PETROLEUM EXPLORATION IN THE SOLIMÕES BASIN

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Introduction
The Solimões sedimentary basin is so far the only commercial Brazilian basin producing from Paleozoic rocks, and contains the second recoverable oil-equivalent volume in Brazil.
The Solimões basin is a vast, east-west trending, Paleozoic intracratonic depression located in the heart of the Brazilian Amazon rain forest, and covers an area of approximately 175,000 mi^2 (450,000 km^2) of the Amazon State, northern Brazil. It is separated from the Acre basin to the west by the Iquitos arch, and from the Amazon basin to the east by the Purus arch (Fig. 1).

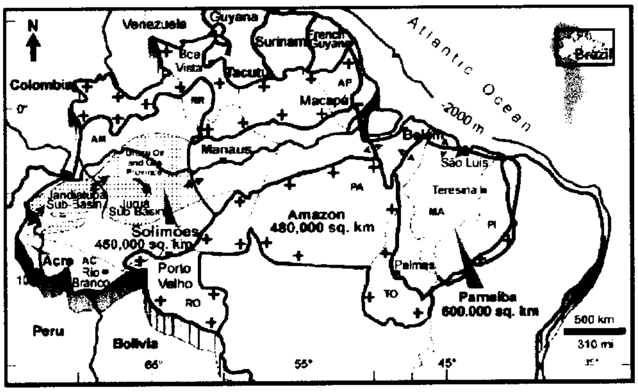

Fig. 1 – Location map of the Amazonian sedimentary basins. The Solimões basin is highlighted as dotted area (Eiras, 1998a).

The Solimões basin is divided into two sub-basins by the north-south Carauari arch: the Juruá and Jandiatuba sub-basins. While considerable exploration effort has been accomplished by Petrobras in the eastern Juruá sub-basin, since 1978, the Jandiatuba sub-basin is virtually unexplored. The presence of several Indian and forest reserves requires special management to account for the environmental protection in Jandiatuba sub-basin.

History of Exploration and Production
Geological and geophysical studies of the Solimões basin began in the late 1950s and early 1960s with the pioneer petroleum exploration of Petrobras in that area. Even so, of the nearly 200 wells now existing in the Solimões basin, only 17 were completed between 1958 and 1963. Operations were conduced along the rivers, to make use of the transportation facilities. Even the wells were mostly drilled on the banks of the main rivers, the exploratory prospects were based only on gravity studies (21,600 mi = 34,750 km of profiles) from surveys carried out from 1957 to 1960.
Petroleum exploration resumed in 1976 based on a reconnaissance seismic reflection survey proposed by Peter Szatmari in 1975 to verify the presence of a fault-and fold-zone crossing the Solimões basin near to Juruá and Jutaí rivers. In this survey, an anticline was detected at the upthrown side of a reverse fault in a generally northeast–southwest direction (Szatmari, 1984). It was the first seismic reflection survey conducted in the basin applying the new techniques being used in the Amazon basin (digital seismic acquisition). This new technology allowed greater precision in defining seismic horizons as deep as 8,200 ft (2,500 m), in spite of the presence of thick diabase sills intruded into the Permian-Carboniferous sequence above 8,200 ft.
The seismic interpretation confirmed the structure. This prospect was tested by the 1-JR-1-AM well, which was the discovery well for the Juruá gas province, starting a new phase in the Amazon petroleum history. The use of helicopters from this time onward increased the seismic production and allowed the use of heliportable rigs, without much dependence on the limited rivers waterways.
The discovery of the Juruá gas field in 1978 provided impetus for new investigations. New discoveries were made between 1980 and 1984, including eight gas fields along the Juruá trend.
In October 1986, the Urucu oil and gas field was discovered. Two years later, oil was already being produced and transported by rafts through the Urucu river to the Manaus refinery, 420 mi (680 km) away.
Under risk contracts, foreign companies also participated in this exploration. During the late 1980s, a consortium consisting of Pecten, Elf, and Idemitsu surveyed 1,242 mi (1,998 km) of 2D seismic on the Coari river region, approximately 75 mi (120 km) northeast of the Urucu province. This consortium drilled an unsuccessful exploratory well to 6,968-ft (2,124-m).
Important discoveries occurred in 1996, this time in structural trends with orientations different from the Urucu and Juruá, but with the same tectonic style. Gas was discovered in the Copacá River and São Mateus fields.
Up to now, more than 200 wells (including around 100 wildcat wells) have been drilled in this basin. Existing seismic coverage includes 41,150 mi (66,210 km) of 2-D data acquired since 1976, and approximately 41,230 registers of 3-D data (surveyed over 462 mi^2 = 1,197 km^2 in the Urucu and São Mateus provinces) acquired since 1988. Potential data include 39,900 mi (64,200 km) of gravity profiles, 12,555 mi (20,200 km) of magnetic profiles, and 231,690 mi (372,790 km) of airborne magnetic profiles.
This exploration effort resulted in the discovery of nine gas fields in the Juruá province, including the Biá River region; five light oil, gas and condensate fields in the Urucu province; three gas and condensate fields in the São Mateus province; and the Copacá River gas field, in addition to some sub-commercial discoveries. There are about 10 oil-and gas-producing zones in the basin. Total reserves are over 850 million barrels of oil equivalent.
All the oil produced in the Solimões basin comes from the Urucu province, but Petrobras is currently investigating areas such Juruá, Biá and São Mateus.
Current production is around 40,000 BOPD, consisting of light oil (42°API) of excellent quality, and liquid natural gas, in addition to approximately 1,700,000 m^3 of natural gas.

A daily production of 45,000 barrels of oil and 6 million m^3 of natural gas is expected to be achieved for this year. A total of 950 tons of liquid petroleum gas will be processed per day, the equivalent of 10,000 barrels of oil and 70,000 encased gas bottles for domestic use.

To fulfill this goal, a 14-in (36-cm) diameter, 450-mi (280-km) long pipeline for oil, liquid natural gas, and condensate has been constructed. This pipeline interconnects the Urucu field to the Solimões terminal, which is 26 mi (16 km) from Coari city, on the south bank of the Solimões river. From there, oil is transported by vessels and rafts to the Manaus refinery. In addition, an 18-in gas pipeline will be constructed to drain off the gaseous fraction directly to Manaus city.

Structural framework

The Solimões basin is located between the Guyana and Brazilian cratons, which occur to the north and south of the basin, respectively.

The Proterozoic basement on which the Solimões basin rests is part of the mobile belt connected to an older terrain known as the Central Amazon province, individualized by descriptive but not genetic characters (Thomaz Filho *et al.*, 1984). This basement consists of igneous and metamorphic rocks in the Jandiatuba sub-basin (Rondoniense mobile belt). In the Juruá sub-basin (Rio Negro-Juruena province), in addition to the igneous and metamorphic rocks there are also sedimentary rocks (Purus Group) deposited in several basins that formed a broad system of Proterozoic rifts.

The tectonic events that are recorded in the Phanerozoic strata acted upon the previous Gondwana lithospheric plate and later on the South American plate. This induced periodic epeirogenic movements in the interior of these plates, which reactivated regional arches and controlled deposition and erosion processes. They also caused intraplate folding and faulting, the most important being the Mesozoic transpressional event named Juruá tectonics. This event reactivated older structures and generated anticlines related to reverse faults primarily in the northeast–southwest direction, and secondary in the northwest–southeast direction. These anticlines are hosting the existing petroleum accumulations.

Stratigraphic framework

The Phanerozoic stratigraphic column is up to 12,470 ft (3,800 m) thick in the Juruá sub-basin and 10,170 ft (3,100 m) thick in the Jandiatuba sub-basin, consisting of four 2nd order Paleozoic stratigraphic sequences and two 2nd order Mesozoic-Cenozoic stratigraphic sequences (Eiras, 1998a,b) (Figs. 2 and 3).

The Paleozoic rocks contain the Upper Devonian petroleum source beds, and the Upper Carboniferous reservoir intervals and seals. In most of the basin, they are intruded by diabase dikes and sills.

Paleozoic rocks do not crop out in the Solimões basin. They are covered by extensive Cretaceous and Tertiary-Quaternary sequences.

Tectonics and sedimentation

The formation and evolution of the Solimões basin are still a matter of debate. One of the most recent hypotheses suggests that the origin of the basin occurred under a west to east flexural regimen related to a rifting that paralleled the western border of Gondwana during the Ordovician. The Solimões basin should have been formed during the subsidence that took place after this rifting phase along with other interior depressions and marginal basins (Campos *et al.* 1991). This rifting event may have played a significant role in basin origin and evolution.

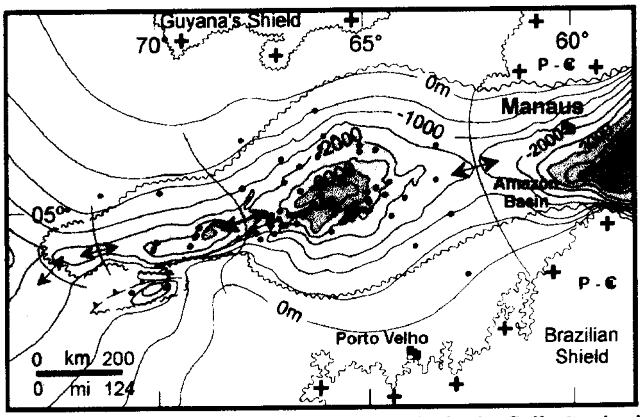

Fig. 2 – Thickness (m) of Phanerozoic rocks in the Solimões basin (contour interval 500 m = 1,640 ft) and distribution of wells that penetrate Proterozoic rocks (Eiras, 1998a).

In the Early Ordovician, the Juruá sub-basin region was a stable platform that was separated from a subsided area to the west (Jandiatuba). This boundary is supposed to be situated roughly where the Carauari arch later developed. Following a subsidence of the region, the first marine sedimentation occurred from the west. The Middle Ordovician Benjamin Constant Formation is the first record of this marine event and is limited to the Jandiatuba sub-basin (Fig. 3).

The initiation of the Carauari arch uplift occurred in the Late Silurian. The sea transgressed the Carauari region and covered the western edge of the Juruá sub-basin. The Jutaí Formation records this event (Fig. 3). It is divided into three 3rd order stratigraphic sequences.

In the Middle Devonian, when the uplift of the Carauari arch was very evident, a third marine invasion occurred. Evidence of a glacial climate during this time occurs in the upper part of this sequence. The Marimari Group, deposited from the Middle Devonian to the Early Carboniferous, is muddy in the Jandiatuba sub-basin, and rich in silica sponges at the Carauari arch and Juruá areas. During the Late Frasnian-Early Famennian, a condensed section was deposited in an anoxic environment, and is interpreted as a maximum flooding surface. Shale layers with the highest total organic carbon content in the basin belong to this interval.

The Tefé Group is the fourth and last record of marine transgression in the basin, deposited during the Late Carboniferous to Early Permian. During this period, the arid climate favored the formation of tidal bars and eolian coastal dunes, which constitute the best reservoir rocks in the basin. Subsequently, a thick evaporite sequence was formed, comprising an effective seal in the basin.

The influence of the Carauari arch on the sedimentation of the Tefé Group can be seen on the total isopach map and on the salt layers distribution. In addition, the erosional unconformity between the Paleozoic and the Mesozoic is more pronounced at the arch area, as can be seen in the geological cross-section (Fig. 3). This fact is also noted on the unconformity at the top of the Marimari Group.

There is no record of Jurassic-Triassic sedimentation in the Solimões basin. Instead, the uplifts related to the Hercynian orogeny caused extensive erosion.

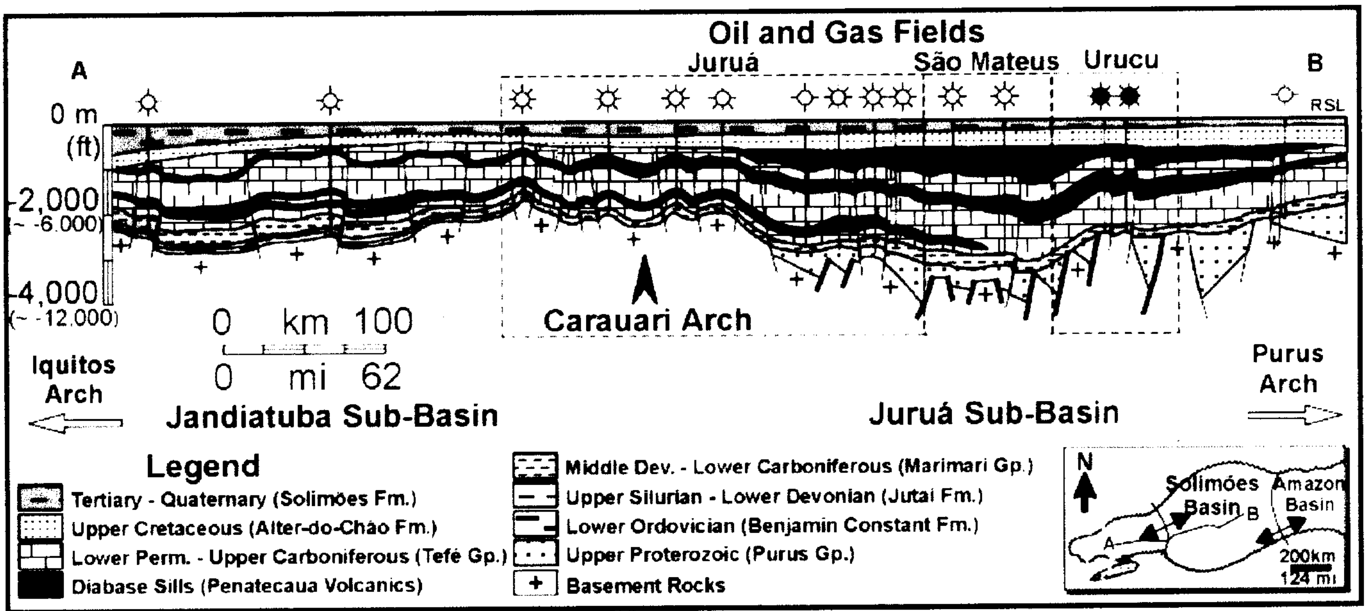

Fig. 3 – East-west cross section A-B across the Solimões basin.

At least three diabase layers intrude into the Permian-Carboniferous sequence, occurring uniformly along bed layers. The magmatism responsible for these intrusions of a great volume of diabase into the Paleozoic rocks took place at approximately 220 Ma ago, during the Triassic Period. This coincides with the Penatecaua magmatic event, broadly identified at the Brazilian platform and correlated with the opening of the Atlantic Ocean.
Based on the total diabase thickness and on the thermo-mechanical modeling, it is estimated that at least 2,600 ft (800 m) of Permian rocks were eroded during this period (Gonçalves *et al.* 1995).
During the Late Cretaceous the basin started to subside again. A high-energy river system developed and deposited a predominantly sandy sequence under humid conditions, which occurs from the Amazon to the Colombian, Peruvian, and Bolivian sub-Andean basins. This river basin drained into the former Pacific Ocean. This sandy unit is named Alter-do-Chão Formation in the Solimões and Amazon basins (Fig. 3).
In the Paleogene, this river basin became isolated. The Andean overload caused a bend in the lithospheric plate and displaced the Tertiary sedimentation depocenter to the sub-Andean region, developing a foreland basin. Cretaceous braided rivers gave way to huge lakes of shallow, fresh water with low water circulation, fed by a low-energy meandering river system. From the Miocene on, during the Andean paroxysm, the basin began to be filled by a great volume of sediments coming from the Andes. A drainage system developed in the direction of the Atlantic Ocean, preceding the present hydrographic basin.
Humid conditions favored the growth of incipient vegetation, which would later become the Amazon forest as it exists today.
In the Quaternary, the gradients of some rivers became steeper, increasing their transport capacity. As a result, sandy sediments were deposited in the region between the Jutaí and the Negro rivers.
The Tertiary-Quaternary sequence forms a sedimentary wedge from the Purus arch up to the sub-Andean basins, where it reaches more than 23,000 ft (7,000 m) in thickness. It is the Solimões Formation in the Solimões and Amazon basins (Fig. 3).

Petroleum systems

The following classification is based largely on the paper published by Maggon and Dow (1994). At least, two petroleum systems can be identified at the Solimões basin: Jandiatuba-Juruá(!) and Jandiatuba-Uerê(.). The Jandiatuba-Juruá(!) system is, by far, the most important. At present it contains all of the commercial petroleum accumulations of the Solimões basin.
The essential elements present good characteristics (Fig. 4): the source rock is the Upper Devonian, radioactive black shale of the Jandiatuba Formation, around 130 ft (40 m) thick. TOC higer than 4%, and vitrinite reflectance (Ro) over 1.00%; the reservoirs rocks are the Upper Carboniferous, eolian dune and tidal bars sandstones of the Juruá Formation, more than 165 ft (50 m) thick with approximately 18% porosity and 1,000 mD permeability; seal rocks are the Upper Carboniferous evaporites (anhydrite and salt) of the Carauari Formation located above the reservoirs rocks.
As the light sediment load was compensated by the thermal effect of the Triassic volcanism, this system is classified as atypical, according to the Maggon and Dow (1994) concept.
There are 18 light oil, gas, and condensate fields in the Solimões basin. A possible scenario is: traps were formed in the Paleozoic, and petroleum began to be generated in the Carboniferous as a result of deep burial, with a transformation rate of 50%. Petroleum expulsion occurred during the Triassic due to the heat of the diabase intrusions, with a corresponding transformation rate of almost 100% (Gonçalves *et al.* 1995).
Primary migration occurred into the Devonian sandstones located above and below the source beds, and secondary migration through these carrier beds or through ancient faults. Petroleum accumulation occurred in multiple trap types such as paleohighs, along hinge lines, or in stratigraphic traps with angular unconformities, pinchouts or sedimentary onlap. Structures were reactivated by the compressional Juruá tectonic event during the

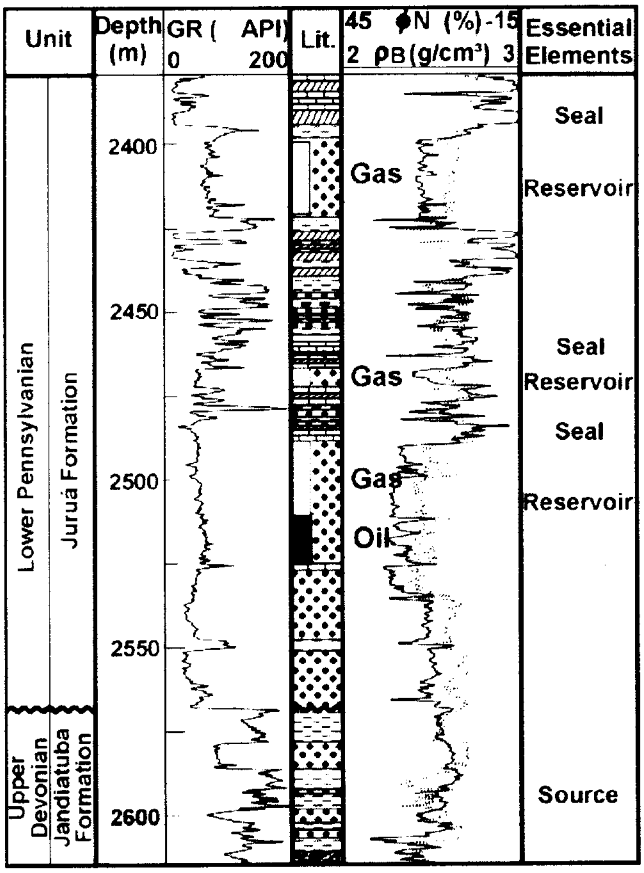

Fig. 4 – Typical well logs showing the essential elements of the Jandiatuba-Juruá(!) petroleum system and gas-oil-water contact in Urucu field.

Jurassic-Cretaceous, followed by remobilization and concentration of the petroleum in new traps. In summary, all the essential elements acted favorably in time and space such as the processes have been able to form commercial accumulations.

The geographic extent of this petroleum system in the critical moment (end of Triassic) included two pods of active source rock in the Juruá and Jandiatuba sub-basins depocenters. All the petroleum discoveries and significant oil shows were derived from these pods.

The term "Jandiatuba-Juruá" refers to the Upper Devonian shale (Upper Frasnian-Lower Famennian) of the Jandiatuba Formation and to the Upper Carboniferous (Lower Pennsylvanian) sandstone beds of the Juruá Formation, which are the source and the reservoir rocks of this system, respectively. This terminology was used according to the proposal made by Maggon and Dow (1994).

The high degree of thermal maturation that affected the Jandiatuba shale resulted in the destruction of biomarkers, which could have been used to correlate between the oil accumulated in the Juruá Formation and the organic extract obtained from the Jandiatuba source bed. However, Rodrigues *et al* (1990) state that the basic geochemical data (organic carbon, pyrolysis, and organic petrography) proved that the oil and gas at the Solimões basin were generated by the Devonian Jandiatuba shale.

The Jandiatuba-Uerê petroleum system is deficient in many aspects and contains relatively little of the petroleum found in the Solimões basin. The reservoir and seal characteristics, together with poor seismic imaging constitute the principal constraint. However, it must be emphasized the potential for a higher liquid:gas ratio for this petroleum system. This is because the reservoir rock is found stratigraphically lower and therefore farther from the heat source of the sills that cracked petroleum in the source rock or within the reservoir.

Conclusions

Although the Solimões basin is a petroleum production area, it is still not well known, and additional petroleum reserves probably exist within the basin. There are several areas that have not been extensively explored and sizable reserves in Juruá-Urucu-like anticlines may be found.

There is no production from the Jandiatuba-Uerê(.) petroleum system so far, but possible stratigraphic and combination traps exist in Devonian rocks beneath the source rock. Also, subtle traps can be explored for at slightly higher risk and cost using new ideas and technologies.

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