Guayabo Formation

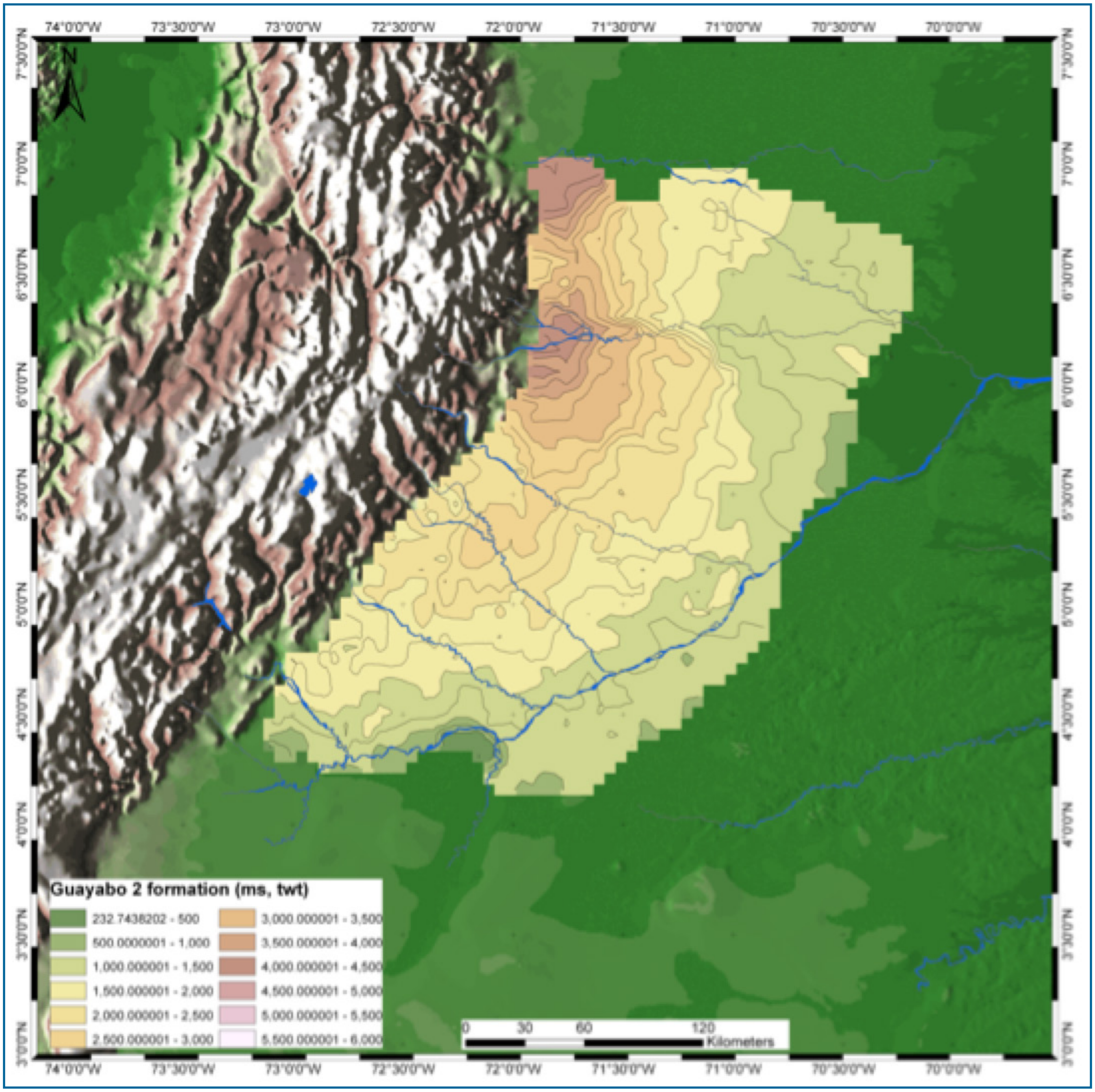


Figure 7C: Part 2 of the Guayabo Formation (Hermeston and Nemčok, 2013).

There is a growing amount of geochemical constraints, indicating pulses of hydrocarbon migration coming from diamondoid-biomarker cracking analysis, compound specific isotope analysis of diamondoids and quantitative extended diamondoid analysis methods (Figure 8) done on oils, asphaltenes and candidate source rocks (e.g., Moldowan et al., 2015). Despite of the understanding being complicated by:

1. severe biodegradation;
2. occurrence of post-mature/cracked oil (Figure 9);
3. multiple source rock kitchens of different organic facies and stratigraphies (Figure 10); and
4. co-sourcing and mixing resulting in migrating oil mixtures (Figure 11),

One can identify several migration pulses, forming NE-SW zones in the foreland basin.

Study Area

The study area (see Figure 4 for location) incorporates the Eastern Cordillera and the Llanos foreland basin.

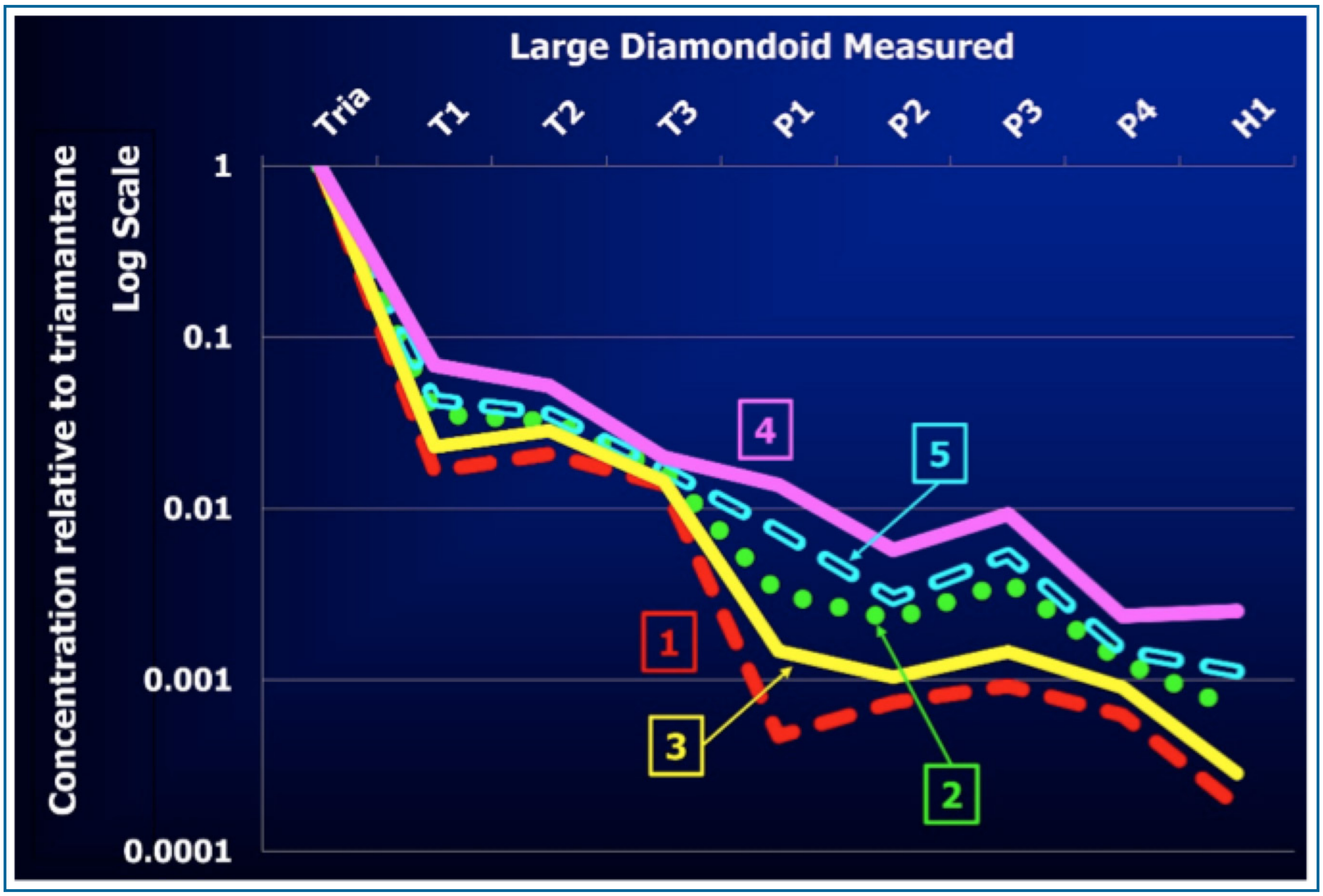


Figure 8. Five oil groups of the Llanos foreland basin determined by the fingerprinting with use of the quantitative extended diamondoid analysis (Moldowan et al., 2015). 1 – Lower Cretaceous or pre-Cretaceous terrestrial-marine shale facies combination, 2 – Upper Cretaceous marine carbonate facies, 3 – Tertiary terrestrial shale facies, 4 – Cenomanian-Turonian marine shale and marl facies combination occurring also in mixture with Tertiary source, 5 – Turonian or younger marine shale and marl facies combination.

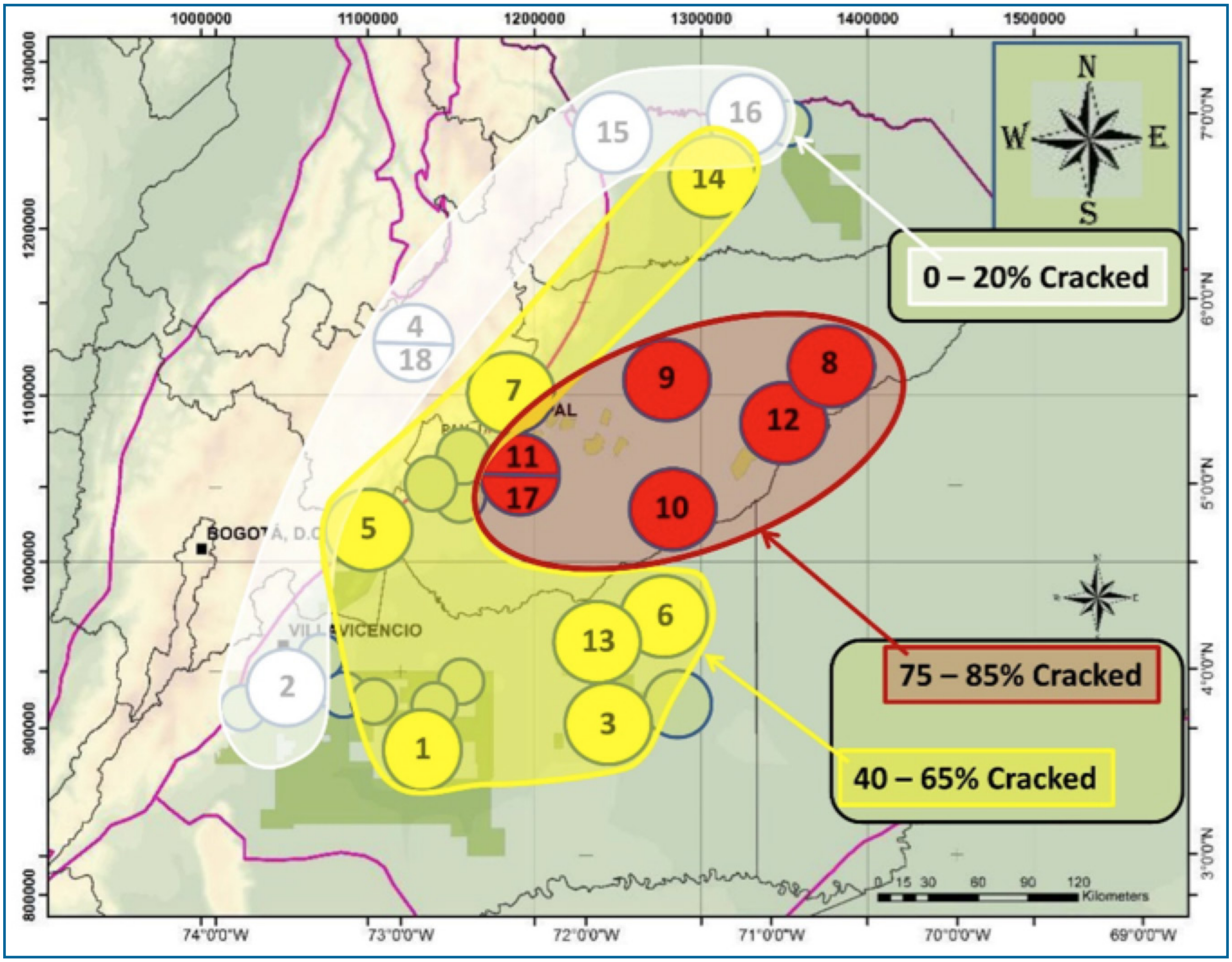


Figure 9. Map showing the distribution of three groups of oils in the Llanos foreland basin based on the extent of their cracking (Moldowan et al., 2015).

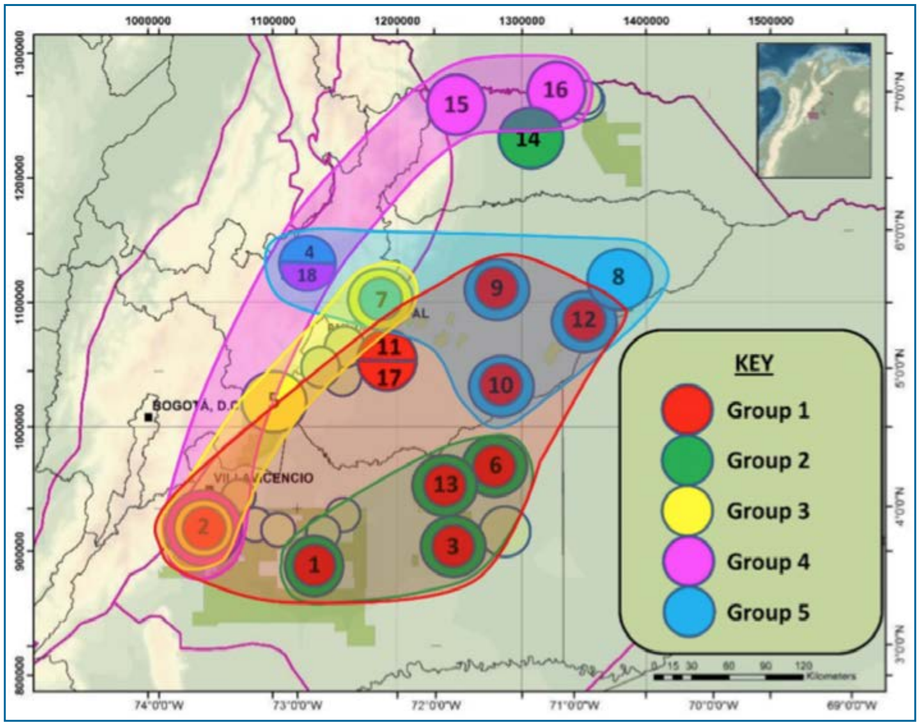


Figure 10. Map showing the spatial distribution of the products of migration from multiple source rock kitchens ignoring their mixing (Moldowan et al., 2015).

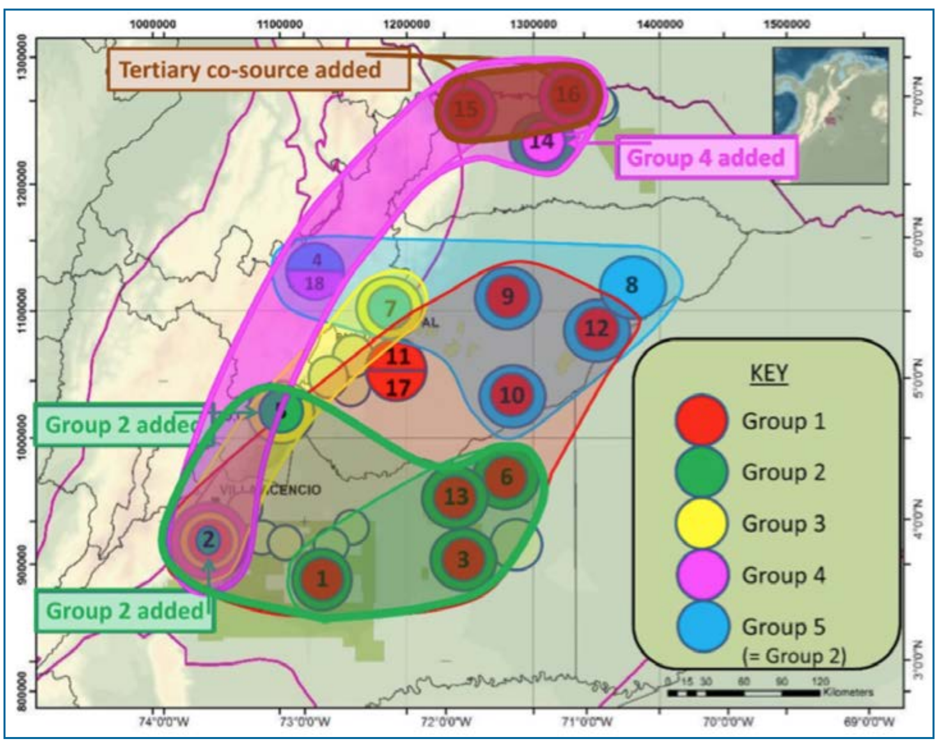


Figure 11. Map showing the spatial distribution of the products of migration from multiple source rock kitchens including their mixing (Moldowan et al., 2015).

Next step further from the outlined knowledge is to:

1. date the sudden burial events along the Eastern Cordilleran front study caused by mountain building;
2. run maturation history and expulsion timing modelling in identified source rock kitchens;
3. study lateral migration-dominated pathways of each recognized migration pulse with known start timing and spatial distribution; and
4. study vertical migration-dominated pathways of migration pulses providing hydrocarbon mixing.

Proposing team is well-suited for proposed set of rigorous tasks because of the amount of both structural and geochemical work already invested into the study area (see Figure 4 for location) in the past. Each of the co-PIs of proposed study led two large 1-year long studies of the region already (Nemčok et al., 2009, 2010; Thul et al., 2016) and co-authored subsequent research studies (Hermeston and Nemčok, 2013; Mora et al., 2013; Nemčok et al., 2013).

The project will be based on an unusually large collection of data for geochemical interpretation enabling precise identification of the spatial distribution of identified oil groups. Original basin modeling will add the temporal distribution aspect. Both spatial and temporal aspects of the mountain-building processes will be added to the picture as well.

Major Goals

1. Determination of the flexural forebulge location of the Llanos foreland basin in time.
2. Determination of the flexure-driven normal fault patterns of the Llanos foreland basin in time and space.
3. Determination of major mountain building events of the Eastern Cordillera in time and space.
4. Determination of the major advance events of the Eastern Cordillera in time and space.
5. Determination of the expulsion timing in the hydrocarbon kitchens of all recognized oil families.
6. More detailed determination of the spatial distribution of results of each individual migration pulse.
7. Determination of lateral and vertical migration segments of each migration pulse.

Significant Tasks

1. **Structural geology and sedimentology:**
    - Determining flexural forebulge location in time
    - Determining flexure-driven normal fault patterns
    - Determining inversion of pre-existing flexure-driven normal fault patterns
    - Determining uplift events of thrust sheets
    - Determining displacement events of thrust sheets
    - Determining accelerated erosion events in the thrustbelt
    - Determining sediment transport pathways from thrustbelt to foreland basin
    - Determining spatial and temporal distribution of accelerated depositional rate events in the foreland basin

2. **Geochemistry:**
   - Dating of cements in reservoir rocks that contain hydrocarbons in their fluid inclusions
   - Determining pressure and temperature conditions of cements with trapped hydrocarbons
   - Determining onset of hydrocarbon expulsion in all known hydrocarbon kitchens defined by previous work by numeric modelling
   - Determining detailed spatial extent of migration pulses in time by original sampling and analytical work
3. **Structural Geology/Geochemistry Combination:**
   - Determining lateral and vertical migration segments for all migration pulses
   - Determining mixing zones of hydrocarbons sourced by different organofacies

Deliverables

1. Arc GIS project including all data, profiles and maps addressing problems to be solved, which are listed in the Task list.
2. Short explanatory text with accompanying graphic documentation on the results of the tasks focused on individual open problems listed in the Task list.

Research Team

Staff	Expertise/Affiliation
Michal Nemčok, Ph.D. Principal Investigator	Structural Geology Research Professor – EGI, University of Utah
Júlia Kotulová, Ph.D. Co-Principal Investigator	Petroleum Geochemistry, Research Scientist – EGI, University of Utah
Samuel Rybár, Ph.D.	Sedimentology – EGI, University of Utah
Prof. Andreas Henk	Technische Universitat, Darmstadt, Germany

Project Timeline, Report & Investment

Project duration is 12 months and investment per sponsor: $56,949 (USD). Project sponsors will be updated regularly regarding analyses and interpretations and a final report will be delivered after the final project meeting.

Tectonics												
Sedimentology												
Geochemistry												
Month	1	2	3	4	5	6	7	8	9	10	11	12

EGI Technical Contact

Michal Nemčok, Ph.D. | Research Professor
Energy & Geoscience Institute at the University of Utah
423 Wakara Way, Suite 300, Salt Lake City Utah 84108
Tel. +421-2-2062-0781 (Bratislava, Slovakia) | Email: mnemcok@egi.utah.edu

EGI Sponsorship & Contract Information

Raymond Levey, Ph.D., EGI Director
Tel. (801) 585-3826 | Fax (801) 585-3540 | Email: EGIDirector@egi.utah.edu

Michal Nemčok, PhD

Research Professor

Michal holds a Ph.D. in Structural Geology from the Comenius University, Bratislava. He has 35 years of applied and basic research experience at the Slovak Geological Survey, University of South Carolina, University of Wales, Cardiff, Imperial College London, University of Salzburg, University of Wurzburg, and University of Utah. He joined EGI in 1998 and is a Research Professor and Structural Group leader. Michal has published 80+ articles, coauthored 5 monographs, and coedited five books.

Continental Break-up Processes & Controlling Factors

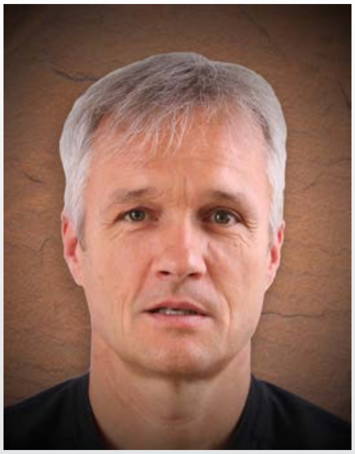
Continental break-up research focuses on both extensional and transform settings, with a focus on driving mechanisms and controlling factors to achieve predictive models with respect to structural architecture, thermal regimes, and petroleum systems. The main research contribution includes understanding anomalous thermal and uplift histories of transform margins, break-up mechanisms in extensional settings, and micro-continent-releasing mechanisms. A summary of his last eight years of break-up research is recorded in a monograph titled *"Rifts and Passive Margins; Structural Architecture, Thermal Regimes and Petroleum Systems"* published by Cambridge University Press, and authored by Nemčok, M. Together with co-authors, a new monograph called *Strike-slip Terrains and Transform Margins—Structural Architecture, Thermal Regimes & Petroleum Systems* is being written in contract with Cambridge University Press.

Thrustbelt Development & Controlling Factors

Michal's current research focuses on the thrustbelt-foreland interactions, with a concentration on driving mechanisms and controlling factors behind thick-skin tectonics, foreland plate flexure mechanisms, and flexural faulting in control of structural architecture and play concept elements. The main research contribution includes the factors and mechanisms leading to the lack of foreland flexing and transitions from initial inversion to full accretion. Accompanying research focuses on modeling of the fluid flow mechanisms occurring in the thrustbelt front and its foreland. A summary of thrustbelt research is written in a monograph called *"Thrustbelts; Structural Architecture, Thermal Regimes and Petroleum Systems",* published by Cambridge University Press, and authored by Nemčok, M., Schamel, S. and Gayer, R.. Current research findings are summarized in several articles included in the Geological Society of London Special Publication 377, which is edited by Nemčok, M., Mora, A., and Cosgrove, J.

Fracture Development Prediction

Fracture prediction research includes both detailed well core, rock outcrop and numerical simulation studies focused on predicting timing, location and kinematics of developing fractures. Most of the fracture studies come from thrustbelts, although some core-based studies come from various geothermal reservoirs. The main research contribution includes tools capable of predicting fracture locations, kinematics and propagation timing in two and three-dimensions for hydrocarbon reservoirs in thrustbelts, which were tested by well-based fracture data. Accompanying research includes understanding the role of mechanical stratigraphy on developing structural architecture. This research is published in a number of journals run by structural and geothermal communities.

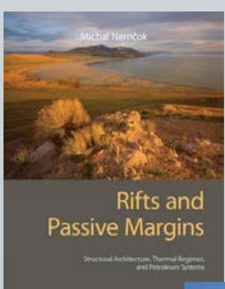


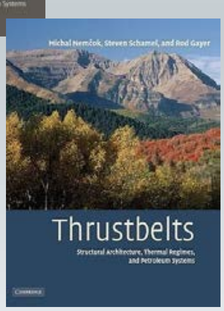
Email
mnemcok@egi.utah.edu

Phone
+421 2-2062-0781 (SK) (Office)

Research Interests

- Continental break-up processes and controlling factors
- Thrustbelt development and controlling factors
- Fracture development prediction





EMAIL:
ContactEGI@egi.utah.edu

PHONE: (801) 585-3826