Deformation history and structural style in the North Ucayali basin

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Introduction

The HC exploration is active on the Peruvian foothills (Fig 1) and so analyses of their petroleum systems are carried out. In the North Ucayali basin, the existence of mature Source Rock is not an issue, HC reserves have been already found. However dry wells exist. Any basin modeling shows that the maturation of the SR started during the Eocene, although the Andean compression in the area is supposed to be more recent. In addition, the large scale uplift due to the subduction of the Nazca aseismic ridge leads to a regional erosion during the quaternary without any increase of the sedimentary load. As a result, the risk of undercharge of the prospects due to a timing problem exists.

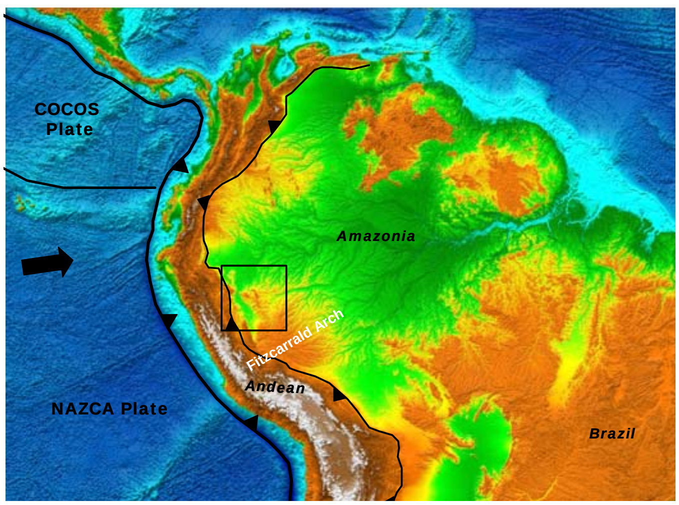

Fig 1: Location of the study area (north Ucayali) and main structural features on the northern South America. Color code: elevation

A calibration of the erosion at the top of the various structures was performed using paelothermometers. It allows us to propose a kinetic of deformation in the area; the structures appear to be not uniformly recent. The role of inheritance on the Andean deformation is large. The importance of the Paleozoic and Cretaceous depocenters and faults, were largely published, however the role of evaporitic pillow has been, up to now, poorly studied. Seismic data shows that the presence of these pillows influence the thrust geometry, the bending of their azimuth as well as the existence of local double verging structures in a regional context of west verging thrusts. Such behavior of the evaporites is similar with the one observed in analogue models and in other compressive fronts, and it clearly impacts the prospectivity of the structures. The presence and tip of such an efficient gliding surface localize strain and so early deformed zones.

Geological Setting

The North Ucayali basin is located in the Peruvian foreland. The compression started in the Andean since the end of the Cretaceous but the modern foreland developed mainly since the Upper Miocene times that corresponds to a major step of the eastern propagation of the compressive front overall South America and especially in Peru as shown by the AFTA values (see Espurt, 2007 and reference within).

In addition of the compression, another tectonic event affected the Ucayali area during the Pliocene: the subduction of the Nazca ridge that results in a regional uplift (see figure 1), and creates the Fitzcarrald arch (Espurt et al., 2007). Following these authors the Nazca ridge reached the Pacific trench about 11 Myr ago but the effects of this subduction (mainly uplift of the overriding plate due to buoyancy) did not affect the foreland before the Pliocene.

A general stratigraphic column of the area is summarized in figure 2, locally changes in thickness and facies as well as missing layers due to erosion are present. The Paleozoic consists on intercalation of sand and shale deposited in a large basin in a context of compression. Then a cycle of extension-sag is recorded with the Tarma-Copacabana-Ene group that ends also with a compressive event (hercynian? Barragan et al., 2008). The Triassic corresponds also to a rift, starting with the deposition of the Mitu Fm. This rift extended southward to Bolivia (from 8º to 22ºS). It started in Peru during the Late Permian and then propagated southward (Sempere et al., 2002). In addition of the tilted blocks and normal faults still visible on the seismic lines that marks the upper crustal extension, the magmatic intrusions are numerous and allow dating the propagation. In the studied area, the Mitu Fm is overlyed by the Pucara limestones deposited in a quieter environment corresponding tectonically to a post rift subsidence (Sempere et al, 2002; Barragan et al., 2008). The Pucara Group contains dolomites and muddy limestones and is overlied by evaporites (Fernandez et al., 2002). The first and end members correspond to shallow marine environment, reef and lagoon, when the central part (Aramachay Fms) consists on deeper shaly limestone (Rosas et al., 2007). This sag phase ends up with de deposition of the Sarayaquillo shaly red bed (continental in the border of the basin and marine in the center). As in almost all rifts, even if this step is still often underestimated, uplift and subsequent erosion separate the synrift from the post rift phase; see for instance Moretti & Chenet (1987) and Moretti (2004) for details and analogy with current rift systems. In addition, local erosions of the noses of the tilted blocks are also visible on the seismic lines resulting in a stronger unconformity between the synrift and the postrift deposits. A second major unconformity separates the Jurassic from the overlying Cretaceous sequence deposited after a no-deposition phase during the Lower Cretaceous. The Cretaceous deposits consist of intercalations of sand and shale (reservoir and source rock) deposited in a rather quite environment of a pericratonic basin. The beginning of the Andean compression, is dated from the Upper Cretaceous, the North Ucayali area became then a foreland, very distal and then proximal. Due to the eastward migration of the thrust front, the compression affected more obviously the area since the Miocene (Baby et al., 2005). At the Pliocene, since 4 Myr, the uplift started in response to the Nazca ridge subduction (Espurt et al., 2007).

Petroleum system

The existence and richness of the source rocks is not an issue in the Ucayali basin. Data shows, as published by PeruPetro (Petroleum System report 2006) that there are at least 4 main source rocks (see figure 2, large red stars):

- **The Triassic-Jurassic Pucara Fm** (known to be the SR of Maquia and Pacaya fields),
- **The Permian Ene Fm** (known to be the SR of the Agua Caliente field, and of the Sepa and La Colpa shows)
- **The Carboniferous Ambo Fm** (known to be the SR of Camisea)
- **The Devonian: Cabanillas Fm** (equivalent to the main SR rock of the large reserves found of Bolivia)

In addition our data base shows locally good HC potential for the Cretaceous Casa Blanca, Huchpayacu, Vivian, Chonta and Raya Fms (Fig 2, small red stars). Southward the Chonta SR correlates with the Santiago basin oil. The source rocks are for a large part mature in the wells as shown by the vitrinite reflectance profiles. Their initial potentials have to be taken from the few immature samples or estimated through a modeling. The initial values that allow us to fit the data are:

- **Pucara Fm**, TOC 4%, HI 500, good oil prone SR for the central part (Aramachay Fm, shaly limestones, marine)
- **Ene Fm,** TOC around 3%, HI up to 655, Excellent type II marine source rock
- **Ambo Fm:** Mixed type II-III source rock with coal bed, average TOC around 5%, low HI
- **Cabanillas Fm**, TOC initial around 2%, estimated initial HI 250. The Devonian shales are clearly not the best SR but due to the locally huge thickness of the series it may be important.

The fluid-source rock correlations show that various source rocks have been active at the same time (PeruPetro, 2006). Northward, in the Marañon basin, the fields are sourced mainly by Jurassic and Cretaceous SR. Southward the fields are sourced mainly by the Paleozoic SR. In the central study area, the North Ucayali basin, it is considered that both exist.

The targeted structures in the area are compressive. As could be seen on figure 3, the inheritance of the extension is large (thickness changes, preexisting faults) therefore the structures are sometimes interpreted as inverted halfgraben (by similitude to the Ecuador Oriente, Baby et al., 2004) or as thrust anticlines. As explained previously, there is no increase of burial in the area during the Pliocene but rather erosion so a modeling of the maturity of the source rock versus time and an understanding of the kinematic of the anticline emplacement is required to quantify the charge of the various prospects.

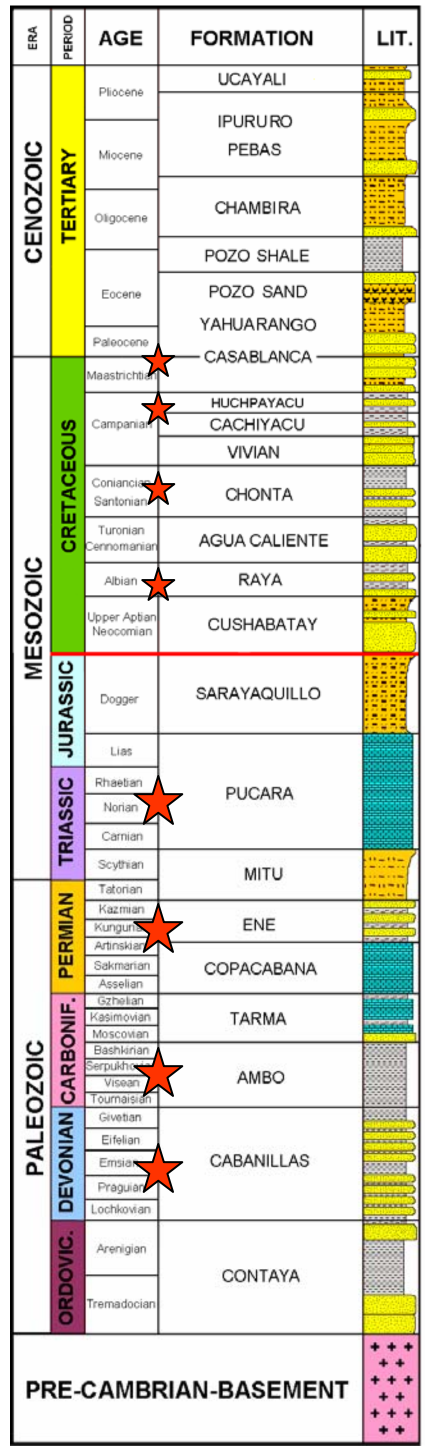

Fig 2: Stratigraphic column with the various source rocks (red starts)

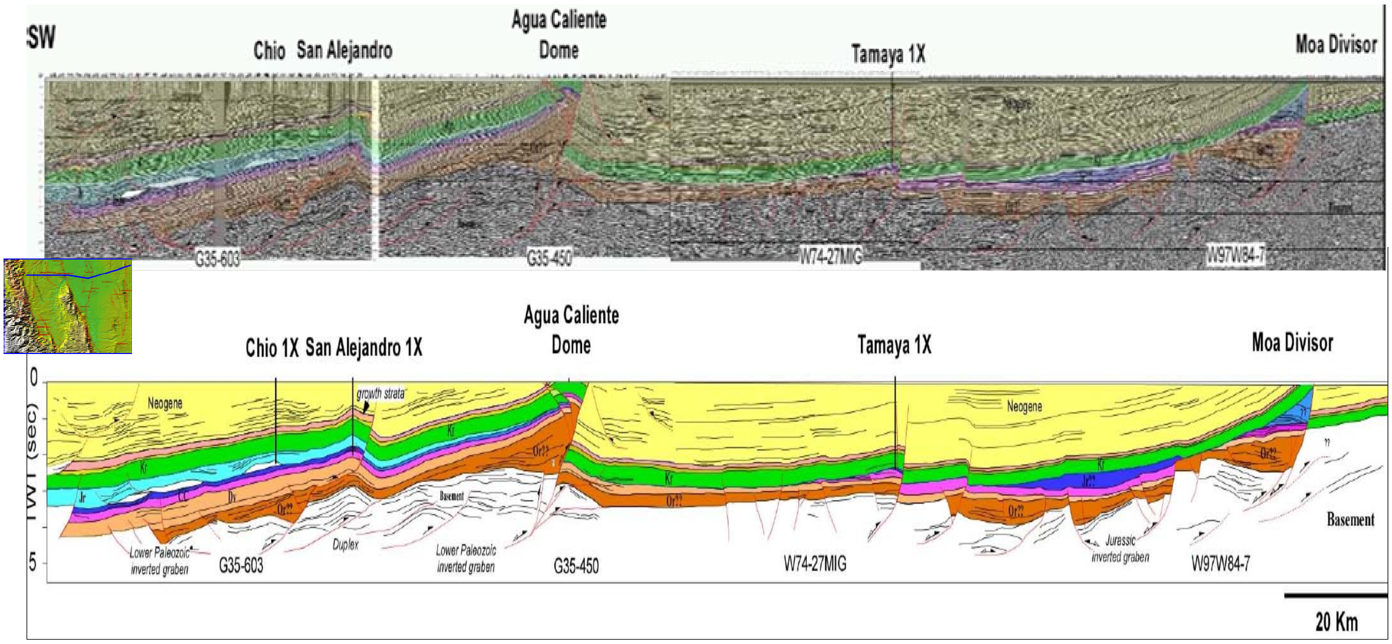

Fig 3: Cross section modified from Hermoza et al. (2007) and location of the wells modeled figure 4.

Structural model

A regional cross section has been already published in the northern Ucayali basin by various authors especially W Hermoza et al. (2006). At large scale we don't have nothing to add to this section, well calibrated for the upper part with the subsurface data and equilibrated (Fig 3). The authors suggested there a localization of the main structures Agua Caliente and Moa Divisor is related to normal faults however they do not preclude that thickness changes within the Paleozoic series inheritate from Paleozoic compressive deformation could also result in the localization of the Andean structures (Hermoza personal communication). In the hypothesis of anticlines created by inversion of half graben there is no need of a shared history and decollement level for the various structures. Under the hypothesis of an east migrating front belt thrust system, affected by not regulated by the preexisting structural heritage, the kinematic of the deformation is much more constrained; a good matching between the shortening, erosion and timing has to be prospected.

The present study is focused on HC exploration so the debate between "inversion versus neoformed thrust" will not be discuss but elements to quantify the kinematic for the structures emplacements will be investage. Age of thrusting will be compare to the one of HC charge.

Modeling of the Erosion

The amount of erosion could be estimated based on various tools that include structural interpretation of the subsurface data and inversion of the paleothermometers data. Paleothermometers record the formal maximum of temperature that could be interpreted in terms of depth when knowing the thermal field. In exploration it is classically done with SR maturation (rock Eval data) when these ones are well known, or alternatively with Vitrinite Reflectance (VR) and Apatite Fission Track Analysis (AFTA).

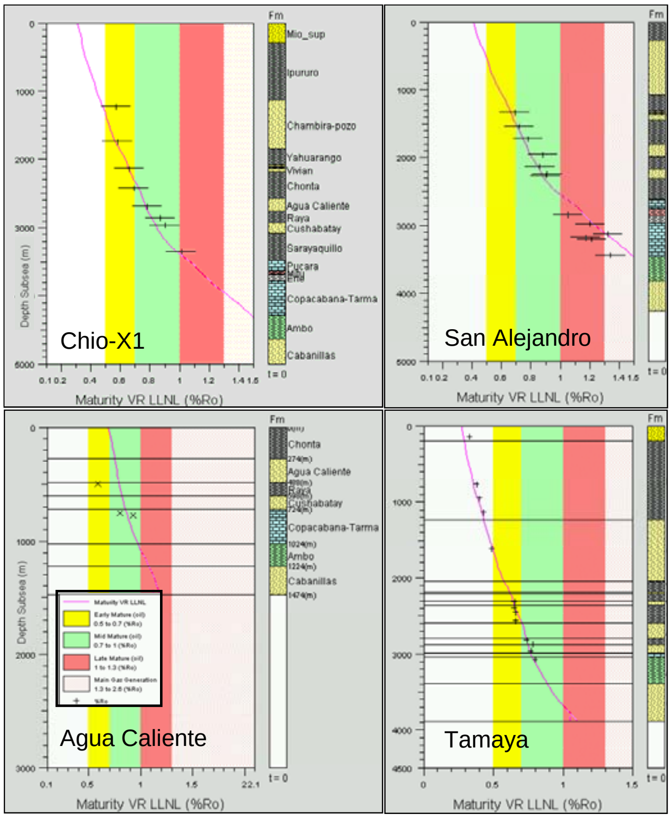

Fig 4: Fit obtained with the paleothermometers for the calibration of the erosion. The stratigraphic column has been interpolated below the well penetration using seismic data

The subsurface data (Fig 3 top) shows some growth features within the Miocene deposits, suggesting that the compression affected the area since the Miocene. However this does not give any information for the structures more deeply eroded as Agua Caliente where the Cretaceous section is outcropping. Quantification of the amount of erosion has been done through VR after a calibration of the heat flow history based on the SR maturation and the current thermicity data. Geological knowledge, seismic evidences and published AFTA has been incorporated to reach the conclusions synthesized here. The quality of the fit on the vitrinite reflectance for the various wells is presented in figure 4

Agua Caliente:
- no more than **1720** m of Andean foreland deposit (Chambira Fm to actual)
- seismic data: the Chambira Fm thickness changes
- geology: northern tip of the Shira Mountain which has never been deeply buried during the Miocene (AFTA data, Espurt 2007)

San Alejandro:
- no more **2570** m of Andean foreland deposit (1500 have been eroded)

Chio:
- about **3100** m of Andean foreland deposit (1250 have been eroded)

Westward:
Current Andean foreland deposit about **3600** m
So the regular foreland depth is definitively higher than the maximum burial of the structures. As a conclusion, the uplift of these three structures started at least during the Chambira Fm deposit, i.e. before the early Miocene.

Source Rock Evolution versus time:

The good calibration of the temperature and erosion in the wells, combined with the surface geology and the seismic data allow us to be quantitative of the evolution versus time modeling. Differing from what is observed in some other parts of the Peruvian foreland, there are no major steps in the maturity profiles; there is an increase of maturation during the Miocene Consequently, no attempt to quantify previous erosions has been done since they did not affect the present maturity state.
The evolution of the transformation ratio of the various SR is shown figure 5 at the level of the Chio-1X well. The Paleozoic SRs get mature during the Mitu rift and are overmature from the Cretaceous. The Pucara SR reached the beginning of generation about 50 Myr and is late mature from 20 Myr. The Cretaceous source rocks reach the oil window during the Miocene. During the last 4 Myr due to the erosion for the Cretaceous SR and to the fact they are already overmature for the oldest ones, there is no increase of the maturation.

Structural evolution through time

Analyze of the data therefore shows us that the San alejandro and Agua Caliente structures are early ones and started to grow when the main thrust belt was still located westward.

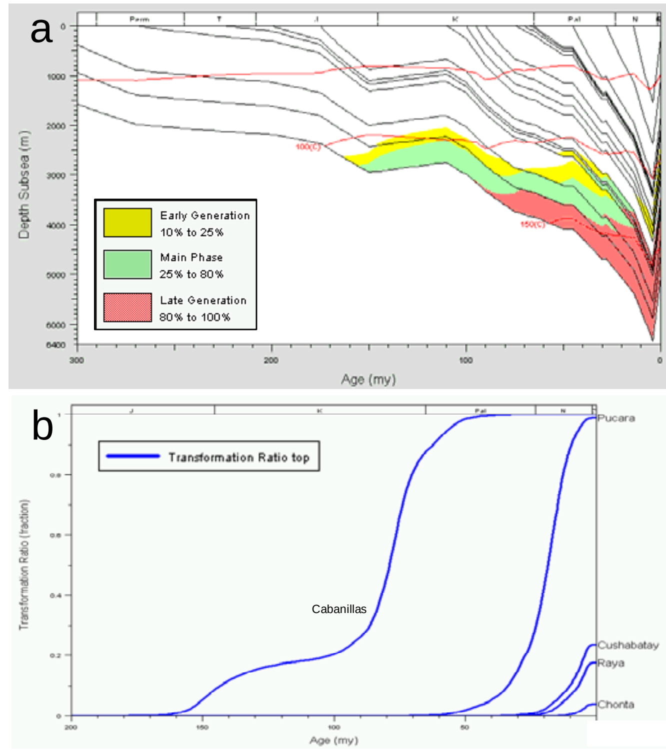

Fig 5: Maturation versus time of the various source rocks at the level of the Chio well i.e. within the current kitchen of the San Alejandro structure. (a) Transformation ratio versus depth and time. (b) TR for various source rocks versus time.

The next question for a geologist is why? Why some structures started to grow up, like fold or blind thrust in a still rather undeformed zone eastward of the front belt. In all the compressive area, the key point to understand the deformation is the knowledge of the potential detachment and the abnormally weak zones. In the Ucayali basin the main decollement is intrapaleozoic (Baby et al., 2008), however, evaporites exist within the Jurassic section; such a facies is known to be an excellent decollement level and to influence structural style.
Let see first what is known on the evaporites in Peru and then what is known about the potential influence of such a facies on the compressive front through analogue models before concluding.

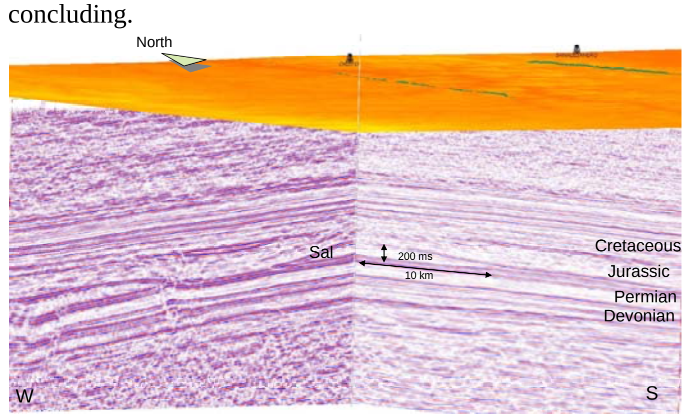

Fig 6: Evaporitic pillow in the seismic lines

Evaporite presence

The existence of evaporites in the North Ucayali is confirmed by a lot of subsurface data, three of them are shown figure 6 and 8. The evaporites outcrops in the Cushabatay Mountains (Fernandez et al., 2002) and has been also found in wells (as Chio-X1). These authors proposed a Sabkha paleo geography (i.e. near costal deposit of the evaporates in an area protected from the Open Ocean by a barrier) at the end of the Pucara deposit. The exact facies of the evaporitic series is out of the scope of this paper and for simplicity we will call “salt” this deposit even it is a very broad acception of the term.

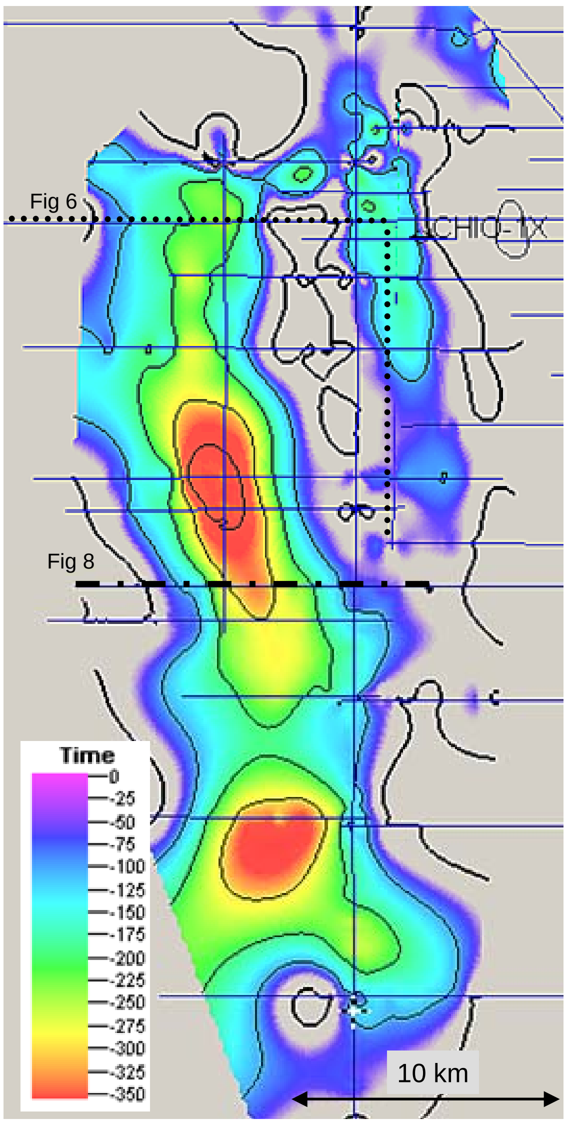

Fig 7: Isochors of the evaporite. The blue lines area the available 2D seismic lines. The dashed lines show the position of the two seismic lines on figure 6.

On the seismic data, salt pillows could be recognized as in figure 6; the two ones visible on the W-E seismic lines have an E-W extension of few kilometers. On the N-S line that crosses the E-W line on one of the pillow the extension is visible. The thickness on these lines in time is of 200 ms that means about 400 meters (max 700 m). The absence of velocity pull down suggests that the evaporite velocity is not very high, see fig 6. The isochors of the pillows is presented figure 7, one may note the elongated trend (N-S, NW-SE) of the pillow. This shape is not acquired during the deposition but highlights the early movements of the evaporites. Fig 8 shows the relationship between the evaporites and the surrounding layers. They are conforming to both the Pucara and the Sarayaquillo Fms. An initial thin evaporitic layer (constant thickness at the deposition time at the level of the studied area) gets “boudinée” in an early stage before the pre-Cretaceous erosion. Such an early deformation of salt, due to differential burial charge or even just slope, is reported along numerous margins such as the Niger delta, the Gulf of Mexico or the Brazilian margin. Apparently after the Cretaceous, the evaporites pillows visible in these lines have not moved.

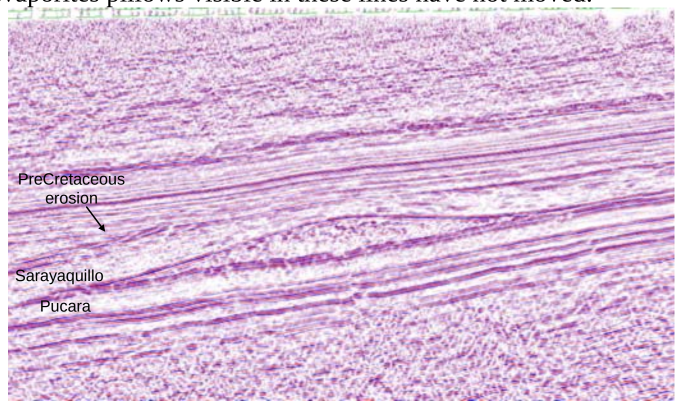

Fig 8 Zoom on the pillow, the evaporites are conform with the pre and post series suggesting an early deformation, boudinage, of the salted layer before the pre-Cretaceous erosion. The unconformity postdates the salt displacement on this specific pillow.

Unusual features

Data show the presence of a large quantity of evaporite, a material with a low viscosity that usually influences the tectonic style. In the literature, the role of the evaporites in the Ucayali basin is not presented as crucial but there are various unusual features in the geometry of the thrusts in the area that failed to be understood:

Festoons in the thrust outcrops
AguaCaliente structure shape
Back thrust in the San Alejandro structure

The Digital elevation model of the area is shown figure 9 with a range of color from 500 m (white) to 150m (black). The first notable anomaly is the shape of the Agua Caliente structure north from the Shira main thrust. This egg like shape is very strange for a thrust anticline and its wavelength is incompatible with a single deep decollement level as seen on the seismic line (fig3). On this DEM it is also possible to note the non-linearity of the relief due to the thrusts, in the Agua Caliente trend as in the San Alejandro trend. These festoons also suggest the influence of something else than a deep decollement levels on the anticline shapes. The third point that needs explanation is the backthrust in the San Alejandro and

Agua Caliente structures. The 2 lines shown in fig10 image the potential evaporitic pillow below part of the SN Alejandro structures and the root of the back thrust on this level. On the contrary, the west verging main thrust has a deeper decollement level.

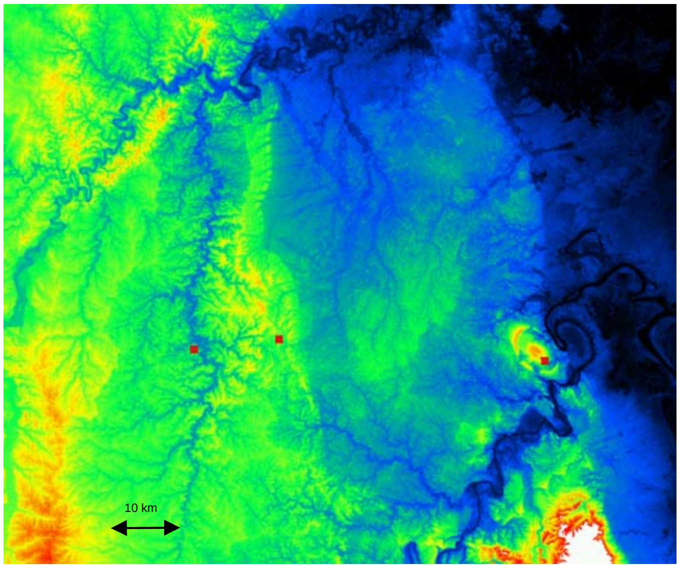

Fig 9: Digital elevation model in the north Ucayali basin. The red points are the well Chio, San Alejandro and Agua Caliente (from West to East respectively)

Theoretical evaporite role as know from analogue model

Analogue models are known to be an useful tool to test concepts in structural geology. The use of X-ray scanner allows getting a complete 4D view of the deformation (Colletta et al., 1991). Experiments could be done rapidly and therefore are an interesting alternative to numerical models. They have limitation on the materials, roughly only silicone and sand are used but the contrast of mechanical behavior between these two materials is rather adequate to model viscous layers (evaporite, shale...) likely to act as decollement level in contrast to brittle layers. Numerous modeling of the salt behavior during extension, gravity gliding on margin and compression have been published. The ones discussed here are extracted from a paper published by Callot et al (2006) with experiments designed for the Zagros. We are absolutely aware of the difference between the Iranian Zagros and the Peruvian foothills in term of salt quantity and role. But analogue model are not done to mimic the reality but to understand phenomena and develop imagination. So keeping in mind all possible restrictions some features could be discussed that will help to understand the North Ucayali superficial structures.

Figure 11 shows a sample of the experiments for the Callot et al paper. The reader will find all the details on the experimental conditions on the paper that analyses the influence of isolated silicone diapirs (pillow, cone, finger) on the geometry of the thrusts during compression and transpression. The main decollement level is a continuous layer of silicone at the base of the model and the other layers are brittle in the analogue model. The Figure 11a gives the position of the isolated pillows at the beginning of the experiment. Figure 11b shows a top view of the box after about 25% of shortening. Fig 11c shows the evolution versus time above one of this pillow.

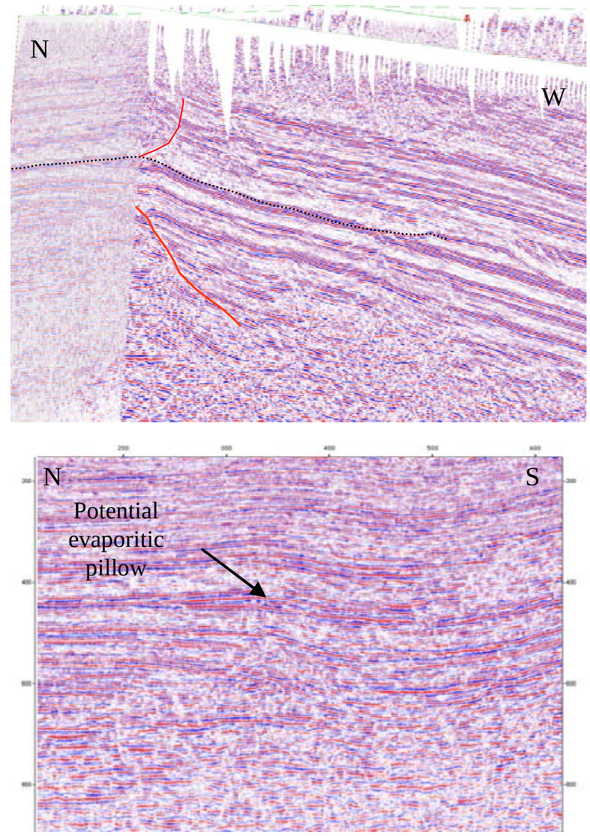

Fig 10: Above 3D montage of 2D seismic line with the interpretation of the top evaporites and of the main west deeping thrust (deep one) and small east deeping backthrust (shallow one). Below the N-S line only partially displayed above (time section, units 10m and 10 ms)

The position of the thrust on 11b shows that the small diapirs create festoons in the thrust trend without influencing so much their position (the layercake simple case theory shows that the distance between two consecutive thrusts is defined approximately by the thickness of the brittle layer) When the pillow is large enough, one observes also festoons but also more drastic change in the front thrust and back thrust may become predominant. The evolution through time shows that an early fault gets created that decoll on the pillow, its lead to the creation of a small relief. Then this fault becomes a thrust connected to the main decollement level and the initial pillow is completely squeezed along the fault zone. In this experiment, having just the last image, an interpreter may minimize the small silicone trace and believe that there was no initial pillow but that only thickness changes (duplex, squeezing) in the deep decollement level.

As already noted the initial conditions on this experiment have not been designed to fit the Ucayali case. For instance in Peru there is another brittle layer between the main decollement level and the pillow. New models are being designed jointly with IFP in order to provide analogs that better match the particular features described above however the presented experiments allow us to propose some guides of interpretation for the unusual features described above.

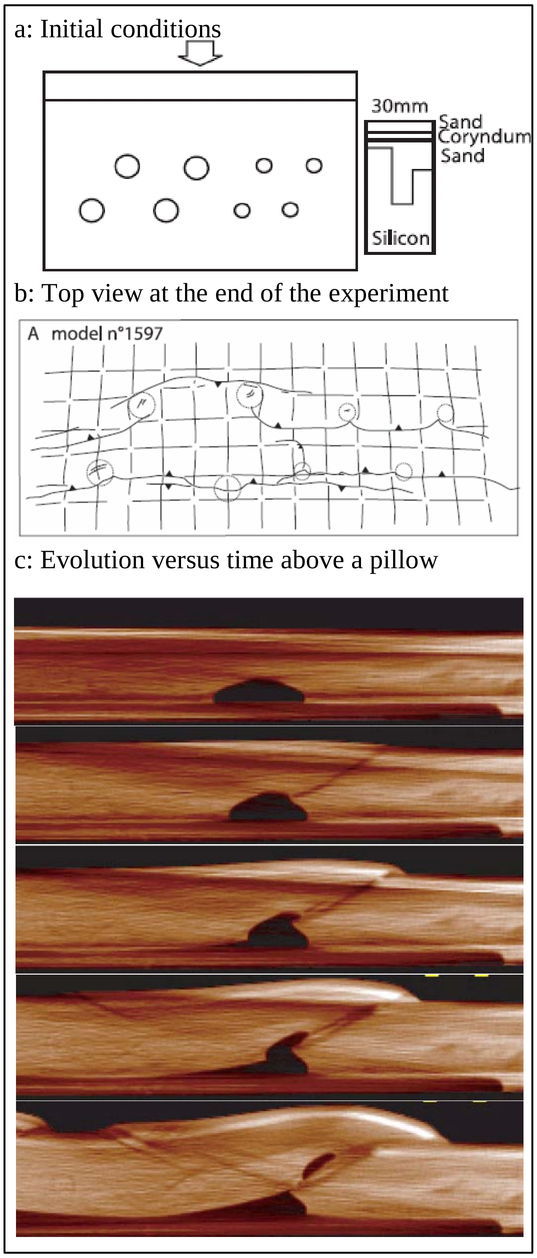

Fig 11: Analogue model of thrust development above an area with isolated salt diapirs. Modified from Callot et al., 2006.

Due to density change versus depth the stop of the salt movements when the burial increases is normal. However, when the burial decreases, as for instance in the hinge of anticline, diapirism is likely to start again as described in other front belts.

Discussions

Our first conclusion is clearly that the evaporite role in the North Ucayali area has been largely underestimated. The main decollement level is deeper so it does not affect the regional schema as published by Hermoza et al. (2006) but they are fundamental for the "small scale" features, the ones that interest the oil industry.

The quantification of the amounts of erosion based on the paleothermometers synthesized fig 12. The San Alejandro and Agua Caliente anticlines are early structures above which the Miocene deposits have been thinner than in the surrounding foreland (eastward as well as westward). For an explorationist it is the main point since it means that there is no "timing issue" for the charge of these structures, they are not postmigration of HC and do not require any complicated scenario (as dismigration of previous traps) to be charged.

Localization of early structures, and so relief, in an area still poorly affected by compression is likely to happen in case of heterogeneity, we suggest a key role for the evaporitic pillow in the North Ucayali area. In the Ecuador Oriente foreland Basin, Baby et al, 2004 have also observed early compressive structures and they interpreted them as basically due to inversion of preexisting extensive structures. It is another way to explain early structures and the model is maybe also valid for the North Ucayali zone; inversion and evaporites may have played a complementary role.

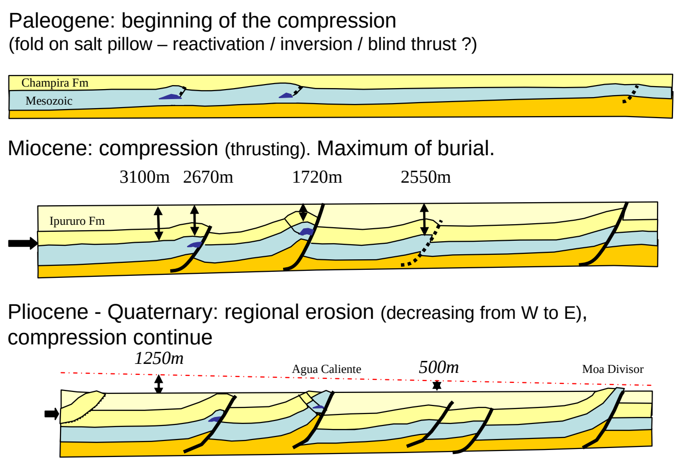

Fig 12: Schematic modeling of the evolution in the North Ucayali foreland. During the Paleogene the compressive front was located westward but the existence of evaporitic layers allow eastward propagation of the compressive stress and tip of the evaporites localized compressive structures. When the thrust front reached the area, the initial pillows get often squeezed within the hinge of the anticline but its influence remains visible on the thrust trends

The backthrust in the San Alejandro structure may also be interpreted in the frame of localization by a formal evaporite pillow. Fig 11c suggests that original pillow could be completely squeezed, so the fact that the final well reports did not describe any evaporitic layer can not be used to discard the presented hypothesis. It is proposed to also interpret the festoons over the San Alejandro thrust trend as due to the presence of evaporitic pillows within the Jurassic. Concerning the Agua Caliente structure, in the current models, the Permian and Jurassic are missing at this level due to erosion but there are some remnant pieces of these deposits eastward within the Moa Divisor. The Agua Caliente structure shape requires a shallow decollement level, in addition to the deep one, the existence of an evaporitic pillow below the structure will allow understanding its size and shape. On our knowledge, subsurface data are still missing to prove, or unprove it.

At large scale the presence of evaporites does not change the structural style of the Peruvian foothills but at the prospect scale, crucial for the oil company, this evaporitic level can't be neglected. In addition to the strain localization discussed here, evaporite means seal and, very often, "pre salt" preserved petroleum system that may have to be prospected here someday.

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