3D Model using Crooked lines on Amazon Northwest

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Abstract

This study emphasizes the using of geological-geophysical data such as mapping, unconventional seismic lines (crooked), and well logs in the Amazon to obtain a 3D seismic stratigraphic model. In order to interpret the layout and stratigraphic limits of the Jandiatuba Sub-Basin and its subsurface. The parameters of crooked lines, such as velocities, 2D images, relief, and rendering attributes, were tied to geophysical drill hole data, which provided essential information for elaborating the "remote" Western Amazon stratigraphic context, where the access by road is limited and displays dense vegetation coverage. Brazil-Colombia-Peru Triple Border (BCPTB) comprises boundary and sedimentary sequences located west of the Jandiatuba Sub-basin (Solimoes Basin). The well to seismic tie allows the visualization and determination of the seismic horizons continuity. From that the surfaces generation and gridding permits a tectonostratigraphic model confection. Using the framework and the petrophysical properties it is possible to obtain a 3D seismic stratigraphic model. These results will contribute to advances in studies related to the Geology of northwestern Amazonia, especially in the triple border region.

Keywords: Amazonas, Crooked, Seismic-stratigraphy, Solimões, 3D Model.

Introduction

In regions with difficulty of access, especially those with a lack of infrastructure or with dense vegetation, it is necessary to use indirect geophysical methods as tools that allow to decipher, investigate and know the geology on the surface and subsurface. In addition, the geophysical data allows a subsurface sampling through the crooked section and well logs, which can be integrated with the existing geological surface mapping in past works, enabling an effective correlation.

For crooked seismic lines (Wu, 1996; Urosevic and Juhlin, 2007), a different treatment from conventional straight data is necessary. Due to irregularities in the acquisition, the data is affected by several factors, such as the water column, suspended sediments, subsurface image points that are not entirely perpendicular, sections that must be viewed and interpreted in three-dimensional modules. The seismic to well tie allows the interpretation and tracking of seismic horizons, in addition to seismic-stratigraphic features and structures. A homogeneous and isotropic medium is assumed, which allows the use of a straightforward velocity function (time-depth) and the correlation of data with different domains. The geological data require a velocity model to integrate and convert the geological and geophysical data to the same domain to perform the correlation between the seismic section and the geophysical well logs (Gamma Ray, Spontaneous Potential and Resistivity).

The stratigraphic framework of the basin divided into five depositional sequences, bounded by regional unconformities: Ordovician (Benjamin Constant Formation), Upper-Devonian Lower Silurian (Jutaí Formation), Lower-Carboniferous Devonian (Marimari Group), Upper-Permian Carboniferous (Group Tefé), and Upper-Cenozoic Cretaceous (Javari Group, with the Alter do Chão and Solimões Formations), individualized by unconformities (Eiras et al., 1994, Wanderley Filho et al., 2007). In the Jandaiatuba sub-basin, the focus of the study area, the substrate is composed of Proterozoic sedimentary rocks of the Purus Group (Prosperança, Acarai, and Prainha formations) and Precambrian (igneous and metamorphic rocks), on which the basin implanted.

The seismic analysis and the last generation three-dimensional visualization, following the methodology of Lynch (2020), allowed to establish the stratigraphic framework of the studied section, Where 6 main surfaces were defined. These surfaces allowed to delimit the crystalline basement and the Proterozoic, Paleozoic, Cretaceous, Miocene-Pliocene, Pliocene-Pleistocene, and Holocene sedimentary units.

Study Area

The Solimões Basin has aproximately 450,000 km² and is located in the Amazonian Craton, belonging to the Phanerozoic Province (Eiras et al. 1994, Wanderley Filho et al. 2007, Serra 2010). It is bounded to the west by the Arco Iquitos and the east by the Arco Purus, separating it from the Acre and Amazon basins. The Guianas bound it and Brazilian Escudos to the north and south, respectively, subdivided into the Juruá and Jandiatuba sub-basins, separated by the Carauari Arch (Galvão et al., 2012).

The seismic survey were acquired at the Solimões-Amazonas river system, at TFBCP, by the Rios-91 project (Heredia, 1992; De Souza, 2018) (Table 1), in Colombian territory, carried out by Fronteras de Exploración Colombiana, its extension is approximately 32 km in the general NW-SE direction, where the water column of the Solimões-Amazonas river system has an average depth of 30 m.

Table 1. Acquisition fiel parameter Crooked line (Amazonas survey).

ACQUISITION PARAMETERS

Equipment	***DFS-V***
Source	80cc-2000psi
Channels	48
Shot Interval	25 m
Fold	1800,00 %
Sample Rate	2 ms
Record Length	4 seconds
Offset (Near)	75 m
Offset (Far)	975 m

Moreover, located NW of the Tabatinga City (Brazil) (Fig. 1) are the wells IAS-105-AM (Maia et al. 1977), from the Carvão no Alto Solimões Project, carried out by the Geological Survey of Brazil (CPRM) in 1977 and 2BTST-1-AM (PETROBRAS). These wells had their logs (Gamma-ray, Spontaneous Potential, and Resistivity) used in the seismic to well tie process.

The surface data shows that in the Solimões Basin western portion emerges sediments and rocks from the Solimões Formation (E2N2s), Quaternary Alluvial (Q2a) and Fluvial Terraces (Q1t) units were defined. (Projeto Radam Brasil, 1997; INGEMMET, 1999 and SGC, 2017; Galvis y Gomez, 1988; IGAC, 1999; Jaramillo et al., 2013; Vargas, 2017).

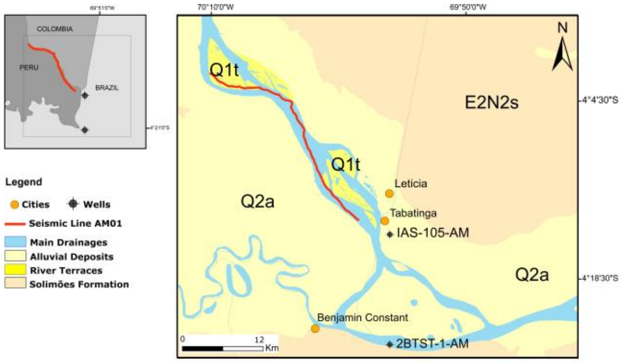

Figure 1. Geological context with the location of the study area, the crooked seismic line (red line) location and the drill holes, in a stretch of the Solimões-Amazonas river system.

Method

Crooked seismic lines differ in the acquisition, processing, interpretation, and modeling (Li, 2004). The field parameters during the seismic survey (Heredia, 1992; De Souza, 2018) correspond to a mixture of terrestrial and marine seismic acquisition (Table 1**).** The analysis of crooked seismic sections requires unconventional processing. The points of reflection in-depth do not fall perpendicularly; thus, could be implemented BIN techniques processing of the projection of the crooked line (Fig. 2A) (Urosevic and Juhlin, 2007; Nedimović and Westz, 2003). The data used in this study correspond to a seismic image with post-stacking migration, the result of processing along with several segments (Fig. 2B) from a point cloud integrated as a crooked.

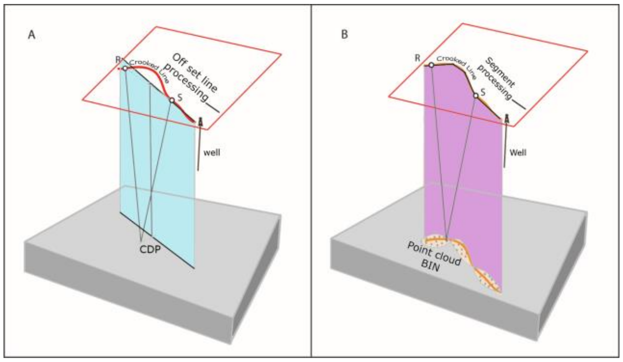

Figure 2. Crooked line and fundamentals of the processing steps according to (A) CDP concept, and a (B) case for the data used, based on point clouds in the BIN.

The upper level corresponds to the water column of the Solimões-Amazonas fluvial system, generating surface waves as a result of the mud roll (Ahmed et al., 2020) related to water columns in marine acquisitions with significant offsets, such as OBC (Ishiyama, 2007). The dispersion properties change from one shot to another in the same area. The datum depends on the type of rock, weathered or low-velocity layers, the thickness of the water column, length, suspended sediment, water density, and chemical properties. In the case of rock packages, it is necessary to find the key surfaces to define the sedimentary sequences established in the section.

Table 2. Well position and velocities, acquired from a well data west of the Solimões Basin. Comparison of values with regional studies De Souza (2018) and Costa (2003).

(Costa, 2003)		(De Souza, 2018)		(This Work, 2021)	
Unity	Velocity (m/s)	Unity	Velocity (m/s)	Unity	Velocity (m/s)
				Datum	0
				Water Column	1350
				Fm Içá (Neogene)	1800
Miocene-Pliocene	1850	N- Q	1800	Fm Solimões	2200
					3100
Cretaceous	2250	K	2200	Cretaceous	3500
		Diabase	6000		5600
Paleozoic	5750	Paleozoic	4000	Paleozoic	4600

The velocities function obtained for the triple Amazonian border allowed a good approximation of the actual rock velocities (Interval Velocities) and can be obtained using classic approximations (Dix, 1955):

$$V_{Interv}^2 = \frac{V_{i+1}^2 * t_{i+1} - V_i^2 * t_i}{t_i - t_{i+1}}, \qquad (1)$$

where (V_i, V_{i+1}) and (t_i, t_{i+1}) are the velocities and times for the upper and lower layers, respectively. In addition, to using the Dix equation, another approach to find the thickness of the layers is to establish the relationship between the time values and the depths of the tops of the different units:

$$\text{Thickness} = \frac{V_{interv} * 2 * (Z_i - Z_{i+1})}{t_i - t_{i+1}} \qquad (2)$$

Thus, according to the processing data and considering the expressions (1) and (2), it is possible to obtain the interval velocities of the geological units of the area, whose function helps in the analysis of the seismic data to be compared with other geophysical studies (Table 2).

For the analysis and lithostratigraphic correlation of the most superior units of the seismic section, the lithological and geophysical profile (R-resistivity, GR-gamma ray and SP-spontaneous potential) of the IAS-105-AM drill hole (Fig. 3A) were tied to the crooked seismic line, which, although it has a reduced depth for this type of analysis, around 337m, allowed to define limits and thicknesses of the sedimentary units.

The well log (NEUT-neutron, GR-gamma rays, and SP-spontaneous potential) from the 2BTST-1-AM (Fig. 3B) and seismic data permit the definition of the sedimentary units marked by the reflectors seen at the bottom of the seismic line and its thicknesses. Unlike the previous one, this well reaches a depth of 1482.3m, which made it possible to correlate reflectors that mark the transition between the sedimentary units and the igneous-metamorphic basement.

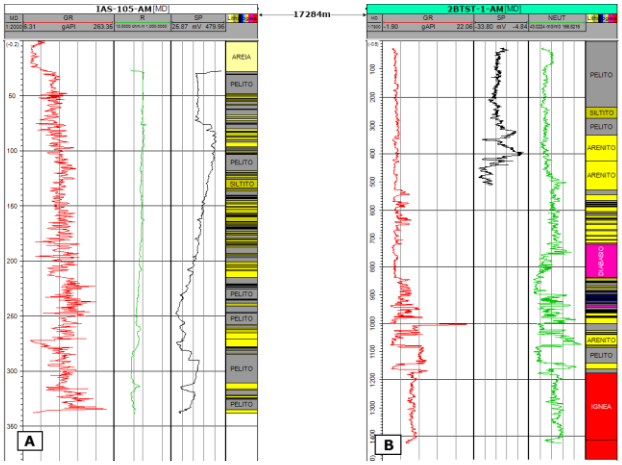

Figure 3. Well logs and interpreted lithological profile from the IAS-105-AM well (A) and 2BTST-1-AM (B) from the western edge of the Solimões Basin (location of the holes in Fig. 1).

The described process includes horizon tracing, which is used to surface generation (fig. 4) that make up the model structure and represent the interpreted sedimentary units. The edges of the model based on a conversion from a polygon to a boundary. From there, create a simple model, where its structure support by grids that form a skeleton; layers fill this skeleton which is nothing more than representing the inner layers (reflectors) of each sedimentary unit interpreted (Fig. 5). Finally, the tectonostratigraphic model results from petrophysical and lithological populations.

Results

The seismic to well tie allowed the elaboration of the stratigraphic context of the BPCTP region. The analyzed section presents a sinuosity, this must be considered. For this reason, it was necessary to visualize the crooked section three-dimensionally in space. From that it was possible to establish a more precise setup that outlines and maps the key surfaces (Datum, Formation tops, unconformities, sequence limits, erosive and flooding surfaces). The stratigraphic sequences allow building the model with the seismic surfaces, a preliminary framework of the spatial arrangement in the subsurface of the geological layers for BPCTP was achieved. With a thickness of approximately 110 meters, the proterozoic unit associate with Purus Group deposits, delimited at the base and the top by the surfaces of discontinuities S1 and S2 (Fig. 4).

The geometric pattern of the reflector referring to the S1 surface, together with its contrast observed in the seismic, allow us to relate this interface to the contact between the Purus Group sedimentary package and the crystalline basement, identified in the 2BTST-1-AM well at a depth of 1177.2 meters. This group constituted by the Prosperança, Acarai, and Prainha formations, has a more expressive occurrence in the W-SW portion of the Solimões Basin, being delimited at the top (surface S2) by an expressive temporal gap with the overlying Paleozoic units, as emphasized by Wanderley Filho et al. (2007). The velocities (Table 2) of the layers above indicate the contact between the Proterozoic-Paleozoic units visualized in 2BTST-1-AM well at a depth of 999,75 meters.

The Paleozoic unit has a thickness of approximately 168 meters, representing the formations Benjamin Constant and Jutaí and Groups Marimari and Tefé. The section presents a slight thinning towards NW, delimited at the base and the top by S2 and S3, respectively. The thinning of this unit is probably related to Orogenia Juruá, which raised the high transpression by more than 1.5km (Caputo, 1988), is responsible for erosion and deformation in this sequence. The S3 surface, at the top of the Paleozoic unit, reflects high contrasts associated with the diabase sills and dykes of the Magmatismo Penatecaua (Triassic), which can be observed at a depth of 719.29 meters in the 2BTST-1-AM well.

The cretaceous unit is about 250 meters thick and is associated with the Alter do Chão Formation, delimited at the base and the top by the surfaces S3 and S4, respectively. The S4 represents a reflector with high contrast, corresponding to a regional surface in the Solimões Basin, and defines a gap of approximately 200 Ma (Wanderley Filho et al., 2007) correlated to the lateritic paleosoil SD1 from the Amazon Basin (Soares, 2007; Abinader, 2008) and the Nonconformity 1 of the Bragantina and Pará regions (Rossetti, 2001). The S4, identified at the base of the IAS-105-AM well (Maia et al., 1977), is defined by the decrease of data of Gamma Rays and Spontaneous Potential with the superimposed unit. The Miocene-Pliocene unit is approximately 240 meters thick. It corresponds to the deposits of the Solimões Formation, being delimited at the base and the top by the surfaces S4 and S5, respectively, both showing reflectors with good contrasts. The layers above and below the S4 surface show velocities (Table 2), indicating contact between different sedimentary units. The S5 surface were identified previously in the borehole IAS-105-AM into the upper portion of the Solimões Formation (Maia et al., 1977). Subsequently, the upper limit of the Solimões Formation, carry on with palynology from outcrops (Nogueira et al., 2013) and boreholes (Maia and Marmos, 2010) in the Solimões Basin can be correlate to the lateritic paleosol SD3 defined in Amazonas Basin (Soares, 2007; Abinader, 2008) and Nonconformity 3 in the Bragantina and Pará regions (Rossetti, 2001).

The Pliocene-Pleistocene unit is about 77 meters thick, corresponding to the predominantly sandy deposits of the Içá Formation (Maia et al., 1977), limited at the base and the top by the surfaces S5 and S6, respectively, which represent well-contrasted reflectors. The layers above and below the S5 show velocities (Table 2) that indicate contact between different sedimentary units. This unit is discreetly covered with Holocene deposits, about 20 meters thick, delimited by the S6 and S7 surfaces, the last one referring to the land surface.

Thus, after defining the sedimentary unit of the study area, it was possible to compose the model's skeleton through the generation of surfaces and grids that support its structure (Fig. 4). These surfaces and grids delimited by the polygon which was converted to a boundary and came to compose the model's edges (Fig. 5). The composition of the sedimentary unit made it possible to layer the gaps between horizons. The stratigraphy framework allowed visualization of each sedimentary package, then finalize the tectonostratigraphic model (Fig. 5).

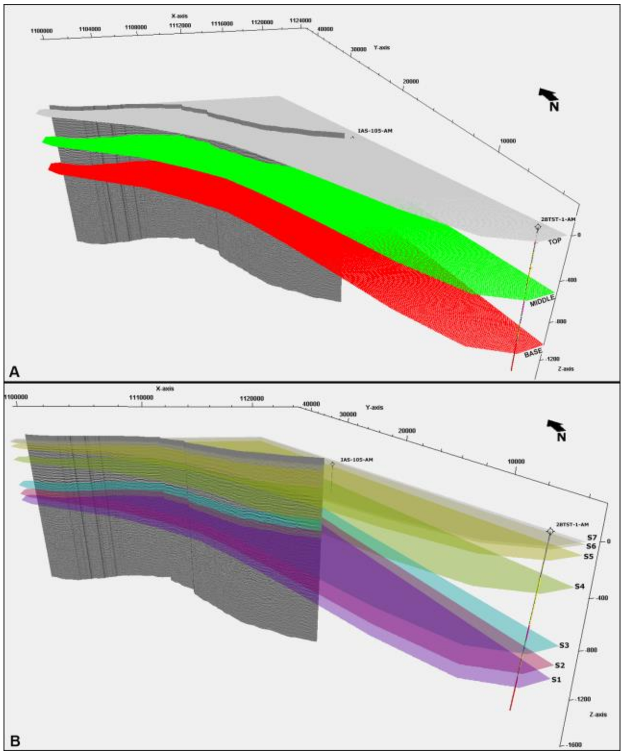

Figure 4. Grids (A) and Surfaces S1 to S7(B).

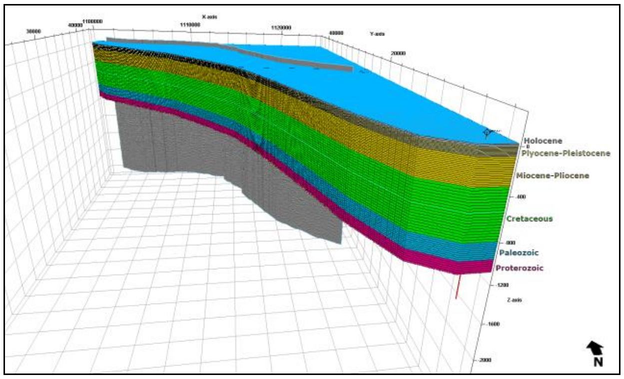

Figure 5. Tectonic-stratigraphic model, composed of horizons, surfaces, grids, edge and inner layers.

Conclusions

This study shows the integration of seismic survey of crooked lines with lithological and geophysical data. The application allowed the definition of the stratigraphic framework of the Solimões Basin portion. Above the crystalline basement, 6 sedimentary units were defined, limited by discontinuities of a regional character, which individualized from the bottom to the top: Proterozoic (Prosperança, Acarai, and Prainha Formations), Paleozoic (Benjamin Constant and Jutaí Formations and Marimari and Tefé Groups), Cretaceous (Alter do Chão Formation), Miocene-Pliocene (Solimões Formation), Pliocene-Pleistocene (Içá Formation) and Holocene Deposits. In general, the interval velocities obtained through seismic processing allowed defining velocity models for the analyzed units, which range from layers with low velocity referring to Holocene sediments with water to more compact and competent units of the Proterozoic-Pleistocene units. The crystalline basement has a chaotic pattern, characteristic of igneous and metamorphic rocks, while the sedimentary units have parallel reflectors indicative of lodging and limiting surfaces.

The use of computational tools integrated with geological-geophysical analyzes helped to feed the group of stratigraphic data and build a 3D model of the western portion of the Solimões Basin. The delimitation between sequences in the BPCTP region base on geophysical features. These features show anomalous contrasts associated with large amplitudes and multiple and high velocities, for example, the identification of reflections associated with the presence of diabase sills from Penatecaua (Triassic) magmatism in the sedimentary section, which marks the S3 surface at the top of the Paleozoic.

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