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RESEARCH PAPER

OIL GENERATION POTENTIAL ASSESSMENT AND PALEOENVIRONMENTAL INTERPRETATION OF IRATI FORMATION (LOWER PERMIAN) IN NORTHWESTERN OF PARANÁ BASIN (BRAZIL)

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Abstract

Total organic carbon (TOC), total sulfur (S) and Rock-Eval pyrolysis analyzes were performed in 41 samples collected along the SP-60-PR core, from the Irati Formation, northwestern of Paraná Basin.

This work aims to show how organic matter content evolved vertically in the Irati Formation and therefore to contribute to the identification of the most attractive levels to generate hydrocarbons, in thermally immature sediments.

The results of these analyses allowed to recognize sharp changes in the types of organic matter and paleoenvironmental conditions, giving rise to eight chemical-stratigraphic units, labeled as A, B and C (Taquaral Member) and D, E, F, G and H (Assistência Member). The units A and C display low organic carbon content and predominance of organic matter type IV, which indicate an oxic environment. The unit B, with higher TOC content, has organic matter predominantly of type II and should be associated to a disoxic environment.

The Assistência Member, mainly with organic matter type II, is differentiated from the previous units by their sharply higher TOC content and hydrogen index values, suggesting a more restricted environment, characterized by disoxic to anoxic conditions.

The bituminous shale of the units E and H have the highest TOC, sulfur and hydrogen index values, representing the units where conditions of the autochthonous organic matter (type II) preservation was more efficient (anoxic environment).

Despite being found organic matter thermally immature in the Assistência Member, the layer with the highest generation potential is the unity H.

The comparison with data of other studied wells evidenced a strong reduction in the potential generator of the Irati Formation toward the north of Paraná Basin.

Keywords: Total organic carbon. Rock-Eval pyrolysis. Chemostratigraphy. Oil generation potential. Depositional environment. Lower Permian.

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1. Introduction

In Brazilian Paleozoic basins, the most important Permian strata for hydrocarbons generation were detected in bearing rich in hydrogen sedimentary layers, with high concentrations of marine organic matter. This is specially observed in the Assistência Member (e.g. Alferes et al., 2011), of the Irati Formation (with an Artinskian/Kungurian age), belonging to Paraná Basin (Rocha-Campos et al., 2011; Fig. 1). This section is thermally immature in most of the Paraná Basin (e.g. Milani and Zalán, 1999; Milani et al., 2007).

In some areas of the Irati Formation, there was high heat flow caused by the presence of Cretaceous igneous intrusions, which generated a hale of heat close to these intrusions. The heat of these intrusions influenced the maturation of organic matter, in non-conventional generator horizons (e.g. Cerqueira and Santos, 1986; Araújo et al., 2000; Santos et al., 2003; Corrêa and Pereira, 2005; Loutfi et al., 2010). It is also considered non-conventional, the industrial generation of hydrocarbons from bituminous shale (e.g. Speight, 2012). In Brazil, the exploration of these non-conventional resources is restricted to that undertaken by the "Unidade de Industrialização do Xisto" (Industrialization Unit of Schist; Petrobras-SIX), in the southern portion of the Paraná Basin. There is no database yet, enough to support a real assessment of the exploratory possibilities of these resources across the Paraná Basin, both considering the generation due to the thermal effect of the igneous intrusions or the industrial heating.

In the case of bituminous shale, to be possible to produce industrially oil and gas, some requirements are essential such as: high concentration of organic matter (>10% TOC), organic matter rich in hydrogen and; thermal immaturity of organic matter (e.g. Speight, 2012). The assessment of these requirements is only possible if detailed geochemical studies of organic matter along cores collected in Paraná Basin, including the recording of the Irati Formation.

The main objectives of this work are to: 1) Evaluate the potential for oil and gas generation in bituminous shale of the Itari Formation, from Paraná Basin, based on geochemical data; 2) Improve the knowledge of the behavior of organic matter preserved in the bituminous shale of the Irati Formation, in the Paraná Basin (Fig. 1).

2. Regional Geological Context

The study area is located in the eastern edge of the intracratonic Paraná Basin, north of the Sapopema city, in Paraná State (PR) (Fig. 1). The Paraná Basin, located in the central-eastern portion of South America (Fig. 1), is an intracratonic type basin, an extensive depositional area, with Paleozoic to Mesozoic age (Zalán et al., 1990). It was developed on Proterozoic cratonic framework blocks surrounded by belts of folding and shoving, predominantly with SW-NE direction (Zalán et al., 1990).

Paraná Basin occupies approximately 1,500,000 km², of which 1,100,000 km² are located in Brazil (Milani et al., 2007). It contains a stratigraphic record from the Ordovician to the Upper Cretaceous, with a maximum cumulative thickness of 7000 m on your depocenter (Milani et al., 2007).

Milani et al. (1998, 2007) subdivided the stratigraphic units of the Paraná Basin in six second order sequences or supersequences. The Irati Formation is included in Gondwana I Supersequence (Westphalian-Scythian), at the beginning of the regressive third order cycle (Fig. 2). It is subdivided into the Taquaral and Assistência members (Fig. 3). The lower member, Taquaral, is essentially siliciclastic, deposited in an open marine environment, and the upper member, Assistência, is characterized by carbonates interbedded with bituminous shale, deposited in a restricted marine environment (Northfleet et al., 1969; Hachiro and Coimbra, 1991; Santos Neto and Cerqueira, 1993; Rodrigues et al., 2010a, 2010b; Alferes et al., 2011; Gama and Rodrigues, 2011; Reis and Rodrigues, 2014).

2. Materials and Methods

This work is based on the study of 41 samples from the Irati Formation, collected with spacing of 50 cm along the core of the SP-60-PR well (referred in this work as SP-60-PR core). This core was drilled by the Companhia de Pesquisa de Recursos Minerais (Mineral Resources Research Company; CPRM) in 1983 (CPRM, 1986) at latitude 23°45'25.72"S and longitude 50°35'21.52"W, near Sapopema city, in the municipality of Congonhinhas (PR), State of Paraná. It was selected for its location and lack of diabase intrusions on their lithological record.

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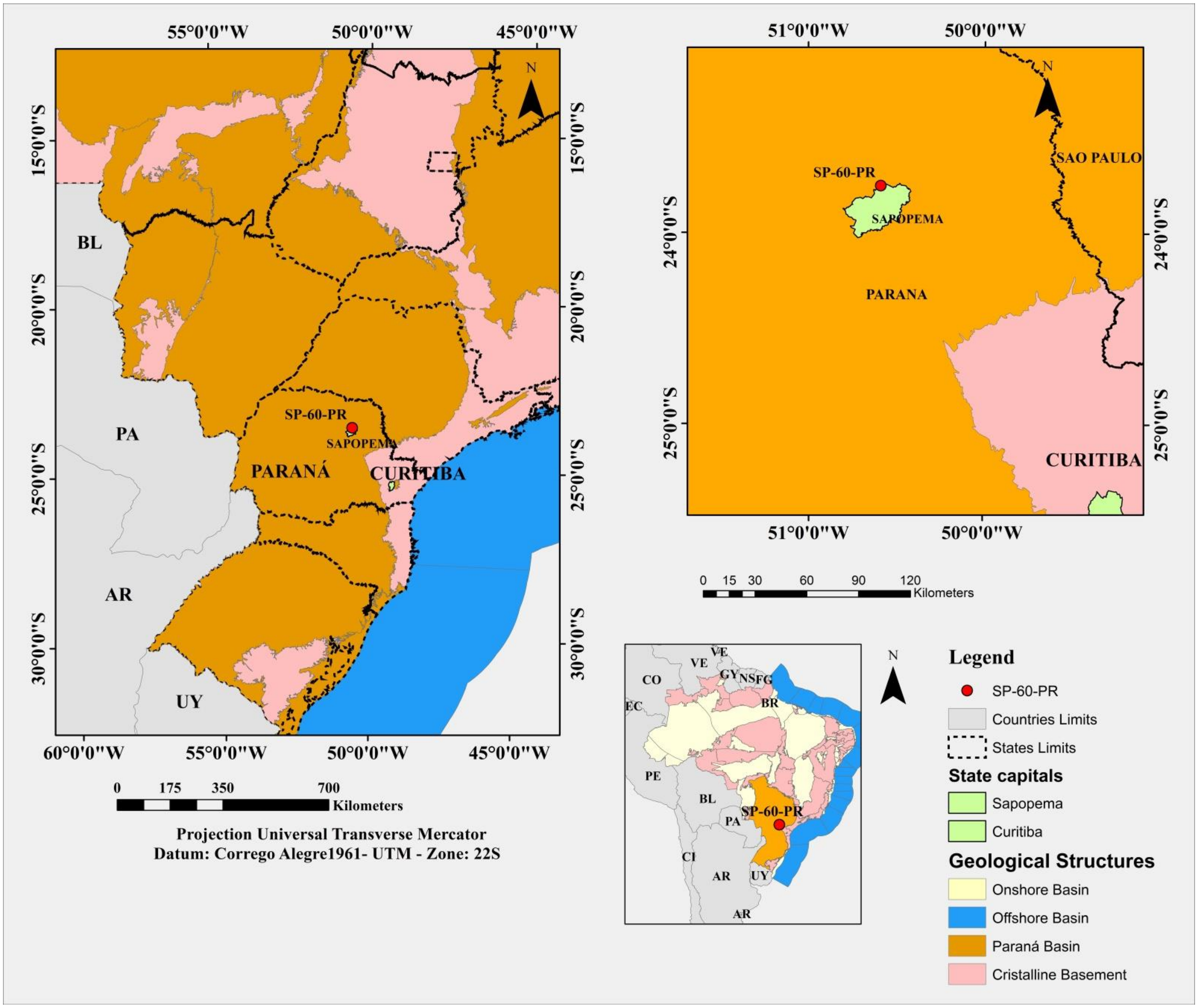

Fig. 1. Location map of the SP-60-PR core collected in: A. SW of Brazil; B. in the northwestern portion of the Paraná Basin; C. Sapopema city, at Northwest of Curitiba (the capital city of Paraná State). Paraná Basin borders with Paraguai, Argentina and Uruguai countries. The offshore and onshore basins and the crystalline basement as well as a metric scale, are indicated in this figure.

The selected samples were collected in layers between 498.7 m and 455.6 m in the SP-60-PR core. The studied section is attributed to the Irati Formation of the Paraná Basin. It was selected by its lithology, as well as Gama Ray and resistivity data which were acquired and analyzed by CPRM (1986).

In this work, the samples collected along the SP-60-PR core were submitted to geochemical analysis of total organic carbon (TOC), sulfur (S), insoluble residue (IR) and Rock-Eval pyrolysis. Results were analyzed to assess the potential for oil and gas generation in bituminous shale of the Irati formation in the study area.

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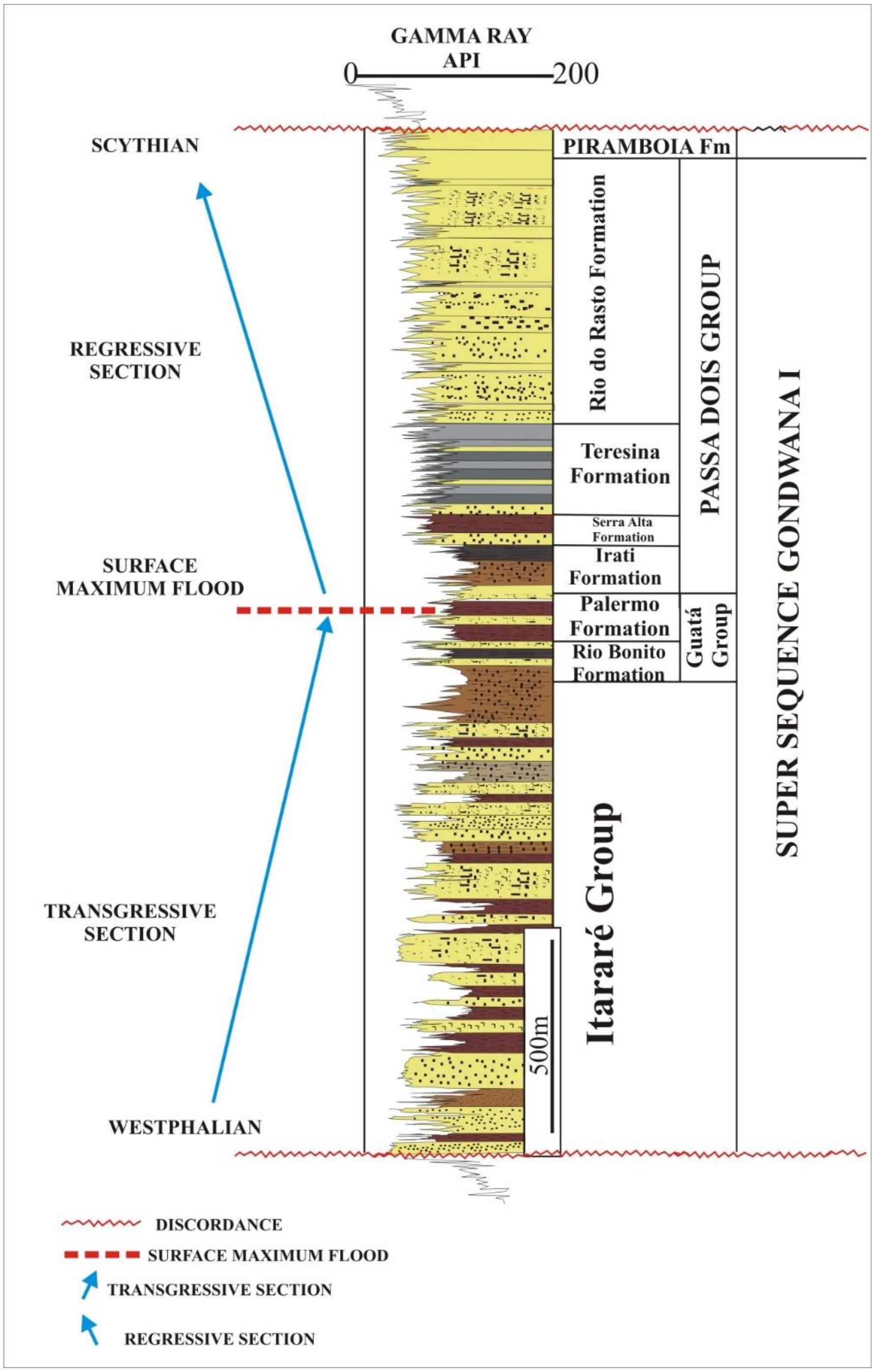

Fig. 2. The stratigraphic lithological pattern of the Supersequence Gondwana I, based on the Gama Ray profile, for the Paraná Basin. This profile is scaled in American Petroleum Institute (API) units. In this figure are signed the Itararé Group, Guatá Group and Passa Dois Group, which make part of the Irati Formation. The top limit of the Passa Dois Group is the Piramboia Formation. In the Supersequence Gondwana I, between the Westphalian and Scythian, there are two discordances and a surface of maximum flood, which are related to a transgressive section and a regressive section. A metric scale is also represented in this figure. Modified of Milani et al. (1998).

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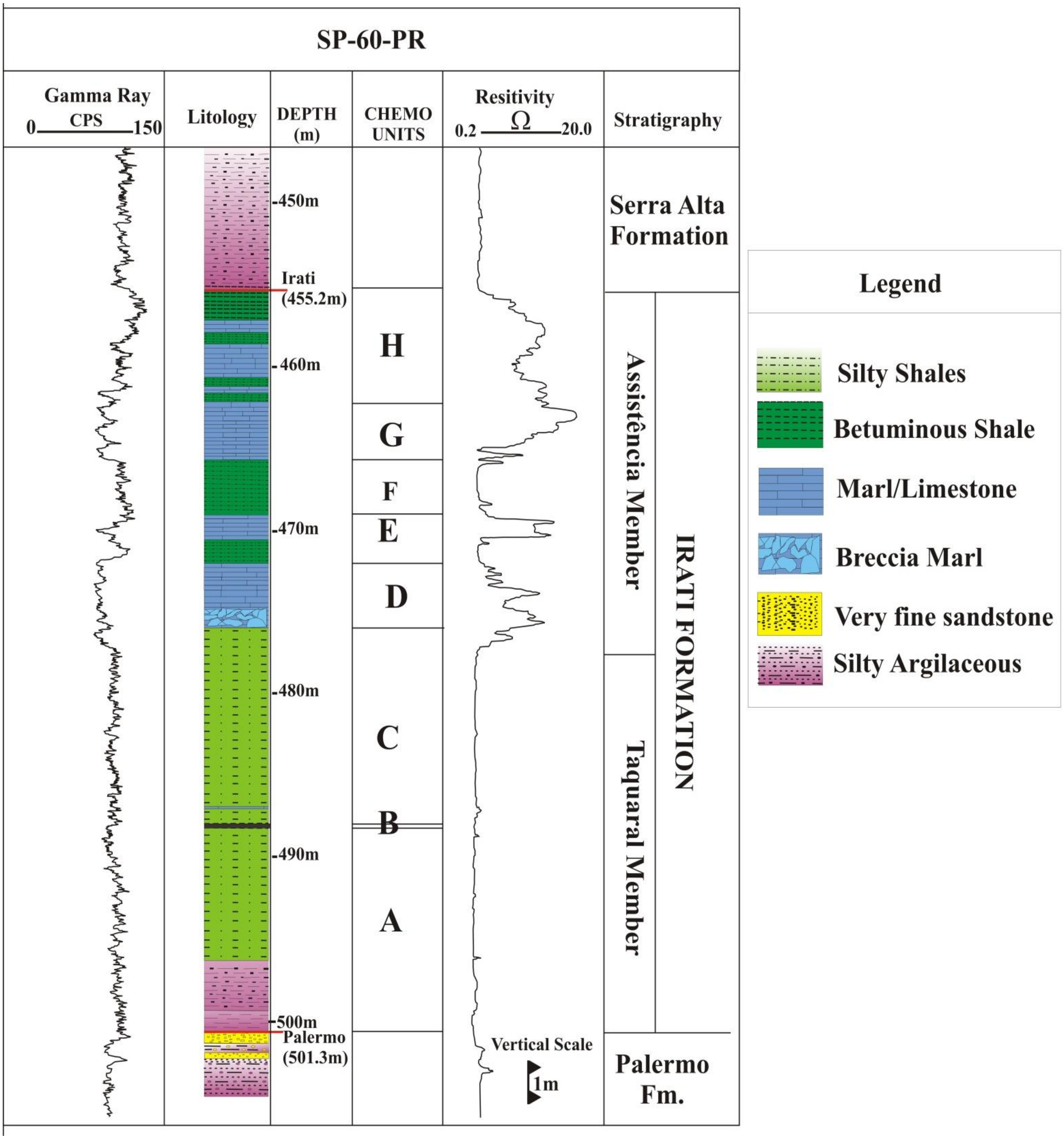

Fig. 3. Stratigraphic profile and the lithology of the Irati Formation in SP-60-PR core with Gama Ray counts per second (cps) units and resistivity (Ω) profiles. The layers recording (from the base to the tope) of Palermo Formation, Irati Formation, including the Taquaral Member and Assistência Member, and Serra Alta Formation are signed in this figure. Metric and granulometric scales are displayed as well as a legend for the lithology. The eight chemostratigraphic units identified in this work are represented. Modified of CPRM (1986).

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Geochemical analyzes were performed at the Laboratório de Estratigrafia Química e Geoquímica Orgânica (Chemostratigraphy and Organic Geochemistry Laboratory), of the Universidade do Estado do Rio de Janeiro (LGQM/DEPA/FGEL/UERJ). The procedures used are described in the following sub-items.

3.1. Total organic carbon (TOC), sulfur (S) and insoluble residue (IR)

After the elimination of carbonates with 50% hydrochloric acid, the samples were analyzed with the Leco SC-632 equipment. The TOC, S and IR values were plotted against the depth of the sample, which allowed to make a semiquantitative assessment of the concentration of organic matter in the analyzed sedimentary layers, using the scale of Peters and Cassa (1994) (Tab. 1). The samples with TOC content ≥0.4% were analyzed by Rock-Eval pyrolysis.

Tab. 1. Semi-quantitative scales of: TOC, according to Peters and Cassa (1994) and; Hydrocarbon Generation Potential (S2), Hydrogen Index (HI) and Thermal Maturation of the organic matter (Tmax °C) according to Espitalié et al. (1985).

Total Organic Carbon TOC (%)	
<0.5	Poor
0.5 – 1.0	Moderate
1.0 – 2.0	Good
2.0 – 4.0	Very Good
>4.0	Excellent
Hydrocarbon Generation Potential – S_2 (mg HC/g rock)	
<2.0	Low potential generator
2.0 – 5.0	Moderate potential generator
5.0 - 10	Good potential generator
>10	Excellent potential generator
Hydrogen Index – HI (mg HC/g TOC)	
IH < 200	Gas Potential
200 < IH < 300	Gas and Condensate Potential
IH > 300	Oil Potential
Maturation – Tmax °C	
<440	Immature
440 – 470	Mature
>470	Senile

3.2. Rock-Eval pyrolysis

Selected samples were analyzed with the Rock-Eval 6 equipment, of Vinci Technologies, for the determination of S1 values (in mg HC/g rock), S2 (in mg HC/g rock), S3 (in mg CO_2/g rock) and the temperature at which occurs the maximum peak height of S2 (Tmax; °C).

Considering TOC (%) concentrations, the hydrogen index was calculated [HI = (S2/TOC) x100 in mg HC/g TOC], as well as the oxygen index [OI = (S3/TOC) x100 in mg CO_2/g TOC], following the procedures of Espitalié et al. (1977).

With values of S2, HI and Tmax, semiquantative evaluations of the hydrocarbon generation potential, type and stage of thermal evolution of organic matter were carried out. The scales used for each case are shown in Tab. 1 (Espitalié et al., 1985).

4. Results

Stratigraphic profile and the lithology of the Irati Formation in SP-60-PR core is included in Fig. 3. The layers constituting the recording (from the base to the top) of Palermo Formation, Irati Formation, including the Taquaral Member and Assistência Member, and Serra Alta Formation are also signed in Fig. 3.

The studied section of SP-60-PR core is composed by a mixed sequence of siliciclastic and carbonate sediments (silty to clayey shale, bituminous shale, marls and limestone). Results of Gama Ray display a relatively monotonous variability in the section of the Taquaral Member which is composed mostly by siliciclastic silt and clayey shale. The highest variability of the values of this parameter are recorded in the Assistência Member, in which the highest values of Gama Ray overlap in general with the sharp rise of the resistivity related to the lithology mostly composed by marls and limestones.

The results obtained in the studied samples of the SP-60-PR core section 498.7 m - 455.6 m are presented in Tab. 2. These geochemical data regarding TOC, S, IR, S2 and HI enabled to recognize eight units with different geochemical characteristics informally named A, B, C, D, E, F, G and H from the bottom to the top of the Irati Formation (Fig. 3).

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Tab. 2. TOC, S, IR, S1, S2, HI, OI and Tmax data of samples of chemostratigraphic units set for the Irati Formation in the SP-60-PR well. * nc = not calculated.

Depth	TOC	S	IR	S1	S2	HI	OI	Tmax	GEOCHEMICAL	STRATIGRAPHIC
m	%	%	%	(mg/g)	(mg/g)	(mg/g)	(mg/g)	(°C)	UNIT	UNIT
455.60	12.4	0.88	92	nc	nc	nc	nc	nc	H	Assistência Member
456.50	7.12	3.35	91.27	2.51	42.56	597.00	11.52	424.00	H	Assistência Member
456.90	7.65	4.26	83.67	2.35	46.43	606.92	17.91	421.00	H	Assistência Member
457.30	9.33	3.50	80.00	2.95	58.42	626.15	14.26	423.00	H	Assistência Member
458.00	5.30	2.70	93.75	2.43	31.26	589.81	15.66	419.00	H	Assistência Member
458.50	9.47	4.20	74.80	3.24	59.02	623.23	12.88	422.00	H	Assistência Member
459.60	4.25	4.68	83.67	2.32	16.05	377.64	29.17	413.00	H	Assistência Member
458.80	5.90	2.77	78.43	3.32	34.65	587.28	16.94	420.00	H	Assistência Member
459.90	5.91	3.87	82.35	2.73	27.84	471.07	25.72	414.00	H	Assistência Member
460.30	6.36	2.89	72.00	3.11	35.07	551.41	20.12	418.00	H	Assistência Member
460.90	5.14	1.94	67.19	3.74	36.19	704.08	14.00	425.00	H	Assistência Member
461.30	5.26	0.65	31.87	6.78	35.93	683.07	19.01	420.00	G	Assistência Member
462.00	4.07	1.31	48.00	2.58	19.72	484.52	25.31	412.00	G	Assistência Member
462.90	3.16	0.84	31.75	2.26	18.89	597.78	22.78	420.00	G	Assistência Member
463.00	4.53	0.98	60.00	3.48	25.04	552.75	21.63	413.00	G	Assistência Member
464.00	2.82	0.64	39.53	3.31	10.31	365.60	28.01	411.00	G	Assistência Member
465.40	0.94	0.08	40.00	0.19	1.22	129.93	56.44	415.00	G	Assistência Member
467.00	0.55	0.44	88.00	0.02	0.12	21.90	65.69	424.00	F	Assistência Member
468.00	1.49	1.09	82.03	0.08	1.09	73.15	37.58	425.00	F	Assistência Member
468.90	3.69	2.03	75.70	0.08	1.09	73.15	37.58	425.00	E	Assistência Member
469.00	8.72	2.73	88.00	2.63	48.35	554.47	15.48	416.00	E	Assistência Member
469.40	1.06	0.42	59.76	0.29	2.22	209.43	48.11	422.00	E	Assistência Member
471.00	1.38	0.58	63.24	0.42	3.16	228.99	36.95	405.00	E	Assistência Member
471.10	3.71	0.41	75.10	1.37	11.78	317.52	21.56	409.00	E	Assistência Member
471.60	2.99	0.19	79.68	0.96	6.65	222.41	16.39	403.00	E	Assistência Member
471.65	1.62	0.21	79.68	0.38	4.08	251.85	22.22	408.00	E	Assistência Member
471.75	2.82	0.37	74.80	0.97	7.75	274.82	21.28	408.00	D	Assistência Member
472.80	2.93	0.34	35.29	4.90	16.27	555.29	32.38	415.00	D	Assistência Member
473.80	3.06	0.30	59.29	3.89	15.59	509.48	25.82	410.00	D	Assistência Member
474.80	2.27	0.56	36.00	2.85	10.92	481.05	31.28	413.00	D	Assistência Member
475.80	2.52	0.44	47.24	2.94	13.33	528.98	30.16	412.00	D	Assistência Member
476.10	1.03	1.31	40.00	0.60	3.40	330.09	44.66	408.00	C	Taquaral Member
477.10	0.57	0.59	82.03	0.04	0.33	57.89	73.68	427.00	C	Taquaral Member
479.10	0.41	0.42	91.63	0.05	0.25	60.82	143.55	428.00	C	Taquaral Member
482.10	0.75	0.46	88.00	0.03	0.86	115.43	55.03	438.00	C	Taquaral Member
485.15	0.64	0.60	75.70	0.01	0.29	45.17	62.31	426.00	C	Taquaral Member
486.15	0.95	0.46	86.96	0.10	2.82	295.90	26.23	436.00	B	Taquaral Member
487.15	0.71	0.74	84.00	0.03	0.65	91.29	66.01	429.00	A	Taquaral Member
492.30	0.45	0.19	87.30	0.02	0.11	24.44	53.33	428.00	A	Taquaral Member
496.10	0.56	0.25	86.96	0.01	0.13	23.17	17.83	424.00	A	Taquaral Member
498.70	0.42	0.04	92.00	0.05	0.06	14.39	71.94	429.00	A	Taquaral Member

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The refereed units were differenced by the values of TOC, IR, S2 and IH. The subdivision of the Irati Formation in eight chemostratigraphic units has already been performed at different wells by Rodrigues et al. (2010a, 2010b), Alferes et al. (2011), Gama and Rodrigues (2011) and Reis and Rodrigues (2014).

The high insoluble residue (IR) values in Taquaral Member spread in a thickness of approximately 21m, are linked with the nature essentially siliciclastic of this section. On the other hand, the Assistência Member, D, E, F, G and H units, are characterized by alternating intervals of high and low IR content (%) ranging from 35.3% and 93.8%.

These values are associated with limestone, interbedded by marl and shale. The contact between the Taquaral Member and the Assistência Member is marked at the base of the first layer of limestone (Figs. 3 and 4).

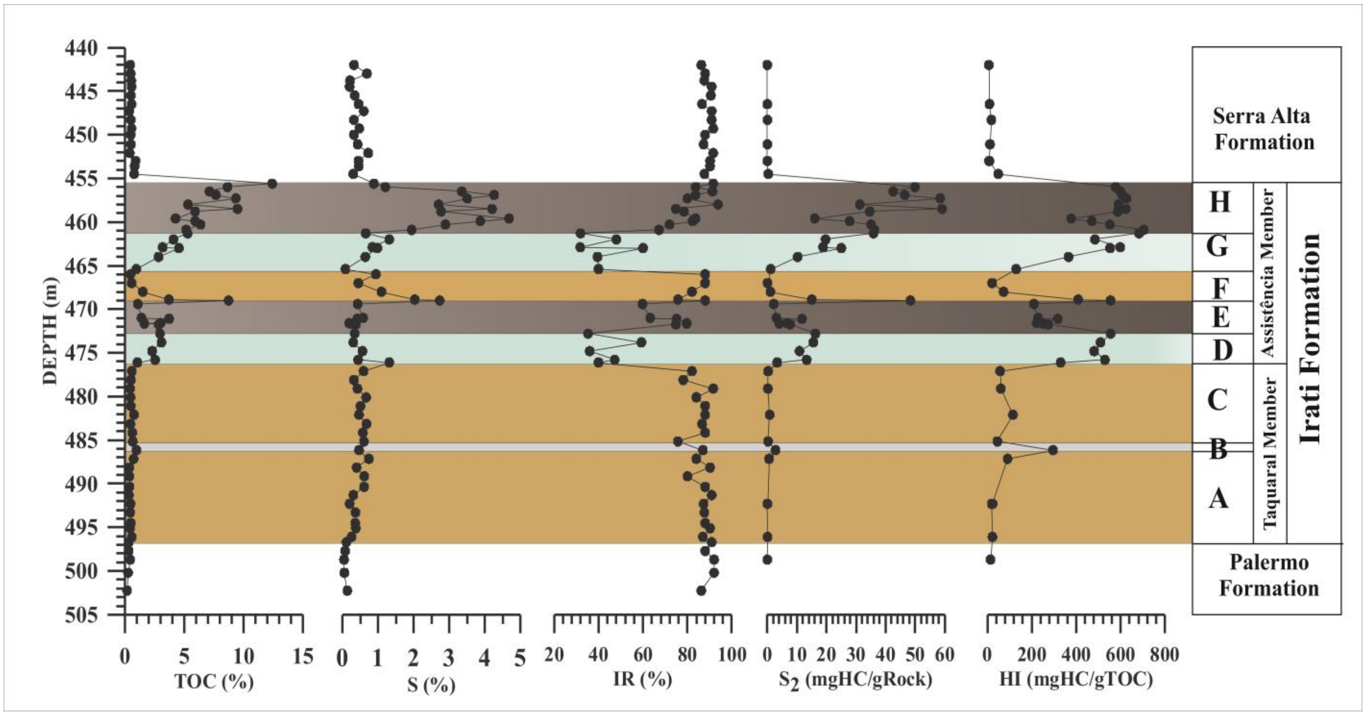

Fig. 4. Depth plots of TOC, S, IR, S2 and HI data. Based on these data the chemostratigraphic division of the Irati Formation in eight units (A-H) in the SP-60-PR core were performed.

The TOC values in Taquaral Member, A, B and C units, are below 1%, while in the Assistência Member, the unites D, E, F, G and H, exhibit alternation between high values (up to 12% mostly in the H unit and punctually in the E unit) and low values (up to 0.60%; Fig. 4).

The average sulfur values (S) of the two carbonate layers are about 0.6%. The E and F units displayed sulfur values of about 0.8%, but the H unit, exhibited a marked increase reaching 3% (Fig. 4).

From the obtained results by Rock-Eval pyrolysis, the S2 and HI values are higher in units belonging to the Assistência Member (Fig. 4). In the studied section, the organic material is thermally immature (Tmax <430 °C).

4. Discussion

In the following items the organic matter types, the oxygen regime of the depositional environment and the generation potential of the organic matter contained in each chemostratigraphic units are discussed. The diagrams presented in Figs. 5-8 give support to data interpretation.

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5.1. Chemostratigraphic Unit A

The Unit A, between 498.70 m and 487.15 m, corresponds to the basal section of the Taquaral Member (Figs. 3 and 4). It consists of light gray shale identified by its high IR values, between 80 and 90% and low TOC (<0.5%) and S (<0.5%) concentrations.

The HI and OI values are <100 mg HC/g TOC and <100 mg CO_2/g TOC, respectively. These values are characteristic of the presence of organic matter of predominantly type IV (Fig. 5A). These features suggest the occurrence of oxic environmental conditions and an organic material with a very low potential (S2 ~2mg HC/g rock) for oil or gas generation (Fig. 4).

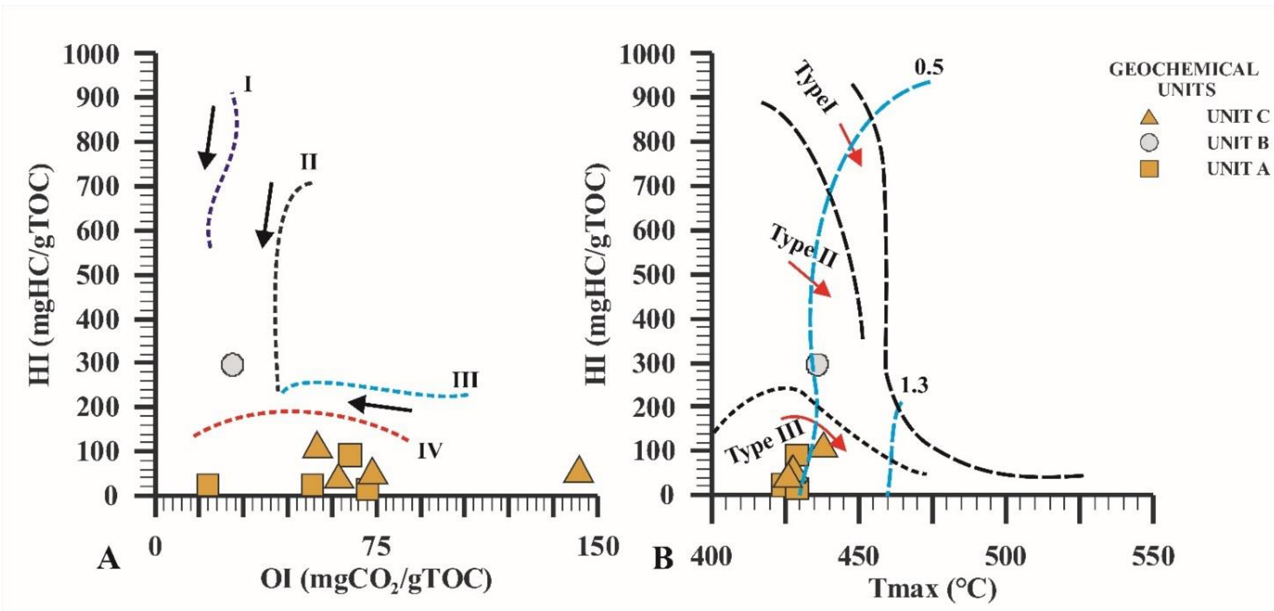

Fig. 5. The relationship between the following data for the studied samples of the chemostratigraphic units of the Taquaral Member in the SP-60-PR core: A. HI and OI and; B. HI and Tmax.

5.2 Chemostratigraphic *Unit B*

The Unit B, situated between 487.15 m and 486.15 m, is represented by darker gray shale (Fig. 3) with high IR values (87%; Figs. 4 and 8). This unit is easily distinguished from the previous units due to the presence of relatively high values of TOC and HI (~1% and 300 mg HC/g TOC, respectively). Although, individually these values are low (Fig. 4) and the S content is <0.5% (Figs. 4 and 7).

When HI and OI values are plotted on a diagram of the type Van Krevelen, it is verified that the Unit B is characterized by the predominance of organic matter of type II (Fig. 5A). TOC, HI and S data, suggest that the sediments of the Unit B were deposited in an oxic/disoxic environment. Given the thinness of this unit it is not possible to expected significant occurrences of hydrocarbons (Fig. 4).

5.3 Chemostratigraphic Unit C

The Unit C, between 486.15 m and 477.10 m, comprises the top of Taquaral Member (Fig. 3). It contains light gray shale identified by high IR values (80-90%) and low TOC, S and HI data (Figs. 4, 7 and 8) suggesting a return to an oxic environment. The predominance of organic matter type IV (Fig. 5A) also indicates this environmental condition. These characteristics suggest that this section does not provide attraction for oil or gas generation.

5.4 Chemostratigraphic *Unit D*

The Unit D, between 477.10 m and 472.80 m, covers the basal section of the Assistência Member (Figs. 3 and 4). It consists of marl, identified by IR values between 35 and 60% (of medium to dark gray color. The contact between the C

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and D units is fairly abrupt, both in lithological composition, indicated by the decrease in IR values, and as in geochemical view, suggested by the increase in TOC and HI values (Fig. 4). When plotted on a diagram of the Van Krevelen type, these results invariably indicate the occurrence of organic matter type II (Fig. 6A). This trend is possibly related to changing of paleoenvironmental conditions at the site of the SP-60-PR well, from oxic to disoxic/anoxic.

The TOC (1-3%), S2 (3-15 mg HC/g rock) and HI (300-600 mg HC/g TOC) values of this unit indicate a good to very good concentration of organic matter with moderate to excellent potential generator for oil.

Nevertheless, this unit consists of little thick interbedded limestone and marl strata, which did not favor the generation of large volumes of hydrocarbons (Fig. 4).

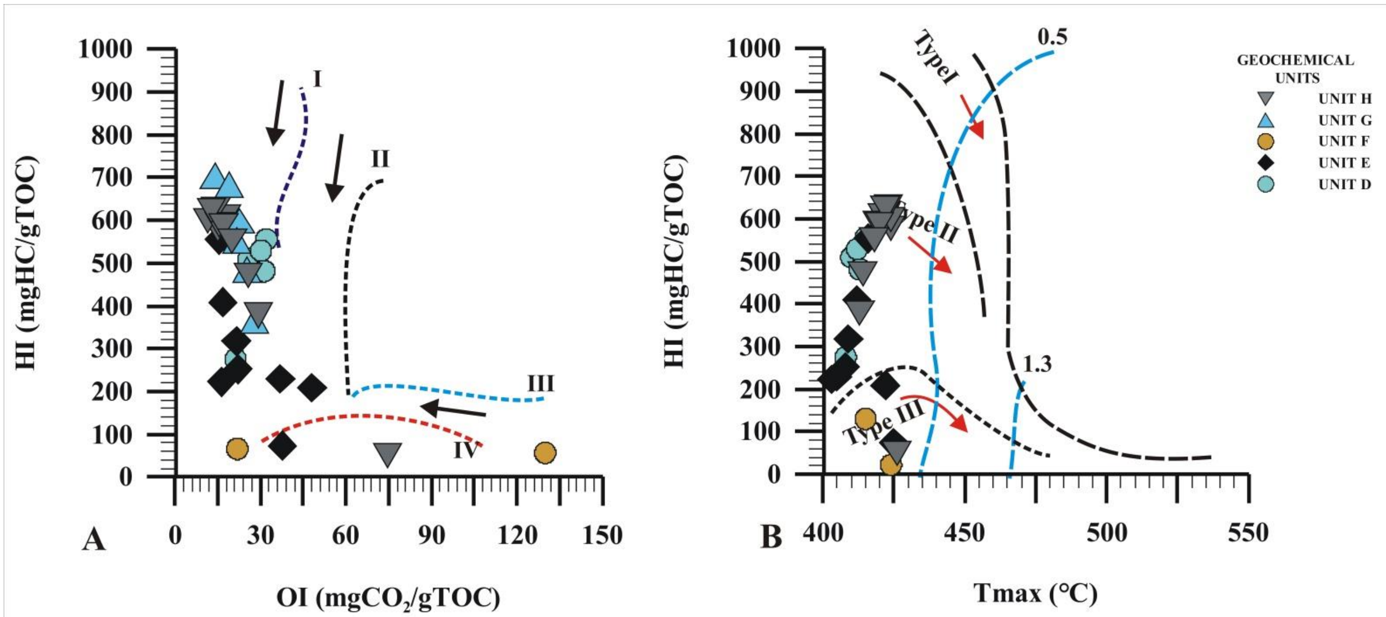

Fig. 6. The relationship between the following data for the studied samples of chemostratigraphic units set for the Assistência Member and Irati Formation in the SP-60-PR core-PR: A. HI and OI and; B. HI and Tmax.

5.5 Chemostratigraphic *Unit E*

The Unit E comprehends the section between 472.80 m and 469 m (Figs. 3 and 4). It consists of medium gray to black shale, which can be distinguished from the marl of the previous unit by their markedly higher values of IR (60-90%).

The coincidence of the highest IR and smaller HI values at the base and middle of the Unit E suggests that this section was deposited in a period of increased influx of siliciclastic material and terrestrial organic matter (type III, as shown in Fig. 6A).

On the other hand, the top of the Unit E is marked by the increase in TOC, S and HI values (9%, 3% and 600 mg HC/g TOC, respectively; Fig. 4), which indicates the return to an anoxic environment, and an organic matter richer in hydrogen (type II, as shown in Fig. 6A). Although the TOC, S2 and HI values are elevated on the top of this unit, its small thickness (0.4 m) makes its bituminous shale unattractive for generating commercial quantities of hydrocarbons (Fig. 4).

5.6 Chemostratigraphic *Unit F*

The Unit F, situated between 469 m and 467 m (Figs. 3 and 4), is predominantly siliciclastic (RI: 80-90%), consisting of medium to light gray shale (Fig. 3).

The TOC, S and HI values are significantly lower related to the previous unit (Fig. 4), indicating the new change of paleoenvironmental conditions from anoxic to oxic. The predominance of organic matter type IV (Fig. 6A) is a consequence of these paleoenvironmental conditions.

The low values of S2 (<2 mg HC/g rock) and HI (<100 mg HC/g TOC) (Fig. 4) indicate that the organic matter of this unit has no potential for oil or gas generation.

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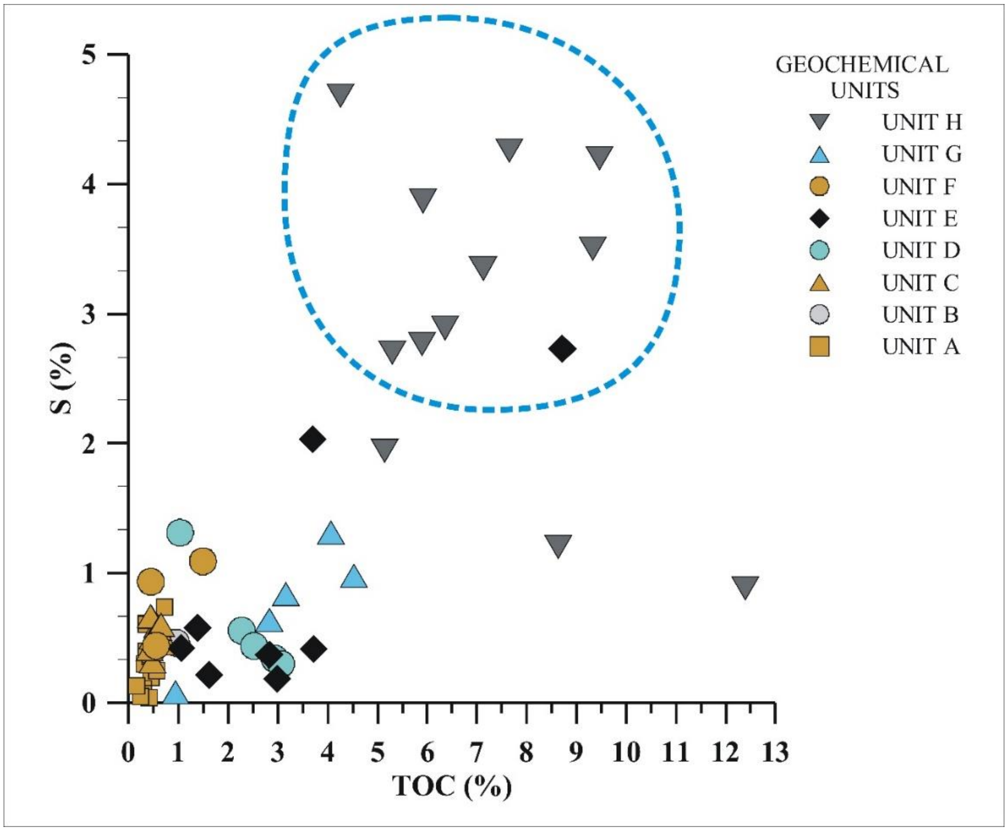

Fig. 7. Relationship between S and TOC percentage for samples of chemostratigraphic units of the Irati Formation in the SP-60-PR core. The sediment layers with the highest S and TOC contents are signed (dashed circle).

5.7 Chemostratigraphic Unit G

The Unit G, between 467 m and 461.30 m, is represented by medium to dark gray marl (Fig. 3). It can be differentiated from the previous shale unit by its markedly lower IR data (30-60%) and higher TOC and HI values (1-5% and 100-700 mg HC/g TOC respectively) (Fig. 4).

These data are suggestive of a more restricted environment, characterized by disoxic to anoxic conditions. Unit G contains predominantly organic matter of type II (Fig. 6A). Despite the adequate geochemical characteristics of this unit, significant occurrences of oil or gas are not expected to find in it due to the occurrence of little thick intercalations of limestone and marl.

5.8 Chemostratigraphic *Unit H*

The Unit H, between 461.30 m and 455.60 m, comprises the top of the Assistência Member (Figs. 3 and 4). It consists of bituminous black shale, which can be distinguished of the marls from the preceding unit by their IR (70-90%) and TOC (4-12%) values markedly higher.

The relationship between S and TOC contents also allows a clear separation of this unit from the other units situated below. The plot of Fig. 7 shows that throughout the all Irati Formation in the SP-PR-60 core, the unit H not only displays the highest organic matter content, but also has an organic matter richer in sulfur. The highest levels of TOC and S and the predominance of organic matter rich in hydrogen (type II, as shown in Fig. 6A) are characteristics of an anoxic environment.

The TOC (4-12%), S2 (15-60 mg HC/g rock) and HI (400-700 mg HC/g TOC) values, beyond a thickness of approximately 6 m, indicate that the bituminous shale of this unit has an excellent concentration of organic matter with excellent potential for oil generation. These data make this bituminous shale unit the most economically important interval in the studied area.

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However, the northern portion of the Paraná Basin is less attractive for industrial extraction of hydrocarbons when compared with southern areas of this basin. In the region of São Mateus do Sul, at south, the corresponding bituminous shale has a greater thickness (6.5 m) and much higher values of TOC and S2, up to 23% and 273 mg HC/g rock respectively (Padula 1969; Alferes et al., 2011), which make this area more attractive for hydrocarbon exploration.

However, considering the potential of generation, migration and accumulation of hydrocarbons related to diabase intrusions, the northern portion of the Paraná Basin remains attractive for hydrocarbon exploration.

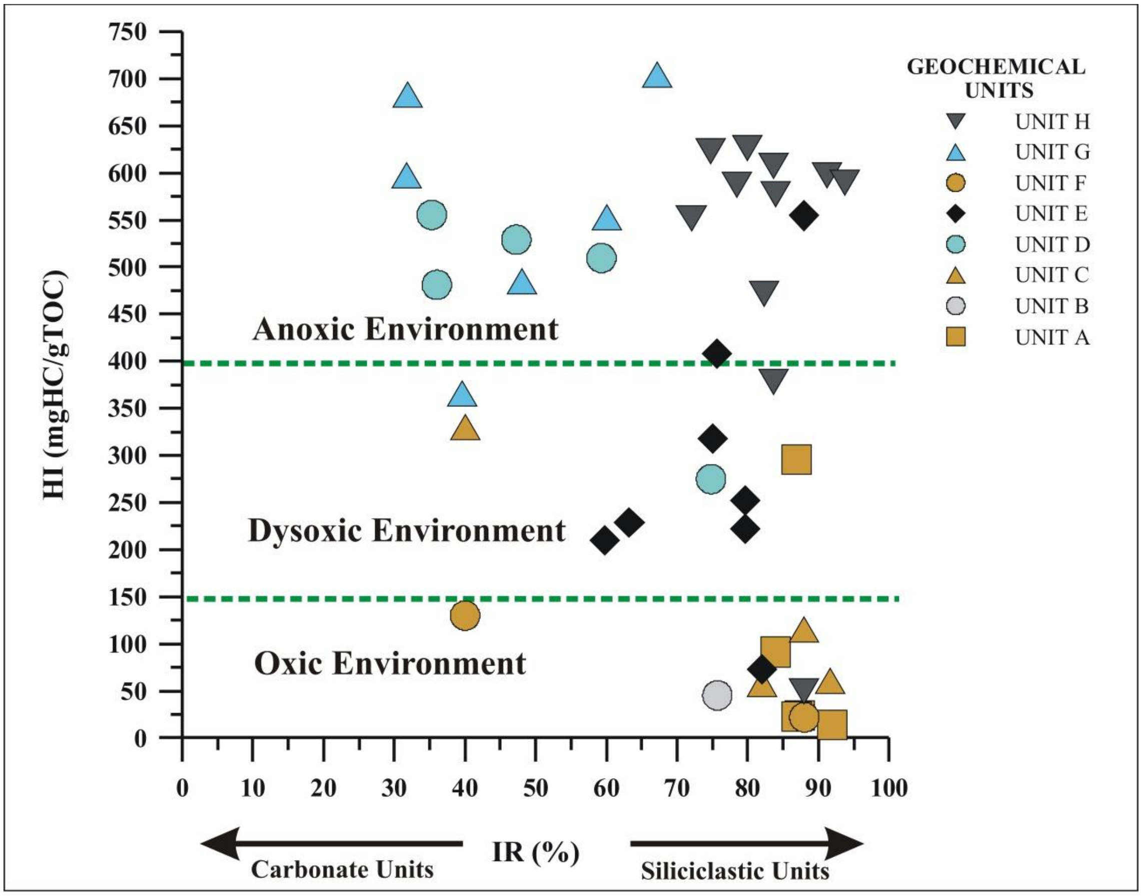

Fig. 8. Relationship between the HI and IR values for samples of the chemostratigraphic units of the Irati Formation in the SP-60-PR core. Environmental conditions are suggested.

5.9 General considerations

Geochemical variations observed in the studied core allowed to distinguish sedimentary layers with different chemostratigraphic characteristics conditioned by the depositional and posdeposicional environment.

The depositional environment of Irati formation is defined as a restricted marine environment (Northfleet et al., 1969; Hachiro and Coimbra, 1991; Santos Neto and Cerqueira, 1993; Rodrigues et al., 2010a, 2010b; Alferes et al., 2011; Gama and Rodrigues, 2011; Reis and Rodrigues, 2014).

These conditions allowed a high accumulation and preservation of organic matter recorded in the Irati formation. The Tmax values indicate no maturation of the organic matter by burial or by the influence of igneous intrusions in the study area.

Through this study was possible to identify and individualize chemostratigraphic units and identify the levels with hydrocarbon generation potential (e.g. units B, D, E and H).

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6. Conclusions

In Taquaral Member only the Unit B shows greater concentration and preservation of organic matter. However, its small thickness limits its importance in terms of hydrocarbon generation.

In Assistência Member, except for the Unit F, the other units present the possibility of oil and gas generation. However, Unit H, due to its high concentration of organic matter and sharply higher hydrocarbon generation potential is the section with better exploratory interest.

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