Avaliação da viabilidade da exploração sustentável do Shale gas na região sudeste do Brasil, com base em aspectos geológicos

Feasibility assessment of sustainable exploration of Shale gas in southeastern region of Brazil, based on geological aspects

DOI:10.34117/bjdv9n2-144

Recebimento dos originais: 23/01/2023
Aceitação para publicação: 24/02/2023

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RESUMO
O gás de folhelho é um dos recursos não convencionais em destaque nas últimasdécadas. A Bacia do Paraná (porção sul do Brasil), principalmente a Formação Irati, é um prospecto bastante interessante para gás de folhelho. Na área estabelecida para este estudo, composta pelos estados de São Paulo, Mato Grosso do Sul e Paraná foram pesquisados 143 trabalhos científicos, que compuseram uma revisão bibliográfica com afinalidade de obter informações acerca de seus principais parâmetros geoquímicos, ondefoi possível determinar um bom potencial para a exploração dos folhelhos. Com o método analógico foi calculado um valor estimado de reservas de 225 TCF. Existem alguns problemas com o processo de exploração desse recurso no Brasil, como a sua

proximidade com o Sistema Aquífero Guarani (SAG em inglês) e o uso de faturamento hidráulico. Uma solução interessante visando uma melhor aceitação do público geral/ambientalista seria de substituir a água no processo de faturamento por dióxido de carbono (CO2) e a combinação da produção de gás natural não convencional com a acumulação geológica de CO2, uma das mais eficientes formas de aprisionar carbono daatmosfera e reduzir as emissões de gás carbônico.

Palavras-chave: Shale gas, Bacia do Paraná, formação Irati, geoquímica orgânica, sistema aquífero Guarani.

ABSTRACT
The shale gas is one of the unconventional resources that are on the spotlight in the last few decades. The Paraná Basin (southern portion of Brazil), mainly the Irati Formation, is a very interesting prospect for shale gas. In the perimeter established for this study, composed by the states of São Paulo, Mato Grosso do Sul and Paraná, there were gathered 143 scientific works, comprising a literature review to provide information about its main geochemical parameters, in which it was possible to determine a good potential for exploration of these shales. With the analogy method it was calculated a value of estimated reserves of shale gas of 225 TCF. There are some issues about the exploration process of this unconventional resource here in Brazil, such as its proximity with the Guarani Aquifer System (GAS) and the use of the hydraulic fracturing technique. An interesting solution from an environmental/public acceptance point of view would be to replace the water in the hydraulic fracturing process by carbon dioxide (CO2) and the combination of the production of unconventional natural gas with geological storage of CO2, one of the most efficient ways to sequester carbon from the atmosphere and reduce greenhouse gas emissions.

Keywords: Shale gas, Paraná Basin, Irati formation, organic geochemistry, Guarani aquifer system.

1 INTRODUCTION

The transition phase from the use of an energy mix based on fossil fuels to renewable energies is expected to take several more decades to maintain the current level of energy consumption. Among the fossil fuels, natural gas is the one that emits the least amount of greenhouse gases, and the shale gas (and oil) is one of the most feasible possibilities for exploration in onshore areas.

To evaluate the potential of a given area for the production of unconventional oil and gas, a multidisciplinary evaluation is required, where the first issue is the complex geological characterization of the layers of potential producing rocks, which will indicate the amount of natural gas included in the reservoir and the geological structures that will ensure the safety of gas exploration and production, to avoid contamination of aquifers and minimize other potential environmental impact factors. However, for shale gas extraction to be feasible, it is necessary to have efficient regulations that protect the interests of society as a whole and, at the same time, do not make the activity unfeasible. Besides this, public perception and acceptance is fundamental, with gains for all those involved in the production of natural gas.

The main objective of this work is to evaluate, from a geological point of view, the possibility of exploration and sustainable production of shale gas in the southeastern region of Brazil, more specifically in the Irati Formation, and suggest ways to make this type of activity feasible.

2 GEOLOGICAL FRAMEWORK

The Paraná Basin is the largest Brazilian intracratonic sedimentary basin and is located in the center eastern portion of the South American continent, with an elliptic shape and a NNE-SSW predominant axis. The basin area has an estimated area of 1500000 km^2, in which are located territorial portions of southern Brazil (a 1100000 km^2 portion), eastern Paraguay, northeast Argentina and northern Uruguay (MILANI ET AL., 2007). The Paraná Basin was formed between the Ordovician (± 450 Ma) and Neocretaceous (± 65 Ma) and is composed by a sedimentary sequence (mainly siliciclastic) and a volcanic sequence with thickness higher than 7000 m (MILANI AND ZALÁN, 1999; MILANI ET AL., 2007). Today, the basin has a contour with a mainlyerosive character that throws back post-Paleozoic events of the South American continent that resulted in the subtraction of areas form the original depositional sequence. The edges of the basin are tectonic and/or erosive. The erosive edges are sediments that become progressively thinner to the edges without tectonicinterference. The tectonic edges are the structural highs: the Alto Parnaíba arc (northeast border), the Ponta Grossa arc (southern border), the Rio Grande arc andthe Assunção arc (western border) and the São Vicente arc (northwest border).According to MILANI (1997), the stratigraphic framework of the Paraná Basin can be divided into six supersequences that were formed in a period between 450 to 65 Ma.

Geological and geochemical studies performed during the last decades allowedthe identification of two intervals as the main hydrocarbon generators in the Paraná Basin: the Devonian shales of the Ponta Grossa Formation and the Late Permian shales of the Irati Formation (MILANI ET AL., 1998). The Irati Formation, which constitutes the geological unit under evaluation to be a potential unconventional gas generator in southeastern Brazil, occurs in a large area extending from the states of Mato Grosso do

Sul, Goiás and Rio Grande do Sul, passing through São Paulo, Paraná

and Santa Catarina, outcropping almost continuously for about 1700 km and reaching thicknesses of up to 70 meters in the central part of the Basin (HACHIRO, 1996). The rocks of the Irati Formation were deposited in a restricted marine environment and are composed of black shales, carbonate rocks, marls, and bituminous black shales (MILANI ET. AL., 1997). The estimated age for the deposition of these rocks is Permian, between 277 and 275 Ma (BASTOS ET. AL., 2021). The Irati Formation is divided into two members, the older being the Taquaral Member and the younger, the Assistência Member (SCHENEIDER ET. AL., 1974).

3 METHODS OF THE WORK

The work was developed from a compilation of geological information and analytical data available in the specialized literature for the Irati Formation. Initially, based on published studies that used well-data from public domain, the best area for exploration and production of unconventional natural gas was selected.

Within the chosen area a set of georeferenced data was collected that included, depth and thickness of the rock layers, mineralogical compositions and geochemical parameters that will indicate whether the rocks have been able to generate and preserve oil and gas. These parameters include Total Organic Content (TOC), kerogen type, Rock-Eval pyrolysis data (such as S_1, S_2, S_3, Tmax) and vitrinite reflectance measurements (%Rr). All the collected data was displayed in tables (Supplementary Table 1, Table 1) and handled in appropriate diagrams for evaluation of results (Tables2 to 4). To estimate important data for the characterization of the potential of shales to produce unconventional gas, such as porosity and permeability, which are not included in previous works for the Irati Formation, average values for black shales from the Barnett and Marcellus gas fields, two of the most important plays in the United States, were considered.

Table 1 – Data available for the samples studied from each research source.

Research	Number of data samples in the study	Number of data samples used	Organic Geochemical Indicators								Depth	Thickness
			TOC	Kerogen	S1	S2	S3	TMAX	Vitrinite reflectance	Mineralogy		
Azevedo da Silva (2007)	53	28	■	■	■	■	■	■	■		■	
Euzébio et al. (2016)	40	40	■	■	■	■		■			■	
Lages (2004)	92	92	■								■	■
Lisboa (2006)	20	20	■	■	■	■	■	■			■	■
Ferreira (2017)	35	35	■							■	■	■
Oliveira (2012)	34	34	■								■	■
Holanda et al. (2018)	11	11	■		■	■		■		■	■	

Table 2 – Average TOC values of each research work used to develop the Supplementary Table 1. Location of the samples from each work (within the cities or nearby): [1]São Mateus do Sul (PR), Sapopema (PR), [2] Sapopema (PR), [3] Sapopema (PR), [4] Ipeúna (SP), Saltinho (SP), Assistência (SP), Laranjal Paulista (SP), [5] São Mateus do Sul (PR), Ortigueira (PR), Anhembi (SP), [6] Ipeúna (SP), Rio dasPedras (SP), Tietê (SP), Iracemópolis (SP), Limeira (SP), Irati (PR), Rebouças (SP), São Mateus do Sul (PR), [7] Sapopema (PR).

Source	Average TOC (wt%) values
Azevedo da Silva (2007)[1]	3.55
Euzébio et al. (2016)[2]	3.53
Lages (2004)[3]	1.84
Lisboa (2006)[4]	4.06
Ferreira (2017)[5]	3.13
Oliveira (2012)[6]	3.47
Holanda et al. (2018)[7]	3.81

Table 3 – Average TOC and genetic potential (S1 + S2) values of the research works used in the Supplementary Table 1. nd – no data.

Source	TOC (wt%)	Genetic potential (mg HC/g)
Azevedo da Silva (2007)	3.55	53.78
Euzébio et al. (2016)	3.53	17.99
Lages (2004)	1.84	nd
Lisboa (2006)	4.06	33.08
Ferreira (2017)	3.13	nd
Oliveira (2012)	3.47	nd
Holanda et al. (2018)	3.81	21.76

Table 4 – Average TOC and S2 values of the research works used in the Supplementary Table 1. nd – no data.

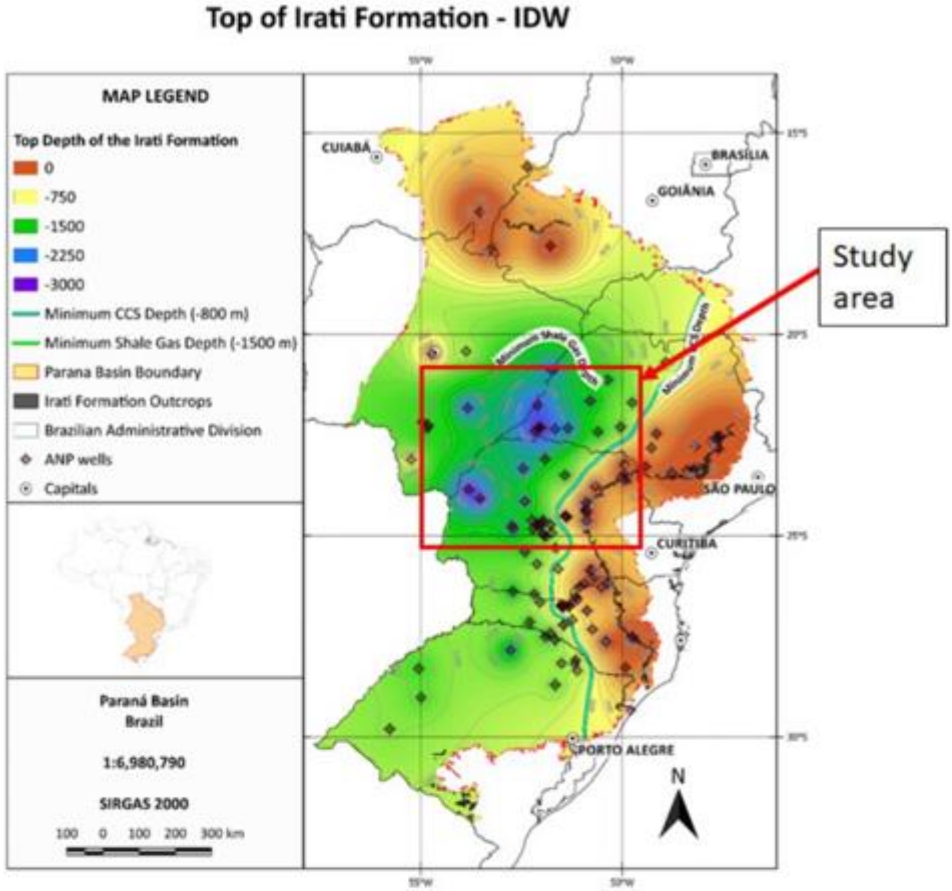
Source	TOC (wt%)	S2 (mg HC/g)
Azevedo da Silva (2007)	3.55	48.52
Euzébio et al. (2016)	3.53	16.24
Lages (2004)	1.84	nd
Lisboa (2006)	4.06	30.03
Ferreira (2017)	3.13	nd
Oliveira (2012)	3.47	nd
Holanda et al. (2018)	3.81	20.02

To estimate the potential natural gas reserves that would be contained in the Irati Formation within the selected area, the method of calculating reserve estimates by analogy was utilized, using the Barnett gas field as an analog, due to the geological similarities between the black shale layers for both Irati and Barnett Formations.

4 RESULTS AND DISCUSSION

Some authors have elaborated prospectivity maps for hydrocarbons in the Paraná Basin, such as ARAÚJO ET. AL., (2000) and the National Agency on Petroleum and Biofuels (from the Portuguese *Agência Nacional de Petróleo, Gás Natural e Biocombustíveis* - ANP (2013)), considering the petroleum system as a conventional resource. SAN MARTÍN CAÑAS (2020) treated the ANP open technical wells dataset available for the Paraná Basin using data mining techniques, machine learning algorithms and spatial analysis, elaborated a prospectivity map for shale gas in the Paraná Sedimentary Basin, in the north of the State of Paraná and in the west of theState of São Paulo, an area of approximately 11,250 km^2 with good potential forexploration and production of shale gas. This area was also considered favorable for shale gas exploration by RICOMMINI ET. AL., (2021) and TASSINARI ET. AL., (2021). In this paper, the area defined in the previously mentioned works (Fig. 1) was considered for the compilation and treatment of the available geological information associated withthe characterization of the potential for shale gas in the southeastern region of Brazil.

Figure 1 - Depth map of the top of the Irati Formation, using the IDW interpolation method, with the study area highlighted inside the red square (extracted from Cañas, 2020).



For the characterization of the shale gas production potential in the selected area, the following geological aspects were analyzed: thickness and extension of the shale layers, organic geochemical properties, such as TOC, thermal maturity, and mineralogical composition to define brittleness degrees, its proximity with the Guarani Aquifer System and estimated values of porosity and permeability (based on the US main plays) to also calculate an estimated volume of gas reserves.

4.1 EXTENSION, THICKNESSES, AND DEPTHS OF THE IRATI FORMATION

There are few depth maps of the Irati Formation available in the literature. There is an isopach map of the member Assistência of the Irati Formation proposed by ZALÁN ET AL., (1987), which also included data from the Teresina and Rio do Rasto Formations. Another map is a depth map of the Irati Formation proposed by SAN MARTÍN CAÑAS

(2020) that used the inverse distance weighting (IDW) deterministic method to interpolate well depth data of the Irati Formation, indicating that in the selected area the Irati Formation reaches depths between 1,500 and 3,500 m (Fig. 1).

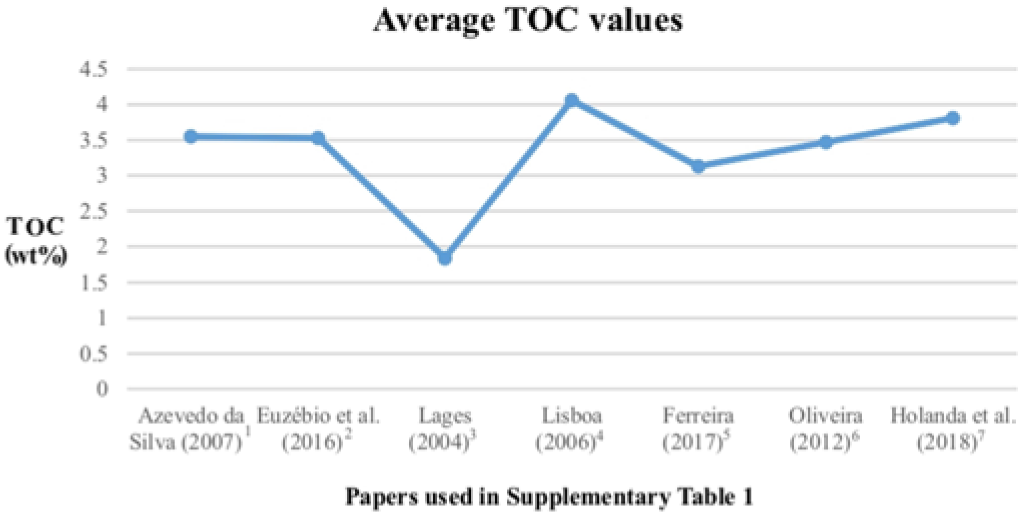
The areas with depths higher than 1,500 m, usually considered the minimum depth value for a safe production of shale gas, are comprised by the southwest region of the São Paulo state, the northwest portion of the Paraná state and the east-southeast part of the Mato Grosso do Sul state. In the regions of Presidente Prudente, Altônia, São Jorge do Patrocínio and Esperança Nova cities (Fig. 1), the shale layers can reach up to 3,000 m in depth (Supplementary Table 1).

Considering the whole Paraná Sedimentary Basin area, the Irati Formation has a maximum thickness of 150 m in which shales and bituminous shales are interleaved with dolomitic carbonates and siltstones (ARAÚJO, 2001). Contrastingly, considering the reported values in the Supplementary Table 1, it was calculated an average thickness value of 24.5 m for the Irati Formation within the selected area. This estimated value is lower than both the usual average value of 40 m (SCHNEIDER ET AL., 1974) and the maximum value of 70 m in some of the central areas of the basin (HACHIRO, 1996).

4.2 TOTAL ORGANIC CARBON (TOC)

Compiled TOC values from organic-rich shales of the Irati Formation vary between 0.5 to 13 wt%, and can reach up to 30% (FERREIRA, 2017; MABECUA, 2018; CIOCCARI AND MIZUSAKI, 2019; ROCHA, 2021). The Assistência Member – upper member of the Irati Formation, is the stratigraphic unit of the Paraná Basin with the best research database of organic matter geochemical data (ARAÚJO ET AL., 2000). The TOC values found in the selected area vary between 0.1 wt% in a borehole sample close to Sapopema (PR) to 17.41 wt% in São Mateus do Sul (PR), with a total average value of 2.98 wt%, (Table 2, Fig. 2). SAN MARTÍN CAÑAS (2020) conducted an evaluation of the generation potential of the Irati Formation in the São Paulo state using organic geochemical data, as a result, pointing out that the studied black shales have all the source rock requirements for shale gas, with an average TOC value higher than 2 wt%.

Figure 2 – Average TOC values of the samples from research works used in the Supplementary Table 1. Location of the samples from each work (within the cities or nearby): 1 São Mateus do Sul (PR), Sapopema (PR), 2 Sapopema (PR), 3 Sapopema (PR), 4 Ipeúna (SP), Saltinho (SP), Assistência (SP), Laranjal Paulista (SP), 5 São Mateus do Sul (PR), Ortigueira (PR), Anhembi (SP), 6 Ipeúna (SP), Rio das Pedras (SP), Tietê (SP), Iracemópolis (SP), Limeira (SP), Irati (PR), Rebouças (SP), São Mateus do Sul (PR), 7 Sapopema (PR).



The lower values of TOC were observed in the cities of Sapopema (between 0.27 and 0.59 wt%) and Ortigueira (PR) (between 0.30 and 0.64 wt%) reported in AZEVEDO DA SILVA (2007) and FERREIRA (2017), respectively (Supplementary Table 1). These lower values can be associated with the conversion and/or elimination of the organic carbon (as a hydrocarbon) due to the effects produced by the heat from intrusions of igneous rocks that promoted the cracking of the organic matter and decreased the values of the original quantities (AZEVEDO DA SILVA, 2007). The higher TOC values were obtained in some samples from Sapopema (PR) (between 12 and 14 wt%) and São Mateus do Sul (PR) (between 10.37 and 21.00 wt%) wells (AZEVEDO DA SILVA, 2007; EUZÉBIO ET AL., 2018; FERREIRA, 2017; OLIVEIRA, 2012 – see Supplementary Table 1 and Fig. 1). Such elevated values can be explained due to several conditions like thermal maturity, presence of hydrocarbons, organic matter distribution and burial, all these factors combined with the igneous intrusions from the Serra Geral Formation (MILANI ET AL., 2007; SANTOS ET AL., 2009; CASTRO, 2019).

TOC measurements obtained by ROCHA (2021) indicate that, despite the high heterogeneity, most of analyzed Irati Formation shale samples present TOC values above 2% and are good hydrocarbon source-rocks. Additionally, about the geographical distribution of the samples from São Paulo State presented a TOC range between 4.42 and 9.64 wt%, while samples from Paraná State (PR) presented an average of 7.7 wt% of

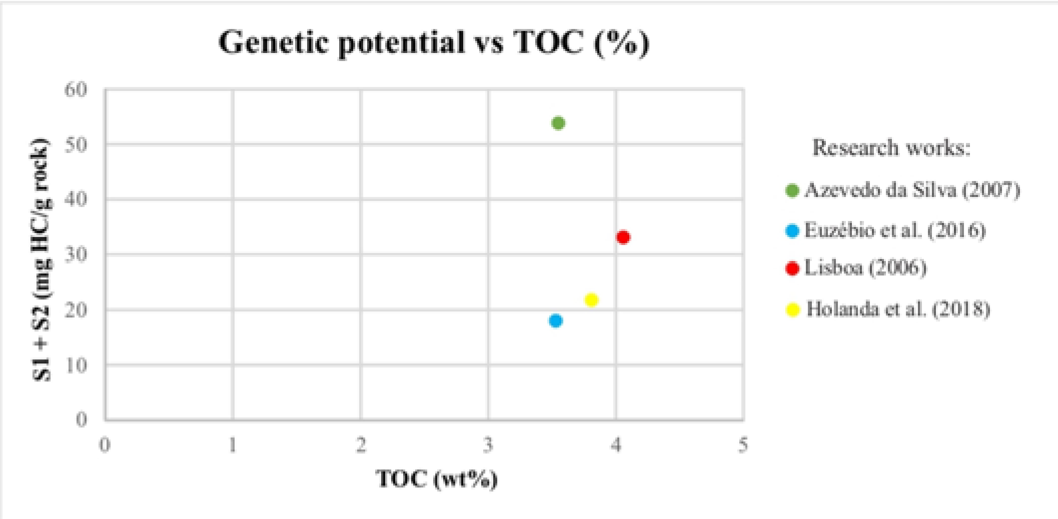
TOC.

4.3 PYROLYSIS ROCK-EVAL RESULTS

The average values of S1, S2, and S3 (respectively, 2.56, 24.67 and 1.87 mg HC/g) are yet inconclusive for determining the hydrocarbon generation potential of the prospect's samples (Supplementary Table 1). Some samples from the cities of Sapopema (Paraná state) and Assistência (São Paulo state) only have S1 and S2 data; however, they have lower rates than the ideal limits for oil and gas prospectivity in our area of study (Supplementary Table 1). Only one sample (CAL-03) from Saltinho (eastern portion of the São Paulo state) has a lower value than the ideal limits (Supplementary Table 1).

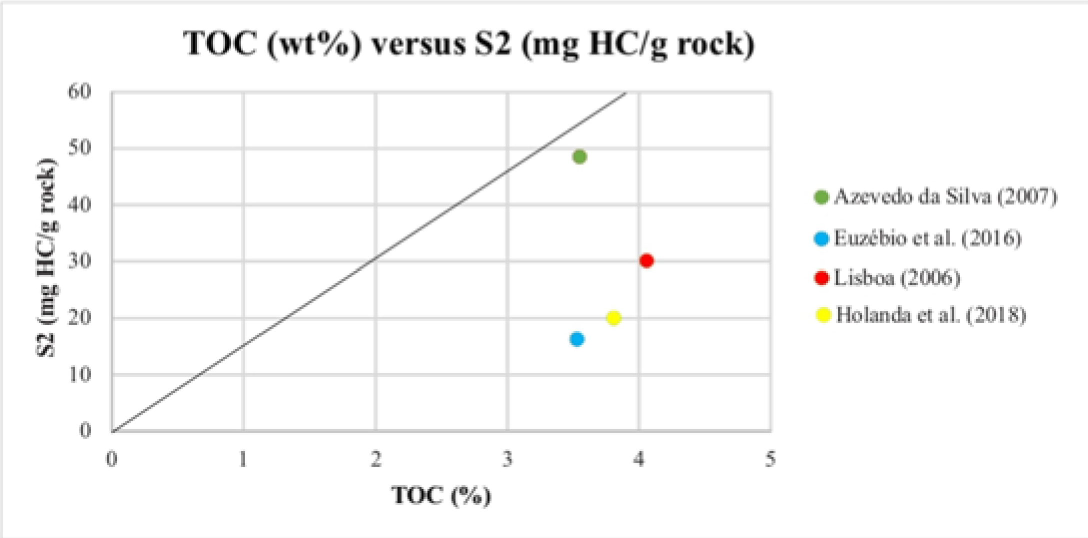
The generative potential (GP) is the quantity of hydrocarbons (oil or gas) that can be generated. Rocks that present S1+S2 values above 6 mg HC/g of rock have good generative potential (TISSOT AND WELTE, 1984; PETERS AND CASSA, 1994 – Table 3, Fig. 3).

Figure 3 – Average genetic potential (GP) versus average TOC (wt%) diagram of research works used in the Supplementary Table 1, showing a good generator potential of hydrocarbonates.



The parameter S_2 (mg HC/g of rock) of the pyrolysis Rock-Eval can be utilized as an estimation of the potential of the hydrocarbon generation through the kerogen cracking. The dataset included in the Supplementary Table 1 and Table 4, the samples have an total average value of 24.67 mg HC/g of rock, in which the highest values are presented in AZEVEDO DA SILVA (2007) (especially in some outcrops near the city of São Mateus do Sul, in the Paraná state, with values between 89.98 and 131.16 mg HC/g of rock), and the lowest values appear in EUZÉBIO ET AL., (2018) (especially in the oldest chemo-stratigraphic units, with values between 0.06 and 3.4 mg HC/g of rock, Fig. 4).

Figure 4 – Average TOC versus average S2 values of the research works used in the Supplementary Table 1, showing a good residual potential of hydrocarbonates generation.



Analysis of kerogen typing through organic petrography and hydrogen indexes reveal a predominance of organic matter type I, algae-based, attributed to the black shales of the Assistência Member, which has associated good oil generative potential (ZALÁN ET AL., 1990; AZEVEDO DA SILVA, 2007).

ROCHA (2021) has studied black shale samples from several locations of the Paraná Sedimentary Basin and indicate that in the northern part (Goiás State) there is the highest concentration of types II-III kerogen, gas-prone organic matter, whereas in the southeastern and south parts of the basin, there is a predominance of type I-II kerogen, oil-prone organic matter. Local concentrations of dark opaque organic matter were also identified as black shales` components, indicating the heterogenous thermal history of the basin, mainly attributed to the Serra Geral igneous intrusions.

Based on compiled Rock-Eval pyrolysis data, most of analyzed samples have pyrolysis parameters values within the expected limits for oil and gas generation. The kerogen type of the samples is mostly from types I (lacustrine organic matter – 21.12%), II (marine or mixed organic matter – 56.33%) and III (continental organic matter – 19.71%), representing 87.33% of the total samples against 12.67% of the samples from type IV (i.e., inertinite), confirming the predominance of kerogen of types I and II, indicating a planktonic marine origin with some algae contribution. Further, it confirms that the origin of the organic matter of the Irati Formation was deposited in a confined-evaporitic marine or gulf environments (MILANI ET AL., 2007; MABECUA, 2018; BASTOS, 2021).

The majority of the Tmax samples values are also inside the ideal limits for oil and gas generation (52.49% of the samples total – see Supplementary Table 1) with an average value of 411.29°C. In general, the Tmax values are uniform in almost all samples (between 400-430°C – see Supplementary Table 1), with some higher values in Assistência (SP) (PAR-05 sample, 487°C – higher thermal maturity) and lower values also in Assistência (SP) and Laranjal Paulista (SP) (PAR-02 and CRU-01 samples, 325 and 387°C – more immature sample temperature), and one sample in the Sapopema (PR) (sample 8 of the SP-32-PR well, 383°C, along with some other immature samples temperatures between 400-410°C), most of them reported in LISBOA (2006) and HOLANDA ET AL., (2018) (Supplementary Table 1).

Vitrinite reflectance (%Rr) of shale gas reserves range from 0.85%Rr to 1.5%Rr depending mainly on depth (EIA, 2013). Most of the samples with vitrinite reflectance, however, have values outside the ideal limits for gas and oil generation, with an average value of 0.64 %Rr, with only a small portion of the samples (14.28 % - Supplementary Table 1) within this interval (AZEVEDO DA SILVA, 2007 - Supplementary Table 1). ROCHA (2021) presents vitrinite reflectance (%Rr) values ranging from 0.67 and 0.74%Rr for samples within the selected area, in the southeastern part of the Paraná Basin, attributing to these an early-maturity stage, which is characteristic of the beginning of oil window.

4.4 PERMEABILITY, POROSITY AND PORE PRESSURE

There are few published porosity and permeability data from the shales of the Irati Formation. DE SOUZA (2018) through analysis of scanning electron microscope images determined values of 4 and 8% for the porosity of the organic matter enriched- black shale from Irati Formation with an average value of 6%.

Nevertheless, it is possible to consider the available petrophysics data from some black shales of one of the main U.S. plays such as Barnett Shale, to make an estimate of ideal ratios for Paraná Sedimentary Basin due to the geological similarities existing between these geological units with the Irati Formation. The Barnett Shale is part of the Fort Worth Basin in which occurs in Texas state in an area of about 130,000 km^2, and has a porosity of 5 – 6% with low permeability, TOC average values of 2.5 wt% – 3.0 wt% and around 25% of water saturation (WANG, 2017).

4.5 MINERALOGY AND BRITTLENESS

The Assistência Member of the Irati Formation is composed by dark grey shales and bituminous black shales associated with limestones, sometimes dolomitic. The main sedimentary structure observed in the bituminous shales is the parallel lamination, meanwhile, in the carbonates there are wave marks, cross lamination, oolites, intraformational breccias and algalic lamination (SCHNEIDER ET AL, 1974).

The mineralogical composition of the considered samples presented in the Supplementary Table 1 is composed by quartz, albite, illite, chlorite, smectite, calcite, pyrite, saponite, dolomite, kaolinite, plagioclase, and muscovite, distributed between black and dark grey shales and grey limestones along the Taquaral and Assistência Members (FERREIRA, 2017; HOLANDA ET AL., 2018; ROCHA, 2021). This composition varies according to the sample's location. In Anhembi (São Paulo state), the basal interval of the Irati Formation presents calcite, and the upper interval presents shales with the highest proportion of pyrite; in São Mateus do Sul (Paraná state), the basal interval contains interstratigraphic illite-smectite occurrences (FERREIRA, 2017). In the area considered in this study, HOLANDA ET. AL., (2018) characterized the mineralogical composition of the black shales of the Assistência Member, indicating the following quantitative composition: Quartz between 36 and 40%, feldspar (mainly plagioclase) between 14 and 15% and clay minerals, mainly illite + muscovite, between 25 and 55%.This mineralogical composition allows us to infer that the Irati Formation black shales present an adequate brittleness index.

It is important to emphasize that the mineralogical composition of the rocks of the Irati Formation was affected, in some places, by the Cretaceous magmatic event that originated basalts of the Serra Geral Formation. This thermal event also affected the mineralogy of the limestones associated with the shales (SANTOS ET AL., 2009; CASTRO, 2019). This particular setup provided the fissile character observed in the black shales of the Assistência Member (HOLANDA ET AL., 2019; OISHI ET AL., 2019). The magmatic event besides modifying the mineralogy also plays an important role in the maturation and accumulation of hydrocarbons of the Irati Formation (ARAÚJO ET AL., 2000;HOMAZ FILHO ET AL., 2008).

4.6 ESTIMATED GAS RESERVES

To calculate an estimated quantity of gas volume within the Irati Formation, the Analogy Method was applied. The method consists of an indirect approach based on geological similarities between analogous shale players, and it is used to estimate the total recoverable resources based on geological interpretations. Although this method has the lowest accuracy among the reserve calculation techniques, it is often used in the preliminary evaluation of undrilled areas, where there are no detailed geological studies related to shale gas exploration, to establish a preliminary order-of-magnitude of the amount of recoverable gas from the reservoir.

As an analogous reservoir of the black shales of the Irati Formation, due to the various geological and geochemical similarities, the Barnett field was used by COLELA (2013) to estimate the unconventional gas reserves in the Brazilian sedimentary basins. Such analogy considered the following parameters for Barnett shale: shales occupied area = 13,000 km^2, average thickness = 92 m, rock volume = 1,196 km^3, estimated reserves of gas = 30 TCF. Using the Analogy Method this author estimated for the Paraná Sedimentary Basin a total of 225 TCF of unconventional gas.

In this study we considered for the Irati Formation, within the region selected as most favorable for shale gas production, the following parameters: an area of occurrence of 302,400 km^2, an average thickness, considering the carbonate rock intercalations, of 40 m, and a black shale rock volume of 12,096 km^3. For the calculation of the estimated reserve by the analogy method, the data for the Barnettplays from ZOU ET. AL., (2017) was used. These data are described as follows: shales occupied area = 15,500 km^2, average thickness = 90 m, rock volume = 1395 km^3, average TOC values = 4.5 wt% and estimated technical recoverable reserves of 7,362 x 108 m^3 or 26 TCF.

5 FINAL CONSIDERATIONS

The potential estimated to this study was based on the total organic carbon (TOC) values, with an average value of 2.98 wt%, and also and considering that 60% of the samples' data compiled within the study limits confirm the potential for shale gas. Moreover, some of the evaluated parameters such as S_2, GP versus TOC (Fig. 3) and S_2 versus TOC (Fig. 4) show that most of the samples have good and favorable values for shale gas exploration. Other parameters linked to the Rock-Eval pyrolysis, such as the Tmax and kerogen typing, are also inside the value range considered in accordance and favorable to shale oil exploration (the first one with an average value of 411.29°C, and the second one with most of the samples with type II kerogen, marine origin). However, the vitrinite reflectance (%Rr) average value of 0.64%Rr is below the interval considered good for shale gas exploration (between 0.7 and 3.0%Rr), confirming a higher potential for shale oil. Despite this last parameter, previous studies of the Irati Formation confirmed the good theoretical potential of this stratigraphic unit for shale gas exploration.

Although more studies about porosity and permeability are necessary to improve the knowledge about the potential of the shales of the Irati Formation, the results from the analog method showed that the layer disposition in the Barnett and Marcellus plays that allows a strong interchange between shales and limestones can be also found in the Paraná Basin, especially in the NW sector of the basin. Furthermore, this analogous layer configuration found in the Irati Formation may improve the permeability of the black shales through the natural fracture system benefiting fluid/gas flows and the fracking activities.

It can be concluded that the shales of the Irati Formation have a good potential of gas exploration with an estimated gas volume of 225 TCF. Therefore, the Irati Formation represents a good prospect for shale gas as an alternative source of natural gas in Brazil. Nevertheless, for a successful natural gas production, appropriate investments efforts are required in areas such as, more detailed geological studies, specialized human resources, public perception studies, and efficient regulatory andlegal frameworks.

ACKNOWLEDGEMENTS

Our thanks to the FINEP Project (Process Number 01.14.0215.00) - Support to the R&D Network in Non-Conventional Gas in Brazil (GASBRAS). Also, thanks to the The National Council for Scientific and Technological Development (CNPq – Process Number 380132/2021-4) and the University of São Paulo (USP), that provided the support with the scholarship that made this project possible. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The data that supports the findings of this study are available in data gathered in papers by this study (presented in the tables at the end of this text) and in the supplementary material of this article (in the Supplementary Table 1).

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ANEXOS

Supplementary Table 1 – All the parameters (organic geochemistry, geographic location) detected in the seven papers that were the main focus of this study. The coordinate precision has values from 1 to 3, in which 1 is the the most precise coordinates to 3, which is the least precise.

Samples	Location/Geographic reference	Coordinate precision	Depth (> 1000 m)	Thickness (15-100 m)	TOC (> 1 wt%)	Kerogen (I, II or III)	S1 (> 0.5 mg HC/g)	S2 (>2.5 mg HC/g)	S3 (> 0.12 mg HC/g)	TMAX (415-475°C)	Vitrinite reflectance (0.7-3.0 %Rr)	Mineralogy	Research work
04-047	Outcrop located near the city of São Mateus do Sul (PR), about 1000 m distant from the bridge over the Iguaçu River	2	680		9.02	II	3.86	53.23	0.56	425	0.49		Azevedo da Silva (2007)
04-048	Outcrop located near the city of São Mateus do Sul (PR), about 1000 m distant from the bridge over the Iguaçu River	2	600		8.98	II	3.23	46.36	0.79	424	0.5		Azevedo da Silva (2007)
04-049	Outcrop located near the city of São Mateus do Sul (PR), about 1000 m distant from the bridge over the Iguaçu River	2	800		21	I	4.91	131.16	8.02	419	0.51		Azevedo da Silva (2007)
04-050	Outcrop of the mining pit of the PETROBRAS company, shale industrialization, SIX, in the city of São Mateus do Sul (PR). Gathering of the upper layer	2	400		0.67		n.d.	n.d.	n.d.	n.d.	0.52		Azevedo da Silva (2007)
04-051	Outcrop of the mining pit of the	2	400		3.07	II	4.18	12.6	0.67	421	0.5		Azevedo da Silva

	PETROBRAS company, shale industrialization, SIX, in the city of São Mateus do Sul (PR). Gathering of the upper layer												(2007)
04-052	Outcrop of the mining pit of the PETROBRAS company, shale industrialization, SIX, in the city of São Mateus do Sul (PR). Gathering of the upper layer	2	410		2.27	II	1.85	10.18	0.72	415	0.46		Azevedo da Silva (2007)
04-053	Outcrop of the mining pit of the PETROBRAS company, shale industrialization, SIX, in the city of São Mateus do Sul (PR). Gathering of the upper layer	2	900		12	I	4.16	89.98	1.25	425	0.49		Azevedo da Silva (2007)
04-054	Survey testimony in the Sapopema region (limit between the states of PR and SP) code SP 53	2	900		12	II/III	2.02	28.82	32.49	431	0.5		Azevedo da Silva (2007)
04-055	Survey testimony in the Sapopema region (limit between the states of PR and SP) code SP 49	2	900		13.4	I	5.73	99.87	4.76	424	0.51		Azevedo da Silva (2007)
05-040	Survey testimony in the Sapopema region (limit between the states of PR and SP) code SP 43	2	800		2.41	II	7.67	28.55	0.14	335	0.59		Azevedo da Silva (2007)

05-042	Survey testimony in the Sapopema region (limit between the states of PR and SP) code SP 30	2	800		0.59		n.d.	n.d.	n.d.	n.d.	0.51		Azevedo da Silva (2007)
05-046A	Survey testimony in the Sapopema region (limit between the states of PR and SP) code SP 32	2	420		2.09	II	9.1	30.75	0.12	348	0.45		Azevedo da Silva (2007)
05-046B	Survey testimony in the Sapopema region (limit between the states of PR and SP) code SP 32	2	420		0.61		n.d.	n.d.	n.d.	n.d.	0.53		Azevedo da Silva (2007)
05-047	Survey testimony in the Sapopema region (limit between the states of PR and SP) code SP 47	2	420		1.61	II	7.22	32.2	0.19	359	0.51		Azevedo da Silva (2007)
05-048	Survey testimony in the Sapopema region (limit between the states of PR and SP) code SP 44	2	300		3.57	II	9.22	18.58	0.23	307	0.57		Azevedo da Silva (2007)
05-049	Survey testimony in the Sapopema region (limit between the states of PR and SP) code SP 44	2	300		0.55		n.d.	n.d.	n.d.	n.d.	0.55		Azevedo da Silva (2007)
05-050	Survey testimony in the Sapopema region (limit between the states of PR and SP) code SP 45	2			0.59		n.d.	n.d.	n.d.	n.d.	1.47		Azevedo da Silva (2007)
05-051	Survey testimony in the Sapopema region (limit between the states of PR and SP) code SP 51	2	420		0.39		n.d.	n.d.	n.d.	n.d.	0.57		Azevedo da Silva (2007)

05-052	Survey testimony in the Sapopema region (limit between the states of PR and SP) code SP 54	2			0.55		n.d.	n.d.	n.d.	n.d.	0.49		Azevedo da Silva (2007)
05-053	Survey testimony in the Sapopema region (limit between the states of PR and SP) code SP 52	2			0.45		n.d.	n.d.	n.d.	n.d.	0.46		Azevedo da Silva (2007)
05-054	Survey testimony in the Sapopema region (limit between the states of PR and SP) code SP 53	2	320		0.61		n.d.	n.d.	n.d.	n.d.	0.57		Azevedo da Silva (2007)
05-057	Survey testimony in the Sapopema region (limit between the states of PR and SP) code SP 40	2			0.54		n.d.	n.d.	n.d.	n.d.	0.77		Azevedo da Silva (2007)
05-058	Survey testimony in the Sapopema region (limit between the states of PR and SP) code SP 46	2			0.51		n.d.	n.d.	n.d.	n.d.	0.58		Azevedo da Silva (2007)
05-059	Survey testimony in the Sapopema region (limit between the states of PR and SP) code SP 35	2			0.27		n.d.	n.d.	n.d.	n.d.	0.57		Azevedo da Silva (2007)
05-060	Survey testimony in the Sapopema region (limit between the states of PR and SP) code SP 50	2			0.58		n.d.	n.d.	n.d.	n.d.	0.44		Azevedo da Silva (2007)
05-061	Survey testimony in the Sapopema region (limit between the states of PR and SP) code SP 48	2			0.41		n.d.	n.d.	n.d.	n.d.	0.94		Azevedo da Silva (2007)

05-062	Survey testimony in the Sapopema region (limit between the states of PR and SP) code SP 56	2			0.26		n.d.	n.d.	n.d.	n.d.	2.38		Azevedo da Silva (2007)
05-063	Survey testimony in the Sapopema region (limit between the states of PR and SP) code SP 55	2			0.58		n.d.	n.d.	n.d.	n.d.	0.62		Azevedo da Silva (2007)
H11	Well SP-60-PR in the city of Sapopema (PR)	1	455.6		12.4		nc	nc		nc			Euzébio et al. (2016)
H10	Well SP-60-PR in the city of Sapopema (PR)	1	456.5		7.12	II	2.51	42.56		424			Euzébio et al. (2016)
H9	Well SP-60-PR in the city of Sapopema (PR)	1	456.9		7.65	I	2.35	46.43		421			Euzébio et al. (2016)
H8	Well SP-60-PR in the city of Sapopema (PR)	1	457.3		9.33	I	2.95	58.42		423			Euzébio et al. (2016)
H7	Well SP-60-PR in the city of Sapopema (PR)	1	458		5.3	II	2.43	31.26		419			Euzébio et al. (2016)
H6	Well SP-60-PR in the city of Sapopema (PR)	1	458.5		9.47	II	3.24	59.02		422			Euzébio et al. (2016)
H5	Well SP-60-PR in the city of Sapopema (PR)	1	459.6		4.25	II	2.32	16.05		413			Euzébio et al. (2016)
H4	Well SP-60-PR in the city of Sapopema (PR)	1	458.8		5.9	II	3.32	34.65		420			Euzébio et al. (2016)
H3	Well SP-60-PR in the city of Sapopema (PR)	1	459.9		5.91	II	2.73	27.84		414			Euzébio et al. (2016)
H2	Well SP-60-PR in the city of Sapopema (PR)	1	460.3		6.36	I	3.11	35.07		418			Euzébio et al. (2016)
H1	Well SP-60-PR in the city of Sapopema (PR)	1	460.9		5.14	I	3.74	36.19		425			Euzébio et al. (2016)
G6	Well SP-60-PR in the city of Sapopema (PR)	1	461.3		5.26	II	6.78	35.93		420			Euzébio et al. (2016)
G5	Well SP-60-PR in the city of Sapopema (PR)	1	462		4.07	II	2.58	19.72		412			Euzébio et al. (2016)
G4	Well SP-60-PR in the city of Sapopema (PR)	1	462.9		3.16	II	2.26	18.89		420			Euzébio et al. (2016)
G3	Well SP-60-PR in the city of Sapopema (PR)	1	463		4.53	II	3.48	25.04		413			Euzébio et al. (2016)

G2	Well SP-60-PR in the city of Sapopema (PR)	1	464		2.82	II	3.31	10.31		411			Euzébio et al. (2016)
G1	Well SP-60-PR in the city of Sapopema (PR)	1	465.4		0.94	III	0.19	1.22		415			Euzébio et al. (2016)
F2	Well SP-60-PR in the city of Sapopema (PR)	1	467		0.55	IV	0.02	0.12		424			Euzébio et al. (2016)
F1	Well SP-60-PR in the city of Sapopema (PR)	1	468		1.49	III	0.08	1.09		425			Euzébio et al. (2016)
E7	Well SP-60-PR in the city of Sapopema (PR)	1	468.9		3.69	III	0.08	1.09		425			Euzébio et al. (2016)
E6	Well SP-60-PR in the city of Sapopema (PR)	1	469		8.72	II	2.63	48.35		416			Euzébio et al. (2016)
E5	Well SP-60-PR in the city of Sapopema (PR)	1	469.4		1.06	II/III	0.29	2.22		422			Euzébio et al. (2016)
E4	Well SP-60-PR in the city of Sapopema (PR)	1	471		1.38	II/III	0.42	3.16		405			Euzébio et al. (2016)
E3	Well SP-60-PR in the city of Sapopema (PR)	1	471.1		3.71	II	1.37	11.78		409			Euzébio et al. (2016)
E2	Well SP-60-PR in the city of Sapopema (PR)	1	471.6		2.99	II/III	0.96	6.65		403			Euzébio et al. (2016)
E1	Well SP-60-PR in the city of Sapopema (PR)	1	471.65		1.62	II/III	0.38	4.08		408			Euzébio et al. (2016)
D5	Well SP-60-PR in the city of Sapopema (PR)	1	471.75		2.82	II/III	0.97	7.75		408			Euzébio et al. (2016)
D4	Well SP-60-PR in the city of Sapopema (PR)	1	472.8		2.93	II	4.9	16.27		415			Euzébio et al. (2016)
D3	Well SP-60-PR in the city of Sapopema (PR)	1	473.8		3.06	II	3.89	15.59		410			Euzébio et al. (2016)
D2	Well SP-60-PR in the city of Sapopema (PR)	1	474.8		2.27	II	2.85	10.92		413			Euzébio et al. (2016)
D1	Well SP-60-PR in the city of Sapopema (PR)	1	475.8		2.52	II	2.94	13.33		412			Euzébio et al. (2016)
C5	Well SP-60-PR in the city of Sapopema (PR)	1	476.1		1.03	II	0.6	3.4		408			Euzébio et al. (2016)
C4	Well SP-60-PR in the city of Sapopema (PR)	1	477.1		0.57	III	0.04	0.33		427			Euzébio et al. (2016)
C3	Well SP-60-PR in the city of Sapopema (PR)	1	479.1		0.41	III	0.05	0.25		428			Euzébio et al. (2016)
C2	Well SP-60-PR in the city of Sapopema (PR)	1	482.1		0.75	III	0.03	0.86		438			Euzébio et al. (2016)

C1	Well SP-60-PR in the city of Sapopema (PR)	1	485.15		0.64	IV	0.01	0.29		426			Euzébio et al. (2016)
B1	Well SP-60-PR in the city of Sapopema (PR)	1	486.15		0.95	II/III	0.1	2.82		436			Euzébio et al. (2016)
A4	Well SP-60-PR in the city of Sapopema (PR)	1	487.15		0.71	III	0.03	0.65		429			Euzébio et al. (2016)
A3	Well SP-60-PR in the city of Sapopema (PR)	1	492.3		0.45	IV	0.02	0.11		428			Euzébio et al. (2016)
A2	Well SP-60-PR in the city of Sapopema (PR)	1	496.1		0.56	IV	0.01	0.13		424			Euzébio et al. (2016)
A1	Well SP-60-PR in the city of Sapopema (PR)	1	498.7		0.42	IV	0.05	0.06		429			Euzébio et al. (2016)
G92	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.33								Lages (2004)
G91	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.78								Lages (2004)
G90	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.4								Lages (2004)
G89	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.36								Lages (2004)
G88	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.34								Lages (2004)
G87	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	3.42								Lages (2004)
G86	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	1.82								Lages (2004)
G85	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.3								Lages (2004)
G84	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.82								Lages (2004)
G83	FP-01-PR, CPRM	1	401	23	4.19								Lages

	well, NE Paraná state, Sapopema city													(2004)
G82	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.36									Lages (2004)
G81	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.42									Lages (2004)
G80	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	7.09									Lages (2004)
G79	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	1.84									Lages (2004)
G78	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.92									Lages (2004)
G77	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.38									Lages (2004)
G76	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	1.96									Lages (2004)
G75	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.26									Lages (2004)
G74	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.85									Lages (2004)
G73	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.45									Lages (2004)
G72	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	3.18									Lages (2004)
G71	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.62									Lages (2004)
G70	FP-01-PR, CPRM well, NE Paraná state,	1	401	23	7.49									Lages (2004)

	Sapopema city												
G69	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.47								Lages (2004)
G68	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	5.98								Lages (2004)
G67	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	6.97								Lages (2004)
G66	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.1								Lages (2004)
G65	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.39								Lages (2004)
G64	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.43								Lages (2004)
G63	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.35								Lages (2004)
G62	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.29								Lages (2004)
G61	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	2								Lages (2004)
G60	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	8.4								Lages (2004)
G59	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.73								Lages (2004)
G58	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.44								Lages (2004)
G57	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	1.06								Lages (2004)

G56	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	2.38								Lages (2004)
G55	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.4								Lages (2004)
G54	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	5.63								Lages (2004)
G53	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	5.06								Lages (2004)
G52	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	2.81								Lages (2004)
G51	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	1.58								Lages (2004)
G50	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	2.45								Lages (2004)
G49	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	0.43								Lages (2004)
G48	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	23	7.58								Lages (2004)
G47	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.68								Lages (2004)
G46	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.4								Lages (2004)
G45	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.45								Lages (2004)
G44	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.44								Lages (2004)
G43	FP-01-PR, CPRM	1	401	21.5	6.8								Lages

	well, NE Paraná state, Sapopema city													(2004)
G42	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.48									Lages (2004)
G41	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	1.08									Lages (2004)
G40	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.77									Lages (2004)
G39	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	1.42									Lages (2004)
G38	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.44									Lages (2004)
G37	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.51									Lages (2004)
G36	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.35									Lages (2004)
G35	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.22									Lages (2004)
G34	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.57									Lages (2004)
G33	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	3.29									Lages (2004)
G32	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	4.45									Lages (2004)
G31	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	3.91									Lages (2004)
G30	FP-01-PR, CPRM well, NE Paraná state,	1	401	21.5	0.57									Lages (2004)

	Sapopema city												
G29	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.42								Lages (2004)
G28	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	1.57								Lages (2004)
G27	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.39								Lages (2004)
G26	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	7.72								Lages (2004)
G25	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.38								Lages (2004)
G24	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	1.89								Lages (2004)
G23	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	3.64								Lages (2004)
G22	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.38								Lages (2004)
G21	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.36								Lages (2004)
G20	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.32								Lages (2004)
G19	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	1.09								Lages (2004)
G18	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.47								Lages (2004)
G17	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	7.37								Lages (2004)

G16	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	3.44								Lages (2004)
G15	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.3								Lages (2004)
G14	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.34								Lages (2004)
G13	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.42								Lages (2004)
G12	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.33								Lages (2004)
G11	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.37								Lages (2004)
G10	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.31								Lages (2004)
G09	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	2.14								Lages (2004)
G08	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.47								Lages (2004)
G07	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	1.22								Lages (2004)
G06	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	1.8								Lages (2004)
G05	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.43								Lages (2004)
G04	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	0.41								Lages (2004)
G03	FP-01-PR, CPRM	1	401	21.5	0.4								Lages

	well, NE Paraná state, Sapopema city												(2004)
G02	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	1.94								Lages (2004)
G01	FP-01-PR, CPRM well, NE Paraná state, Sapopema city	1	401	21.5	8.48								Lages (2004)
BON-01	Bonanza Mining, city of Ipeúna (SP)	1	200	15	5.31	II	1.4	28.6	0.3	426			Lisboa (2006)
BON-02	Bonanza Mining, city of Ipeúna (SP)	1	200	15	3.71	II	1.3	20.9	0.2	415			Lisboa (2006)
CAL-01	Calgi Mining, city of Saltinho (SP)	1	280	33	14.3	I	3.1	100	2	425			Lisboa (2006)
CAL-02	Calgi Mining, city of Saltinho (SP)	1	280	33	4.88	I	2.3	30.9	0.3	414			Lisboa (2006)
CAL-03	Calgi Mining, city of Saltinho (SP)	1	280	33	5.05	I	3.1	39	0.1	411			Lisboa (2006)
PAR-01	Partezani Mining, city of Assistência (SP)	1	100	15	5.56	II	14.6	18.3	0.3	426			Lisboa (2006)
PAR-02	Partezani Mining, city of Assistência (SP)	1	100	15	1.31	IV	0	0	0.3	325			Lisboa (2006)
PAR-03	Partezani Mining, city of Assistência (SP)	1	100	15	1.1	IV	0.1	0.2	0.2	407			Lisboa (2006)
PAR-04	Partezani Mining, city of Assistência (SP)	1	100	15	2.34	IV	0.2	0.3	0.3	398			Lisboa (2006)
PAR-05	Partezani Mining, city of Assistência (SP)	1	100	15	0.55	IV	0	0.1	0.2	487			Lisboa (2006)
CRU-01	Embracal Cruzeiro Mining, city of Laranjal Paulista (SP)	1	220	15	5.52	I	3.8	34.3	0.3	387			Lisboa (2006)
CRU-02	Embracal Cruzeiro Mining, city of Laranjal Paulista (SP)	1	220	15	8.09	I	5	53	0.5	395			Lisboa (2006)
VIT-01	Vitti Mining, city of Saltinho (SP)	1	250	15	0.02		-	-	-	-			Lisboa (2006)
VIT-02	Vitti Mining, city of Saltinho (SP)	1	250	15	0.02		-	-	-	-			Lisboa (2006)
VIT-03	Vitti Mining, city of Saltinho (SP)	1	250	15	4.62	II	2.8	25.5	0.5	396			Lisboa (2006)

VIT-04	Vitti Mining, city of Saltinho (SP)	1	250	15	5.31	II	2.8	28.9	0.5	400			Lisboa (2006)
VIT-05	Vitti Mining, city of Saltinho (SP)	1	250	15	6.17	I	3.8	43	0.3	407			Lisboa (2006)
OLE-02	Vitti Mining, city of Olegário (SP)	1	200	15	5.61	II	3.4	33.4	0.6	391			Lisboa (2006)
OLE-03	Vitti Mining, city of Olegário (SP)	1	200	15	5.45	I	3.2	37.8	0.4	399			Lisboa (2006)
STA-01	Stavias Mining, city of Assistência (SP)	1	150	10	6.17	I	3.8	43	0.3	407			Lisboa (2006)
STA-02	Stavias Mining, city of Assistência (SP)	1	150	10	5.61	II	3.4	33.4	0.6	391			Lisboa (2006)
FP-07-T1	(São Mateus do Sul, PR) - Located in the SW flank of the Ponta Grossa Arc	2	78.6	43.5	14.7							Quartz, albite, chlorite, illite, pyrite	Ferreira (2017)
FP-07-T2	(São Mateus do Sul, PR) - Located in the SW flank of the Ponta Grossa Arc	2	78.6	43.5	14.34							Quartz, albite, chlorite, illite, pyrite	Ferreira (2017)
FP-07-T3	(São Mateus do Sul, PR) - Located in the SW flank of the Ponta Grossa Arc	2	78.6	43.5	9.8							Quartz, albite, chlorite, illite, pyrite	Ferreira (2017)
FP-07-T4	(São Mateus do Sul, PR) - Located in the SW flank of the Ponta Grossa Arc	2	78.6	43.5	9.73							Quartz, albite, chlorite, illite, pyrite	Ferreira (2017)
FP-07-T5	(São Mateus do Sul, PR) - Located in the SW flank of the Ponta Grossa Arc	2	78.6	43.5	11.24							Quartz, albite, chlorite, illite, pyrite	Ferreira (2017)
FP-07-T6	(São Mateus do Sul, PR) - Located in the SW flank of the Ponta Grossa Arc	2	78.6	43.5	10.3							Quartz, albite, chlorite, illite, pyrite	Ferreira (2017)
FP-07-B1	(Ortigueira, PR) - Close to the Ponta Grossa Axis	2	78.6	43.5	0.55							Quartz, albite, chlorite, illite,	Ferreira (2017)

												dolomite (?), pyrite	
FP-07-B2	(Ortigueira, PR) - Close to the Ponta Grossa Axis	2	78.6	43.5	0.5							Quartz, albite, chlorite, illite, dolomite (?), pyrite	Ferreira (2017)
FP-07-B3	(Ortigueira, PR) - Close to the Ponta Grossa Axis	2	78.6	43.5	0.52							Quartz, albite, chlorite, illite, dolomite (?), pyrite	Ferreira (2017)
FP-07-B4	(Ortigueira, PR) - Close to the Ponta Grossa Axis	2	78.6	43.5	0.38							Quartz, albite, chlorite, illite, dolomite (?), pyrite	Ferreira (2017)
FP-07-B5	(Ortigueira, PR) - Close to the Ponta Grossa Axis	2	78.6	43.5	0.64							Quartz, albite, chlorite, illite, dolomite (?), pyrite	Ferreira (2017)
FP-07-B6	(Ortigueira, PR) - Close to the Ponta Grossa Axis	2	78.6	43.5	0.62							Quartz, albite, chlorite, illite, dolomite (?), pyrite	Ferreira (2017)
FP-07-B7	(Ortigueira, PR) - Close to the Ponta Grossa Axis	2	78.6	43.5	0.43							Quartz, albite, chlorite, illite, dolomite (?), pyrite	Ferreira (2017)
FP-07-B8	(Ortigueira, PR) - Close to the Ponta	2	78.6	43.5	0.39							Quartz, albite,	Ferreira (2017)

	Grossa Axis											chlorite, illite, dolomite (?), pyrite	
FP-07-B9	(Ortigueira, PR) - Close to the Ponta Grossa Axis	2	78.6	43.5	0.41							Quartz, albite, chlorite, illite, dolomite (?), pyrite	Ferreira (2017)
FP-11-T1	(Ortigueira, PR) - Close to the Ponta Grossa Axis	2	350.8	34	0.46							Quartz, albite, chlorite, illite, calcite, pyrite	Ferreira (2017)
FP-11-T2	(Ortigueira, PR) - Close to the Ponta Grossa Axis	2	350.8	34	0.3							Quartz, albite, chlorite, illite, calcite, pyrite	Ferreira (2017)
FP-11-T3	(Ortigueira, PR) - Close to the Ponta Grossa Axis	2	350.8	34	0.35							Quartz, albite, chlorite, illite, calcite, pyrite	Ferreira (2017)
FP-11-T4	(Ortigueira, PR) - Close to the Ponta Grossa Axis	2	350.8	34	0.36							Quartz, albite, chlorite, illite, calcite, pyrite	Ferreira (2017)
FP-11-B1	(Ortigueira, PR) - Close to the Ponta Grossa Axis	2	350.8	34	0.64							Quartz, albite, chlorite, illite, calcite, pyrite (?)	Ferreira (2017)

FP-11-B2	(Ortigueira, PR) - Close to the Ponta Grossa Axis	2	350.8	34	0.32							Quartz, albite, chlorite, illite, calcite, pyrite (?)	Ferreira (2017)
FP-11-B3	(Ortigueira, PR) - Close to the Ponta Grossa Axis	2	350.8	34	0.34							Quartz, albite, chlorite, illite, calcite, pyrite (?)	Ferreira (2017)
FP-11-B4	(Ortigueira, PR) - Close to the Ponta Grossa Axis	2	350.8	34	2.29							Quartz, albite, chlorite, illite, calcite, pyrite (?)	Ferreira (2017)
FP-11-B5	(Ortigueira, PR) - Close to the Ponta Grossa Axis	2	350.8	34	0.36							Quartz, albite, chlorite, illite, calcite, pyrite (?)	Ferreira (2017)
FP12-T1	(Anhembi, SP) - Located NE Ponta Grossa Arc	2	274.5	39.5	6.44							Quartz, albite, chlorite, illite, calcite, pyrite	Ferreira (2017)
FP12-T2	(Anhembi, SP) - Located NE Ponta Grossa Arc	2	274.5	39.5	3.74							Quartz, albite, chlorite, illite, calcite, pyrite	Ferreira (2017)
FP12-T3	(Anhembi, SP) - Located NE Ponta Grossa Arc	2	274.5	39.5	5.01							Quartz, albite, chlorite, illite,	Ferreira (2017)

												calcite, pyrite	
FP12-T4	(Anhembi, SP) - Located NE Ponta Grossa Arc	2	274.5	39.5	3.43							Quartz, albite, chlorite, illite, calcite, pyrite	Ferreira (2017)
FP12-B1	(Anhembi, SP) - Located NE Ponta Grossa Arc	2	274.5	39.5	2.63							Quartz, albite, chlorite, illite, calcite, pyrite (?)	Ferreira (2017)
FP12-B2	(Anhembi, SP) - Located NE Ponta Grossa Arc	2	274.5	39.5	1.75							Quartz, albite, chlorite, illite, calcite, pyrite (?)	Ferreira (2017)
FP12-B3	(Anhembi, SP) - Located NE Ponta Grossa Arc	2	274.5	39.5	1.77							Quartz, albite, chlorite, illite, calcite, pyrite (?)	Ferreira (2017)
FP12-B4	(Anhembi, SP) - Located NE Ponta Grossa Arc	2	274.5	39.5	1.88							Quartz, albite, chlorite, illite, calcite, pyrite (?)	Ferreira (2017)
FP12-B5	(Anhembi, SP) - Located NE Ponta Grossa Arc	2	274.5	39.5	1.86							Quartz, albite, chlorite, illite, calcite, pyrite (?)	Ferreira (2017)
FP12-B6	(Anhembi, SP) - Located NE Ponta	2	274.5	39.5	1.64							Quartz, albite,	Ferreira (2017)

	Grossa Arc											chlorite, illite, calcite, pyrite (?)	
FP12-B7	(Anhembi, SP) - Located NE Ponta Grossa Arc	2	274.5	39.5	1.43							Quartz, albite, chlorite, illite, calcite, pyrite (?)	Ferreira (2017)
FP12-B8	(Anhembi, SP) - Located NE Ponta Grossa Arc	2	274.5	39.5	1.4							Quartz, albite, chlorite, illite, calcite, pyrite (?)	Ferreira (2017)
IP-41	Outcrop in the SP-308 road, near to the city of Ipeúna (SP)	2	200	5	1.77								Oliveira (2012)
IP-40	Outcrop in the SP-308 road, near to the city of Ipeúna (SP)	2	200	3	0.43								Oliveira (2012)
IP-30	Outcrop in the SP-127 road, between the cities of Rio das Pedras and Tietê (SP)	2	200	20	6.15								Oliveira (2012)
IP-31	Outcrop in the SP-127 road, between the cities of Rio das Pedras and Tietê (SP)	2	200	25	7.1								Oliveira (2012)
IP-42-F1	Outcrop in the SP-127 road, close to the city of Iracemópolis (SP)	2	280	15-20	2.61								Oliveira (2012)
IP-42-F2	Outcrop in the SP-127 road, close to the city of Iracemópolis (SP)	2	280	15-20	2.61								Oliveira (2012)
IP-42-F3	Outcrop in the SP-127 road, close to the city of Iracemópolis (SP)	2	280	15-20	2.24								Oliveira (2012)
IP-42-F4	Outcrop in the SP-127	2	280	15-20	1.93								Oliveira

	road, close to the city of Iracemópolis (SP)												(2012)
IP-42-F5	Outcrop in the SP-127 road, close to the city of Iracemópolis (SP)	2	280	15-20	2.32								Oliveira (2012)
IP-42-F6	Outcrop in the SP-127 road, close to the city of Iracemópolis (SP)	2	280	15-20	2.63								Oliveira (2012)
IP-42-F7	Outcrop in the SP-127 road, close to the city of Iracemópolis (SP)	2	280	15-20	2.13								Oliveira (2012)
IP-42- F8	Outcrop in the SP-127 road, close to the city of Iracemópolis (SP)	2	280	15-20	2.31								Oliveira (2012)
IP-42- F9	Outcrop in the SP-127 road, close to the city of Iracemópolis (SP)	2	280	15-20	2.31								Oliveira (2012)
IP-42-F10	Outcrop in the SP-127 road, close to the city of Iracemópolis (SP)	2	280	15-20	2.11								Oliveira (2012)
IP-42-F11	Outcrop in the SP-127 road, close to the city of Iracemópolis (SP)	2	280	15-20	2.86								Oliveira (2012)
IP-42-F12	Outcrop in the SP-127 road, close to the city of Iracemópolis (SP)	2	280	15-20	3.03								Oliveira (2012)
IP-42-F13	Outcrop in the SP-127 road, close to the city of Iracemópolis (SP)	2	280	15-20	2.09								Oliveira (2012)
IP-42-F14	Outcrop in the SP-127 road, close to the city of Iracemópolis (SP)	2	280	15-20	1.51								Oliveira (2012)
IP-42-F15	Outcrop in the SP-127 road, close to the city of Iracemópolis (SP)	2	280	15-20	1.94								Oliveira (2012)
IP-42-F16	Outcrop in the SP-127 road, close to the city of Iracemópolis (SP)	2	280	15-20	2.79								Oliveira (2012)
IP-42-F17	Outcrop in the SP-127 road, close to the city	2	280	15-20	1.78								Oliveira (2012)

	of Iracemópolis (SP)												
IP-44-F5	Outcrop in the SP-151 road, between the cities of Iracemópolis and Limeira (SP)	2	100	14	1.52								Oliveira (2012)
IP-44-F6	Outcrop in the SP-151 road, between the cities of Iracemópolis and Limeira (SP)	2	100	14	2.15								Oliveira (2012)
IP-44-F7	Outcrop in the SP-151 road, between the cities of Iracemópolis and Limeira (SP)	2	100	14	2.03								Oliveira (2012)
IP-44- F8	Outcrop in the SP-151 road, between the cities of Iracemópolis and Limeira (SP)	2	100	14	2.31								Oliveira (2012)
IP-44- F9	Outcrop in the SP-151 road, between the cities of Iracemópolis and Limeira (SP)	2	100	14	2.31								Oliveira (2012)
IP-44-F10	Outcrop in the SP-151 road, between the cities of Iracemópolis and Limeira (SP)	2	100	14	2.11								Oliveira (2012)
IP-44-FA1	Outcrop in the SP-151 road, between the cities of Iracemópolis and Limeira (SP)	2	100	14	2.11								Oliveira (2012)
IP-44-FA2	Outcrop in the SP-151 road, between the cities of Iracemópolis and Limeira (SP)	2	100	14	2.08								Oliveira (2012)
IP-44-FA3	Outcrop in the SP-151 road, between the cities of Iracemópolis and Limeira (SP)	2	100	14	2.98								Oliveira (2012)
IP-44-FA4	Outcrop in the SP-151 road, between the cities of Iracemópolis	2	100	14	2.04								Oliveira (2012)

	and Limeira (SP)												
PR-03	Outcrop in the city of Irati (PR)	2	550		9.79								Oliveira (2012)
PR-04	Outcrop in the BR-354 road, between the cities of Irati and Rebouças (PR)	2	680		7.83								Oliveira (2012)
PR-05-A	Outcrop in the PR-151 road, close to the city of São Mateus do Sul (PR)	2	150	8	10.27								Oliveira (2012)
PR-05-B	Outcrop in the PR-151 road, close to the city of São Mateus do Sul (PR)	2	150	8	17.41								Oliveira (2012)
1	SP-32-PR well in the city of Sapopema, NE Paraná state	3	141.8		5.4		0.9	23.8		426		Quartz (40.5%), plagioclase (14%), pyrite (2%), analcime (2%), gysum (tr), illite/muscovite (39.5%)	Holanda et al. (2018)
2	SP-32-PR well in the city of Sapopema, NE Paraná state	3	142.7		3.8		2.2	19.8		415		Quartz (39.2%), plagioclase (14%), pyrite (tr), analcime (2.9%), gypsum (tr), illite/muscovite (42.9%)	Holanda et al. (2018)
3	SP-32-PR well in the city of Sapopema, NE Paraná state	3	143.3		14.4		4.5	85.6		422		Quartz (39.7%), plagioclase (15.6%), pyrite	Holanda et al. (2018)

												(1.9%), analcime (4.2%), gypsum (tr), illite/muscovite (42.9%)	
4	SP-32-PR well in the city of Sapopema, NE Paraná state	3	146.2		8.2		3.4	44.7		413		Quartz (36.1%), plagioclase (14.6%), pyrite (3.2%), analcime (3.1%), gypsum (tr), illite/muscovite (42.5%)	Holanda et al. (2018)
5	SP-32-PR well in the city of Sapopema, NE Paraná state	3	148.3		3.2		3	19.2		417		Quartz (37%), plagioclase (15%), illite/muscovite (43%), expanded chlorite (5%)	Holanda et al. (2018)
6	SP-32-PR well in the city of Sapopema, NE Paraná state	3	151.8		1.5		1	6.1		407		Quartz (37.1%), plagioclase (14.5%), illite/muscovite (43.3%), expanded chlorite (5.1%)	Holanda et al. (2018)
7	SP-32-PR well in the city of Sapopema, NE Paraná state	3	153.1		0.8		0	0.4		425		Quartz (37%), plagioclase (18.4%),	Holanda et al. (2018)

												illite/muscovite (44.6%)	
8	SP-32-PR well in the city of Sapopema, NE Paraná state	3	155.5		1.6		1.7	6.4		383		Quartz (29.2%), plagioclase (16.3%), illite/muscovite (37.7%), chlorite (9.4%), kaolinite (7.4%)	Holanda et al. (2018)
9	SP-32-PR well in the city of Sapopema, NE Paraná state	3	156.8		0.9		1.1	5.6		412		Quartz (32.4%), plagioclase (15.9%), illite/muscovite (37.6%), chlorite (8.5%), kaolinite (5.6%)	Holanda et al. (2018)
10	SP-32-PR well in the city of Sapopema, NE Paraná state	3	158.5		1.1		0.7	4.2		402		Quartz (30.5%), plagioclase (14.8%), illite/muscovite (38.7%), chlorite (11.8%), kaolinite (4.2%)	Holanda et al. (2018)

11	SP-32-PR well in the city of Sapopema, NE Paraná state	3	159.5		1.1		0.7	4.5		406		Quartz (19.7%), calcite (17.8%), dolomite (36.6%), illite/muscovite (16.5%), chlorite (6.6%), kaolinite (2.8%)	Holanda et al. (2018)