Hydrocarbon generation in relation to thrusting in the Sub Andean Zone from 18 to 22°S, Bolivia

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ABSTRACT: Formation of the Bolivian eastern cordillera started at the end of the Oligocene and continues to the present day with thrusting affecting the Sub Andean Zone since late Miocene. The 'classical' source rock is the Devonian, but the Silurian interval has some potential. Their initial original potential is not high but they are thick (700 m, Los Monos Fm) and may be thicker still due to stacking in thrust duplexes. The three phases of sedimentation during the Tertiary each start with conglomeratic deposits and are discordant over the previous one. Seismic data allow us to correlate these steps with three periods of tectonic accretion: Late Miocene (Tariquia Fm), Pliocene (Guandacay Fm) and Plio-Quaternary (Emborozu Fm). Modelling demonstrates two phases of hydrocarbon generation. A first phase from Devonian to Carboniferous is due to the deepening of the Palaeozoic basin. The second phase of maturation is due to the Tertiary deposits in the foreland and under the piggyback basins. The central area (Santa Cruz) has never been more deeply buried than during the Palaeozoic and has been a high during the Tertiary.

KEYWORDS: *Bolivia, South Sub Andean Zone, hydrocarbon generation, thrusting*

INTRODUCTION

The present study combines field work, subsurface data analysis, balanced cross-section building, source rock sampling from both outcrops and wells, Rock Eval and fission track analysis and finally modelling, in order to quantify the structural evolution of the Bolivian Sub Andean Zone and its petroleum potential. The key point, as usual in compressional areas, is the relative timing between thrust emplacement and hydrocarbon maturation. When syn-orogenic deposits are numerous, and well dated, schemes of deformation may be proposed arranged in different steps. Thrust propagation may be mainly in-sequence or display a more chaotic scheme. Piggyback deposits record this evolution (Zoetemeijer & Sassi 1992; Zoetemeijer 1994) and could be successfully studied to understand the history and to imagine the deepest structures (Roure *et al.* 1990). In contrast with the northern Sub Andean Zone of Bolivia where large and up to 6 km deep piggybacks have been described (Baby *et al.* 1995), piggybacks are scarce in the Santa Cruz area and poorly known in the south due to the inferior quality of the seismic data. In addition, the present level of erosion of the internal structure is rather high in the Santa Cruz zone. Hence, the study of the intramontane syntectonic deposits does not provide a precise definition of the thrusting history and another tool has to be used to study the palinspatic evolution. Maturity data from each anticline, as well as fission track analyses, allow us to quantify the maximum level of burial of the material, and even if they are not very precise, lead to conclusions about the thrust emplacement. One may separate for instance the early structure, i.e. pre-Tertiary burial, from the late structures which post-date some Tertiary burial.

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REGIONAL SETTING

The Bolivian Sub Andean Zone is a foreland fold-and-thrust belt which constitutes the eastern border of the Andes (Roeder 1988; Sheffels 1990) (Fig. 1). Between 18° and 22°S it is rather wide (150 km). Shortening is large in the south, about 140 km, and decreases in the north of the area to 70 km (Baby *et al.* 1994). Development of the Neogene foreland started during the Oligocene (27 Ma ago) when the deformation front migrated eastward from the current Altiplano position (Marshall & Sempere 1991). Later, in late Miocene times, the current Sub Andean Zone was affected by compression (Gubbels *et al.* 1993). A large part of the Mesozoic and the Neogene foreland deposits are continental and thus difficult to date, but some new data are now available. In this study, subsurface data were used to correlate the erosional phases and the depositional sequences.

Pre-Andean series

The sedimentary column involved in the thrusts may be divided into six tectono-sedimentary units which have been recently revised by YPFB and ORSTOM (Sempere 1990, 1994, 1995; Oller 1992) (Fig. 2).

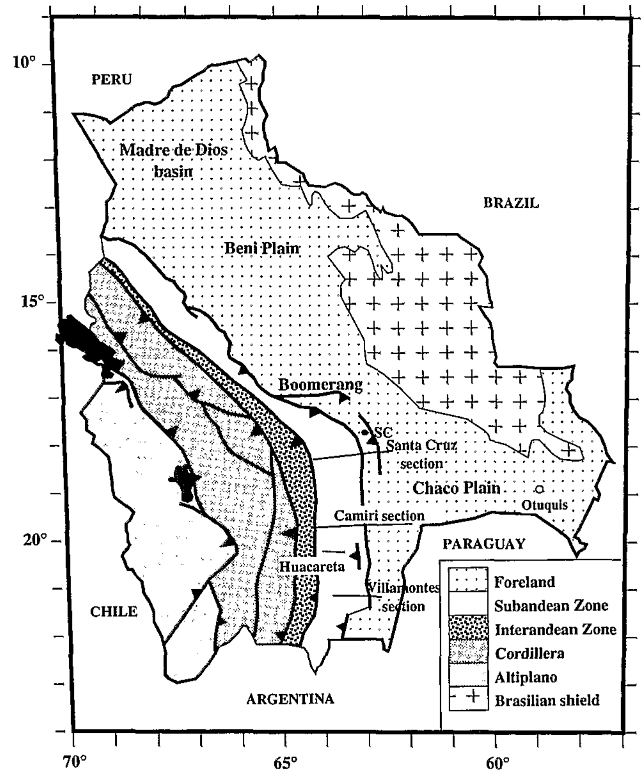


Fig. 1. Simplified tectonic map of Bolivia showing location of the studied cross-sections. In its central part, the Bolivian Sub Andean Zone forms a bend (Santa Cruz bend) characterized by the prominent Boomerang–Chapare transfer zone. In the northern and central part, the propagation of the orogenic front was guided by the northern boundary of the Palaeozoic sedimentary wedge. SC, Santa Cruz.

Upper Cambrian–Upper Ordovician
(Tacsara supersequence)
This sequence is marine. An extensional context has been described which progressively evolved to a compressional foreland basin where the sedimentation rate was high. These layers only crop out in the Cordillera and the central Sub Andean Zone. The sequence may reach 5000 m in thickness and is involved in the thrusts in the north of Bolivia up to Santa Cruz.

Upper Ordovician–Upper Devonian
(Cordillerano supersequence)
This interval starts with a fast deepening of the basin, and contains some glacio-marine deposits (Cancañiri Fm). Then four sequences of siliciclastic marine platform deposits are known from the Silurian to the Devonian, always in a foreland context (Montemurro 1992, 1994). The alternance of sandy and shaly beds on this supersequence led to the development of various décollement levels. As will be discussed later, numerous duplexes have been recognized involving part of the supersequences, particularly the Los Monos shale. The sandstones have good reservoir qualities especially the Iquiri (producing in the Camiri, Tatarenda and Caigua fields) and the Humampampa Fms.

Upper Devonian–Upper Carboniferous
(Villamontes supersequence)
This supersequence started with a rapid subsidence of the basin. A turbiditic sequence has been described in the Itacua Fm. This rapid evolution is still debated because no evidence of extension or crustal thinning is known and it is thus difficult to postulate a large deepening of the basin. The Carboniferous is characterized by a glacial marine environment studied, for the Altiplano part (Cumana Fm) by Diaz & Isaacson (1994). Lateral facies variations are numerous, as well as channels and erosion surfaces, and are still poorly studied. The sandstone infilling these channels has good reservoir qualities and produces in most of the southern fields (e.g. San Roque, Vuelta Grande).

Upper Carboniferous–Lower Triassic
(Cuevo supersequence)
In the study area, two formations characterize this supersequence. The sandstone of the Cangapi Fm has an aeolian origin and is a lateral equivalent to the Copacabana Fm which corresponds to a marine platform carbonate in the northern part of Bolivia. The limestones of the Vitiacua Fm show evidence of an important marine transgression (Sempere *et al.* 1992; Sempere 1995).

Middle Triassic to Jurassic (Tacuru supersequence)
The Triassic tectonic setting was mainly extensional (Oller & Sempere 1992). The Entre Rios basalt and the Ipaguazu Fm petrology show an intra-continental rifting event during the middle Triassic (Soler & Sempere 1993). After the rift abortion, large erosion occurred, reaching 1000 m in the northern part of Bolivia and continental fluvial-aeolian sedimentation took place in the south (Tapekua and Castellon Fm). These units are progradational. The following widespread desert conditions led to the deposition of the aeolian sandstones of the Ichoa Fm. This event can also be identified in Brazil and South Africa. These sandstones may have good reservoir characteristics, and are producing hydrocarbons in the Monteagudo and Rio Grande fields. In the north of the Bolivian Sub Andean Zone, information on Triassic erosion plays a major role in assessing petroleum prospectivity, since a large part of the source rock was at least partially mature before these events (Baby *et al.* 1995). Southward, the amount of erosion is more restricted.

Kimmeridgian to Palaeocene (Puca supersequence)
This supersequence is missing south of 19°S. In the Santa Cruz area, the Upper Cretaceous (Cajones Fm) appears from 18°S. The Cajones Fm is a continental sandstone with conglomeratic events. The formation has been dated from mammiferous bones to be from 70 to 60 Ma (Gayet *et al.* 1991). It corresponds to the more shaly and organically rich Flora Fm in the north and to the El Molino Fm (Maastrichtian to Danian) in the Altiplano area. The rest of the Palaeogene (Middle Paleocene to Oligocene) is very condensed, about 10 m at the level of Santa Cruz, and is mainly represented by palaeosols.

At this time Pacific subduction was already active. In the Altiplano area, cretaceous extensional features are known which may be interpreted as a backarc system. Later, more continental conditions prevailed and a foreland started to be developed further west in the coastal regions in the early Senonian (Sempere 1994, 1995); this phase has also been described northward (Peru & Ecuador) as the Turonian–Coniacian events (Jaillard 1994). The deformation then migrated to the east and affected the Oriental Cordillera in Oligocene and the current Sub Andean Zone at the end of the Miocene.

Syn-orogenic series

In the Sub Andean Zone, synorogenic sedimentation started with the uplift of the Oriental Cordillera 27 Ma ago (Sempere

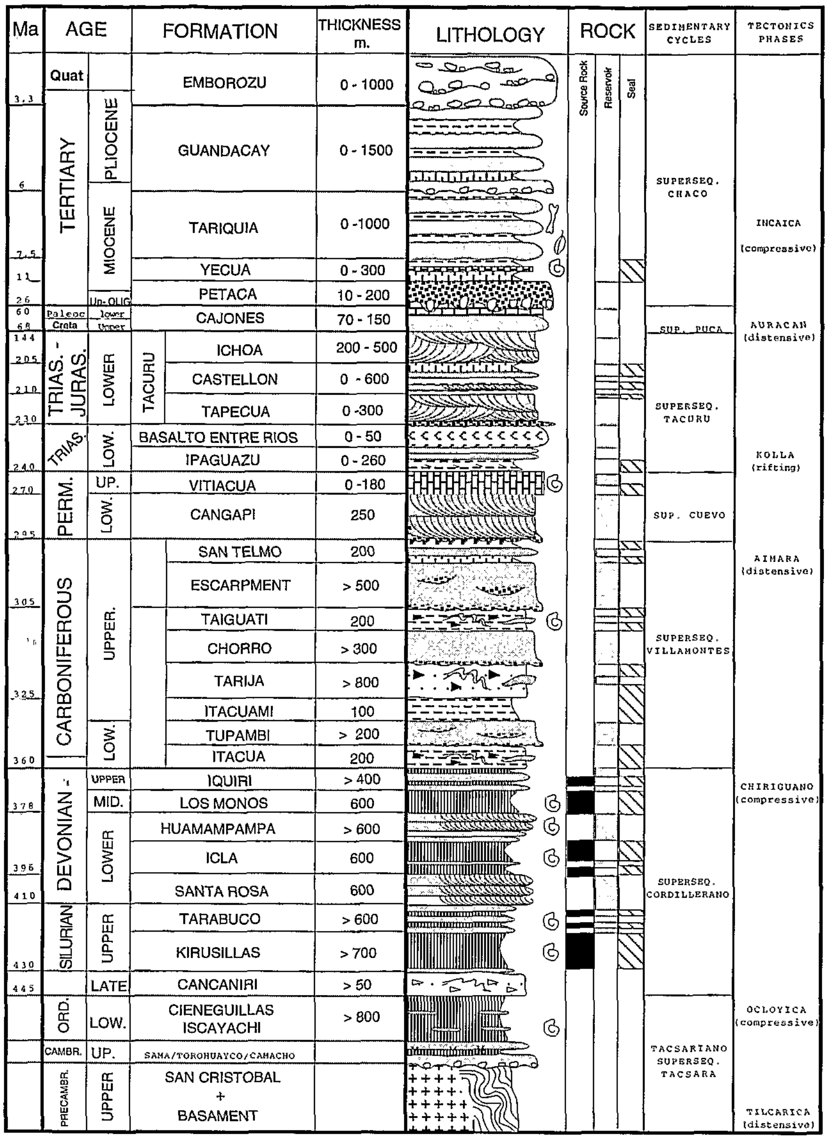


Fig. 2. Stratigraphic column. The given ages are the ones used in the modelling but are mainly hypothesized.

et al. 1990). All the formations are continental except for the Yecua Fm which shows marine influence. The palaeobathymetry was very shallow and the transgression came from the south (Marshall *et al.* 1992). New data now allow dating of even the continental series (Marshall & Sempere 1991; Marshall *et al.* 1992). Sedimentation started with the Petaca Fm from the Oligocene to the Miocene (11 Ma). The deformation did not affect the Sub Andean Zone before the late Miocene (10 Ma, Gubbels *et al.* 1993). Two main discontinuities are described at the base of the Guandacay Fm and at the base of the Emboruzu Fm. An approximate age of 6 Ma has been estimated for the first event. A tuff located on the Emborozu Fm at Abapo (Rio Grande) has recently been dated to 3.3 Ma.

Between Villamontes and La Vertiente, seismic data (Fig. 3) show the three main Tertiary sequences, as well as the two erosional unconformities that have been respectively dated at 6 and 3.3 Ma. The Tariquia Formation (7.5–6 Ma) does not display any thickness variation and must have been deposited before the compressional events of the area. The Guandacay Formation (6 to 3.3 Ma) onlaps the Tariquia Fm and progressively covers the La Vertiente structure. One may then conclude that this structure grew between 6 and 3.3 Ma ago. The second erosional unconformity, at the base of the Emborozu Fm (3.3 Ma) cuts the two anticlines (Villamontes and La Vertiente). The last deposits do not show large thicknesses variations but one can notice a reactivation of the previous faults, slightly affecting the Emborozu Fm.

The two erosional discontinuities are known over all the Sub Andean Zone. Uncertainties remain about the age of these events. As already mentioned, data are scarce because all the deposits are continental and it cannot be proved whether the events are synchronous throughout the Sub Andean Zone. Because of the regional extension of the three sequences and the constant number of erosional events, these events will be considered as regional and the same age will be used on the three studied sections of the southern Sub Andean Zone.

STRUCTURAL STYLE

The structural style of the foothills as well as the north to south variations have been described in several papers (see for instance Baby *et al.* 1994). To summarize, this style is a function of the shortening amount and the various activated décollement levels (Baby *et al.* 1989, 1992). In this zone, the shortening decreases from south to north. To the north, the sediments involved in the thrusts are thick and the structures large. To the south, the main décollement level is the Silurian

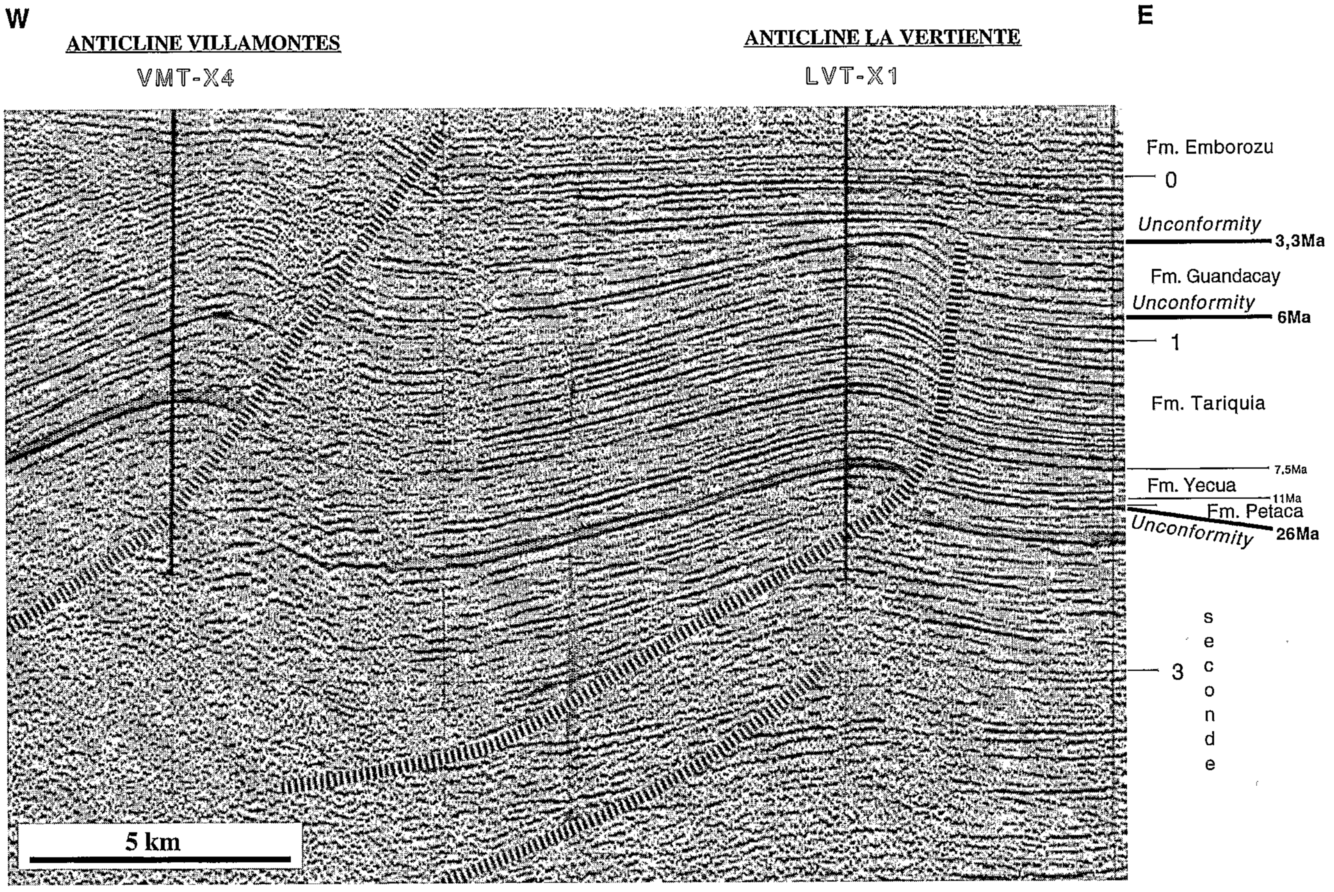


Fig. 3. Seismic section Villamontes–La Vertiente. The three unconformities recognized on this section are used as regional unconformities in this study.

but a few others are also active in the Middle and Upper Devonian. This leads to the existence of transfer zones between the faults related to one of these various décollement levels (Guillier *et al.* 1992) even if the structures are largely cylindrical. The switch from one décollement level to another may be due to lateral facies variations.

Westward, to the foredeep, the shortening is weak and the mean current structures are blind thrusts detached on the Silurian décollement level. Figure 3 emphasizes the presence of a large-scale high zone called Alto Izozog to the east where the Devonian is outcropping. The origin of this uplift is still

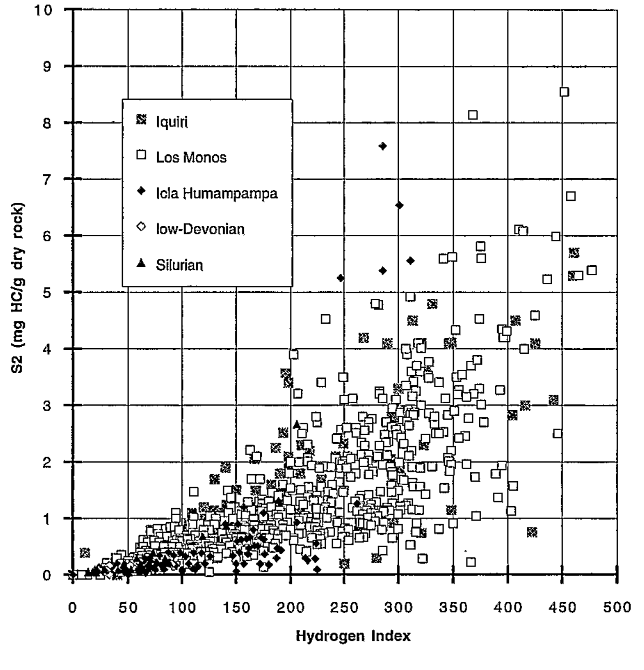


Fig. 4. Source rock potential of the Devonian and Silurian of the south Sub Andean Zone based on well and outcrop data (about 1000 samples).

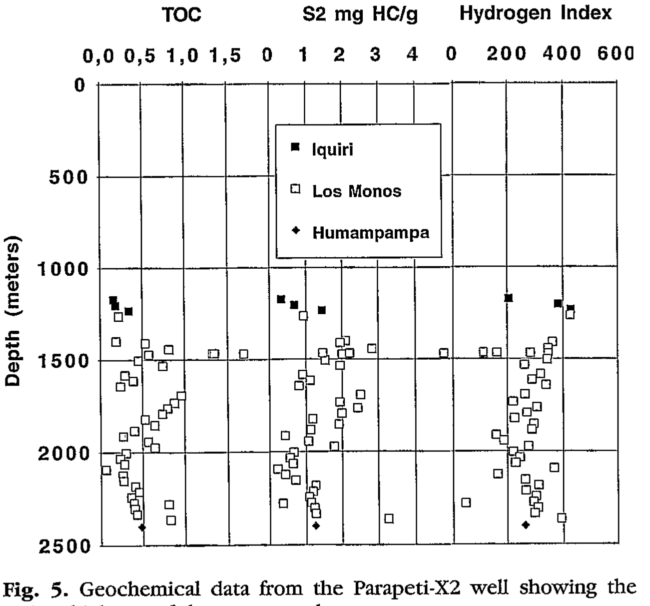


Fig. 5. Geochemical data from the Parapeti-X2 well showing the active thickness of the source rock.

debated. It may have started during the Carboniferous (Coudert 1992) or even before—a Devonian age has been sugested by Pucci (1991). The high present-day heat flow seems to indicate a current mantle anomaly which may be much more recent.

SOURCE ROCKS

Four source rocks have been identified in the Sub Andean Zone (Baby *et al.* 1995): the Copacabana Fm (Permian), the Retama Fm (Lower Carboniferous to Upper Devonian), and all the shaly beds from the Devonian and Silurian. Only the last two are present in the south. Due to facies variations, the Copacabana and Retama Formations do not have any potential in the south where the corresponding deposits (Cangapi Fm, Lower Carboniferous and Upper Iquiri Fms) are sandy.

Geochemical logs have been made for 13 wells and for more than 110 outcrop analyses. In addition, the YPFB database, containing more than 3000 analyses for the Sub Andean Zone, has been consulted (Moretti *et al.* 1995).

The Devonian and Silurian deposits correspond to a siliceous clastic platform. All the shaly beds of the Devonian (Lower Iquiri, Los Monos, Huamampampa and Icla Fms) as well as of the Silurian (Kirusilla Fm) have some petroleum potential (Fig. 4). As already mentioned, the Carboniferous and Permian do not have any potential to the south, and Tertiary deposits are continental sandstones without any hydrocarbon potential.

Devonian

By reputation, the Los Monos is the major source rock. No immature rock was sampled but the original potential may be estimated from the remaining one. The highest current HI is over 500 and the TOC over 5% but the average present-day value is around 1%. Most of the samples are in the oil window. The highest content is found on the Chaco on the eastern part of the foredeep , where the HI reaches 616 and the S2 $6.52\,\mathrm{mgHC\,g^{-1}}$ at the upper part of the Limoncito which corresponds to the Los Monos (Otuquis-well). This may be due to an originally richer potential or to better preservation, since the Devonian is immature to early mature ($T_{max} = 437\,°C$ at 500 m) in this area.

As shown by well data, the full layer presents some potential as it is imaged on the Parapeti-2 geochemical log (Fig. 5). The normal thickness is 700 m but duplexes may lead to stacking of the layers and may result in a final thickness over 1800 m, as is the case at the Camiri-201 well (see location Fig. 9). For the modelling an initial TOC of 1.5% was used, with an initial HI of 540. Fifty percent of the layer is considered to have potential.

The Huamampampa Fm is more sandy, but the shaly part also shows a low potential. At outcrop, the upper Devonian often contains impregnations and numerous oil seeps have been described, especially near major faults.

Silurian

The Silurian, which corresponds to the same depositional environment as the Devonian, has some potential but is now

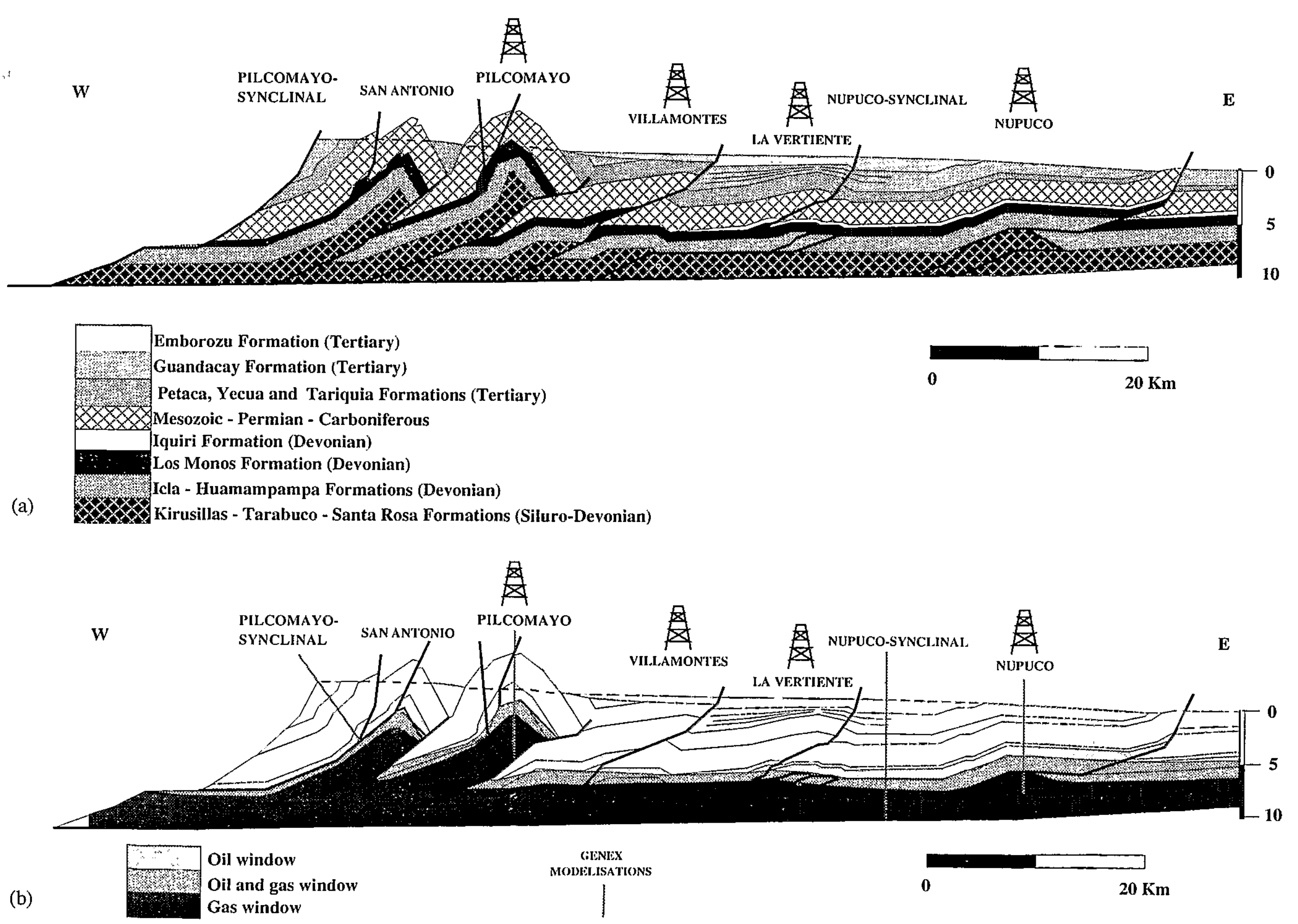


Fig. 6. Cross-section at Villamontes: (a) geology and location of the samples; (b) present-day oil and gas windows.

almost always overmature in the south of the Sub Andean Zone. Nevertheless the residual TOC sometimes reaches 5%, with an average value around 0.5%. This fact precludes the existence of a very good initial potential but a minimum initial TOC of 1% may be envisaged for the Kirusillas Fm. In addition, some biomarker analysis from oil seeps has suggested a Silurian source. This source rock, though it is still poorly known, may play an important role in the final petroleum charge, as in the Boomerang area. This central zone corresponds to the wedge of the Palaeozoic basin, where Devonian and Upper Palaeozoic strata are thinner and Silurian rocks remained immature to early mature until the Miocene. The Silurian has been drilled and sampled in some wells of the Boomerang and Chaco area and shows a rather good potential, with S2 up to 13 mgHC g^{-1} (Moretti *et al.* 1995). In the south, the Kirusillas Fm has an average thickness of about 600 m.

MODELLING

Method and hypotheses

The 1D program Genex has been used to quantify the subsidence history and the maturation of the source rocks. The expulsion in this program is based on a saturation threshold which is not known for the various source rocks, thus an arbitrary value of 20% has been used. Large uncertainties remain in this value as well as in the description of the original potential and this paper will not discuss the generated quantities of hydrocarbons. 1D programs are not designed for compressive areas with large horizontal displacement. The duplexes, which are known to exist under some structures, are especially difficult to model. When necessary, the geometry has been slightly simplified in the maturation model.

The present heat flow is a classical continental one, 45–55 mW m^{-2} in the Santa Cruz area and 47–68 mW m^{-2} in the Camiri zone (Henry 1981 and YPFB database). Quantification of heat flow variations from the Devonian is unfortunately out of range of the presently available data. Nevertheless, assuming a constant heat flow during 400 Ma is a rather broad hypothesis. Various trials have been carried out on a Triassic eventual increase of heat flow during the early Pangean breakup (Soler & Sempere 1993). Triassic erosion, which was mainly active in the north, is supposed to come from a general uplift and then from an increase of heat flow, but large normal faults have never been recorded and then a crustal thinning is precluded. An increase up to 20 mW m^{-2} in the heat flow has been tested in the modelling without having any drastic effect on the petroleum maturity history. Hence a constant basal heat flow was used in the modelling and eventual incompatibilities with the data will be interpreted in terms of maximum depth of burial and not in terms of heat flow variation. Deepening of the hydrocarbon window may come from transient thermal effects when the sedimentation rate is high. Such blanketing is calculated by the program and data from the wells located in the foredeep give evidence of this phenomena. For instance, on the Itaguasurenda well located a few kilometres east from Parapeti and where the late Tertiary burial (from 10 Ma to today) reaches 3500 m, the Los Monos Fm is early mature at 5300 m.

The kinetic parameters of each kerogen may only be

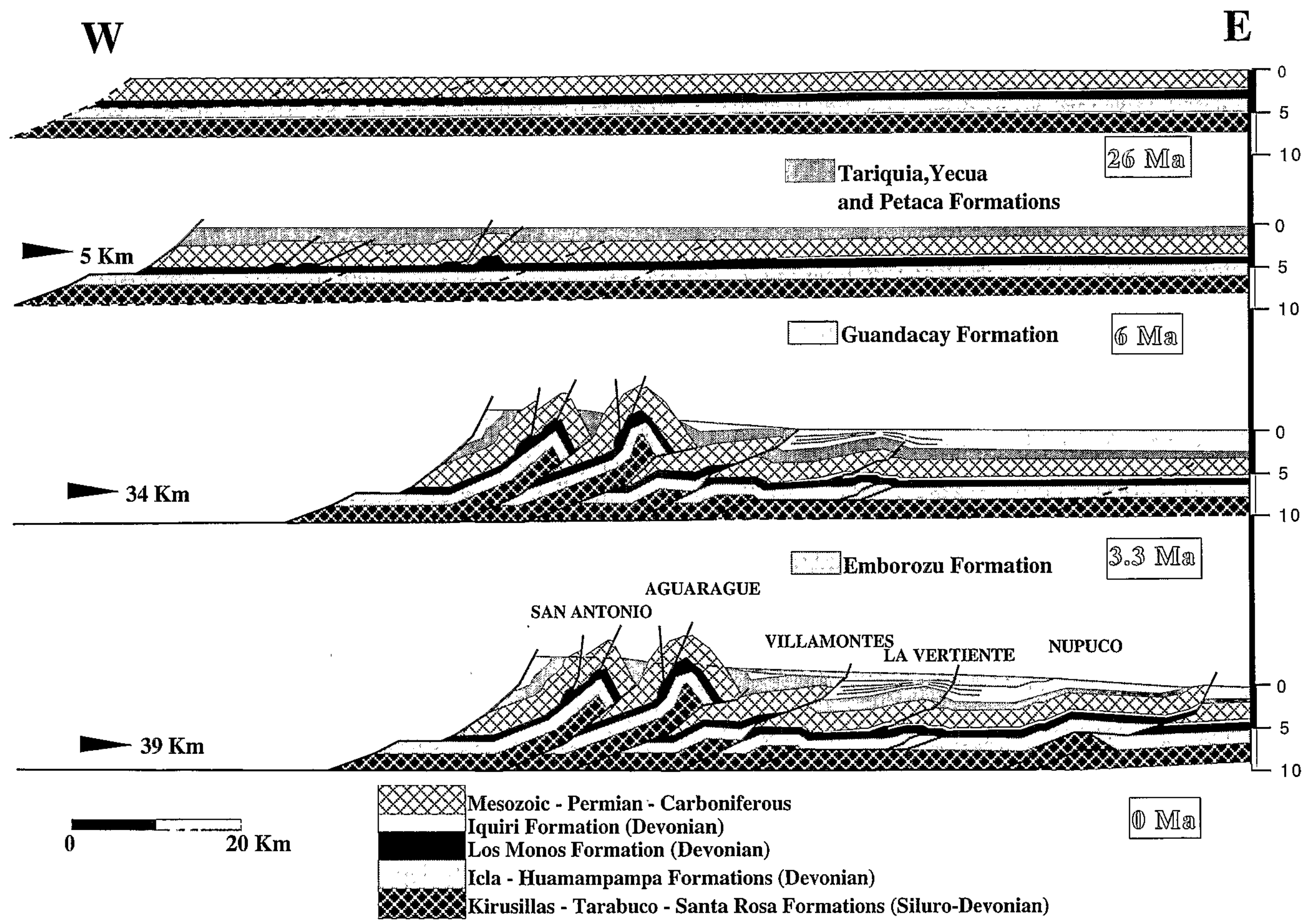


Fig. 7. Schematic evolution of the Villamontes area compatible with maximum burial deduced from the maturity data.

computed when an immature sample is available. The only one available was the Tomachi Fm (Upper Devonian, equivalent in age to the Iquiri Fm) from the Madre de Dios Basin. The initial HI was 540 for $S2 = 29\,mgHC\,g^{-1}$. Despite being a marine (type II) source rock, the profile of maturation versus depth is rather different from the default value which is the Toarcian of the Paris basin in GENEX. With a gradient around $30\,°C\,km^{-1}$, the oil window is 800 m deeper for the Tomachi Fm. These parameters have been used for the four Devonian source rocks since they correspond to the same sedimentary cycle and the same basin. As in the northern part of the Sub Andean Zone, well data show very little evolution of the T_{max} values with depth between the immature and the early mature source rock. The smallest T_{max} is around 440 °C. Nevertheless, the HI decreases from the first steps of maturation and thus will be a better parameter to calibrate the model.

The assumptions for the initial potential are

- Iquiri Fm: TOC 1.5% for 50% of the layer, marine kerogen, Tomachi type.
- Los Monos Fm: TOC 1.5 % for 50 % of the layer, marine kerogen, Tomachi type.
- Huamampampa Fm and Icla Fm: TOC 1% for 25% of the layer, marine kerogen Tomachi type.
- Silurian: TOC 1% for 50% of the layer, marine kerogen, type II (default value). This hypothesis has been made for the modelling in order to quantify the level of maturity of the Upper Silurian. The resulting quantity of generated hydrocarbons is obviously out of range of the data precision since the thickness of the Silurian source rock has not been quantified.

Villamontes cross-section (Fig. 6)

Apatite fission track analysis

Two Tertiary sandstones were sampled, one from the east flank of the Pilcomayo syncline and one west from Salato. Both gave a fission track age older than the stratigraphic one, and thus the only conclusion is that they never reached the annealing temperature of 110 °C. This means that the burial never exceeded 3.5 km.

Maturity data

The frontal thrust has been drilled at Nupuco, and oil shows were found in the Carboniferous as well as in the Ichoa Fm; however, the closure of the structure is further north. This first well proved gas and condensate which have not yet been produced. A new well is currently being drilled. Well data from Nupuco show a high maturity level compatible with a maximum burial of 5000 m at the bottom of the Los Monos Fm. Quaternary erosion deduced from this level of maturity is about 900 m.

The Aguarague (Pilcomayo) trend is producing in two fields. Los Monos and Caigua produce condensate and oil, respectively, from the Devonian. At the level of the section, the structure is eroded and the Los Monos Fm is outcropping. Its maturity level is at the beginning of the oil window.

The San Alberto structure, which is en échelon with the San Antonio one, has been drilled. Oil has been found in the Carboniferous and gas in the Huamampampa Fm. Reserves should be around 1 TCF but have not yet been produced for economic reasons.

Evolution

Figure 7 summarizes the structural evolution of the area. The San Antonio/Pilcomayo structure, which is early mature, grew up during the first period of deformation. The thickness of the Palaeozoic is large enough to explain the maturity level, and this structure has then never been buried below Tertiary deposits. On the anticline, the Upper Devonian has a Transformation Ratio around 30%, which reaches 70% in the syncline due to the 700 m of the Tariquia Formation. The lower Devonian and the Silurian were mature before Triassic erosion, due to the Carboniferous subsidence but the timing is favourable for charging the structure by the upper Devonian source rock.

The evolution is clearly different between the anticlines, where the Devonian often crops out and where data are available, and the synclines where Tertiary sedimentation may be large. Figure 8 shows the comparison between the maturity evolution in the Nupuco anticline and in the corresponding westward syncline. In the syncline the Tertiary thickness is about 4000 m: 1000 m of Taraquia Fm, 2000 m of Guandacay Fm and 900 m of Emborozu Fm. The Silurian and the lower Devonian were mature in the Carboniferous but the Los Monos

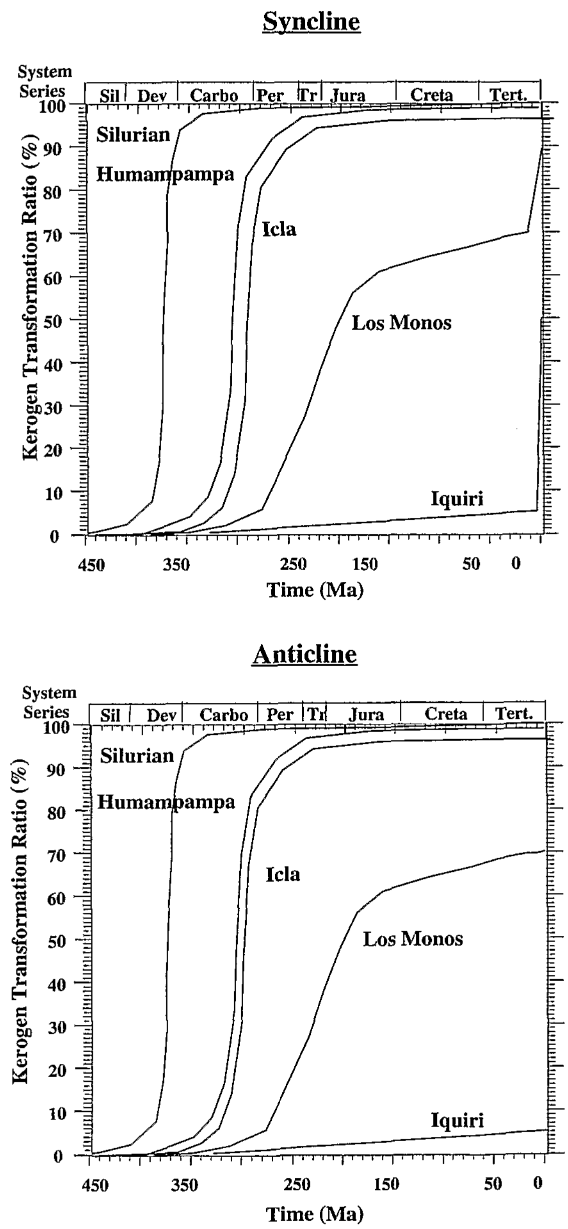


Fig. 8. Villamontes cross-section, maturity level on the Nupuco structure, comparison between synclinal and anticlinal locations.

and Iquiri Fms remain at the beginning of the oil window. A second phase of oil generation and expulsion is due to the Tertiary infilling in the syncline and it is thus contemporaneous with the structure emplacement. Figure 6b shows the current oil and gas windows for the source rock throughout the section. One may distinguish the inherited maturity, which follows the geology, from the Tertiary one which follows the topography.

Camiri cross-section (Fig. 9)

For outcropping quality purposes, another short section on the Rio Huacareta was sampled parallel to the one presented here but about 50 km south (see Fig. 1). On this river, the full section from the Carboniferous to the Icla Fm crops out allowing complete sampling of the Upper and Middle Devonian. These data are on a trend with the so-called Huacareta anticline in Fig. 9a. The structure deepens to the north and so projection was carried out using the measured outcropping data to the section where the Devonian is buried.

Apatite fission track analysis

Six fission track analyses have been made along this section (see location in Fig. 9a and result Fig. 14). Two are from the Carboniferous at the top of the Huacareta section. In both cases the fission track age is Tertiary and present lengths indicate late Tertiary uplift respectively between 10 and 2 Ma (Carboniferous) and between 15 and 5 Ma (Huamampampa Fm). Three of the samples are Tertiary but have an older fission track age. The Devonian sample from the Yanguillo anticline has a Miocene fission track age indicating a Miocene cooling, which means structure formation followed by erosion during Miocene times.

Maturity data

The Yangillo anticline (equivalent to the Huacareta one at the level of the section) is early mature, and thus the maximum thickness of the Tertiary deposit cannot exceed 1500 m. Currently, all the reservoirs crop out and no petroleum accumulation can be found. However, oil seeps are numerous in the field as well as impregnation in the source rocks.

Further east the Monteagudo structure is producing oil from the Cangapi Fm and the Carboniferous but it has not been possible to obtain a geochemical profile, as the few samples were too poor in organic material (S2 < 1 mgHC g^{-1}) to interpret the T_{max} or the decrease of HI.

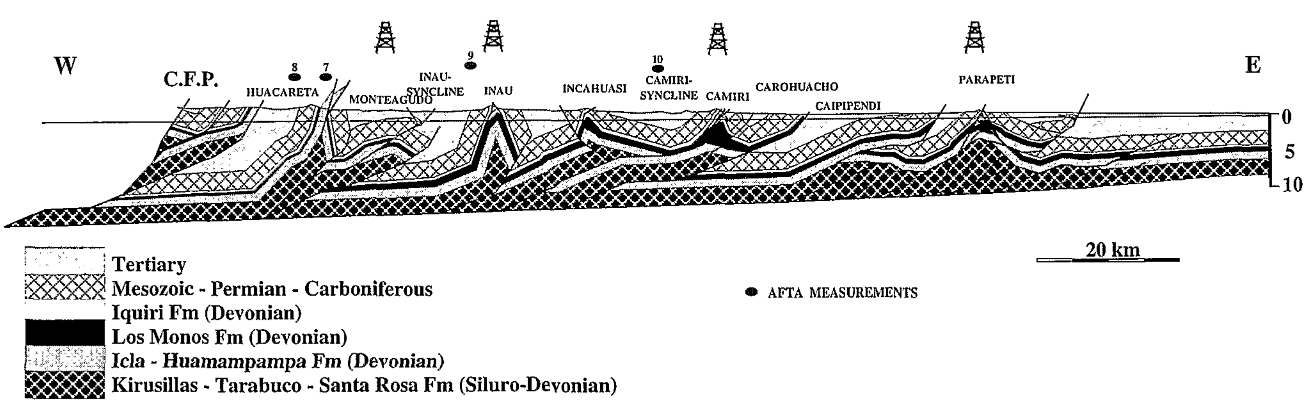
At the Inau anticline, the Devonian crops out and a well situated on the flank of the structure has been sampled (Fig. 10). Well data are compatible with 2500 m of Tertiary burial, meaning that the full Tariquia Fm and part of the Guandacay Fm were deposited. This structure is thus a late one.

Data from the Camiri well show a rather high residual HI, which precludes a deep Tertiary infilling. The maximum thickness of the Tertiary deposits is 500 m, which is less than the thickness of the Tariquia Fm. The Camiri structure is thus an early one and was formed before 6 Ma. Eastward, data from the Carohuacho structure show a higher maturity level, compatible with thicker Tertiary deposits. This structure is thus more recent and was developed after the deposition of the Guandacay Fm; an age of 3.3 Ma may be proposed.

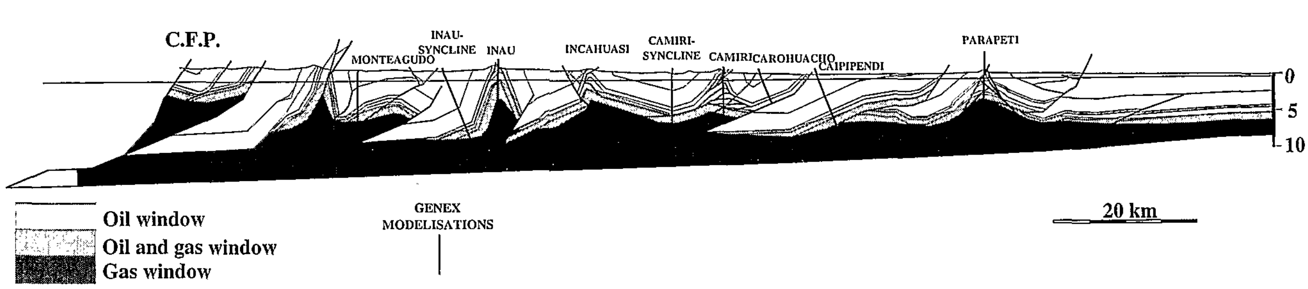
Evolution

The schematic evolution of the area is proposed in Fig. 11. The Camiri and Incahuasi structures developed during the deposition of the Guandacay Fm whilst the Inau and Carohuacho ones are more recent. The original passive roof duplexes of the Camiri structure were reactived by a blind thrust and the Incahuasi one by a back shear during this second phase.

The present oil and gas windows are displayed in Fig. 9b and



(a)



(b)

Fig. 9. Camiri cross-section: (a) geology and location of the samples; (b) oil and gas windows.

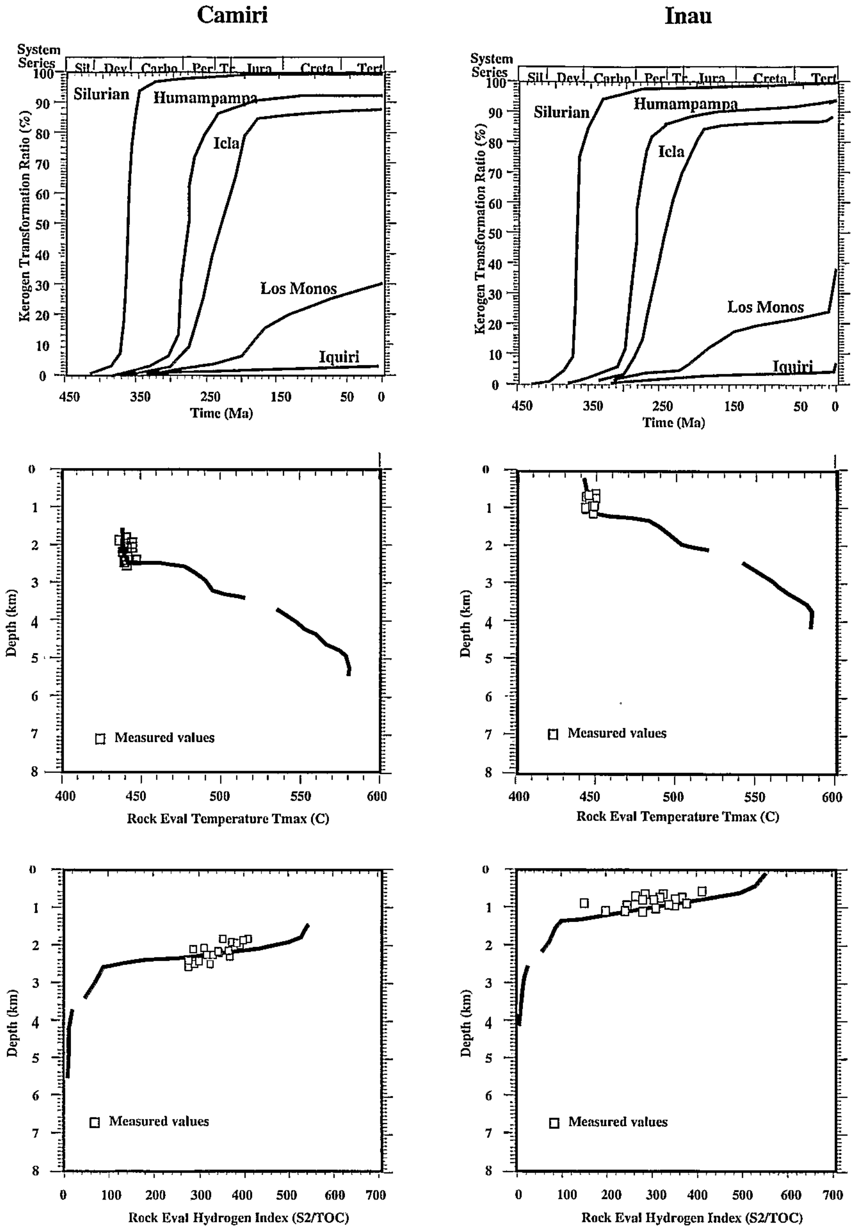


Fig. 10. Modelling of the source rock evolution of the two wells: Camiri and Inau. For the T_{max} and hydrogen index, the squares represent the data and the lines the Genex-computed curves. As for many of the anticlines in this area, the drilled tops of the structures are at the beginning of the oil window.

the maturity modelling for the Camiri well in Fig. 10. The Silurian, as well as the lower Devonian source rocks, are now overmature and have been since Carboniferous time (see Fig. 10) but the Upper Devonian is now generating, especially in the synclines where the burial is still increasing.

In terms of their hydrocarbon fill, the first structures, such as the Camiri one, are contemporaneous with oil generation, whereas the more recent structures (less than 3.3 Ma) are expected to be filled by gas and condensate. The Camiri and Monteagudo fields are the only two large oil fields in the southern Sub Andean Zone. The existence of various deformation phases seems to be the key to predict the type of hydrocarbon in each structure.

Santa Cruz cross-section (Fig. 12)

Apatite fission track analysis

Four samples have been analysed: 1 and 2 on Fig. 12, and 3 and 4 located west of the section. All show annealing of the early traces and a Tertiary cooling (between 70 and 2 Ma), dated as Miocene for sample 3 (Fig. 14). For the other samples (1, 2, 4) the dispersion of the data is too large to allow for a precise assessment of the cooling , i.e. uplift, age.

Maturity data

Outcrop data from the Espejos structure show an early mature Devonian (Los Monos Fm), compatible with a maximum Tertiary sequence of 400 m. This indicates an early structure, thrusted during the deposition of the Tariquia Fm. At the well, the Los Monos Fm is much more mature, and 2000 m of burial during the Tertiary are necessary to explain the level of maturity. As the two locations are close it is difficult to imagine that the Tertiary thickness changes so quickly. But the well is situated on the footwall of the structure and the burial may be explained by the thrust itself. This anticline produced some oil from the Humampampa but the quantity was very low and the production period did not exceed one year.

On the Samaipata structure, data are rather variable but a residual high hydrogen index (up to 420) precludes too high a maturity level. The Carboniferous thickness is large enough to

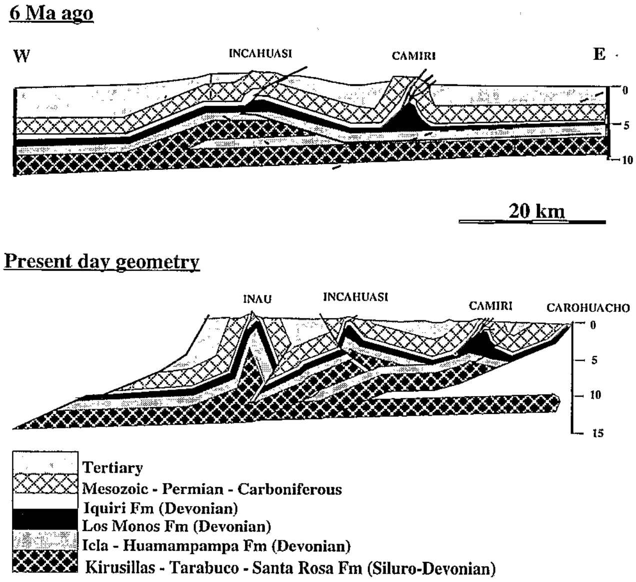


Fig. 11. Schematic evolution of the structures. The Camiri and the Inacahuasi structures developed during an early phase of deformation. The Inau structure is a very recent one corresponding to an out-of-sequence propagation.

explain the level of maturity and no Tertiary deposits are expected.

At the La Copa structure, the data are similar: the Upper Devonian is now at outcrop and a medium residual hydrogen index (up to 350) precludes a high maturity level and the deposition of a thick Tertiary sequence. The Carboniferous burial is enough to reach the measured maturity level. It was assumed that the Carboniferous in La Copa was 2300 m thick, the Ichoa Fm 350 m thick and the Cajones Fm 200 m thick. These units have been eroded during the Tertiary.

Evolution

Figure 13 shows the subsidence and maturation history of the La Copa structure. The results are representative of what occurs on this section. Silurian and Lower Devonian source rocks were mature before the Triassic due to Carboniferous and Permian burial. The Los Monos and Iquiri Fms are still in the oil window but the burial did not increase very much from the Palaeozoic, 150 m in this hypothesis. The increase of Transformation Ratio and the generation of hydrocarbons since the Triassic is then reduced. There was no Tertiary infilling of the syncline to form the kitchen of the structures. A dry well has been drilled on the La Copa structure as well as at Mataral, northward on the same trend.

The current oil windows of the final section are shown in Fig. 12b. The hydrocarbon windows follow the Devonian geometry and are thus inherited from a pre-Andean burial.

CONCLUSIONS

(1) In the southern part of the Sub Andean Zone, the Devonian and Silurian intervals have a low original hydrocarbon potential but the thicknesses of the various source rocks are large, amounting to at least half of the 700 m from the Los Monos Fm, 25% of the 1000 m from the other Devonian formations, and half of the 600 m thick Silurian Kirusillas Formation.

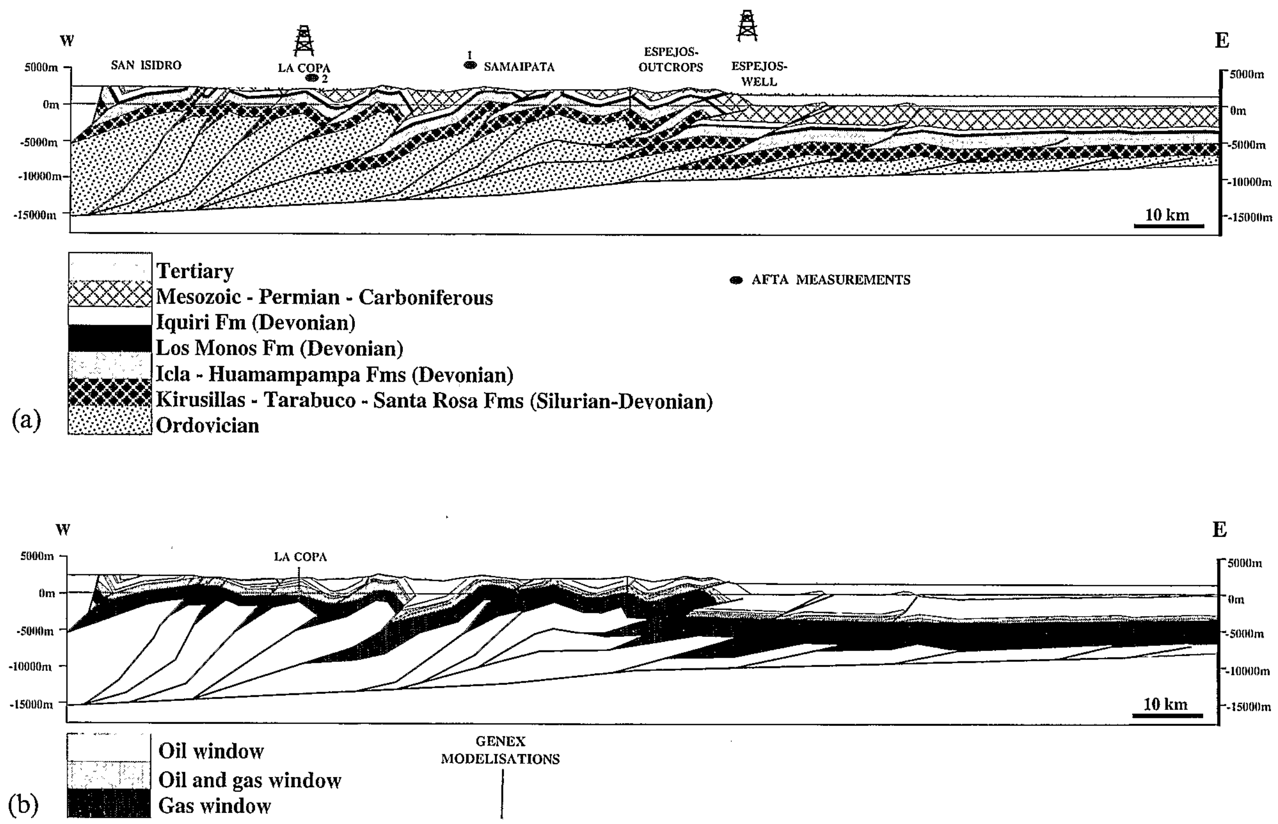


Fig. 12. Santa Cruz cross-section: (a) geology and location of the samples; (b) oil and gas windows.

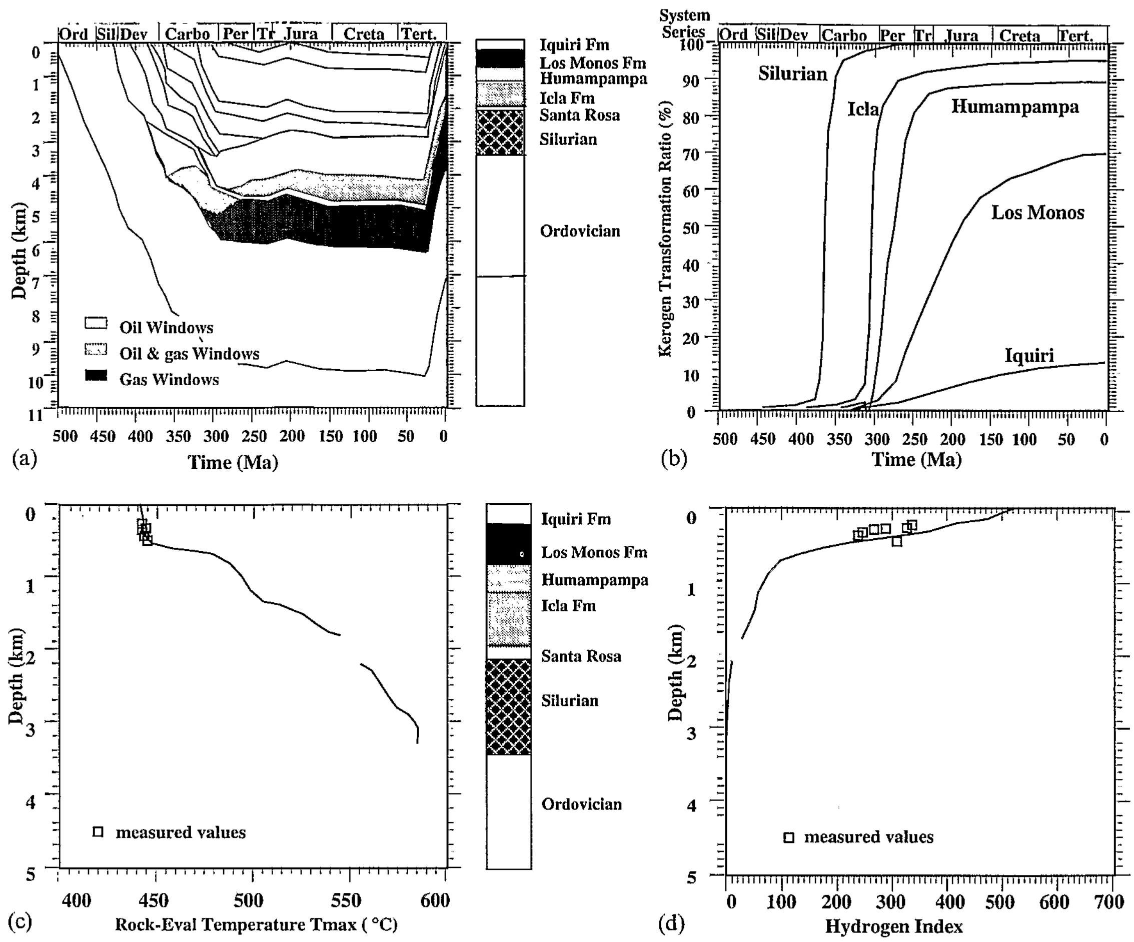


Fig. 13. Modelling of the source rock evolution at La Copa. There was no increase in the burial from the Miocene to the Present. (a) Hydrocarbon windows; (b) transformation ratio of source rock; (c) T_{max} versus depth; (d) HI versus depth.

(2) The subsurface data show three events in the structuring of the southern Sub Andean Zone. They range in age from 10 Ma to present day.

(3) Rock Eval data, as well as fission track analyses, show variations of the level of maturity of the different anticlines. Some of them display a very low maturity which precludes a deep Tertiary burial. The early structures are like this. These data also indicate some out-of-sequence thrust propagation.

(4) In the Santa Cruz area, the low level of maturity indicates a weak Tertiary burial of the area. The structures are deeply eroded and the Jurassic and Carboniferous reservoirs, when not eroded, are now outcropping in many places. The petroleum potential of the area is therefore expected to be low.

This combined study of structural analysis and maturity level allows us to define more accurately the thrusting history and the timing of maturation. Nevertheless, uncertainties clearly remain concerning the hydrocarbon potential of the area. The reserves of the fields are often small in the southern Bolivian Sub Andean Zone. This may come from the scale of the structures, the seal quality or from the lack of charge. The current level of understanding of the expulsion for a poor source rock is also rather low. A high ratio of hydrocarbon remaining in the source rock itself is expected, eventually inducing overpressures. With increasing maturity, lightest compounds are generated which are expelled much more easily. In the southern Sub Andean Zone, overpressures in the Los Monos Fm have been mentioned by Perez (1994) in some wells (Nupuco, San Alberto, Toro-X40). In the Nupuco well, these overpressures correspond effectively to the relatively rich (S2 up to 6 mgHC g^{-1} and HI up to 477) zone of the Los Monos which is in the first part of the oil window. Another element in favour of this late expulsion is the high level of maturity of the produced oils, which show all maturity levels greater or equivalent to a vitrinite reflectance of 1, since source rocks are known at all levels of maturity from very early mature to overmature.

Because of the poor knowledge of the initial potential of the Silurian and Devonian source rocks, quantification of the generated and accumulated hydrocarbons is difficult. In addition, the existence of intermediate pre-Andean accumulations with current remigration to new structures may also be hypothesized. If new data confirm the influence of the Silurian on the current oil accumulations, the possibility of such a remigration must be seriously studied since the known thicknesses of the Devonian and Carboniferous deposits would have resulted in a late Palaeozoic maturation of the Silurian source rock.

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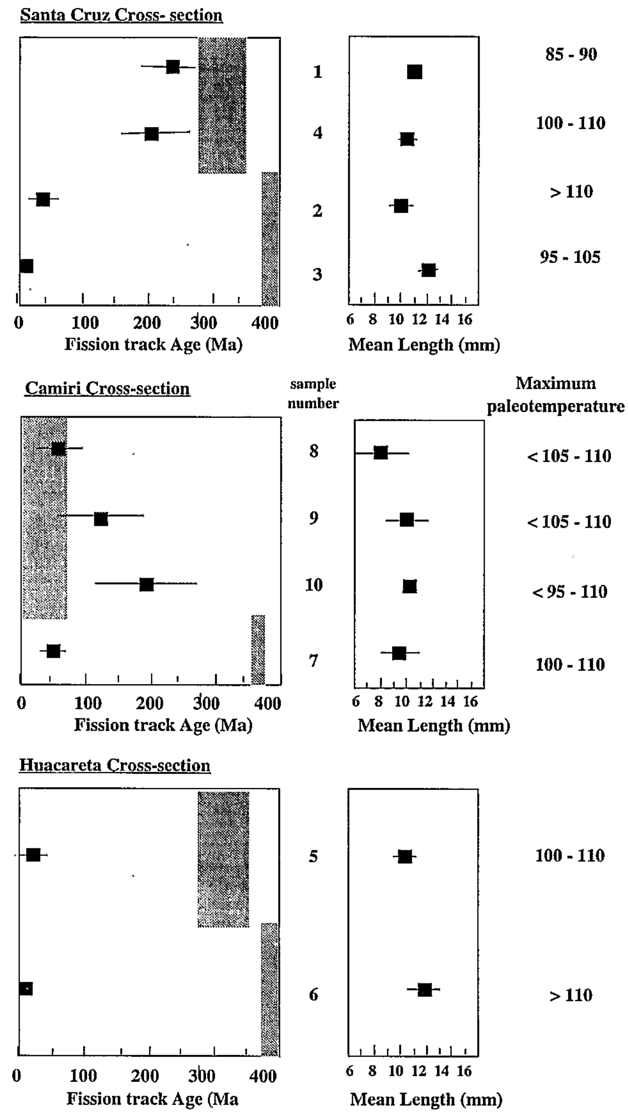

Fig. 14. Apatite fission track data summary from the area. See Figs 9 and 12 for location of the samples . The grey zones indicate the stratigraphic ages of each sample and the horizontal lines on the squares the uncertainty on the fission track age and mean length. Interpretation from Geotrack (1993).

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