

# **The Peruvian and Northern Bolivian Subandean Fold and Thrust Belt: Structural Complexity Overview and Geochronologic Constraints\***

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## **Abstract**

The Subandean fold and thrust belt of Bolivia and Peru is characterized by strong shortening and a complex structural north-south partitioning, which induced the individualization of sub-basins characterized by different types of structural plays. This north-south structural evolution was controlled by the Paleozoic and Mesozoic heritages and the slab subduction geometry variations. Structural overview of the Subandean zone is presented from serial balanced cross-sections. Geochronologic data are provided by thermochronology and stratigraphic growth strata evidenced in seismic and corroborated by field observation. The results presented in this paper provide a better calibration of the Paleozoic and Mesozoic petroleum systems and new perspectives for future hydrocarbon exploration in this region.

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## Optimizing Exploration and Development in Thrust Belts and Foreland Basins

6-8 June 2018 | Santa Cruz, Bolivia

10:45 AM - 11:15 AM

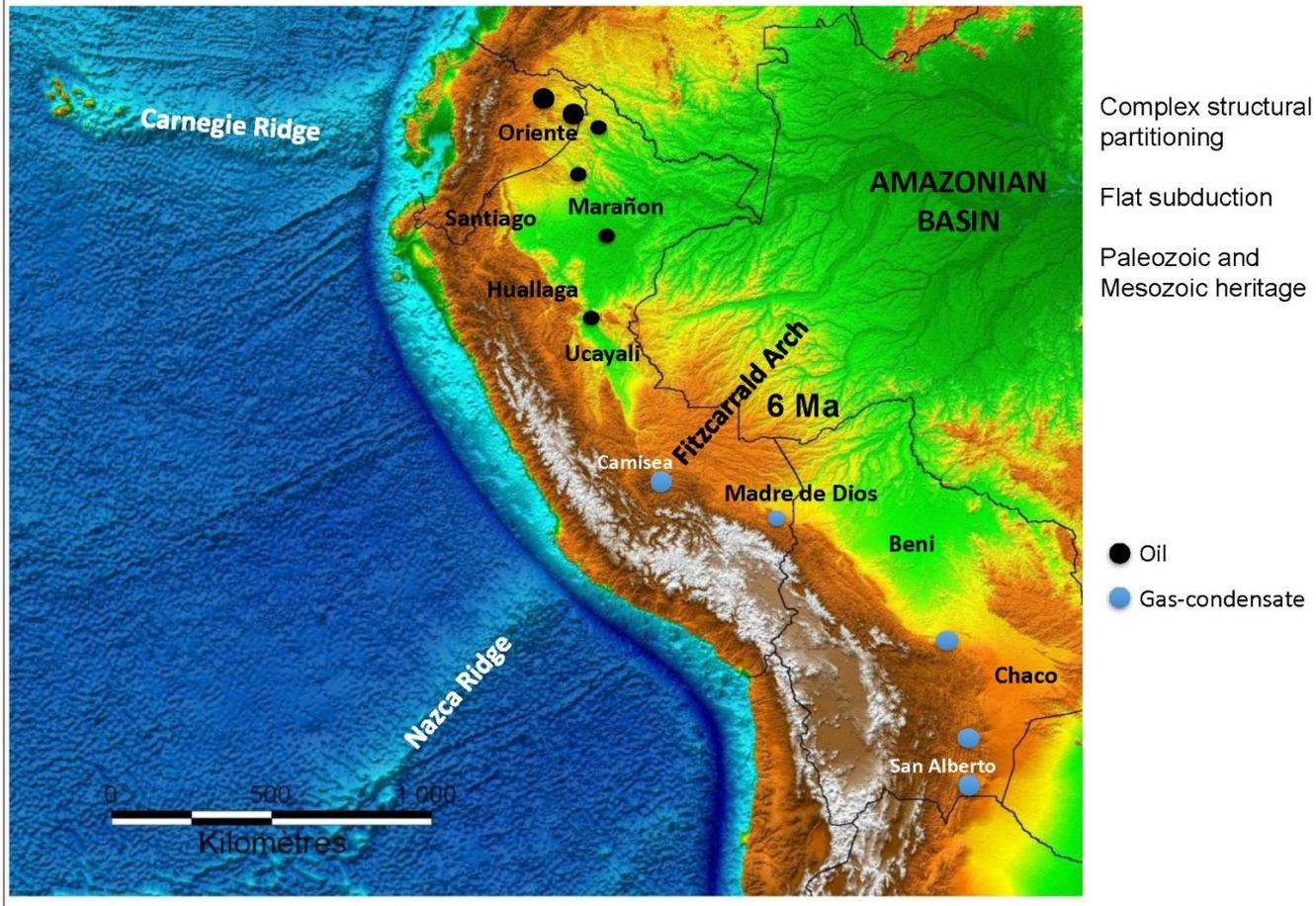
### The Peruvian and northern Bolivian Subandean fold and thrust belt: structural complexity overview and geochronologic constraints



*P. Baby, Y. Calderon, C. Hurtado, N. Espurt, M. Louterbach, S. Brusset, M. Roddaz, J. Oller, R. Mayta, J. Gutierrez et al.*

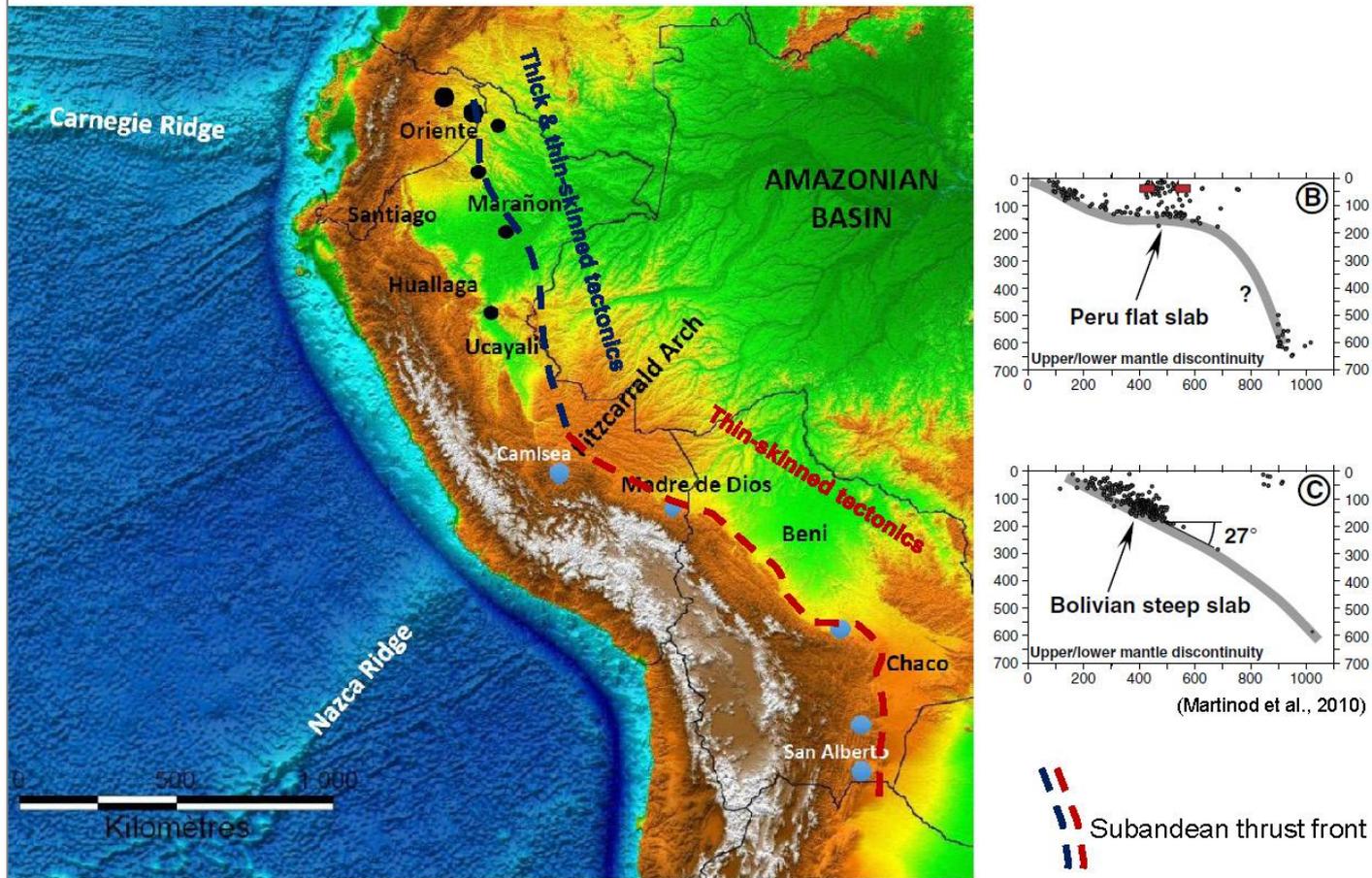
Presenter's notes: In this talk, I will present some results of two research agreements with IRD. IRD is a French research institute working with developing countries. The first agreement is in Peru, with Perupetro, and the second one in Bolivia with YPFB. Many geologists students and researchers from Bolivia, Peru and France have been involved in this project. The topic of the talk is the Peruvian and the northern Bolivian Subandean fold and thrust belt. I will present a structural overview, new geochronologic constraints and some conclusions on the potential structural traps.

## SUBANDEAN FORELAND BASINS

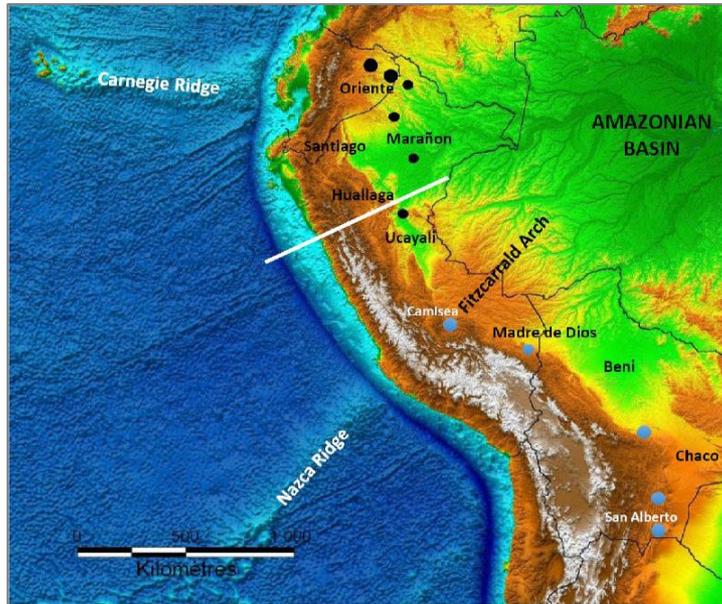


Presenter's notes: This is a map of the Central Andes from Ecuador to Bolivia. Various giant Subandean gas fields have been discovered in the front of the Subandean foothills, as the San Alberto field in southern Bolivia, and the Camisea field in Peru. From North to South, the Peruvian –Bolivian subandean fold and thrust belt shows a complex structural partitioning. This partitioning is controlled by a Paleozoic and Mesozoic heritage, but also by the flat subduction of the Nazca Ridge, which produced the Fitzcarrald Arch uplift in the Amazonian foreland basin. The Fitzcarrald Arch started around 6 Ma and seems to be the northern limit of the Peruvian- Bolivian gas province. To the North, an important oil province develops from the Ucayali Basin to the Oriente Basin.

# SUBDUCTION GEOMETRY



Presenter's notes: Front of the Peruvian flat subduction, the Subandean deformation is characterized by thin and thick-skinned tectonics, and the thrust system develops far to the east in the foreland. In contrast, front of the Bolivian steep subduction, the Subandean zone is only characterized by thin-skinned tectonics, and is much more narrow.



## PERU FLAT SLAB

Strong Cenozoic  
crustal horizontal  
shortening

Subandean  
thin and  
**thick-skinned**  
tectonics

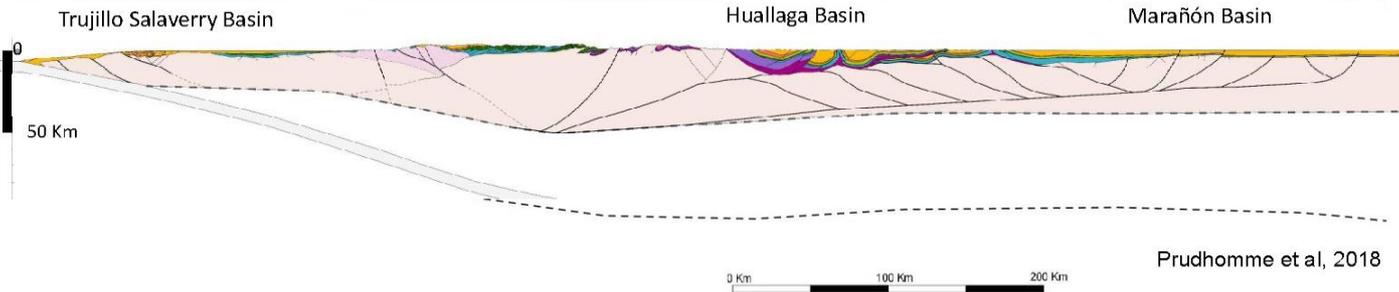
Complex and  
extensive  
foreland basin  
system

WSW

SUBANDEAN CRUSTAL SHORTENING=70 KM

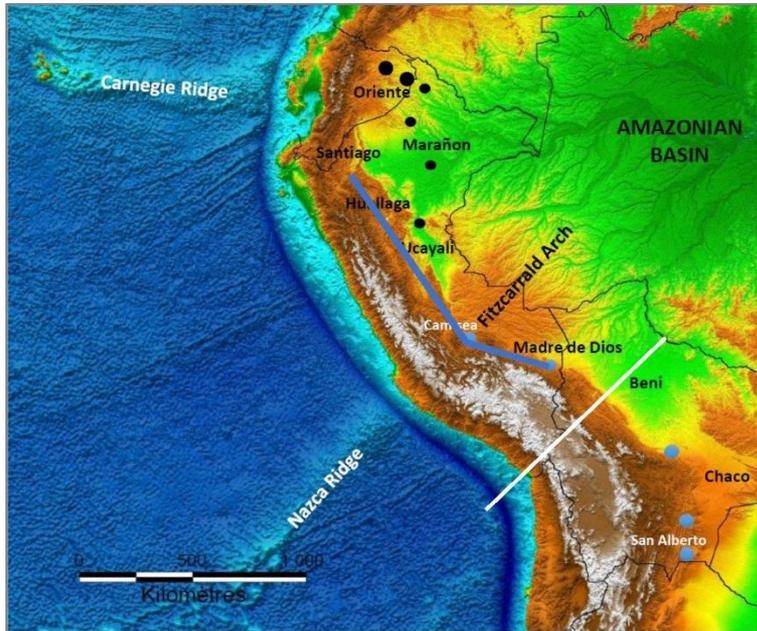
ENE

Offshore Basins    Western Cordillera    Eastern Cordillera    Subandean Foreland Basin System



Prudhomme et al, 2018

Presenter's notes: This is a crustal cross-section through the Andes of northern Peru, from the Trujillo-Salaverry forearc basins to the Marañón Amazonian Basin. It shows the Peruvian flat subduction, and a complex and extensive Huallaga-Marañón Subandean foreland basin system, deformed by thin and thick-skinned tectonics and a strong shortening of 70 km. This foreland basin system occupies half of the Andean chain.

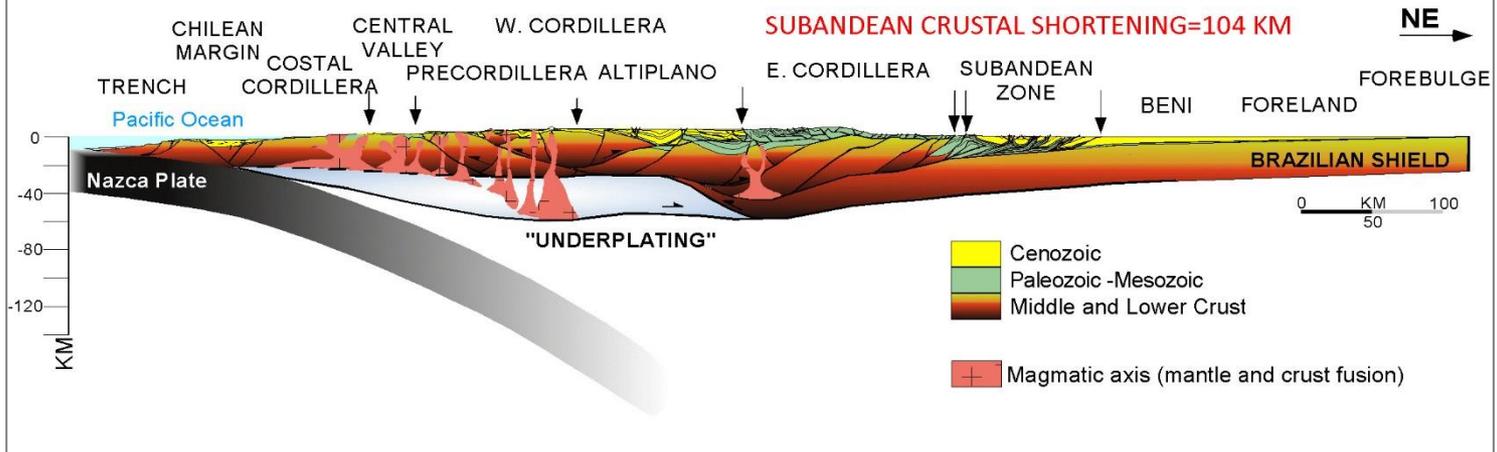


## BOLIVIAN STEEP SLAB

Strong Cenozoic  
crustal horizontal  
Shortening

Subandean  
**thin-skinned**  
tectonics

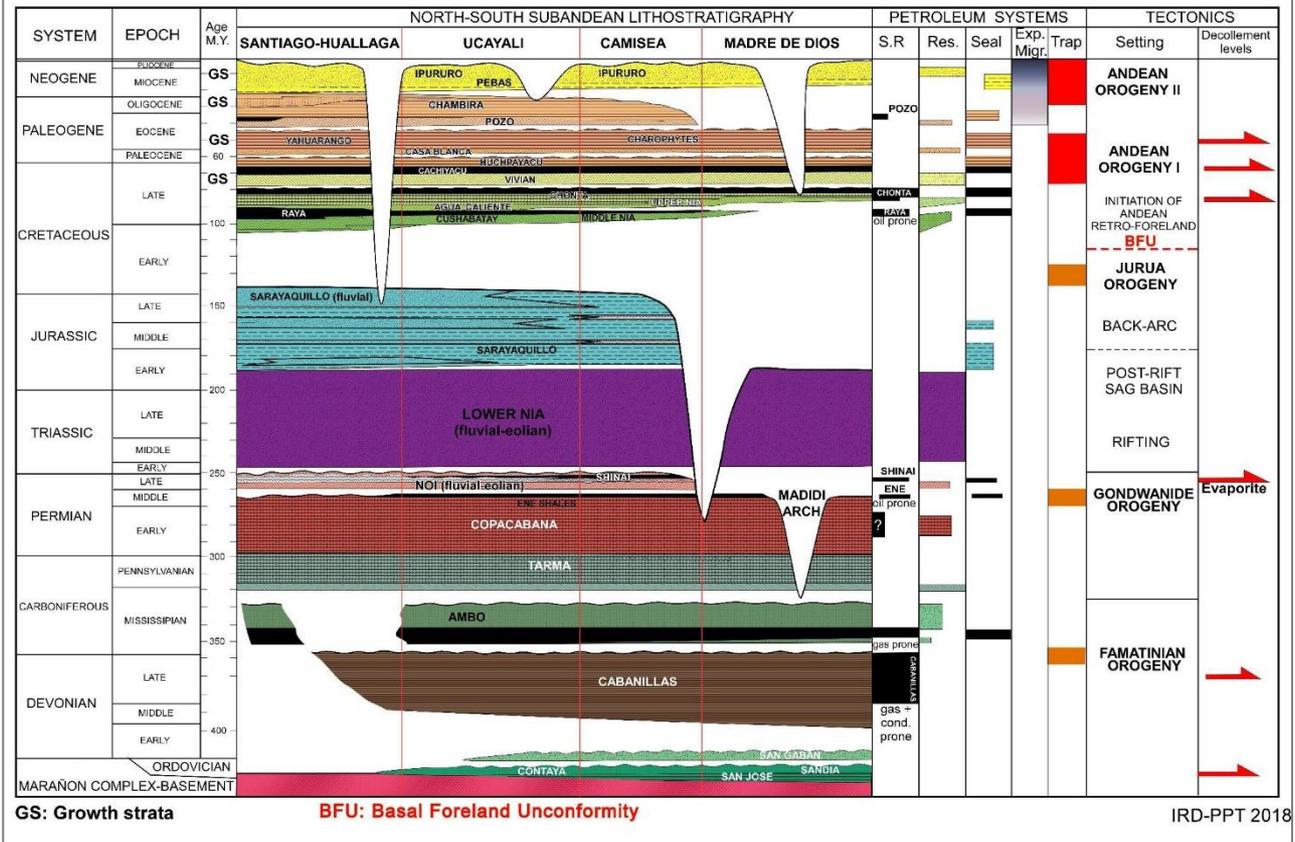
Classic and  
extensive  
foreland basin  
system



Presenter's notes: In northern Bolivia, where the slab is steep, this crustal Andean cross-section shows also a strong horizontal shortening of one hundred kilometers, but the Subandean foreland basin system is more classic, and only deformed by thin-skinned tectonics and narrower. Now, I am going to show a north-south lithostratigraphic correlation in the Peruvian Subandean zone.

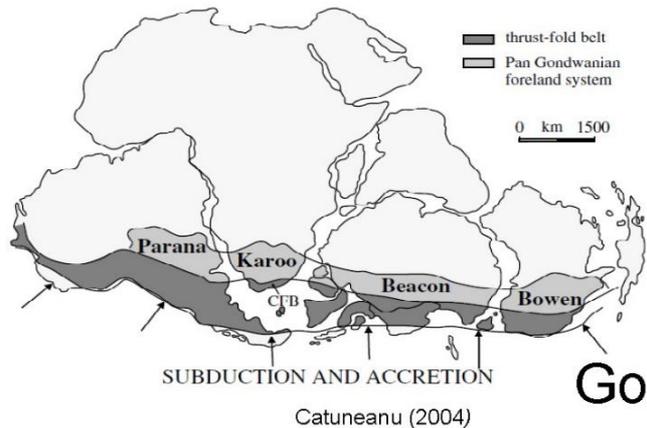
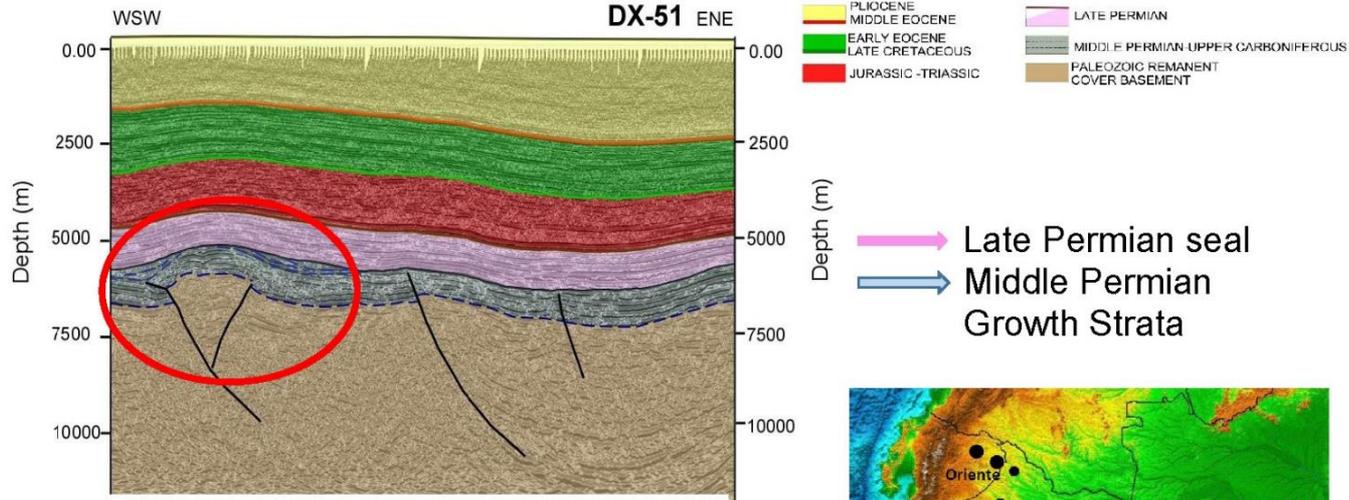
# PALEOZOIC AND MESOZOIC HERITAGE MIDDLE PERMIAN OROGENY

## 2 ANDEAN OROGENIES



Presenter's notes: In the Peruvian Subandean zone, from north to south, the stratigraphic column shows an almost continuous series from Paleozoic to Neogene, with one intensive period of erosion during the Early Cretaceous, which marked the beginning of the Andean retro-foreland basin system and corresponds to the foreland basal unconformity. Pre-Andean tectonic settings are characterized by a succession of rifting and foreland basin periods. Three active petroleum systems are proven: a Paleozoic PS, a Triassic-Jurassic PS and a Late Cretaceous PS. New geologic constraints as thermochronology or stratigraphic records show two periods of Andean orogeny, one in the Late Cretaceous and Paleogene, and a second in the Mio-Pliocene. The Middle Permian Gondwanide orogeny deformation has been also recently evidenced in the Subandean zone.

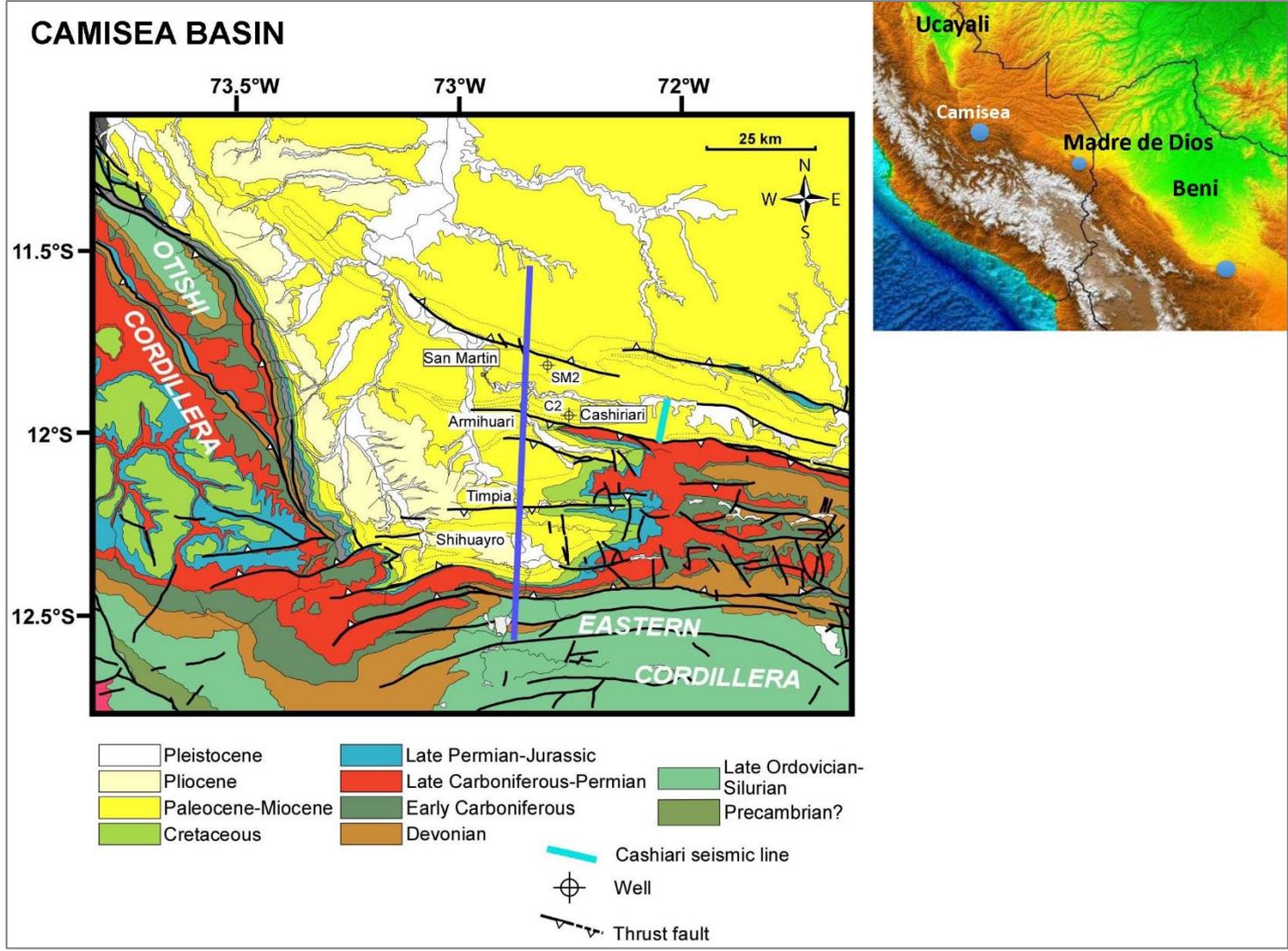
# PALEOZOIC HERITAGE : REACTIVATION OF PERMIAN THRUSTS



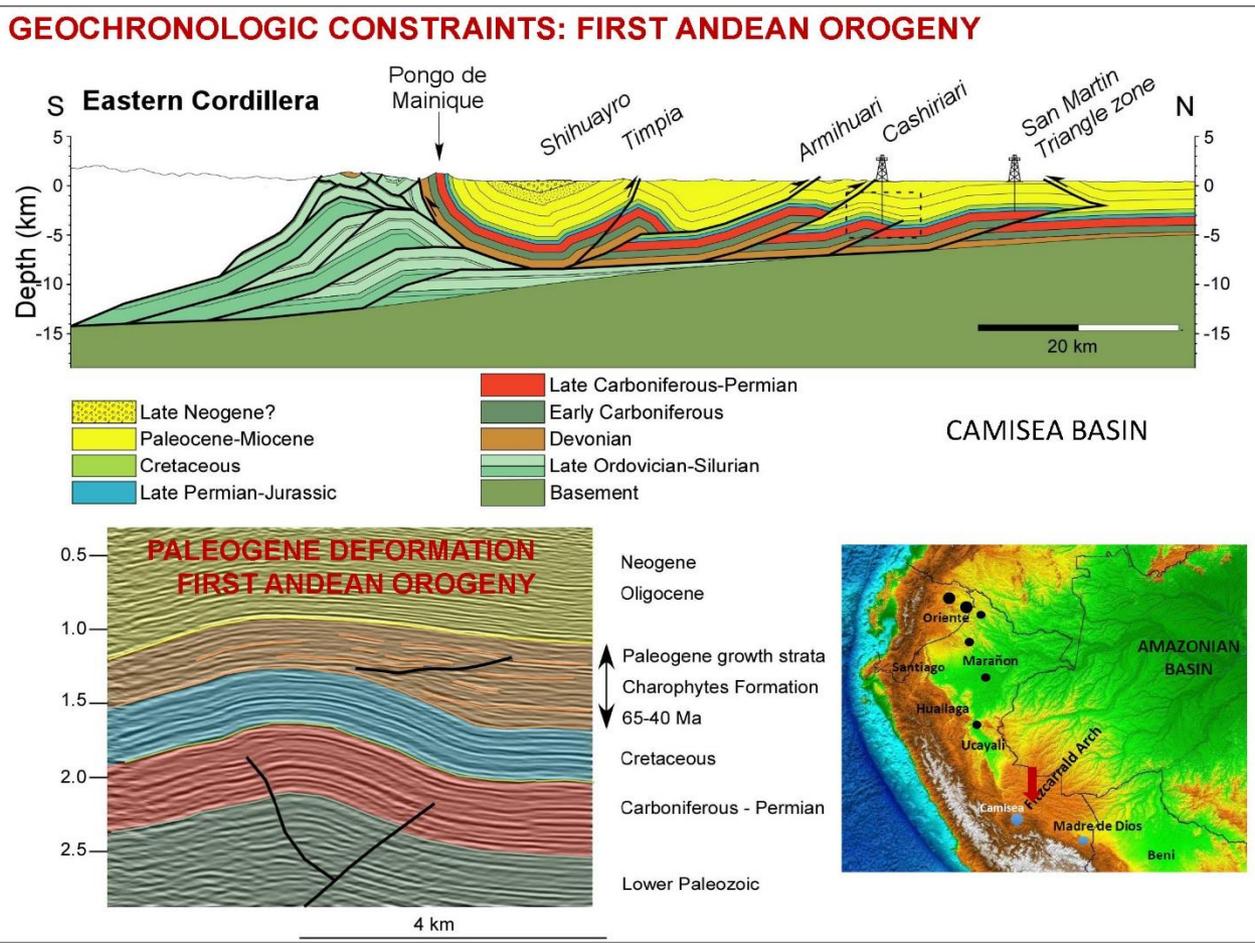
## Gondwanide Orogeny



Presenter's notes: In Peru, this Gondwanide orogeny has been mainly evidenced in the Marañón Basin, but it is probably present in all the Andes as shown by the reconstruction proposed by Catuneanu. As an example, this seismic section shows a preserved Middle Permian thrust fold reactivated during the Andean orogeny. This fold shows growth strata in Middle Permian sediments and is eroded and sealed by the Late Permian. This kind of structure could represent a new play for the Marañón Basin exploration.



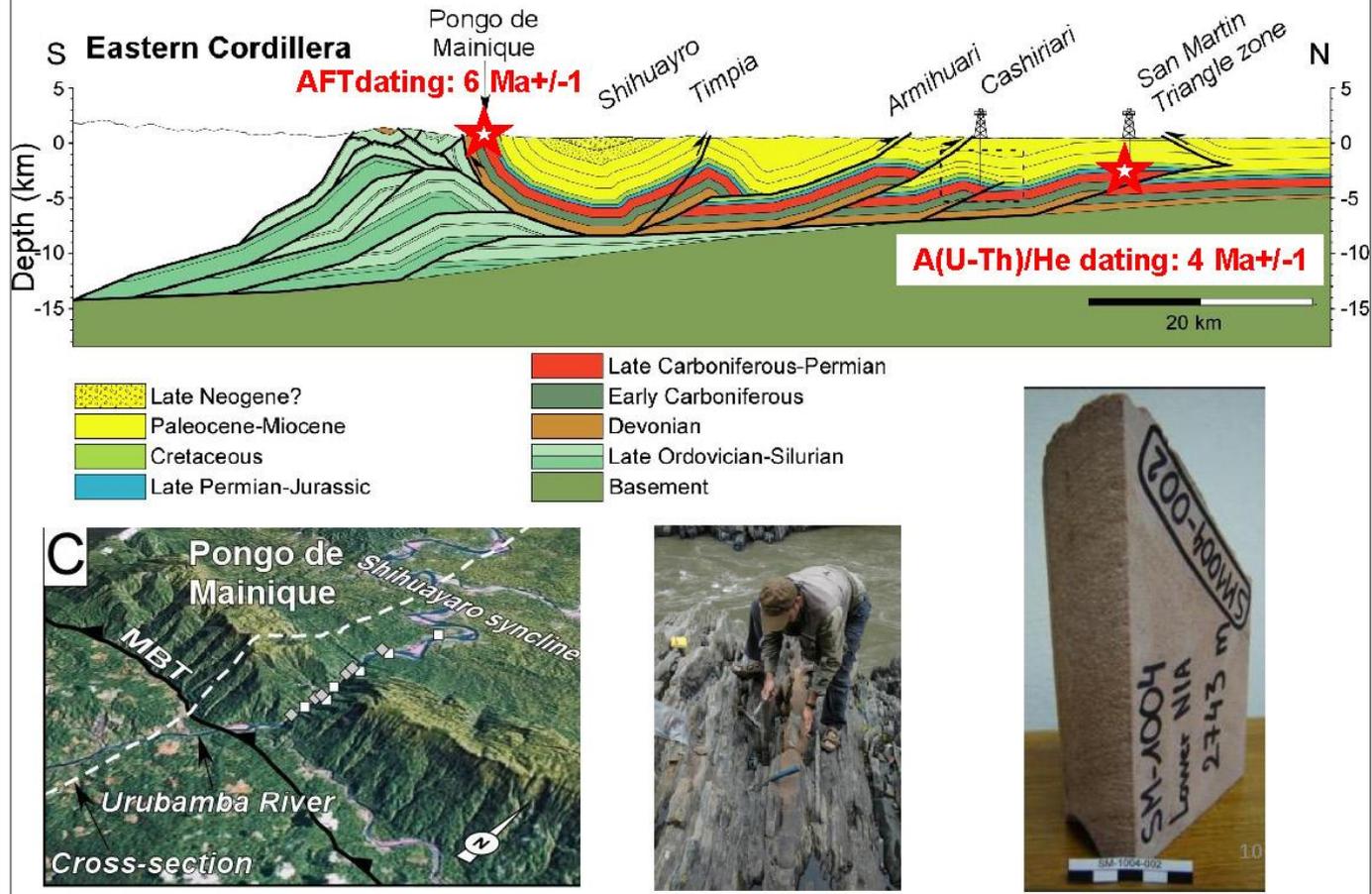
Presenter's notes: We move now to the south in the Camisea Basin, in the most famous petroleum basin of Peru, to illustrate the two Andean deformations that characterize the Subandean zone. We analyse these deformations from a north-south structural cross-section constructed from seismic data and field data.



Presenter's notes: This N-S balanced cross-section shows the typical thrusts system of the Camisea Basin, with two main décollements at the base and at the top of the Lower Paleozoic series. The propagation of the 4 ramp anticlines of the Camisea Basin corresponds to the accommodation of the shortening of an internal duplex. In the southern part of the Cashiriari structure, we found a seismic section showing growth strata in the Paleocene and Lower Eocene foreland series which recorded the first Andean deformation between 65 and 40 Ma. This first orogenic period is sealed by Oligocene and lower Neogene sediments. This Paleogene deformation implies the presence of consequent old structural traps which can explain the presence of giant gas fields in the Camisea Basin.

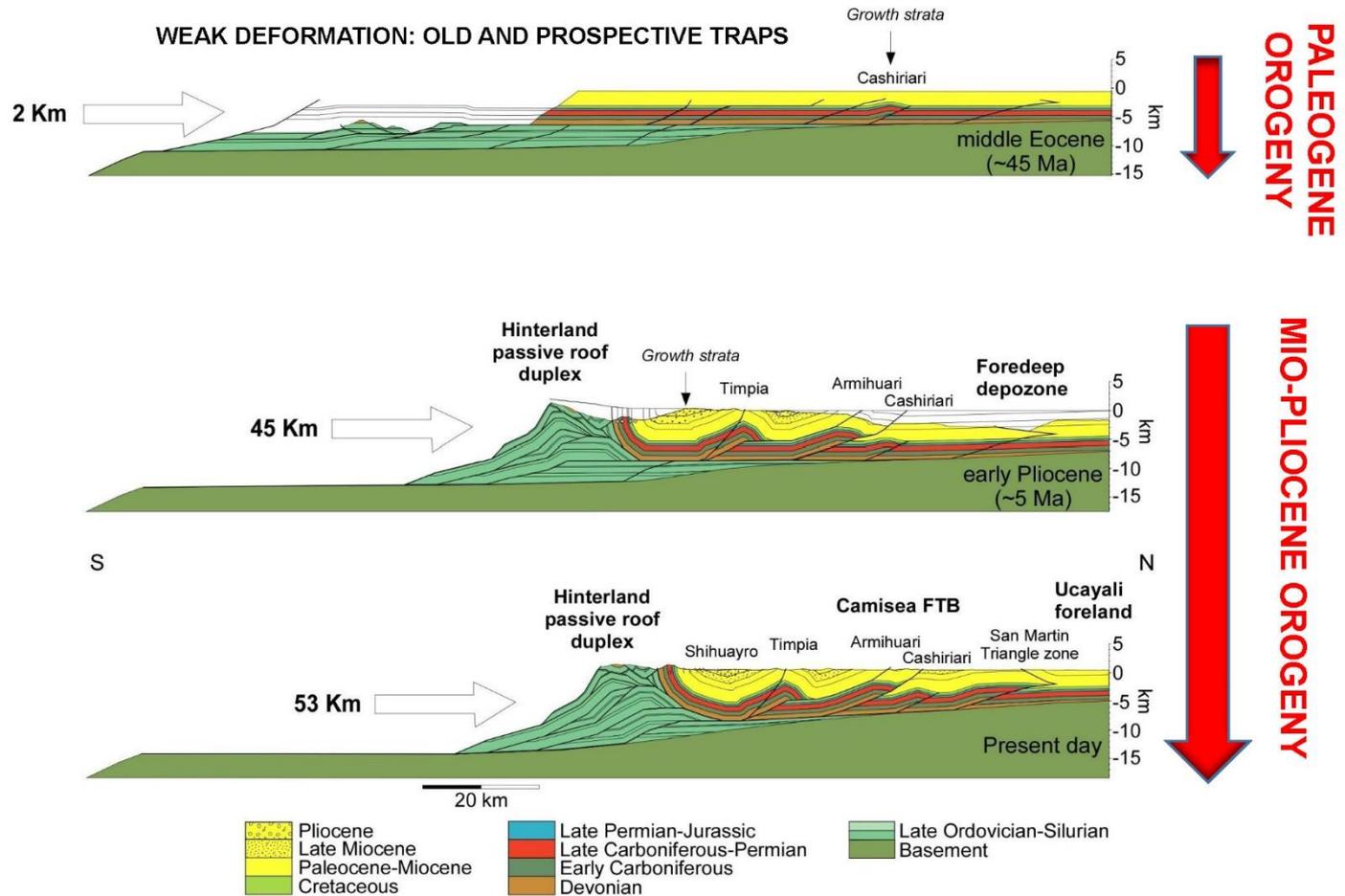
## GEOCHRONOLOGIC CONSTRAINTS: SECOND ANDEAN OROGENY

Direct dating of thrusts by apatite  $(U-Th)/He$  and fission track thermochronometry

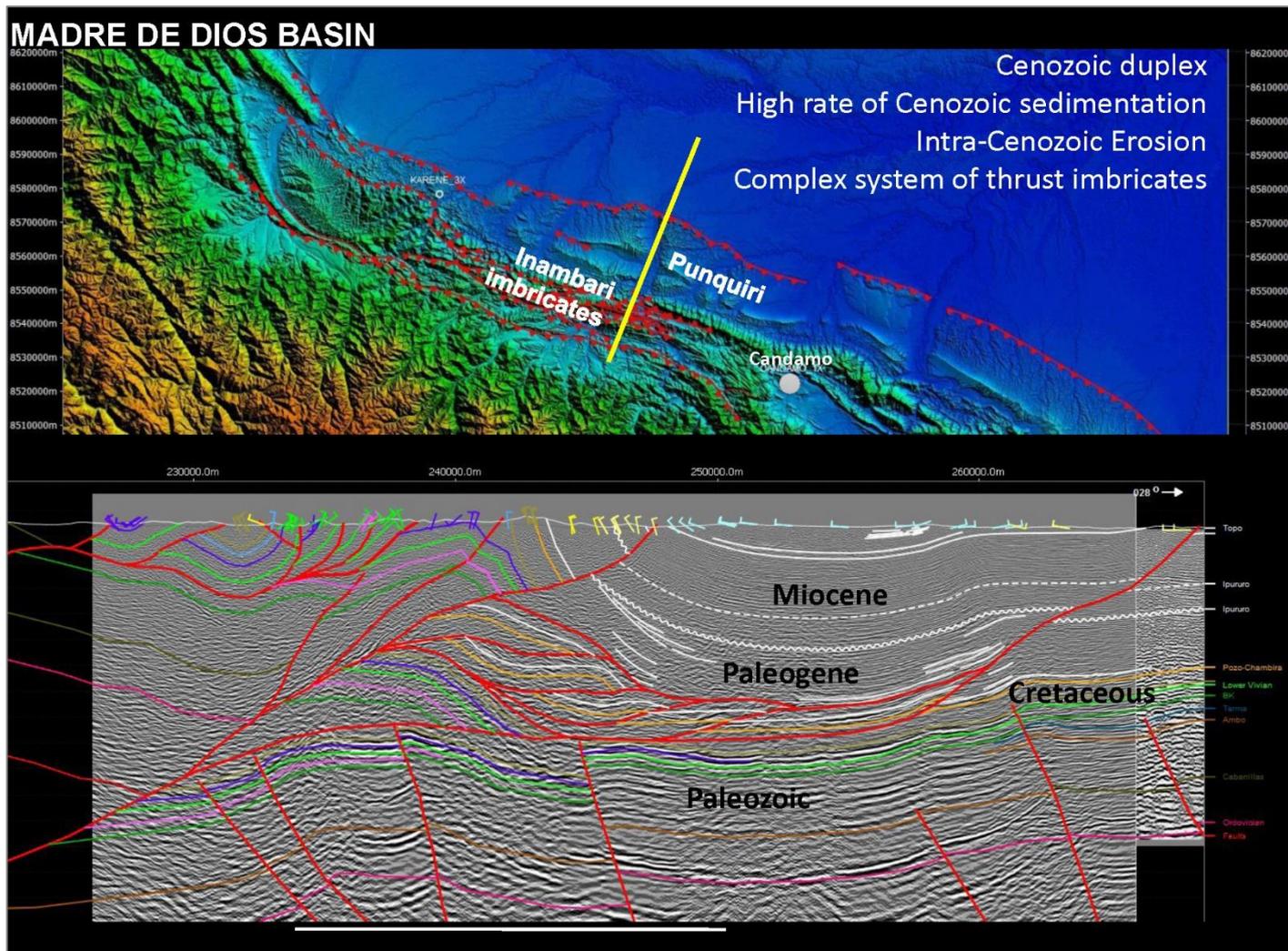


Presenter's notes: The second Andean orogenic period is evidenced by direct dating of thrusts by apatite thermochronometry. We used for this dating, samples of the Pongo de Mainique stratigraphic section, where is outcropping more than 7 km of vertical strata from Paleozoic to Cenozoic. Thanks to Pluspetrol, we used also a core of the Permian sandstones in the San Martin anticline. The results show a young period of exhumation which implies a propagation of the thrust system, from 6 Ma in the internal duplex to 4 Ma in the San Martin anticline.

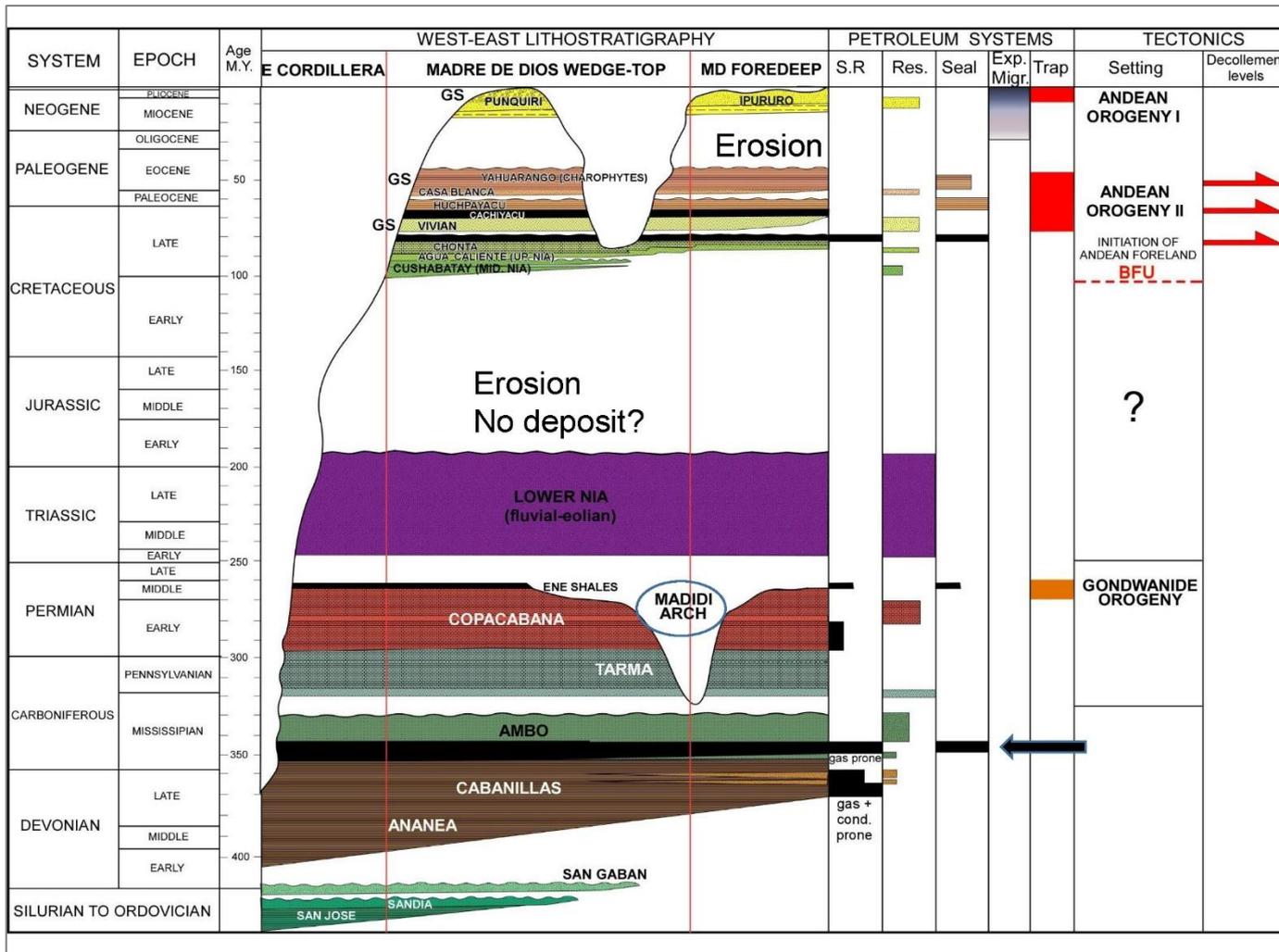
# SEQUENTIAL RESTORATION



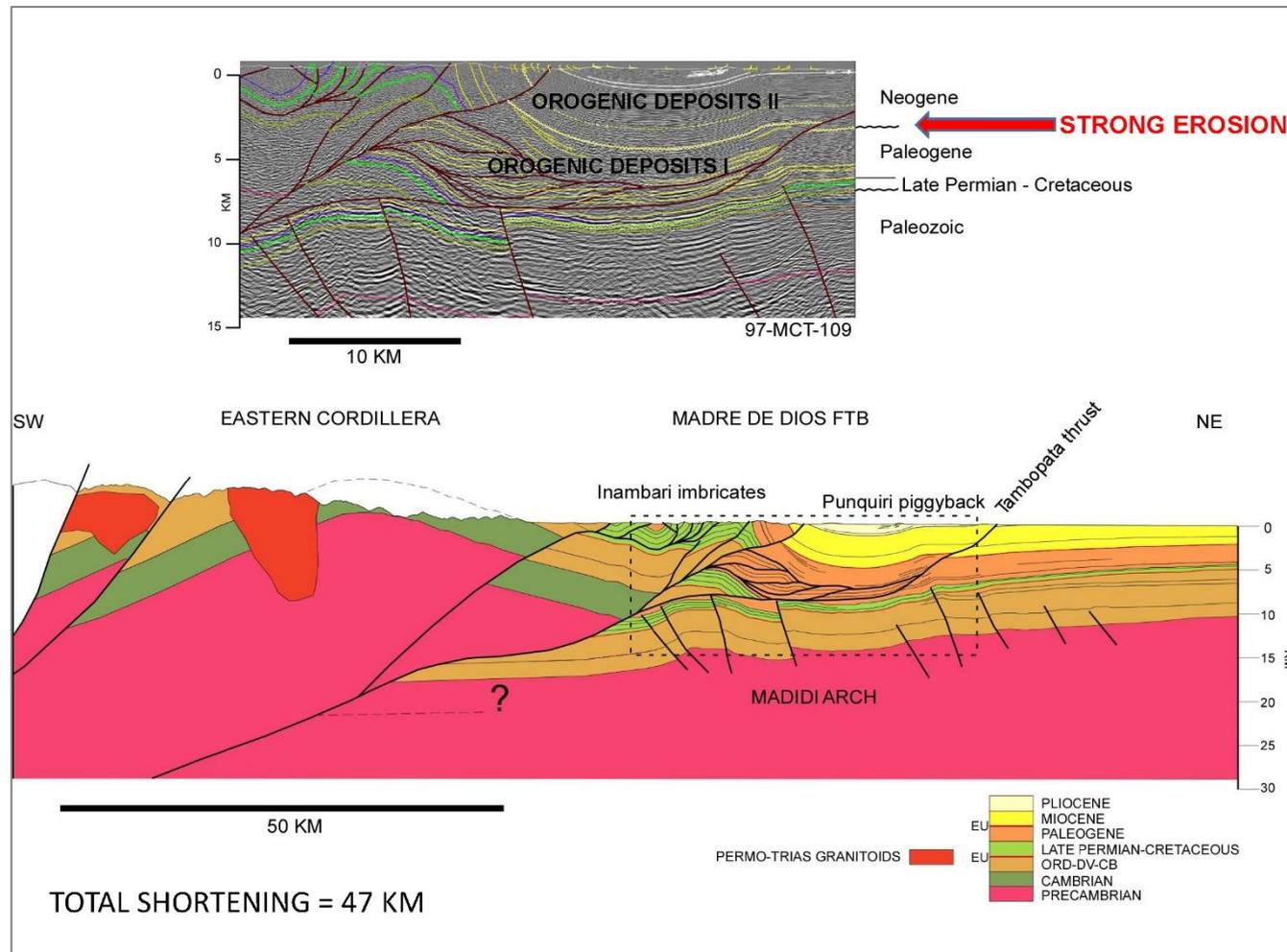
Presenter's notes: The balanced cross-section method and the previous geochronologic constraints permit to propose a sequential restoration of the Subandean deformation. The Middle Eocene stage represents the end of the Paleogene orogeny with weak deformation. The second orogenic phase is represented by these two sections and developed from the Late Miocene to the present day.



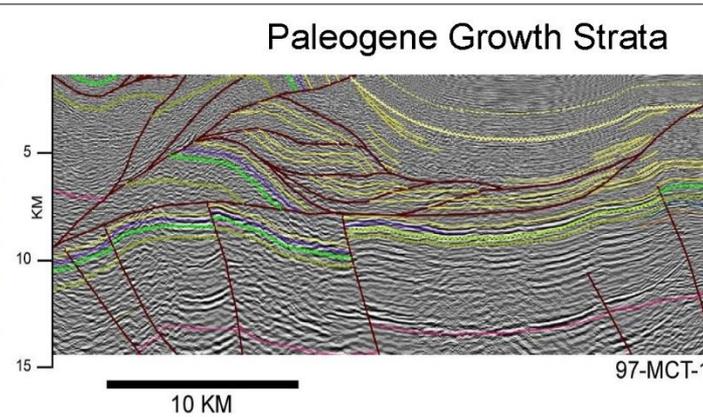
Presenter's notes: More to the south, the Subandean foothills of Madre de Dios is strongly deformed as shown by this seismic section. It is characterized by Cenozoic duplex, high rate of Cenozoic sedimentation, and an intra-Cenozoic erosion. We have constructed a balanced cross-section north to the Candamo gas field, along the Inambari River where is outcropping a complex system of thrust imbricates.



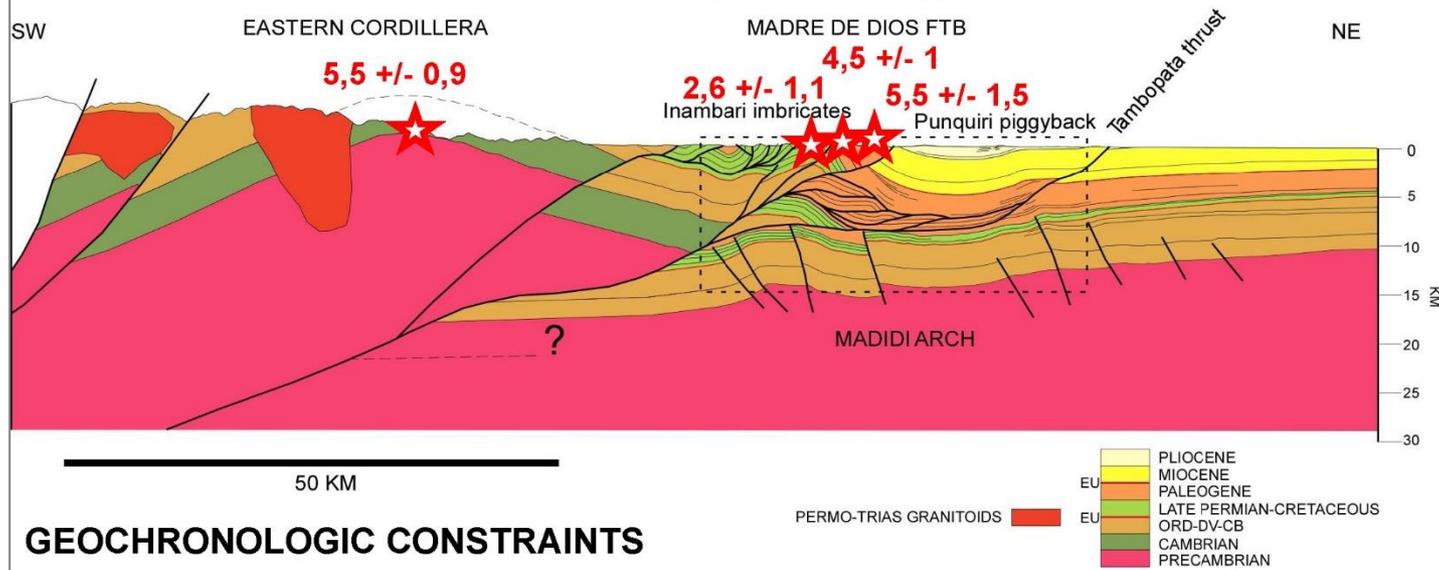
Presenter's notes: But first, an overview of the stratigraphy. In the Madre de Dios Basin, the Paleozoic sedimentary is almost complete and is characterized by good gas prone source rocks, as the Ambo shales. The Gondwanide orogeny is recorded by the Madidi Arch uplift, which has been eroded and sealed by the Late Permian Noi reservoir, one of the best reservoirs of the Camisea gas field. Between the Paleozoic and the Late Cretaceous foreland deposits, there is an important gap. Jurassic has been eroded by the Late Cretaceous Basal Foreland Unconformity, or no deposit. A second period of erosion occurred between the two Andean orogenies.



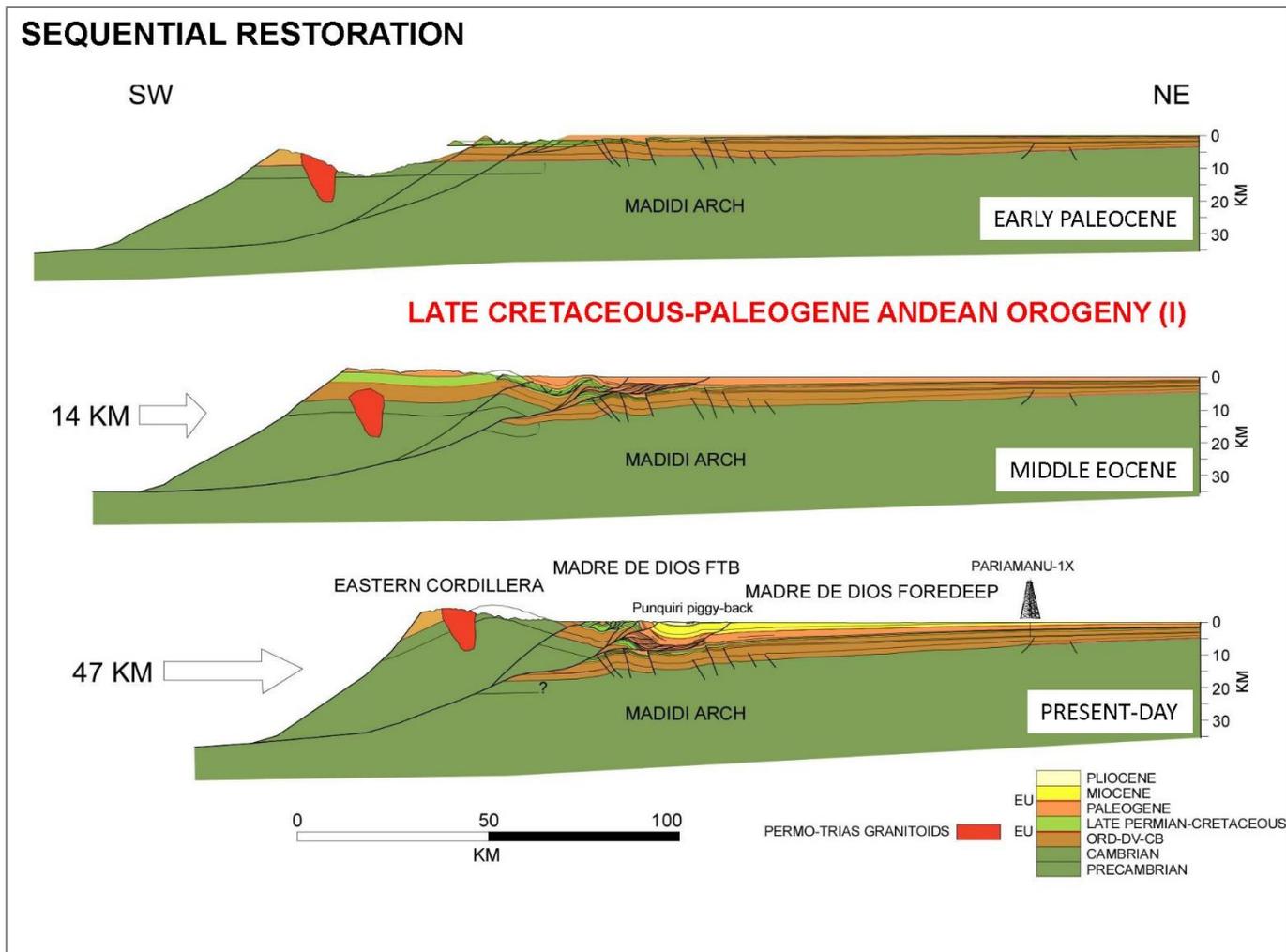
Presenter's notes: This balanced cross-section has been constructed from seismic sections and field data. Total shortening is 47 km. It shows an important duplex developed in the Paleogene syn-orogenic series, and an important over-thrust of the Eastern Cordillera with imbricates in the Cretaceous cover. The shortening of the duplex is accommodated by the propagation of the Punquiri piggyback syncline on the Tambopata thrust. Paleozoic and Cretaceous petroleum systems are involved in the deformation. The Cenozoic foreland deposits are 8 km thick and divided in two parts by a strong erosion: here the Paleogene deposits of the first Andean period, and here the Mio-Pliocene deposits of the second Andean period.



### THERMOCHRONOLOGY, AFT dating (Ma):

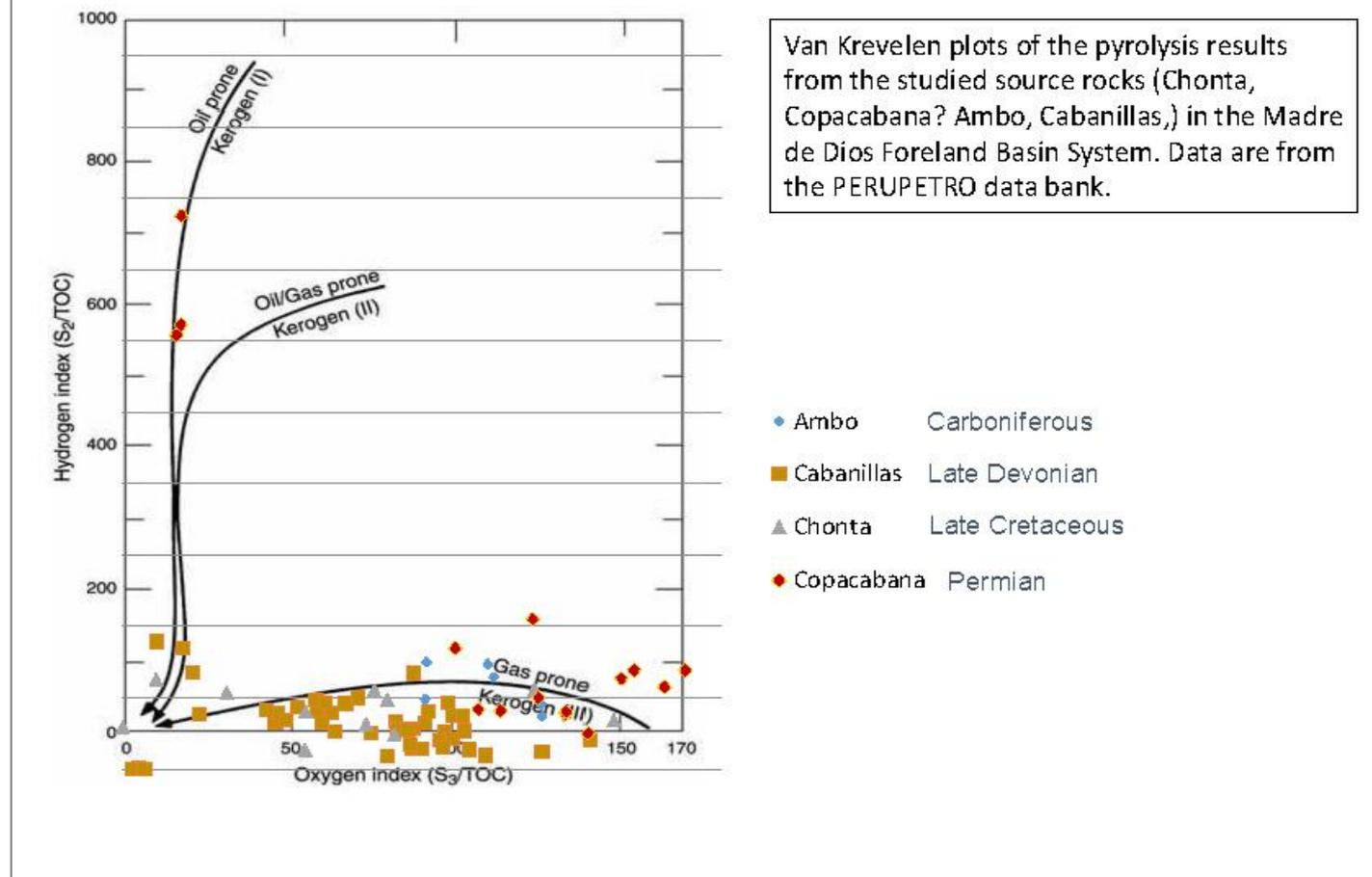


Presenter's notes: The geochronologic constraints confirm the two Andean orogenic periods. The first Andean orogeny is recorded by Late Cretaceous growth strata, as in this outcrop of the Inambari imbricates, and by Paleogene growth strata that seal the duplex in this seismic section. The second orogenic period is evidenced by thermochronologic dating of the Eastern Cordillera and Subandean thrusts, that recorded as in the Camisea Basin an important tectonic uplift from 6 Ma.



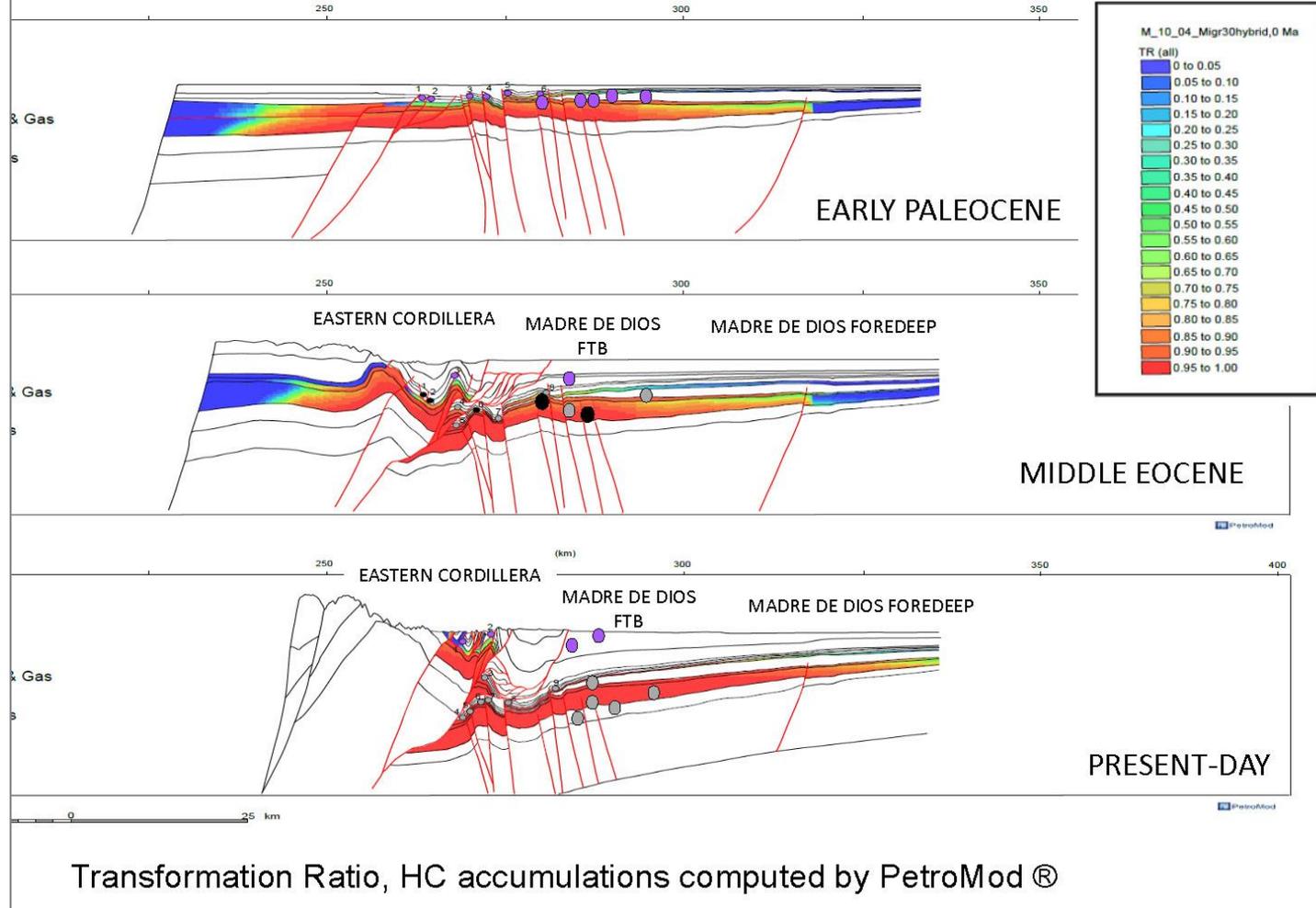
Presenter's notes: This is the sequential restoration of the Inambari cross-section constructed from the previous geochronologic constraints. It shows that in the Middle Eocene the Cenozoic duplex was well developed with 14 km of shortening. It represents the final stage of the first Andean orogeny, which has been submitted to strong erosion. From the Late Miocene to the present-day, the second Andean orogeny is characterized by strong shortening, important thrusting of the Eastern Cordillera, and flexural subsidence with high rate of sedimentation.

# PETROLEUM SYSTEMS



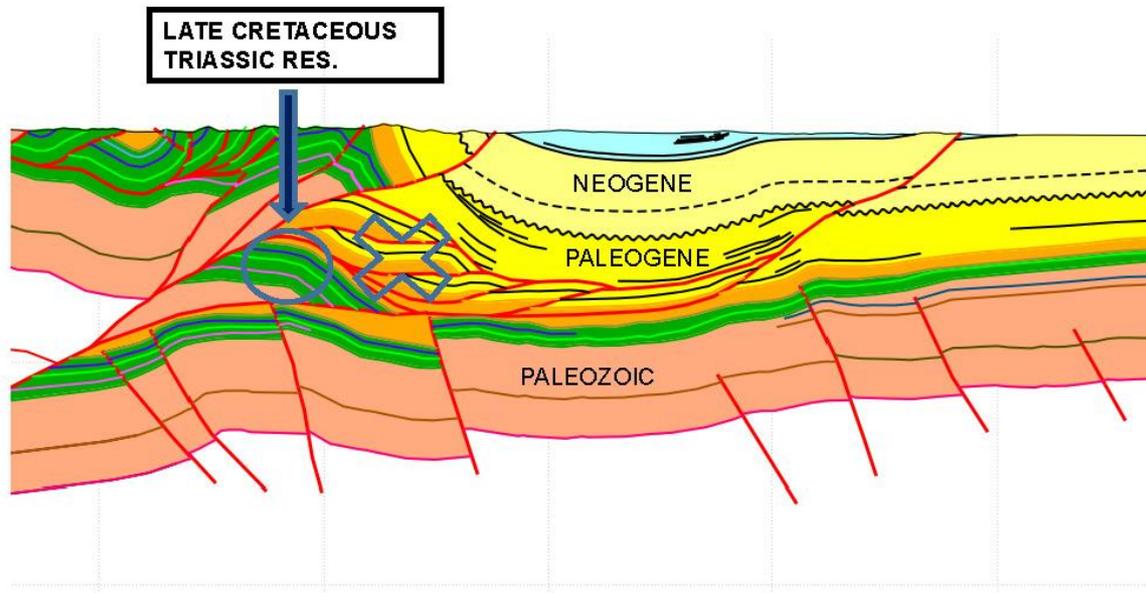
Presenter's notes: From the sequential restoration, we realized a 2D modeling of the petroleum systems using the four mean source rocks of the region. The Carboniferous Ambo shales, the Late Devonian Cabanillas shales, the late Cretaceous Chonta shales and some levels of the Copacabana limestones. All these source rocks are practically type 3.

## 2D PETROLEUM SYSTEMS MODELING FROM SEQUENTIAL RESTORATION



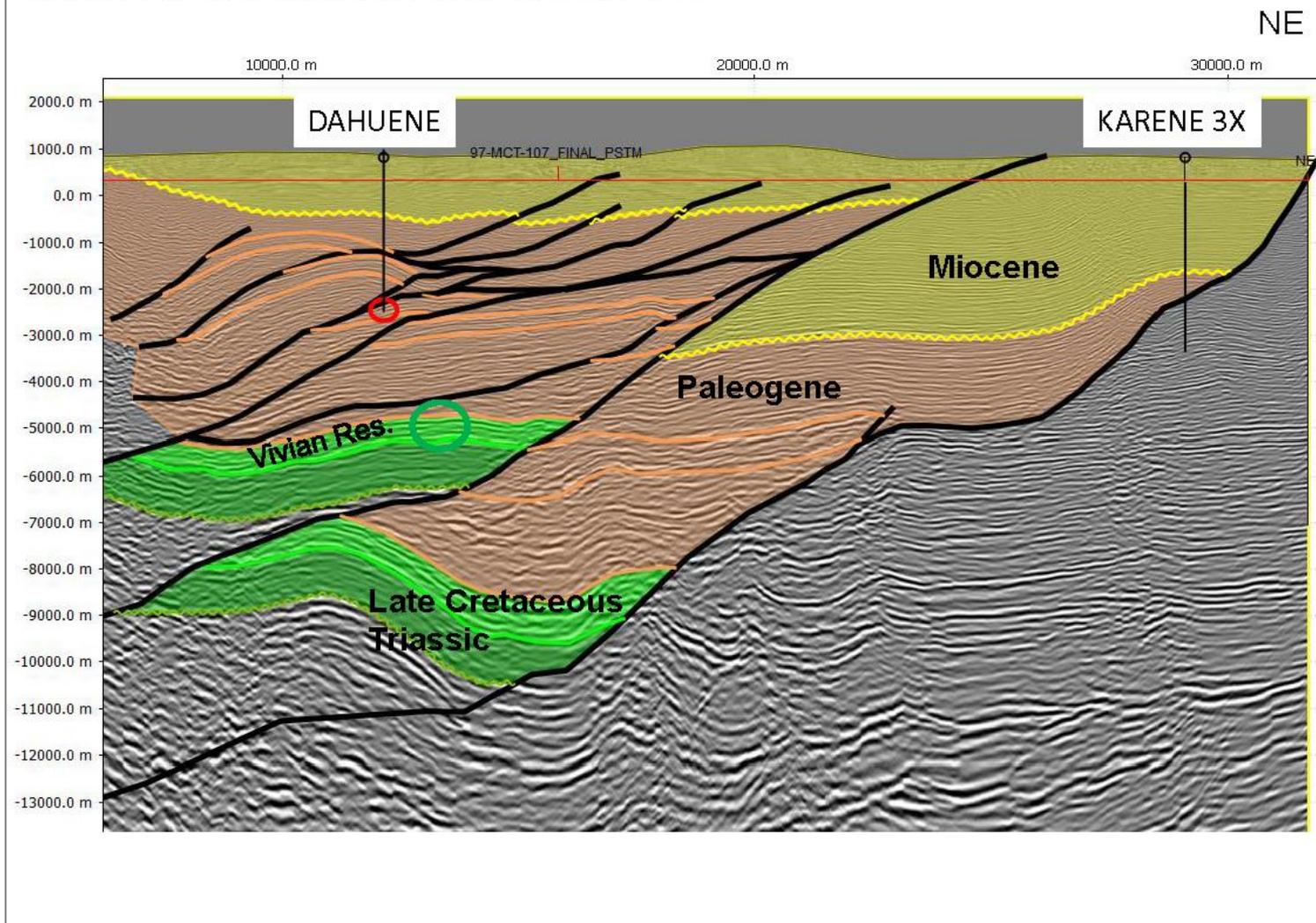
Presenter's notes: This is the 2D modeling of the petroleum systems from the Early Paleocene to the present-day. It shows the maturity evolution of the source rocks and HC accumulations computed by PetroMod. In the present-day cross-section, gas accumulations appear in deep sub-thrusts and reservoirs of Late Permian and Cretaceous ages.

## STRUCTURAL RISK: PALEOGENE DUPLEX



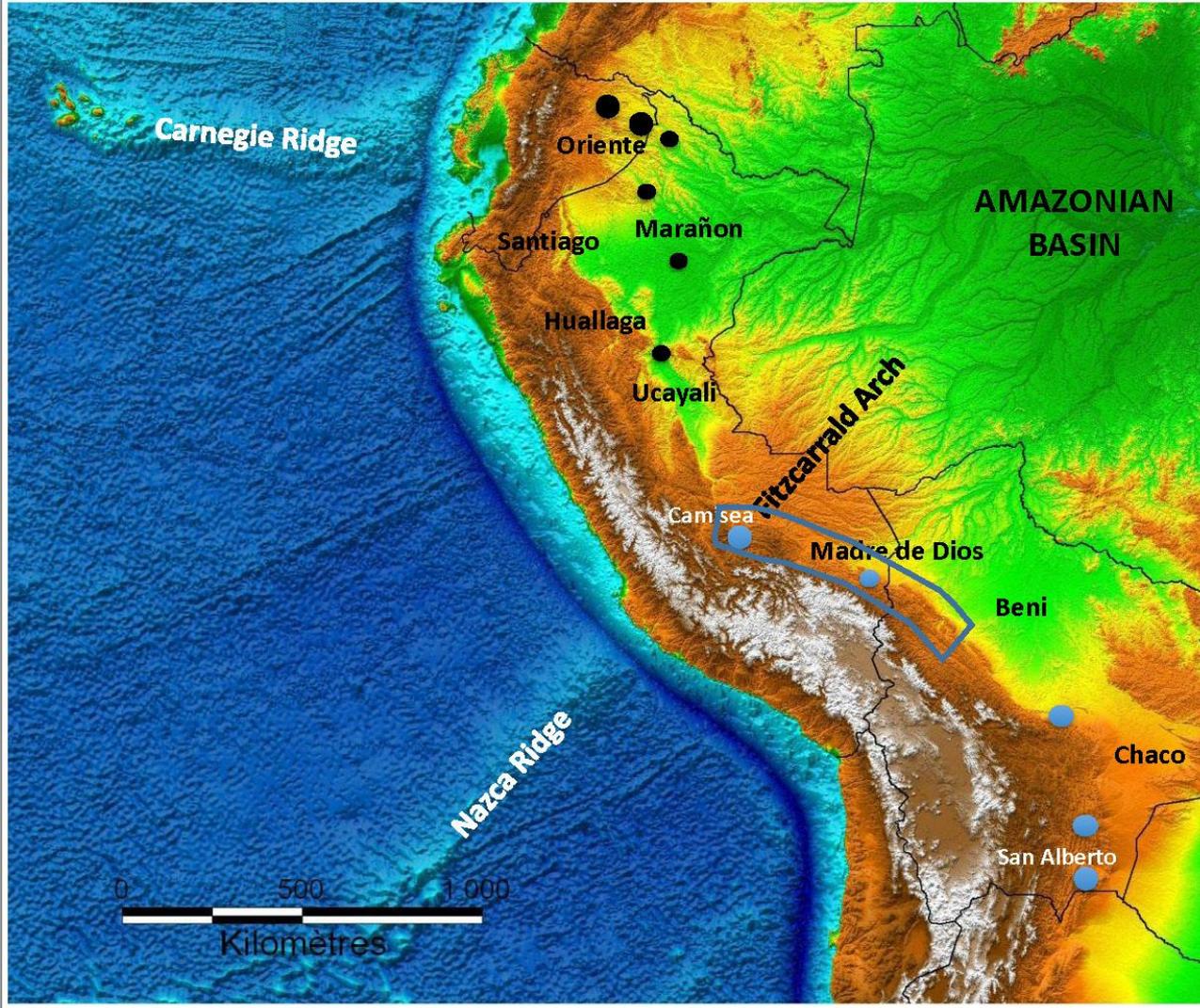
Presenter's notes: In conclusion, in the Madre de Dios foothills, one of the major structural risk is this Cenozoic duplex that seems very attractive, but that developed in continental foreland sediments with poor possibilities of reservoirs. On the other hand, the petroleum modeling shows possibilities of gas accumulations in Late Permian and Cretaceous reservoirs of sub-thrusts.

# STRUCTURAL RISK: PALEOGENE DUPLEX

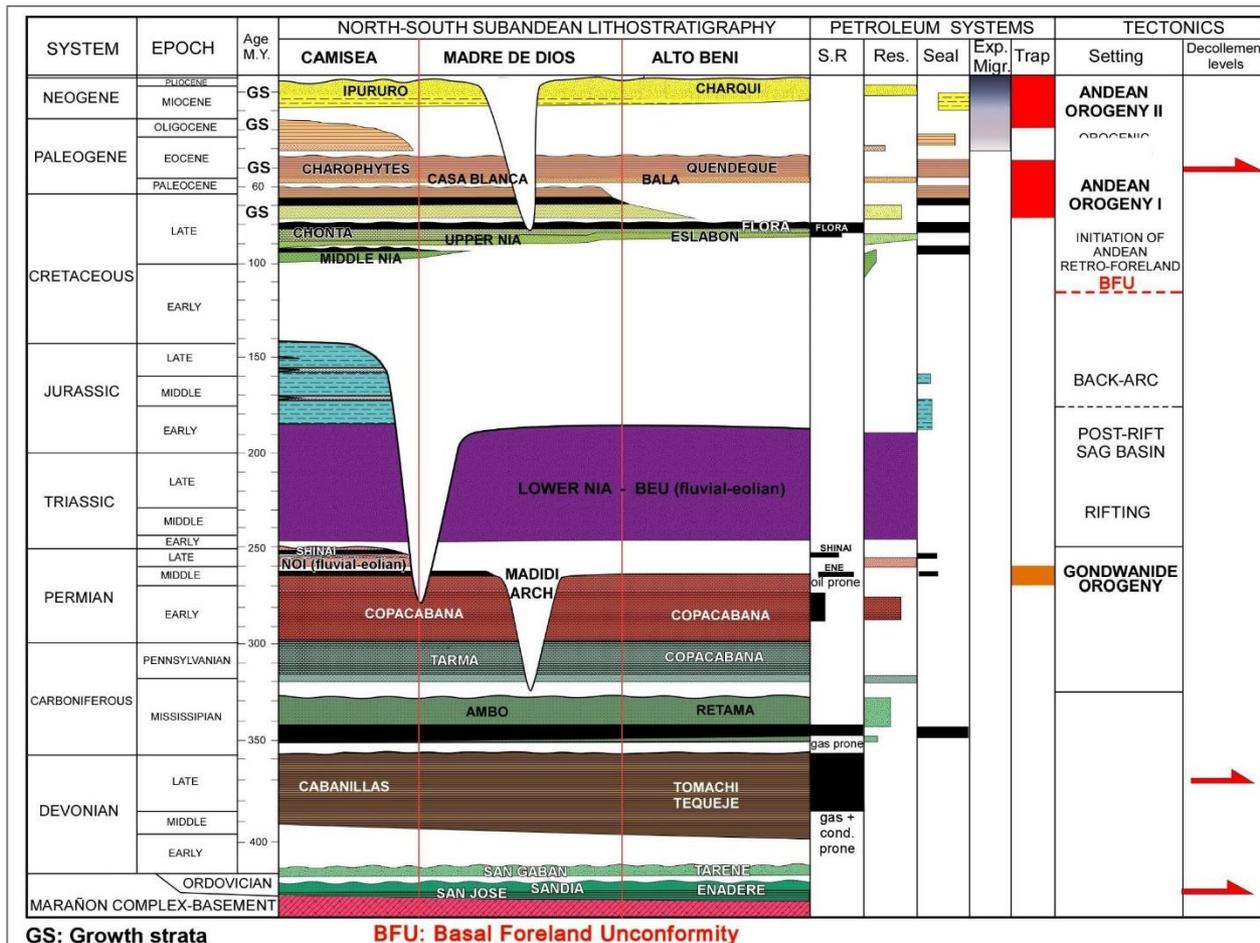


Presenter's notes: This structural risk has already been tested by the last exploration well in Madre de Dios, the Dahuene well that stopped in the Paleogene duplex without reaching the Late Cretaceous reservoir located in depth in these two sub-thrusts.

## CAMISEA-MADRE DE DIOS-BENI PROVINCE



Presenter's notes: Now, I propose to analyse how does the Peruvian Madre de Dios foothills connect with the Beni foothills?



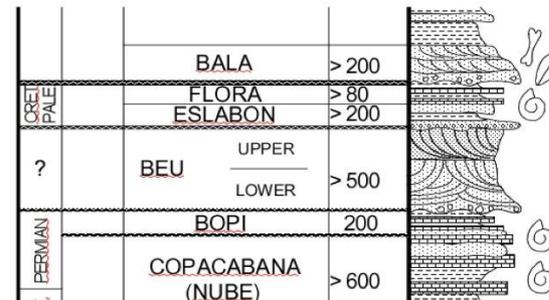
Presenter's notes: This is the stratigraphic north-south correlations that we propose between Camisea, Madre de Dios and Alto Beni foothills. In the Alto Beni, the stratigraphic is similar to that of Madre de Dios. The Paleozoic series is almost continuous, and probably thicker in Bolivia. It constitutes the main petroleum system. The top of this Paleozoic series is eroded and sealed by the Noi and Beu sandstones that we consider as Late Permian. The age of the Noi Formation is well constrained in Peru. As in Madre de Dios, in the Alto Beni Basin, there is a big gap between the Beu Formation and the Late Cretaceous Andean foreland deposits. The two Andean orogenies are associated to the Quendeque and Charqui formations. Detachment levels are located at the base of the Paleozoic series, in the Devonian, and locally in the Quendeque Formation.

TRIASSIC  
EOLIAN RESERVOIR

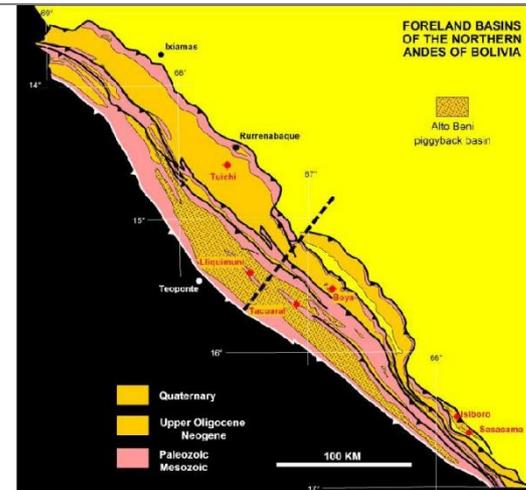
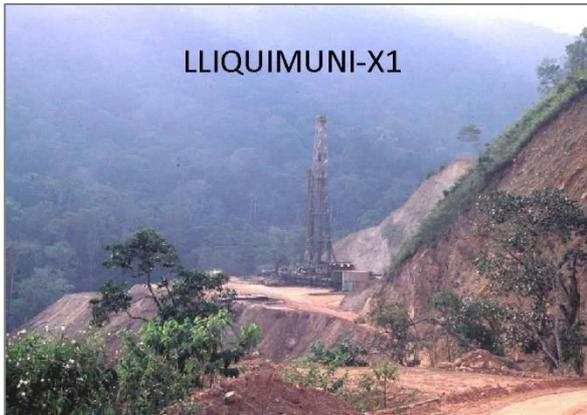


**LOWER NIA Fm. (Subandean zone, Peru)**

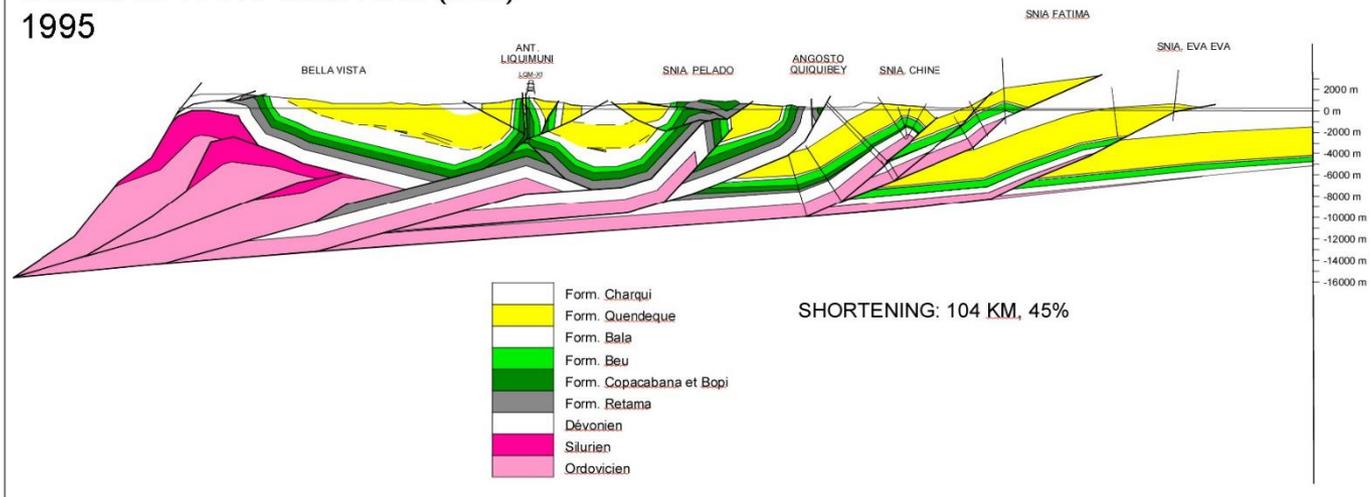
**BEU Fm. (Rurrenabaque, Alto Beni)**



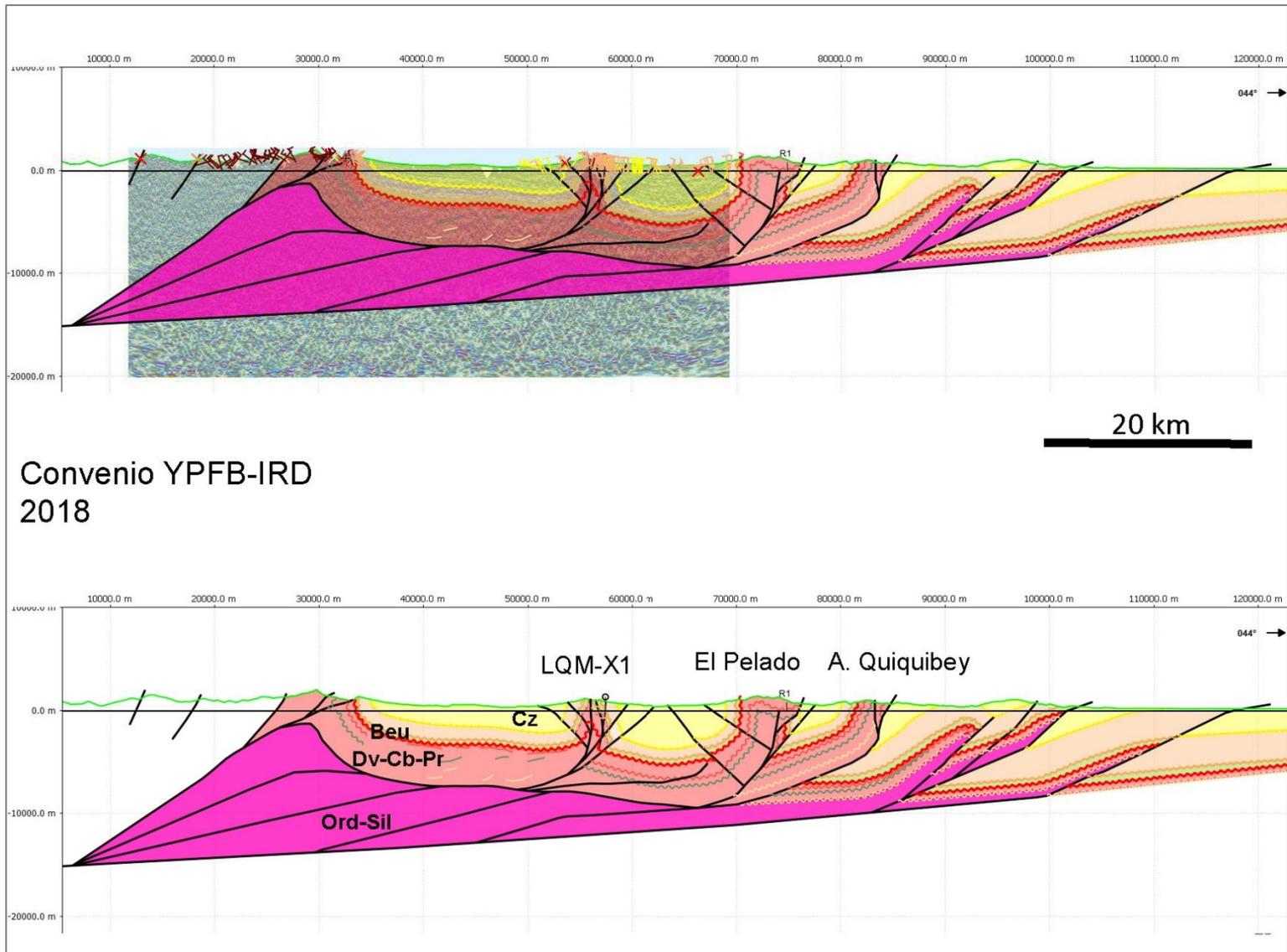
Presenter's notes: The Late Permian eolian reservoir is probably the best reservoir of the Camisea-Alto Beni hydrocarbon province. This is a photo of the eolian sandstones of the Noi Formation in Camisea, and here a photo of the eolian sandstones of the Beu Formation in Rurrenabaque. As in Peru, the eolian sandstones correspond to the upper part of the formation. The Beu is not dated, but it is located between the Late Cretaceous and Permian and can easily be considered as an equivalent of the Late Permian Noi Formation.



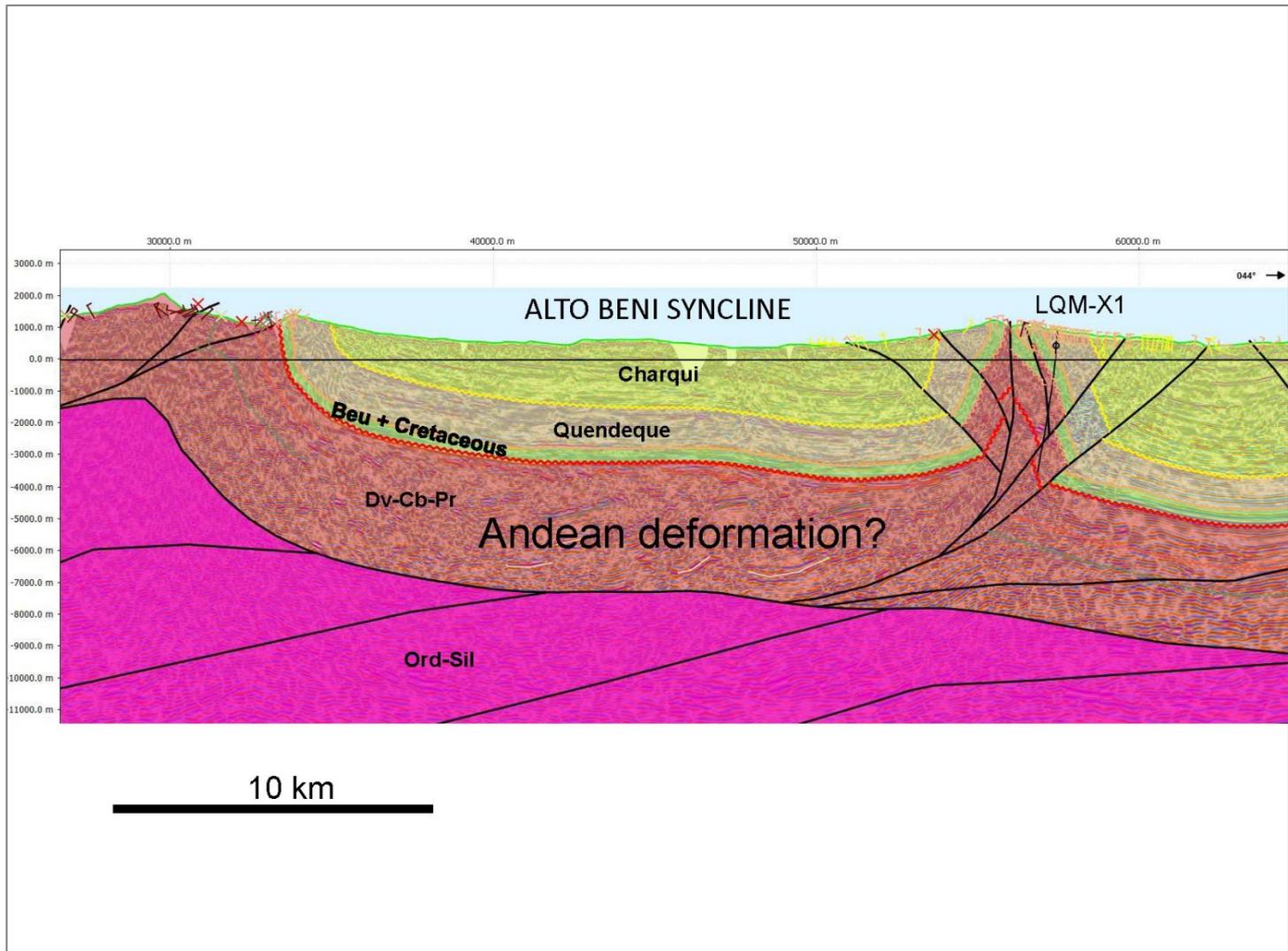
Convenio YPFB-ORSTOM (IRD)  
1995



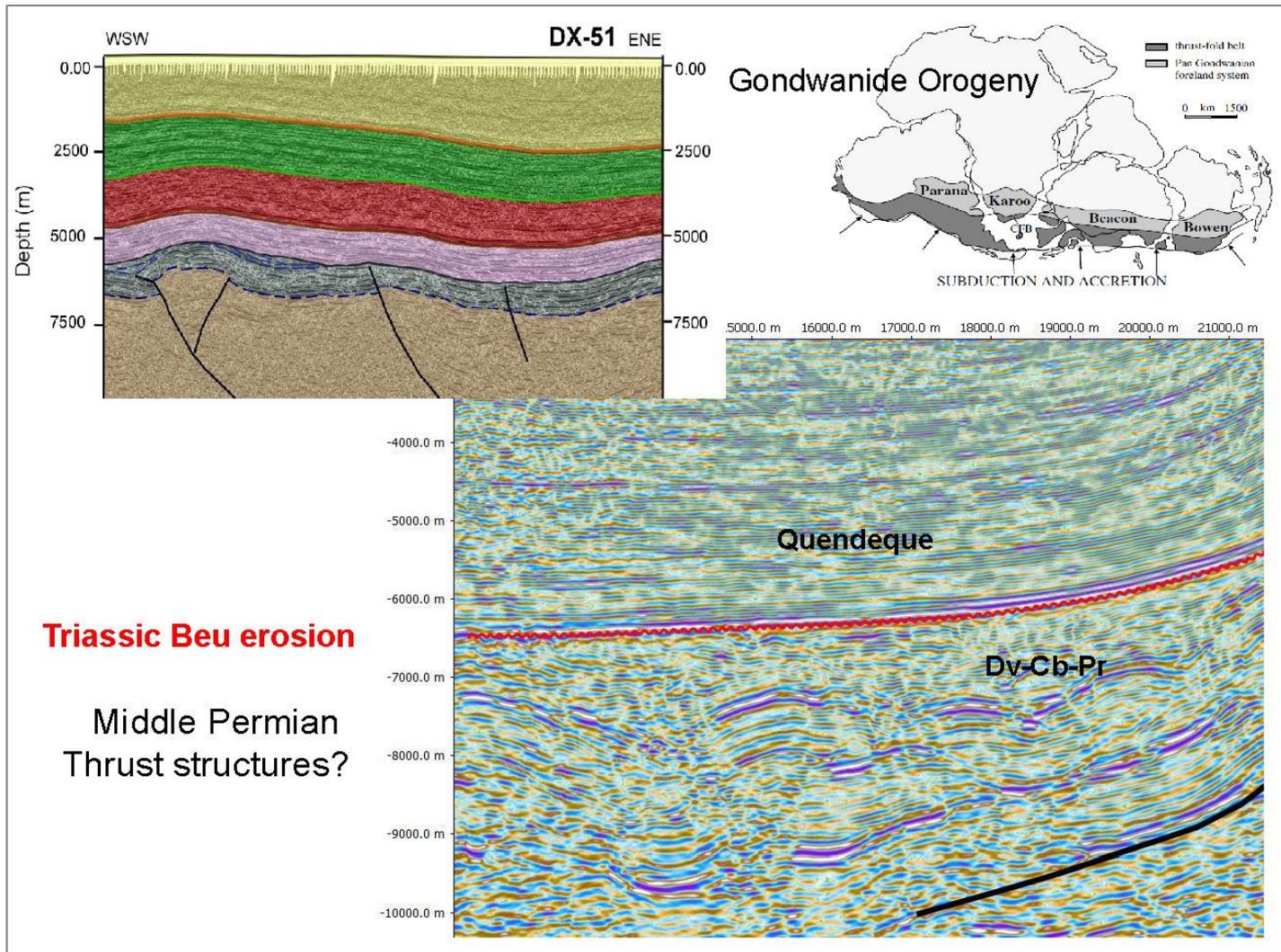
Presenter's notes: More than twenty years ago, in the YPFB-ORSTOM (now IRD) convenio, during the first Lliquimuni well perforation, we have constructed the first balanced cross-section in the Alto Beni foothills. This is a perfect thin-skinned tectonics model which involves the entire sedimentary series from the base of the Paleozoic to the Neogene. The back-stop is formed by a big Ordovician duplex, and the frontal thrust system presents classic fault-propagation folds. Shortening is strong, more than one hundred kilometers, and 45 %. Unfortunately, the Lliquimuni well has been perforated in the most complex structure of the Subandean zone.



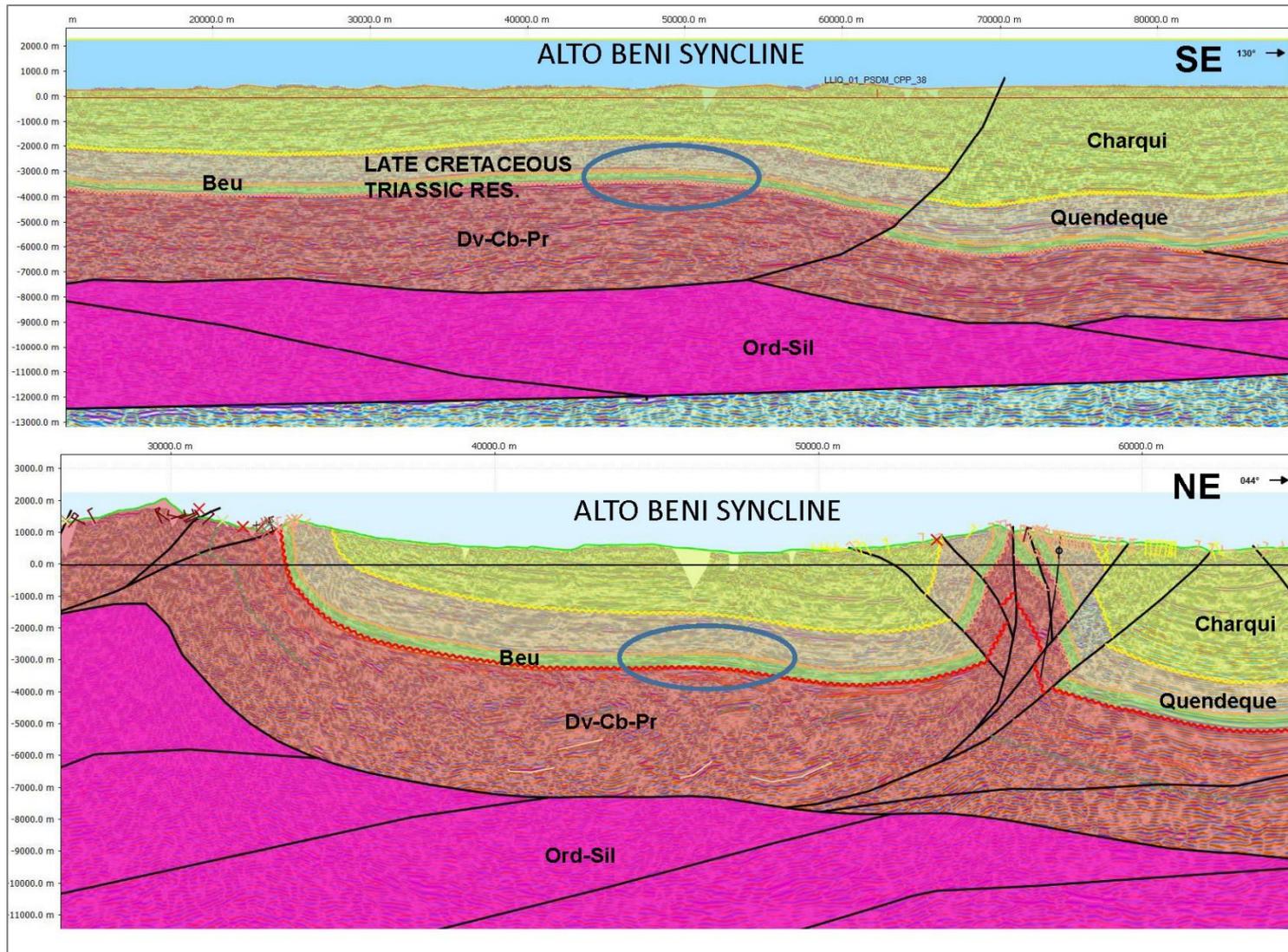
Presenter's notes: Today, in a new agreement with YPFB, we start working again on the same cross-section, using new seismic information. The model is almost the same, and seems simpler.



Presenter's notes: The new seismic shows the deep Ordovician and Silurian duplex, the complex Lliquimuni anticline, the well preserved Alto Beni syncline, and an homogeneous deformed and thickened level of Devonian, Carboniferous, and Permian strata. The question is what is this deformation preserved below the Alto Beni syncline? Is it Andean deformation?

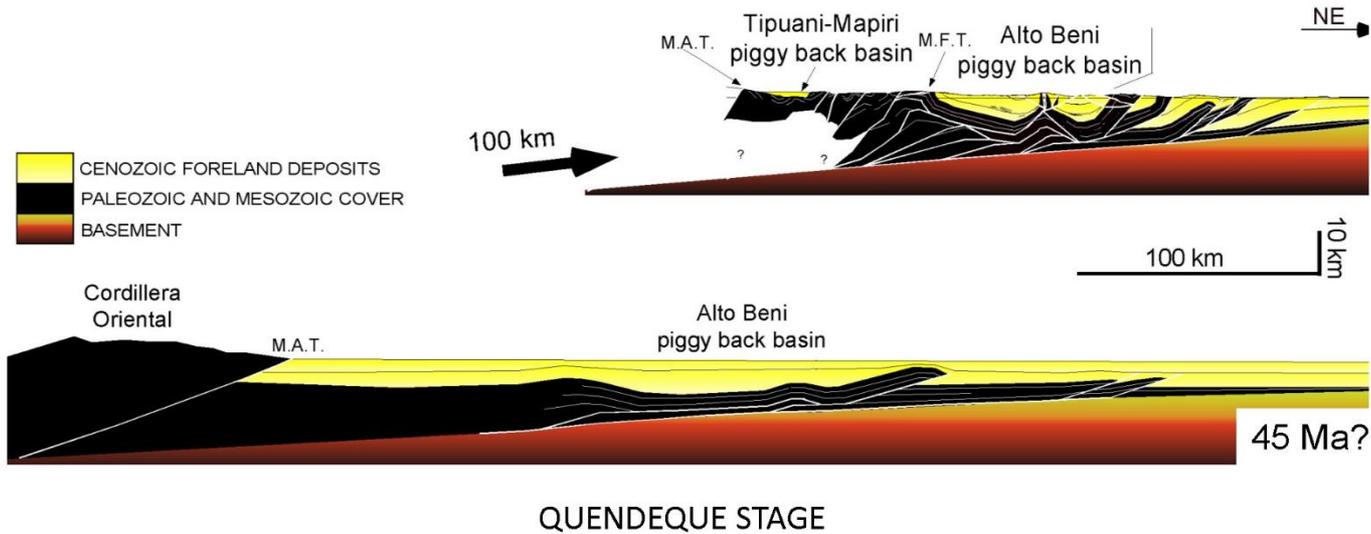


Presenter's notes: Looking in details the seismic, it seems that the deformation of the Devonian and Permian strata are eroded and sealed by the base of the Beu Formation. These second order thrust anticlines are very similar to the Middle Permian structures observed in Peru and resulting from the Gondwanide orogeny. That is why we interpret these second order structures as preserved Permian structures, and not Andean structures. They can be a good option for future explorations in the Alto Beni syncline.



Presenter's notes: One other possible structural play below the Alto Beni syncline corresponds to large anticlines like this one, that can be observed in cross-sections as in longitudinal section. You can see that the structure closes in both directions. The main reservoir is the Beu Formation that can be easily filled by HC expelled from Devonian, Carboniferous, or Permian source rocks.

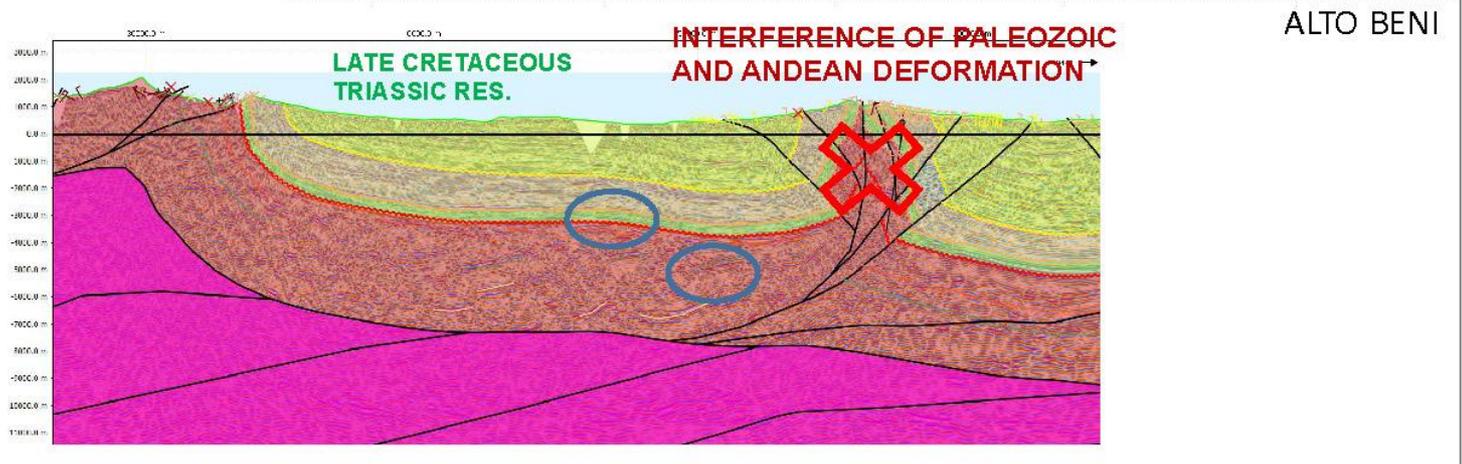
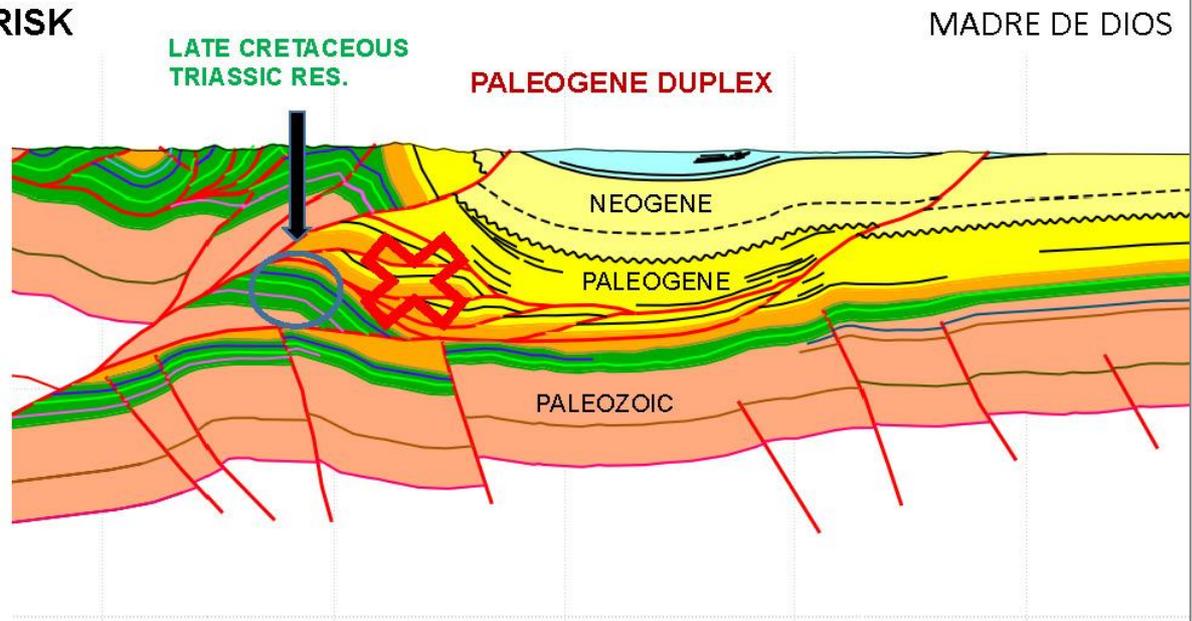
## Are there the two periods of Andean orogenesis in the Subandean zone?



Must be constrained by thermochronology and Cenozoic infill analysis (growth strata?)

Presenter's notes: Are there the two periods of Andean orogenesis in the Bolivian Subandean zone? In the first convenio with YPFB, we propose this model, using thicknesses variations of the Cenozoic formations. We evidenced two stages of Andean deformation. The first stage was associated with the Quendeque deposits. The problem is that we don't have datations of the Quendeque Formation. This type of restoration must be now constrained by thermochronology and Cenozoic infill analyse.

# STRUCTURAL RISK



Presenter's notes: To conclude about the structural risk in the Peruvian-Bolivian Subandean zone. Complex structures as Paleogene duplexes in Madre de Dios, or interferences of Paleozoic and Andean deformations in the Alto Beni should be avoided. Deep large Andean anticlines preserved below the foreland sediments, or preserved Middle Permian folds are better targets.

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