VII INGEPET 2011 (EXPR-3-WH-10-E)

PALEOZOIC DEFORMATION AND ITS HYDROCARBON POTENTIAL IN THE NORTHERN ANDEAN FORELAND BASIN

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Abstract

The Paleozoic petroleum potential has been proved in many sub Andean basins (Subandean and Chaco, Madre de Dios, Beni basins). In these basins, Paleozoic sedimentary sequences contain excellent source rocks, reservoirs and seals. More than 40.17 BBOE (Billon of Oil Equivalent) of recoverable reserves have been discovered in the foreland basin of the Central and Septentrional Andes. More than 40% of the total reserves are associated to Paleozoic petroleum system. The hydrocarbon accumulations associated to Paleozoic system discovered are trapped in Cenozoic compressive and stratigraphic structures.

The Paleozoic deformation history and its hydrocarbon potential in many foreland basins remains poorly understood. In the northeastern part of Colombia and Venezuela, the Paleozoic is characterized by a large overthrusted transpressional features, slightly reactivated during the Andean compression. In the north of Peru, the Paleozoic deformation is overprinted by Mesozoic extensional episodes and later Cenozoic Andean deformation. In the southern part of Peru, the pre- Late Carboniferous is characterized by a thick- skinned thrust belt system. Paleozoic thrusting has associated synorogenic and transported “piggyback basins”. Many of these mini basins contain prolific source rocks and excellent reservoirs. Erosional surfaces or unconformities truncate these compressional structures and are overlain by subhorizontal Upper Carboniferous and Cenozoic series. The Paleozoic structures could represent a good opportunity in many foreland basins for future exploration strategies

Introduction

Hydrocarbon exploration in the eastern edge of the Andes has been focused in the Foreland Basin System. The evolution of this basin started during the Upper Cretaceous, as a result of the eastwards subduction of the oceanic Nazca Plate beneath the continental plate. Modern morphological and structural configuration of the thrust belt and foreland sub basins occurs during the last 15 Ma.

In the foreland basin of the Central and Septentrional Andes from Venezuela (Barinas- Apure Basin; Fig. 1) to Bolivia (thrust belt and Chaco Basin; Fig. 1) have been discovered more than 40.17 BBOE of recoverable reserves (IHS, 2011). More than 40% (16.95 BBOE) of the total reserves are associated to Paleozoic petroleum system (12.46 BBOE from the thrust belt and Chaco in Southern Bolivia and 4.49 BBOE from the Ucayali south and Madre de Dios basins in Peru).

Regionally from north to south (Fig. 1), the petroleum systems evolve from younger to older systems. To the north, Apure, Barinas, Llanos Orientales and Llanos thrust belt (Venezuela and Colombia) all hydrocarbon fields are associated to the Cretaceous and the Tertiary source rocks and reservoirs. In the Putumayo and Oriente basins as well as in the associated thrust belts (Colombia and Ecuador), the main source rocks and reservoirs are the Cretaceous series.

In the northeastern of Peru, it has been discovered around 1.93 BBOE of recoverable reserves (IHS, 2011). The hydrocarbon fields are related to Cretaceous and Jurassic petroleum system. Almost 100% of the total reserves discovered come from the Marañón basin. The Cretaceous reservoirs host over 1.91 BBOE, whilst 0.025 BBOE (25 MMBOE) are in Tertiary reservoirs. Up to now, there are no significant hydrocarbon discoveries in the fold and thrust belt of the Subandean basins.

Large gas and condensates discoveries located in the Subandean zone characterized the southern east of Peru (Ucayali and Madre de Dios thrust belt), with recoverable reserves estimated in more than 4.49 BBOE (IHS, 2011). The petroleum systems are associated to the Paleozoic source rocks and Cretaceous and Upper Paleozoic reservoirs. More than 60% (2.75 BBOE) of the total recoverable reserves discovered in the southern Peru is hosted by the Cretaceous reservoirs whilst 40% (1.73 BBOE) are from the Upper Paleozoic reservoirs. Until today, no hydrocarbon accumulations have been found in the less deformed Madre de Dios foreland part. Exploratory wells indicate the presence of oil shows in the lower Paleozoic sequences.

In northern Bolivia, the Beni Basin, which is located in the southern prolongation of Madre de Dios, holds a small hydrocarbon accumulation (1 MMBOE). The hydrocarbon is also correlated with Lower Paleozoic source rock.

The southern Bolivia (fold thrust belt and Chaco basin) contains the most important hydrocarbon accumulations associated to the Paleozoic petroleum system (Fig. 1) with recoverable reserves estimated around 12.46 BBOE. The Paleozoic sequences host the main source rock and reservoir.

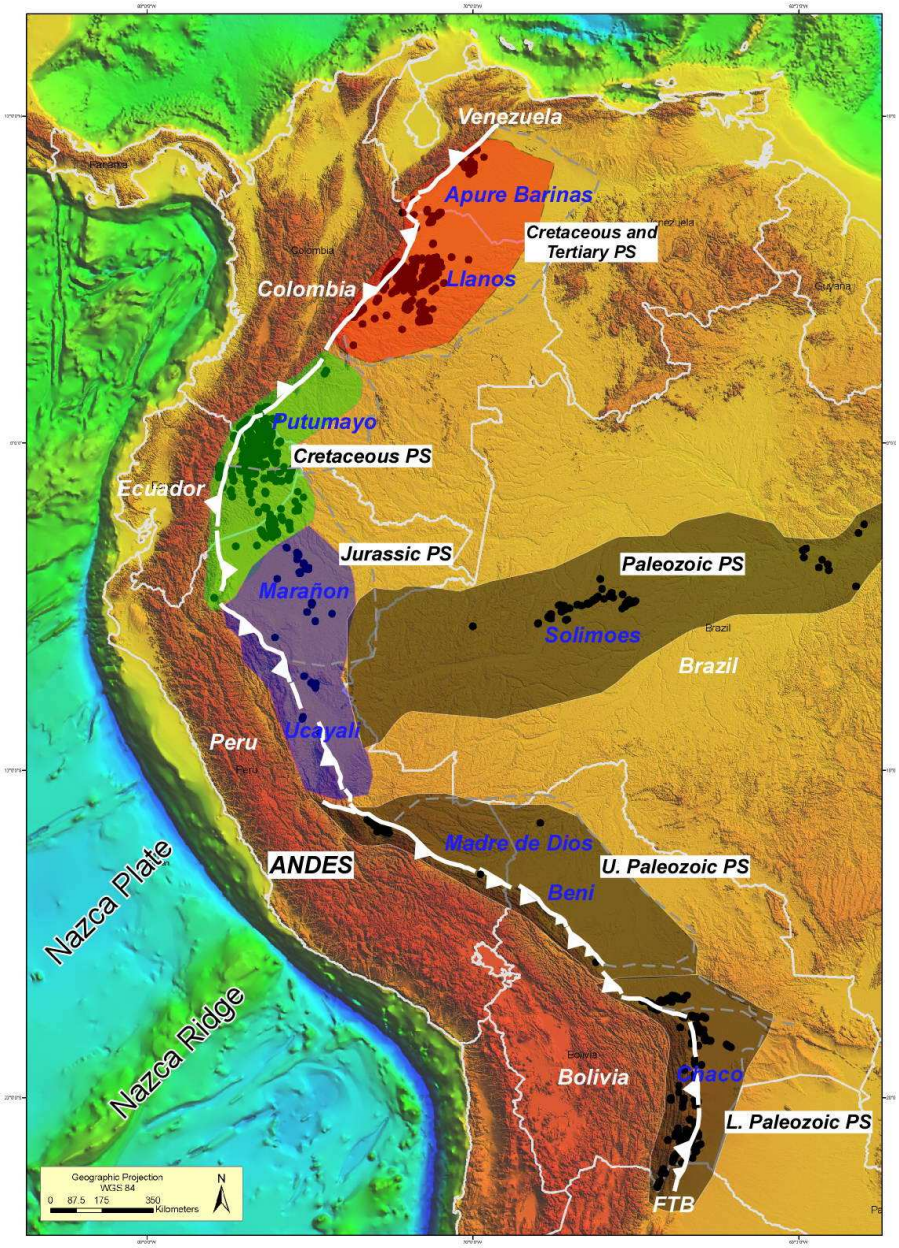

Figure 1. Map showing the hydrocarbon field distribution (fileds are in black circles) and the main petroleum systems along the thrust belt and foreland basin of the Central and Sepetentrional Andes

Recent studies in the Andes illustrated the different episodes of subduction, volcanic arc migration and terrain collisions. These episodes occured in the western active margin of Gondwana during Paleozoic times. The pre-Andean deformation with Paleozoic series overlying basement reveals a complex tectonics. Probably, it includes pre- Ordovician extension; Late Devonian to Lower Carboniferous compression and peneplanation, followed by late Permian uplift and erosional episodes. Paleozoic contractional features widely developed along the Andes, (Zubierta Rossetti et al., 1993; Colletta et al., 1997; Jacobshagen et al., 2002; Alvarez - Marron et al., 2006) must be taken into account for their subsequent implications on the Subandean zone structural evolution.

A subduction- related magmatism and accreted terranes characterized the western Gondwana margin during Early Paleozoic, (e.g. Williams K. E., 1995; Chew et al, 2007, Ramos 2010; Restrepo- Pace 2010). During Ordovician times, volcanic arcs apparently were present in the northern margin of Gondwana. Remnants evidences are now located in the Andes of Colombia (Williams K. E., 1995). Ordovician extensional tectonic has affected more to the southwestern margin of Gondwana, producing an intra cratonic rift basin in Bolivia and northern Argentina (Williams K. E., 1995).

The Middle Silurian is characterized by a widespread glaciation period. Distribution of these glacial sediments suggests that the South Pole was centered in Africa. (Williams K. E., 1995). In the Andes, some Silurian limestone and diamictites suggest a lateral displacement tectonics (Williams K. E., 1995). This lateral faulting episode probably has occurred in the Early Carboniferous. During this time, the extensional activity persisted into the southwestern area of Gondwana (Present day Argentina; Ramos et al., 1986).

During Devonian, several highland or mountainous areas owe their uplift to this tectonic episode. These highlands formed local glacial centers at various times during the Carboniferous. The Devonian has huge impact in the hydrocarbon exploration in the current foreland basin, as the marine shales deposited during this time are the best source rocks. Sandstone units of this period are also excellent reservoirs. These units are well known in the southern Peru, Bolivian and northern Argentina producing basins. Devonian shales are also the source for hydrocarbons discovered in the Solimoes and Amazon Basin of Brazil (Williams K. E., 1995).

The Carboniferous plate reconstruction done by Williams et al. (1995) shows that the Amazon basin subsided rapidly, as a result of the collision of North America and Europe supercontinents with the southern continents of Gondwana. As well as subsidence along the western margin of the Gondwana continent related to subduction process (Williams K. E., 1995). These collisional and subduction events give rise to a regional compressional episode generating a thrust belt system.

During the Late Carboniferous - Permian, Pangea was influenced by a wide variety of stresses as a precursor to the fragmentation that would occur in the Mesozoic. The South Pole was located off Antarctica (Williams K. E., 1995), which resulted in a warmer climate than in Carboniferous–Permian time. In the Central Andes developed a wide carbonate platform and large eolian dunes.

In this paper we are focusing in the Paleozoic deformation and its hydrocarbon potential. In many forelands basins, Paleozoic deformation has generated large compressive and transpressive features. These structures remained frozen or slightly reactivated during the Andean deformation.

Paleozoic Petroleum potential

Paleozoic petroleum potential has been proved in many sub Andean basins (Subandean Chaco Basin, Beni-Madre de Dios, Solimoes; Fig. 1). In these basins, Paleozoic sedimentary

sequences contain excellent source rocks, reservoirs and seals. The biggest gas fields discovered in the Andean foreland basin are related to Paleozoic petroleum systems.

In southern Bolivia and northwestern Argentina, the Devonian Los Monos, Iquiri and the Silurian Kirusillas Formations range from fair to very good quality as source rocks. TOC varies from 1% to 2%. Organic matter is type II – III (Moretti et al., 1996; Cruz et al., 2002). Reservoirs are represented by Lower Devonian Huamanpampa, Icla and Santa Rosa formations. Seals are also the Intra Paleozoic shales (Los Monos, Iquiri Formations). These sedimentary sequences have generated the biggest hydrocarbon accumulation in the Southern Bolivian and northern Argentina (Monteagudo, Camiri, Monteagudo, Tatarenda, Ramos fields etc)

In northern Bolivia and southern Peru, studies by Mobil reveals that the upper Devonian rocks in the Madre de Dios and Beni Basins could be considered as potential world class source rock, richer than the Upper Jurassic source rock in Central Saudia Arabia or North Sea (Peters K. E. et al., 1997). The Upper Devonian Tomachi Formation in the Beni Basin shows high TOC (2 to 6%), with type II - III organic matter. In Pongo de Coñec area (Madre de Dios Basin), a shale interval in the Cabanillas Formation, shows good source rock quality, with TOC varying from 1.4 % to 3 %. In addition, the Silurian, Lower Carboniferous and Upper Permian shales are excellent quality source rocks. Reservoirs correspond to Permian eolian sandstone and Cretaceous reservoirs. These sequences sourced many hydrocarbon fields (Pando; Candamo and San Martin, Cashiriari, Kinteroni fileds).

In western Brazil (Solimoes Basin), the Upper Devonian (Frasnian) Jandiatuba shale represents one of the main source rocks in this basin. TOC is around 8.25%. Main reservoir rocks correspond to the Carboniferous Eolian and fluvio-deltaic sandstones of the Juruá Formacion. The hydrocarbon discovery in the Solimoes Basin is derived from The Upper Devonian source rock.

In many basins, the Paleozoic petroleum potential and stratigraphy is poorly known, as many exploratory wells are suspended once they encountered Paleozoic rocks. Except for few wells, most are drilled to the uppermost part of the Paleozoic section. Recent studies in foreland basins suggested that the classical Pre Cretaceous unknown series correspond to Devonian and Carboniferous series (potential source rock and reservoirs and seals).

Paleozoic deformation

Many authors agreed, that aspects of the regional geology and hydrocarbon potential of this area, including regional shape, geometry style of deformation and exploration play variations are related to pre-existing paleogeography (Paleozoic and Early Mesozoic extensional basin). These paleogeographies controlled the source rocks quality and oil fields distribution. Also, it is the main control for the different structural styles during Andean deformation. Paleozoic contractional features and Mesozoic extensional basins widely developed along the Andes and must be taken into account for their subsequent implications on the thrust belt foreland deformation.

The foreland basins and thrust belt zones are affected by several tectonic elements (Arauca, Vaupes, Contaya, Manu, Fitzcarrald, Madidi arches, Pastaza cone, Shira Mountains, etc). Many of these tectonic elements were active during Paleozoic times and therefore controlled the sedimentation and Paleozoic depocenters distribution. The Shira and Vaupes structural elements seem to be related to Paleozoic compressional structures reactivated during the Andean uplift. The Fitzcarrald arche and Pastaza cone apparently are very young tectonic elements.

From Venezuela to Bolivia, the fold thrust belt or Sub Andean zone (active area of the foreland basin system) is organized in various structural segments. Each segment is characterized by different styles of deformation and exploration plays (Macellari & Hermoza, 2009).

The strong deformation in the active fold thrust belt zone and sub Andean basins does not allow analyzing pre- Andean deformation in detail. As this paper is focused in the Paleozoic deformation and its exploration potential, we will then focus in the foreland basins. These basins less deformed than the thrust belt have preserved many pre- Andean structures.

To illustrate the main Paleozoic features, we present eight cross sections along the Barinas-Apure basin (Venezuela), Llanos Orientales basin (Colombia), Marañon and Ucayali (Peru, Fig. 2). These cross sections are supported by seismic interpretation and previous works (Coletta et al., 1997; Parnaud et al., 1995; Espurt et al., 2008)

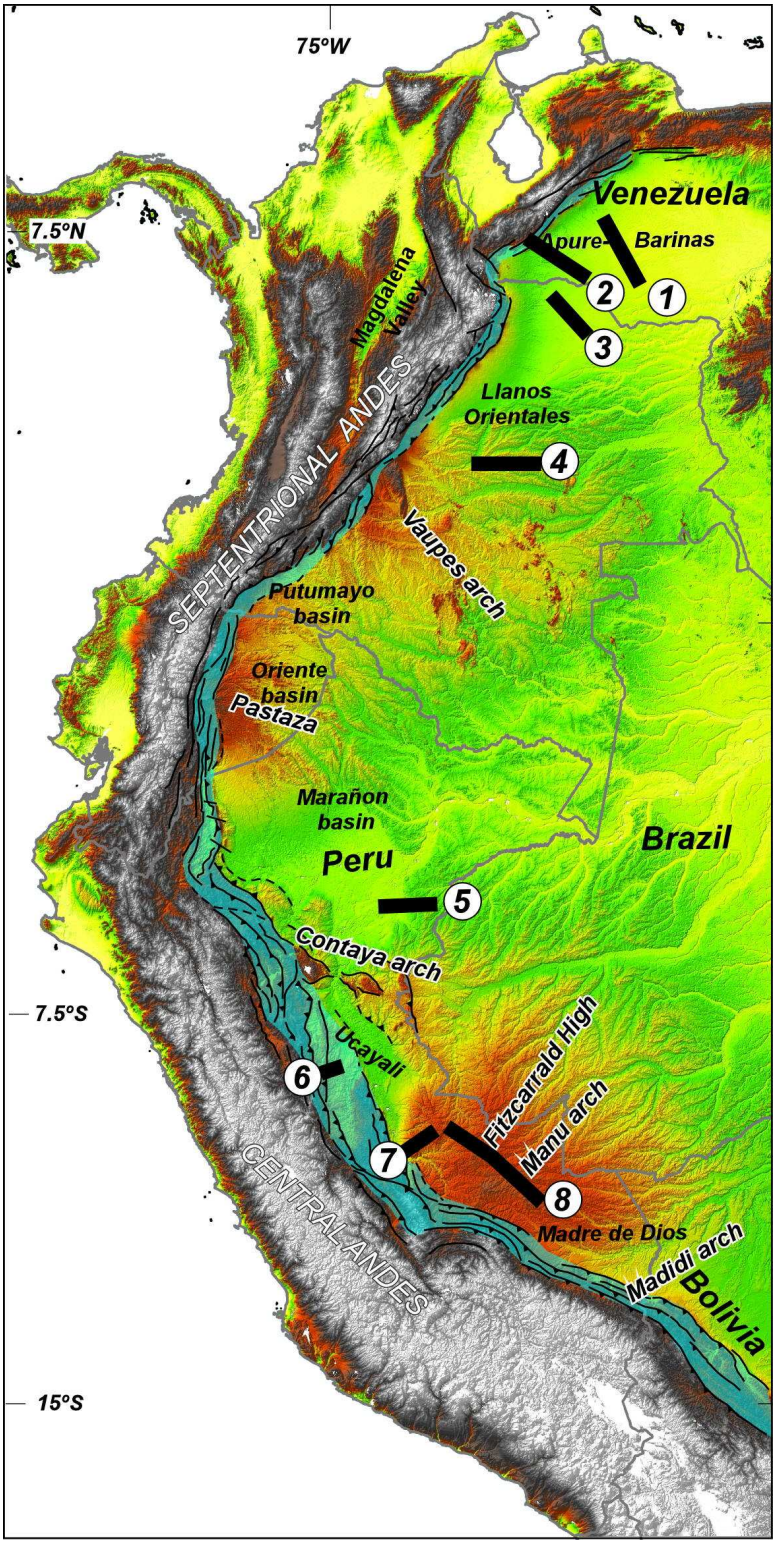

Figure 2. Map showing the location of the cross sections in black line along the foreland basin.

The two cross-sections from the Barinas – Apure Basin, (Figs. 3 and 4) are located in the eastern part of the basin. The thick Paleozoic interval is characterized by thrusting and stacking features involving the Paleozoic and Basement, which lies below the regional Cretaceous unconformity, which seals the Paleozoic structures. These features were very slightly reactivated during the main Andean deformation.

Hydrocarbon contribution from Paleozoic source rock is controversial in this basin. Some authors suggest that Paleozoic or pre- Cretaceous series probably have an impact in the volumes of hydrocarbons discovered in the basin (Olivares et al., 2002; Mora et al., 2006)

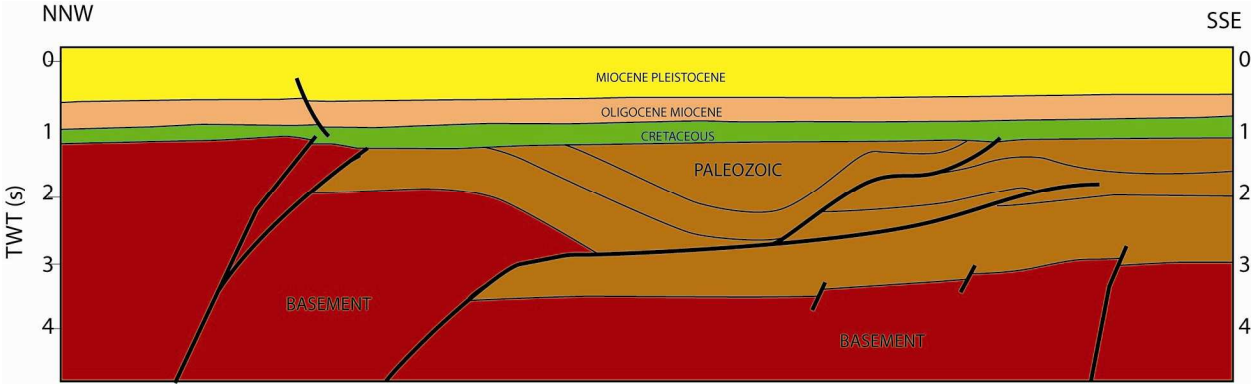

Figure 3. Cross section 1 through the eastern part of the Barinas basin, vertical scale in TWT. Location map in the figure 2 (modified from Colleta et al., 1997).

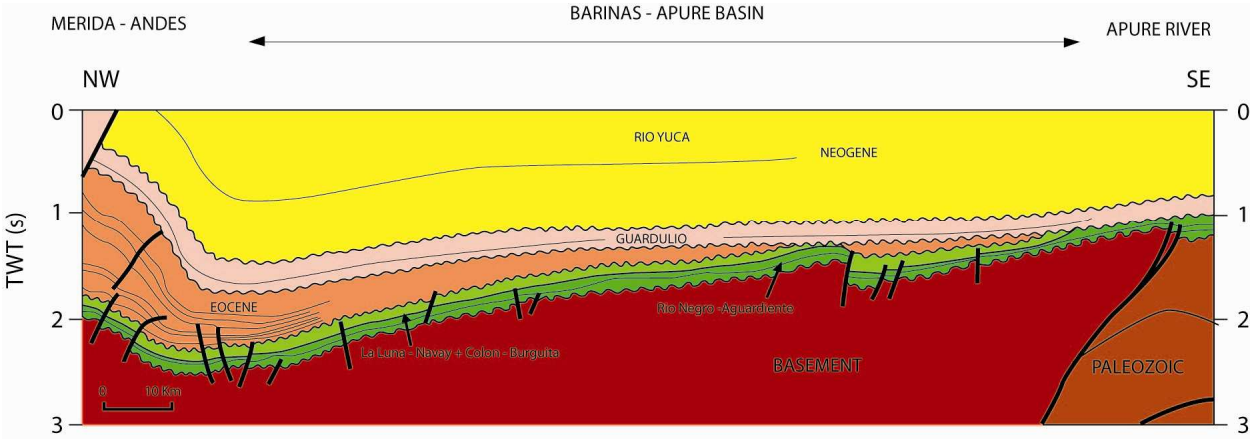

Figura 4. Cross section 2 along the southern part of Barinas Apure Basin, vertical scale in TWT. Location map in the figure 2 (modified from Parnaud et al., 1995)

In the Llanos Orientales Basin, the Paleozoic interval is strongly deformed (Figs. 5 and 6). Intense transpressional deformation is apparently related to different Paleozoic orogenies that triggered the development of a thrust belt system, which lies below a regional Cretaceous unconformity. Style of deformation of the Paleozoic features corresponds to inversion of Cambrian- Early Ordovician extensional basins. Paleozoic thrust belt was submitted to an intense denudation and peneplanization period during the early Mesozoic.

The structures in the Paleozoic are large and widespread, thus, they have a strong potential for the entrapment of hydrocarbons. However, to date, in the Mesozioc and Tertiary hydrocarbon accumulacions there are not clear evidence of hydrocarbon contribution from Paleozoic source rocks. In the Llanos basin several wells reveal gas indications (seeps) which support the possible hydrocarbons accumulation in the Paleozoic features.

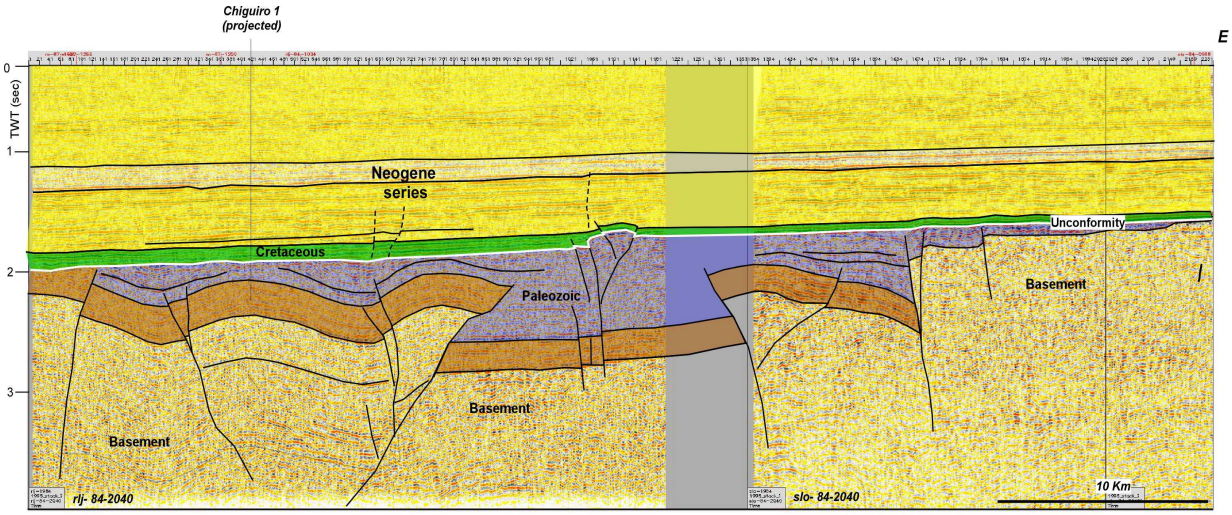

Figure 5. Cross section 3 located in the northern east part of Llanos Orientales Basin, vertical scale in TWT. Location map in the figure 2.

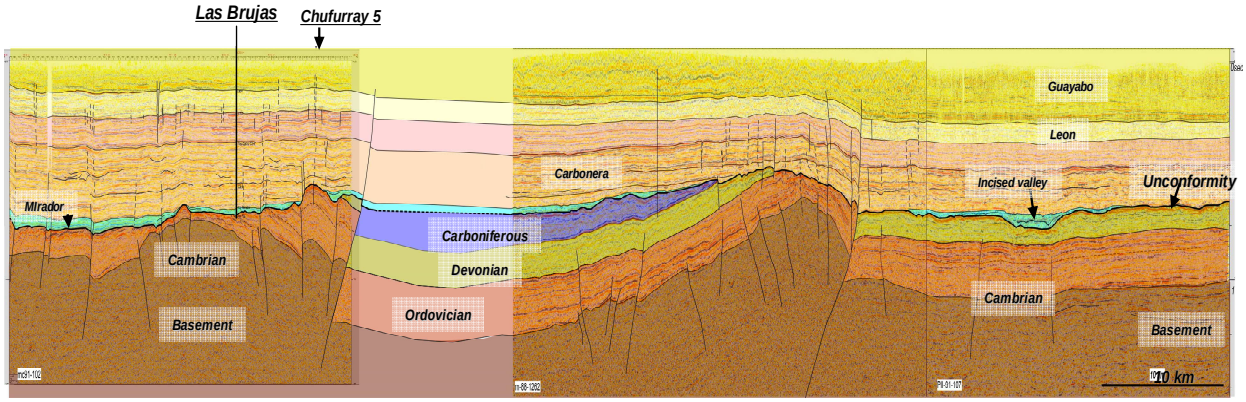

Figure 6. Cross section 4 across the southern part of the Llanos Basin, showing the Paleozoic deformation slightly reactivated during the Andean deformation, vertical scale in TWT. Location map in figure 2.

The Marañon Basin deformed by inversion of Triassic – Jurassic half grabens, which started during the Late Cretaceous. The main deformation period occurred during the last 10 Ma.

The pre Cretaceous paleogeography is characterized by the Triassic – Jurassic extensional basins, which had overprinted the compressional Paleozoic deformation. This paleogeography does not permit to analyze the Paleozoic deformation; however seismic images and well data give some evidences of the Paleozoic deformation in the south east part of the basin (Fig. 7).

The cross-section 5 (Fig. 7) shows a thick Paleozoic interval deformed by strike slip faulting. These features were eroded and sealed by a basal Cretaceous unconformity and were subsequently slightly reactivated during the Andean deformation. The Paleozoic interval probably contains the potential Devonian, Carboniferous, Permian source rocks, reservoirs and seals.

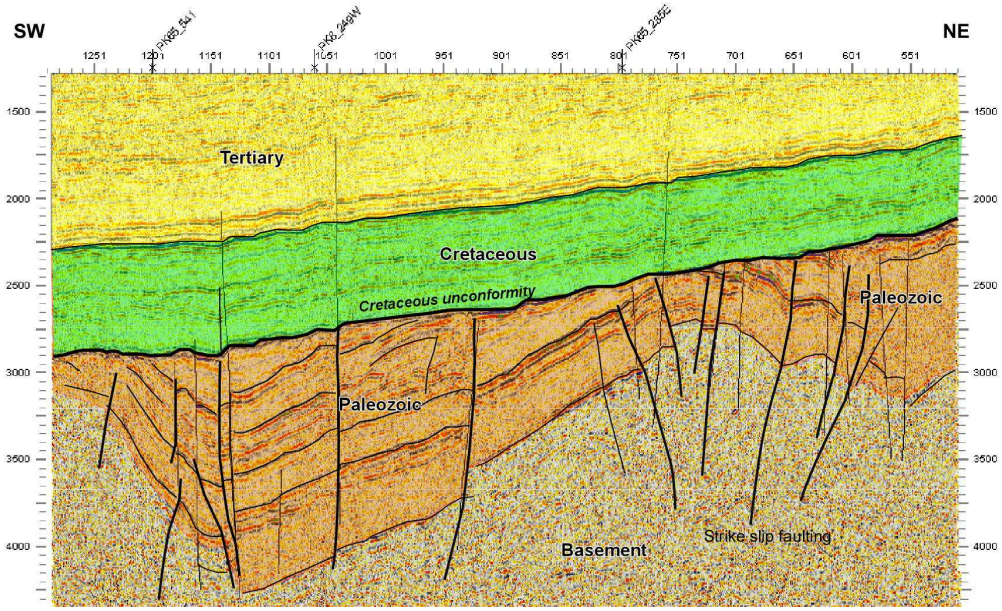

Figure 7. Cross section 5 located in the southeastern part of the Marañon basin, vertical scale in TWT. Location map in figure 2 (Modified from Perupetro 2010).

The Western Ucayali or Pachitea basin is characterized by the interaction of tectonic inversions of Triassic - Jurassic extensional basins and the reactivation of Carboniferous thrust belt during Neogene times. Below the Mesozoic sequences, some seismic images reveal a thrusting system developping duplex and transported synclinal (Fig. 8). This deformation involves the Paleozoic and probably the Lower Mesozoic series. During the Neogene deformation times, apparently these features were slightly reactived.

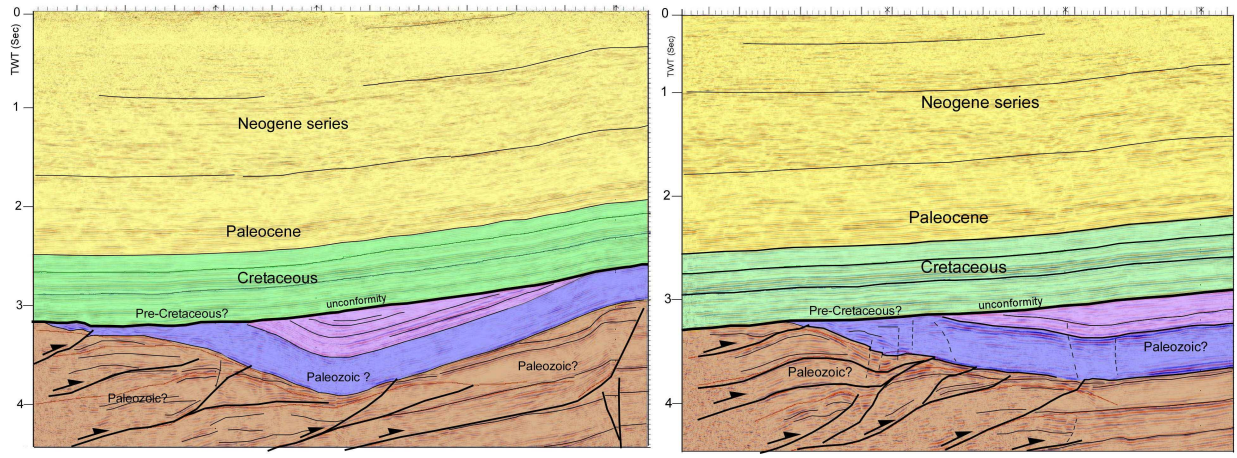

Figure 8. Cross section 6 located in the western part of the Ucayali basin, vertical scale in TWT. Location map in figure 2 (Modified from Perupetro 2010).

The Southern Ucayali and Madre de Dios basins are not affected by the Triassic - Jurassic rift events, therefore these basins preserve the best evidences of Paleozoic deformations in the foreland. The style of deformation of the Ucayali thrust belt has been vertically divided into two stacked thrust wedges (Espurt et al., 2008): a lower structural wedge controlled by deep seated detachments involving Paleozoic thick-skinned thrusts, and an upper structural wedge, the Subandean zone, limited to the sedimentary cover and essentially driven by thin skinned thrusts

The southern Ucayali Basin exhibits Devonian and Early Carboniferous thick skinned thrusting, eroded and sealed during the Late Carboniferous (Tarma - Copacabana fms) and subsequently

reactivated during the Andean deformation. Shira and Sepa structures are good examples of this process.

The cross section 7a (Fig. 9) show the Sepa anticline formed above an east verging thick skinned thrust. To the East, the cross sections exhibits east verging thick skinned thrusting sealed below the intra Carboniferous unconformity. On the eastern side of the cross secction 7a and 7b, growth stratal patterns of the Ambo Formation testify the compressional tectonics during the Devonian and Lower Carboniferous (Fig. 9, 10, 11).

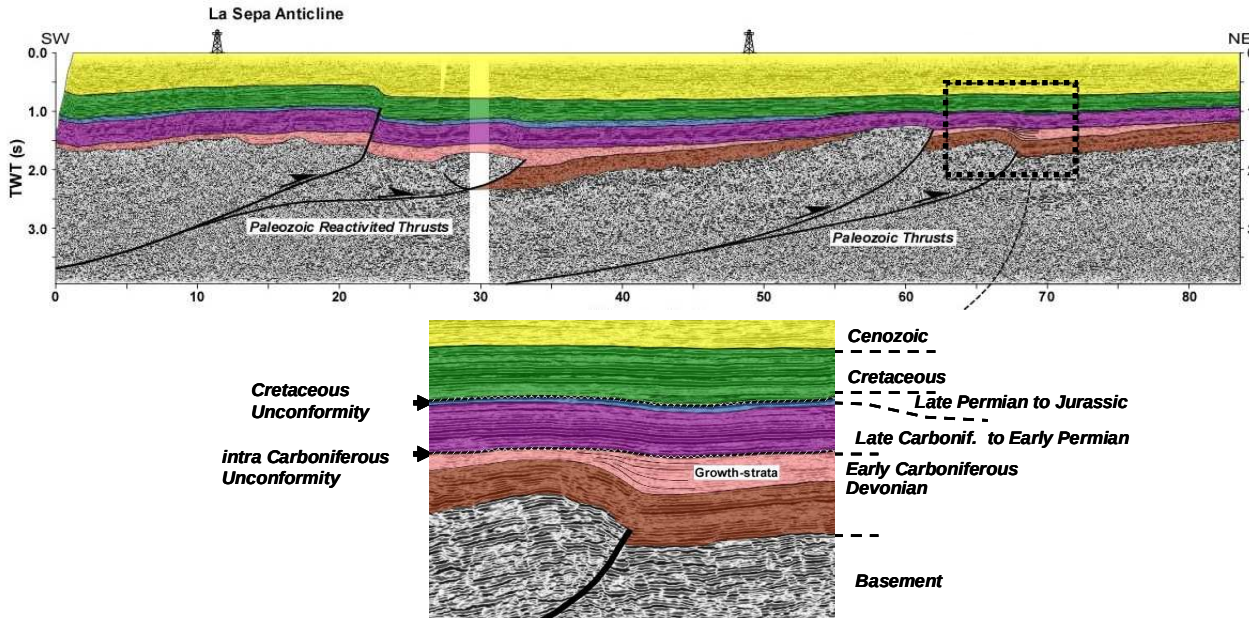

Figure 9. Cross section 7a located in the souther east part of the Ucayali basin, vertical scale in TWT. Location map in figure 2 (modified from Espurt et al., 2008).

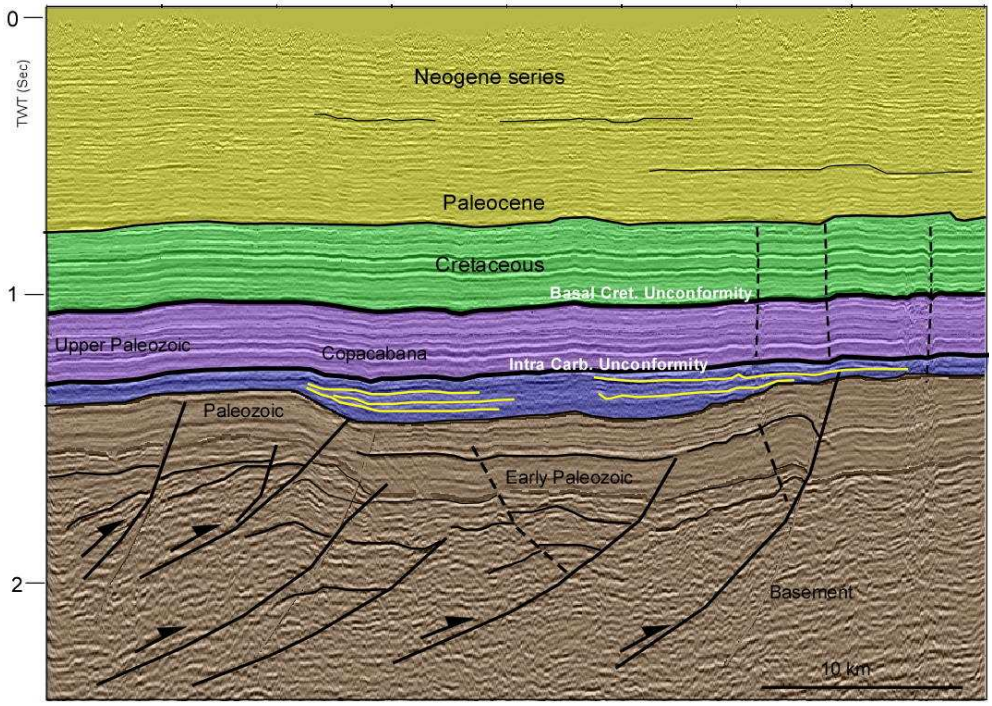

Figure 10. Cross section 7b located in the southern east part of the Ucayali basin, vertical scale in TWT. Location map in figure 2

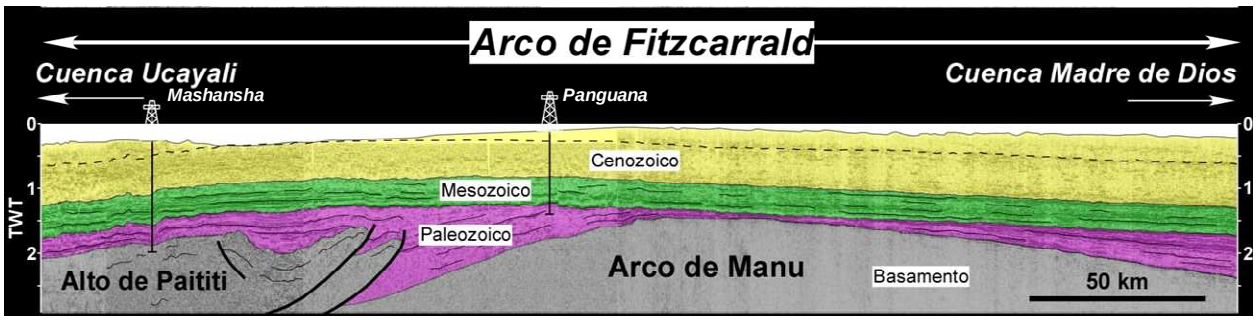

Figure 11. Cross section 8 located in the souther east part of the Ucayali basin, vertical scale in TWT. Location map in figure 2 (modified from Espurt et al., 2008).

Conclusions

The Paleozoic petroleum potential has been proved in many sub Andean basins (Subandean and Chaco, Madre de Dios, Beni basins). In these basins, Paleozoic sedimentary sequences contain excellent source rocks, reservoirs and seals. More than 40.17 BBOE of recoverable reserves have been discovered in the foreland basin of the Central and Septentrional Andes. 16.95 BBOE of the total reserves are associated to Paleozoic petroleum system (12.46 BBOE from the thrust belt and Chaco in the Southern Bolivia and 4.49 BBOE from the Ucayali south and Madre de Dios basin in Peru). These hydrocarbon accumulations discovered are trapped in Cenozoic compressive structures.

The Paleozoic deformation history and its role in the present Andean retroforeland remains poorly understood. In the northeastern part of Colombia and Venezuela, the Paleozoic is characterized by a large overthrusted transpressional features, slightly reactivated during the Andean compression. In the north of Peru, the Paleozoic deformation is overprinted by Mesozoic extensional episodes and later Cenozoic Andean deformation. In the southern part of Peru has been controlled by two stacked thrust wedges that differ in terms of tectonic styles. The lower thrust wedge is formed by deep-seated décollements within the basement related to thick-skinned foreland structures inherited from an Early Carboniferous thrust system. Seismic reflection data shows that this Paleozoic compressional system has been eroded and unconformably covered by Late Carboniferous clastic sediments. It generated an irregular Paleozoic sedimentary architecture controlling the Andean thrust propagation. The upper thin-skinned thrust wedge developed within this Paleozoic sedimentary series and constitutes the Subandean zone. Paleozoic thrusting has associated synorogenic and transported “piggyback basins”. Many of these mini basins contain prolific source rocks and excellent reservoirs. Erosional surfaces or unconformities truncate these compressional structures and are overlain by subhorizontal Upper Carboniferous and Cenozoic series. Even thought, in many basin the Paleozoic interval presents all the elements for an economic petroleum system proven source rocks, good reservoirs and seals.

Up to date, Paleozoic structures are still unexplored. There is no much information about size, shape, extension of these structures and Paleozoic depocenters distributions that could have a strong potential for the entrapment of hydrocarbons. Even, when many foreland basins have not finished the first exploration period a second one can begin with a deeper exploration.

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