Basin Modeling Uncertainties Related to the Hybrid Devonian Petroleum System (Conventional Plus Atypical) of the Solimões Basin (Brazil)*

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Abstract

The Solimões Basin is a Paleozoic intracratonic basin comprising up to 4,300 m of sediments covering 440,000 km^2 within the Amazon rain forest in northern Brazil. The stratigraphic framework comprises five depositional sequences limited by regional unconformities: Ordovician, Upper Silurian-Lower Devonian, Middle Devonian-Lower Carboniferous, Upper Carboniferous-Permian and Upper Cretaceous-Tertiary (Wanderley et al., 2007).

Sills and dykes were intruded stratigraphically above the Devonian source rocks during the Penatecaua magmatic event in the Triassic, around 201Ma (Wanderley et al., 2007). In the modeled area, three sets of diabase sills were seismically discriminated. The lower set of sills (up to 168 m thick) was intruded around 500 m above the source rock. The middle and upper sets (up to 500 m and 449 m thick, respectively) were intruded about 1,560 m and 1,140 m above the source rocks. The dating methods do not have enough accuracy to support different ages of emplacement for the different sets of sills, despite the several surveys undertaken. Regardless of this uncertainty, according to the different modeled scenarios, the Solimões Basin can be characterized as a hybrid petroleum system, with up to 40% of the source-rock transformation ratio due to overburden and the remaining 60% related to the high heat flow during the magmatic event of sill insertion (conventional plus atypical petroleum system; Magoon and Dow, 1994).

The reservoir-source rock contact within the Juruá Formation is direct, with the Carboniferous reservoir overlying the Devonian source rocks. An effective seal is provided by Upper-Carboniferous evaporites (Carauari Formation). The main trap was formed in the Permian, and later amplified during the Juruá tectonic event at 125 Ma. The petroleum system efficiency was proved by discoveries of 11 gas accumulations and three oil and gas fields encompassing reserves over 500 MM BOE, with oil API gravity ranging from 37 to 65º and gas-oil ratio (GOR) up to 9000 m^3/m^3.

Four Models

In this work the investigation was focused on the effect of the igneous intrusions on the thermal evolution of the Devonian source rocks. To test the uncertainty related to the emplacement age of various igneous bodies and their thermal effect on kerogen cracking, the PetroMod 3D software (IES-Schlumberger) was used. The investigation and modeled area covered three condensate and gas fields, which constitute the main petroleum province in the Solimões Basin. Usually, when a number of stacked sill sets occur, the upper set is the thickest and oldest (Linsser, 1973). In this case history, this would imply that the upper set of sills was emplaced before the others. At least in terms of sill thickness distribution, this pattern was observed in the Solimões Basin (Conceição et al., 1993). Following this approach, four different scenarios of diabase sills emplacement were simulated to test the coherence between modeled and observed source-rock maturity and the physicochemical properties of the generated oil and gas. The results of the calculated thermal history were used in the GOR-Isotopes software (GeoIsoChem Co.) to compare the carbon isotopic signatures of gases sampled in condensate fields, and the modeled theoretical curves based on fractionation models for stable carbon isotopes.

The first scenario was simulated assigning a simultaneous emplacement to all sets of sills. Due to the high thermal stress caused by the instantaneous intrusion, source rocks were submitted to very fast heating, reaching maximum temperatures from 290º C to 350º C after 70 Ka from the igneous insertion at the East and West petroleum kitchens close to the fields (Figure 1).

The second scenario was simulated considering only the emplacement of the upper set of the thickest sills. The thermal stress in the source rock calculated in the West and East kitchens attained the maximum temperatures of 190º C to 170º C some 80 Ka after the sills emplacement (Figure 1).

The third scenario was simulated considering only the emplacement of the middle set of sills. The maximum thermal stress in the source rocks occurred 50 Ka after igneous insertion, with maximum temperatures of 240º C to 220º C in the kitchens near the fields (Figure 1). These temperatures decreased to 100º C in 70 Ka.

In the fourth scenario, which consisted of the intrusion of only the basal thin sill bodies, the thermal stress was weaker, with temperatures up to 110º C after 50 Ka from the sills insertion (Figure 1).

Results

Using the thermal histories from the four modeled scenarios, the theoretical carbon isotopic signals for C_1-C_3 gases generated by a type II kerogen were calculated using the GOR-Isotopes software. The calculated carbon isotopic compositions of the gases, when compared to measured values from field samples, seem to be more coherent with scenario 2 (insertion of the upper set of sills). This interpretation is based on the better match between the theoretical curve of stable carbon isotopic fractionation of ethane and propane with the field isotope data (Figure 2). Additionally, all gases are showing a light isotopic signature that reinforces a moderate thermal stress when compared to that from scenario 3. Scenarios considering the thermal effect of the upper sills being added up to heat derived from the sequential emplacement of the middle sills 20 ka, 50 ka, 70 ka, 100 ka and 150 ka after the upper sills are quite similar to scenario 1 that provides temperatures which are incompatible with the observed isotopic signal of the gases ($\delta^{13}C1$ from -36.6‰ to -42.5‰) and GOR (< 1000 up to 9000 m^3/m^3).

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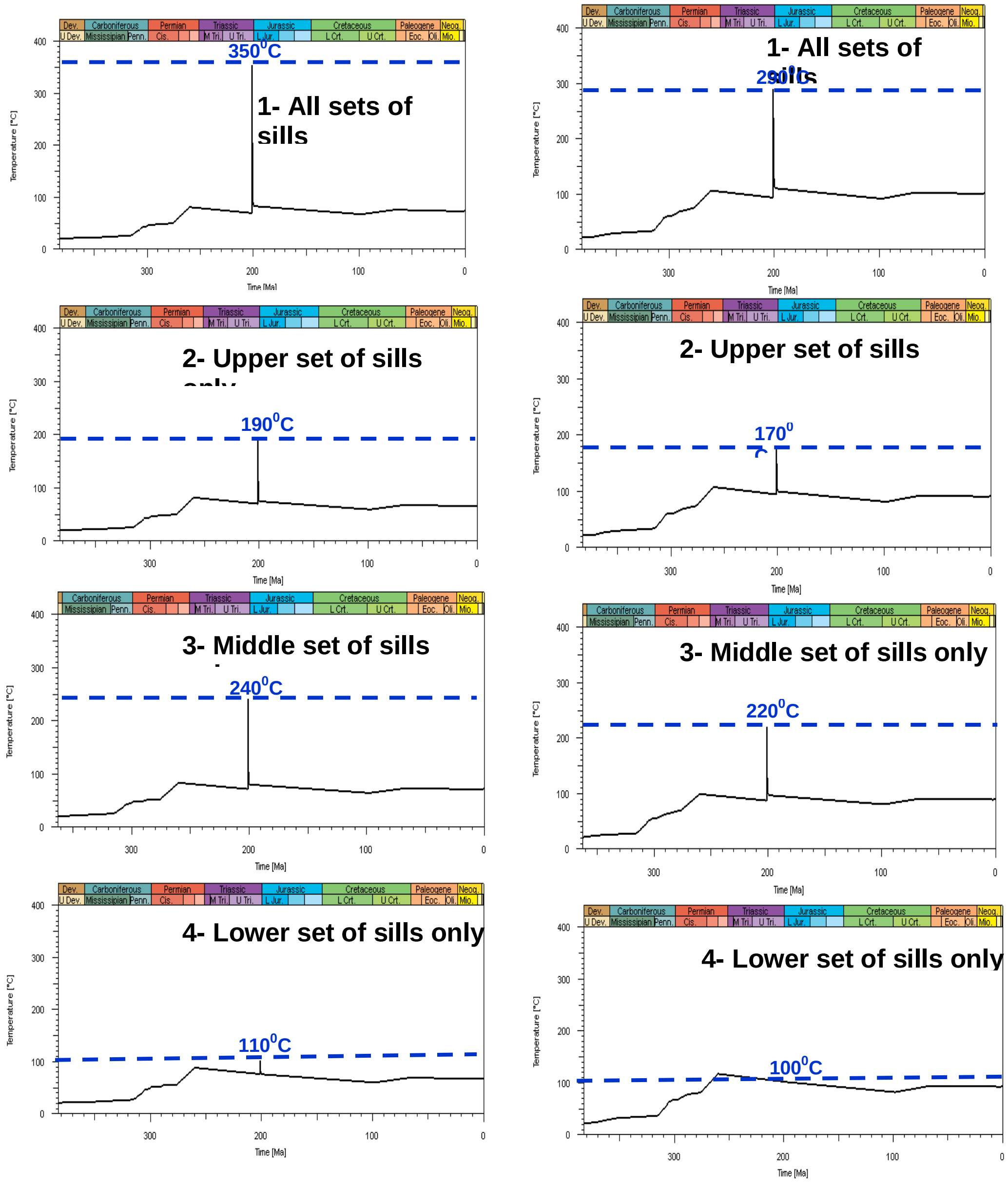

Figure 1. Thermal history extracted from the same point of the East (left column) and West (right column) petroleum kitchens for scenarios 1, 2, 3 and 4.

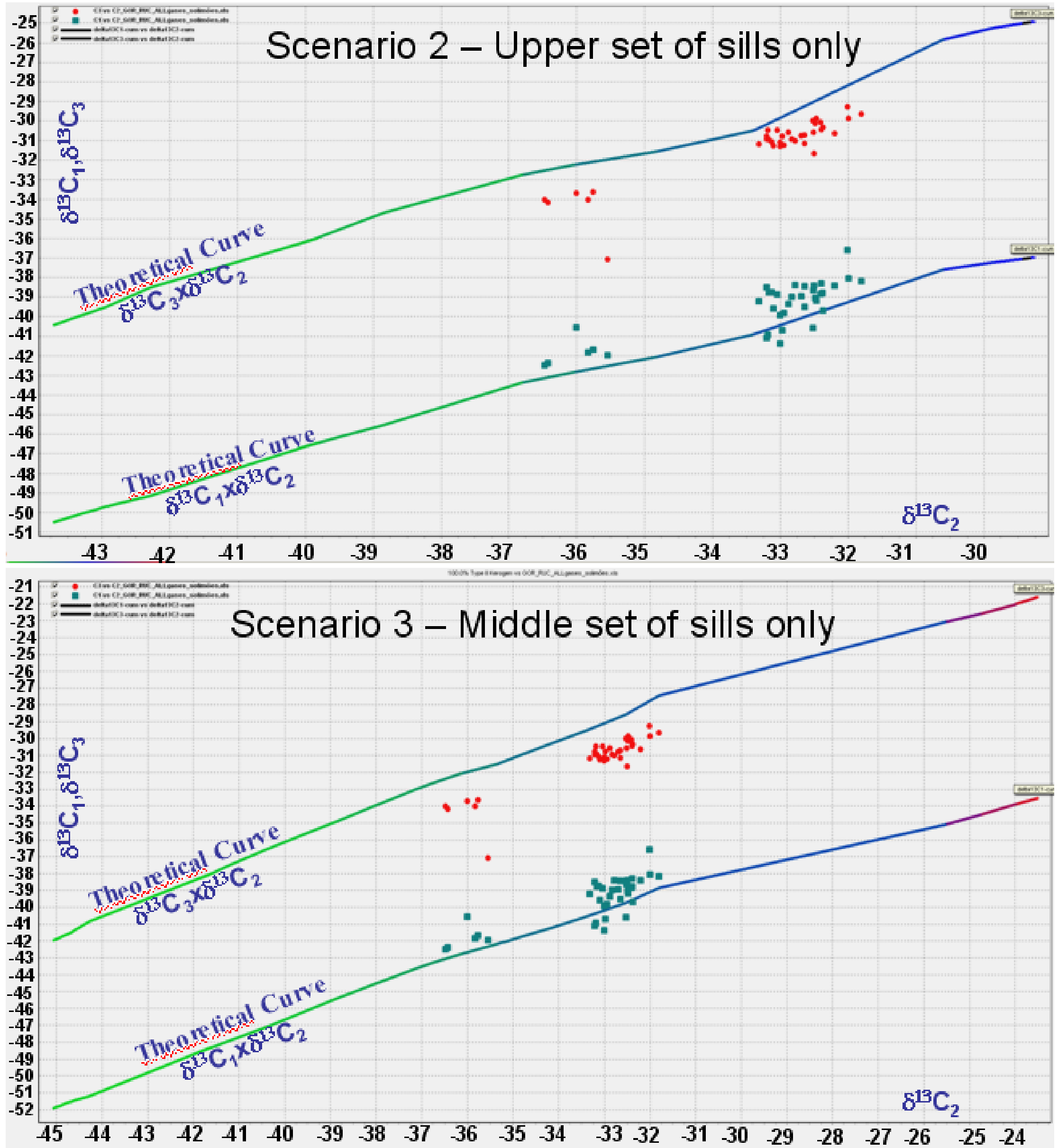

Figure 2. Graph of cumulative carbon isotopic values of methane ($\delta^{13}C_1$) and propane ($\delta^{13}C_3$) as a function of ethane ($\delta^{13}C_2$ in ‰). The modeled trends are shown in the continuous lines and the measured sample data as dots.